Inflating Hot Jupiters: Ohmic Dissipation and the Mechanical Greenhouse
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Cold vs. Hot Jupiters

- **Cold Jupiter**: Size (mostly) determined by entropy (adiabat) of convective interior.
- **Hot Jupiter**: Radiative layer mediates cooling & contraction.

**Radiative**

**Convective**
Recipes to Inflate Hot Jupiters
(b/c irradiation not enough)

Idea:
- Add Heat
- Slow Cooling

Mechanisms:
- Tides
- Winds
- Hydrodynamic Dissipation
- Ohmic Dissipation
- Mechanical Greenhouse
- Opacity effects
Energetics of Hot Jupiter Inflation

- Matters where & efficiency
- 0.1% in convective interior (Bodenheimer et al. 2001)
- 1% near “surface” (Guillot & Showman 2002)
- between 1-40 bars
- At convective boundary:
  \[ \epsilon \sim \frac{F_{\text{core}}}{F_{\text{irr}}} \sim \left( \frac{150 \text{ K}}{1500 \text{ K}} \right)^4 \sim 10^{-4} \]

\[ \epsilon = \frac{dE/dt}{L_{\text{irr}}} = \frac{d(E/A)/dt}{F_{\text{irr}}} \]

Zonal Winds: Not quite deep enough(?) (Showman et al. 2009)
Observational Clues / Tests

- Only HOT Jupiters are inflated
  - above $T_{\text{irr}} = 1000$ K
  - also Demory & Seager (2011)

- Easier to inflate (and evaporate?) lower mass planets (Bodenheimer et al. 2001)

- Evidence of period dependence of Kepler size distributions (Youdin 2011)
Ohmic Dissipation

- Surface winds induce currents which dissipate (at depth?)

\[ \mathbf{J} = \sigma ( \mathbf{v} \times \mathbf{B} + \mathbf{E} ) \]

- Applied to SS (Liu et al. 2008) and to Hot Jupiters

- Upper atmosphere crucial for wind driving/damping (Perna, Menou, Rauscher 2010, etc.)

- Global models study inflation

Kirk & Stevenson (1987)

Batygin & Stevenson (2010)
Inflating Hot Jupiters with Ohmic Dissipation

- Fixed wind profile (to 10 bars)

- Hot Jupiters bloated for fixed dissipative efficiency $\geq 1\%$
  - Consistent with Guillot & Showman (2002)

- Fixed efficiency and calculated conductivity means...
  - $v_{\text{wind}} \times B$ adjusts to what is required

\[ \varepsilon = 1\% \]

\[ \text{Batygin, Stevenson & Bodenheimer (2011)} \]
Large B-fields Required

Conductivities revised downward by $10^3$:

$0.1 \text{ S/m} \rightarrow 10^{-4} \text{ S/m}$


BSB11 scalings...

... then imply

$$B \sim \frac{1}{v_\phi} \sqrt{\frac{\epsilon}{\sigma_e} \frac{F_{\text{irr}}}{H}}$$

$$\sim 300 \left( \frac{\text{km/s}}{v_\phi} \right) \sqrt{\frac{\epsilon}{0.01} \frac{10^{-4} \text{ S/m}}{\sigma_e}} \text{ G}$$
Constraint on Ohmic Inflation

- Ohmic dissipation (up high) limits wind speeds
- For strong B-fields &
- High temp. (ionization)
- Need all three for inflation
- More study needed to determine severity of constraint

Photospheric Wind Speeds (Menou 2011)

\[
B \sim \frac{1}{v_\phi} \sqrt{\frac{\epsilon F_{\text{irr}}}{\sigma_e H}} \sim 300 \left( \frac{\text{km/s}}{v_\phi} \right) \sqrt{\frac{\epsilon}{0.01}} \frac{10^{-4} \text{ S/m}}{\sigma_e} \text{ G}
\]
Size (mostly) determined by entropy (adiabat) of convective interior. Radiative layer mediates cooling & contraction.
The Mechanical Greenhouse: Consequences of Mixing a Hot Jupiter

- **Radiative zones** of Hot Jupiters likely turbulent, with diffusion coefficient $K_{zz}$
- Delivers dust & disequilibrium molecules to the photosphere
- Driven by winds and/or ohmic heating
- Buries heat, inflates planet
- **Convection** in reverse!

$$F_{\text{eddy}} = -K_{zz} \rho T \frac{dS}{dz}$$

$$= -K_{zz} \rho g \left( 1 - \frac{\nabla}{\nabla_{\text{ad}}} \right)$$

Youdin & Mitchell (2010)
Energy Transport Basics: Radiation vs. Convection

- Simple analogy for planetary (or stellar) atmosphere

- **Radiation** transports modest heat fluxes, $F_{\text{rad}}$

- Too much heat triggers *convection*
  - Can drive large heat flux, $F_{\text{eddy}}$
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A Hot Jupiter Analogue with Mechanical Mixing

- Flux from star, $F_{*,in} \gg$ cooling flux
- Suppresses convection (hot over cold) in outer layers
- Forced turbulence drives “anti-convective” flux, the “Mechanical Greenhouse”
  - Replaces cooling flux & heats interior
- Dissipation adds more heat, further aids inflation

\[ g F_{\text{rad, out}} F_{*, in} F_{\text{eddy}} \]

(Youdin & Mitchell 2010)
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(Youdin & Mitchell 2010)
Energy Balance: Radiation + Turbulence

- Radiative flux in diffusion approximation

- **Turbulence:**
  - Heat burial via eddy flux
  - Dissipates ($\epsilon$)

- Compute **Temperature profile**
  - Solution for location of radiative-convective boundary $\Rightarrow$ cooling rate

**Net Flux**

$$F = F_{rad} + F_{eddy}.$$  

$$F_{eddy} = -K_{zz} \rho T \frac{dS}{dz}$$

$$= -K_{zz} \rho g \left( 1 - \frac{\nabla}{\nabla_{ad}} \right)$$

$$\frac{dF}{dP} = -\frac{\epsilon}{g}$$

$$\frac{dT}{dP} = \frac{F + F_{iso}}{K_{rad} + F_{iso}P/(\nabla_{ad} T)}$$

$F_{iso} \equiv K_{zz} \rho g$
Inflation by the Mechanical Greenhouse Effect

- Preferentially inflates hotter planets
  - Also lower mass giants (not shown)
- Efficient way to inflate a hot Jupiter
  - Simply replaces core flux
- Constraints: delivery of condensates to photosphere (TiO, dusty hazes)
  - See poster by Nawal Husnoo et al.
  - $K_{zz}$ relevant for photochemical models

Solutions match mechanical greenhouse flux to structure models of Arras & Bildsten (2006)
Conclusions

• **Hot Jupiters** are inflated ... or never shrank
  
  • Need a mechanism to enhance effects of **irradiation**
  
• **Ohmic Dissipation** hypothesis: self-consistency not yet demonstrated
  
  • Strong **B-fields** damp strong **winds** in **hot** atmosphere ... all required
  
• **Mechanical Greenhouse**: turbulent mixing **efficiently** replaces cooling flux
  
  • Source of **deep, weak turbulence** unspecified (meridional, MHD)
  
• **Observational connections** to condensate/photochemical mixing models