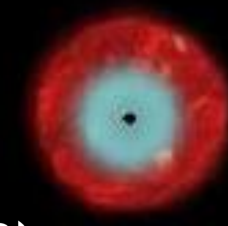
Testing atmospheric evolution scenarios by UV-transit observations of Earth-like exoplanets around M-stars



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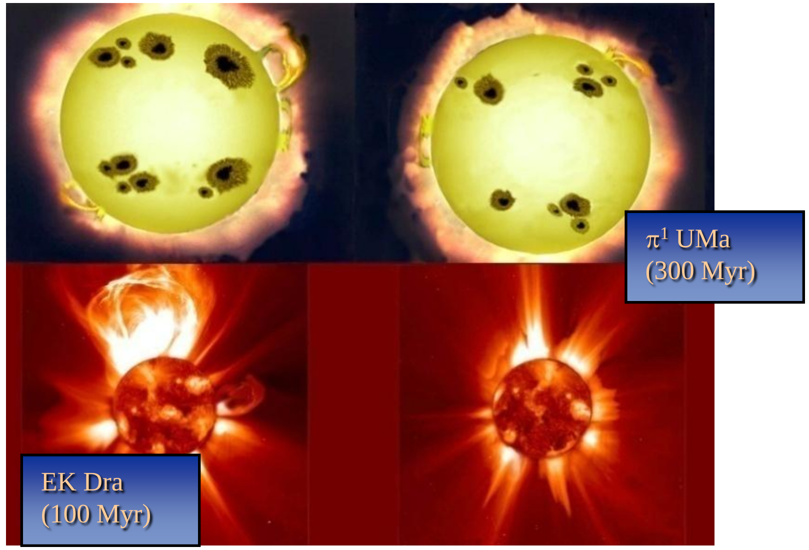
The big open questions in planetary atmosphere evolution & habitability

- What is the response on early planetary atmospheres against high energy radiation (X-ray, SXR, EUV, UV) and dense/fast plasma of the young Sun/stars?
  - In time: From a few hours up to evolutionary timescales (Gyr)
  - From star to star: Less massive stars tend to have higher activity levels for longer time scales → M-type stars
  - The scale of the variations is huge: up to 3 orders of mag!
- How can the early atmospheres of Earth-type planets survive the stellar activty during these active periods from Post T-Tauri stage to times when the SXR and EUV fluxes decrease to values which are $\leq$ 7 times that of the present Sun?
- What is the role of intrinsic and induced magnetic fields in upper atmosphere protection?
- What is the role of atmospheric composition in early atmospheres?
  - Were the early atmospheres hydrogen-rich?
  - The role of CO_2 as a greenhouse gas and upper atmosphere IR-cooler vs. CH_4, H_2O

The Sun’s radiation environment during the first 500 Myr



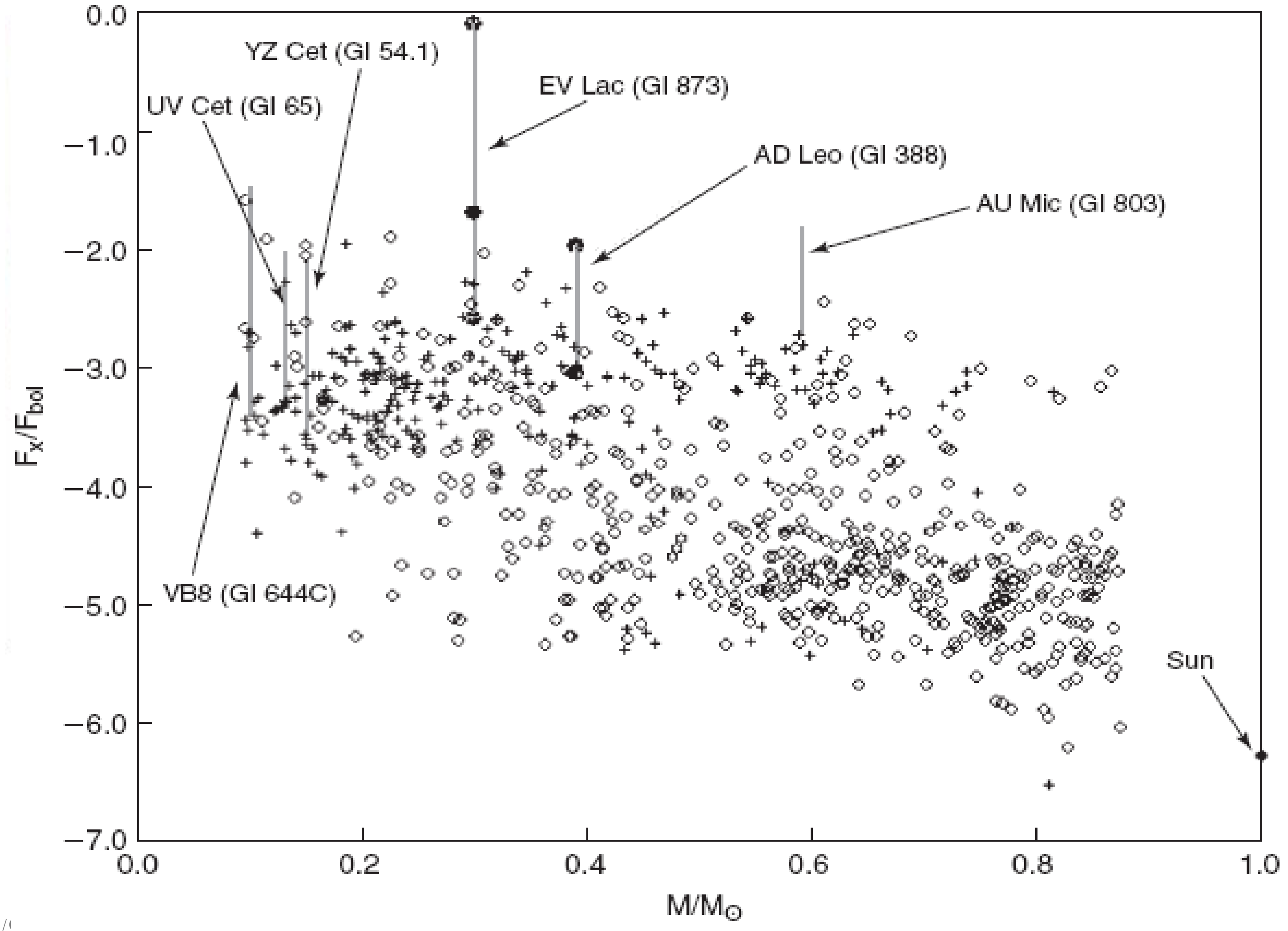
Solar radiation environment during the first 500 Myr after the Sun arrived at the ZAMS

During the post T–Tauri stage the high energy emissions were even higher!

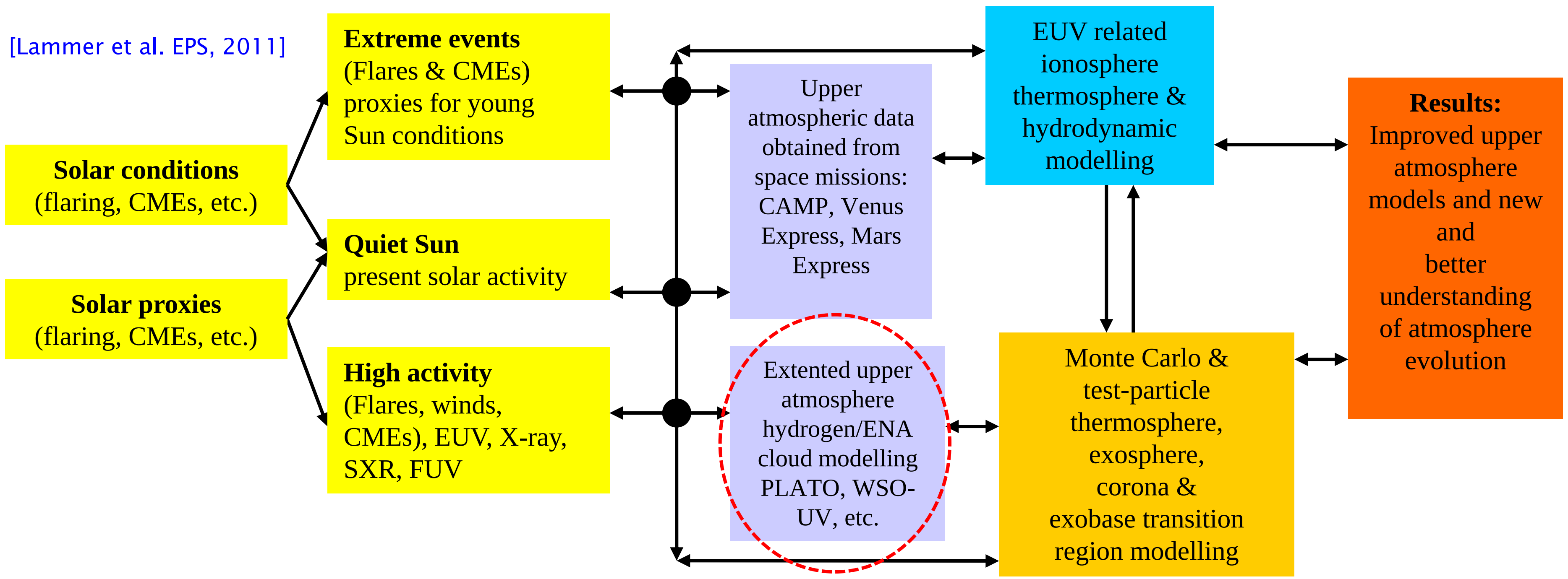
Solar age [Gyr]	*t* b.p. [Gyr]	X-ray [1–20Å]	SXR [20–100Å]	EUV [100–920Å]	FUV [920–1180Å]	Lyman-α [1200–1300Å]	UV [1300–1700Å]
0.7	3.9	37	11	8.6	5	3.9	–
0.65	3.95	43	12	9.4	5.3	4.1	5.8
0.6	4.0	50	13	10	5.7	4.3	–
0.55	4.05	59	15	11	6.1	4.6	–
0.5	4.1	71	17	13	6.6	4.9	–
0.45	4.15	87	19	14	7.2	5.3	–
0.4	4.2	109	22	17	8	5.8	–
0.35	4.25	141	26	19	9	6.4	–
0.3	4.3	189	32	23	10	7.1	10.6
0.25	4.35	268	40	28	12	8.1	–
0.2	4.4	412	54	37	14	9.6	–
0.15	4.45	715	77	51	18	11.8	–
0.1	4.5	1558	129	82	26	15.8	40.5

[Ribas et al. ApJ, 2005; Güdel 2007; Lammer et al. EPS, 2011]

X-ray, SXR, EUV activity of M-stars



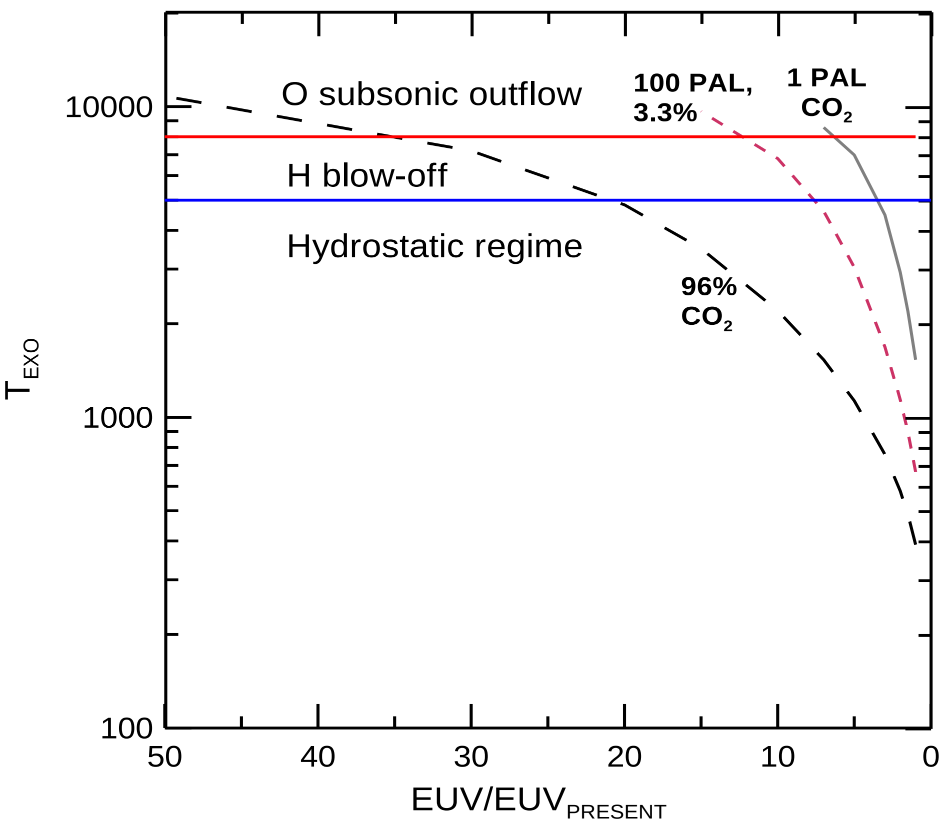
Solar EUV response of upper atmospheres



- Heating due to O_2, N_2, and O photoionization by solar XUV radiation ($\lambda \leq 1027$ Å)
- Heating due to O_2 and O_3 photodissociation by solar UV radiation ($1250 \leq \lambda \leq 3500$ Å)
- Chemical heating in exothermic binary and 3-body reactions
- Neutral gas molecular heat conduction
- IR-cooling in the vibrational-rotational bands of CO_2 (15 μm), NO, O_3, OH, NO^+, $^{14}N^{15}N$, CO, H_3^+, etc. and 63 μm O line
- Heating and cooling due to contraction and expansion of the thermosphere
- Turbulent energy dissipation and heat conduction

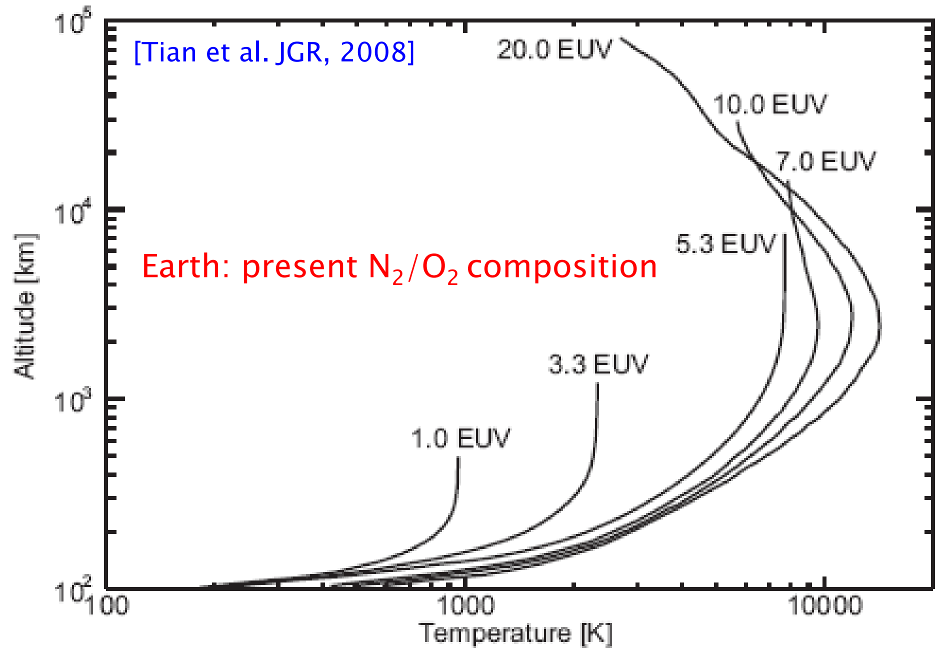
Exobase temperature

Hydrostatic regime

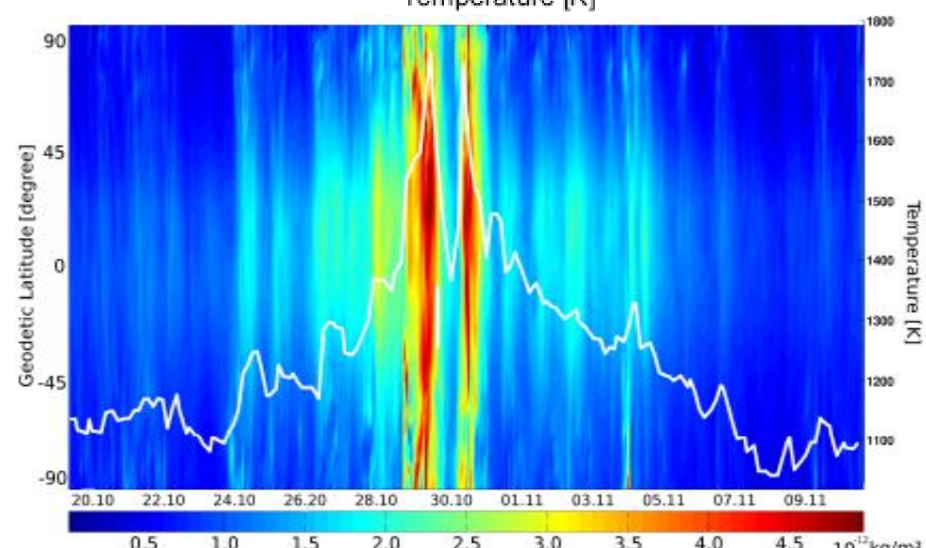


[Kulikov et al. Space Sci. Rev., 2007]

Non-hydrostatic regime

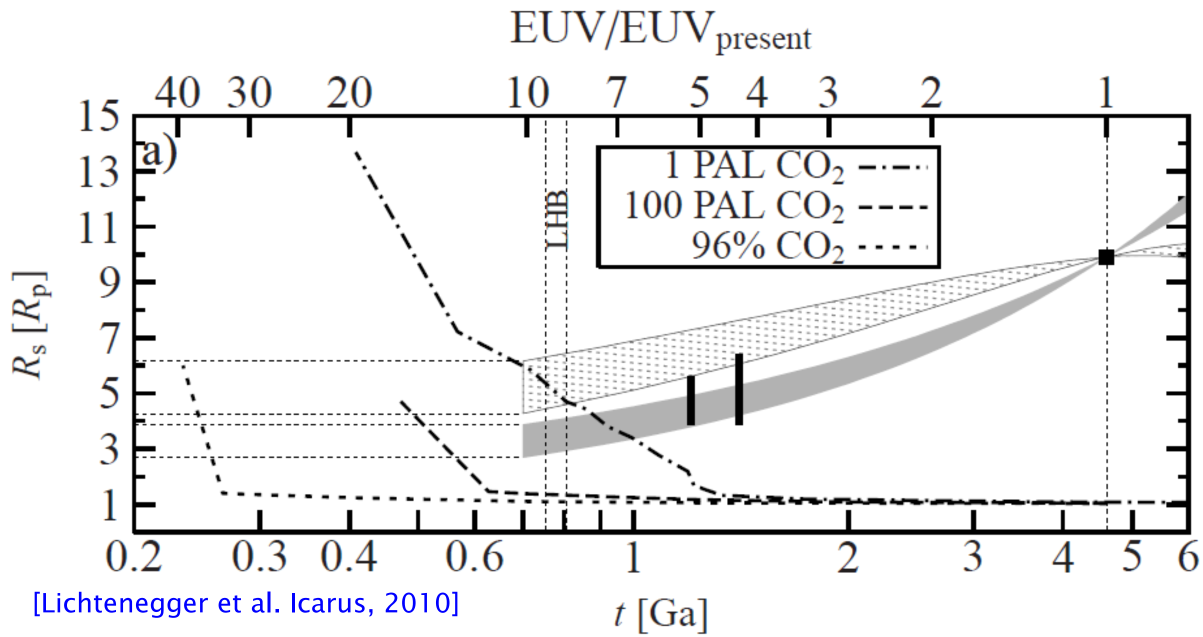


Density impact of a X17.2 flare (Oct. 2003) observed by the GRACE satellite and temperature variation at orbit height is represented by the white curve



[Shematovich et al. SSR, 2011; Lammer et al. EPS, 2011]

Magnetopause/exobase distances: early Earth with N_2/O_2 atmosphere

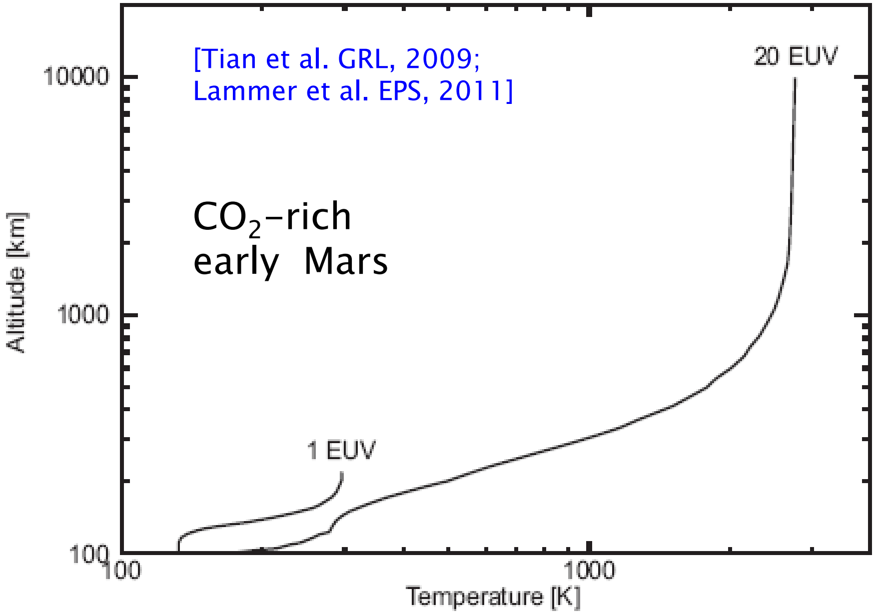


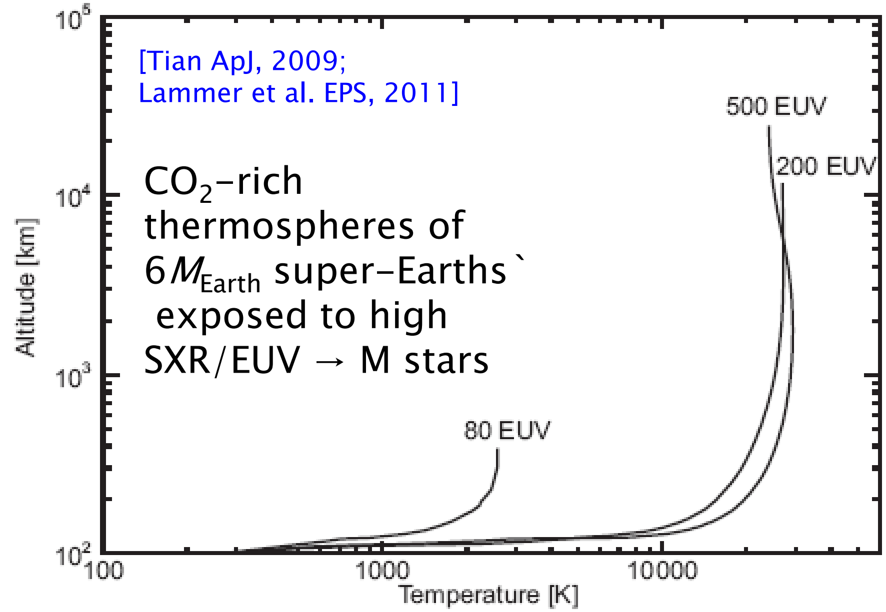
[Lichtenegger et al. Icarus, 2010]

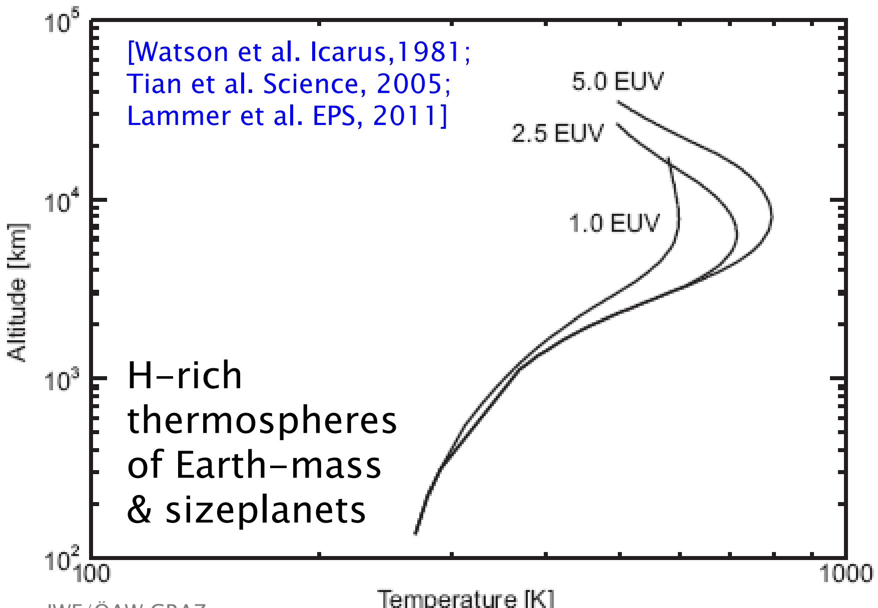
- Are N_2-rich atmospheres around Earth-size and mass planets stable during SXR and EUV exposure > 7 times that of the present Sun?

EUV	age [Ga b.p.]	obstacle [R_E]	$n_N^{obstacle}$ [cm^{-3}]	T_{exo} [K]	loss rate [s^{-1}]	loss rate [bar/Ma]
7^a	3.7	2.7 (MP)	8.6×10^4	7600	8.9×10^{29}	0.1
7^b	3.7	4.7 (MP)	2.1×10^4	7600	8.1×10^{29}	0.1
10	3.9	4.9 (Exo)	4.5×10^4	5600	1.9×10^{30}	0.3
20	4.2	12.7 (Exo)	1.5×10^4	2500	7.7×10^{30}	1.1
7^c	3.7	10.7 (MP)	3.7×10^3	7600	1.2×10^{29}	0.02
10^c	3.9	10.8 (MP)	6.5×10^3	5600	2.5×10^{29}	0.04
20^c	4.2	12.7 (Exo)	1.5×10^4	2500	8.4×10^{29}	0.1

SXR & EUV heated and extented upper atmospheres







- Depending on the atmospheric composition, size and mass of the planet, highly SXR and EUV exposed atmospheres should extend to several planetary radii and even beyond possible magentopause locations

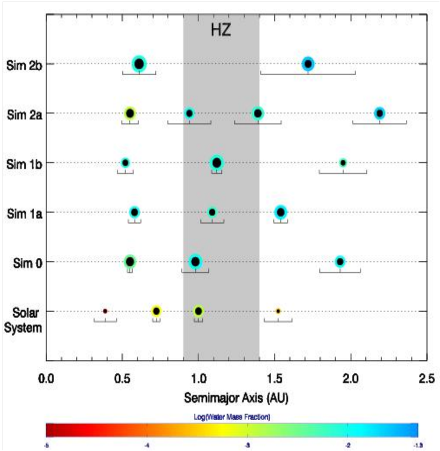
- Hydrogen-rich upper atmospheres may even expand several 10s of Earthradii during the extreme EUV epochs of their host stars

- Can we detect and study non-hydrostatic upper atmospheres?

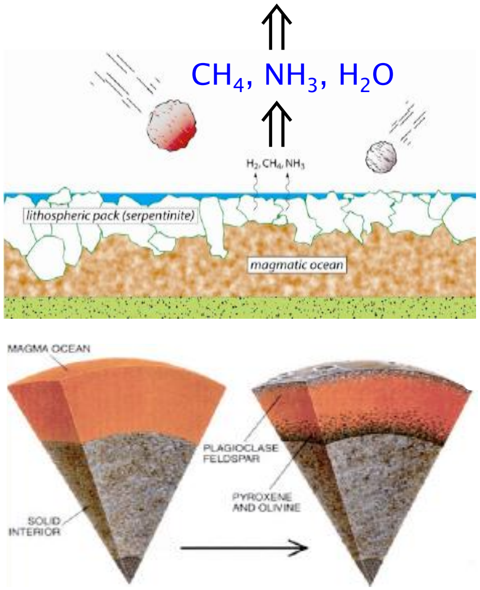
Response of CO_2-rich and H-rich thermospheres

Extented upper atmospheres should be common features during SXR, EUV active stellar stages [Lammer et al. A&SS, 2011b]

- dense hydrogen envelopes which remained from the primordial nebulae;
- hydrogen-rich thermospheres produced via dissociation of CH_4, NH_3 and H_2O molecules;
- ocean planets or planets which evaporate their initial H_2O reservoir;
- evaporation of H_2O oceans due to cometary or asteroidal impacts.



[e.g., Raymond et al. Astrobiology, 2007]

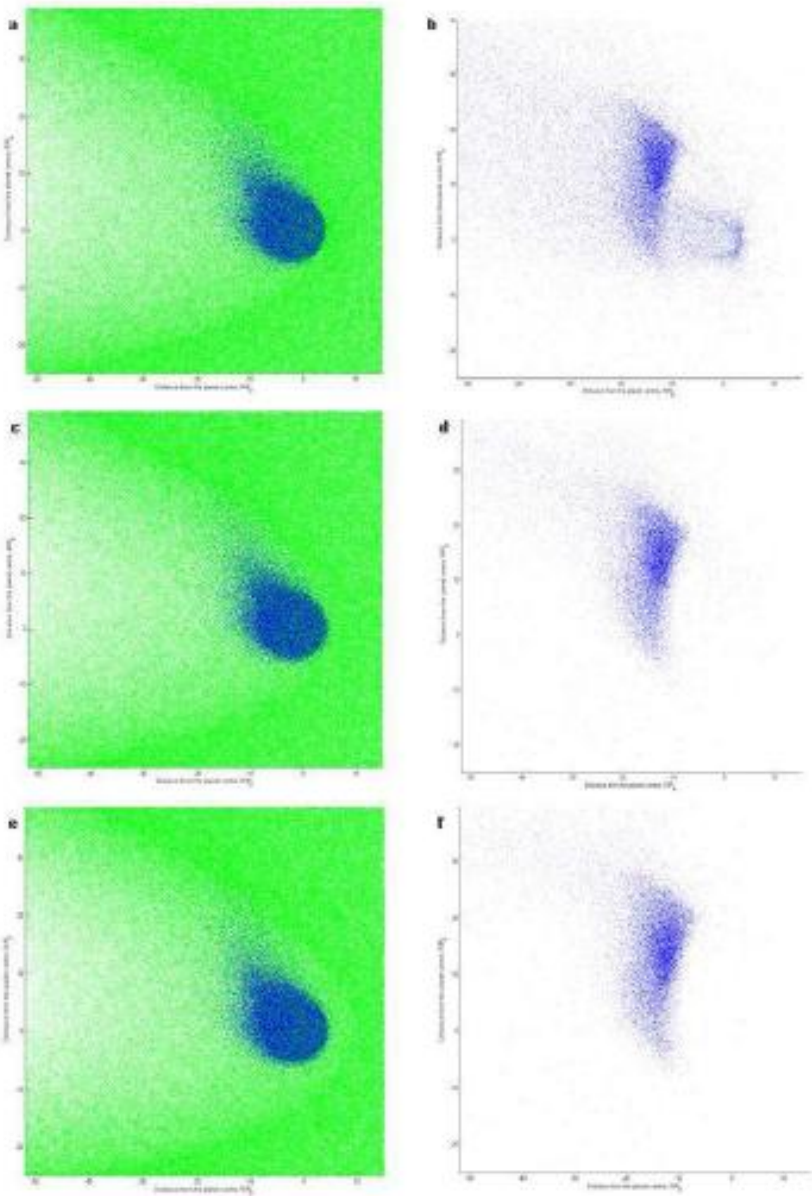


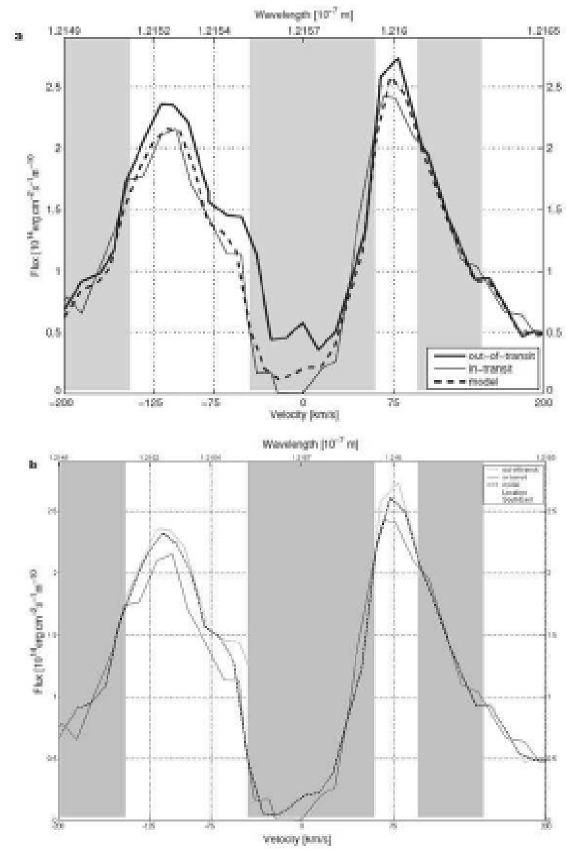
- Extented upper atmospheres may have dominated the planetary envrionment during 100s of Myr up to Gyr time scales

ENA-cloud observation and modelling a tool to study star-exoplanet interaction

Hydrogen coronae & ENA clouds around Hot Jupiters

→ see Poster K. G. Kislyakova,
M. L. Khodachenko, H. Lammer, I. Alexeev
E. Belenkaya, J.-M. Grießmeier,
M. Holmström, Yu. N. Kulikov,
V. I. Shematovich, D. Bislikalo,
A. Hanslmeier:
Transit observations and hydrogen and ENA-cloud modelling as a tool for exoplanet magnetic and plasma environment characterization





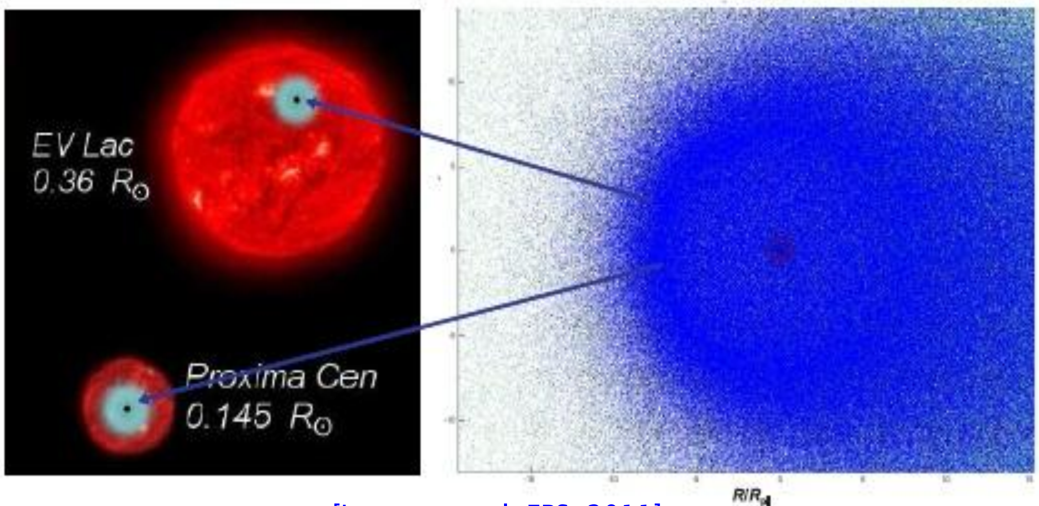
UV Lyman-α HST observations of HD 209458b

[Vidal Madjar et al. Nature, 2003;
Vidal Madjar et al. ApJ, 2004;
Ben-Jaffel & Hosseini ApJ, 2010;
Linsky et al. ApJ, 2010]

Observations of energetic neutral hydrogen atoms and O and C beyond the Roche lobe

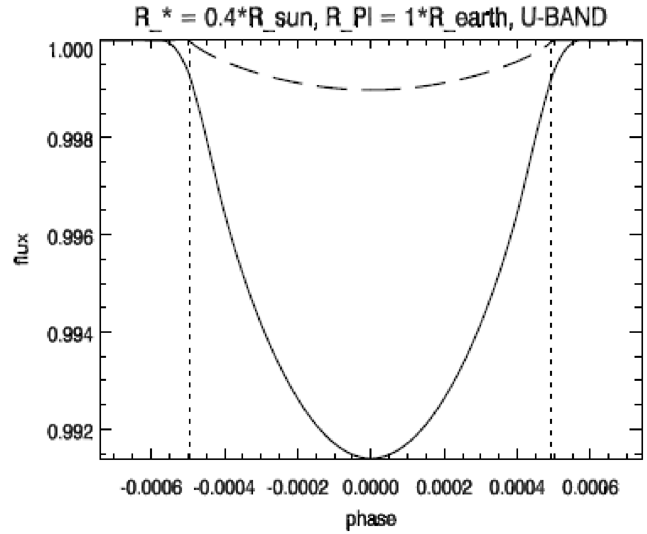
[Holmström et al. Nature, 2010;
Ekenbäck et al. ApJ, 2010;
Lammer et al. A&SS, 2011a]

ENA-cloud observation and modelling around Earth-size exoplanets



[Lammer et al. EPS, 2011]

Production of H energetic neutral atoms (ENAs) and clouds around Earth-size exoplanets within M-star orbits



[Lammer et al. A&SS, 2011b]

Modeled transit light curves of an Earth-sized planet transiting an M-star with 0.4$R_{\rm Sun}$.

$H^+_{sw} + H_{pl} \rightarrow H^{ENA}_{sw} + H^+_{pl}$, → planetary hydrogen cloud & ENAs similar as at “hot Jupiters”

$H^+_{sw} + N_{pl} \rightarrow H^{ENA}_{sw} + N^+_{pl}$, → N_2 corona & stellar wind produced hydrogen ENAs

$H^+_{sw} + O_{pl} \rightarrow H^{ENA}_{sw} + O^+_{pl}$, → O corona & stellar wind produced hydrogen ENAs

$H^+_{sw} + C_{pl} \rightarrow H^{ENA}_{sw} + C^+_{pl}$, → C corona & stellar wind produced hydrogen ENAs

Observations of hydrogen clouds & ENAs with WSO-UV around Earth-size exoplanets within orbits of dwarf stars discovered by PLATO would enhance our understanding how the Earth`s early atmosphere survived during the active young Sun period (e.g. role of magnetic obstacles, atmosphere composition, possible hydrogen envelopes, etc. → how habitable worlds evolve!

Testing atmosphere evolution scenarios by H cloud & ENA observations