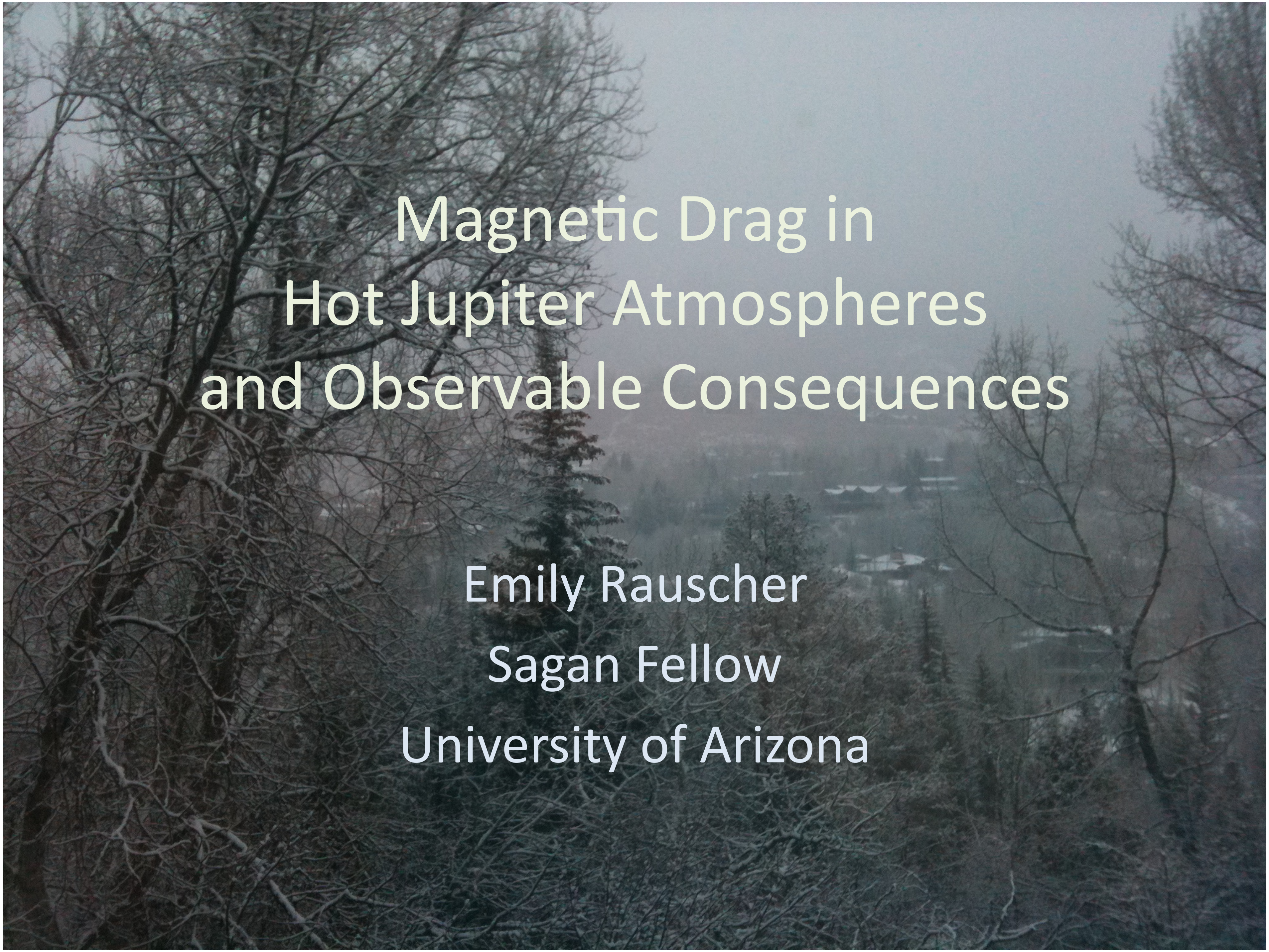

Magnetic Drag in Hot Jupiter Atmospheres and Observable Consequences

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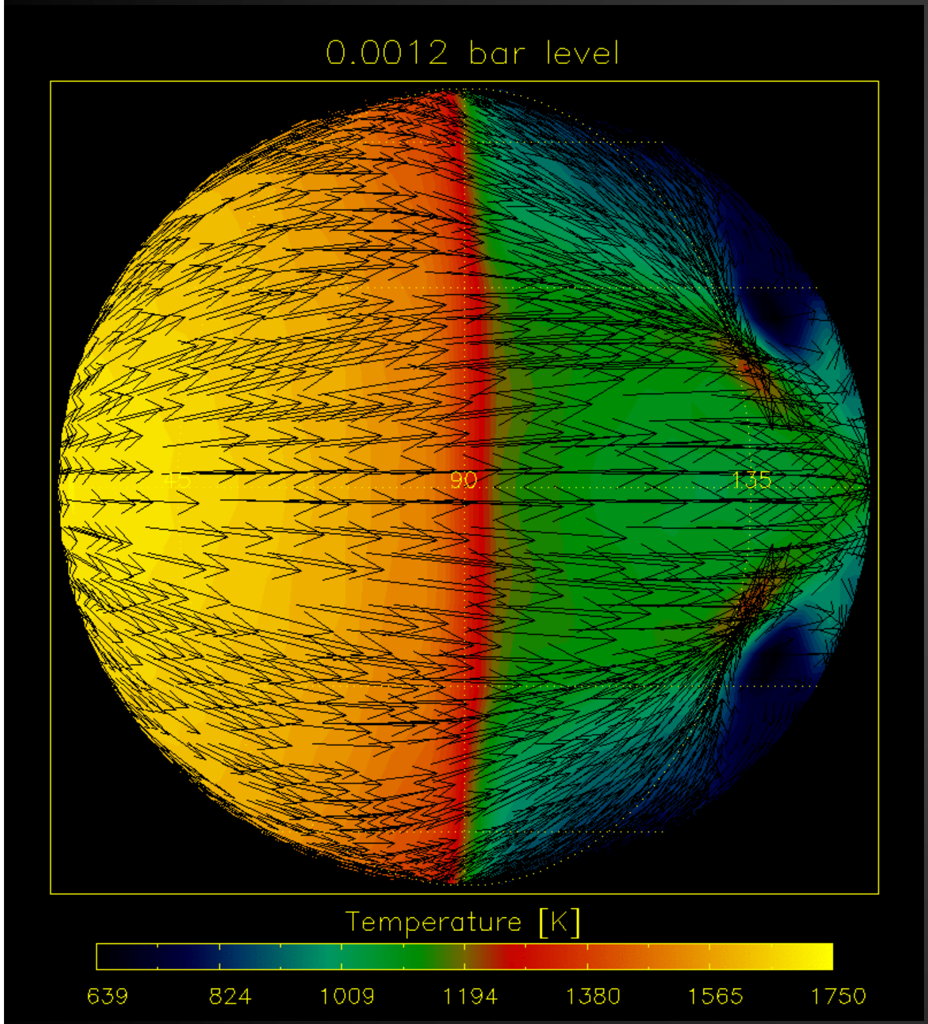
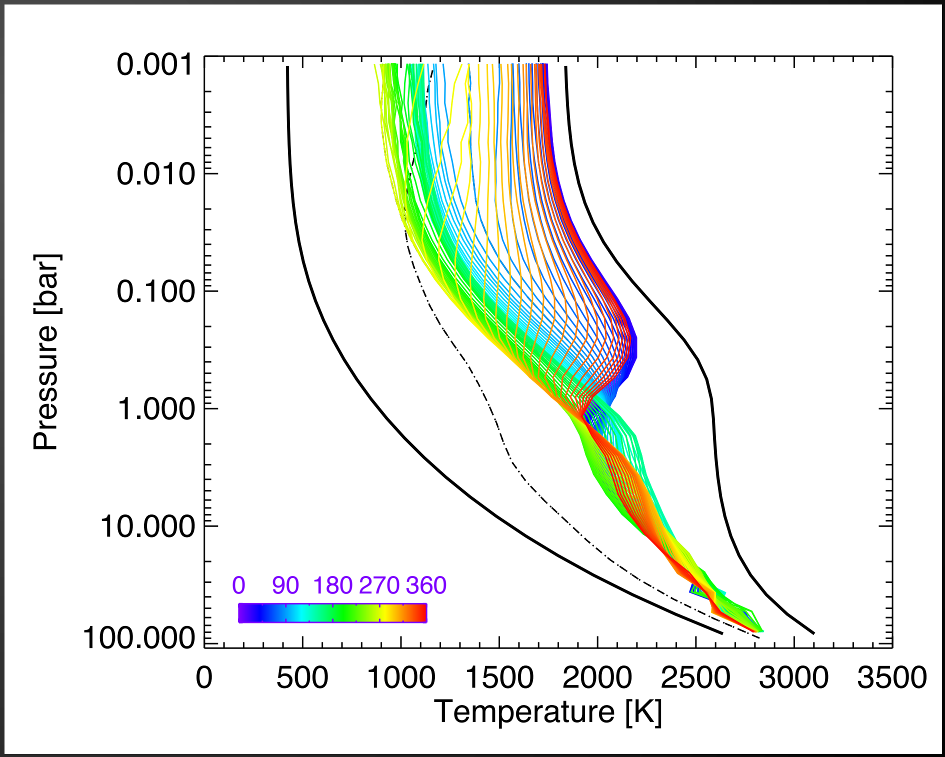
Atmospheric structure

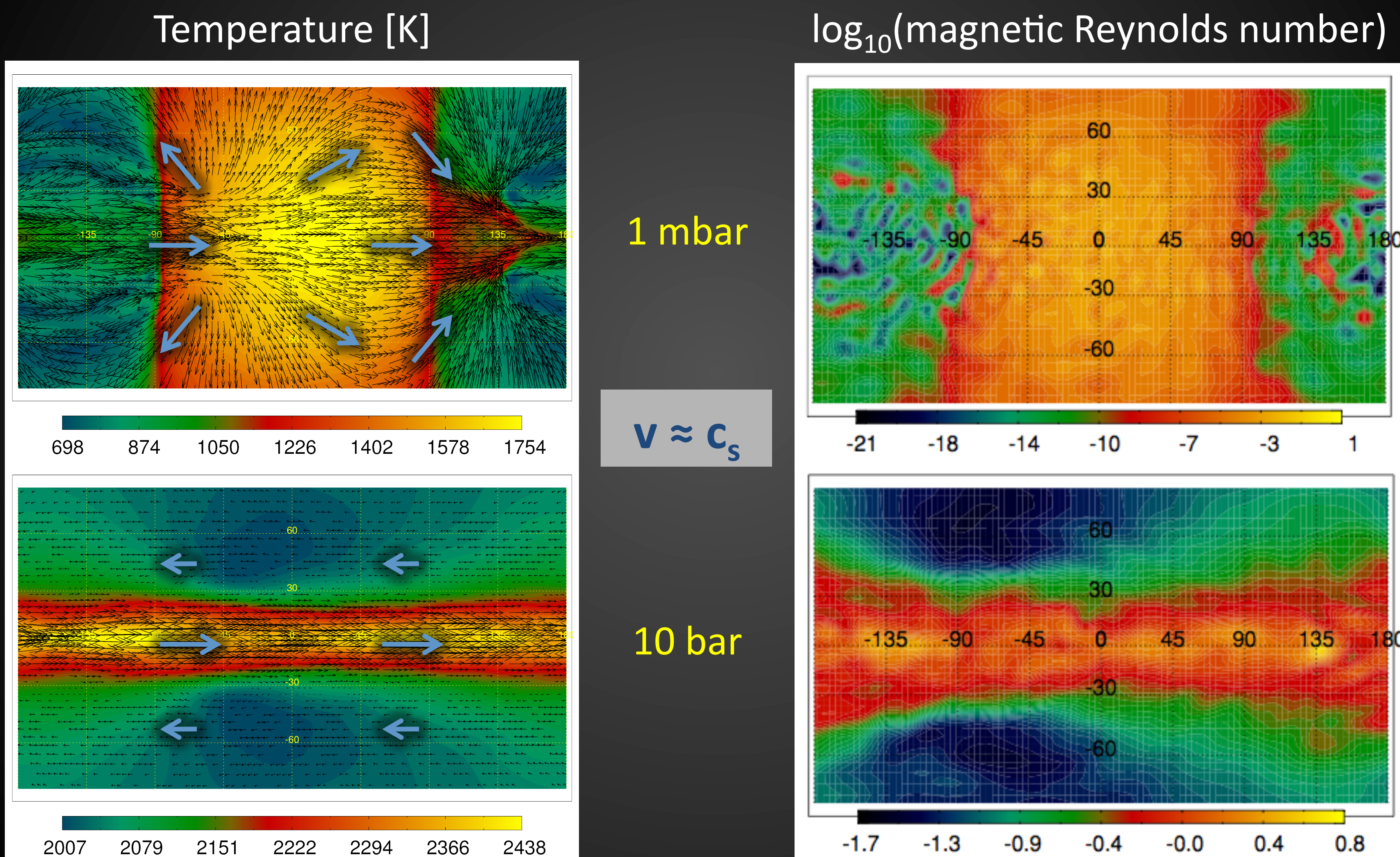
Upper atmosphere:
day = hot night = cold
Lower atmosphere:
equator = hot poles = cold





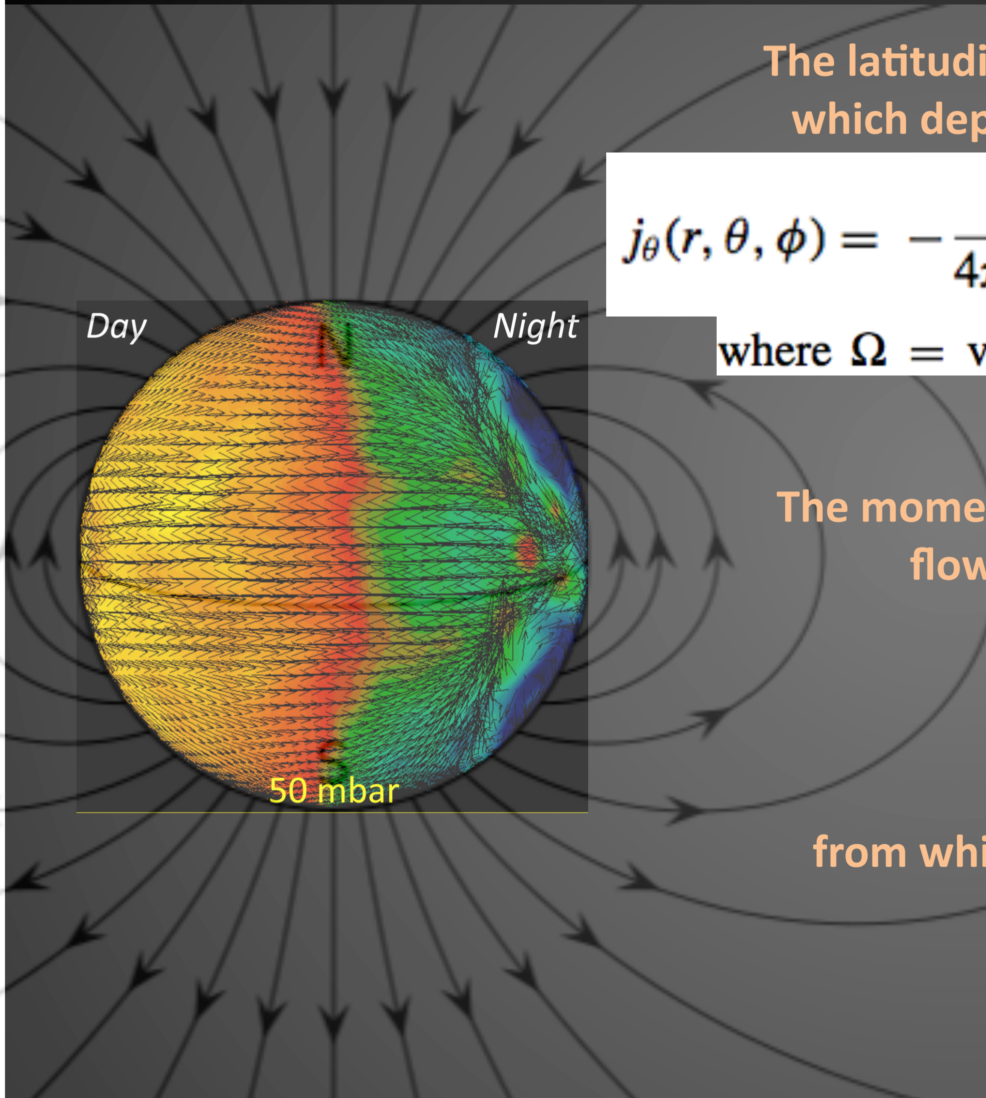
Rauscher & Menou (2011)

Thermal ionization *+ winds*



Perna, Menou, & Rauscher (2010a)

Magnetic Drag



The latitudinal component of the induced current, which depends on v, B, and the local resistivity:

$$j_\theta(r,\theta,\phi) = -\frac{c\sin\theta}{4\pi r\eta(r,\theta,\phi)}\int_r^R dr' r'^2\left(\frac{\partial\Omega}{\partial r'}B_r + \frac{1}{r'}\frac{\partial\Omega}{\partial\theta}B_\theta\right)$$

where $\Omega = \mathrm{v}_\phi r^{-1}\sin^{-1}\theta$ in spherical coordinates $(r,\ \theta,\ \phi)$.

The momentum equation for the (mostly neutral) flow now includes an ion drag term:

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

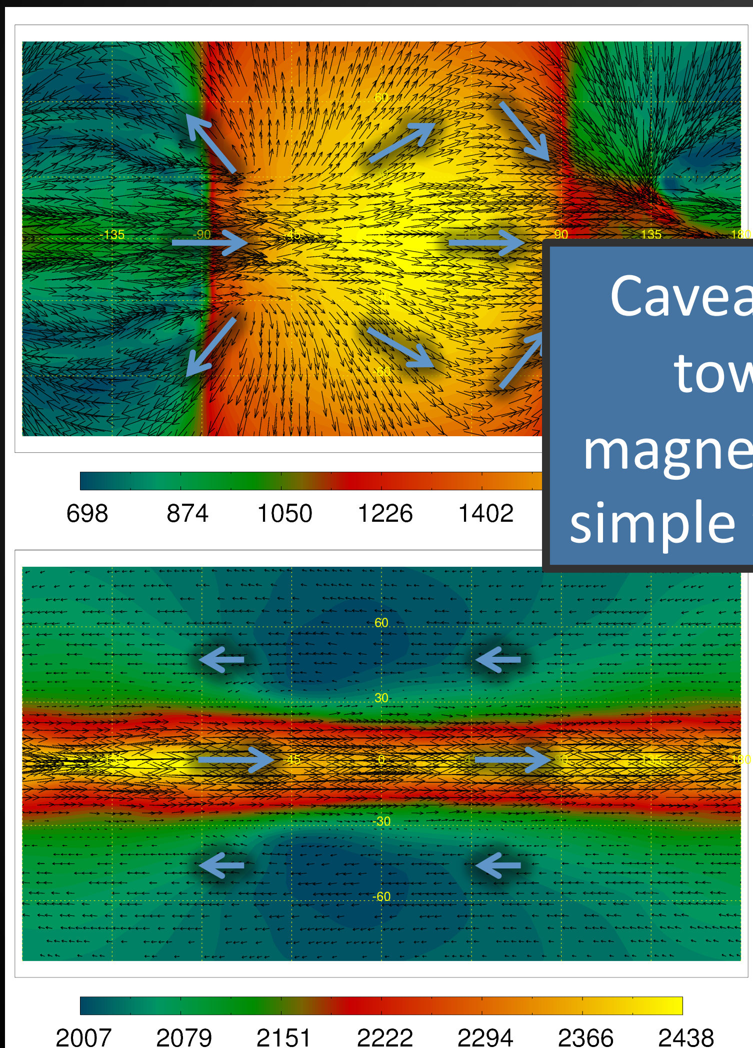
from which we can calculate a drag timescale:

$$\tau_{\rm drag} \sim \frac{\rho\,\left|\mathrm{v}_\phi\right|\,c}{|\mathbf{j}_\theta\times\mathbf{B}|}$$

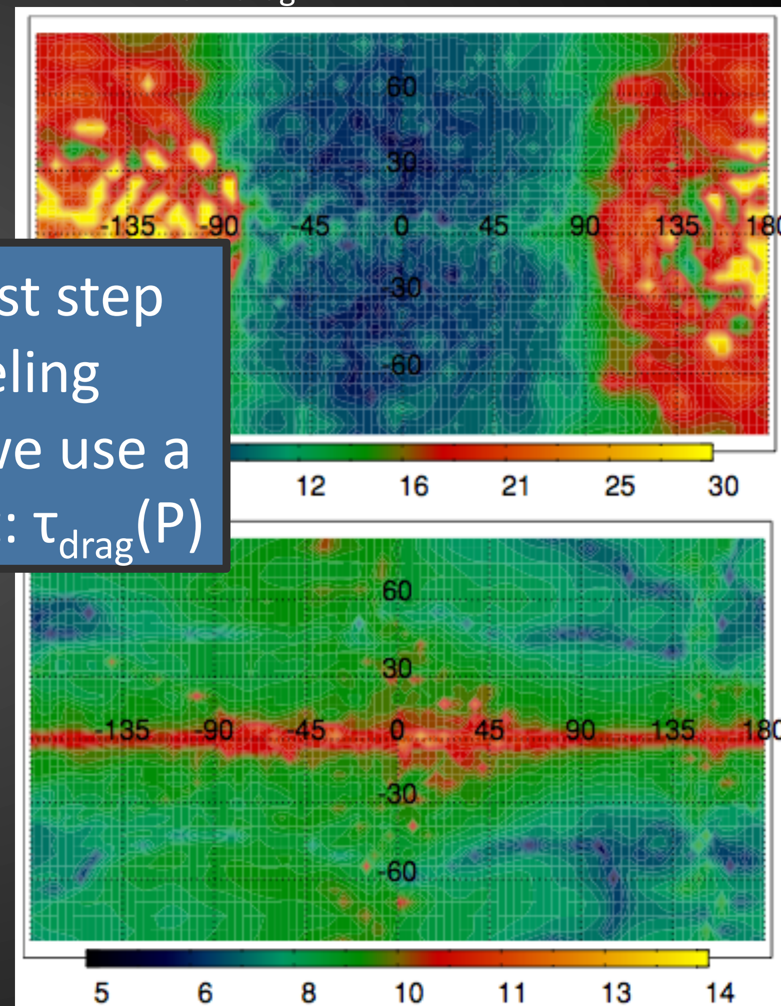
Perna, Menou, & Rauscher (2010a); see also Zhu et al. (2005), Liu et al. (2008)

Complex drag structure

Temperature [K]



$\text{Log}_{10}(\tau_{drag})$: blue = strong drag



1 mbar

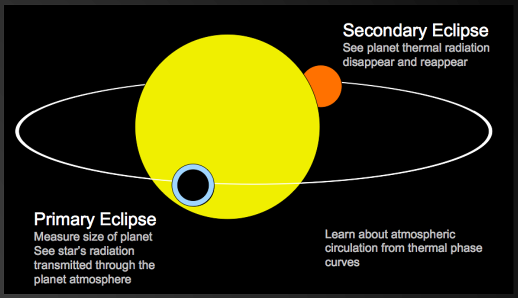
10 bar

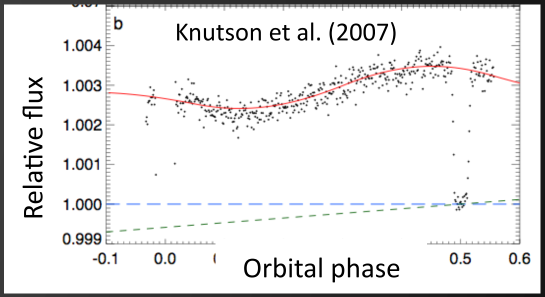
Caveat! As a first step toward modeling magnetic drag, we use a simple treatment: $\tau_{drag}(P)$

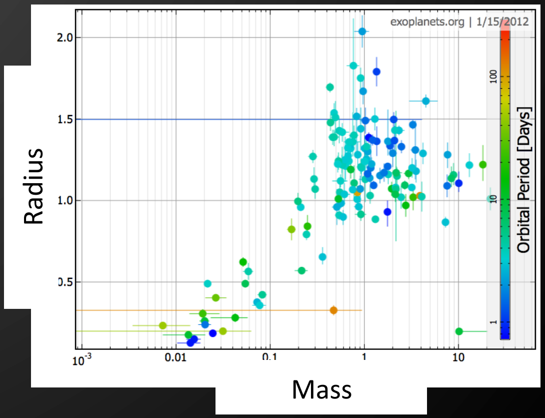
Perna, Menou, & Rauscher (2010a)

Observable Consequences

- Slower winds
  - direct measurement of wind speeds?
- Altered temperature structure
  - phase offset of flux maximum
- Ohmic dissipation and extra heating
  - amount of radius inflation







Wind speeds

1 bar to 10 µbar

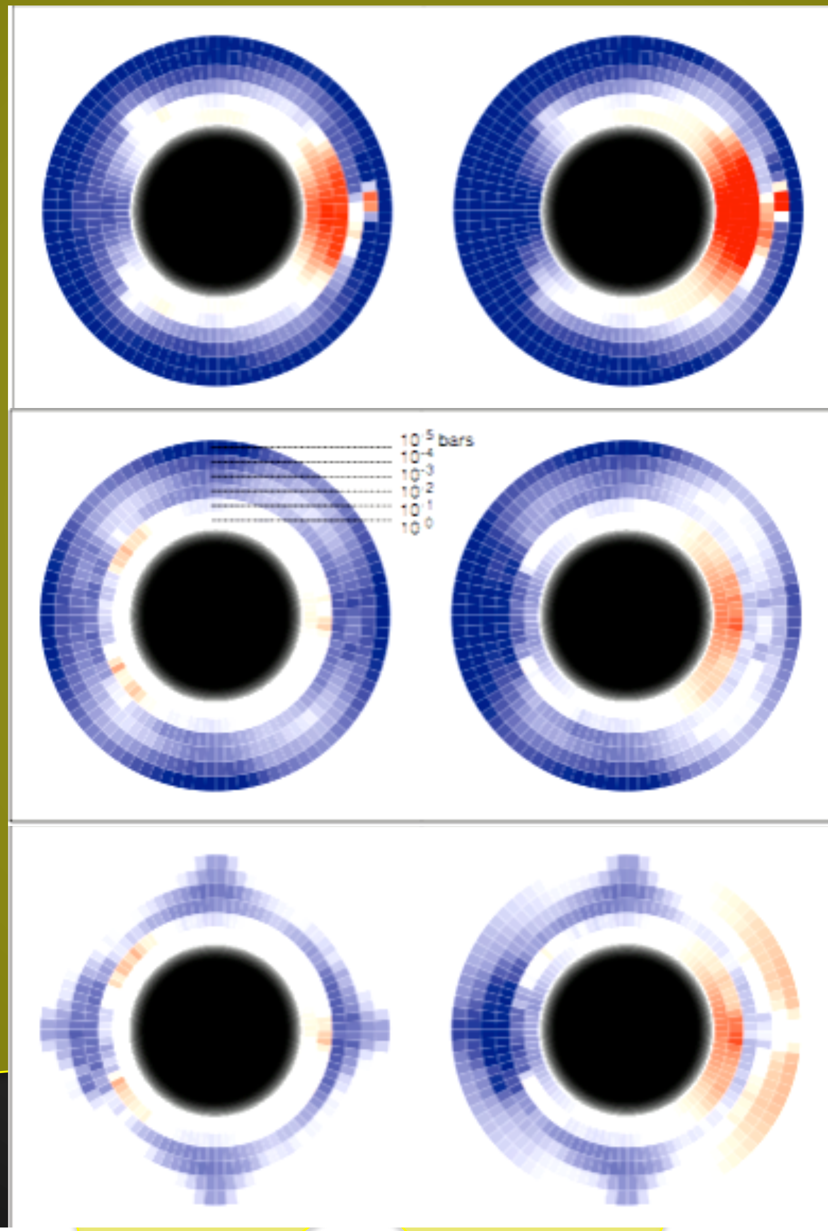
≤ -5 km/s

≥ 5 km/s

drag-free

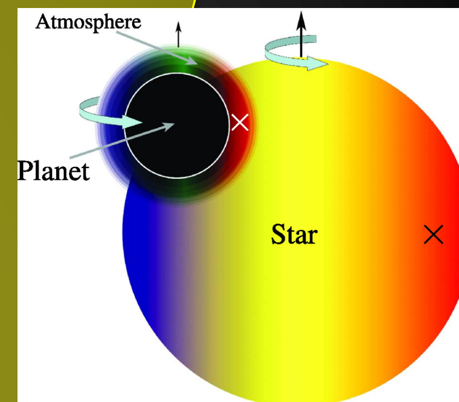
with magnetic drag, version 1

with magnetic drag, version 2



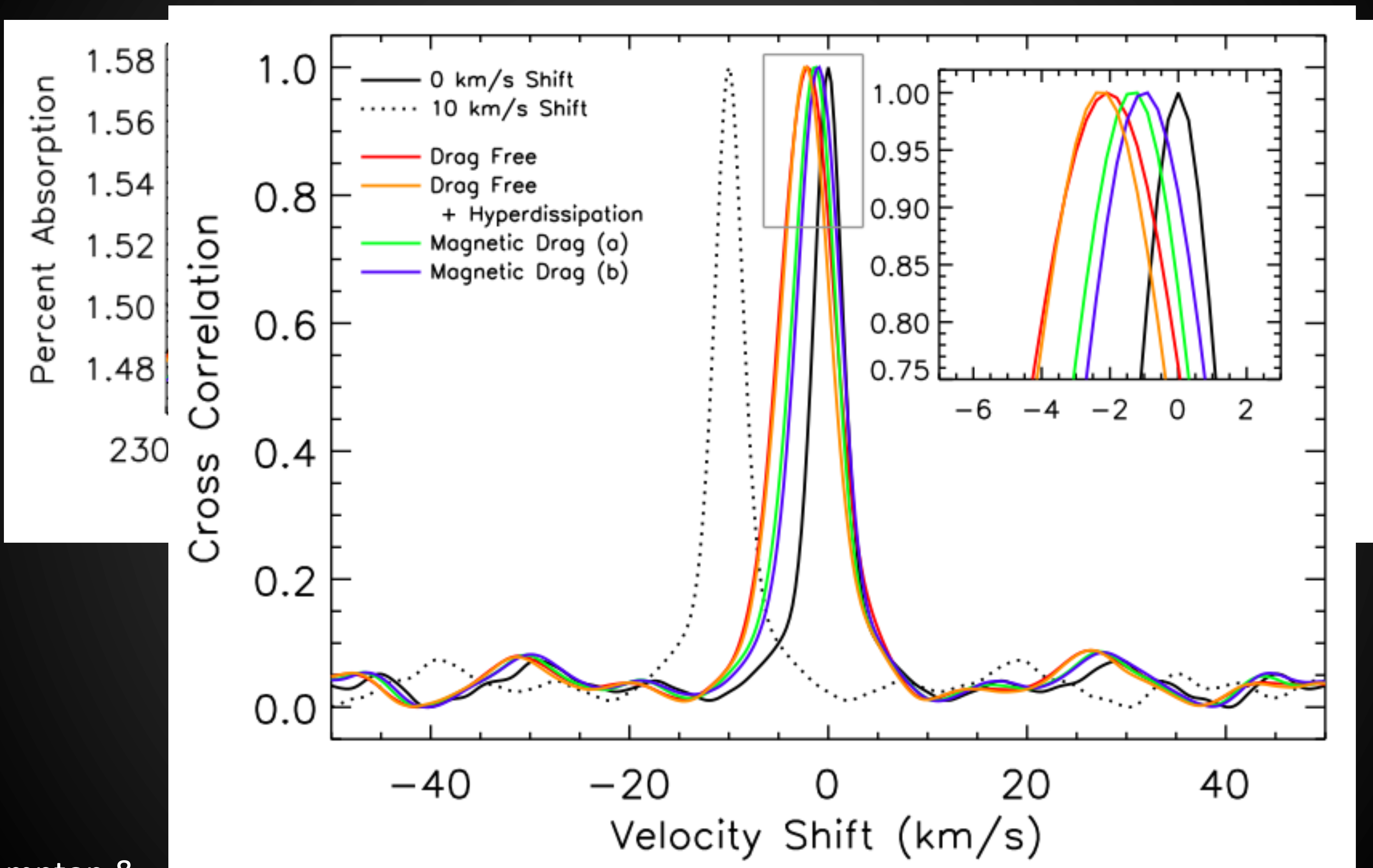
including rotation

Spiegel et al. (2007)



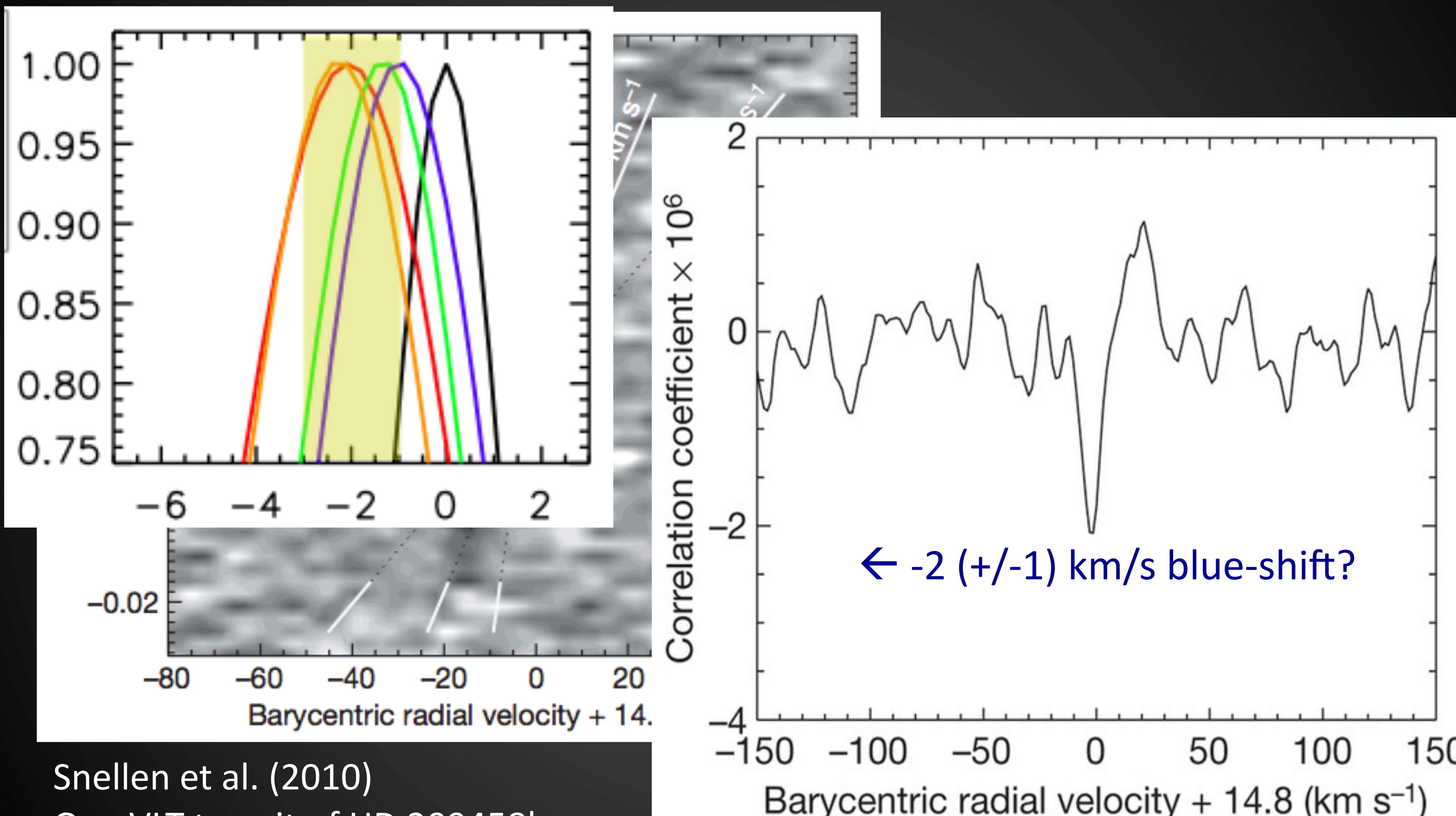
Kempton & Rauscher (2011)

Transmission spectra



Kempton & Rauscher (2011)

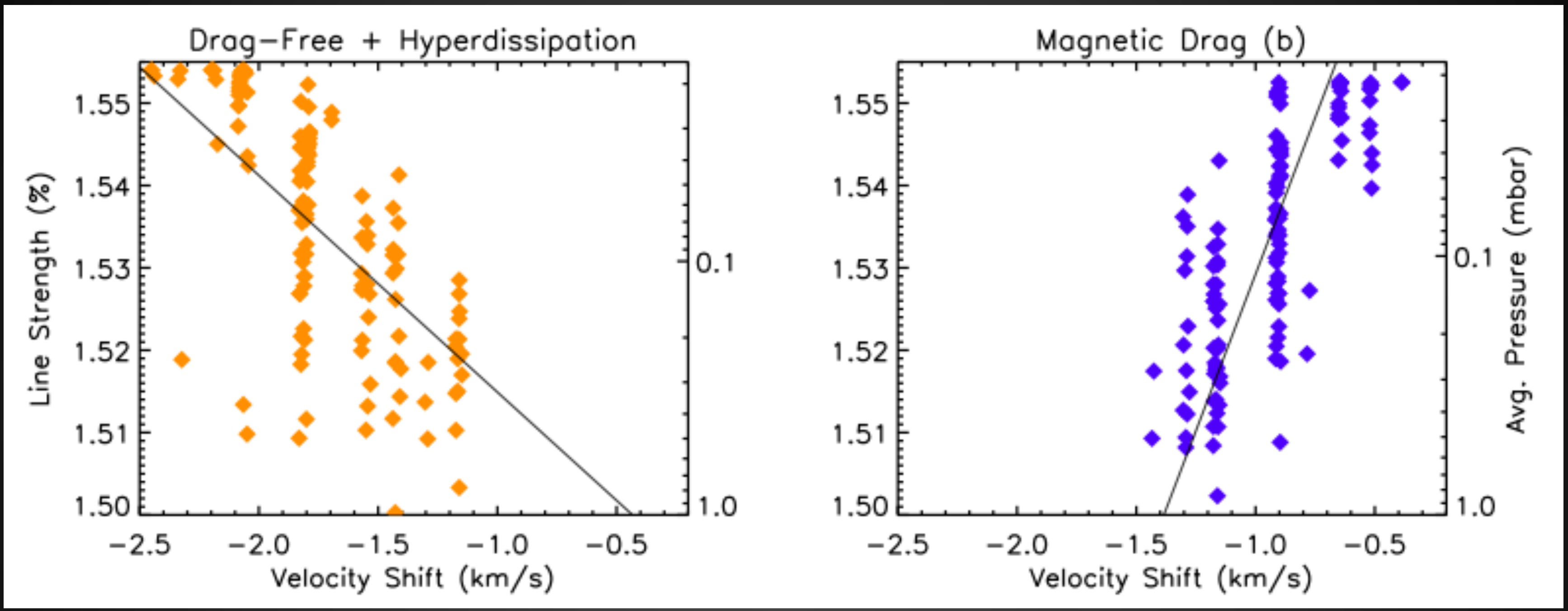
Direct measurement of wind speed (?)

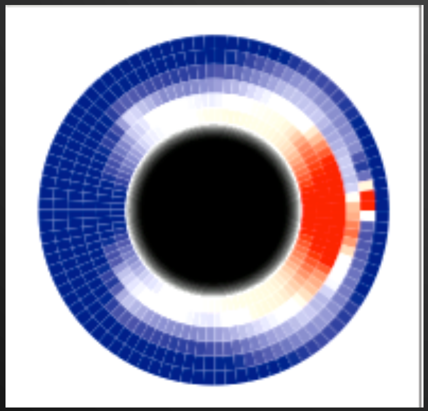


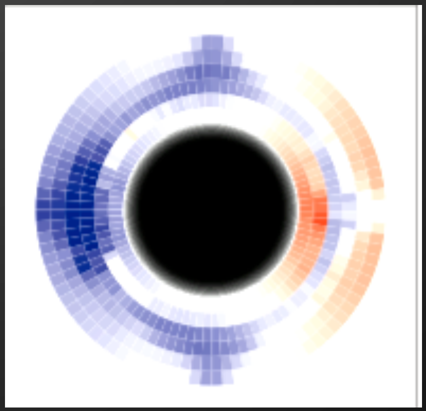
Snellen et al. (2010)
One VLT transit of HD 209458b,
from 2291 to 2349 nm, with R = 10^5.

(see also Redfield et al. 2008, Jensen et al. 2011)

In the more distant future … vertical wind shear





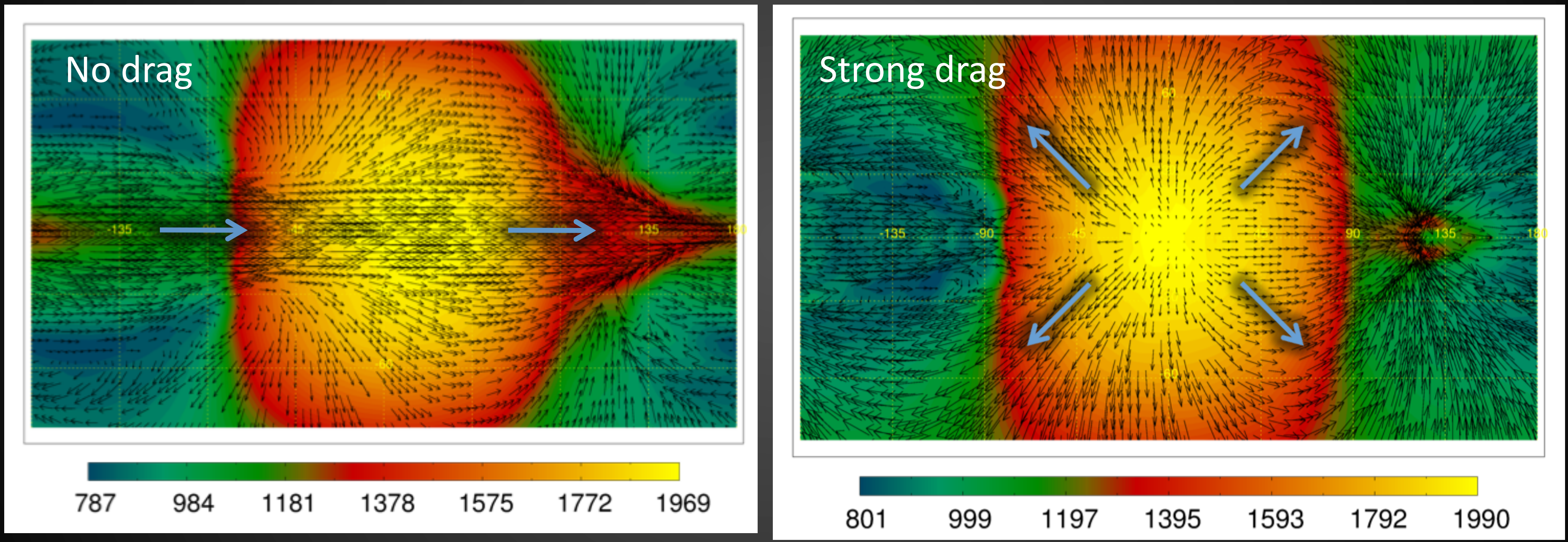


Kempton & Rauscher (2011)

Magnetic drag → less efficient advection

Maximum wind speed: 8 km/s

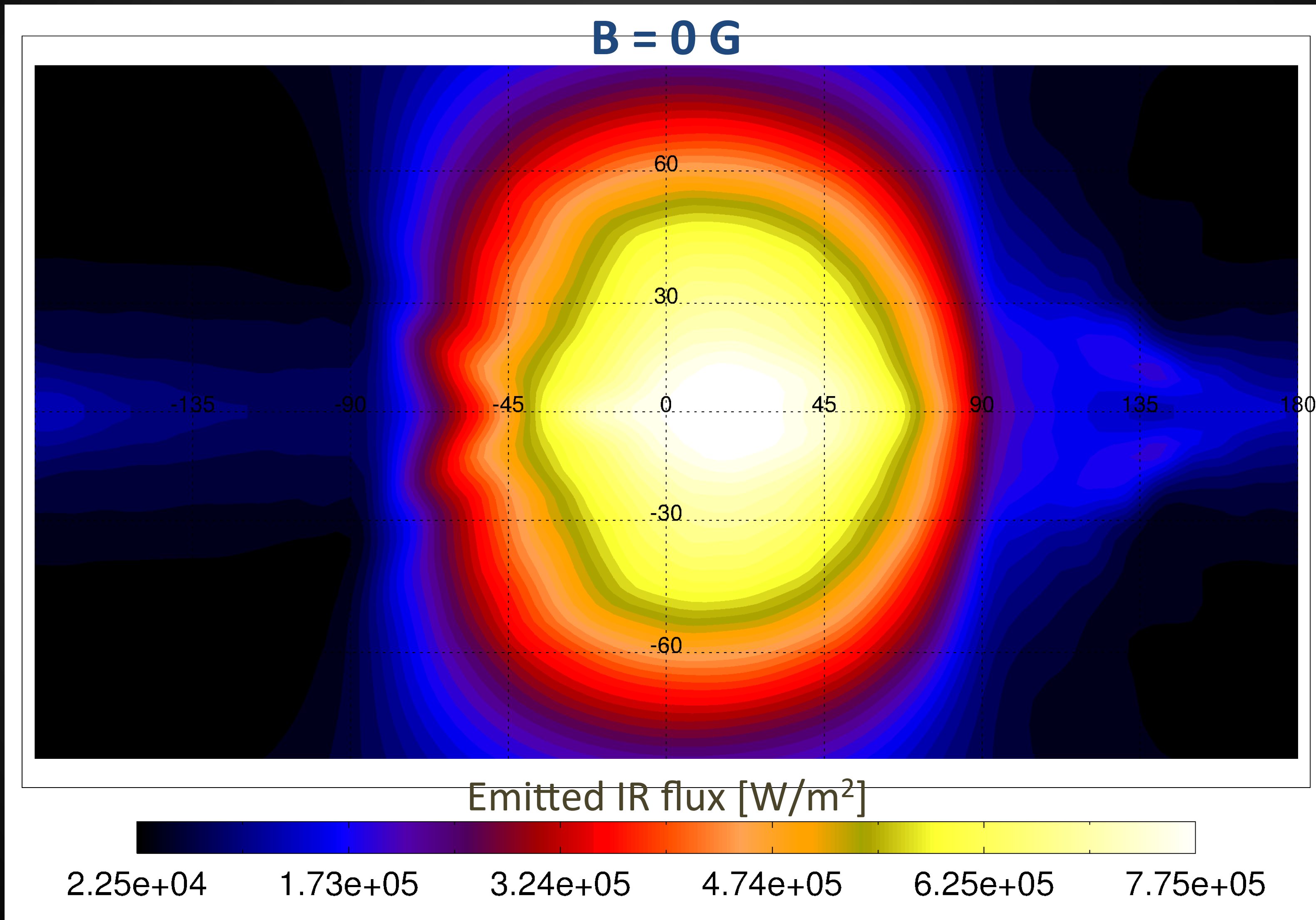
Maximum wind speed: 6 km/s



Temperature [in K]
at photosphere, P = 50 mbar

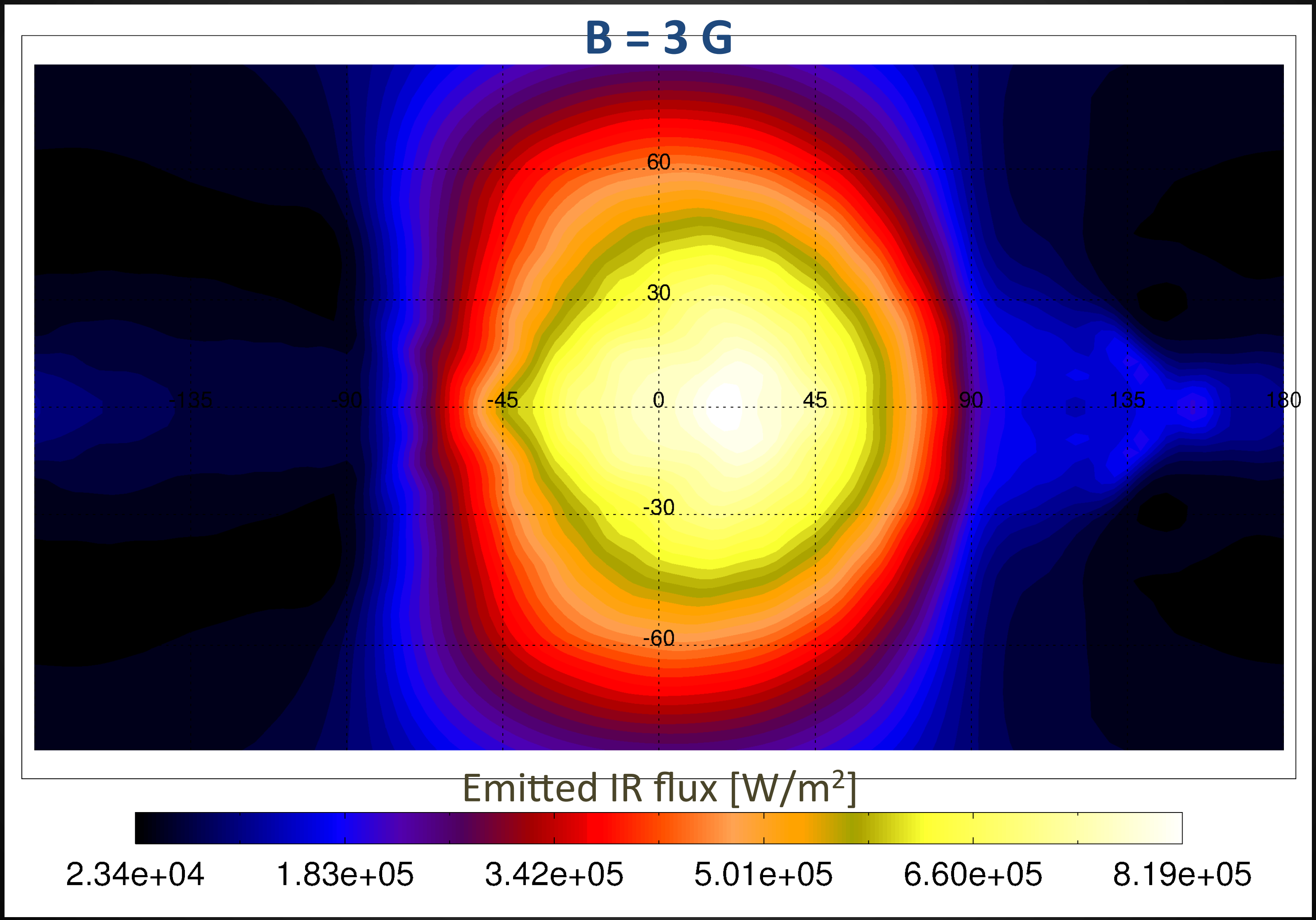
Rauscher & Menou (2011)

Changes in longitude of hotspot



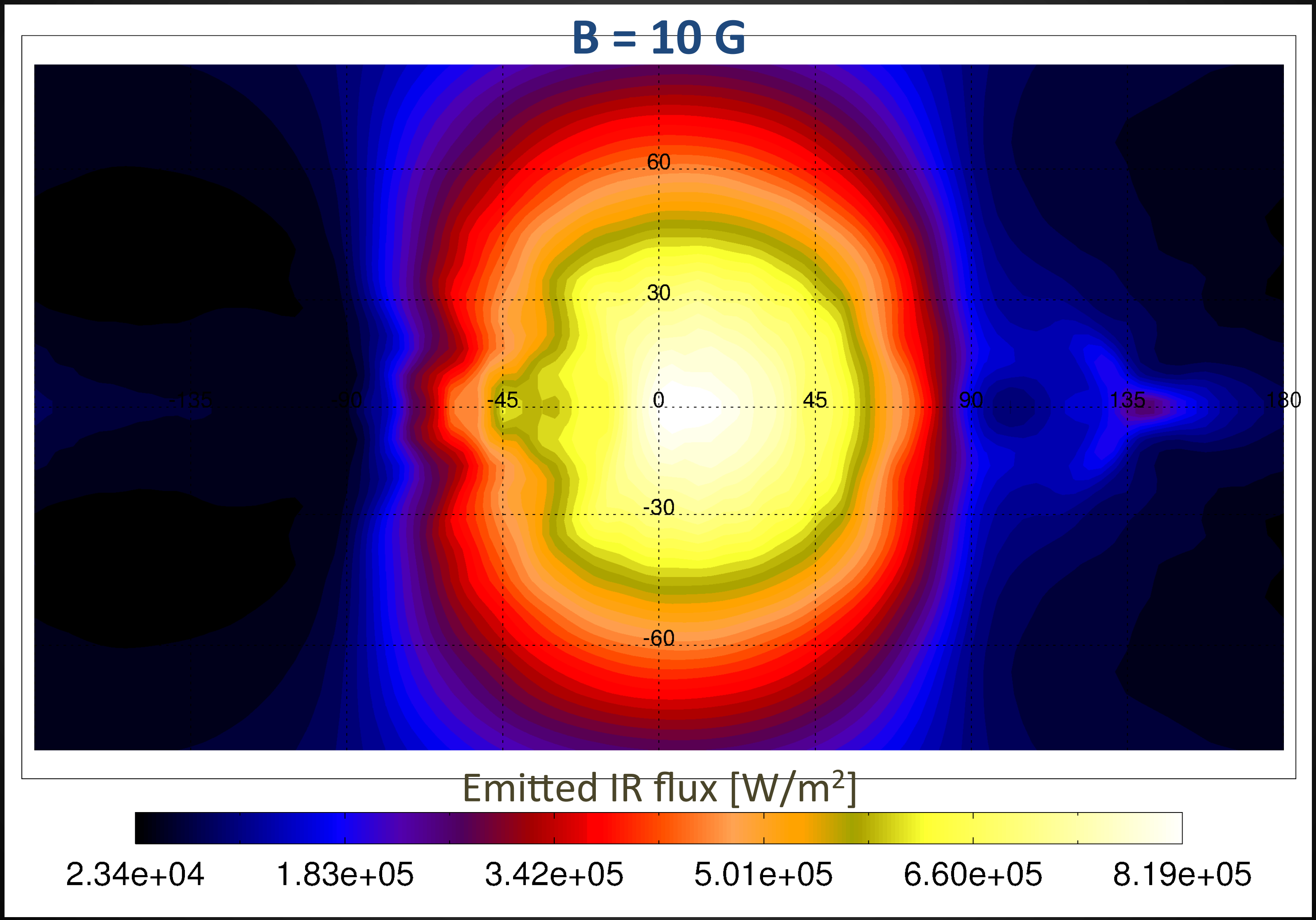
Rauscher & Menou (2011)

Changes in longitude of hotspot



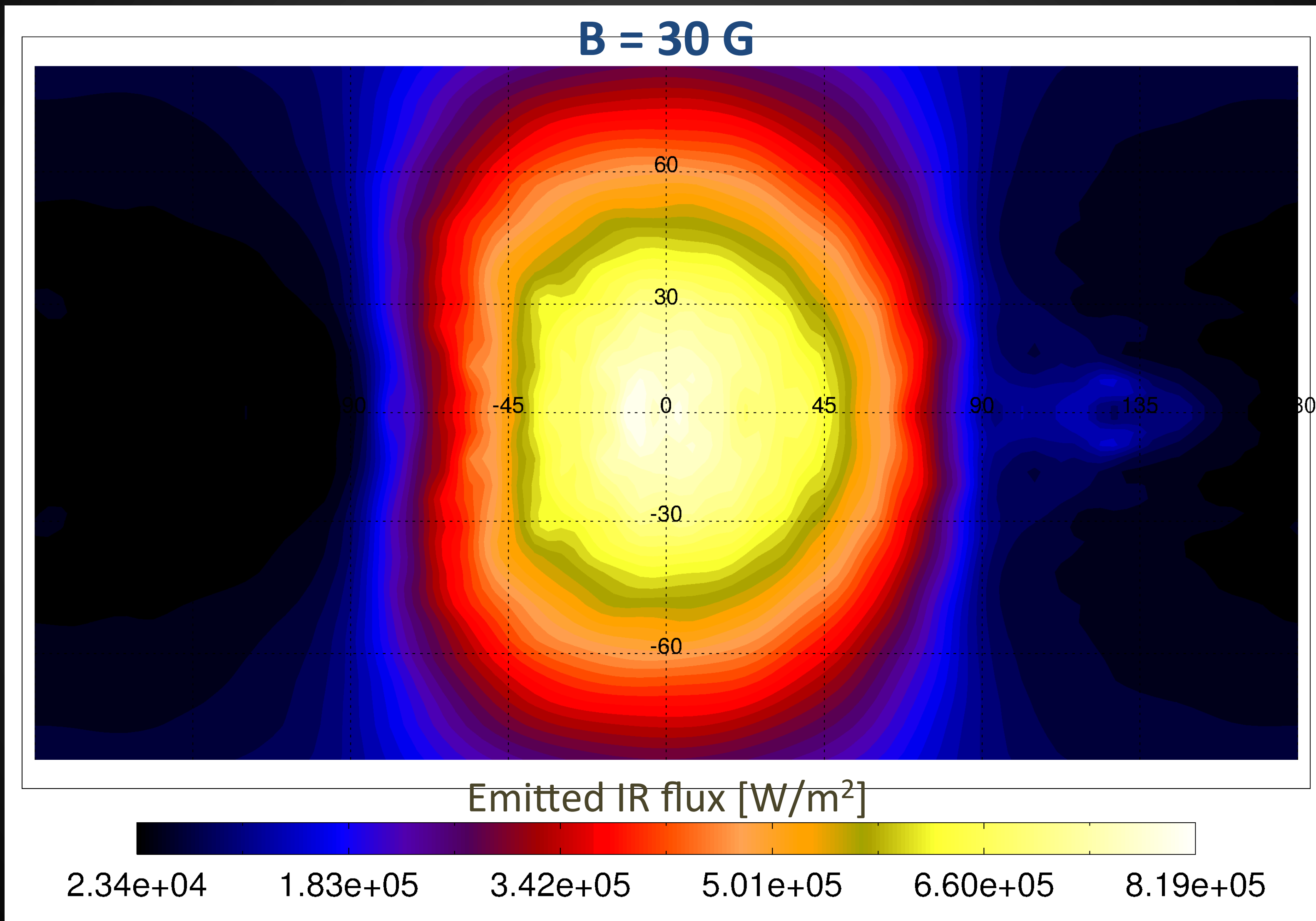
Rauscher & Menou (2011)

Changes in longitude of hotspot



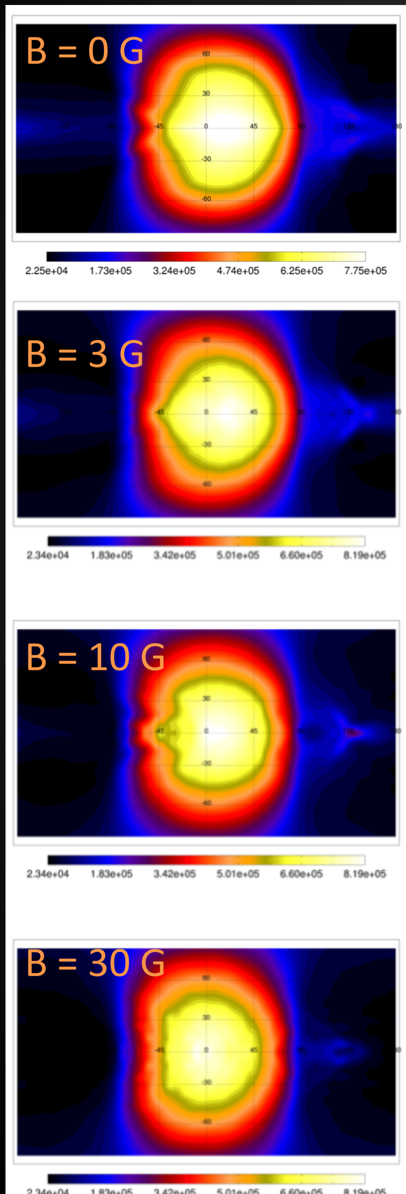
Rauscher & Menou (2011)

Changes in longitude of hotspot

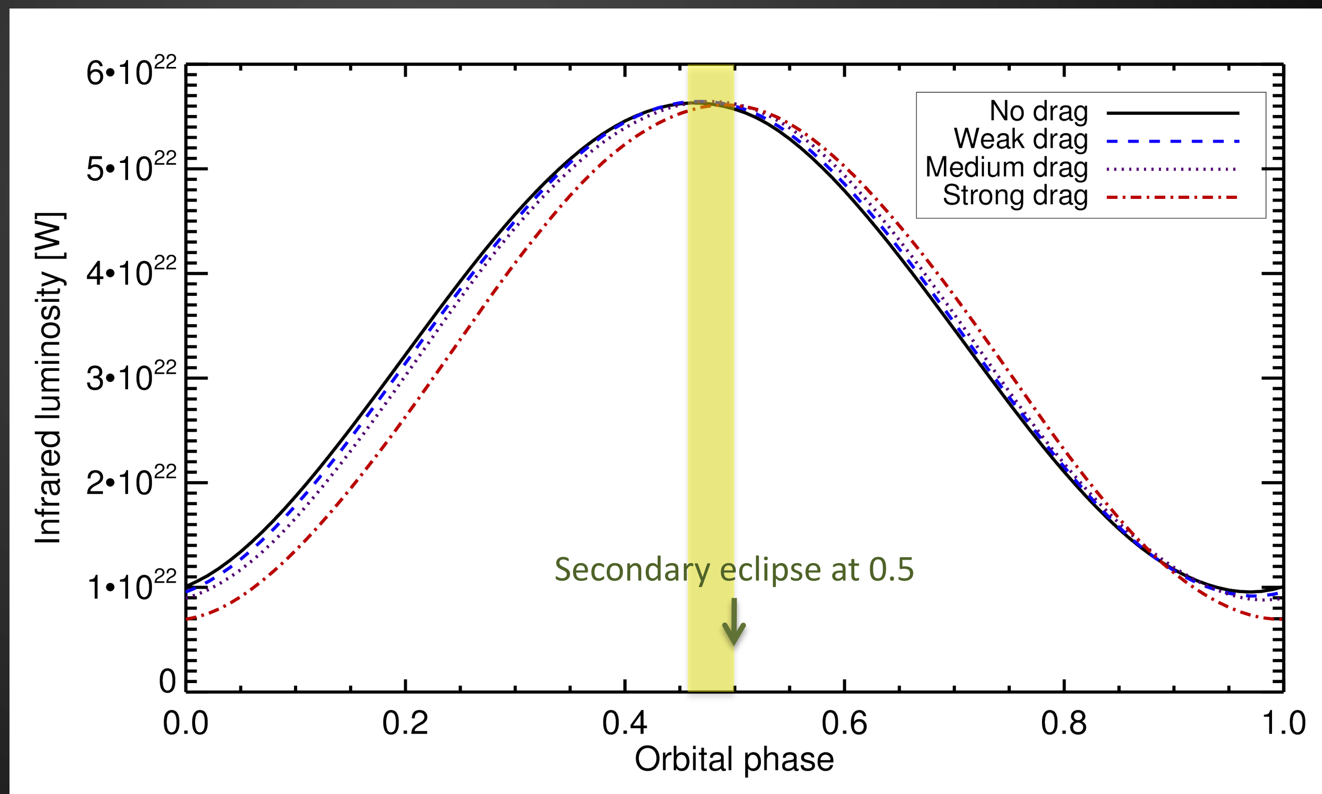


Rauscher & Menou (2011)

Changes in phase offset of max flux



	B = 0 G	B = 3 G	B = 10 G	B = 30 G
Phase of max flux	0.467	0.469	0.481	0.494



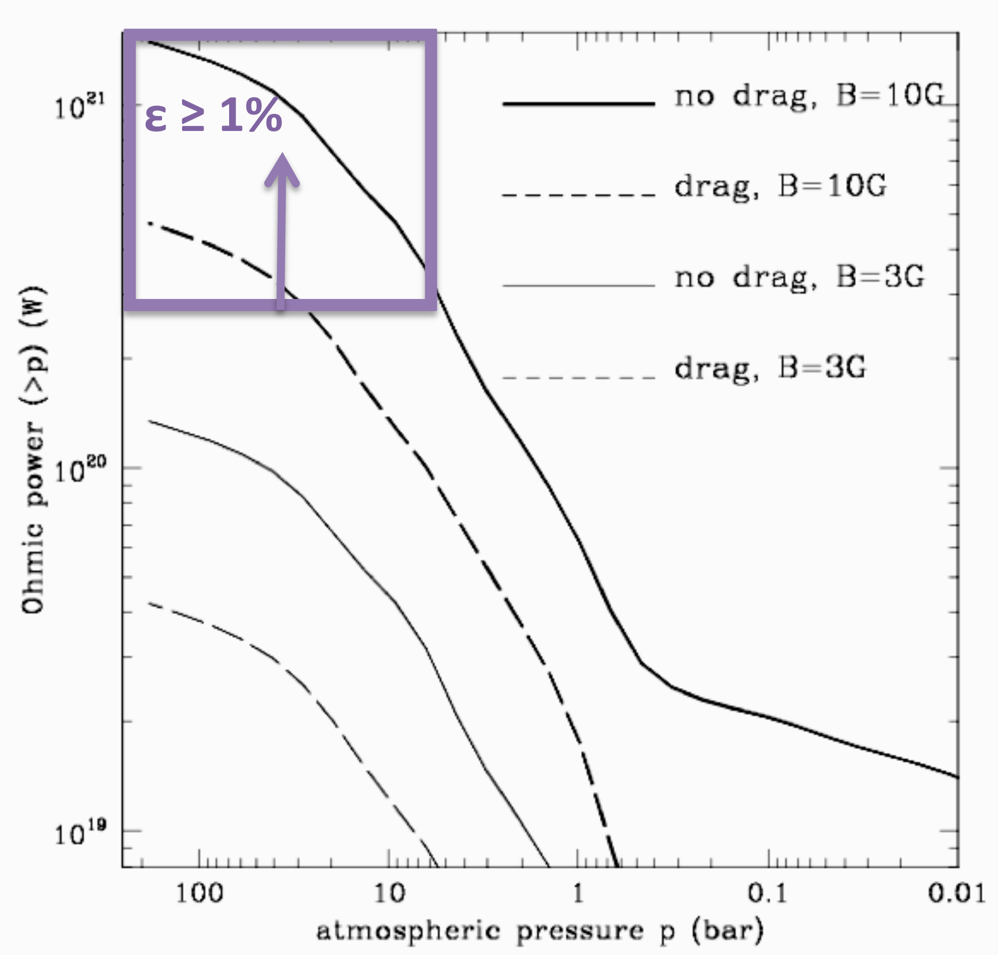
Rauscher & Menou (2011)

Ohmic dissipation and heating

$$Q_J(r,\theta,\phi) = \frac{[j_\theta(r,\theta,\phi)]^2}{\sigma_e(r,\theta,\phi)}$$

Efficiency: $\varepsilon = \frac{\text{ohmic heating}}{\text{stellar heating}}$

$\varepsilon = \frac{\text{KE lost through drag}}{\text{stellar heating}}$



Perna, Menou, & Rauscher (2010b)

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

Summary: set of related observables

	B = 0 G	B = 3 G	B = 10 G	B = 30 G
Ohmic heating efficiency, ε	0%	0.6%	3%	*60%*
Longitude of hotspot	12°	11°	7°	2°
Blueshift of transmission lines	2 km/s			1 km/s

caveat: these numbers will change for more complex (complete) models

As the strength of the magnetic field ↑:

↑ the amount of ohmic heating and radius inflation

↓ the longitude of the hotspot and offset in the phase curve

↓ the wind speeds (constrained by transmission spectra?)

… but not without limit.

Kempton & Rauscher (2011), Rauscher & Menou (2011)