The loss of the early Martian atmosphere and its water inventory due to the active young Sun

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The case for a wet, warm Mars: But where is all the water and the atmosphere ?

- Observations of a network of valleys in crater rich areas of the southern hemisphere suggests that Mars had once a significant hydrologic activity [e.g., Carr Nature 326, 30, 1987; Baker Nature 412, 228, 2001; Carr & Head III JGR 108, E5, 5042, 2003]

- Asteroids and comets from beyond 2.5 AU provide the source of Mars' water, which totals 6 – 27 % of the Earth's present ocean equivalent to 600 – 2700 m depth on the Martian surface or in the crustal regolith [Lunine et al. Icarus 165, 1, 2003]

- Enrichment and fractionation of heavy isotopes [e.g., Pepin Icarus 111, 289, 1994]

- Estimations of volumes of potential early Martian water reservoirs from geo-morphological analysis of possible shorelines by MGS images and MOLA data $\rightarrow$ d $\approx$ 150 - 160 m [Carr & Head III JGR 108, E5, 5042, 2003]
  - Stored in present polar caps $\rightarrow$ d $\approx$ 20 - 30 m
  - Surface ground water $\rightarrow$ d $\approx$ 80 m ?
  - Escaped to space $\rightarrow$ d $\approx$ 50 - 80 m ?

- Early atmosphere $\approx$ 1 – 5 bars [e.g., Pollack, Kasting et al. Icarus 71, 203, 1987]

Thermal atmospheric loss processes

- **Thermal atmospheric loss** → **neutral particles**
  - **Jeans escape**
    - → light species (H, H_2) on present solar X-ray and EUV (XUV) conditions, dependent on planetary mass, thermospheric species and resulting exospheric temperature
    - → heavy atoms (O, C, N) during high solar XUV flux periods of the young Sun
  - **Hydrodynamic blow-off**
    - → light (H, H_2) but also heavy (O, C, N, etc.) species dependent on planetary mass, thermospheric species during high XUV periods of the young Sun

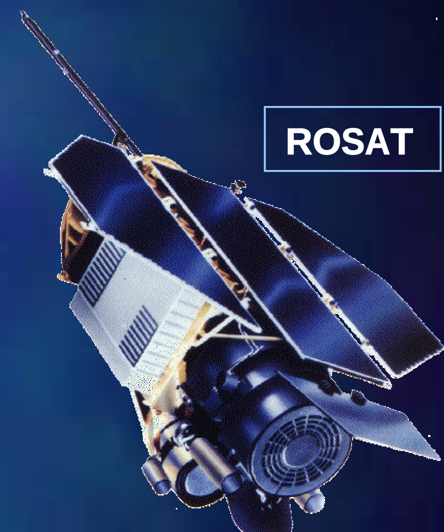
Non-Thermal atmospheric loss processes

- Non-thermal atmospheric loss → ionized but also neutral particles
  - Photo-chemical reactions
    → light and heavy species (H, O, N), which are released by photo-chemical reactions
  - Ion pick up (non-magnetized → reduced on early Mars)
    → light and heavy ions, which can be picked up by the solar wind plasma flow
  - Sputtering (non-magnetized → reduced on early Mars)
    → light and heavy species of the upper atmosphere can be sputtered by solar wind plasma if the planet has no or a weak magnetic field
  - Plasma instabilities (non-magnetized → reduced on early Mars)
    → all ion species at the ionopause-transition layer, dependent on the solar wind and ionospheric conditions
  - Momentum transport (non-magnetized → reduced on early Mars)
    → light and heavy ions, which have energies larger than the escape energy

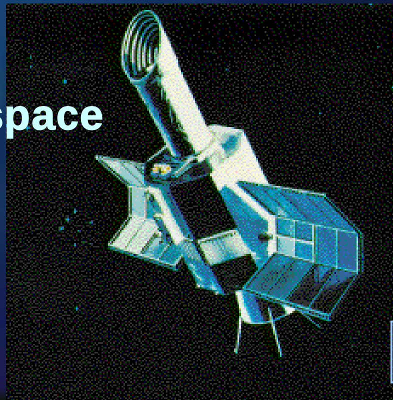
Solar irradiances and particle emission as function of time

Main Targets of the "Sun in Time" Program

Star	HD	Spectr. Type	M_V (mag)	$T_{\rm eff}$ (K)	Mass ($M_\odot$)	Dist. (pc)	$P_{\rm rot}$ (d)	Age (Gyr)	Age Indicator
47 Cas	12230	~G1 V	5.13	–	1.06	33.6	~1	0.07	Pleiades Stream
EK Dra	129333	G0 V	4.91	5818	1.07	33.9	2.75	0.10	Pleiades Stream
π^1 UMa	72905	G1.5 V	4.86	5840	0.98	14.3	4.68	0.3	UMa Stream
HN Peg	206860	G0 V	4.69	5970	1.06	18.4	4.86	0.3	$P_{\rm rot}$-Age Rel.
χ^1 Ori	39587	G1 V	4.72	5940	1.04	8.7	5.08	0.3	UMa Stream
9 Cet	1835	G3 V	4.84	5780	0.99	20.4	7.6	0.65	Hyades Stream
κ^1 Cet	20630	G5 V	5.02	5700	0.96	9.2	9.2	0.75	$P_{\rm rot}$-Age Rel.
β Com	114710	G0 V	4.51	5950	1.10	9.2	12.4	1.6	$P_{\rm rot}$-Age Rel.
15 Sge	190406	G1 V	4.60	5850	1.01	17.7	13.5	1.9	$P_{\rm rot}$-Age Rel.
Sun	–	G2 V	4.84	5777	1.00	1 AU	25.4	4.6	Isotopic Dating
18 Sco	146233	G2 V	4.79	5785	1.01	14.0	23	4.7	Isochrones
β Hyi	2151	G2 IV	3.45	5800	1.09	7.5	~28	6.6	Isochrones
16 Cyg A	186408	G1.5 V	4.32	5790	1.00	21.6	~35	8.5	Isochrones

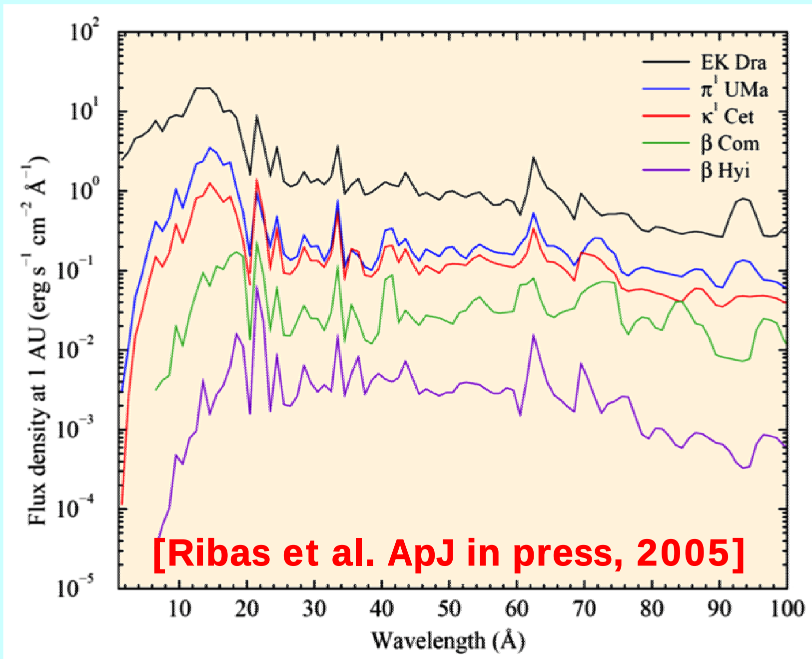


- High-energy radiation observations from space
- Stellar wind observations from space (Ly-α) and radio mm wavelengths
- Extended time series (several days) to evaluate short-term variability

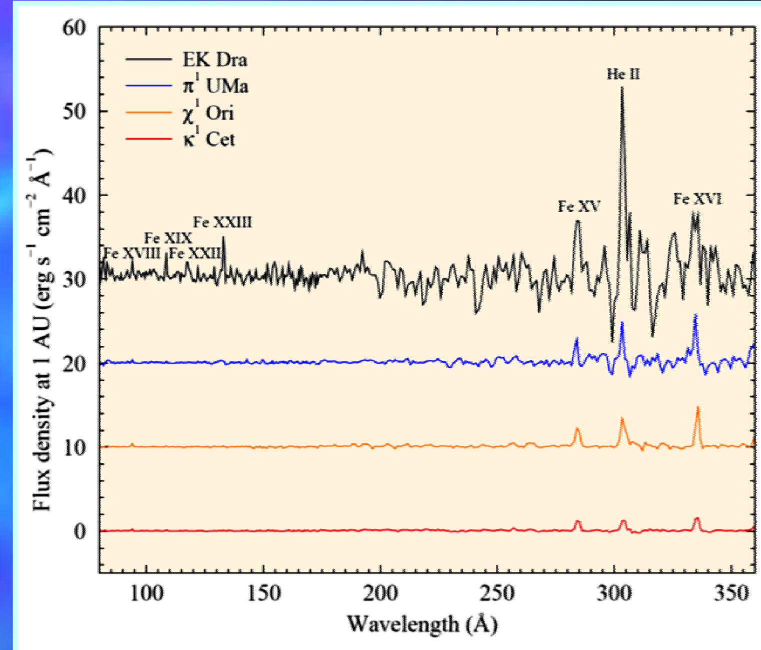


High-energy irradiances

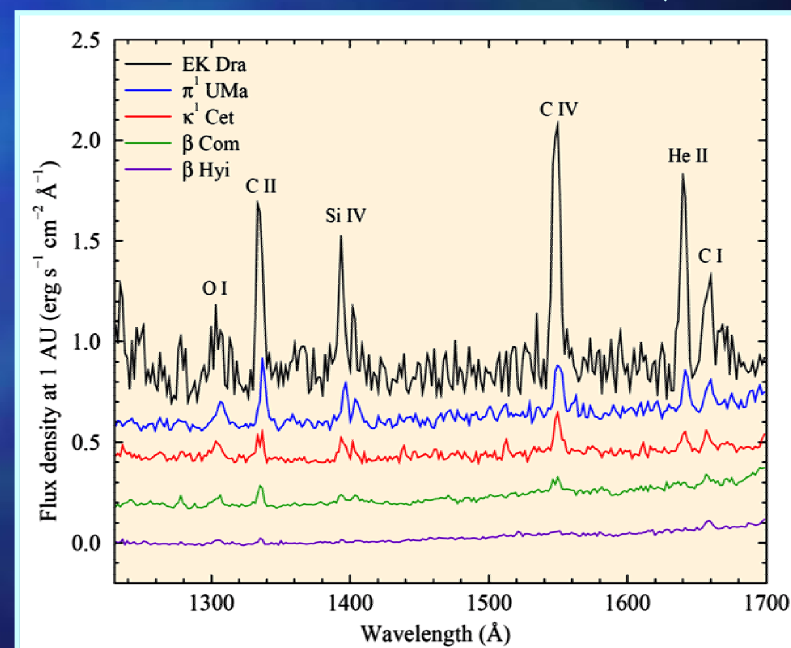
X-rays



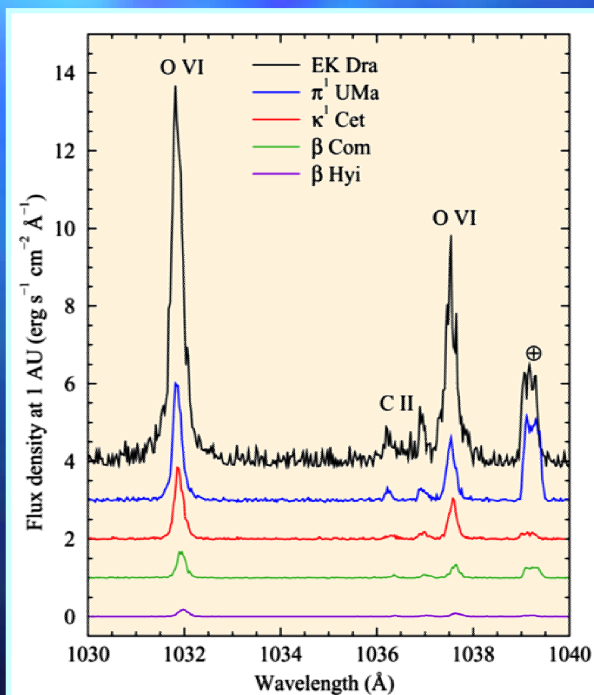
EUV



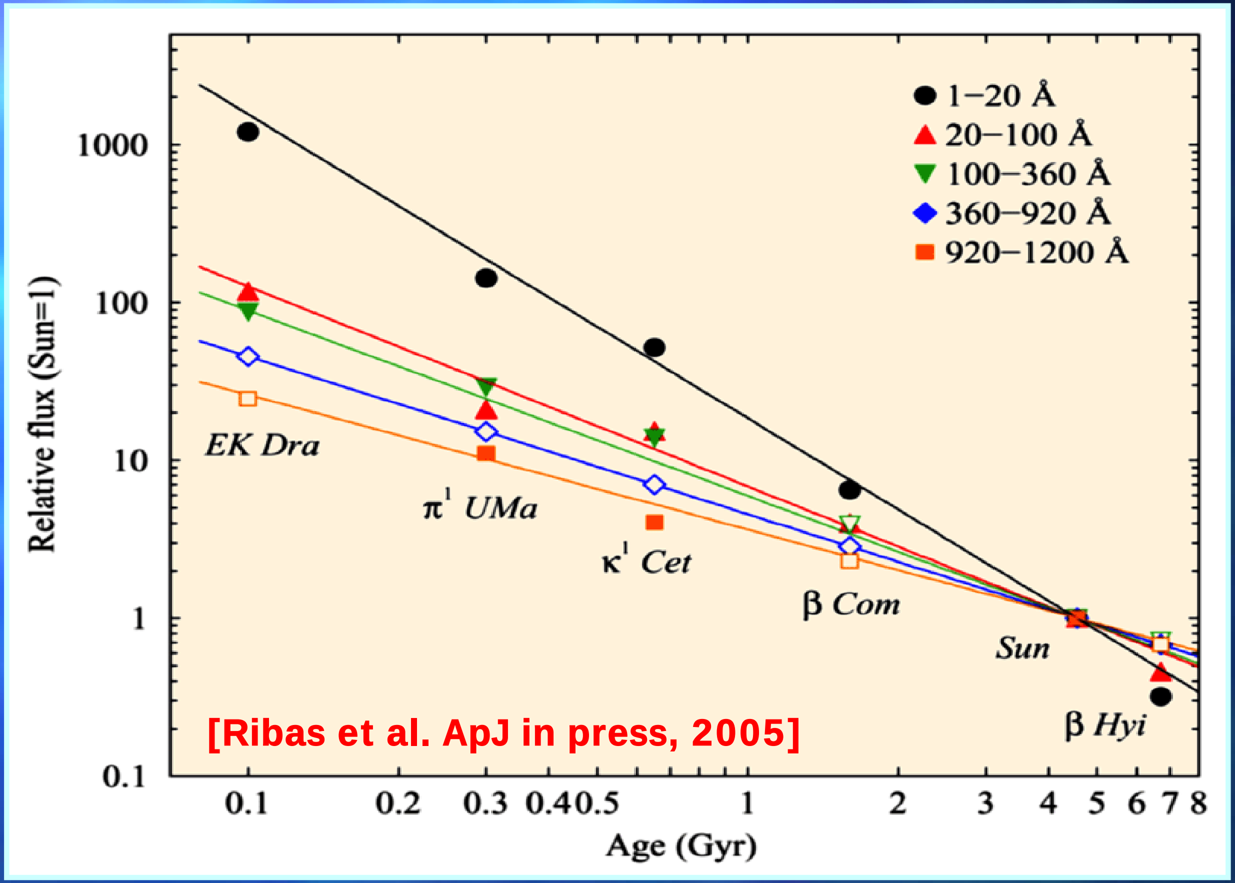
UV



FUV

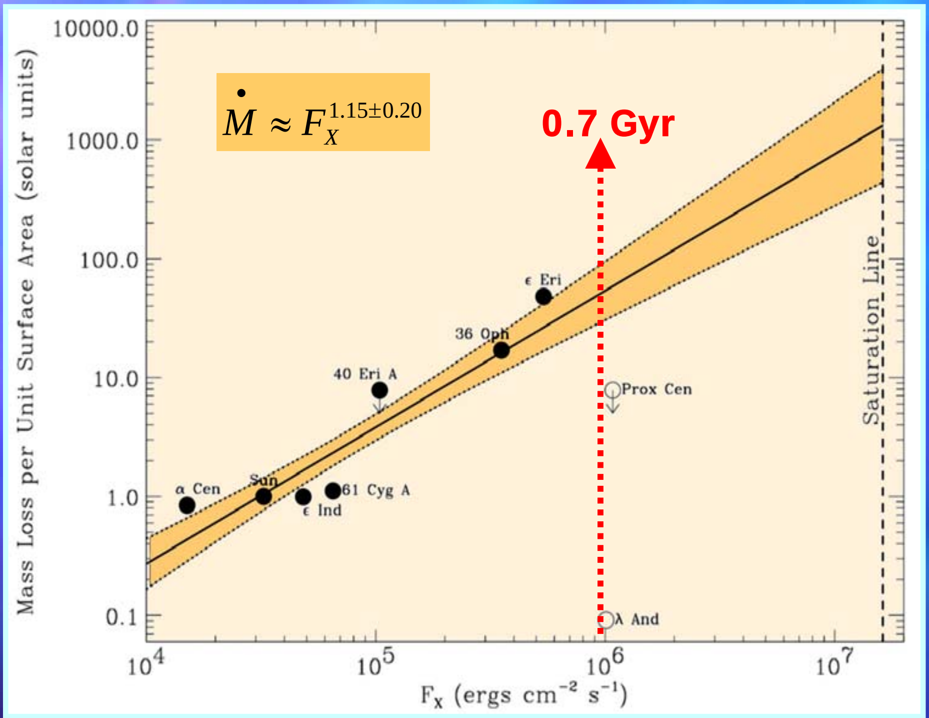


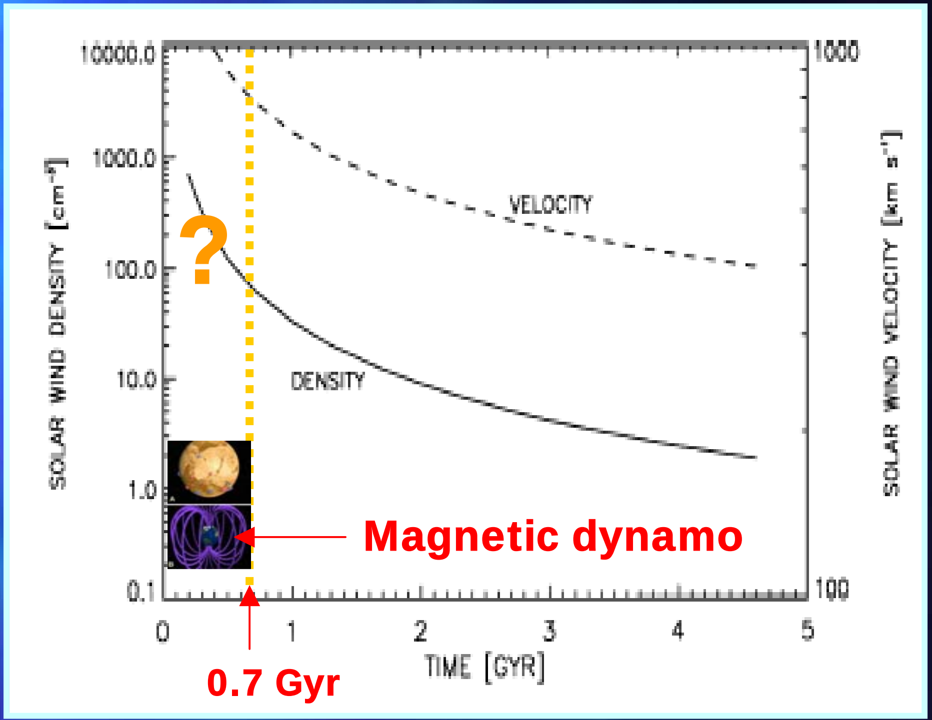
Solar X-ray and EUV evolution



- The flux density evolution scales well with power-law relationships
- The overall XUV flux (1 - 1200 Å) decreases with a slope of - 1.2 → 3× higher than today 2.5 Gyr ago, 6× 3.5 Gyr ago, 100× ZAMS!
- The important Ly-α line (1215 Å) decreases with a slope of - 0.72

Evolution of the solar wind density and velocity



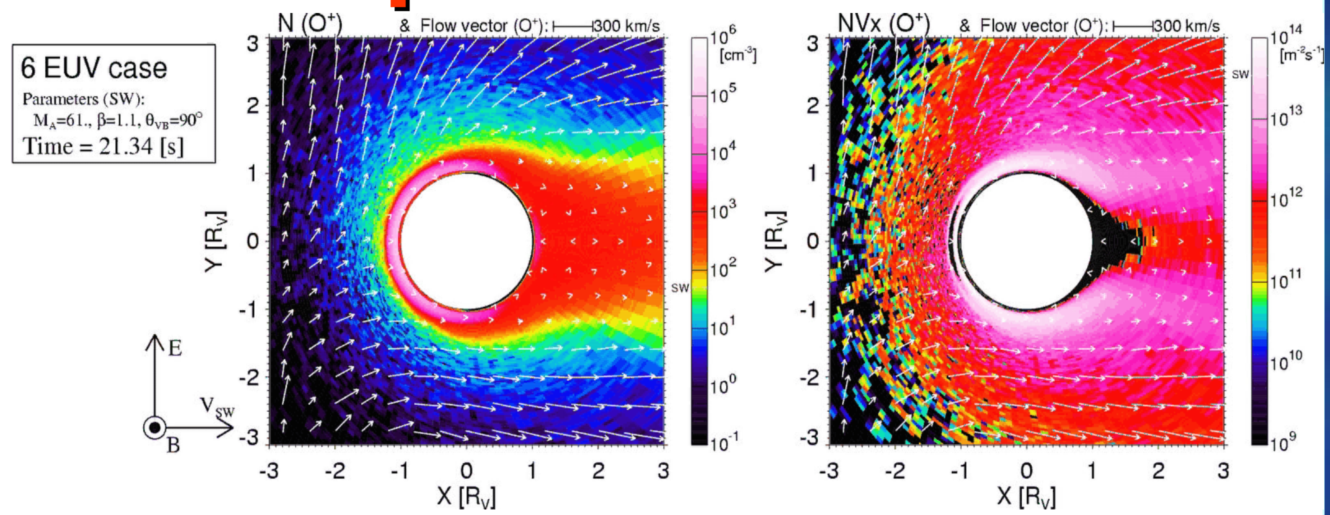


[Wood et al. ApJ, 574 (1), 412, 2002]

[Lammer et al. Icarus 125, 9, 2003]

- This is the last ingredient of stellar activity (stars have hot coronae and lose mass at a certain rate)
- The mass loss rate also seems to correlate with *L*x
- New observational campaigns of very young stars are going on
- Until we have no data for the first Gyr one has to be careful

Escape rates [s^{-1}] of various species from present Mars to 3.5 Gyr ago



[Terada et al. submitted to Icarus, 2005]

Species	Present	2.5 Gyr	3.5 Gyr
H_2O	9.5E+25	2.0E+26	2.5E+27
Total: O	6.4E+24	2.0E+26	2.5E+27
Pick up: O^+	3.0E+24	4.0E+25	8.3E+26
Dissociative recombination: O	6.0E+24	3.0E+25	8.0E+25
Sputtering: O	3.5E+23	1.3E+25	1.5E+27
Sputtering: CO_2	5.0E+22	2.3E+24	4.0E+25
Sputtering: CO	3.7E+22	2.0E+24	2.5E+25

[Lammer et al. Icarus 125, 9, 2003]

$$d = \frac{\Delta M}{4\pi R_M^2 \rho_{H_2O}},$$

d ≈ 12 m

Assuming a self-regulation mechanism between the loss of O and H as postulated by McElroy and Donahue [1972], we obtain a total H_2O loss over the past 3.5 Gyr of ≈ 12 m GEL (Global Equivalent Layer)

- **Test particle models and complex hybrid simulations give about similar results for total loss rates**

X-ray and EUV heating over Martian's history

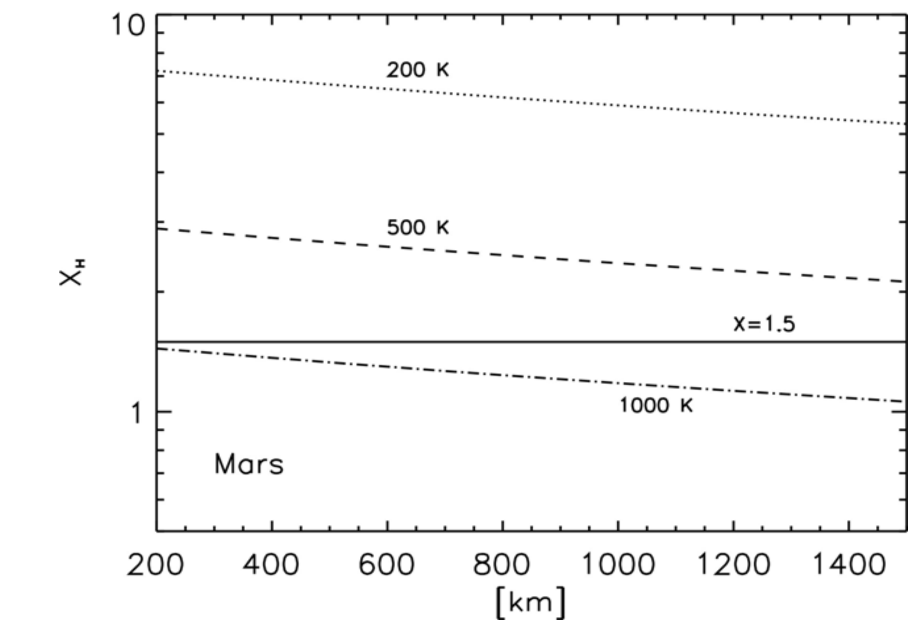
- Thermospheric model solves the equations
  - of continuity,
  - hydrostatic and heat balance
  - equations of vibrational kinetics for radiating molecules

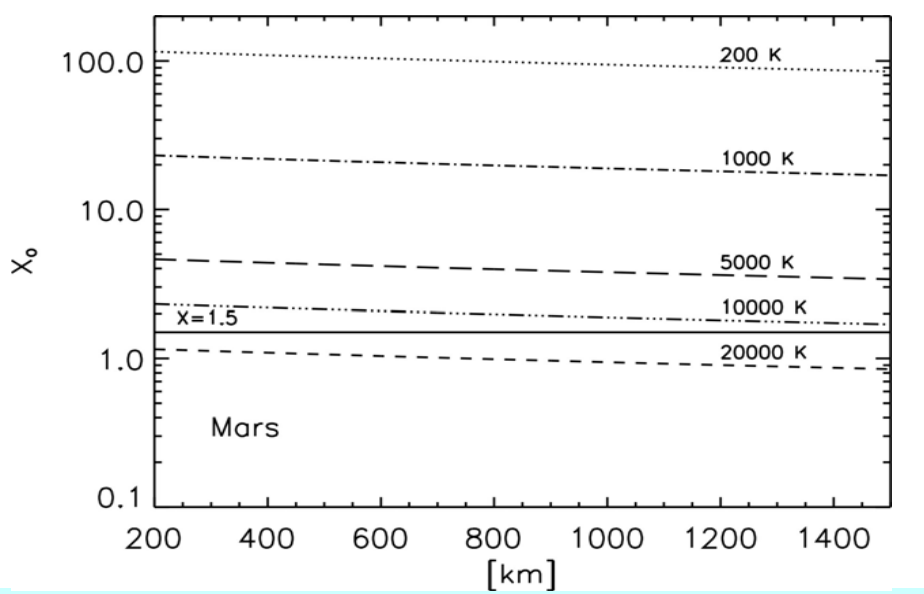
The applied model is self-consistent with respect to the neutral gas temperature and the vibrational temperatures of the minor species radiating (cooling) in the IR [e.g., Gordiets et al., JGR 87, 4504, 1982]

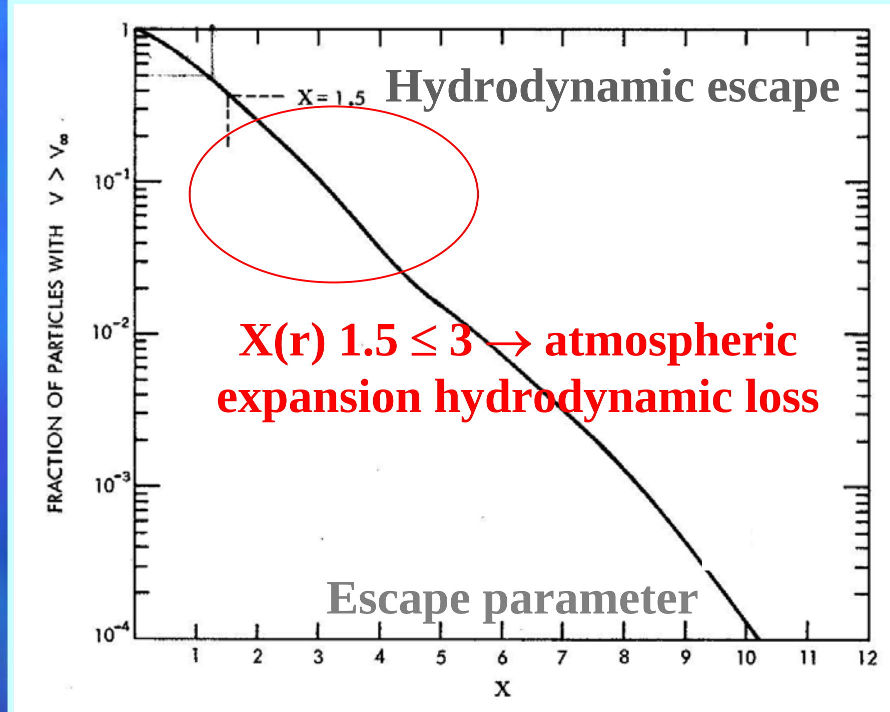
- Heating due to the N_2, O_2, and O photoionization by XUV-radiation ($\lambda \leq 1027$Å)
- Heating due to O_2, and O_3 photodissociation by solar UV-radiation, chemical heating in exothermic reactions with O and O_3
- Neutral gas heat conduction
- IR-cooling in the vibrational-rotational bands of CO_2, NO, O_3, OH, NO^+, $N^{14}N^{15}$, CO, in the 1.27 μm O_2 IR atmospheric band and in the 63 μm O line that strongly depends on the neutral atmosphere temperature
- Heating and cooling due to contraction and expansion of the thermosphere
- Turbulent energy dissipation and heat conduction

For dense CO_2 atmospheres the 15 μm CO_2 IR band is very important for cooling

Jeans escape parameter for H and O on Mars



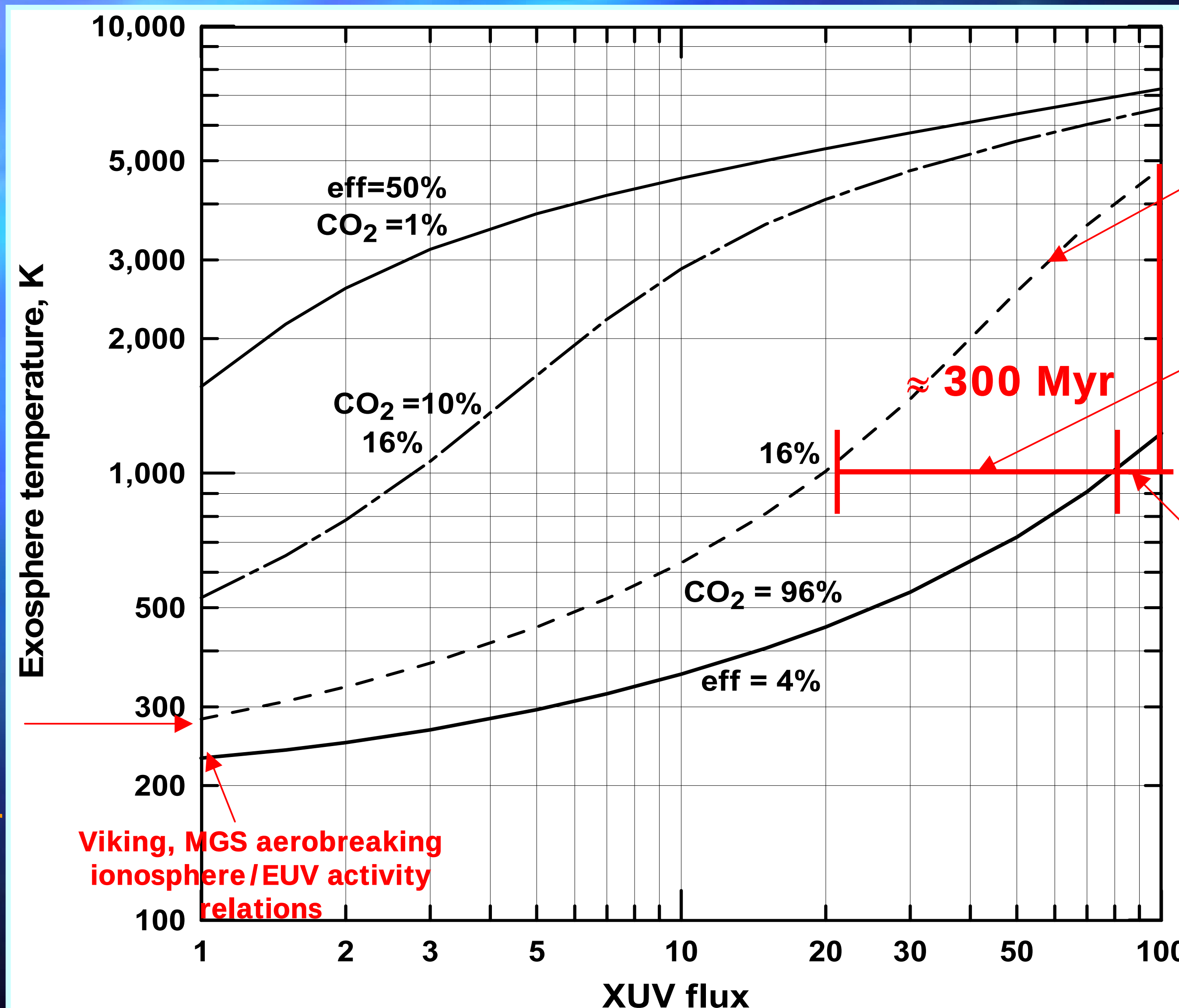




$$X(r)=\frac{GM_{Pl}m_i}{rkT_\infty}=\frac{v_{esc}^2}{v_0^2}$$

- Due to expansion H reaches blow-off → dynamic escape at temperatures around 800 - 1000 K

Evolution of the exospheric temperature



high O loss rates

dynamic loss of H

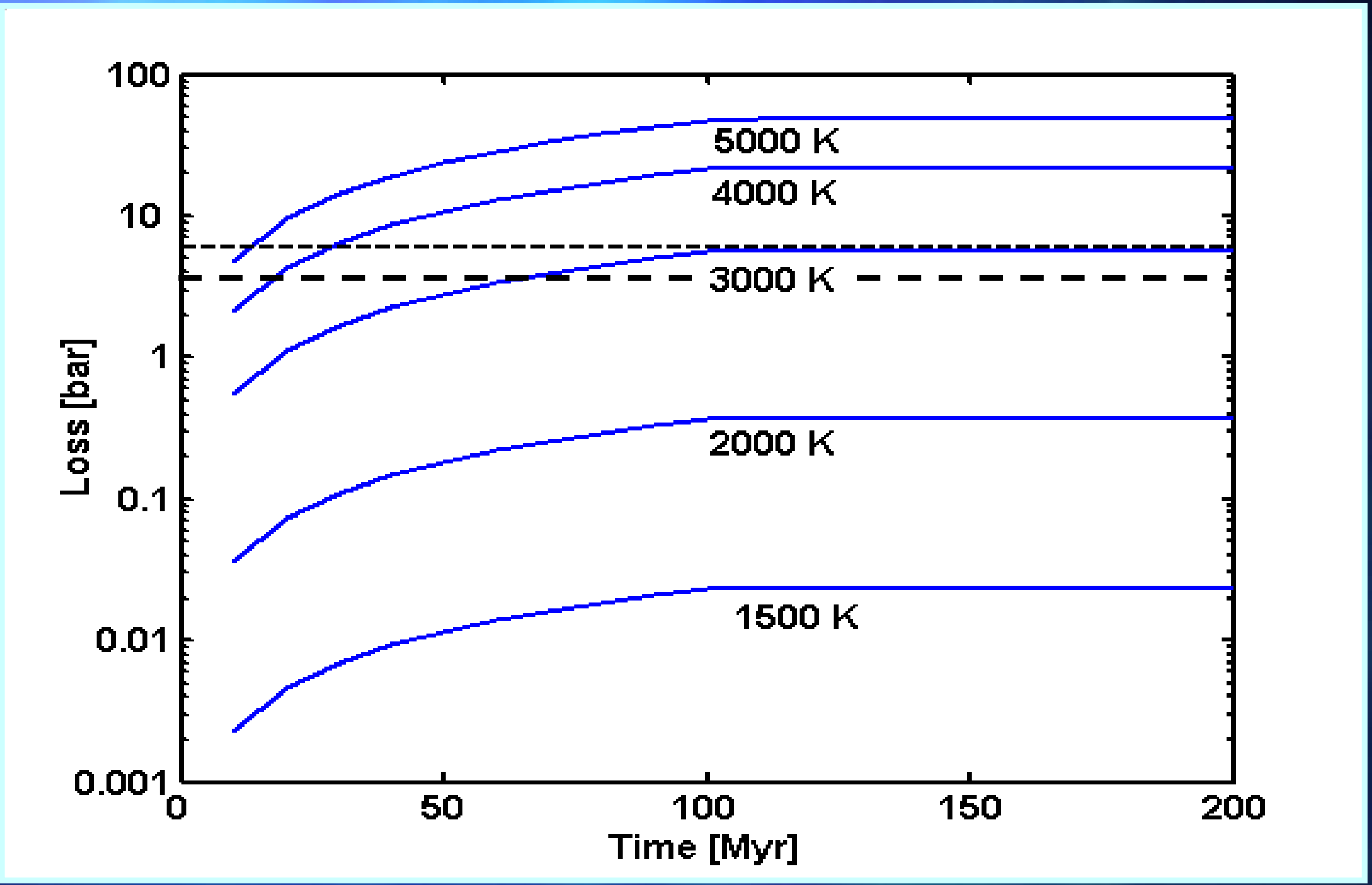
dynamic loss of H

≈ 130 Myr

Model simulations high variation of exosphere Temperature

[e.g., Bougher et al. JGR 99, 14609, 1994]

Loss of O due to large Jeans escape rates



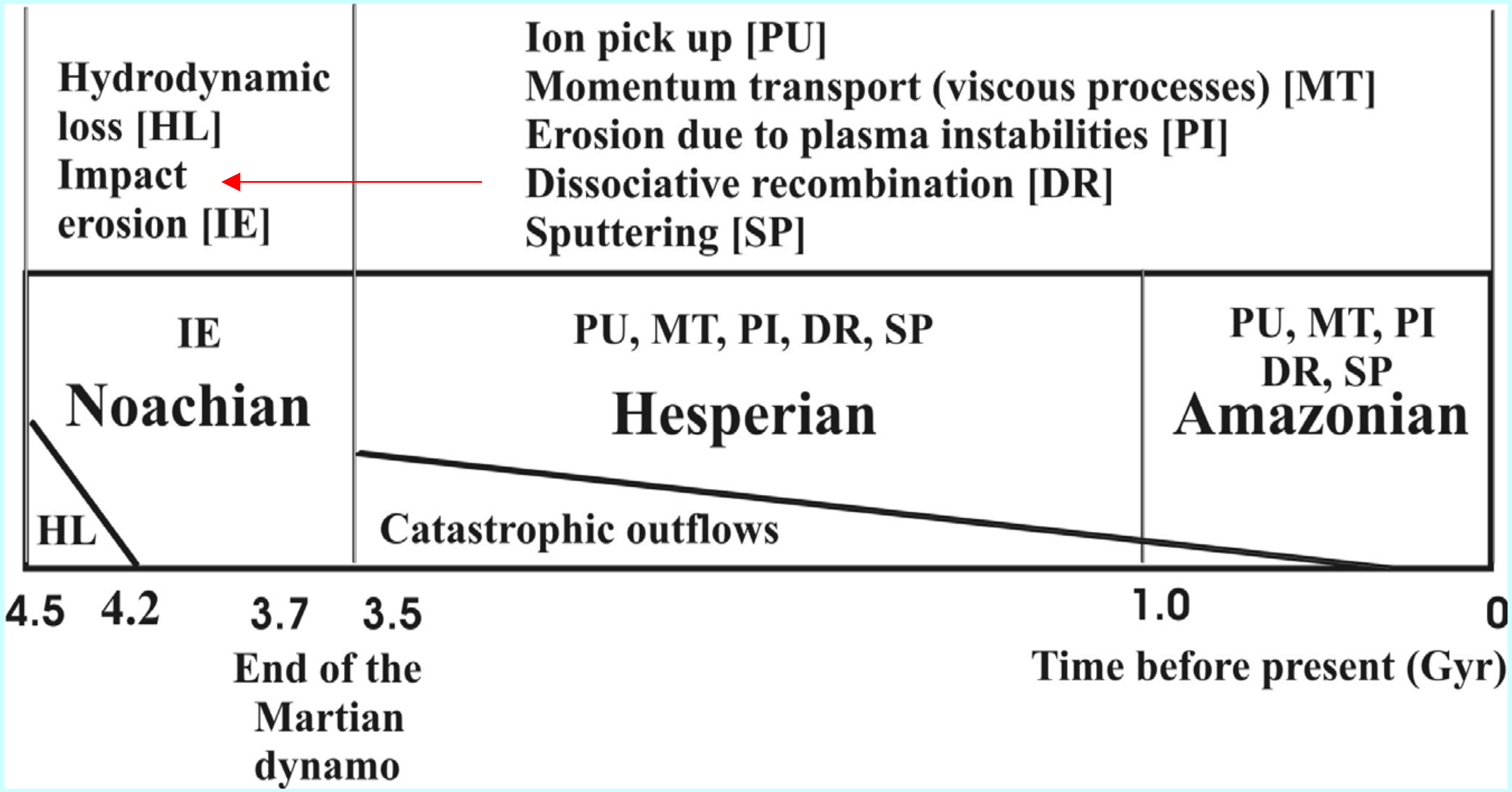
- Diffusion limited escape of hydrogen can be $\geq 10^{11} - 3 \times 10^{11}$ $cm^{-2}\ s^{-1}$
  [e.q., Hunten, Science 259, 915, 1993; Kasting and Pollack, Icarus 53, 479, 1983]

[Kasting and Pollack, Icarus 53, 479, 1983]

$$\Delta t(Gyr) = 2.4 \times 10^{9} \frac{\Delta p(H_2O)[bar]}{\phi_{esc}(H)[cm^{-2}s^{-1}]}$$

$\rightarrow$ 50 – 100 Myr (d = 150 m)

Effects on the Martian atmospheric and water environment



- How much H_2O-ice is stored in present subsurface ice reservoirs ?
  → Mars Express MARSIS
- Application of a hydrodynamic loss model to hydrogen loss and impact erosion → diffusion-limited loss of hydrogen
- Coupling between research on water vapour in early Mars atmosphere