Atmospheric Escape Hot Jupiters & Interactions Between Planetary and Stellar Winds

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~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

\[ L_{\text{UV}} \sim 10^{-6} L_{\text{bol}} \]

hot Jupiter \( \sim 0.05 \text{ AU} \)
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

1.5% dip
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.

Ben-Jaffel 2007

Vidal-Madjar et al. 2003
The Equations

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

Momentum: \[ \rho v \frac{\partial v}{\partial r} = -\frac{\partial P}{\partial r} - \frac{GM_p \rho}{r^2} + \frac{3GM_* \rho r}{a^3} \]

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: \[ n_0 \frac{F_{\nu_0} e^{-\tau}}{h\nu_0} a_{\nu_0} = n^2_+ \alpha_{\text{rec}} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 n_+ v) \]

Solved using a relaxation code
\( T_{\text{eff}} \approx 1300 \text{K} \)

1 bar surface of planet

\( R_p \sim 10^{10} \text{ cm} \)

\( T_{\text{wind}} \approx 10,000 \text{ K} \)

Sonic point

\( 2-5 \ R_p \)

\( R_p \sim 10^{10} \text{ cm} \)

\( T_{\text{eff}} \approx 1300\text{K} \)

Photoionization base \( (T_{UV} = 1) \)

\( 1.1 \ R_p \)

\( H, H^+ \)

Roche lobe radius

\( 4.5 \ R_p \)

H\(_2\)

exobase

mean free path = scale height

hydrodynamic wind
Hydrodynamic Wind Model

\[ F_{UV} = 450 \text{ erg/cm}^2/\text{s} \]

- \( M_p = 0.7 \ M_J \)
- \( R_p = 1.4 \ R_J \)
- \( h \nu_0 = 20 \text{eV} \)
- \( \rho_{\text{base}} = 4 \times 10^{-13} \ g \)
- \( T_{\text{base}} = 1000 \ K \)
- \( f_{\text{base}} = 10^{-5} \)
- \( \tau_{\text{sp}} = 0.0046 \)
Hydrodynamic Wind Model

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

- Photoionization Heating
  - UV photon
  - $e^-$
- Lyman-$\alpha$ Cooling
  - $e$
  - Lyman-$\alpha$ photon
  - Collisionally excited line emission
- PdV Work Cooling
- Hot Jupiter
- Wind

Graph showing velocity ($v$) in $10^3$ km/s as a function of $r/R_p$ with $\tau = 1$ and sonic point.
Hydrodynamic Wind Model

\[ F_{\text{UV}} = 450 \text{ erg/cm}^2/\text{s} \]

Photoionization is balanced by gas advection \textit{not} radiative recombination

\[ T_{\text{advect}} \sim R_s/c_s \sim 10^4 \text{ s} \]
\[ T_{\text{recombine}} \sim 1/n\alpha \sim 10^6 \text{ s} \]
Integrated mass-loss rate:

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

(Lammer et al. 2003; Baraffe et al. 2004, 2005)
Dependence on UV Flux

\[ \dot{M} = \frac{\epsilon F_{\text{UV}} 1 R_p}{\pi F_{\text{XV}} (3 R_p)^3 G M_p} \]

Ly\(\alpha\) cooling

ionization energy

ionization radius

\[ \dot{M} \propto F_{\text{UV}}^{0.6} \]

\[ \dot{M} \propto F_{\text{UV}}^{0.9} \]
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?
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

\[ F_{\text{UV}} = 5 \times 10^5 \, \text{erg/cm}^2/\text{s} \]

- \( M_p = 0.7 \, M_J \)
- \( R_p = 1.4 \, R_J \)
- \( h \nu_0 = 20 \, \text{eV} \)
- \( \rho_{\text{base}} = 8 \times 10^{-13} \, \text{g} \)
- \( T_{\text{base}} = 1000 \, \text{K} \)
- \( f_{\text{base}} = 10^{-5} \)
- \( \tau_{\text{sp}} = 0.01 \)
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 \(< 5 \times 10^{10} \text{ g/s}\). The planet will lose \(<1\% \text{ of its mass}\) over its lifetime.

• We predict that at line center, stellar Ly\(\alpha\) and Ly\(\beta\) 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 Jupiter systems are needed