Hot-Jupiter Inflation
due to deep energy deposition

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Inflated Hot Jupiters

Baraffe+14

- $Z=2\%$
- $50\% \text{H}_2\text{O}$
- $10\% \text{H}_2\text{O}$
- $100\% \text{H}_2\text{O}$
- $100\% \text{rock}$
- $100\% \text{Fe}$

$R/R_{\text{Jup}}$

$log M/M_{\text{Jup}}$

Stellar irradiation slows cooling

$\sim 1.3 R_J$

Not enough $1.5 - 2.0 R_J$ for Gyr old planets
Inflated Hot Jupiters

Stellar irradiation slows cooling

- Explains $\sim 1.3R_J$
- Not enough $1.5 - 2.0R_J$
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Gyr old planets
Inflated Hot Jupiters

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Baraffe+14

Extra power
Internal Luminosity of Irradiated Planets

$\tau-U$ Plane

- $U \equiv aT^4$
  radiation

- $\tau \equiv \int \kappa \rho dr$
  optical depth
Internal Luminosity of Irradiated Planets

τ-U Plane

- \( U \equiv aT^4 \) radiation
- \( \tau \equiv \int R \kappa \rho dr \) optical depth

Convective Interior

\[
\frac{U}{U_c} = \left( \frac{\tau}{\tau_c} \right) ^\beta
\]

Radiative Envelope

\[
U = U_{eq} + 3 \frac{L_{\text{int}}}{c \ 4\pi R^2} \tau
\]
Internal Luminosity of Irradiated Planets

\( \tau-U \) Plane

- \( U \equiv aT^4 \) radiation
- \( \tau \equiv \int^R \kappa \rho dr \) optical depth

Convective Interior

\[
\frac{U}{U_c} = \left( \frac{\tau}{\tau_c} \right)^\beta
\]

Radiative Envelope

\[
U = U_{eq} + \frac{3}{c} \frac{L_{int}}{4\pi R^2} \tau
\]

\[\tau_{rad} \approx 10^5 \quad \tau_c \approx 10^{11}\]

\[U_{eq}/(1-\beta) \approx 2 \cdot 10^3 K\]

\[U_{eq} \approx 2 \cdot 10^3 K\]

\[T \approx 4 \cdot 10^4 K\]
Internal Luminosity of Irradiated Planets

**τ-U Plane**

- **U ≡ a T⁴**  
  radiation

- **τ ≡ ∫ R κρ dr**  
  optical depth

**Convective Interior**

\[
\frac{U}{U_c} = \left( \frac{\tau}{\tau_c} \right)^\beta
\]

**Radiative Envelope**

\[
U = U_{eq} + \frac{3}{4\pi R^2} \frac{L_{int}}{c} \tau
\]

- Irradiation → Convective Interior
- Convective Interior → Radiative Envelope
- Radiative Envelope → Deep Radiative Zone
- Deep Radiative Zone → Lower Luminosity
Additional Power Deposition

Cooling too Fast
Baraffe+03, Liu+08, Burrows+07

Additional Power Source

1 Bodenheimer+01, Guillot&Showman02, Ibgui&Burrows09, Batygin&Stevenson10, Leconte+10, Perna+10
Additional Power Deposition

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Additional Power Source

- Power $L_{dep}$
- Depth $\tau_{dep}$
Additional Power Deposition

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Additional Power Source

- Power $L_{\text{dep}}$
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Effectively Stronger Irradiation

$U_{\text{eq}}(1 - \beta) \approx 2 \cdot 10^3 \text{K}$
$U_{\text{eff}} \approx 2 \cdot 10^3 \text{K}$

$U_{\text{eq}} \approx 1.5 \cdot 10^3 \text{K}$

$T \approx 2 \cdot 10^3 \text{K}$

$T \approx 1.5 \cdot 10^3 \text{K}$

stronger "irradiation"  slower cooling
Cooling too Fast
Baraffe+03, Liu+08, Burrows+07

Additional Power Source
- Power $L_{\text{dep}}$
- Depth $\tau_{\text{dep}}$

Effectively Stronger Irradiation

\[
\frac{U_{\text{eff}}}{U_{\text{eq}}} \sim \left(1 + \frac{L_{\text{dep}}\tau_{\text{dep}}}{L_{\text{eq}}} \right)^\beta
\]

\[
U_{\text{eq}}/(1 - \beta)
\]

\[
T \approx 2 \cdot 10^3 \text{K}
\]

\[
U_{\text{eq}}/\tau_{\text{rad}}
\]

\[
T \approx 1.5 \cdot 10^3 \text{K}
\]

Convective
Radiative without Source
Radiative with Source
Secondary Convective Region

stronger “irradiation” → slower cooling
Comparison with Numerical Results

Radius Evolution

\[ L_{\text{int}}(T_c) \propto \frac{dT_c(t)}{dt} \]
\[ \Delta R(t) \propto T_c(t) \]

Equilibrium Inflation

Chabrier+04

Burrows+07, Liu+08
Comparison with Numerical Results

Radius Evolution

- $L_{\text{int}}(T_c) \propto \frac{dT_c(t)}{dt}$
- $\Delta R(t) \propto T_c(t)$

Equilibrium Inflation

Chabrier+04
Burrows+07, Liu+08

Spiegel&Burrows13

- HD 209458b
- Still contracting
Comparison with Numerical Results

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Equilibrium Inflation

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  - Still contracting
  - Fit \( \eta \sim 1 \)

\[ \Delta R_{\text{dep}} = \Delta R_0 \left[ \left( 1 + \eta \frac{L_{\text{dep}} \tau_{\text{dep}}}{L_{\text{eq}}} \right)^\delta - 1 \right] \]
Over Inflated Hot Jupiters

- Irradiation cannot explain $\sim 2R_J$ planets
Summary

Over Inflated Hot Jupiters

- Irradiation cannot explain $\sim 2R_J$ planets

Irradiated Planets

- Reproduce previous results
  (Guillot+96, Arras&Bildsten06, Youdin&Mitchell10)

Analytical Model

\[ a + b = c \]
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Additional Energy Deposition

- \( \frac{L_{\text{dep}} \tau_{\text{dep}}}{L_{\text{eq}}} \gtrsim 1 \quad L_{\text{dep}} \gtrsim L^0_{\text{int}} \)
- Fit numerical results

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Additional Energy Deposition

- $\frac{L_{\text{dep}} \tau_{\text{dep}}}{L_{\text{eq}}} \gtrsim 1$, $L_{\text{dep}} \gtrsim L^0_{\text{int}}$
- Fit numerical results

Applications

- Observational correlations (Laughlin+11, Schneider+11)
Thank you!

JUPITER HAS SUNBURN...