Planetary Upper Atmospheres Under Strong XUV radiation

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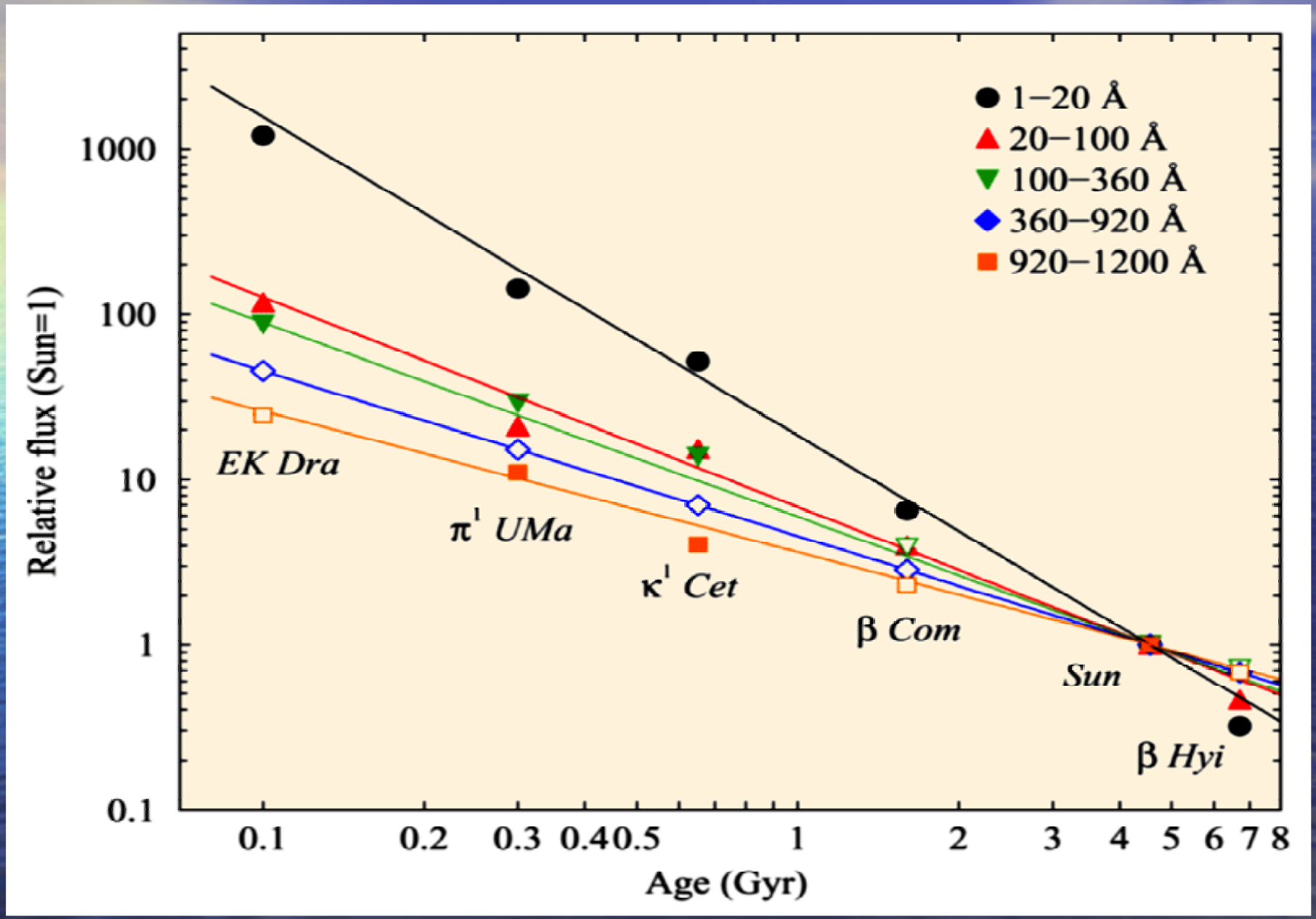
March 4th, 2010

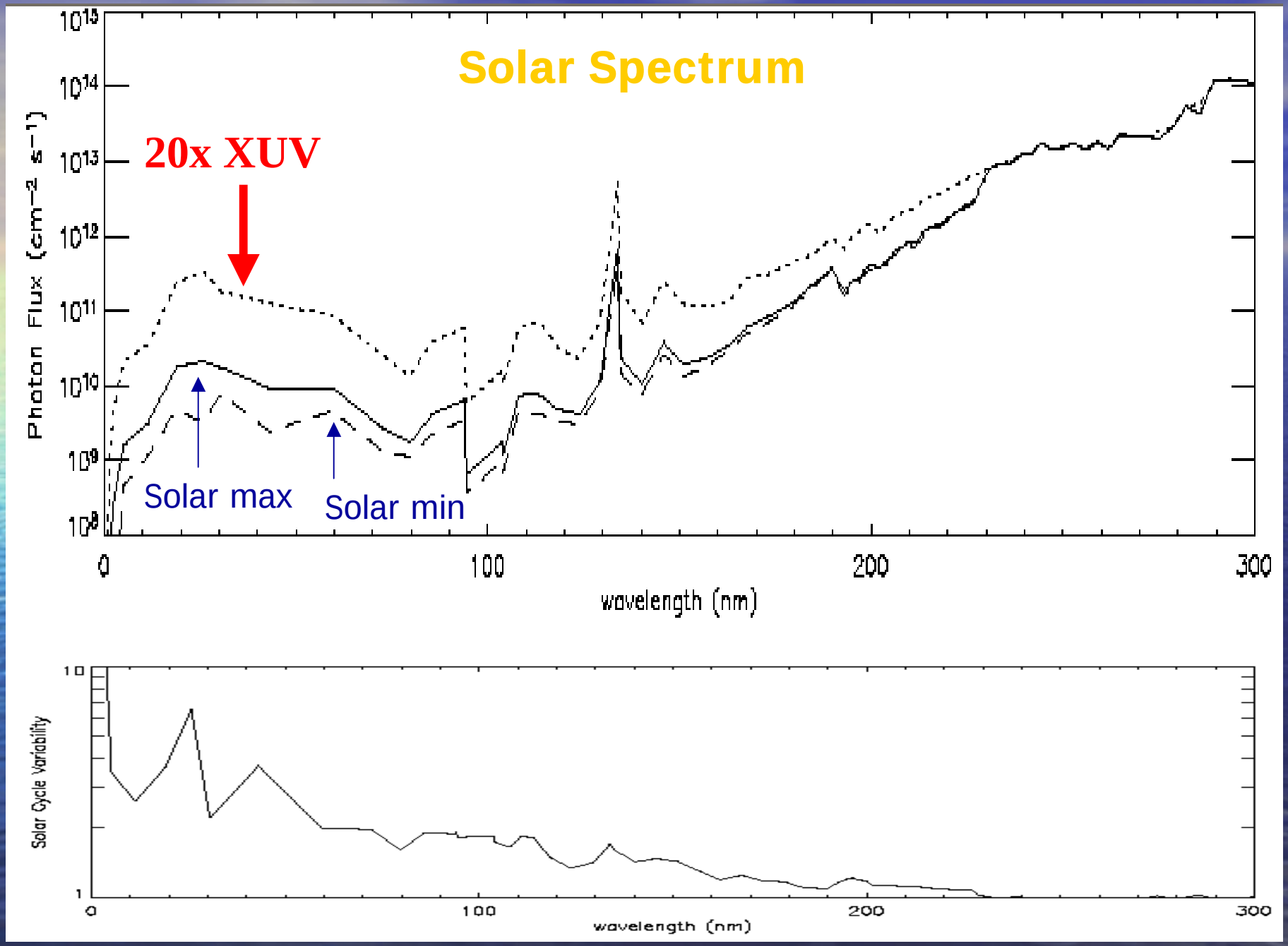
Outline

- **Early Solar XUV radiation was strong.**
- **Planetary atmospheres expand under strong XUV -- fast escape of major atmospheric gases occurs – cold early Mars?**
- **Planetary atmospheres in the hydrodynamic regime – an energy budget analysis.**
- **Total atmosphere escape is conserved.**
- **Observations to check the theory.**

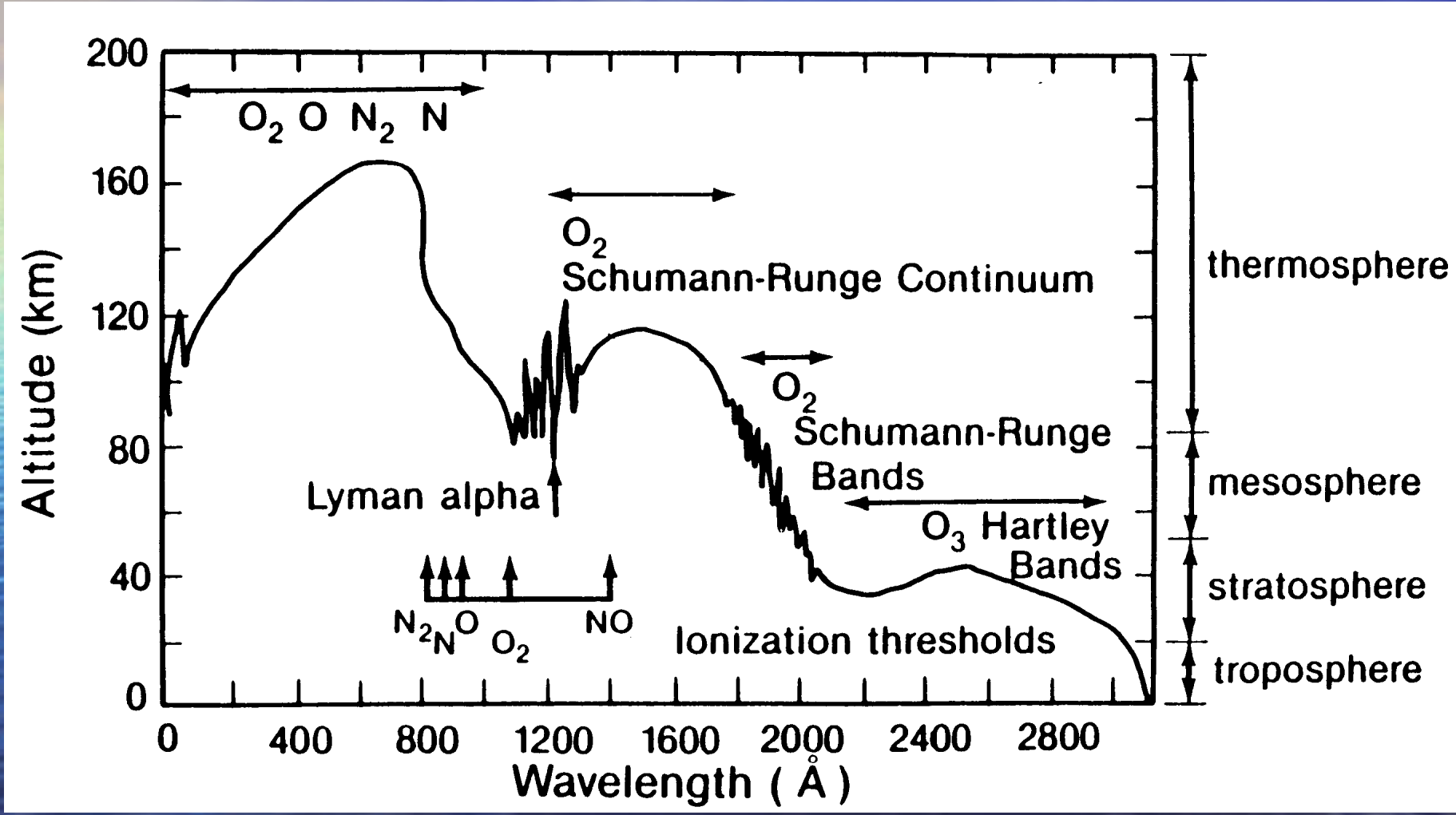
The Sun in Time

Ribas et al. 2005



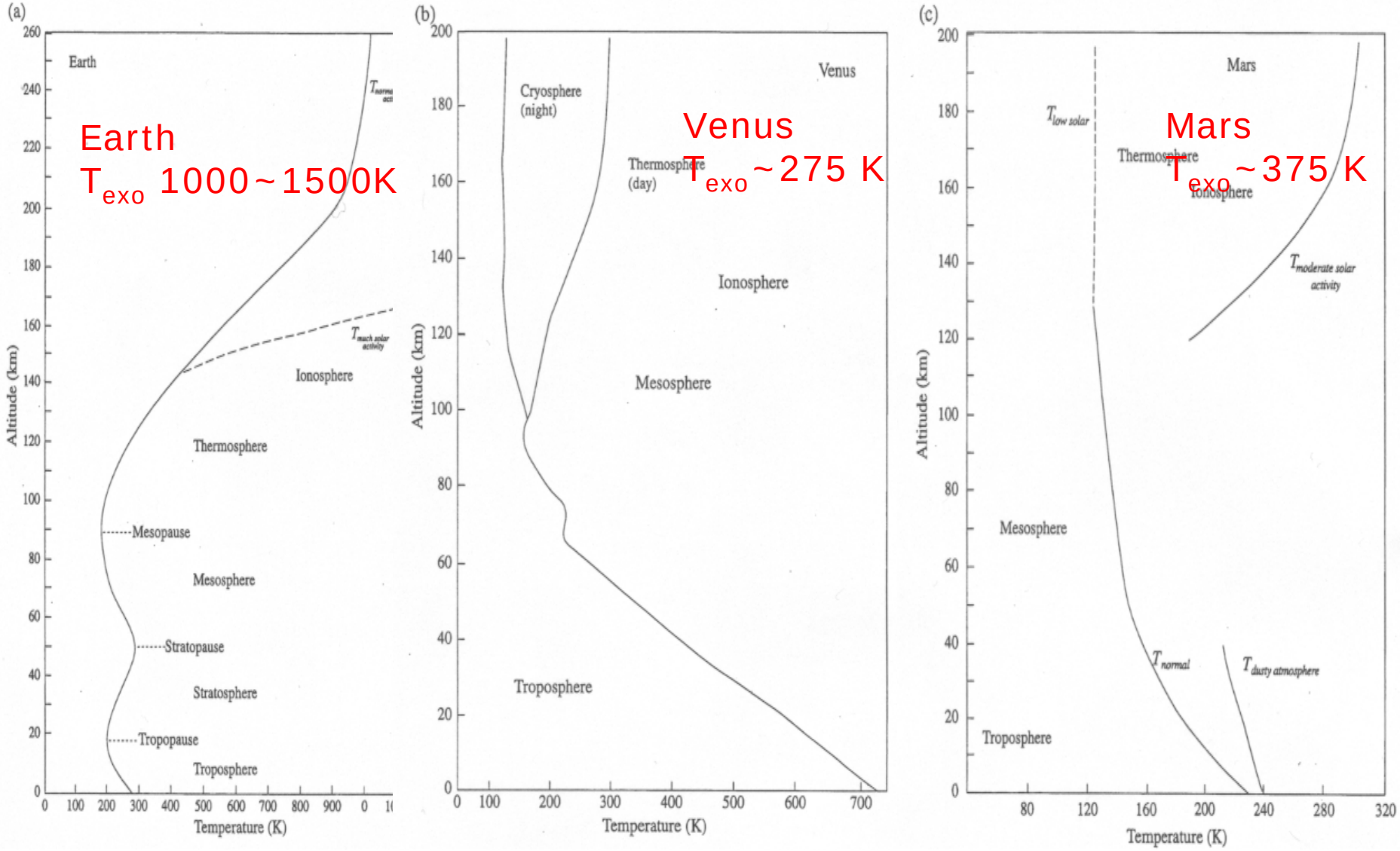

Solar Spectrum
20x XUV
Solar max
Solar min
Photon Flux (cm^{-2} s^{-1})
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
0
100
200
300
wavelength (nm)
Solar Cycle Variability
10
1
0
100
200
300
wavelength (nm)

Penetration Depth (τ = 1)



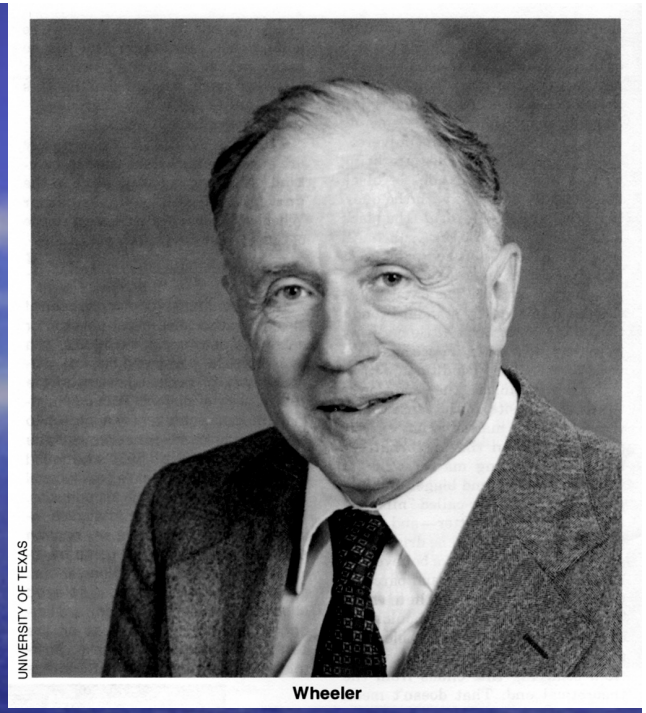
Thermospheres of Terrestrial Planets

(de Pater and Lissauer 2001)



RADICAL CONSERVATISM

J.A. Wheeler 1911-2008



- **Insist on adhering to well-established physical laws (<u>be conservative</u>) but follow those laws into their most extreme domains (<u>be radical</u>), where unexpected insights into nature might be found.**

- Following this principle, we “torture” different planetary atmospheres with XUV photons……

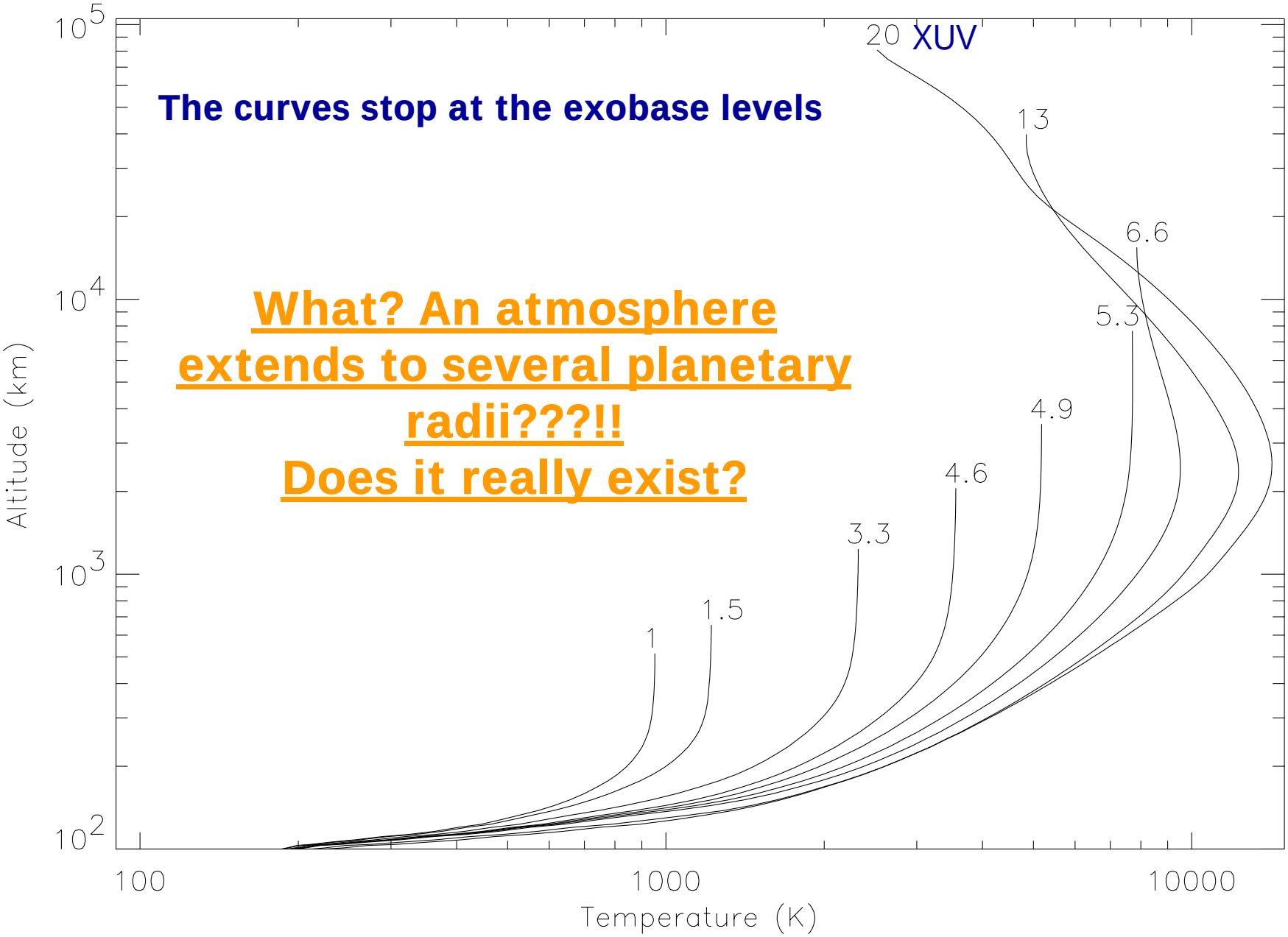
1-D multi-fluid hydrodynamic model

(Tian et al. 2008a, b, 2009)

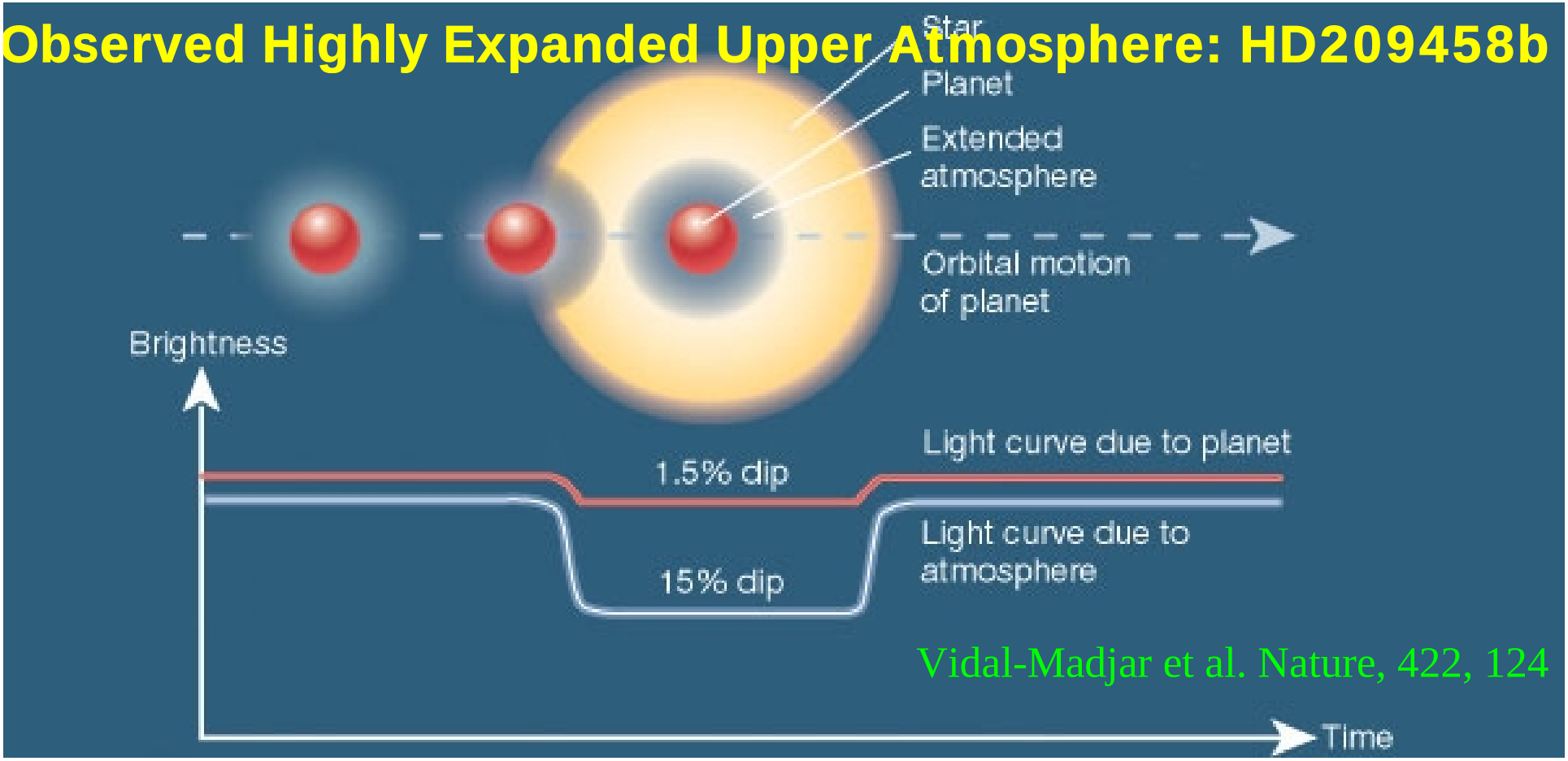
- Solves the continuity, momentum, and energy equations of one background fluid with variable molecular weight
- Solves minor constituent diffusion equations in a moving background for 16 long-lived species (O, O_2, N, N_2, H_e, H, H_2, CO, CO_2, C, NO, H_2O, O^+, N^+, H^+, C^+)
- Chemical equilibrium for short-lived species (O_3, HO_2, OH, H_2^+, H_3^+, $O^+(^2P)$, $O^+(^2D)$, N_2^+, CO^+, CO_2^+, O_2^+, NO^+, OH^+, $N(^2D)$, $O(^1D)$, H_2O_2, $O_2\ (^1\Sigma_g)$, $O_2\ (^1\Delta_g)$)
- 200+ chemical reactions (include reactions in existing thermosphere/ionosphere models for terrestrial planets and hot Jupiters)
- No assumption on heating efficiency -- couple energetic electron transport model to compute ionization and ambient electron heating rates (Tian et al. 2008b)

Responses of N_2-O_2-rich atmosphere to strong XUV

(Tian et al. 2008a)

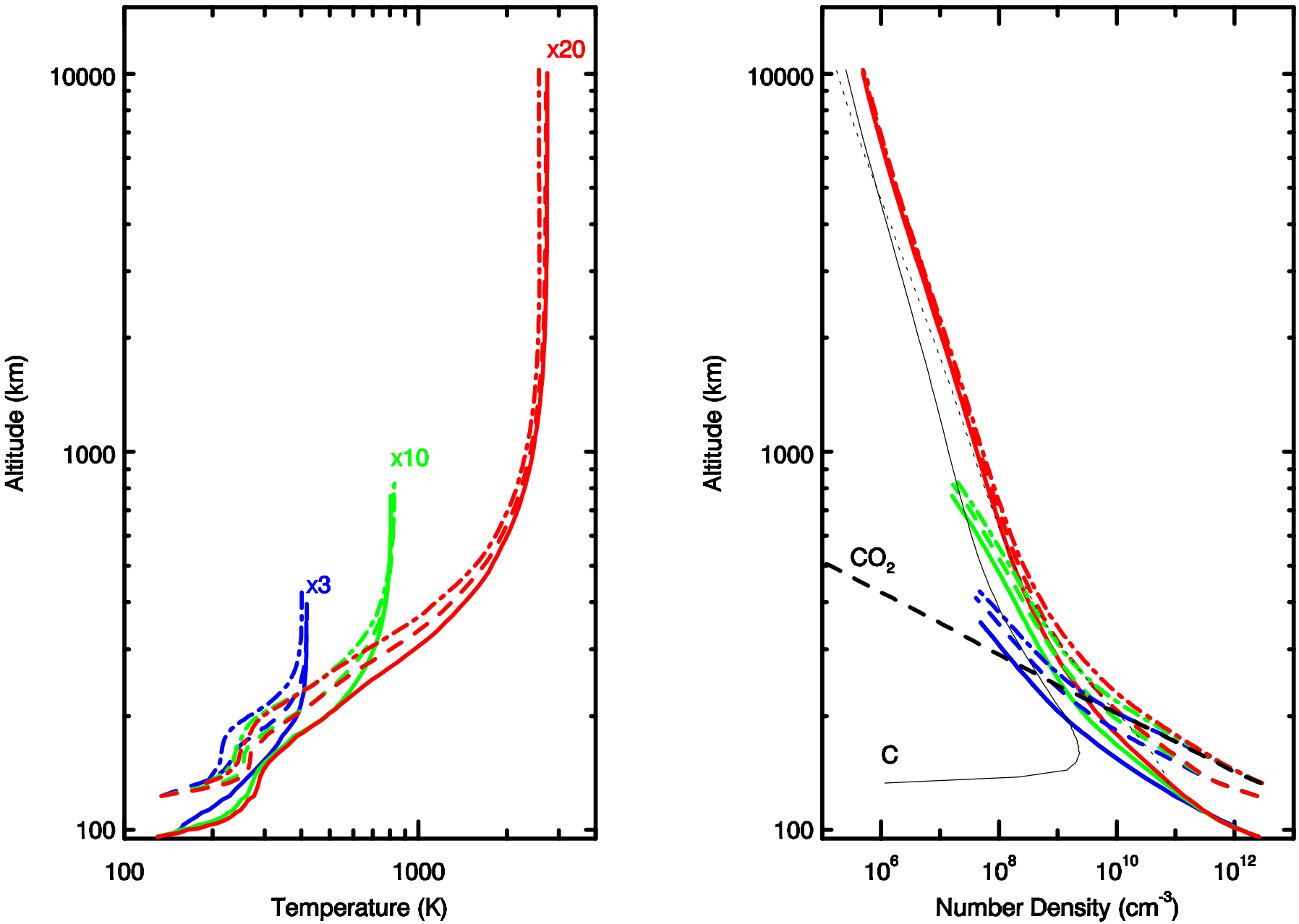


Observed Highly Expanded Upper Atmosphere: HD209458b



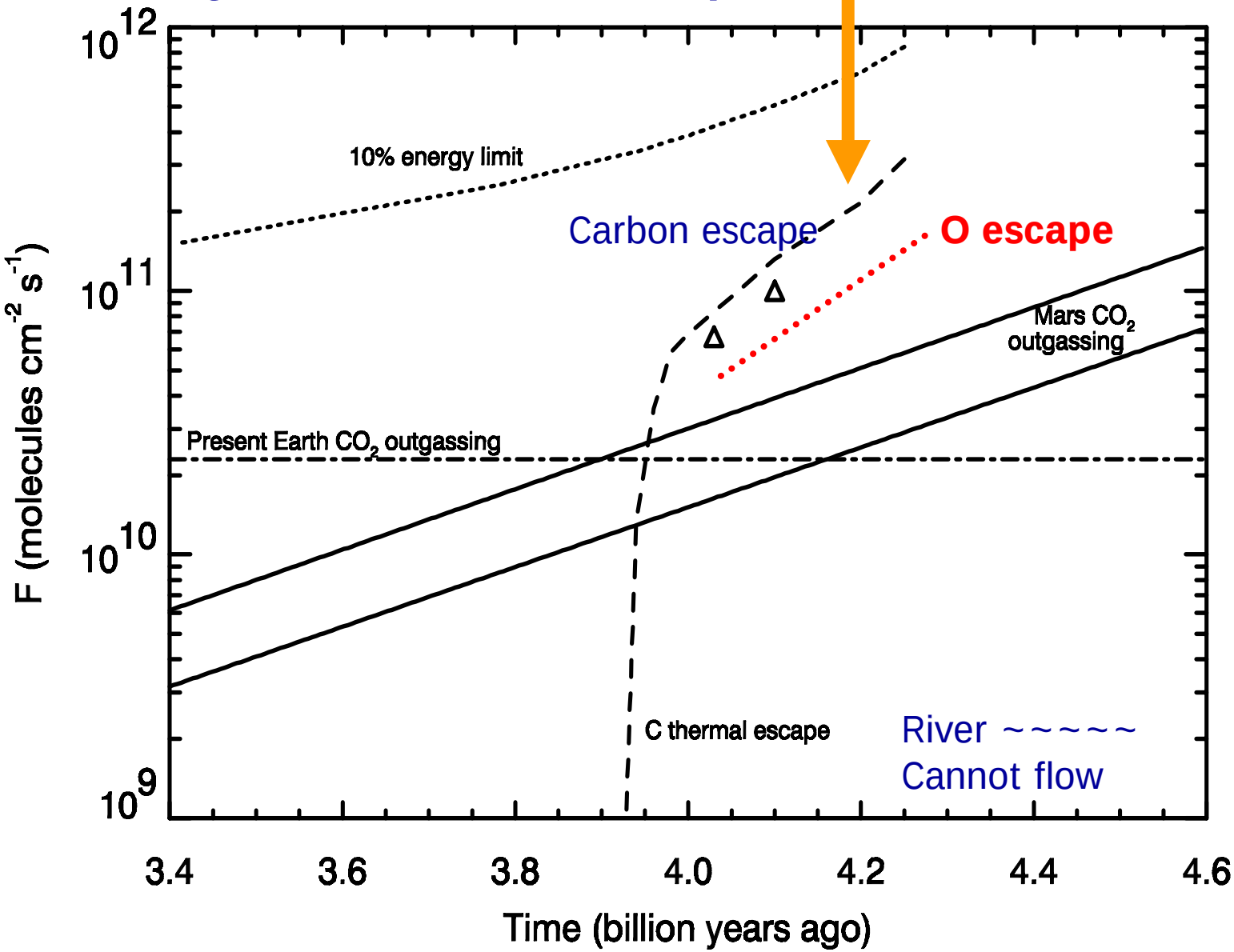
- 15±4% Lyman α absorption observed during the transit (Vidal-Madjar, A. *et al*. *Nature* **422**, 143-146, 2003). Only 1.5% light reduction observed at most other wavelengths.
- equivalent hydrogen cloud radius ~ 6.5 planetary radius
- absorption line extends ~0.5 Å from line center → strong broadening → high temperature (10^4~10^5K)

Early Mars Upper Atmosphere (Tian, Kasting, & Solomon GRL 2009)



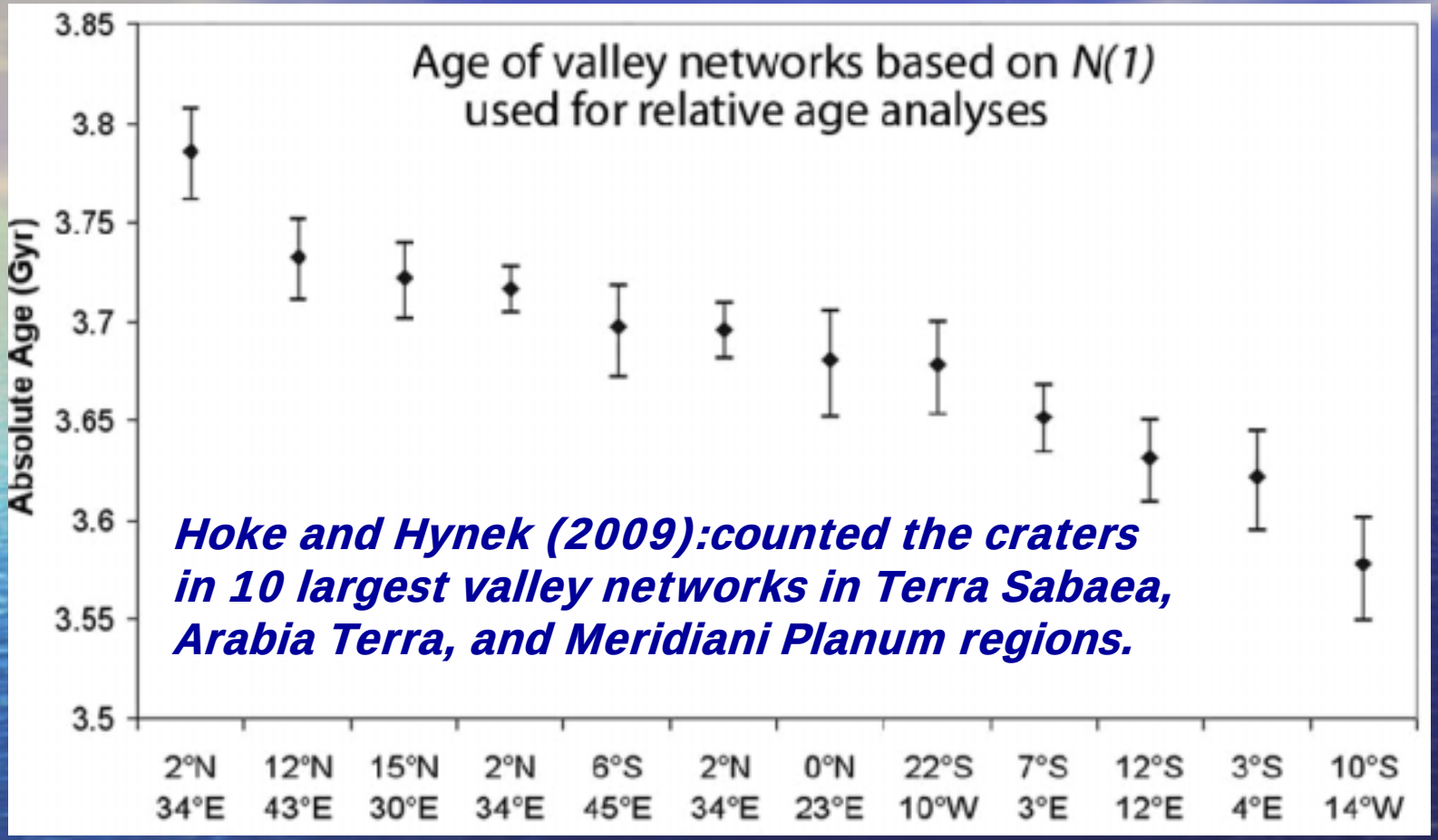
Fast thermal escape of carbon = CO_2 loss

(Tian, Kasting, & Solomon GRL 2009)



Snowball Early Noachian Mars

Support of such a *WILD* idea?

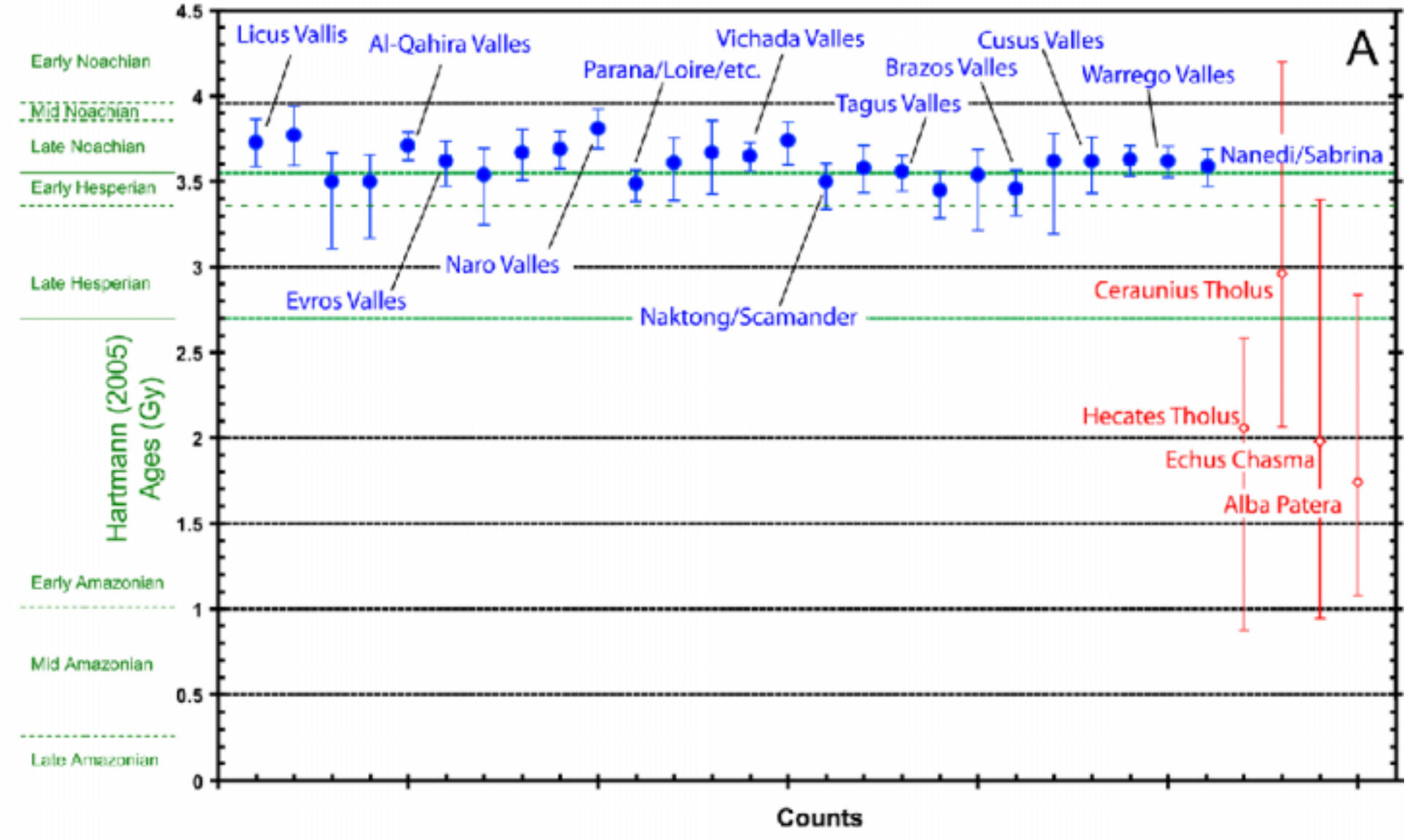


Hoke and Hynek (2009):counted the craters in 10 largest valley networks in Terra Sabaea, Arabia Terra, and Meridiani Planum regions.

The lack of valley networks in this large region older than the Late Noachian is surprising. This observation could indicate that valley network formation in Terra Sabaea, Arabia Terra, and Meridiani Planum did not occur earlier in the Noachian, or that any traces of valleys whose formation ceased earlier in the Noachian have been erased. If

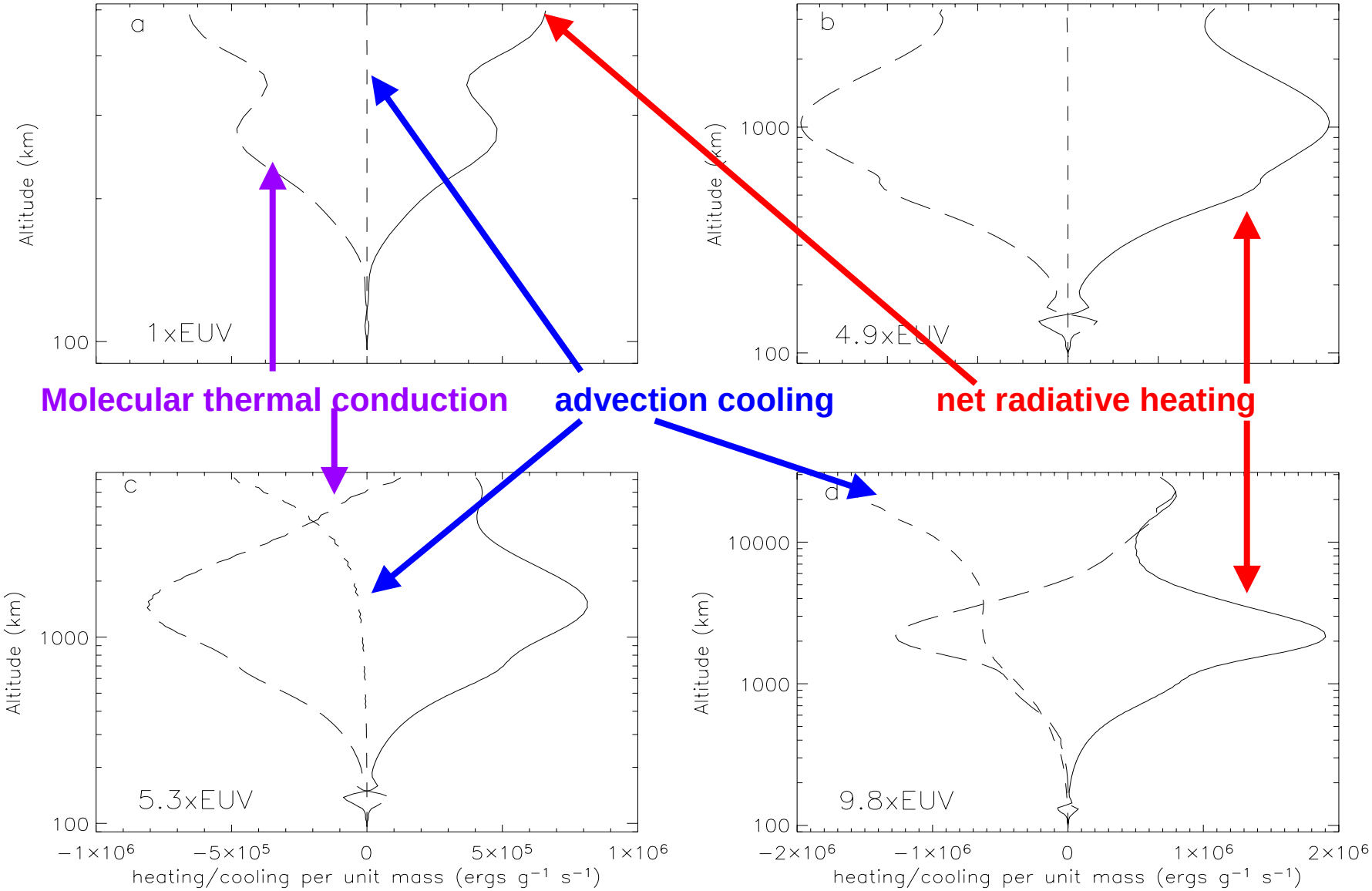
Support of such a *WILD* idea?

Fassett and Head 2008



A thermosphere under strong XUV is controlled by cooling associated with the radial outflow – the hydrodynamic regime

Total atmosphere escape could be conserved.

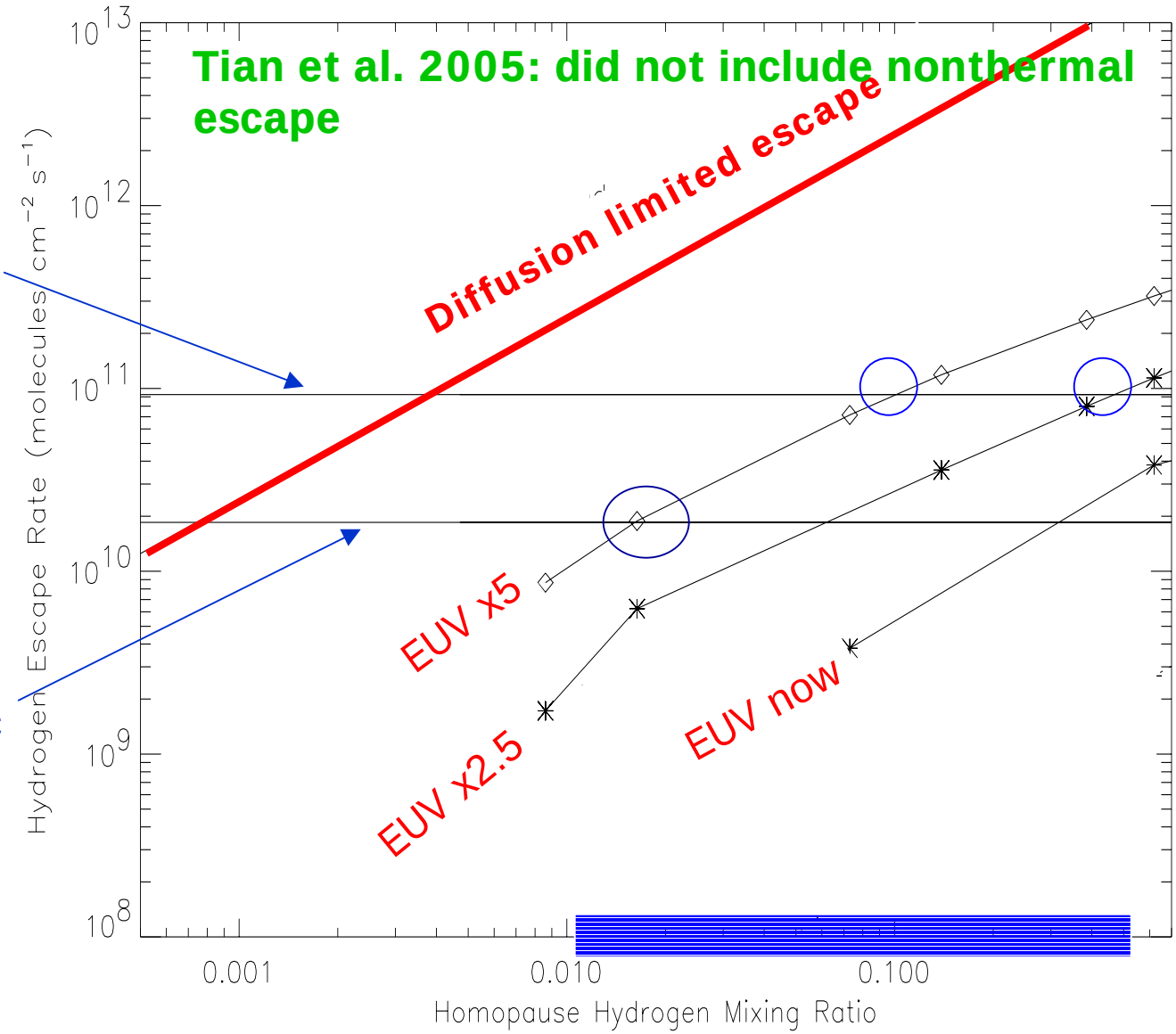


(Tian et al. 2008a)

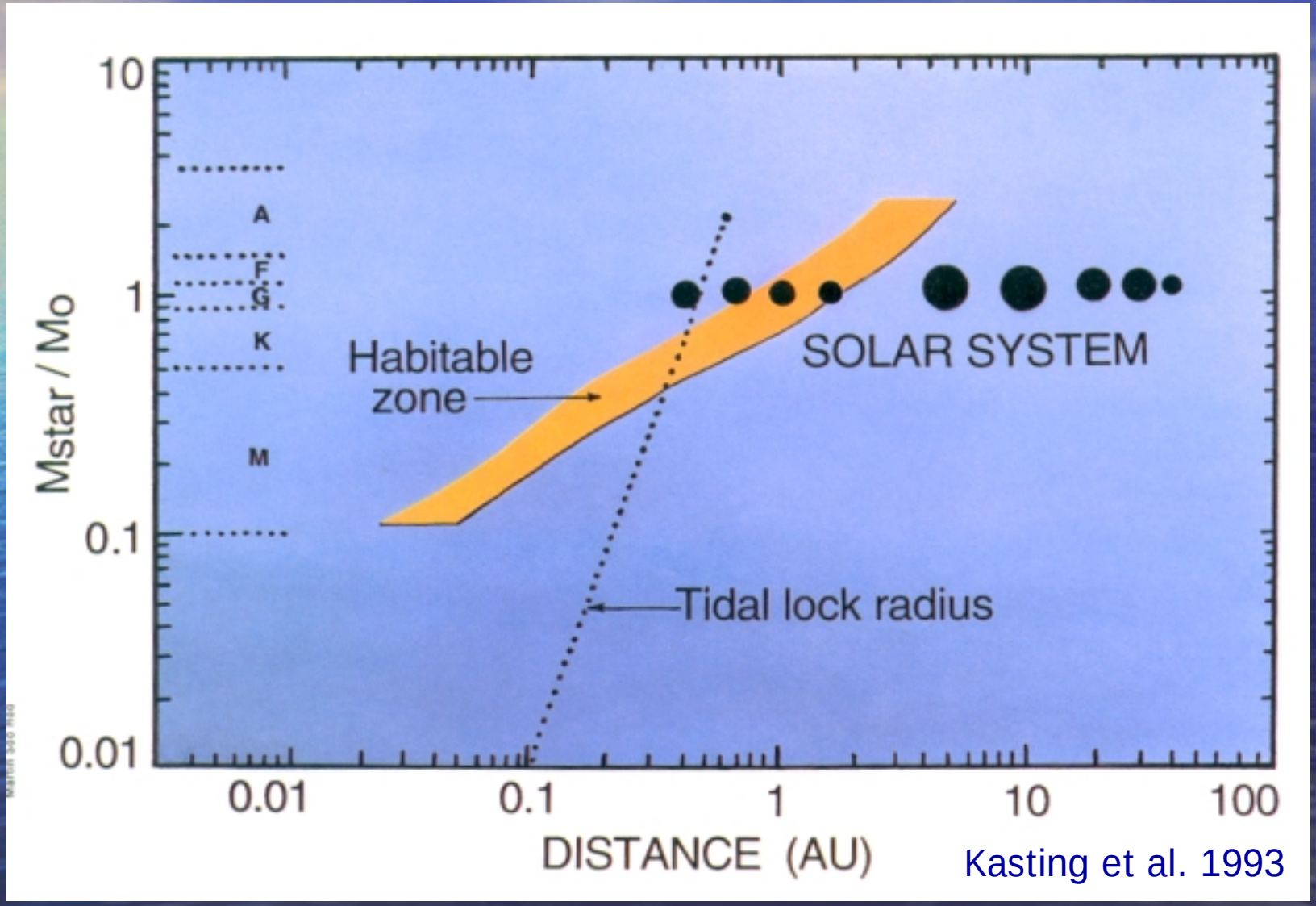
Impact on early Earth Hydrogen Content?

H_2 outgassing rate 5 times higher on early Earth due to larger heat flux, Turcotte (1980).

Present H_2 volcanic outgassing rate 1.8×10^{10} cm^{-2} s^{-1}, Holland (2002).



Observations to check the Theory?



Kasting et al. 1993

Summary

- **Early Solar XUV radiation was strong.**
- **Planetary atmospheres can expand to several planetary radii under strong XUV -- fast escape of major atmospheric gases occurs – a snowball early Noacian Mars?**
- **Total atmosphere escape from planetary atmospheres in the hydrodynamic regime is conserved.**
- **Observations to check the theory will be available soon (journal club tomorrow).**