Untwisting the Atmospheric Twirls of Hot Jupiters

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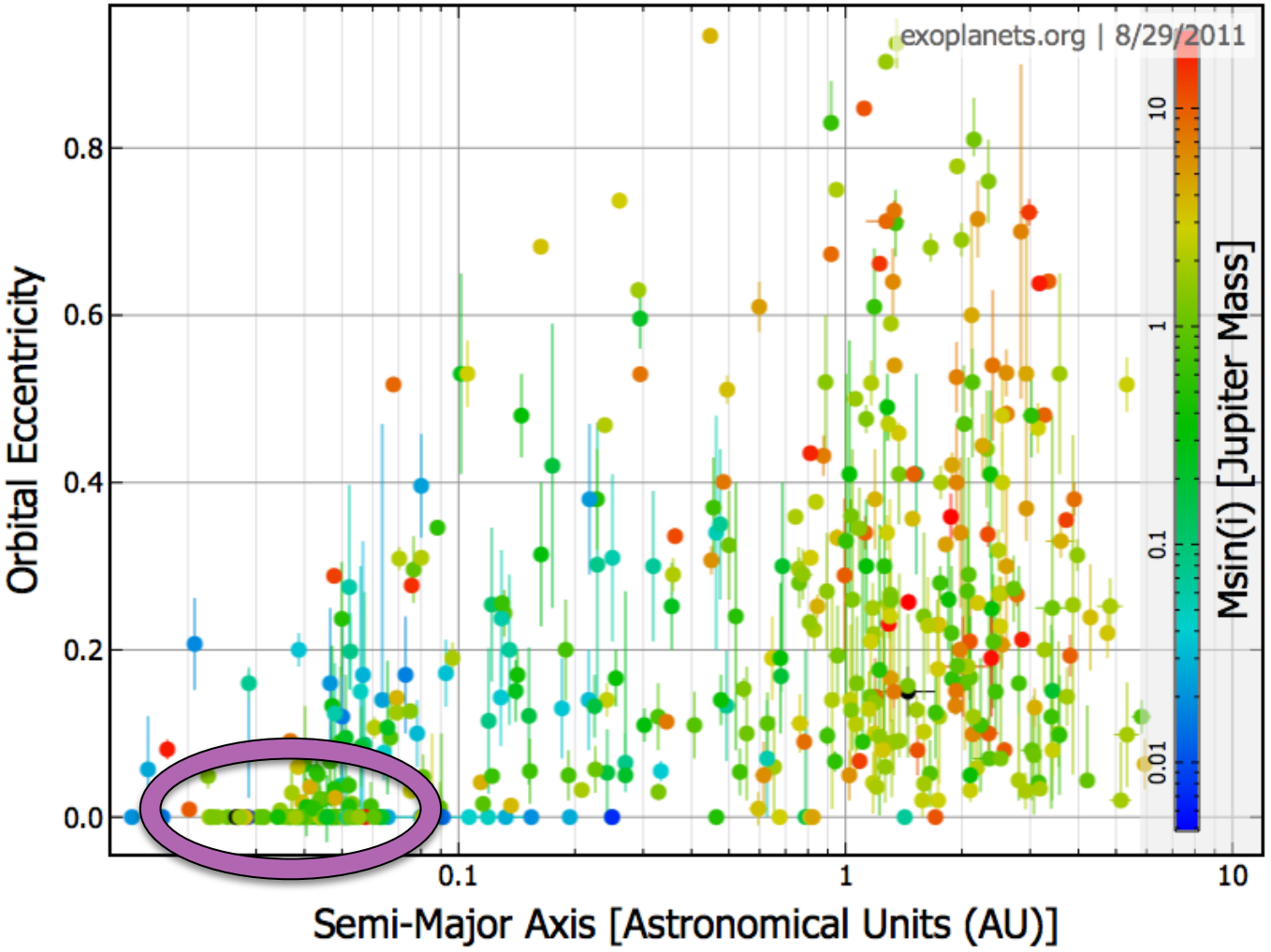
Hot Jupiters: the best and the brightest

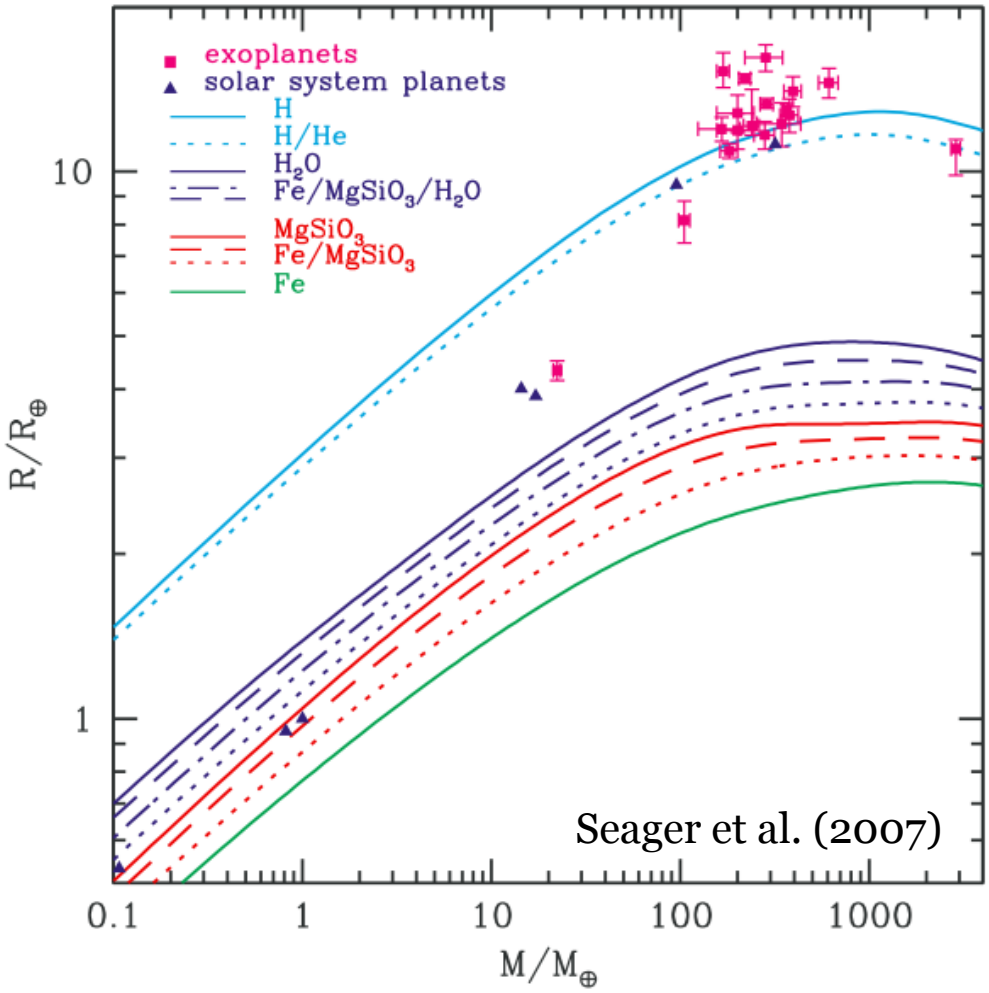


← Jupiter mass

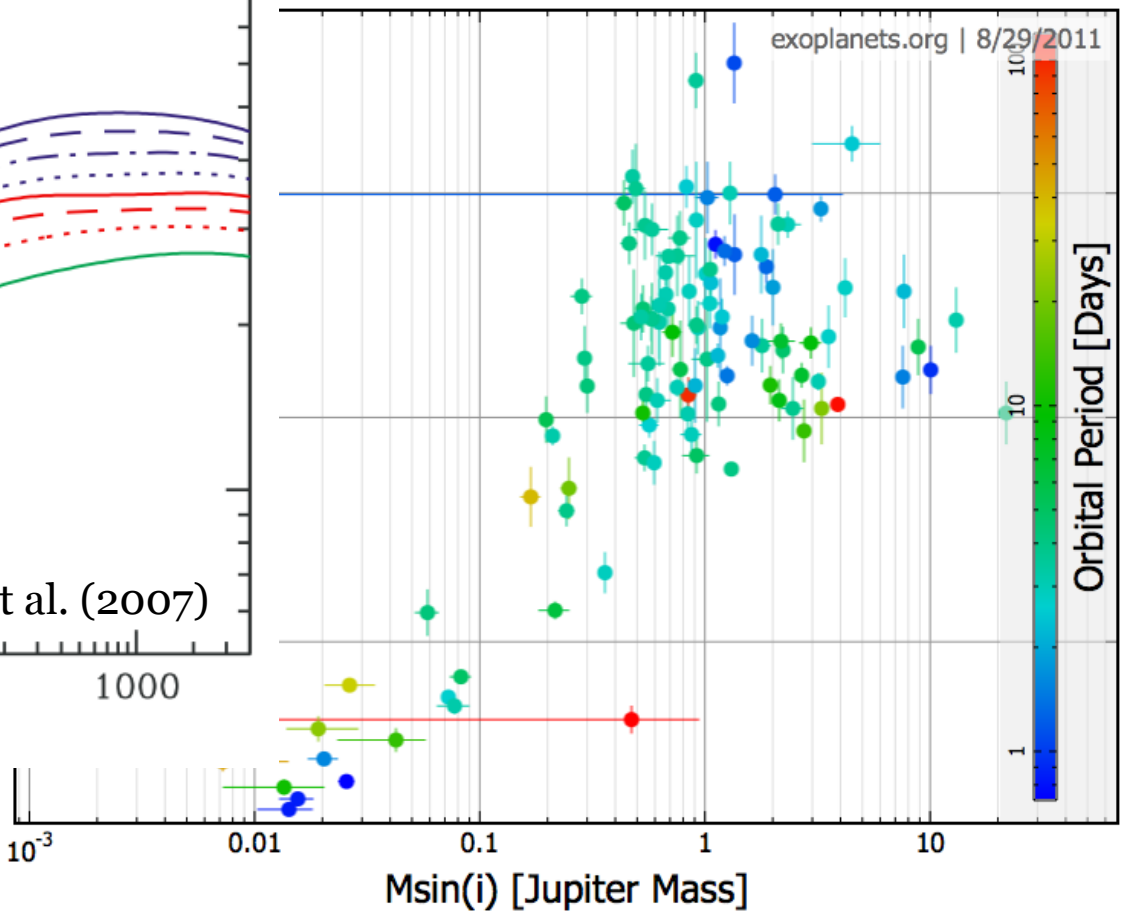
← Neptune mass

← Earth mass

Transiting planets: even better



Seager et al. (2007)



Open question: "anomalous" radii

Tidal heating?

Ohmic heating?

?

Downward KE?

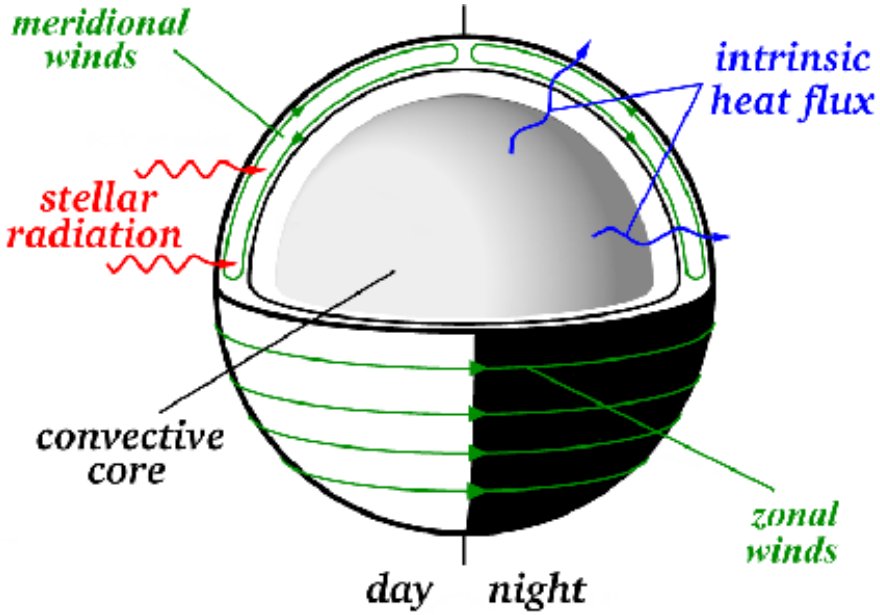
Increased opacity?

e.g., Bodenheimer+ 01, Guillot & Showman 02, Chabrier & Baraffe 07, Jackson+ 08, Ibgui & Burrows 09, Arras & Socrates 10, Batygin & Stevenson 10, Perna+ 10, Miller & Fortney (2011), etc.

Hot Jupiter Models

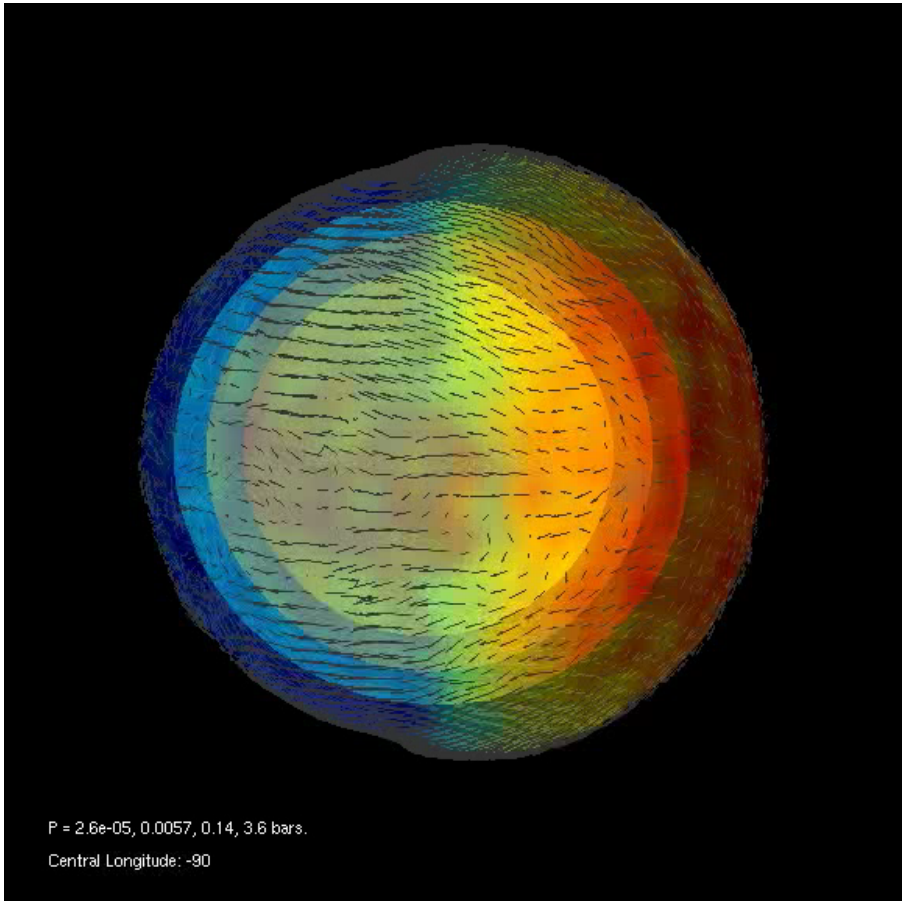
Three main differences between hot Jupiters and Jupiter:

1) Intense irradiation
2) Asymmetric irradiation
3) Slow rotation



Showman & Guillot (2002)

3D hot Jupiter circulation models

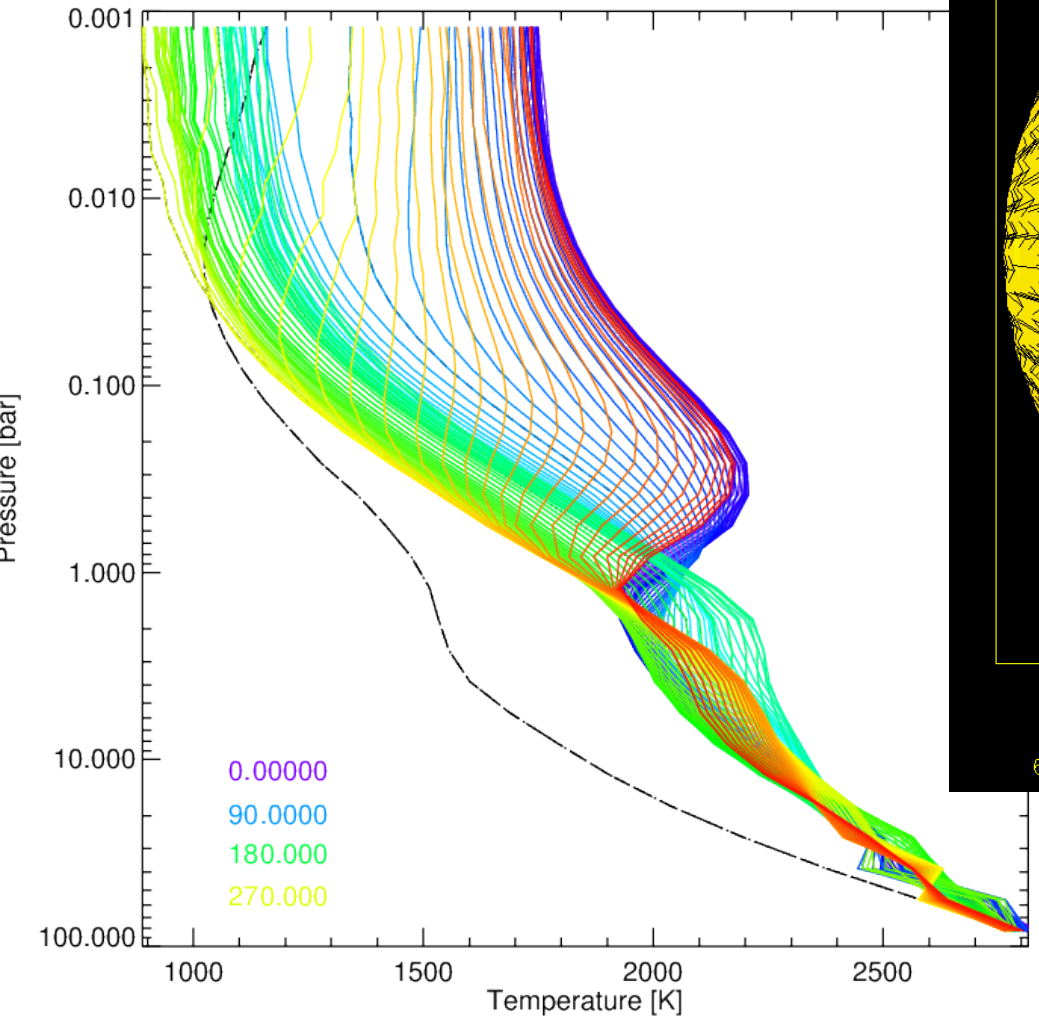


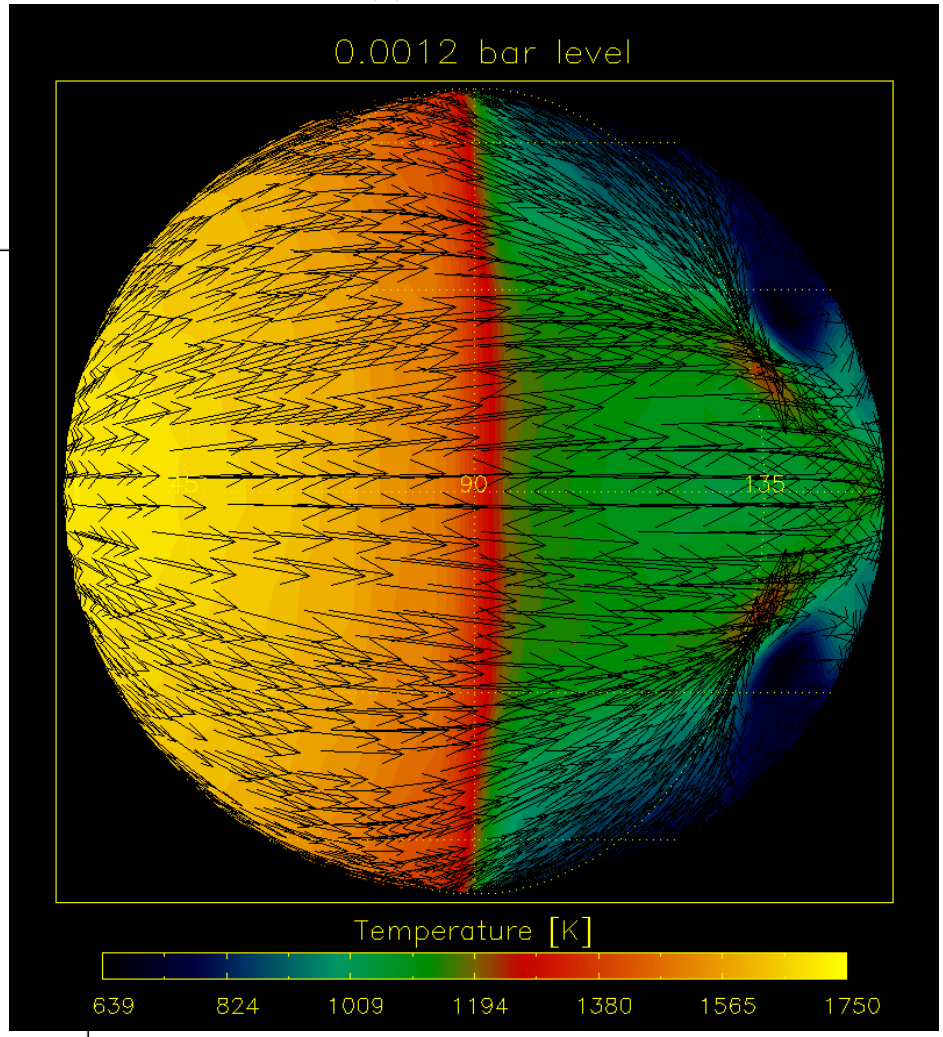
Courtesy of D. Spiegel

Current groups and approaches:

- Full Navier-Stokes equations,
  with simplified radiative transfer
  (Dobbs-Dixon et al.)
- Primitive equations of meteorology,
  with complex radiative transfer
  (Showman et al.)
- Primitive equations,
  with simplified radiative transfer
  (Heng et al.)
- Primitive equations,
  with simple radiative forcing
  (Cho et al.)

The global picture

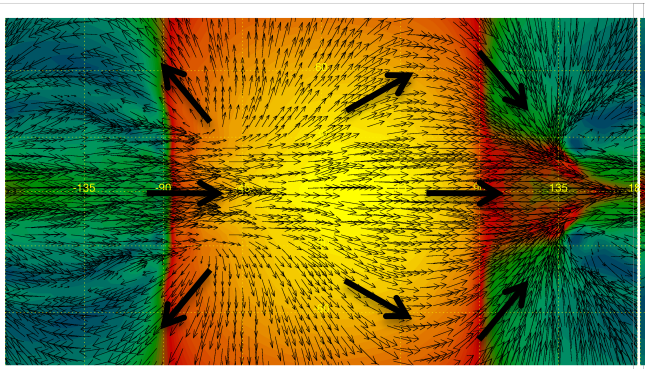




Rauscher & Menou, in prep

Overview of atmospheric structure

Upper atmosphere: 2 mbar

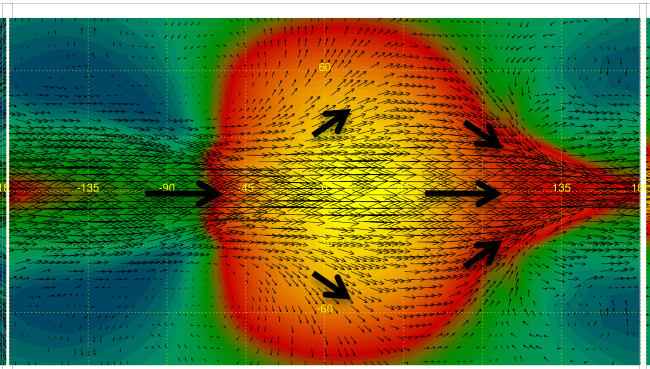


698 874 1050 1226 1402 1578 1754

Temperature [K]

Max winds: 10 km/s

200 mbar

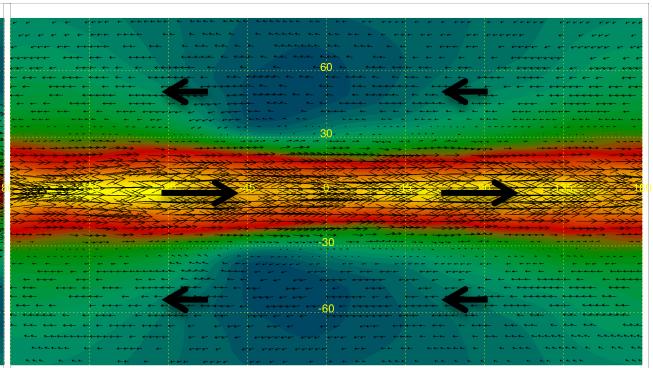


1002 1196 1389 1583 1776 1970 2163

Temperature [K]

Max winds: 7 km/s

Lower atmosphere: 20 bar



2007 2079 2151 2222 2294 2366 2438

Temperature [K]

Max winds: 2 km/s

Radiation dominated and Transonic winds

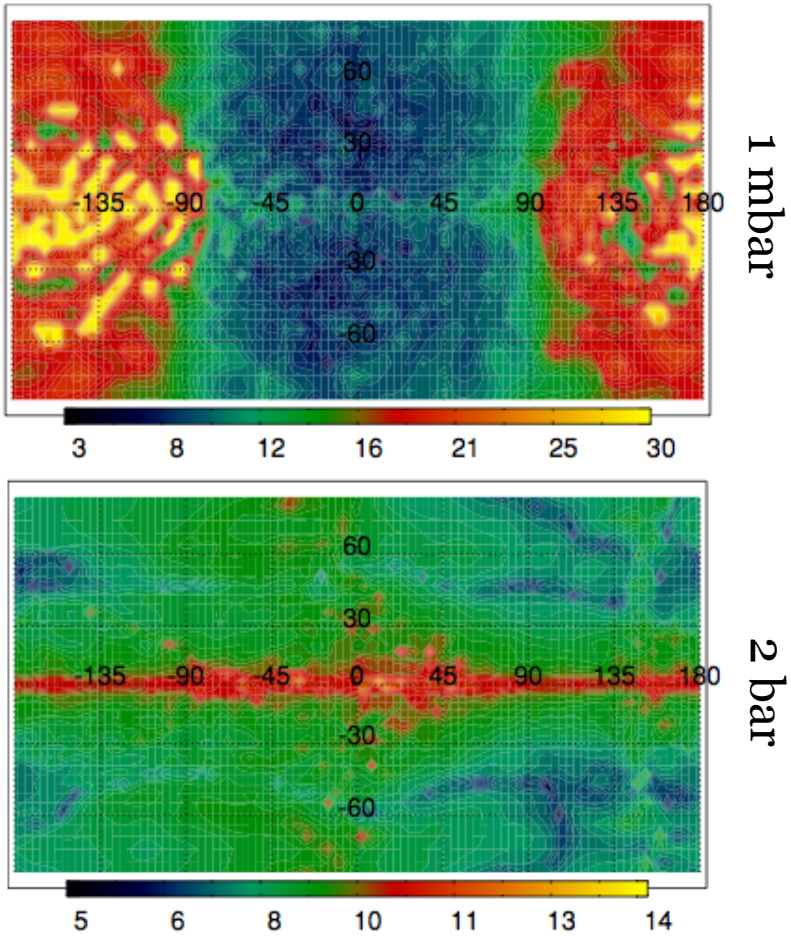
Advection dominated and Subsonic winds

Magnetic Complications

Magnetic drag

- The atmosphere is weakly thermally ionized.
- Assume the planet has a magnetic field.
- The atmospheric flow will generate a new component of the magnetic field and associated currents.
- The winds will experience drag.

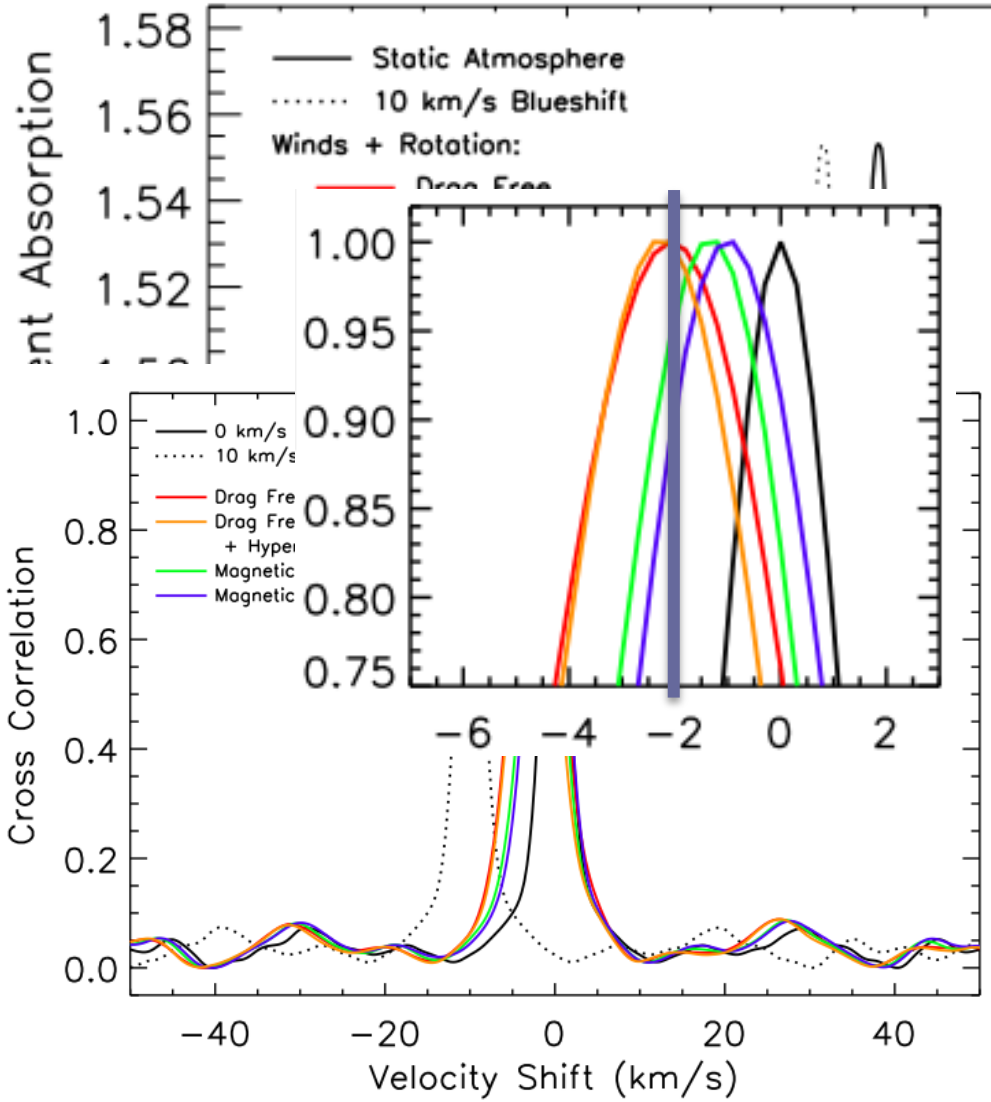
$Log_{10}(t_{drag})$: blue = strong drag

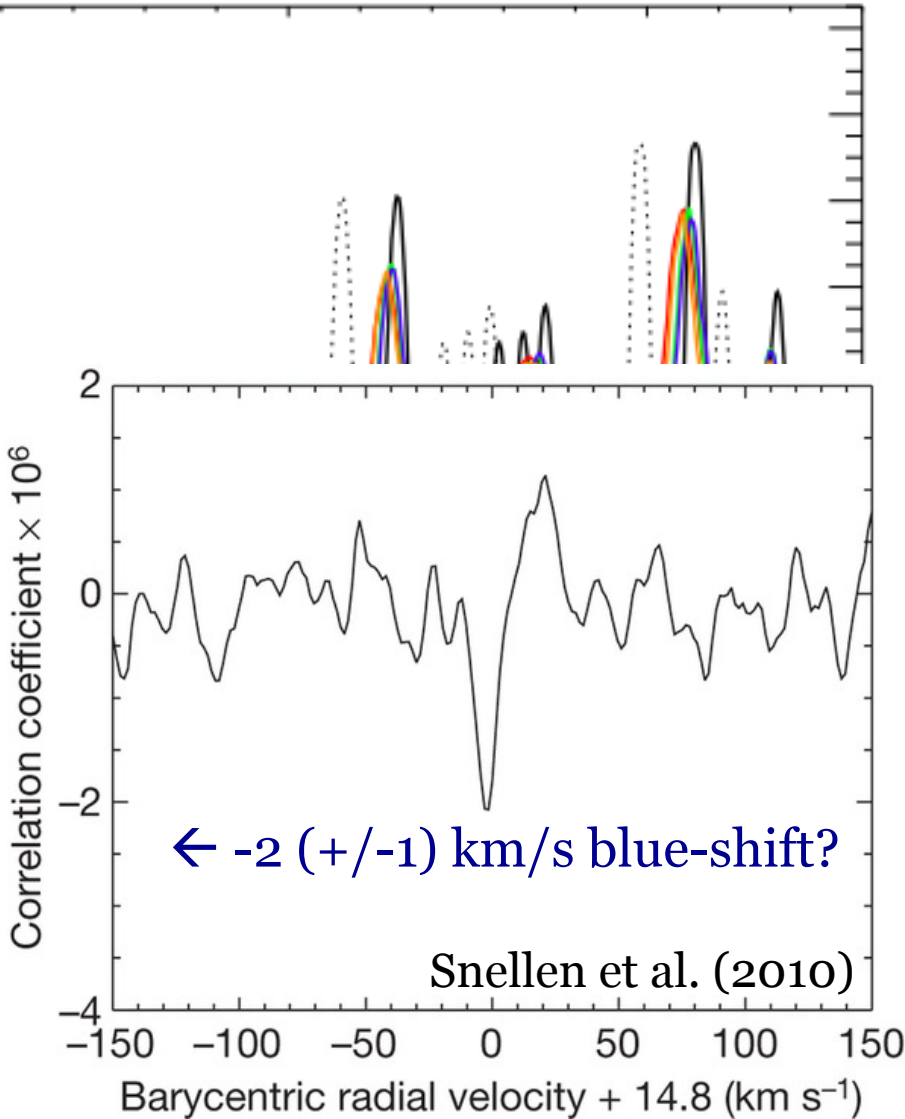


Perna, Menou, & Rauscher (2010a)

(Future?) Observational constraints

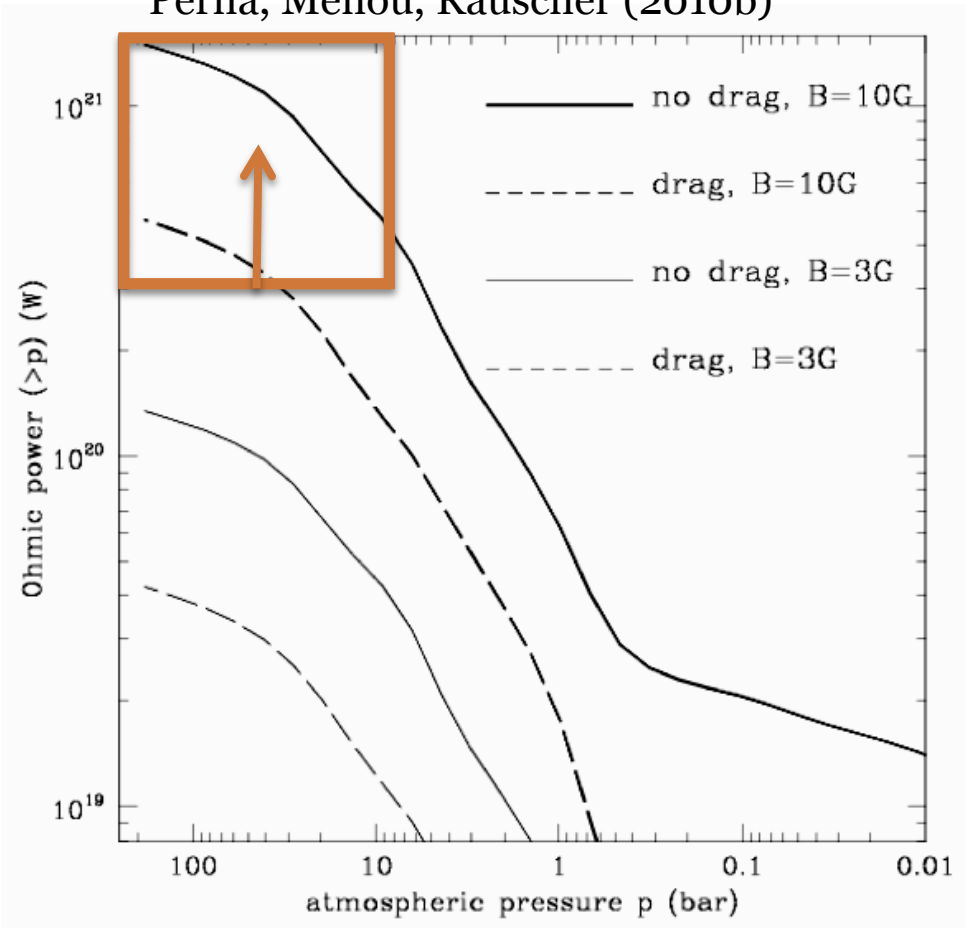
Kempton & Rauscher, in prep





Ohmic heating and the radius anomaly

Perna, Menou, Rauscher (2010b)

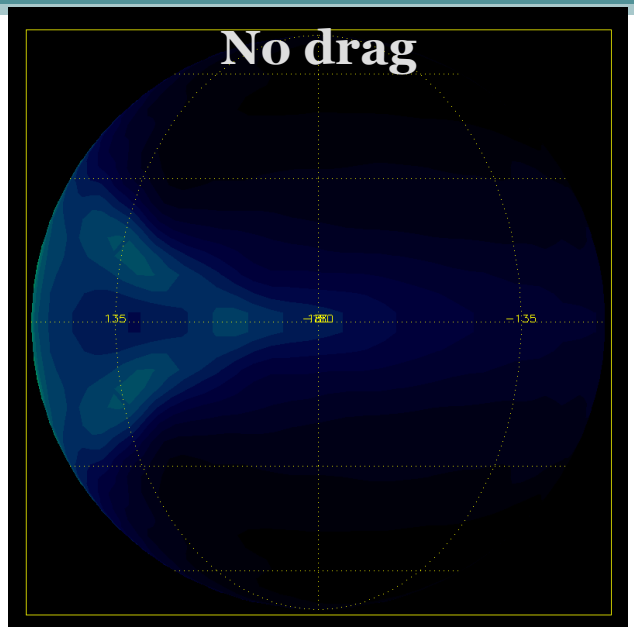


Prediction:
Anti-correlation between the amount of radius inflation and the shift of the hot spot.
Menou (2011)

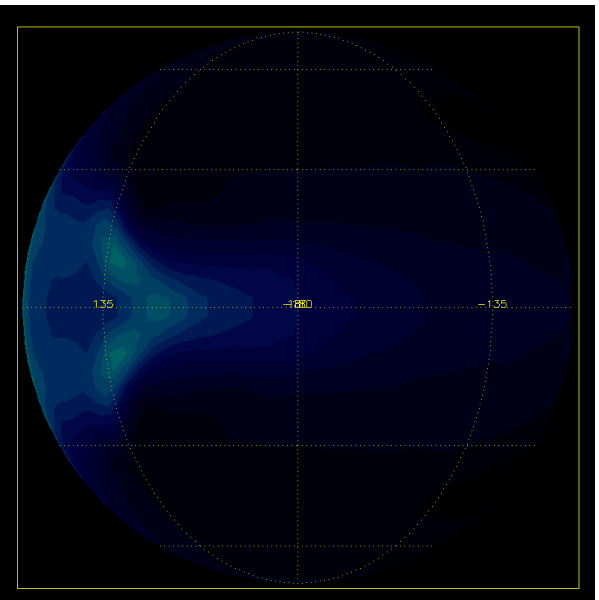
see also Batygin & Stevenson (2010), Batygin et al. (2011), Laughlin et al. (2011)

Preliminary results

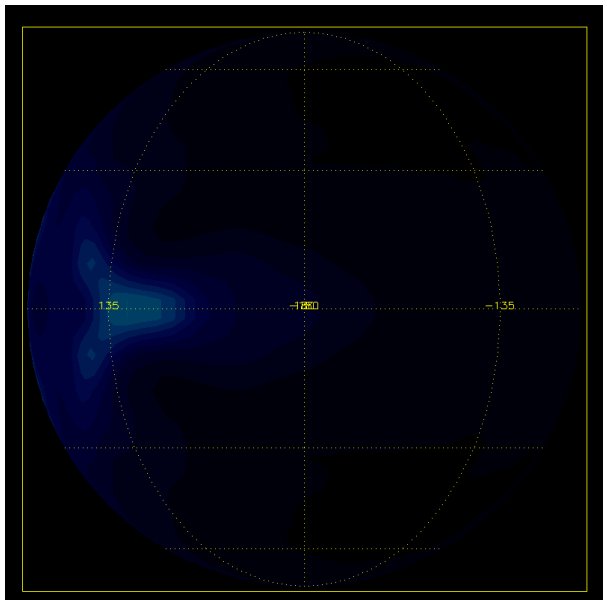
Maps of the emitted IR flux



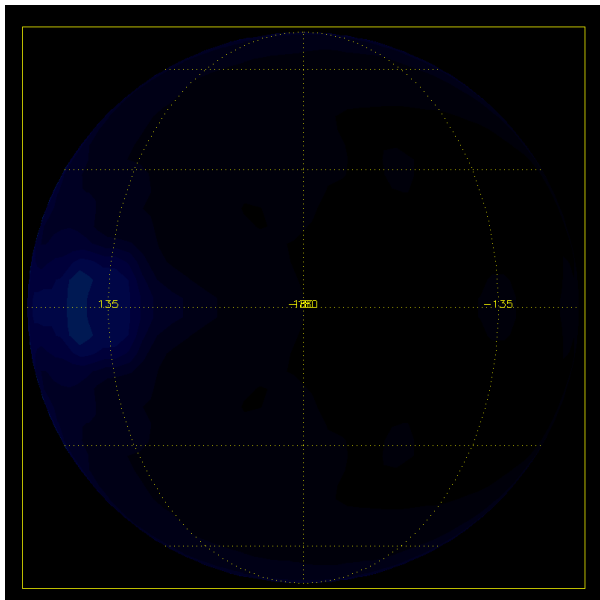
Weak



Medium



Strong



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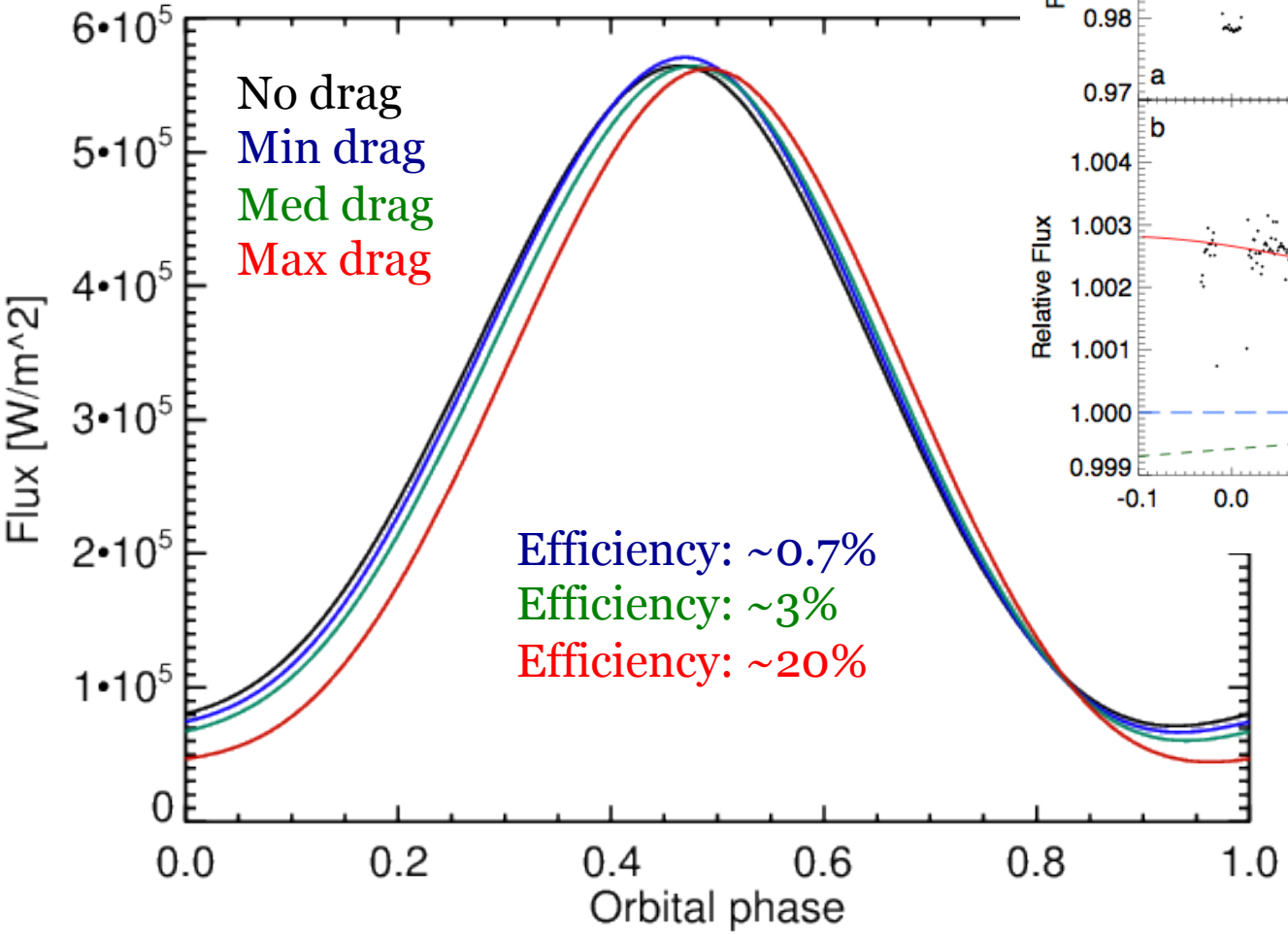

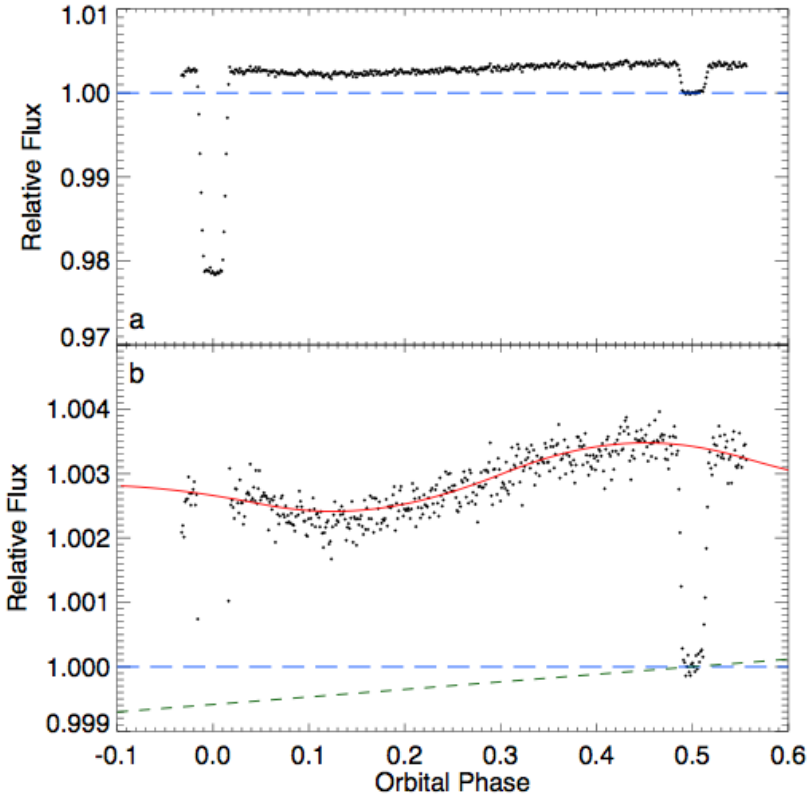

Knutson et al. (2007)

The Future (is bright, of course)

- "Generic" hot Jupiters are understood, but … hot Jupiter diversity is not.

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- Near-future observations will test predictions (shifted hot spots, inflated radii, Doppler shifted transmission).

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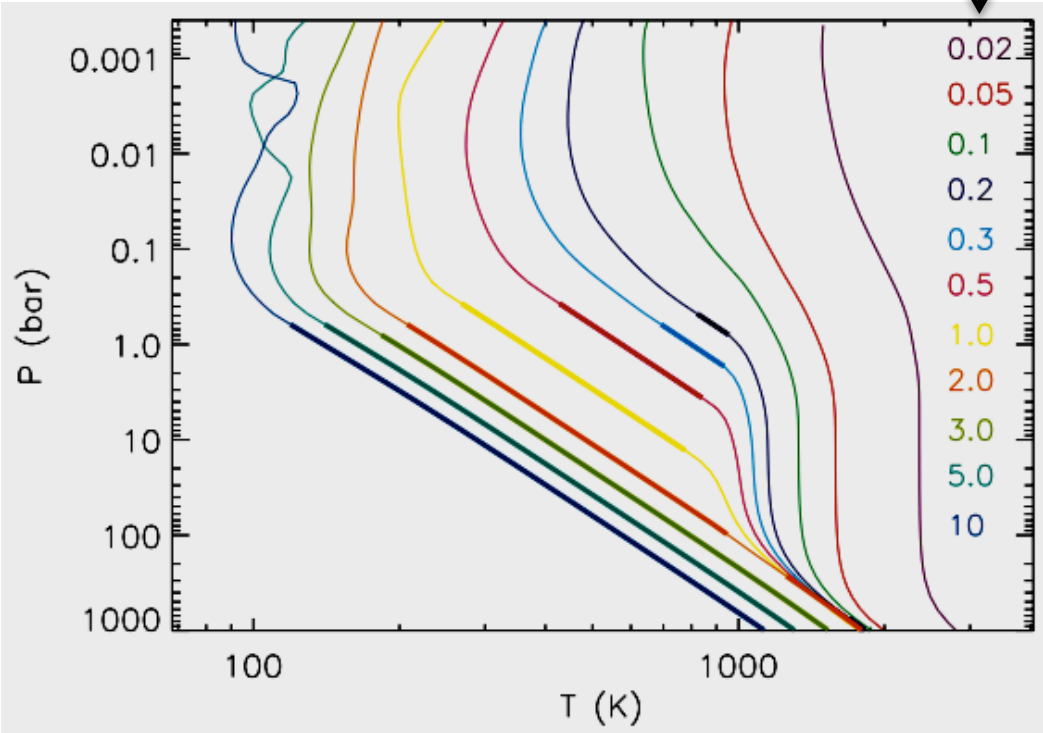
- Near-future observations will test predictions (shifted hot spots, inflated radii, Doppler shifted transmission).
- Farther-future observations will ensure that our theories are incorrect (JWST!).

distance from
"Sun" in AU



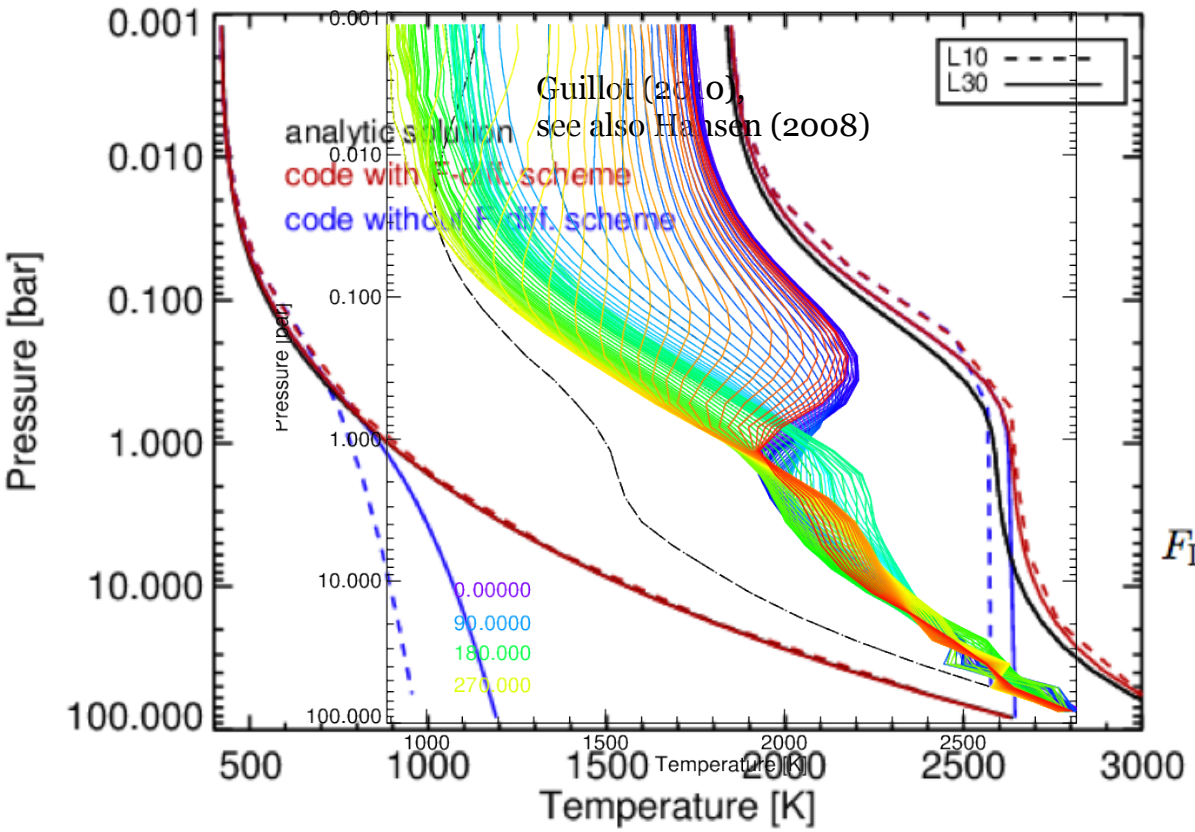
Fortney et al. (2007)

Our GCM, with double-gray radiative transfer

$$F_{\downarrow \mathrm{vis}}(P) = (1-A)\mu_0 F_{\mathrm{inc}} \exp\left(-\frac{1}{\mu_0}\int_z^\infty \kappa_{\mathrm{vis}} du\right)$$
$$= (1-A)\mu_0 F_{\mathrm{inc}} \exp\left(-\frac{1}{\mu_0}\frac{\kappa_{\mathrm{vis}}}{g} P\right)$$

$$F_{\uparrow,\downarrow \mathrm{IR}}(P) = \int \left(1 - \exp\left[-\frac{1.66}{g}\int \kappa_{\mathrm{IR}} dP\right]\right)\frac{d\sigma T^4}{dP} dP$$

$$\kappa_{\mathrm{IR}} = \kappa_{\mathrm{IR},0}(P/P_{\mathrm{ref}})^{\alpha}$$

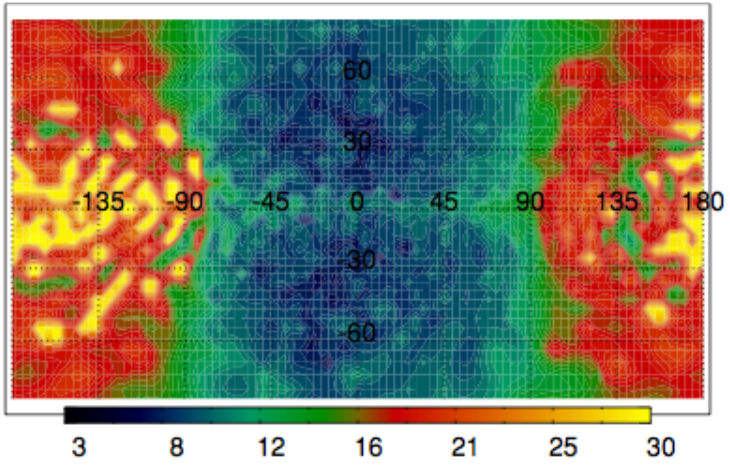


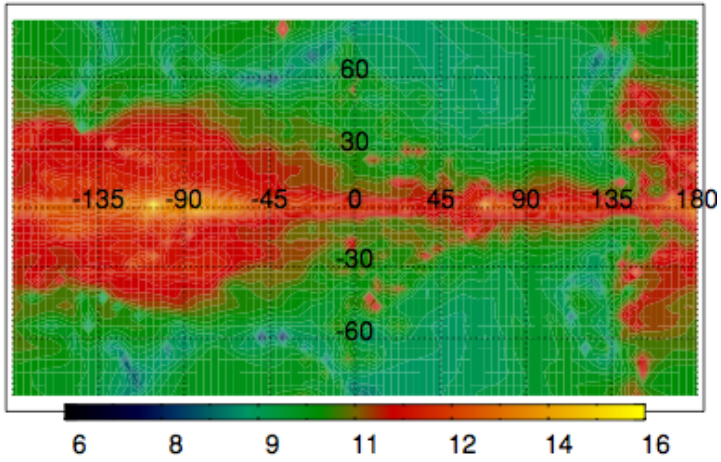
$$F_{\mathrm{IR}} = \frac{16 g \sigma T^3}{3\kappa_{\mathrm{IR}}}\frac{dT}{dP}$$

Magnetic drag

$Log_{10}(t_{drag})$: blue = strong drag

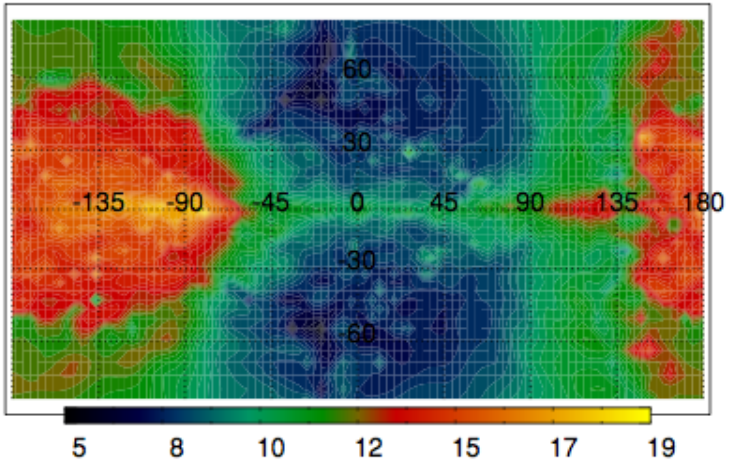
1 mbar

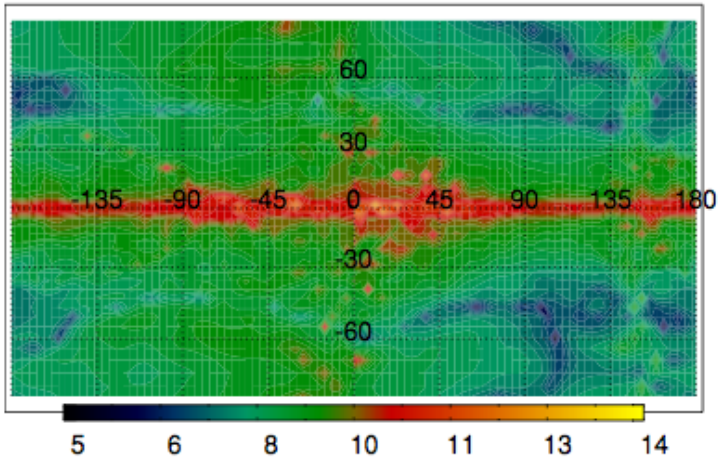




0.5 bar

40 mbar





2 bar

Perna, Menou, & Rauscher (2010a)

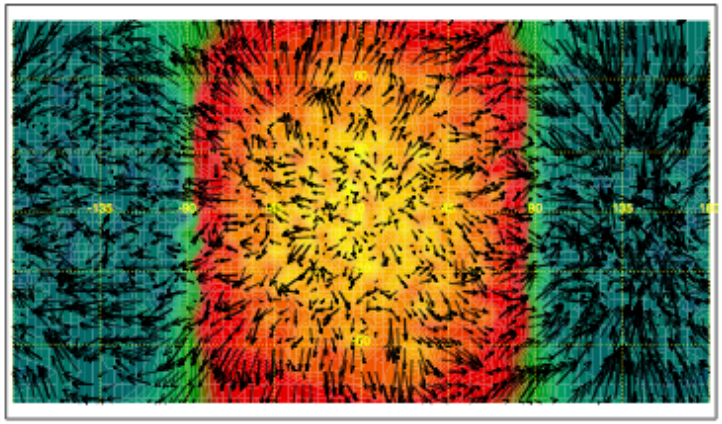
$$\rho \frac{d\mathbf{v}}{dt} \propto \frac{1}{c} \mathbf{j} \times \mathbf{B}$$

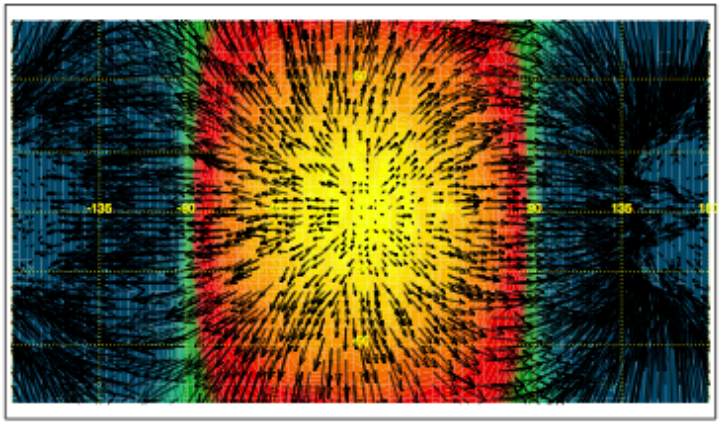
Magnetic drag and wind speeds

Max wind = 15 km/s

Max wind = 4.5 km/s

No drag





Mag drag, A

Temperature [K]

272 471 671 870 1070 1269 1469

334 505 676 847 1017 1188 1359

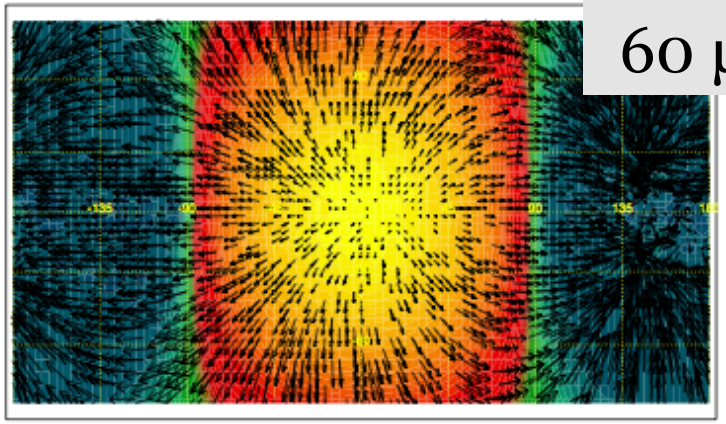
Temperature [K]

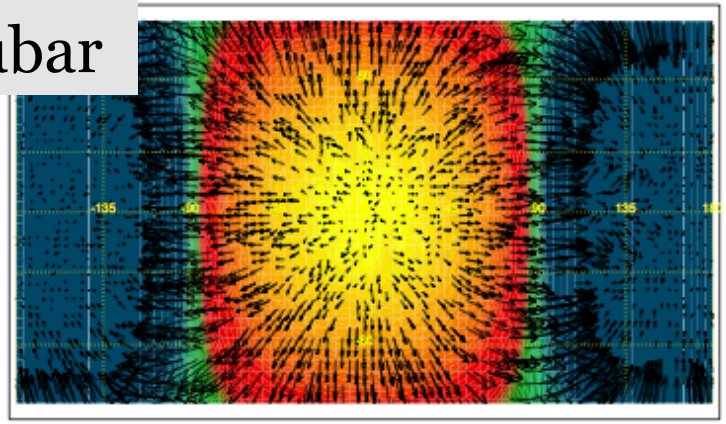
Max wind = 11 km/s

Max wind = 2.5 km/s

60 μbar

No drag, extra hyperdissipation





Mag drag, B

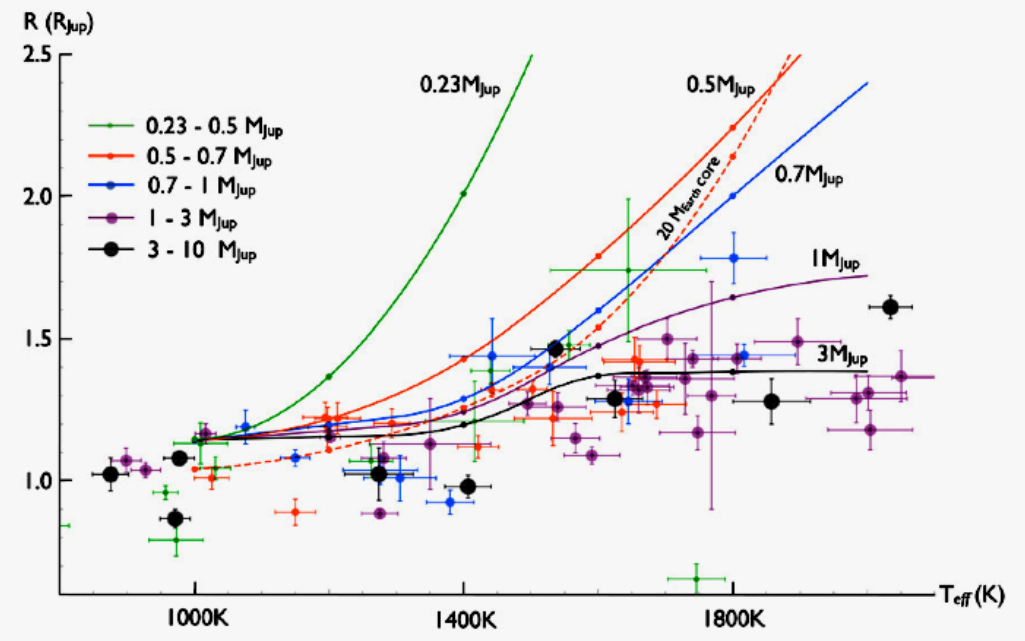
Temperature [K]

326 495 665 835 1004 1174 1344

339 510 680 851 1022 1193 1363

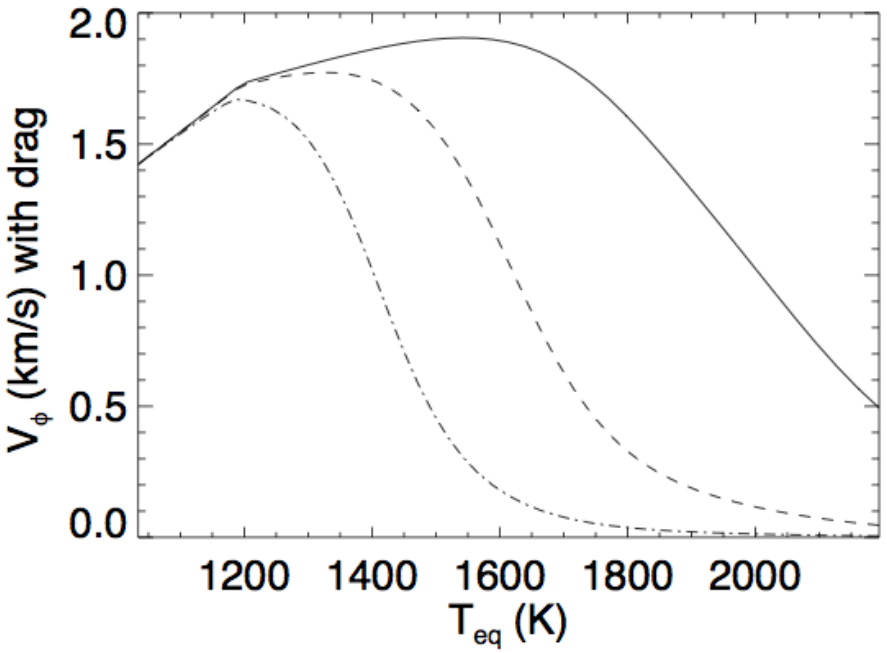
Temperature [K]

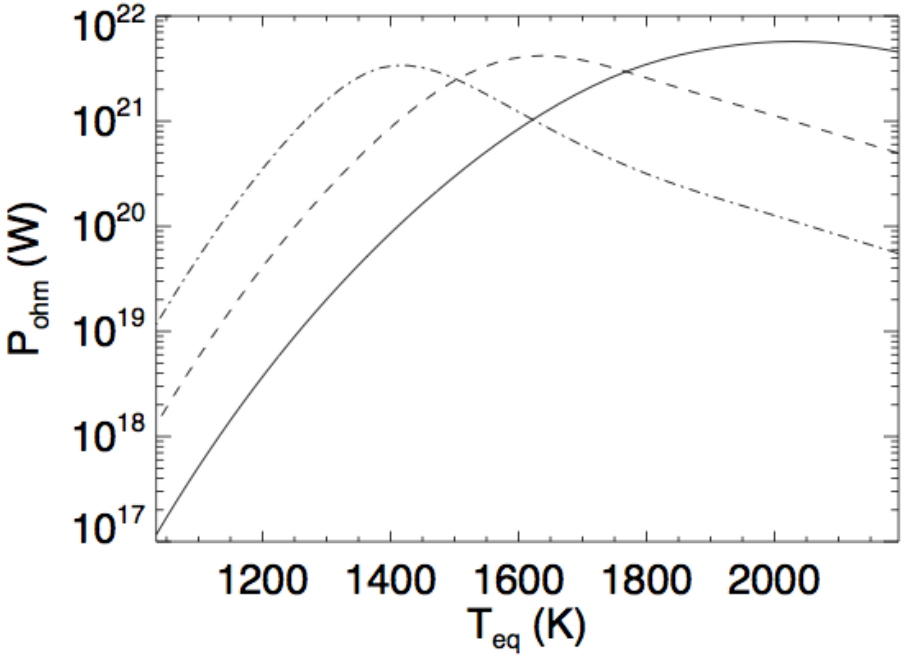
1% efficiency



Prediction: hot spot offset vs. radius inflation

Menou (2011)





———	Weak,	B = 3 G
- - - - - - -	Medium,	B = 10 G
—·—·—·-	Strong,	B = 30 G