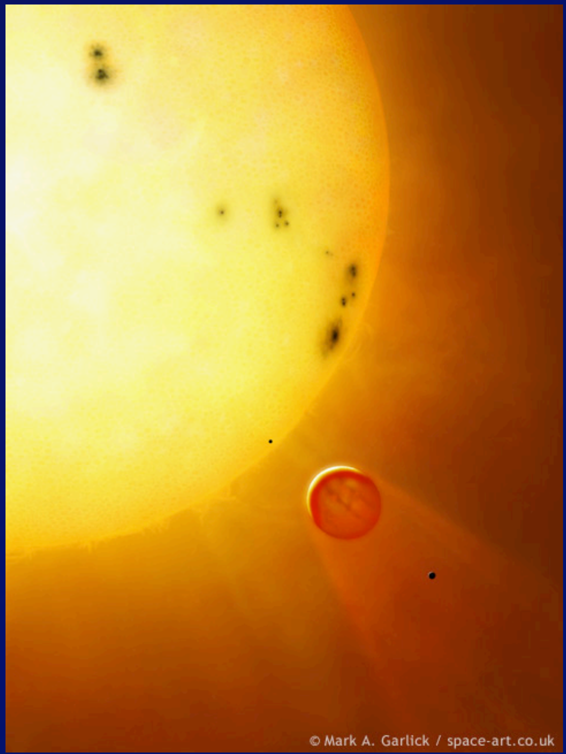
Atmospheric Escape Hot Jupiters
&
Interactions Between Planetary and Stellar Winds



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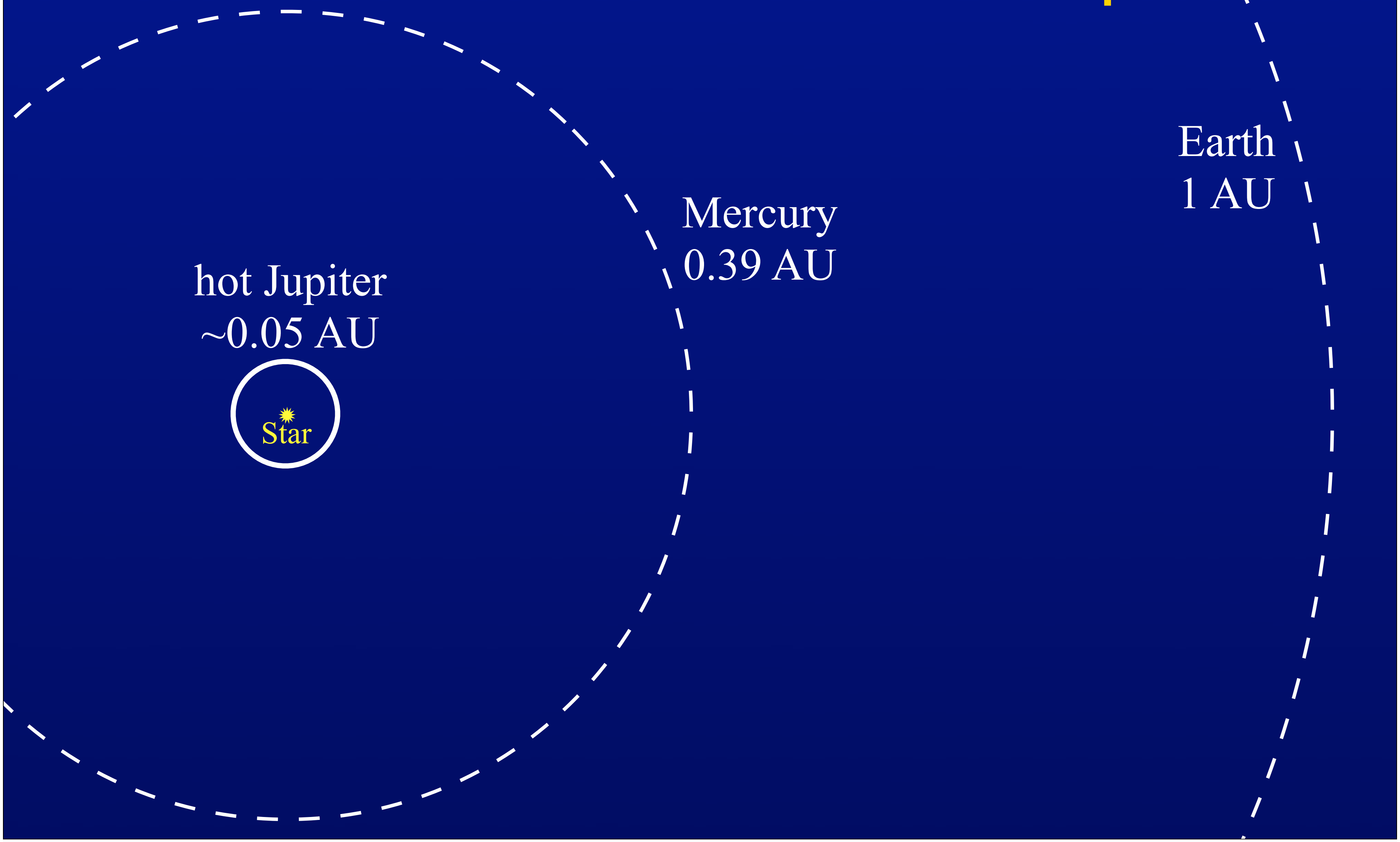
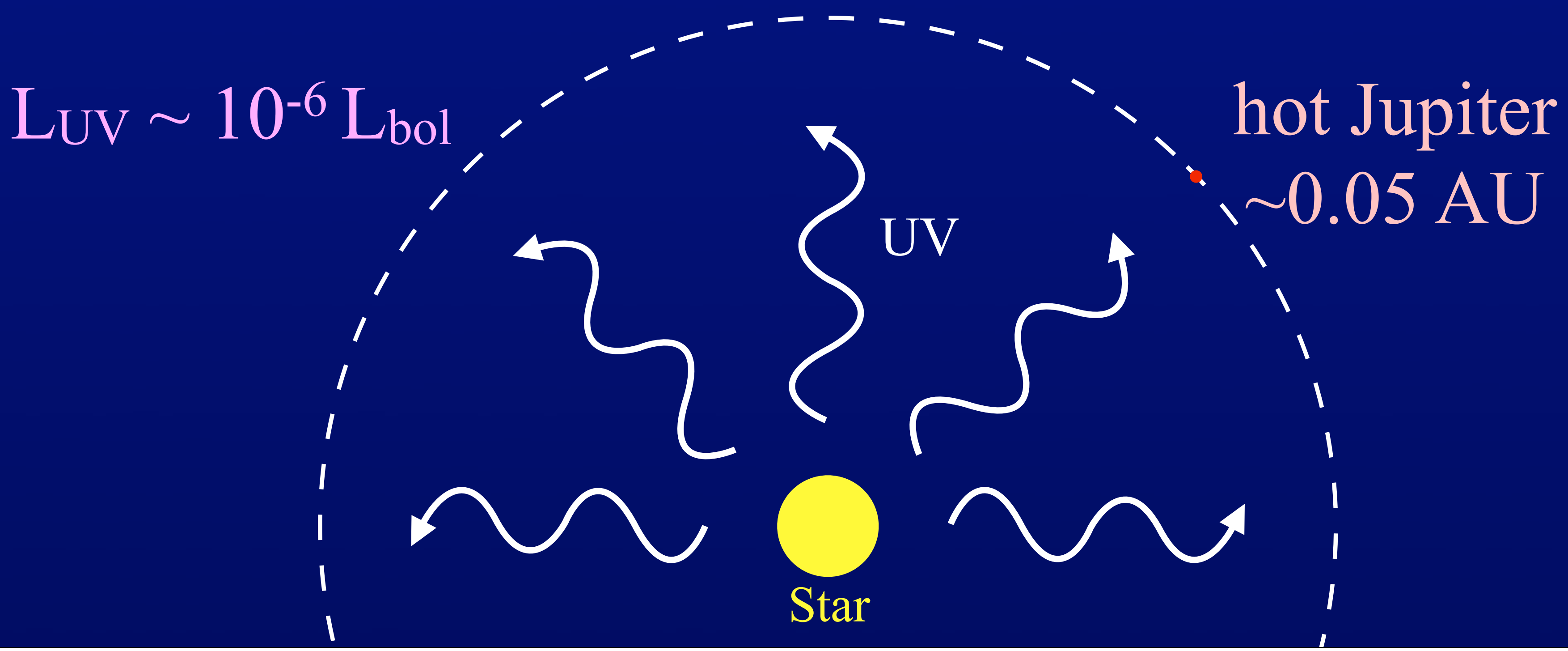
Theory Division
Collaborators: Eugene Chiang, Norman Murray

~20% of the exoplanets discovered to date are hot Jupiters

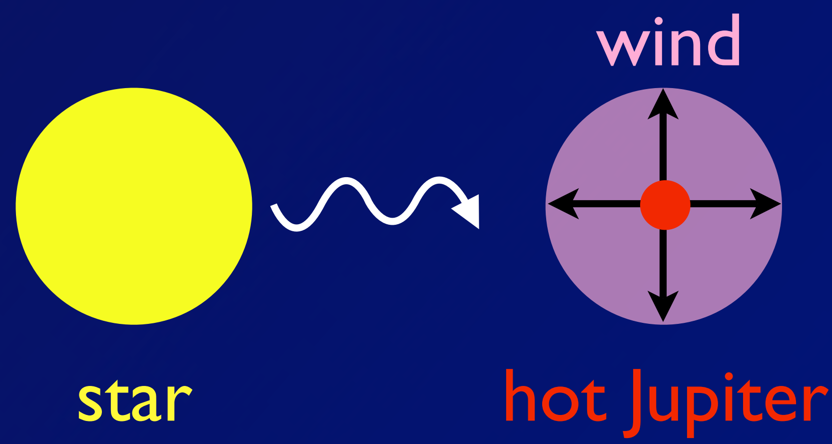


0.05 AU is an extreme environment

- hot Jupiters probably formed further out and migrated in
- once parked, they are bathed in UV radiation



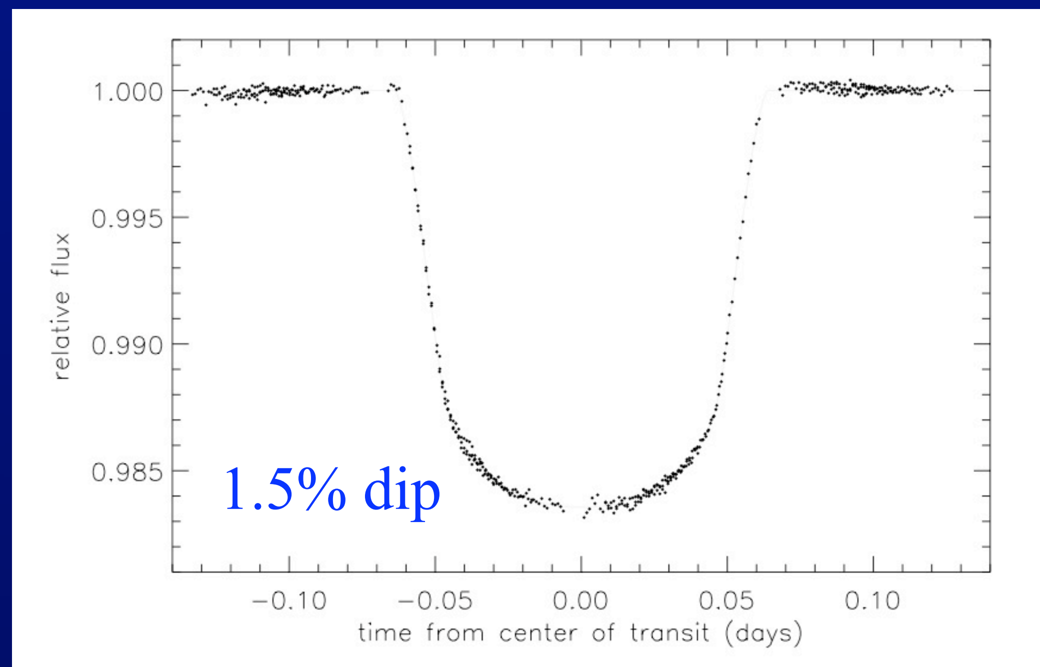
UV Photoionization Heating Drives a Thermal (Parker) Wind



HD 209458b:
A transiting hot Jupiter

Henry et al. 2000, Charbonneau et al. 2000

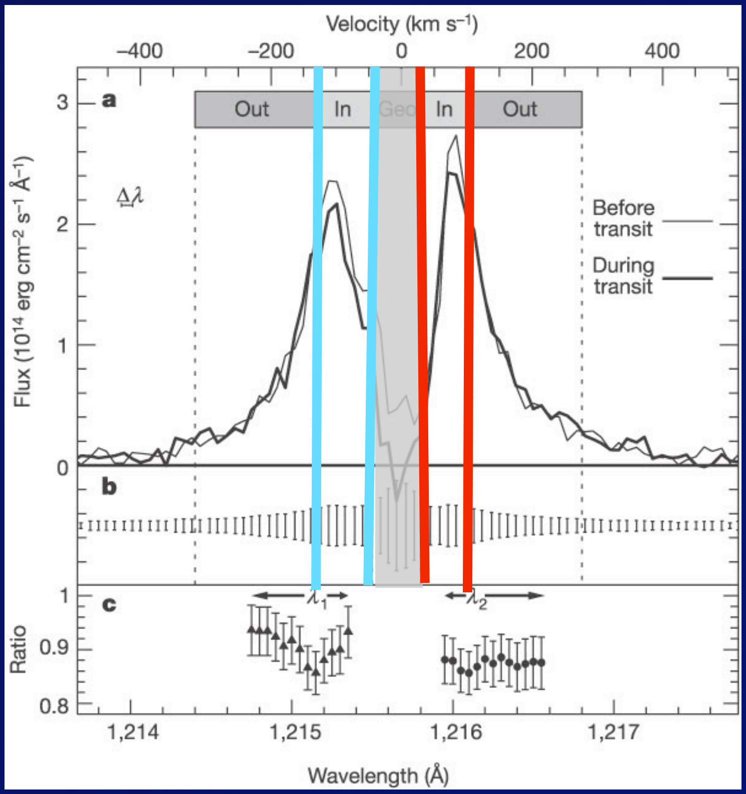
HST transit light curve



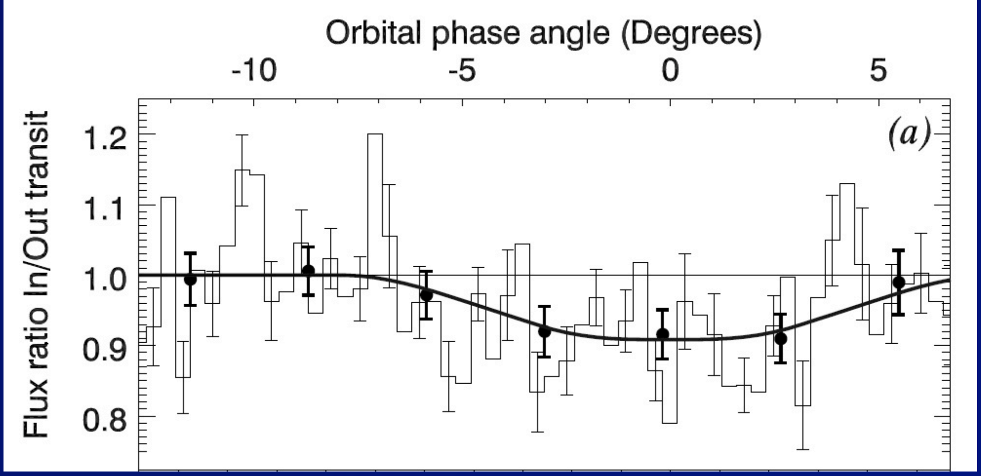
Brown et al. 2001

Observations suggest that UV heating might cause hot Jupiters to lose mass

Neutral H in an extended atmosphere around HD 209458b may have been detected.



Vidal-Madjar et al. 2003



Ben-Jaffel 2007

The Equations

Mass continuity: $$\frac{\partial}{\partial r}(r^2 \rho v) = 0$$

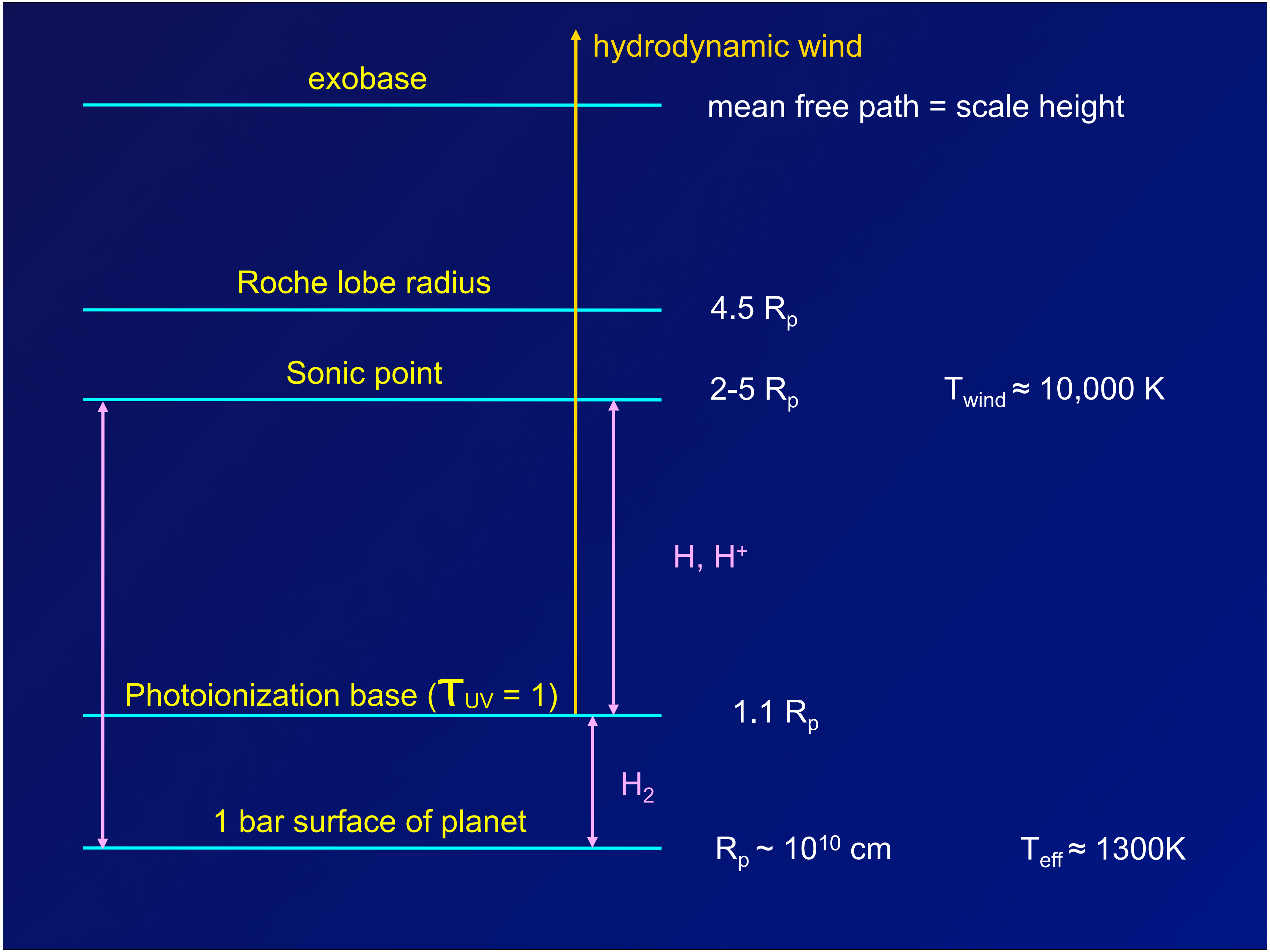
Momentum: $$\rho v \frac{\partial v}{\partial r} = -\frac{\partial P}{\partial r} - \frac{G M_{\mathrm{p}} \rho}{r^2} + \frac{3 G M_* \rho r}{a^3}$$

Energy: $$\rho v \frac{\partial}{\partial r}\left[\frac{kT}{(\gamma - 1)\mu}\right] = \frac{kTv}{\mu}\frac{\partial \rho}{\partial r} + \epsilon F_{\nu_0} e^{-\tau} a_{\nu_0} n_0 + \Lambda$$

Ionization equilibrium:

$$n_0 \frac{F_{\nu_0} e^{-\tau}}{h\nu_0} a_{\nu_0} = n_+^2 \alpha_{\mathrm{rec}} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 n_+ v)$$

Solved using a relaxation code


hydrodynamic wind
exobase
mean free path = scale height
Roche lobe radius
4.5 R_p
Sonic point
2-5 R_p
$T_{wind} \approx 10{,}000$ K
H, H^+
Photoionization base ($\tau_{UV} = 1$)
1.1 R_p
H_2
1 bar surface of planet
$R_p \sim 10^{10}$ cm
$T_{eff} \approx 1300$K

Hydrodynamic Wind Model

F_{UV} = 450 erg/cm^2/s

$M_p = 0.7\ M_J$

$R_p = 1.4\ R_J$

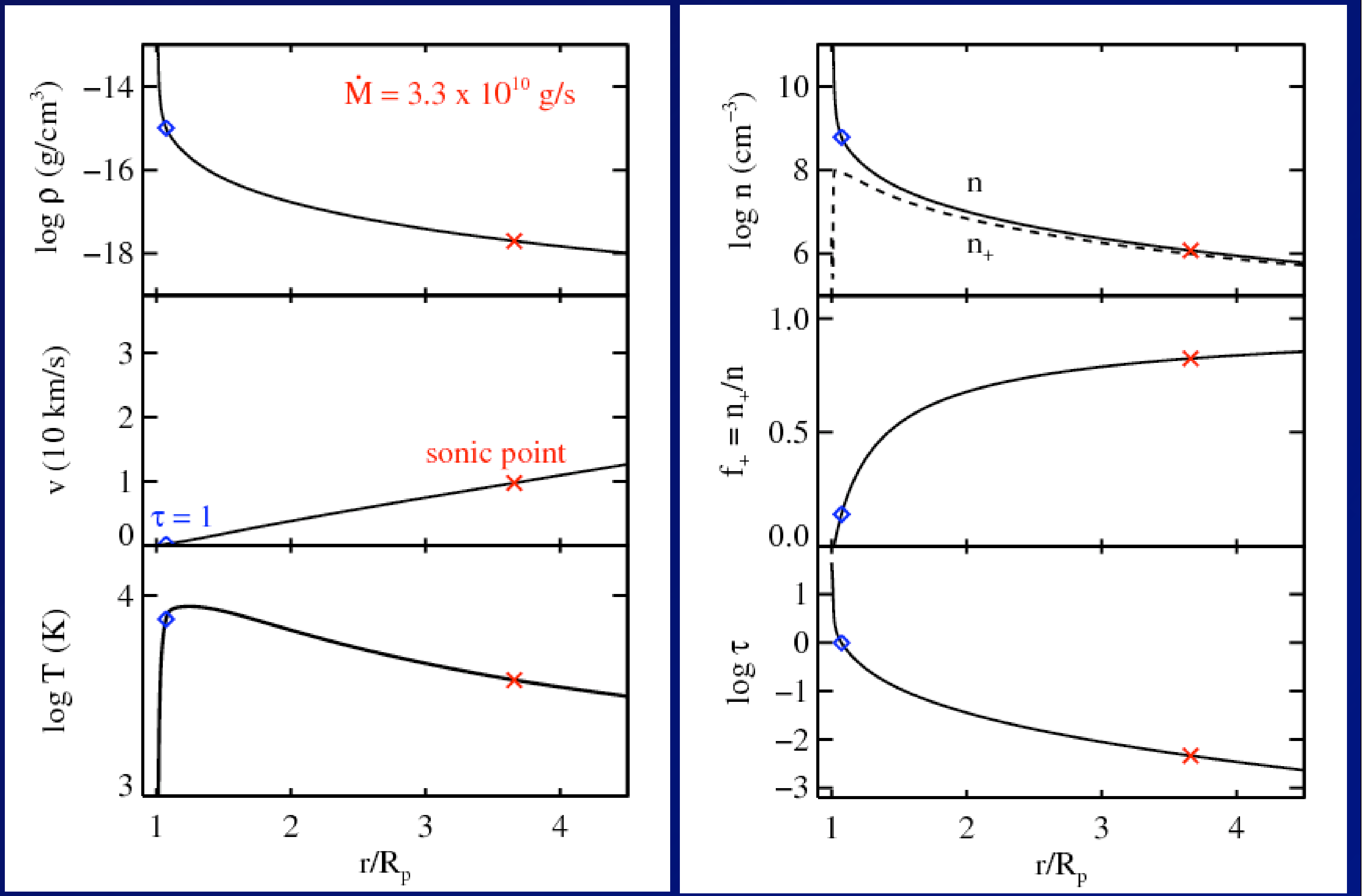
$h\nu_0 = 20$eV

$\rho_{base} = 4\times10^{-13}$ g

$T_{base} = 1000$ K

$f_{base} = 10^{-5}$

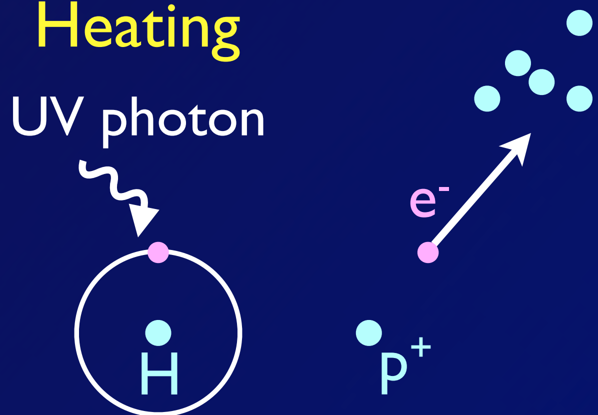
$\tau_{sp} = 0.0046$

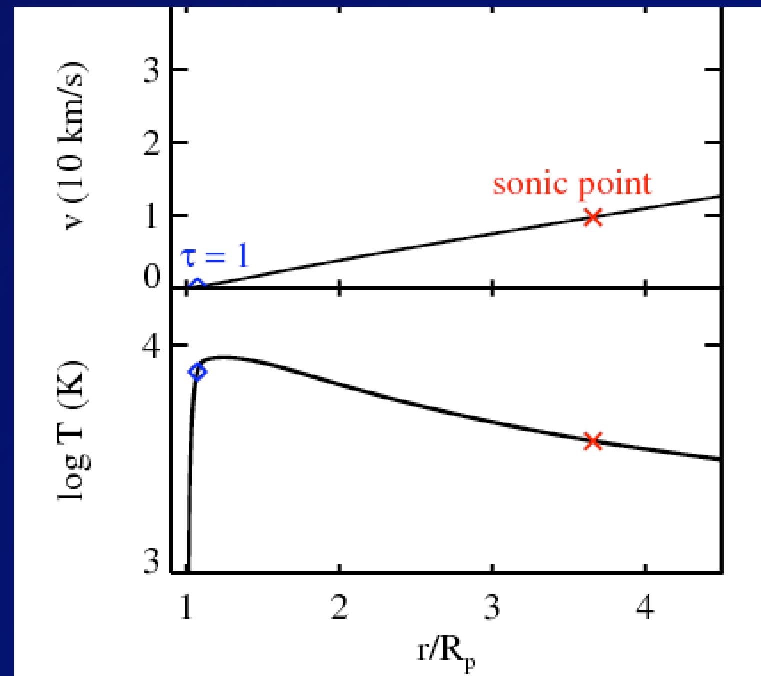


Hydrodynamic Wind Model

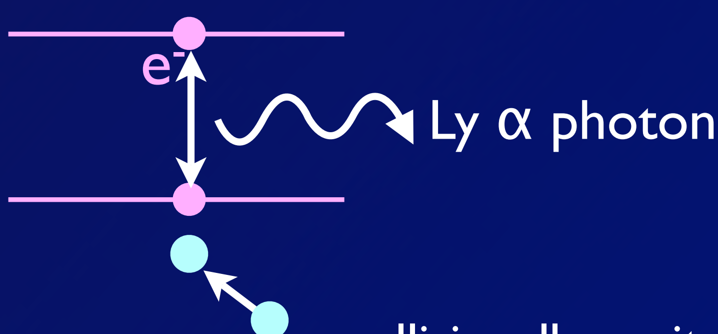
F_{UV} = 450 erg/cm^2/s

Photoionization Heating





Ly α Cooling



collisionally excited
line emission

PdV Work Cooling

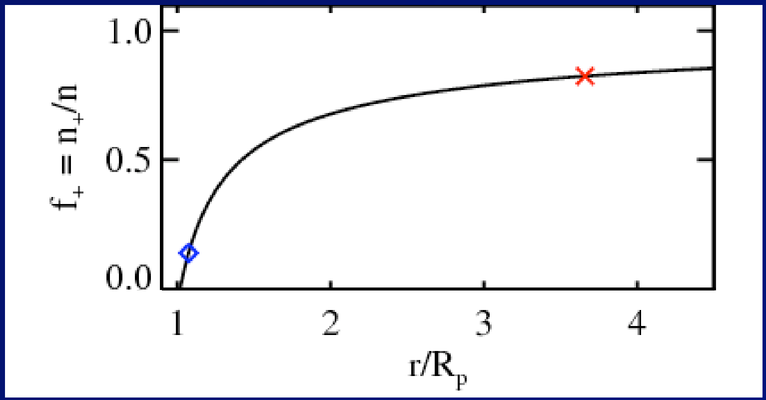
Hydrodynamic Wind Model

F_{UV} = 450 erg/cm^2/s

Photoionization is balanced by gas advection *not* radiative recombination

$T_{advect} \sim R_s/c_s \sim 10^4$ s

$T_{recombine} \sim 1/n\alpha \sim 10^6$ s



Integrated mass-loss rate:

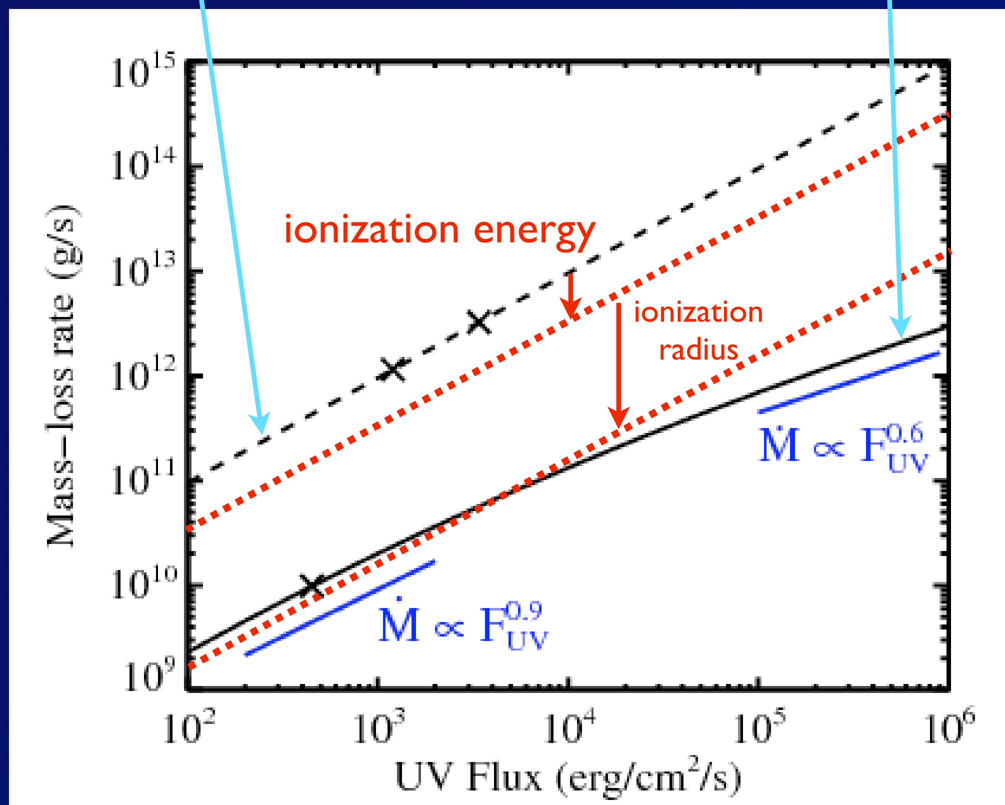
$$\dot{M} \sim 10^{10}\ \mathrm{g/s} \ll 1\text{-}3 \times 10^{12}\ \mathrm{g/s}$$

(Lammer et al. 2003;
Baraffe et al. 2004, 2005)

Dependence on UV Flux

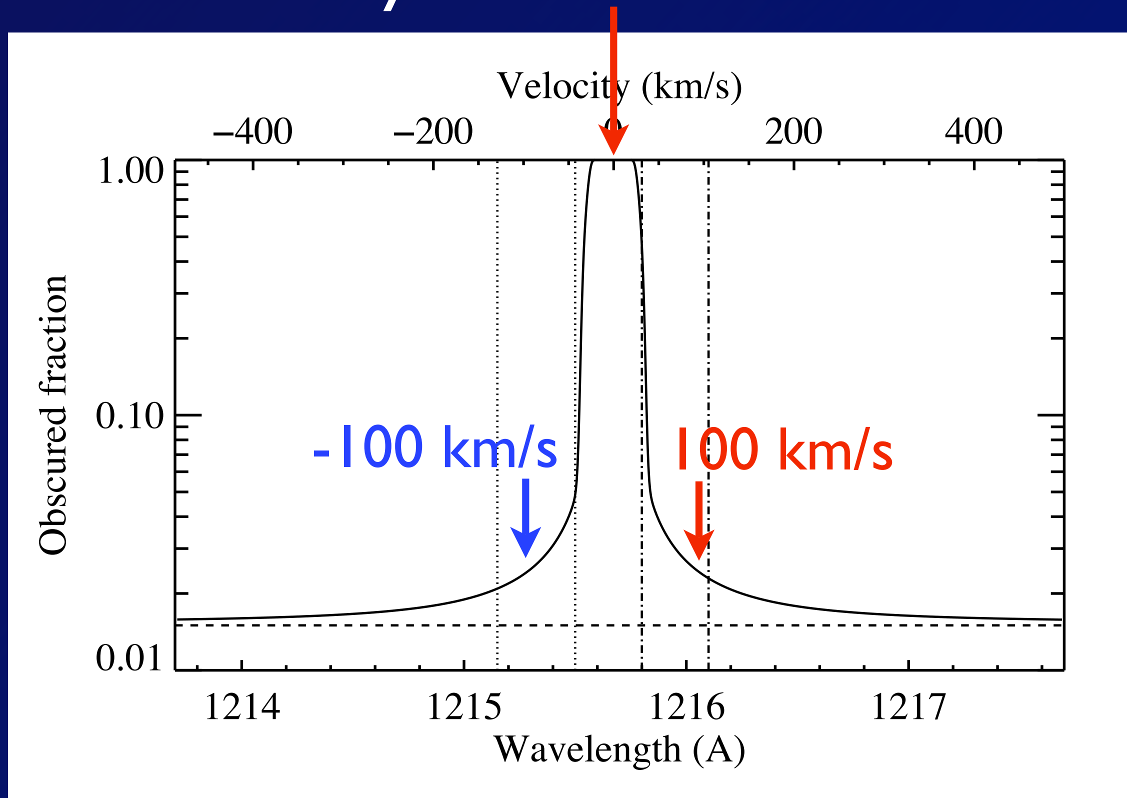
$$\dot{M} = \frac{\overset{\epsilon F_{\rm UV}}{\pi \cancel{F_{\rm UV}}}\;\overset{1 R_{\rm P}}{(\cancel{3 R_{\rm P}})^3}}{G M_{\rm p}}$$

Lyα cooling



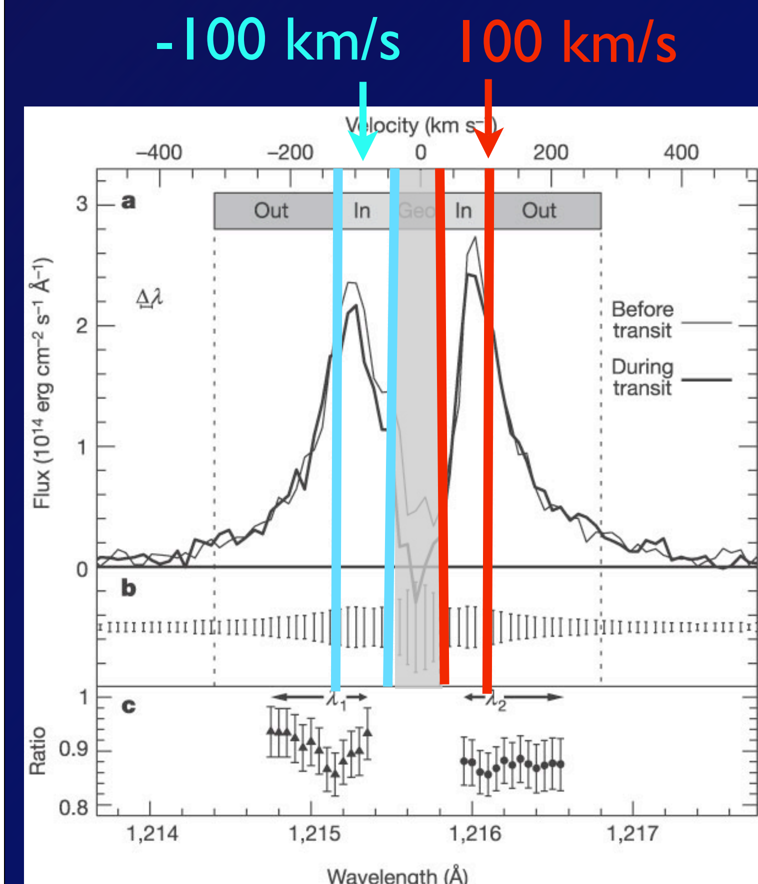
Ly α Absorption by the Planetary Wind

Ly α Line Center

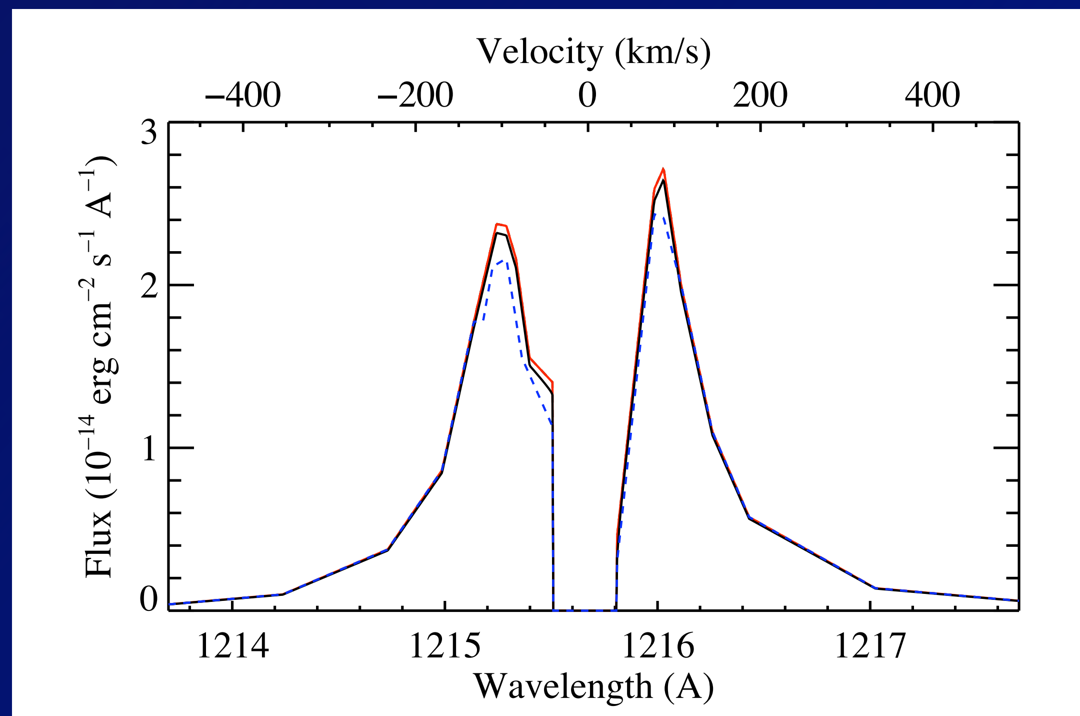


integrated ~10 km/s thermal broadening
centered on wind velocities of ~20 km/s

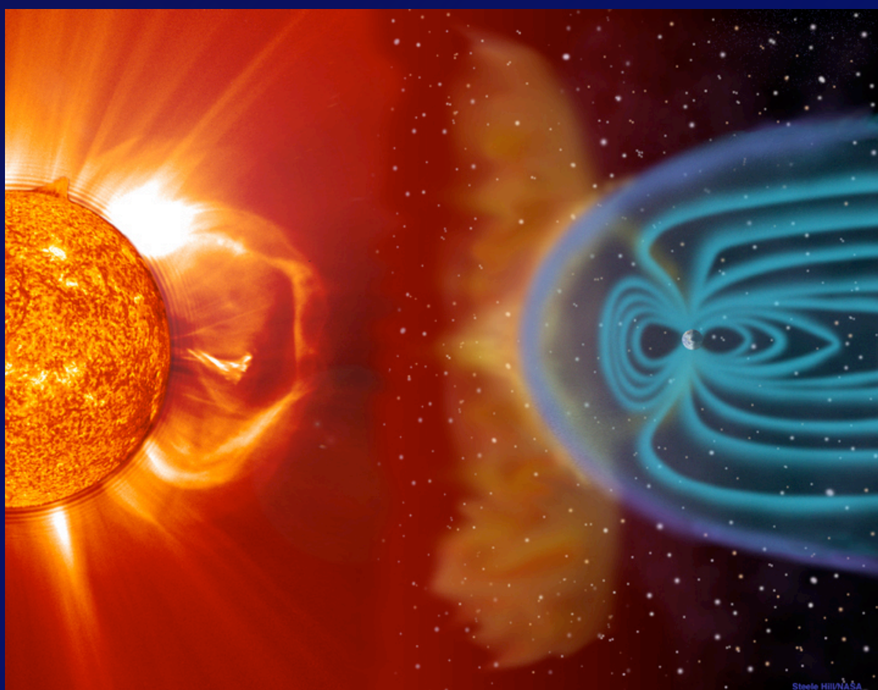
The wind cannot generate enough absorption at ±100 km/s to reproduce measurements of HD 209458b, but it may produce ~5% unresolved absorption.



Vidal-Madjar et al. 2003

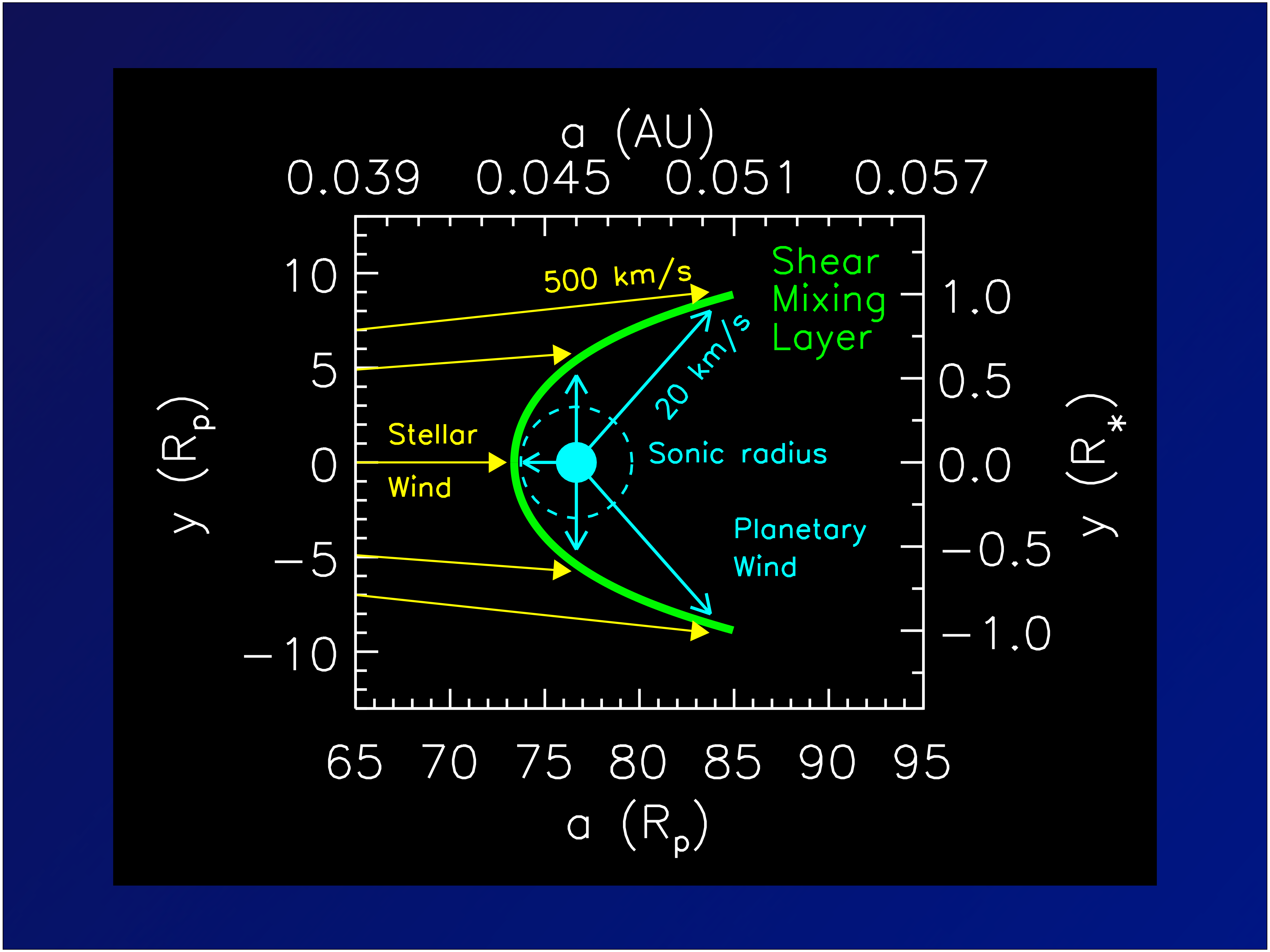


What about the stellar wind and the planetary magnetic field?



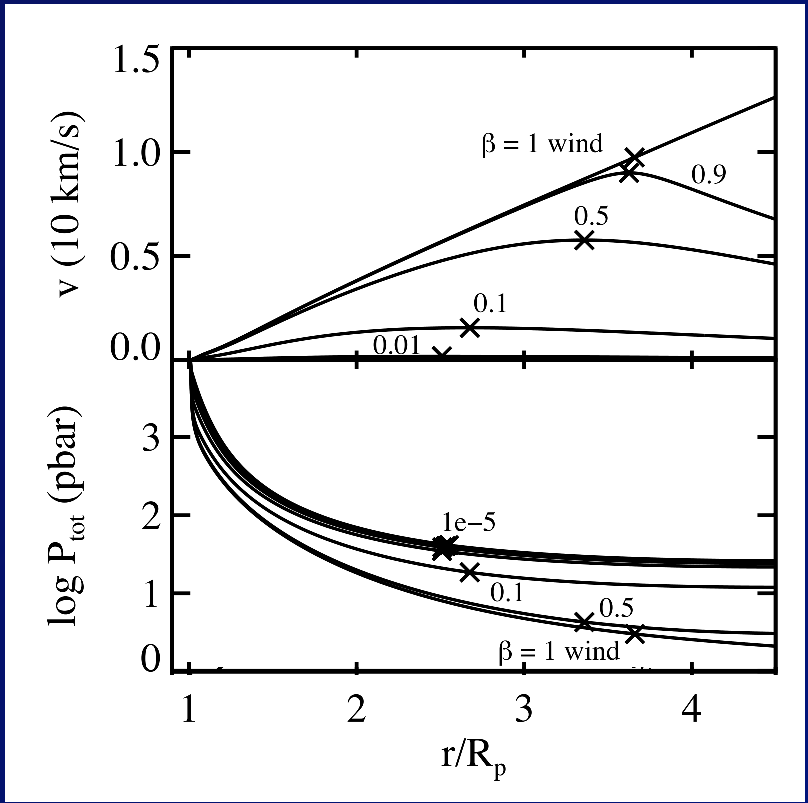
NASA

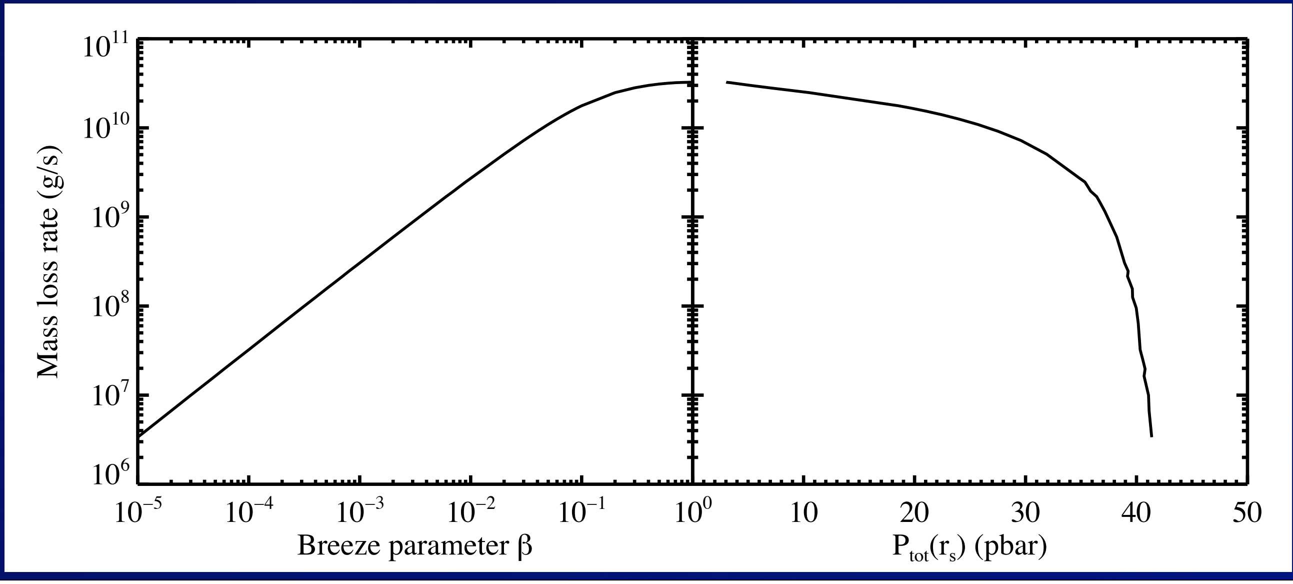
NASA


a (AU)
0.039
0.045
0.051
0.057
10
5
0
−5
−10
1.0
0.5
0.0
−0.5
−1.0
y (R_p)
y (R_*)
500 km/s
Shear
Mixing
Layer
20 km/s
Stellar
Wind
Sonic radius
Planetary
Wind
65
70
75
80
85
90
95
a (R_p)

Our mass loss rates are upper limits

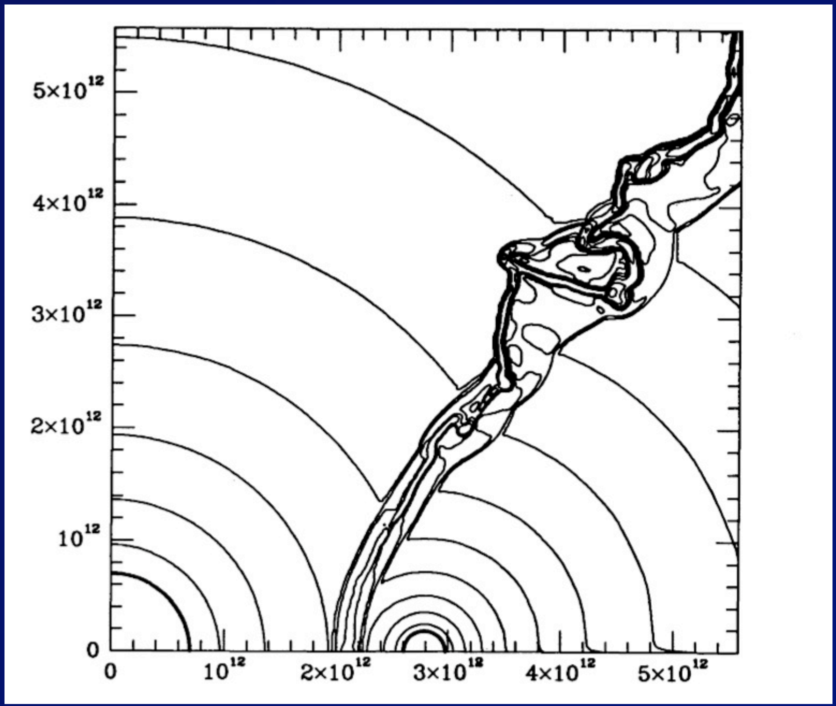
confinement by the stellar wind





Hydrodynamic instabilities in colliding winds could generate high-velocity neutral hydrogen

colliding stellar winds



Stevens, Blondin, & Pollock 1992

Hydrodynamic Wind Model

$F_{UV} = 5\times10^5$ erg/cm^2/s

$M_p = 0.7\ M_J$

$R_p = 1.4\ R_J$

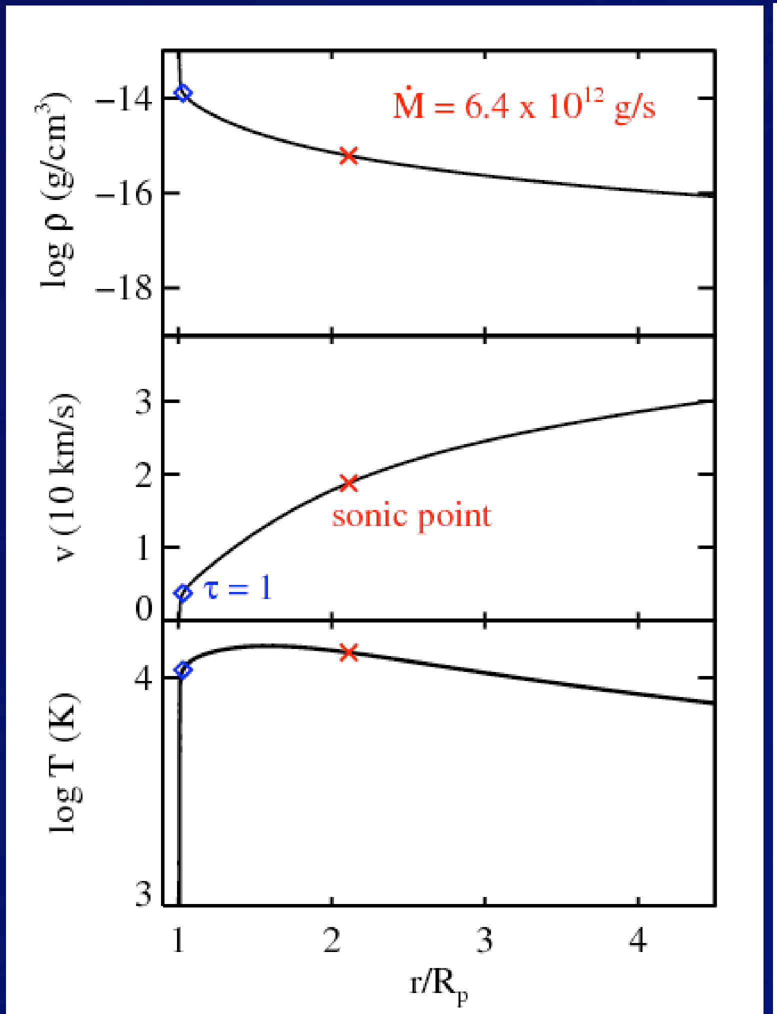
$h\nu_0 = 20$eV

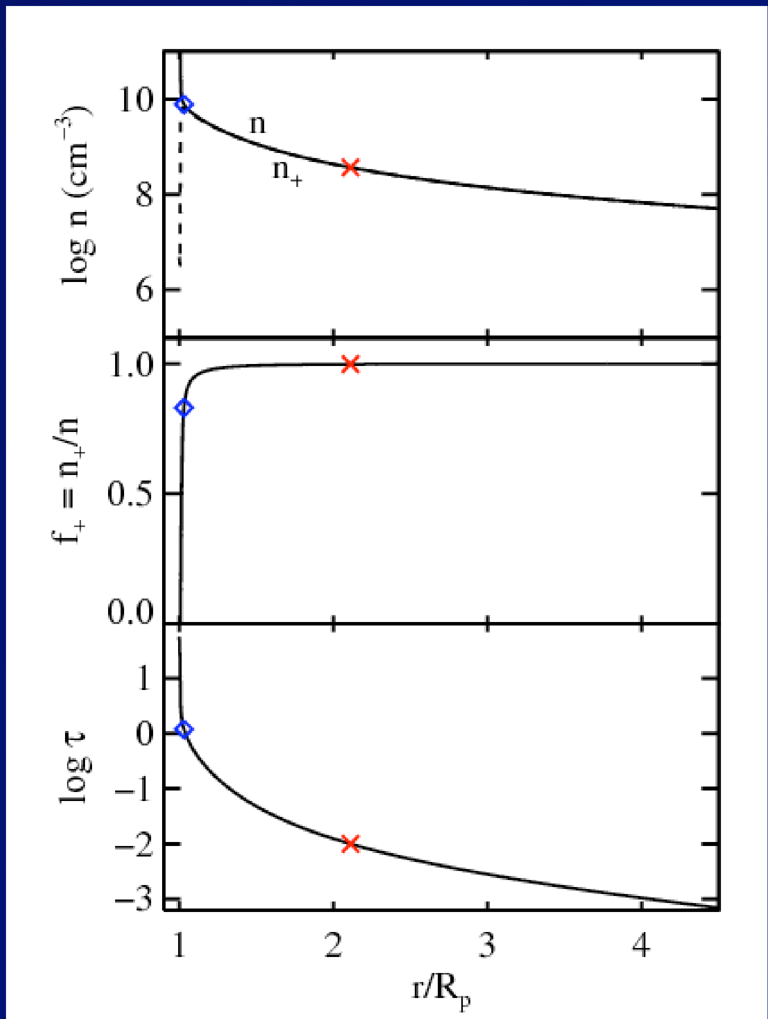
$\rho_{base} = 8\times10^{-13}$ g

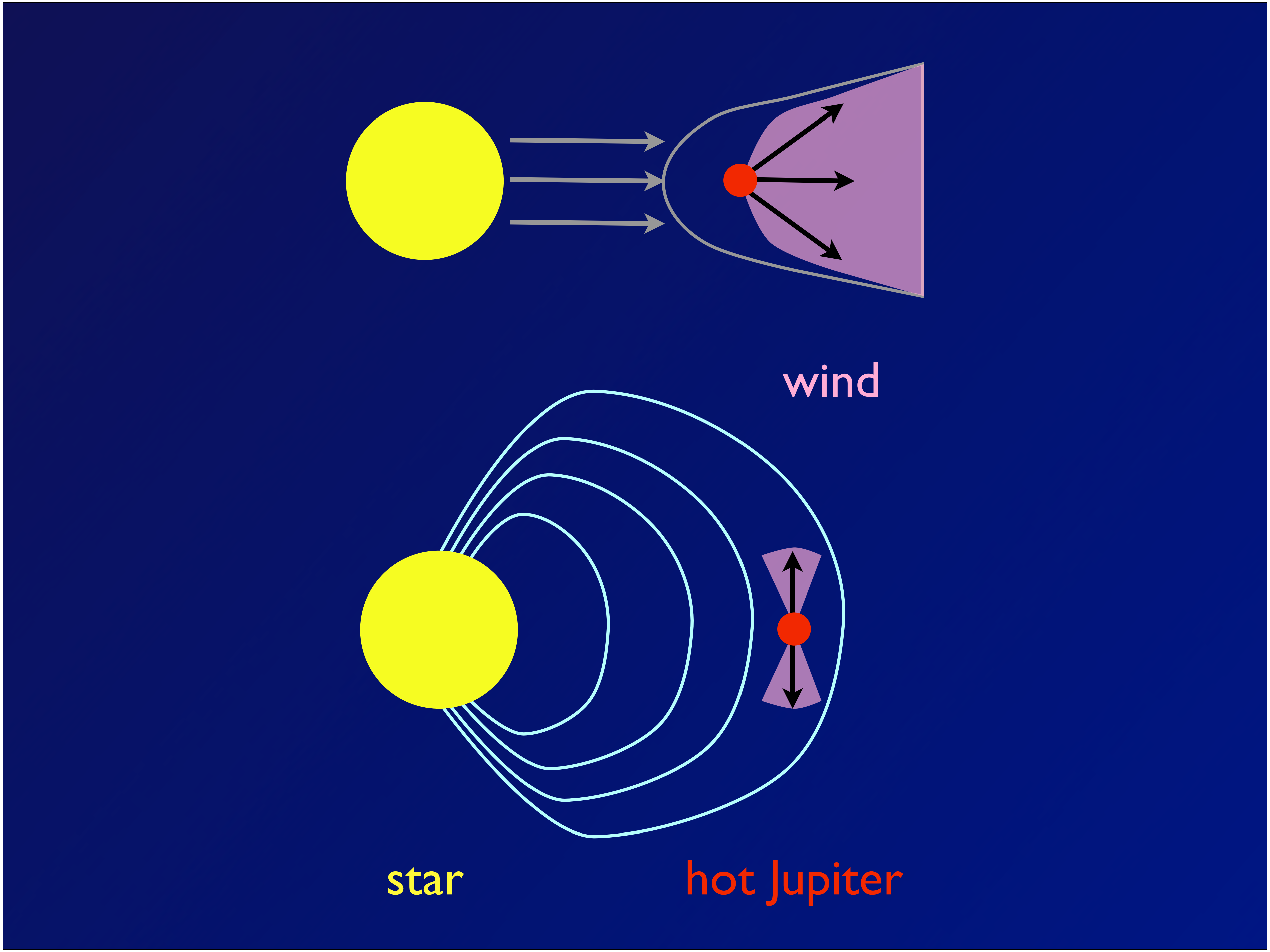
$T_{base} = 1000$ K

$f_{base} = 10^{-5}$

$\tau_{sp} = 0.01$






wind
star
hot Jupiter

Conclusions

- Hot Jupiters lose mass in the form of hydrodynamic winds driven by stellar UV heating.
- The mass loss rate for HD 209458b is $< 5\times10^{10}$ g/s. The planet will lose <1% of its mass over its lifetime.
- We predict that at line center, stellar Lyα and Lyβ is completely obscured during transit.
- Atmospheric escape does not significantly alter the masses of hot Jupiters
- 3D simulations of the interactions between stellar and planetary winds in hot Juipter systems are needed