The stability of early Earth's nitrogen atmosphere

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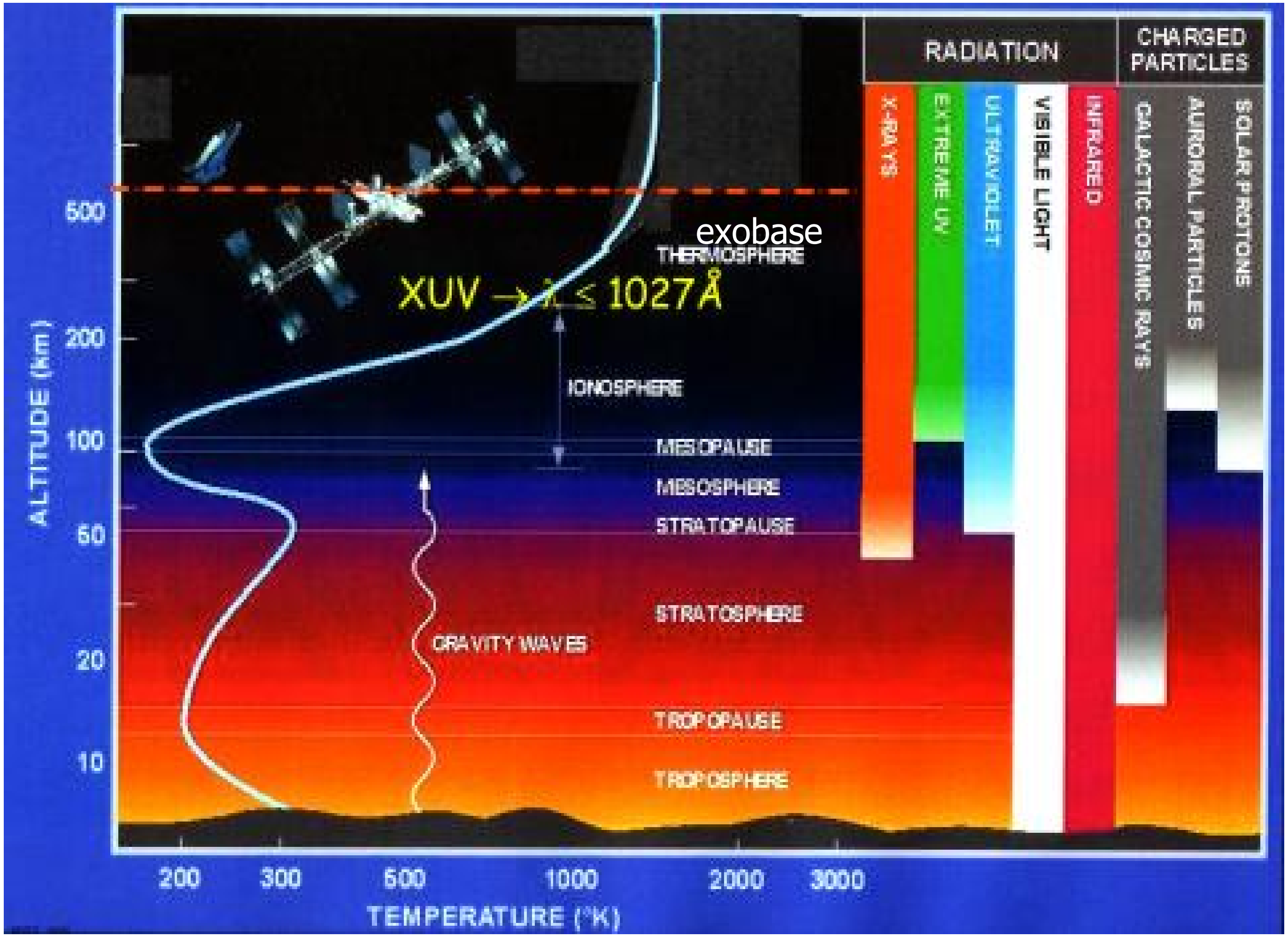
ESLAB Symposium on Comparative Planetology

11-15 May 2009

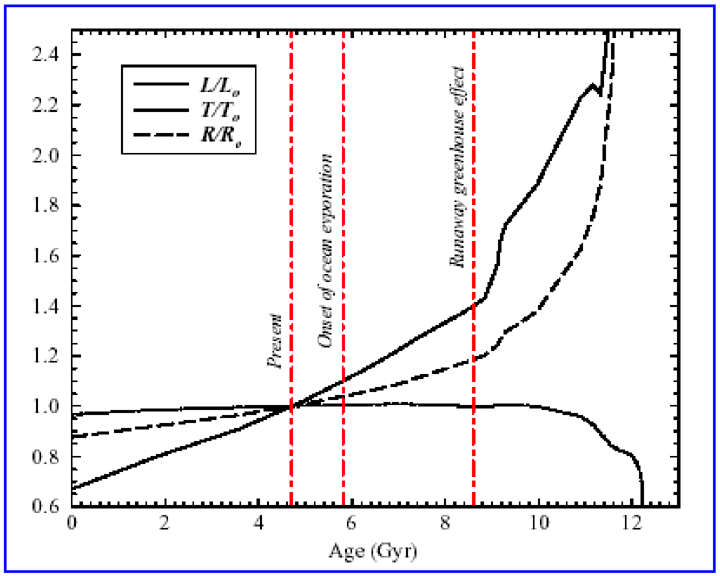
ESTEC, Noordwijk

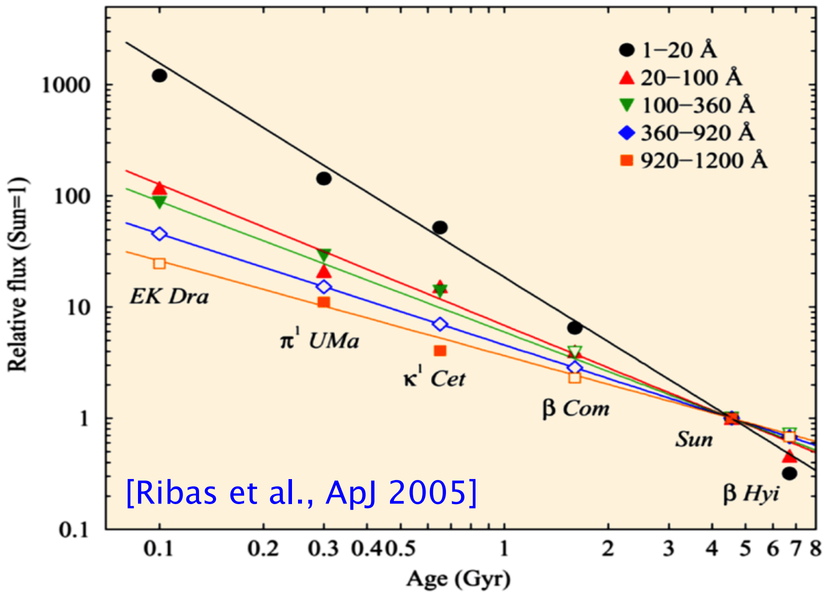
Solar EUV heating of the upper atmosphere



Atmosphere is sensitive to radiation and particle input

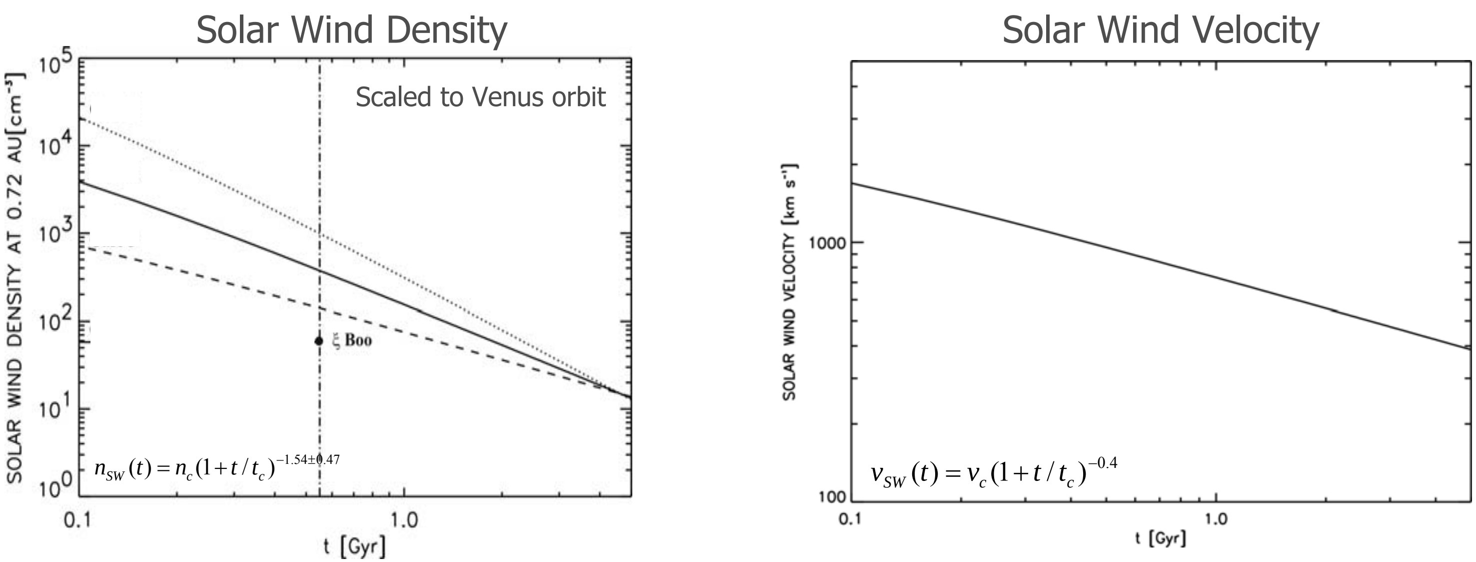
Observational evidence for a much more active phase of the Sun in the past





t [Gyr] b.p.	present	1.3	2	2.7	3.3	3.6	3.8	4.03	4.13	4.24	4.33	4.37	4.5
XUV	1	1.5	2	3	5	7	10	15	20	30	50	70	100

The Young Sun: SW Density and Velocity



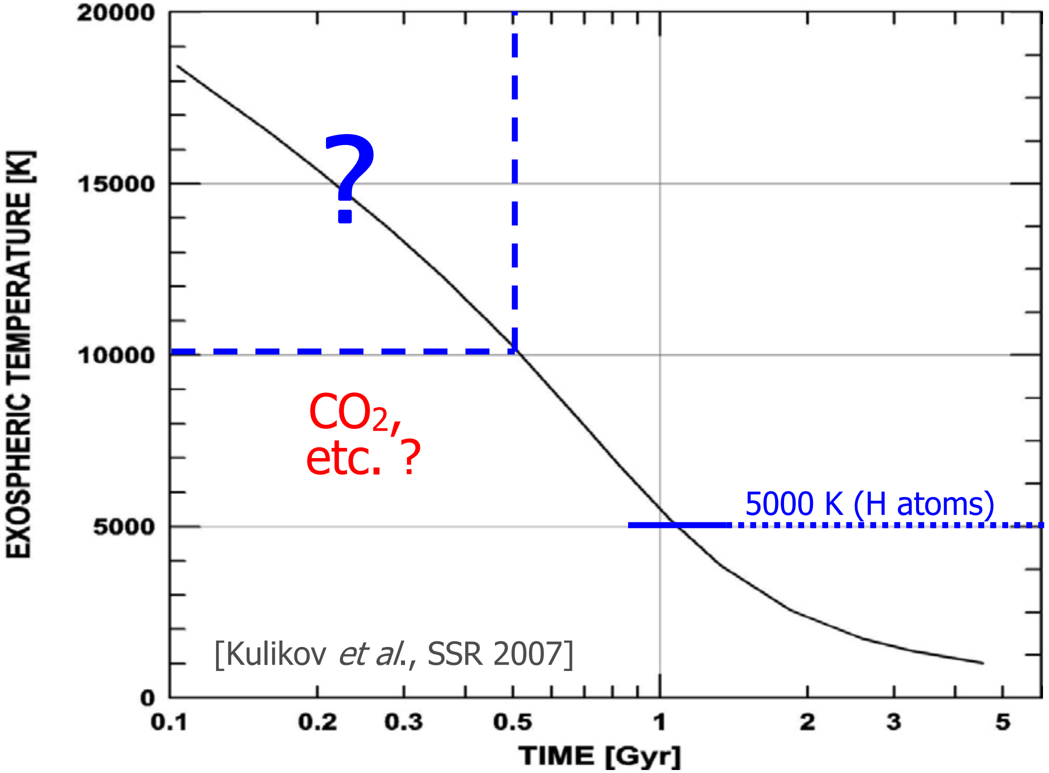
HST observations of H Lyman α of nearby main-sequence stars of the interaction between fully ionized coronal winds and the partially ionized ISM

[Newkirk, Geochi. Cosmochi. Acta Suppl. 1980, Wood et al., ApJ 2002, 2005]

Thermospheric Heating/Cooling Processes

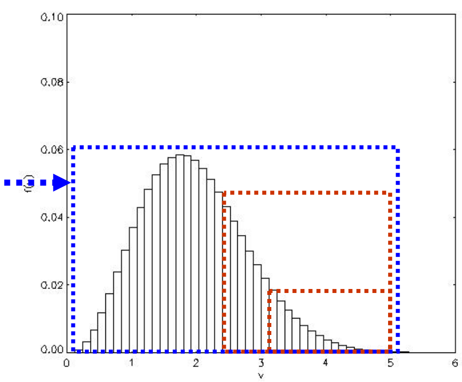
- Heating due to O_2, N_2, and O photoionization by solar XUV radiation ($\lambda \leq 1027$ Å)
- Heating due to O_2 and O_3 photodissociation by solar UV radiation ($1250 \leq \lambda \leq 3500$ Å)
- Chemical heating in exothermic binary and 3-body reactions
- Neutral gas molecular heat conduction
- 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

Time Evolution of Exobase Temperature based on Present Atmospheric Composition



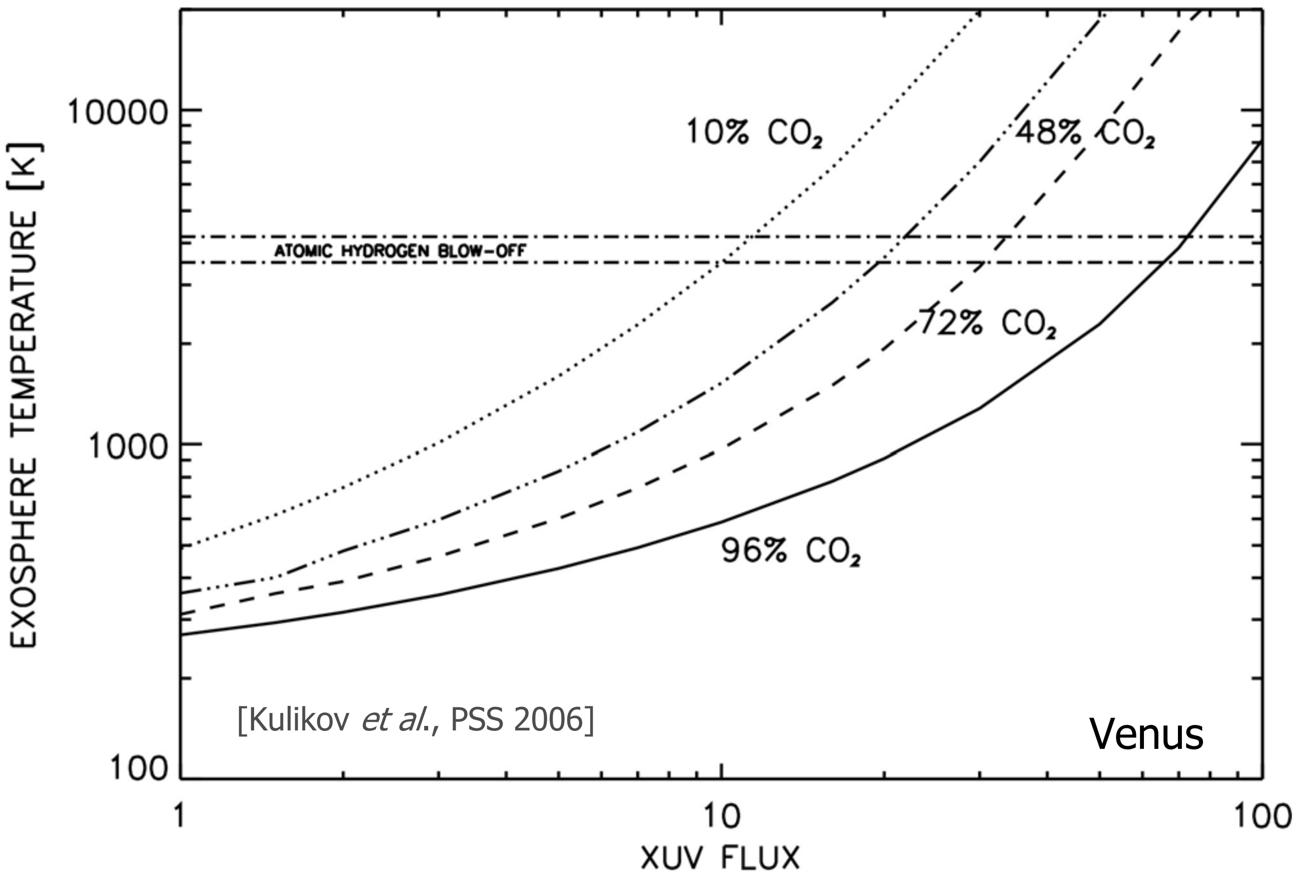
Hydrostatic equilibrium is assumed

→no hydrodynamic flow or adiabatic cooling included

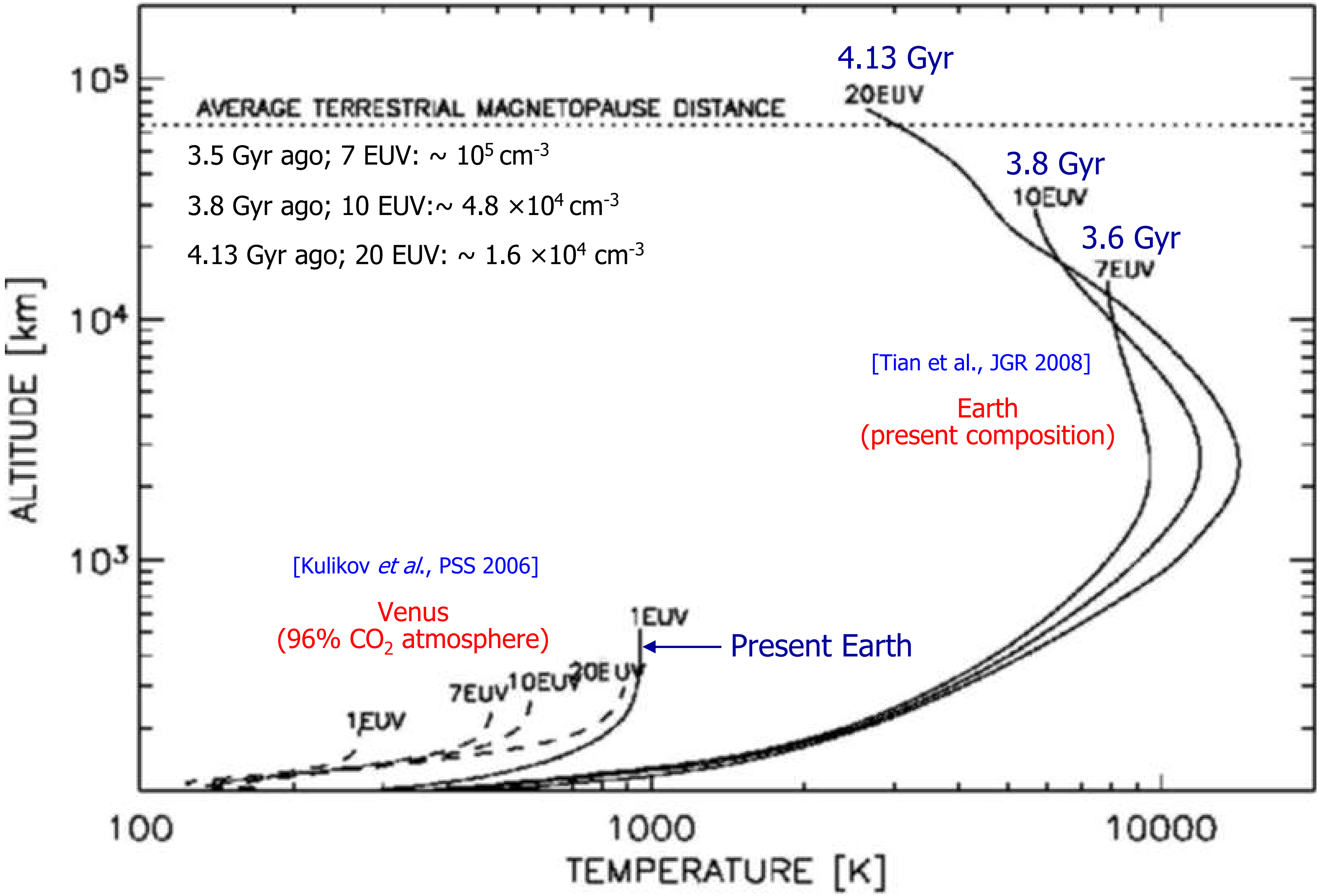


- The blow-off temperature for atomic hydrogen of about 5000 K would be exceeded during the first Gyr
- For XUV fluxes more than 10 times the present flux (>3.8 Gyr ago) one would expect extremely high exospheric temperatures
- Therefore, the abundance of IR-cooling species in the Earth's thermosphere during the first 500 Myr should be **much higher** than at present

CO_2/N_2 mixing ratios

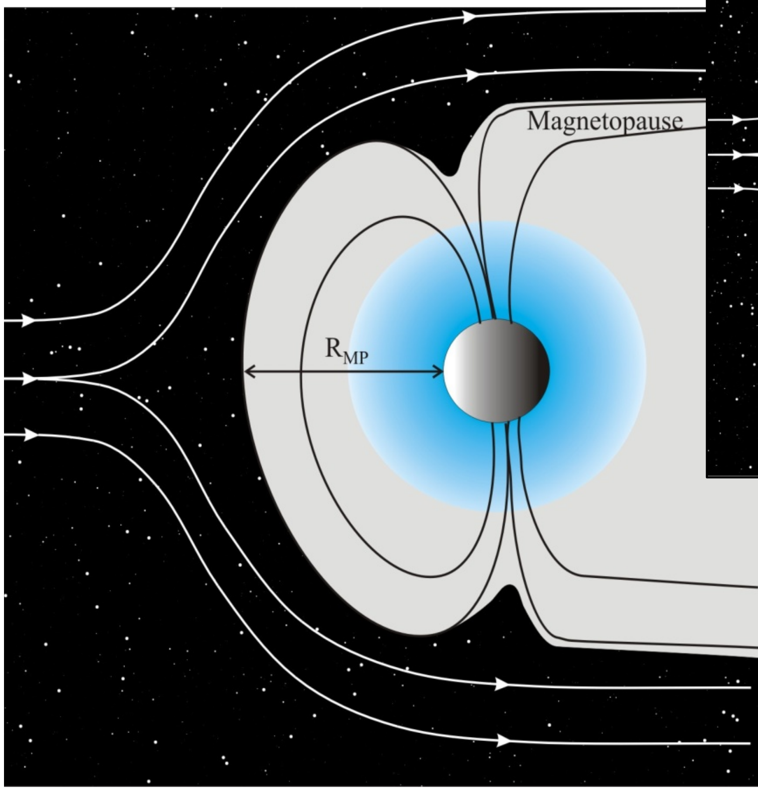


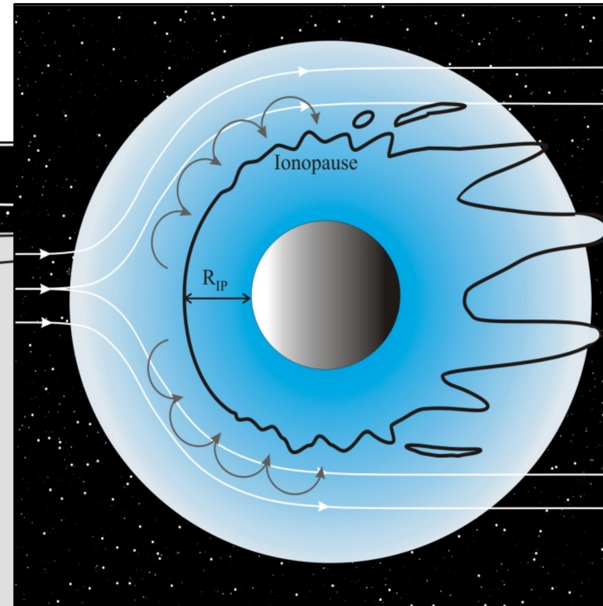
Atmospheric Response during XUV Epochs



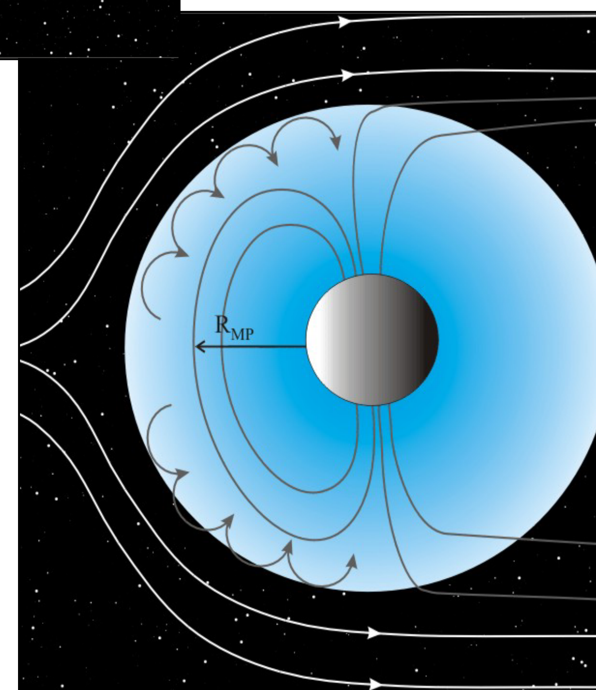
Solar Wind Interaction with Planetary Bodies

Present Earth





Present Venus and Mars



Early Earth?
Terrestrial exoplanets

Model for N^+ Pick Up Ion Loss Estimation

Exosphere density

$$N(r) = N_b(r)\zeta(\lambda) = N_c e^{-(\lambda_c - \lambda)}\zeta(\lambda),$$

$$\zeta(\lambda) = \frac{2\pi}{r^2(2\pi M k T_c)^{3/2}} \iint e^{-p_r^2/2MkT_c - P_\chi^2/2MkT_c r^2} P_\chi \, dP_\chi \, dp_r.$$

Exosphere density above the exobase is obtained from Chamberlain´s theory

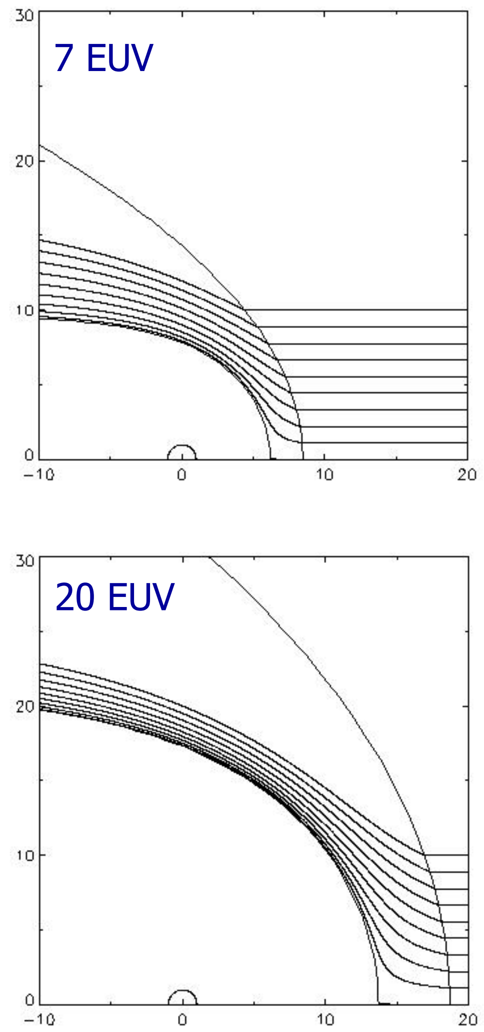
Ionization processes in the extended exosphere

Solar EUV: hν + N → N^+ + e^-

Solar wind charge exchange: p^+ + N → N^+ + H^{ENA}

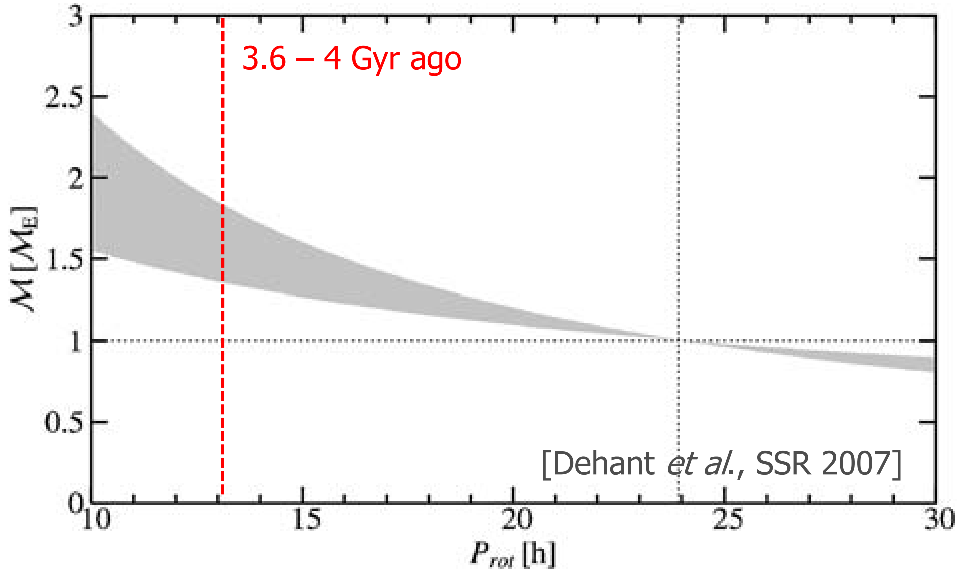
Electron impact ionization: e^- + N → N^+ + $2e^-$

Cummings et al. ApJ 578:194, [2002]
NIFS data base:
http://dpc.nifs.ac.jp/aladin/



Magnetic Moment of Early Earth

Rotational Effect on Magnetic Dynamo



Estimated magnetic moment of early Earth, relative to its present-day value, as a function of possible early planetary rotation periods in hours. The dotted vertical line denotes the present-day sidereal rotation rate of the Earth.

Model Results of N^+ Pick Up Ion Loss for Early Earth

Model SW parameters (conservative values)

7 EUV: n^{sw} ~ 90 cm^{-3}; v^{sw} ~780 km/s
R^{MP} (24 h) ~ 5.2 R^{Earth} → R^{exo} ~ 2.5 R^{Earth}
R^{MP} ~ 6.1 R^{Earth} → R^{exo} ~2.5R^{Earth}

10 EUV: n^{sw} ~ 200 cm^{-3}; v^{sw} ~ 900 km/s
R^{MP} ~ 5.2 R^{Earth} → R^{exo} ~ 4.8 R^{Earth}

20 EUV: n^{sw} ~ 270 cm^{-3}; v^{sw} ~1010 km/s
R^{MP} ~ 4.7 R^{Earth} → R^{exo} ~ 12.7 R^{Earth}

Estimated nitrogen ion pick up loss rate

7 EUV (3.6 Gyr ago), subsolar obstacle distance 6.1 R^{Earth}: ~ 5×10^{28} s^{-1}

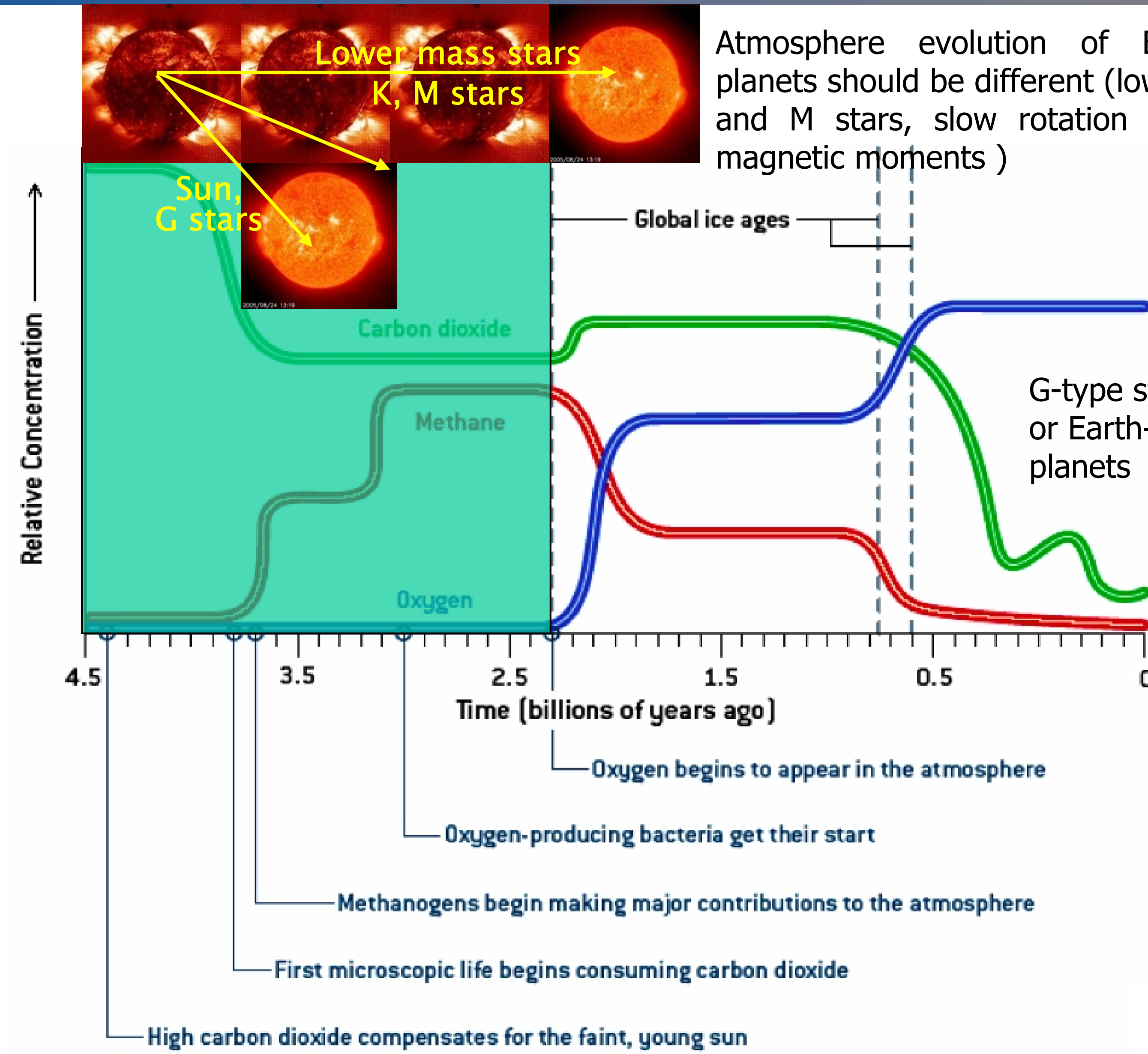
10 EUV (3.8 Gyr ago), subsolar obstacle distance 5.2 R^{Earth}: ~5×10^{29} s^{-1}

20 EUV (4.13 Gyr ago), subsolar obstacle distance 12.7 R^{Earth}: ~2×10^{30} s^{-1}

→ Total loss of nitrogen would result in an equivalent amount of
≤ 20 bar during ~ 50 Myr

Implication for Expected Atmosphere Evolution

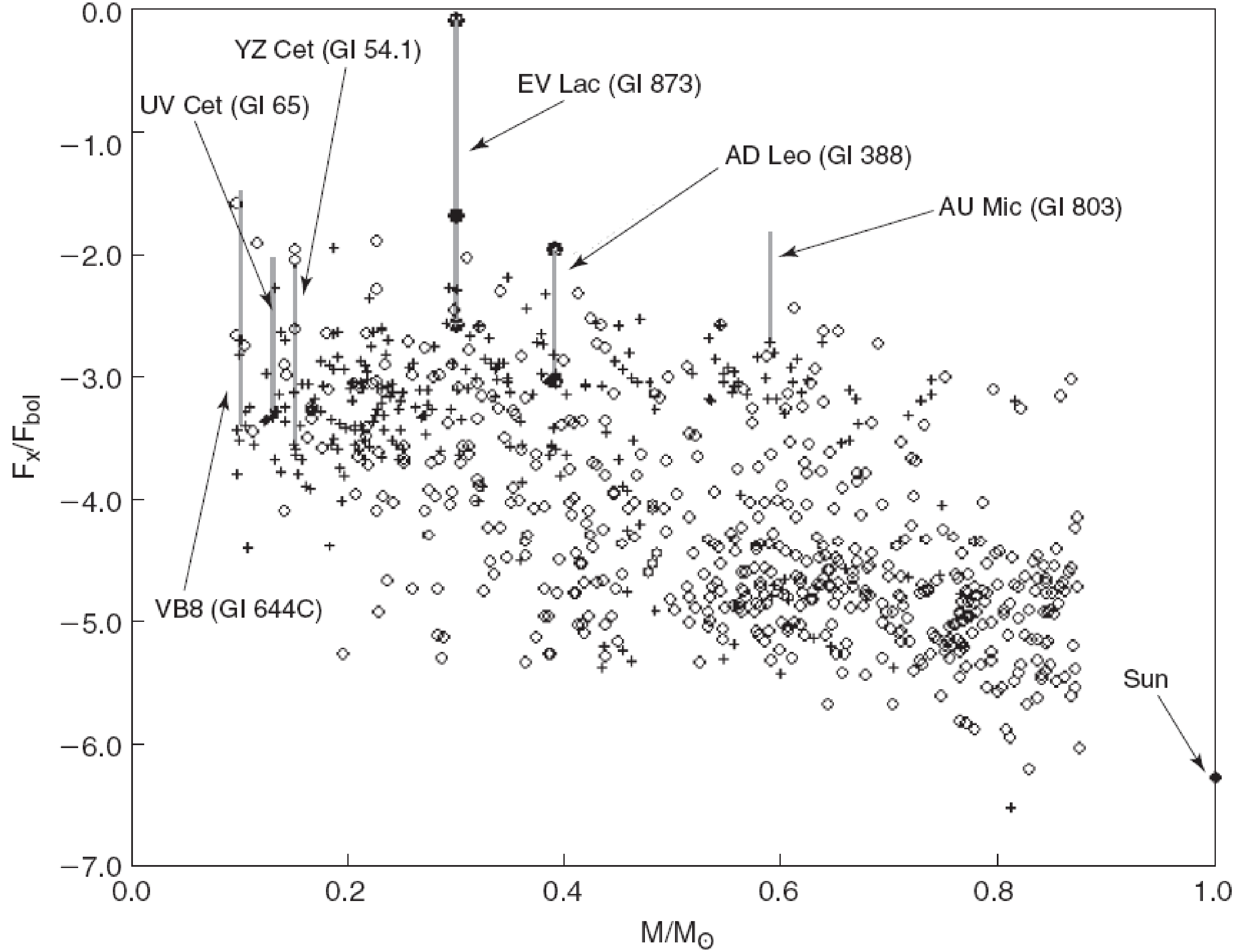
Atmosphere evolution of Earth-like planets should be different (low mass K and M stars, slow rotation → weak magnetic moments)



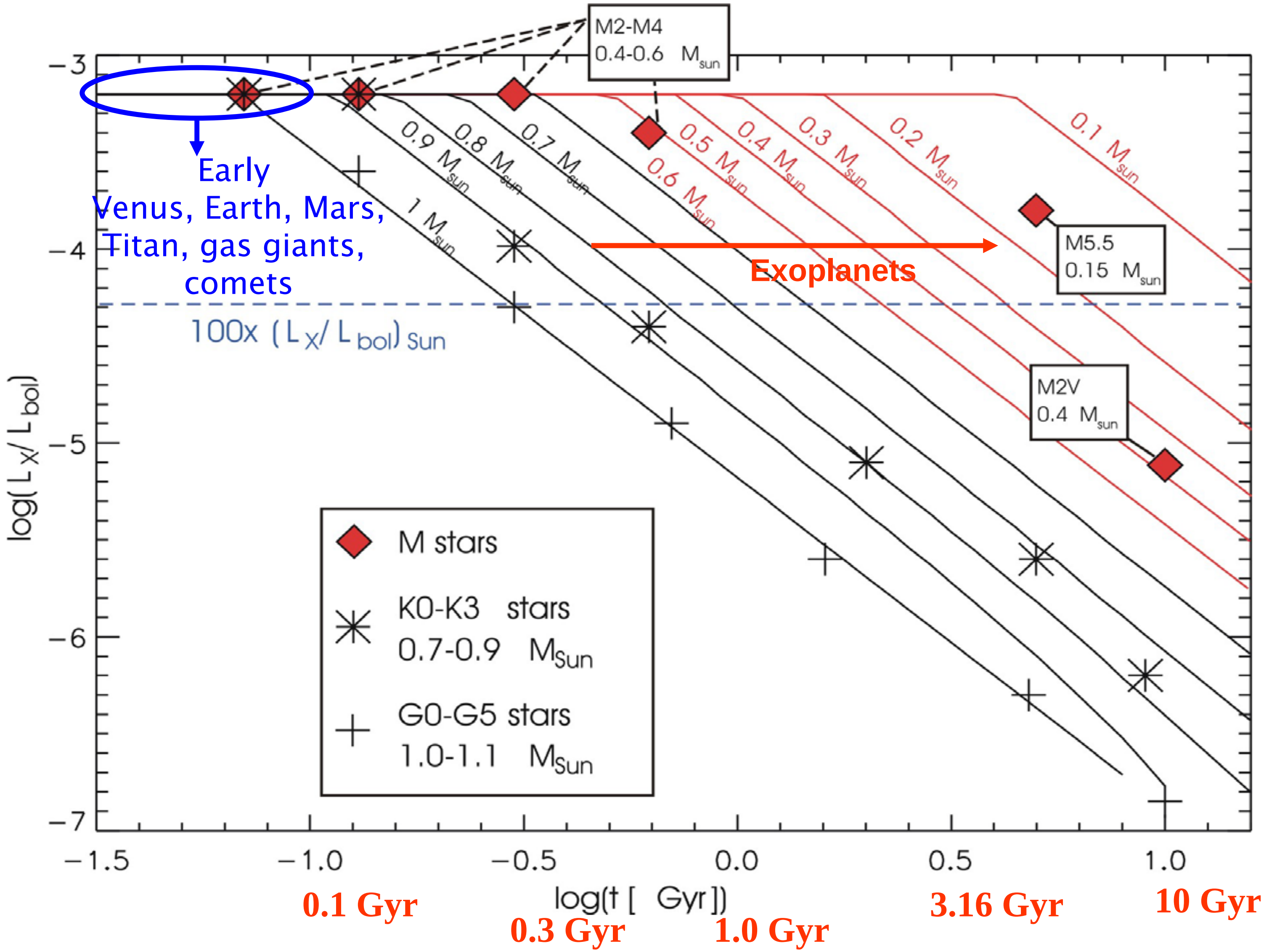
G-type star & Earth or Earth-like planets

and cools the upper atmosphere so that expansion and loss rates should be reduced

M Stars and Radiation Activity



X-Ray/EUV Activity of Low Mass Stars



[Scalo *et al.*, Astrobiology 2007]

Summary

- For solar EUV fluxes larger than ~10 times the present value, the Earth with its present atmospheric composition would most likely loose its nitrogen atmosphere due to solar wind erosion
- A magnetosphere alone can not protect a nitrogen-rich early atmosphere of the Earth (or of Earth-like planets) during active X-ray/EUV periods
- During the very early stage of the young Sun the terrestrial atmosphere needs species which can actively cool the thermosphere (most likely CO_2)
- These results have important consequences for the habitability of Earth-like exoplanets which orbit active dwarf stars (more massive Super-Earth planets should be better protected against these processes)
- For future studies we plan to apply a sophisticated MHD model which can self-consistently calculate in case of the extreme extended atmospheres the ionopause obstacles and total ion escape rates of nitrogen-rich Earth-like planets