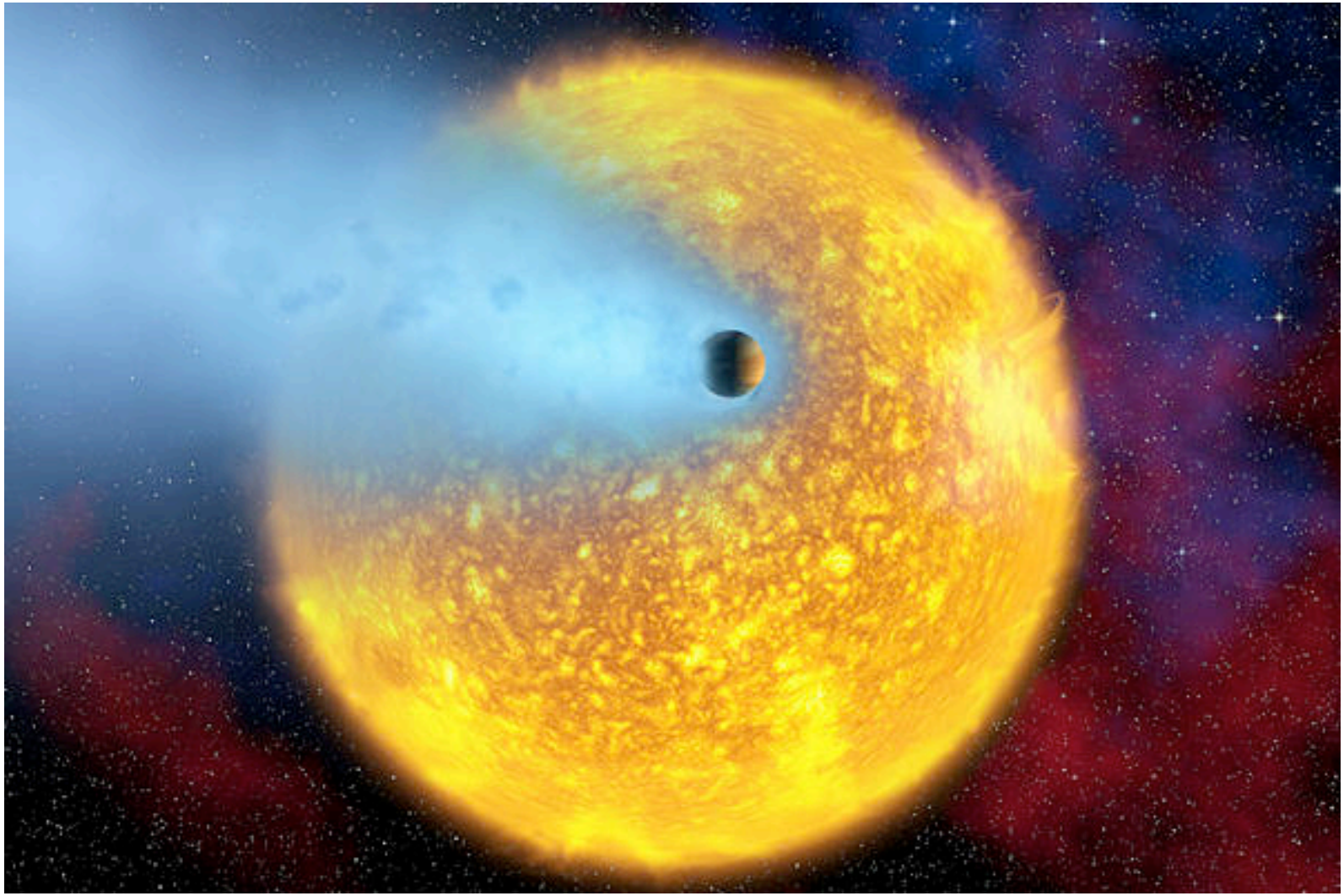
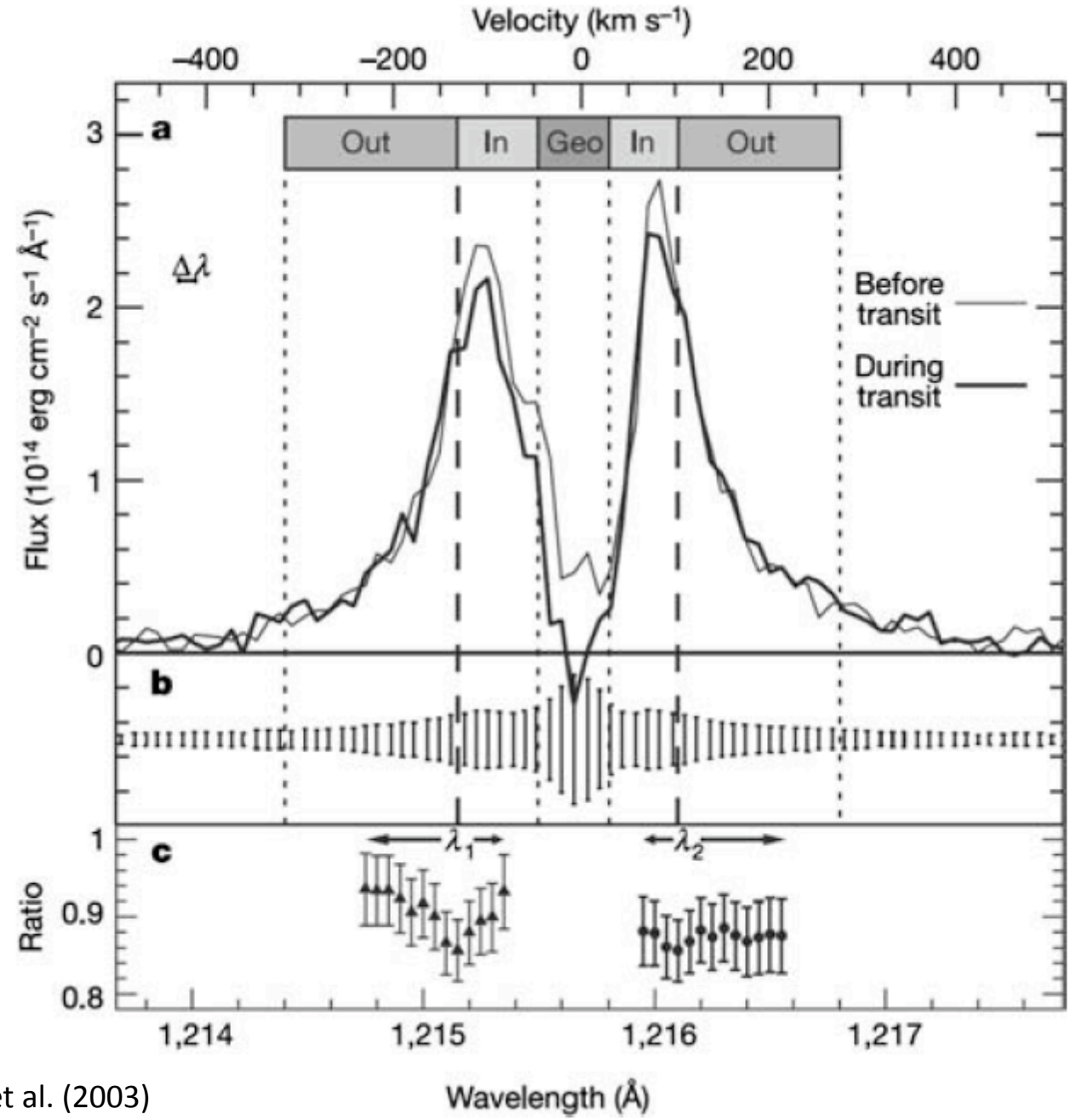
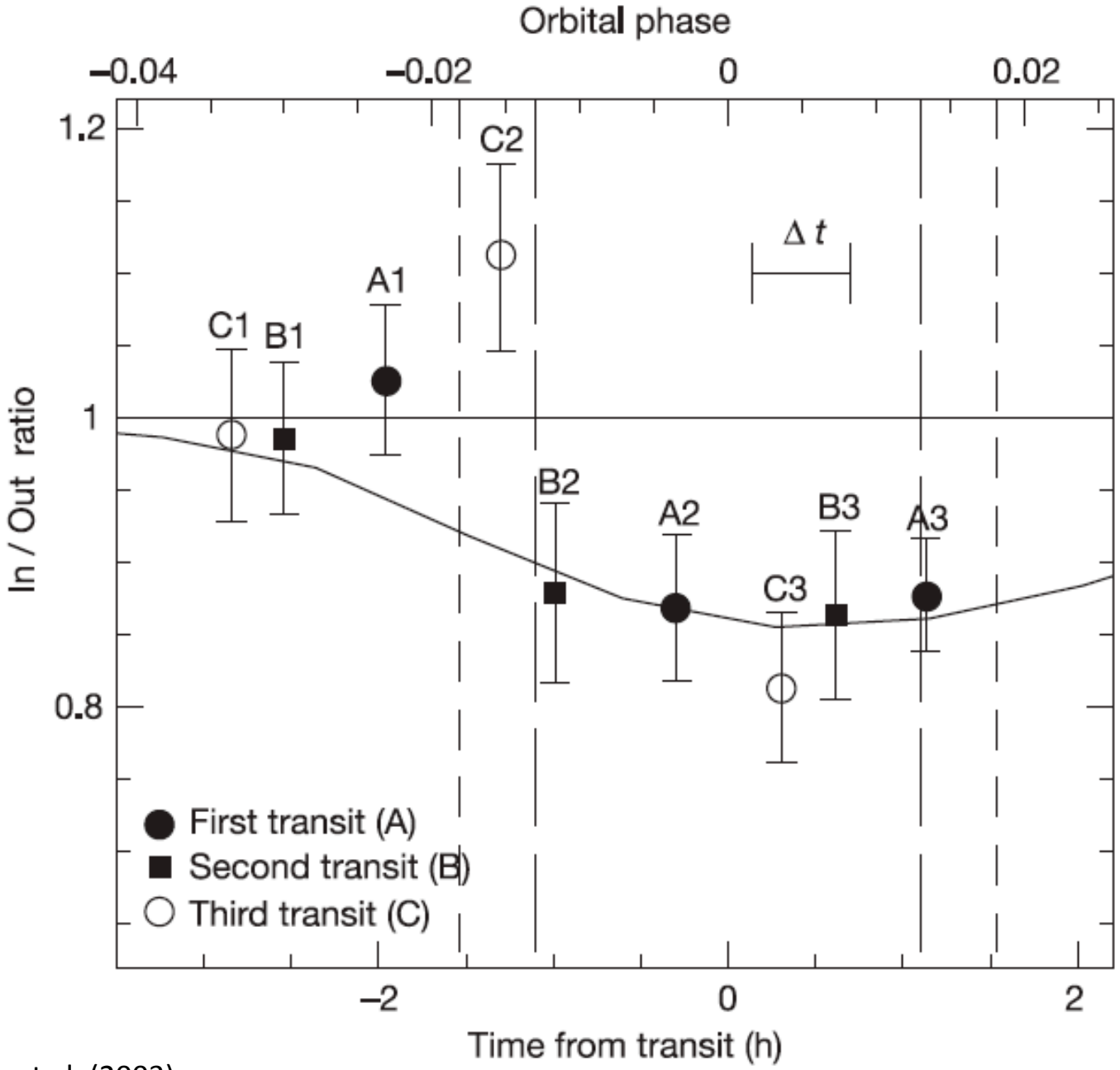
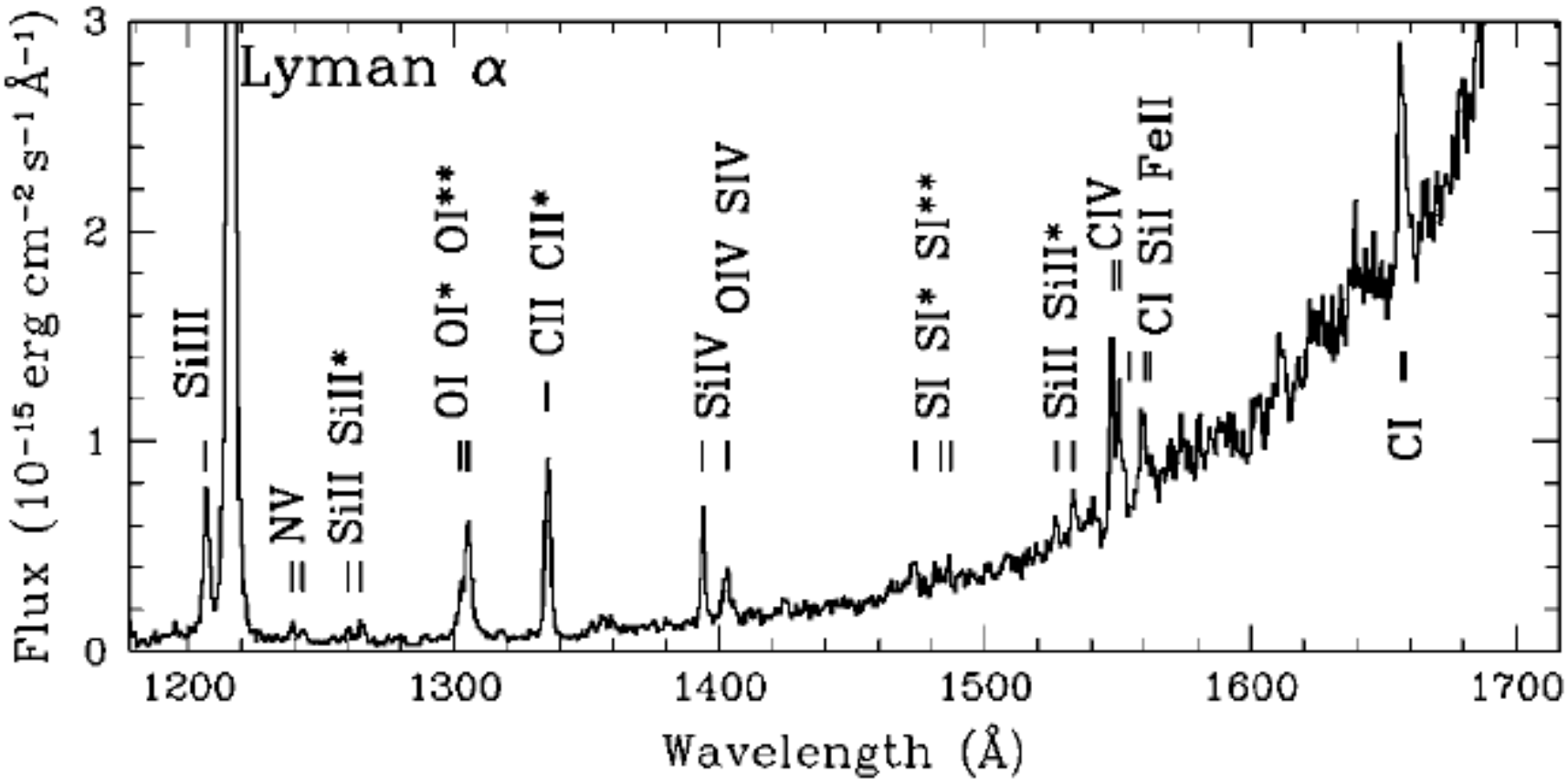




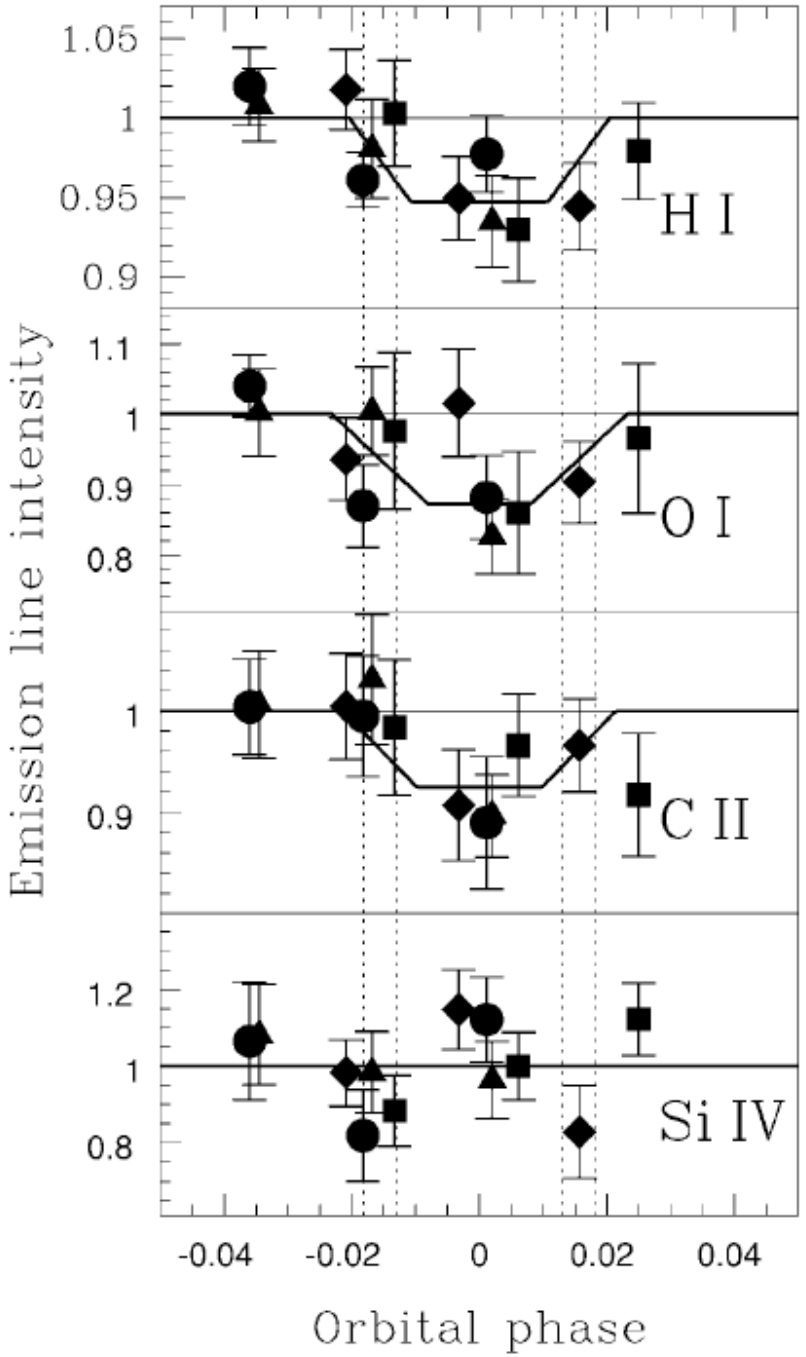
Vidal-Madjar et al. (2003)



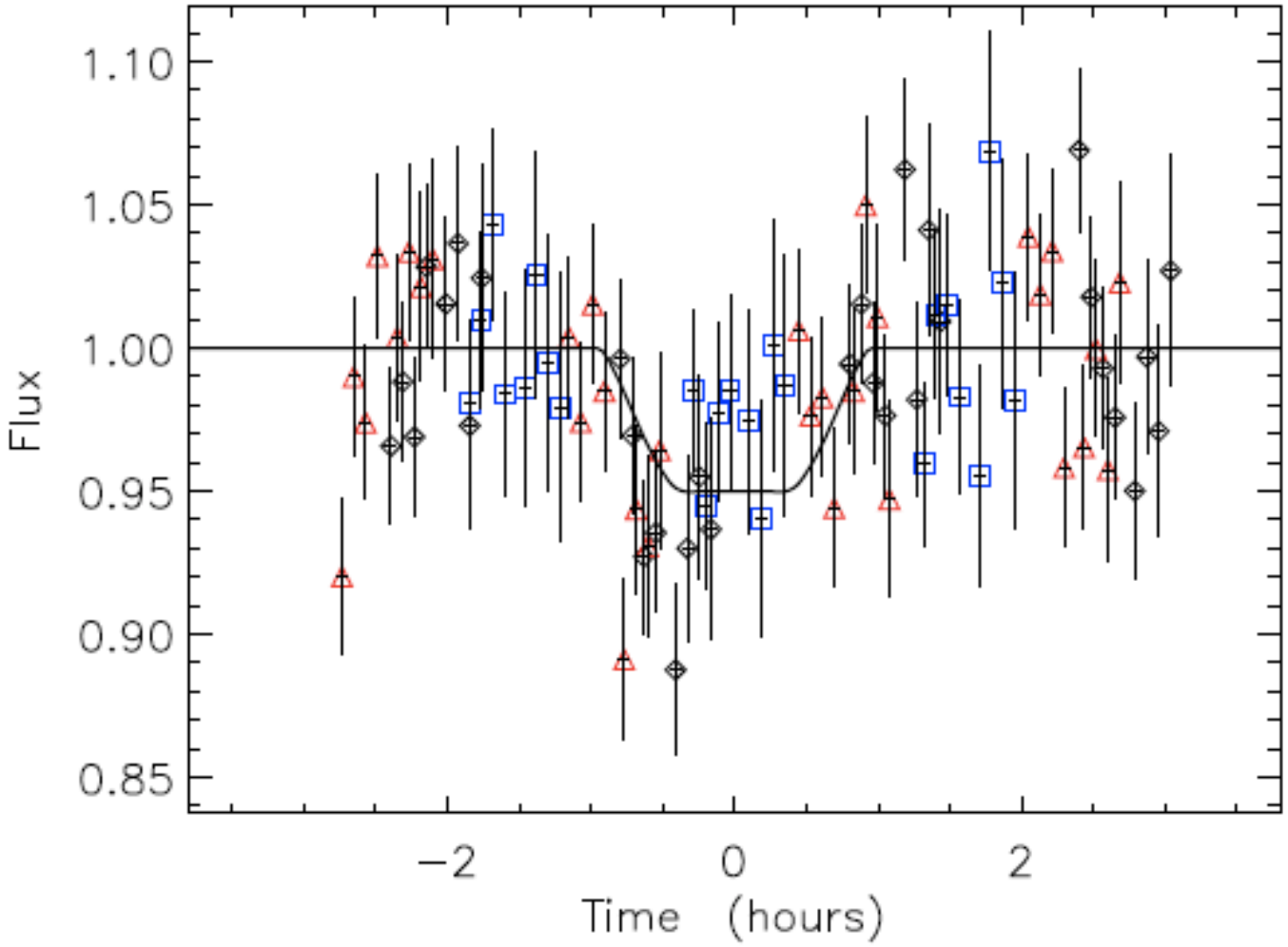
Vidal-Madjar et al. (2003)



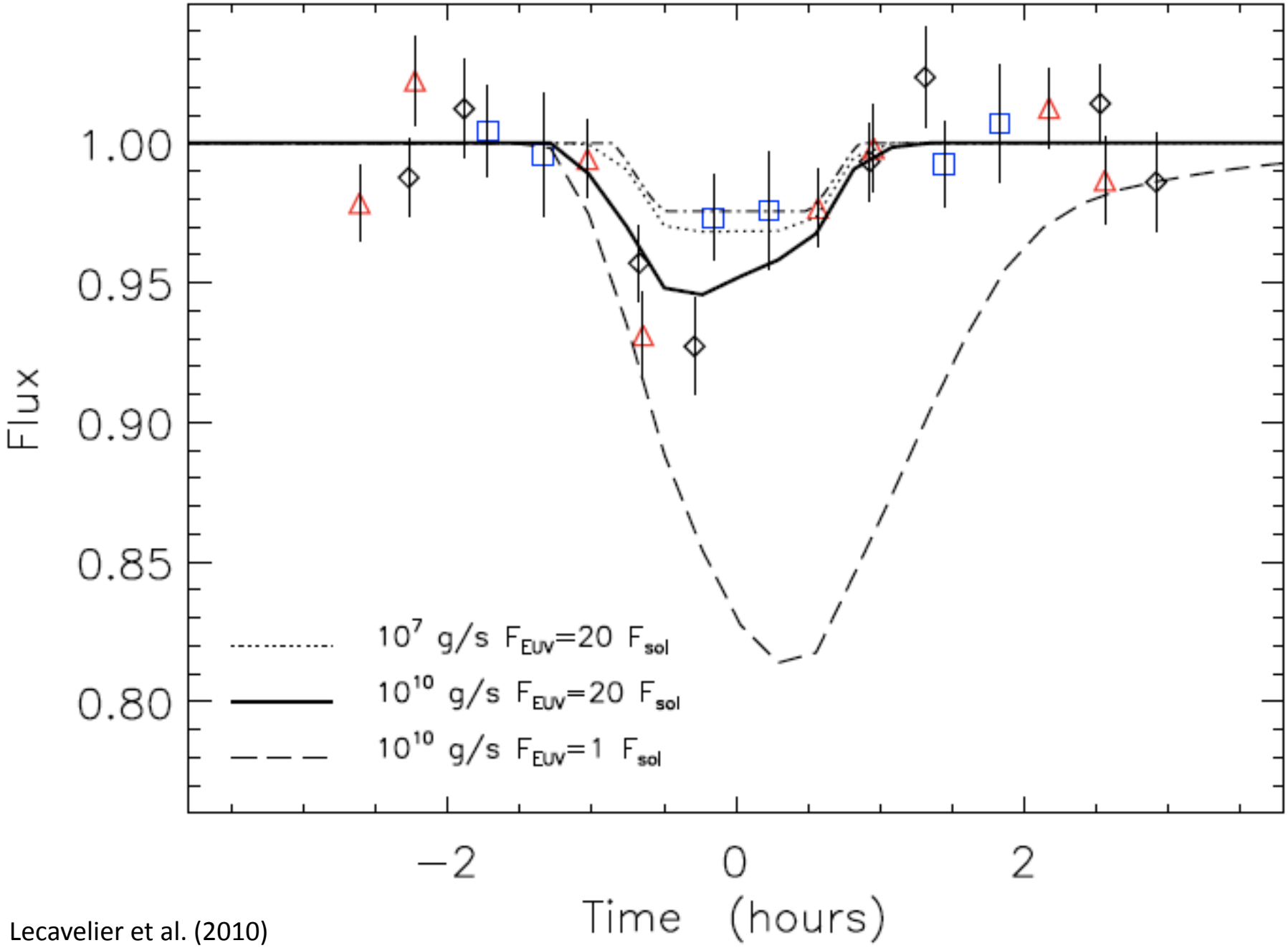
Vidal-Madjar et al. (2004)



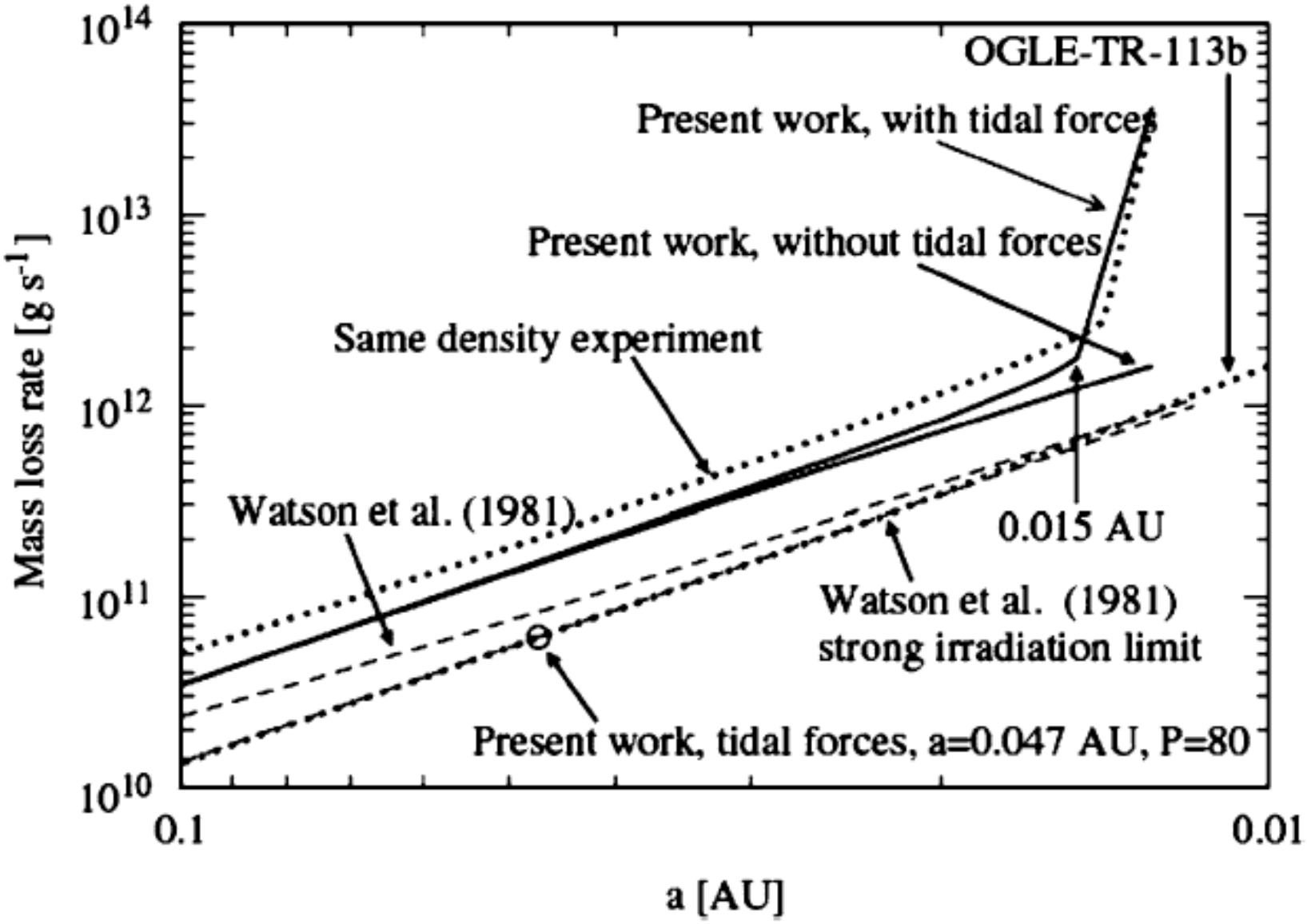
Vidal-Madjar et al. (2004)



Lecavelier et al. (2010)



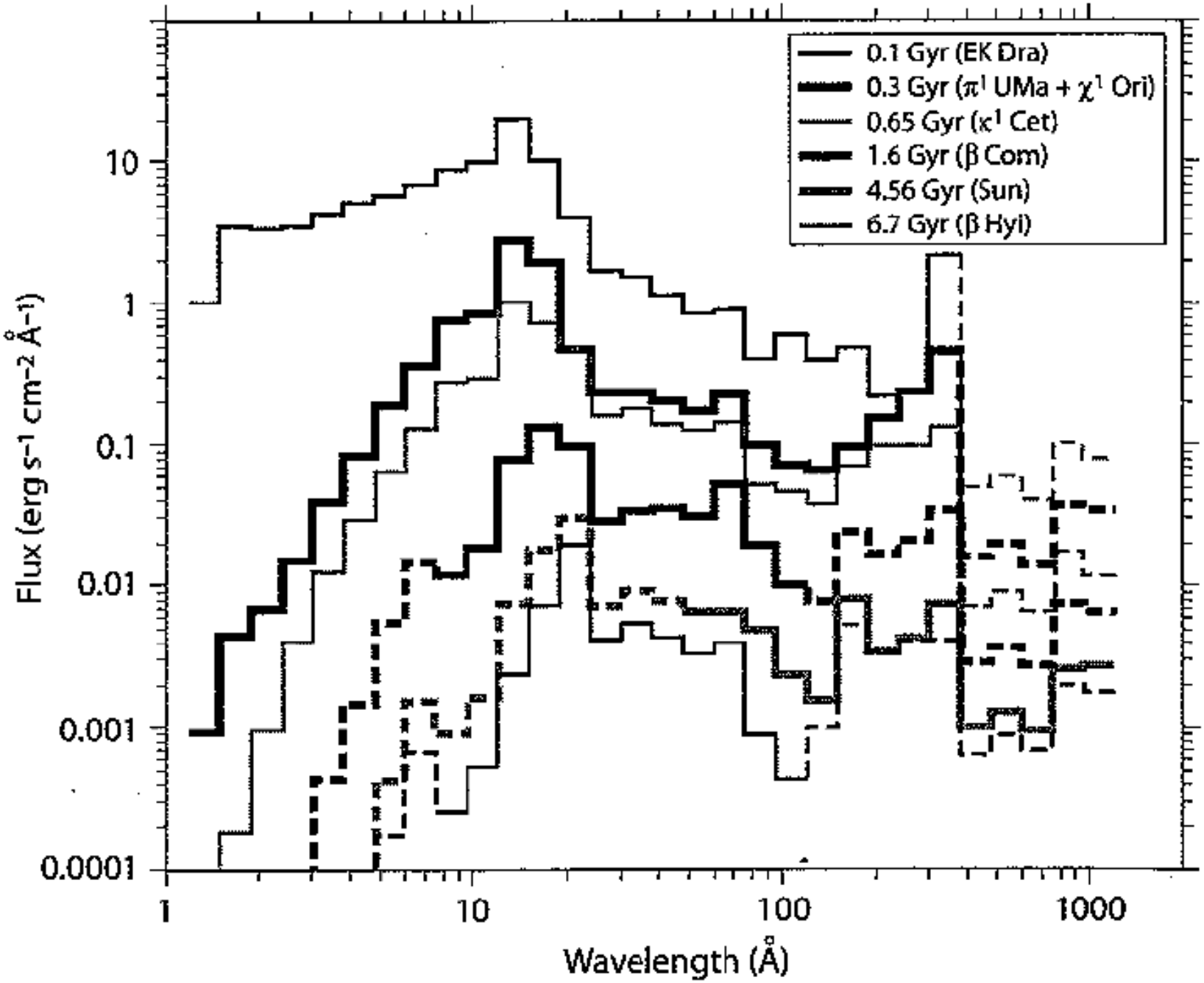
Lecavelier et al. (2010)



Yelle et al. (2008)

Escape rate ($g\,s^{-1}$)	Author	Comments
5×10^{11}	Lecavelier des Etangs et al. (2004)	Assumed T, used Jeans formula
$\sim 10^{12}$	Lammer et al. (2003)	Watson et al. (1981) approximation
4.5×10^{10}	Yelle (2004)	Navier-Stokes equations with variable composition
3.5×10^{10}	Tian et al. (2005)	Navier-Stokes equations with constant composition
4.8×10^{10}	Muñoz (2007)	Navier-Stokes equations with variable composition
3.5×10^{10}	Penz et al. (2008)	Navier-Stokes equations with constant composition

Yelle et al. (2008)


0.1 Gyr (EK Dra)
0.3 Gyr (π¹ UMa + χ¹ Ori)
0.65 Gyr (κ¹ Cet)
1.6 Gyr (β Com)
4.56 Gyr (Sun)
6.7 Gyr (β Hyi)
Flux (erg s⁻¹ cm⁻² Å⁻¹)
10
1
0.1
0.01
0.001
0.0001
1
10
100
1000
Wavelength (Å)

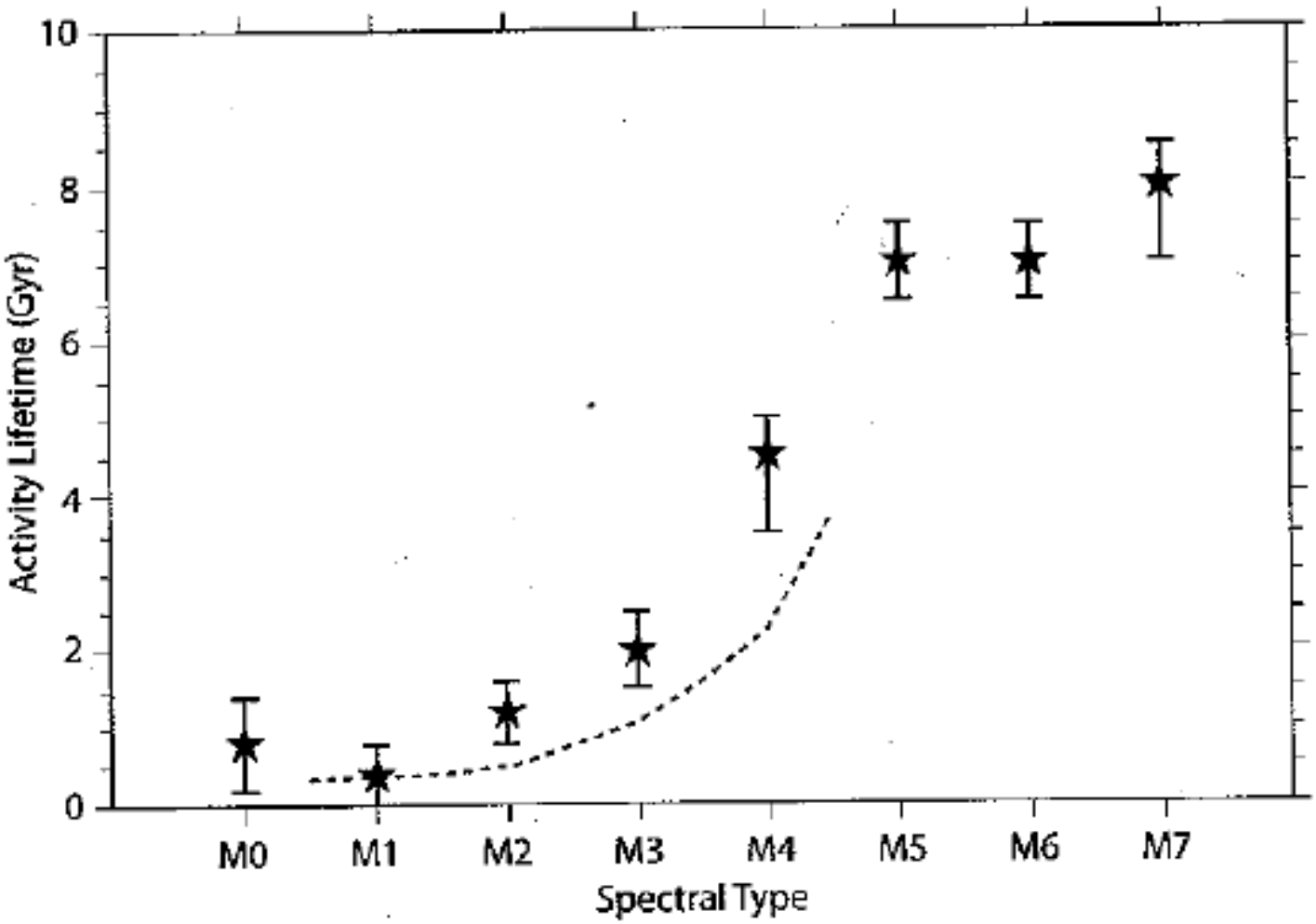
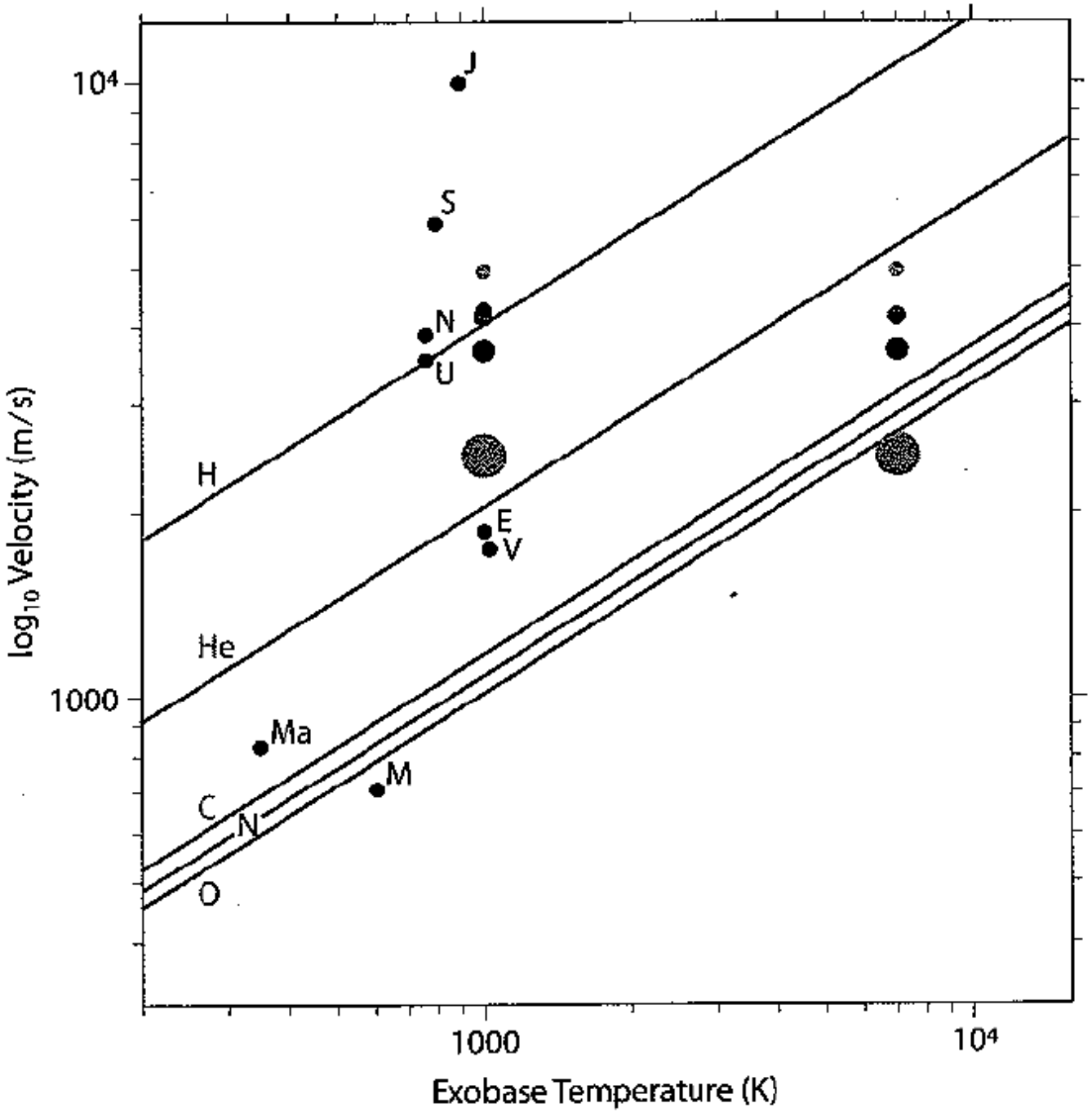


Figure 4.15 Stellar activity lifetimes for M stars. While solar-type stars (not shown) are active for at most a few hundred million years, M stars can be active for billions of years. The strong EUV radiation during the active phase can drive thermal atmospheric escape on exoplanets. Adapted from [24].


10^4
1000
$\log_{10}$ Velocity (m/s)
1000
10^4
Exobase Temperature (K)
J
S
N
U
E
V
Ma
M
H
He
C
N
O

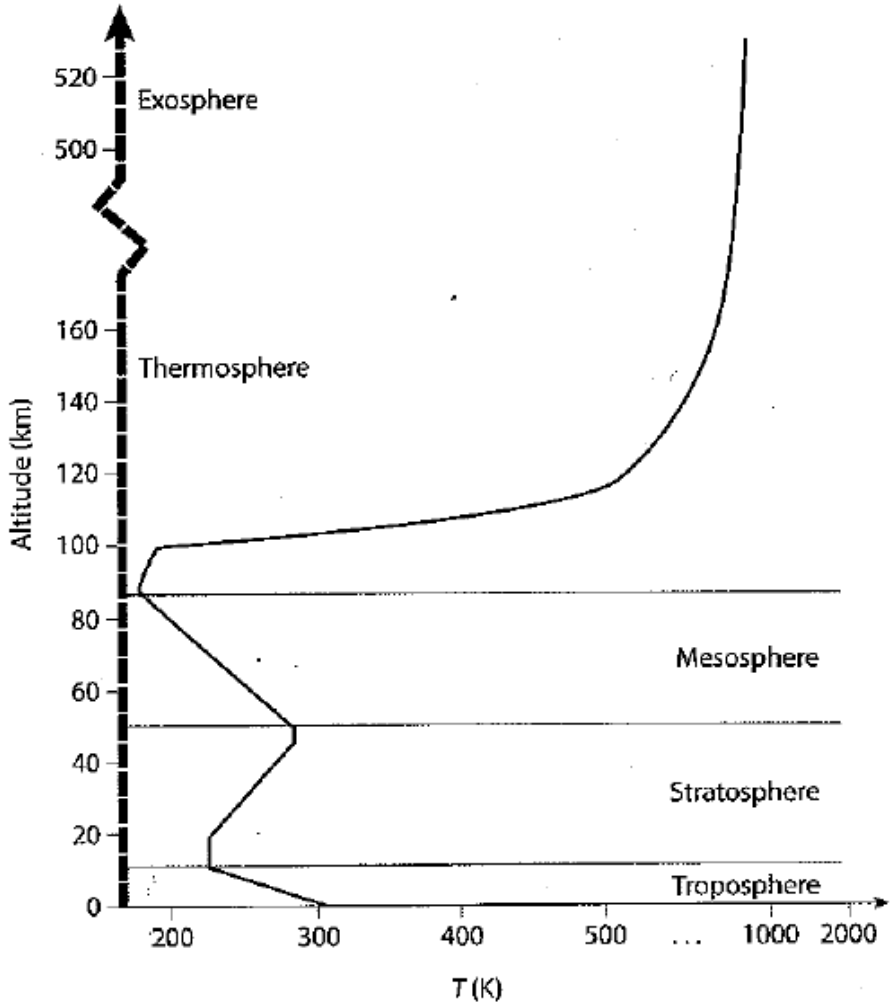
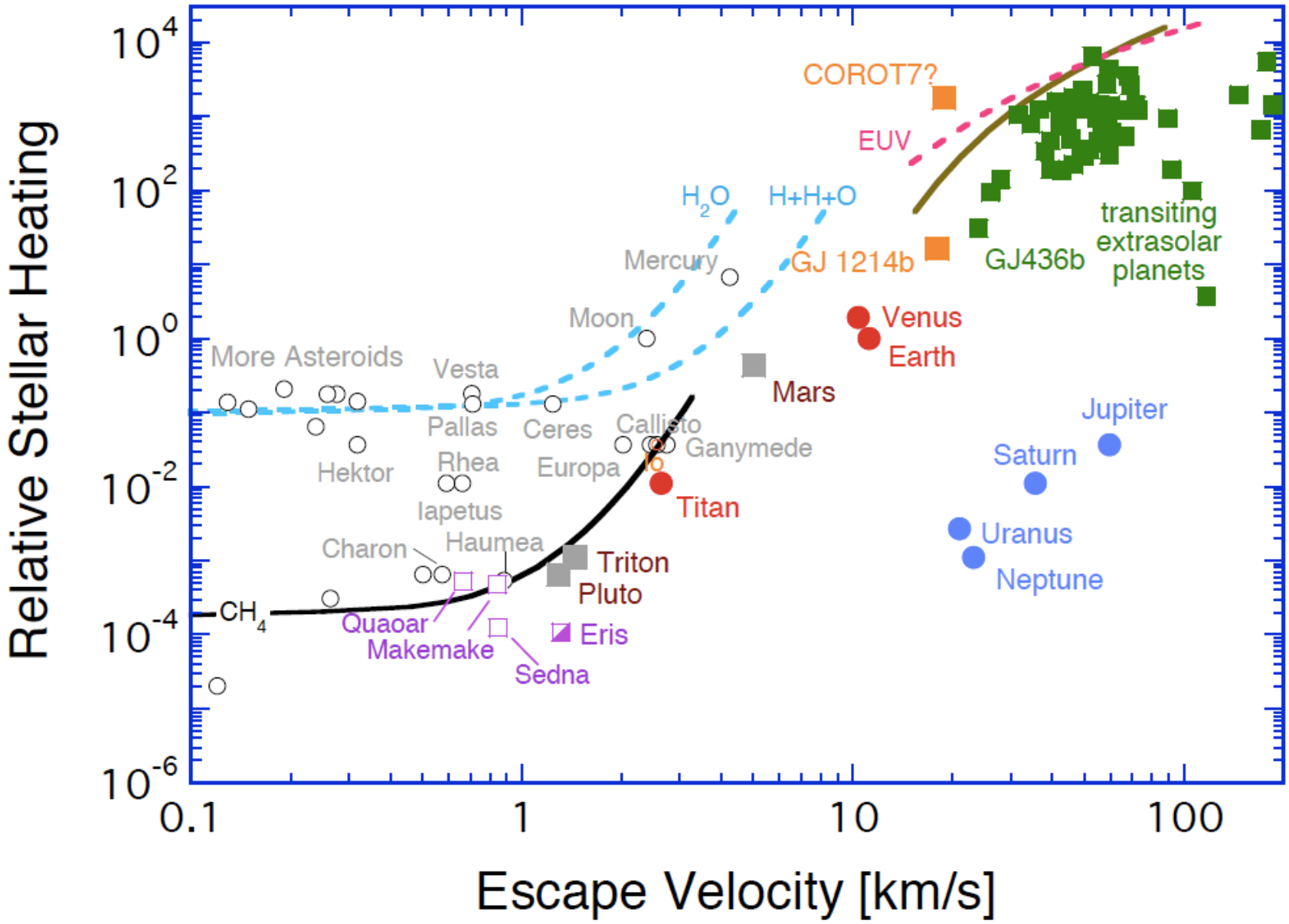


Figure 4.16 Earth's temperature profile showing the thermosphere and the exosphere. The exosphere extends to an altitude 500 km above Earth's surface. The ionosphere is a layer within the thermosphere. The temperature profile is from Earth's standard reference atmosphere and is based on measurements.

Process	Examples	Planet (gas) example
Charge exchange	$H + H^{+*} \rightarrow H^{+} + H^{*}$	Earth (H, D)
	$O + H^{+*} \rightarrow O^{+} + H^{*}$	Venus (He)
Dissociative	$O_2^{+} + e \rightarrow O^{*} + O^{*}$	Mars (O), E, G, C (O)
recombination	$OH^{+} + e \rightarrow O + H^{*}$	Venus (H), Mars (N),
		Titan (H_2)
Impact dissociation	$N_2 + e^{*} \rightarrow N^{*} + N*$	Mars (N), Titan (N)
Photodissociation	$O_2 + h\nu \rightarrow O^{*} + O^{*}$	
Ion-Neutral reaction	$O^{+}H_2 \rightarrow OH^{+} + H^{*}$	
Sputtering or	$Na + S^{+} \rightarrow Na^{*} + S^{+*}$	Io (Na, K)
knockon	$O^{*} + H \rightarrow O^{*} + H^{*}$	Venus (H)
Solar-wind pickup	$O + h\nu \rightarrow O^{+} + e$	Mercury (He, Ar)
	then O^{+} picked up	
Ion escape	H^{+*} escapes	Earth (H, D, He)
Jeans escape		Earth (H, D), Mars (H, H_2),
		Titan (H, H_2), Pluto (CH_4)

The * represents excess kinetic energy. The Jeans escape is a thermal process but is included in this table for completion. Adapted from [16].


Relative Stellar Heating
Escape Velocity [km/s]
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0.1
1
10
100
COROT7?
EUV
H_2O
H+H+O
transiting extrasolar planets
GJ436b
GJ 1214b
Mercury
Moon
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
More Asteroids
Vesta
Pallas
Ceres
Callisto
Ganymede
Europa
Io
Titan
Hektor
Rhea
Iapetus
Charon
Haumea
Triton
Pluto
Eris
CH_4
Quaoar
Makemake
Sedna