Magnetically Driven Circulation and Hotspot Shift on Tidally-locked Hot Jupiters

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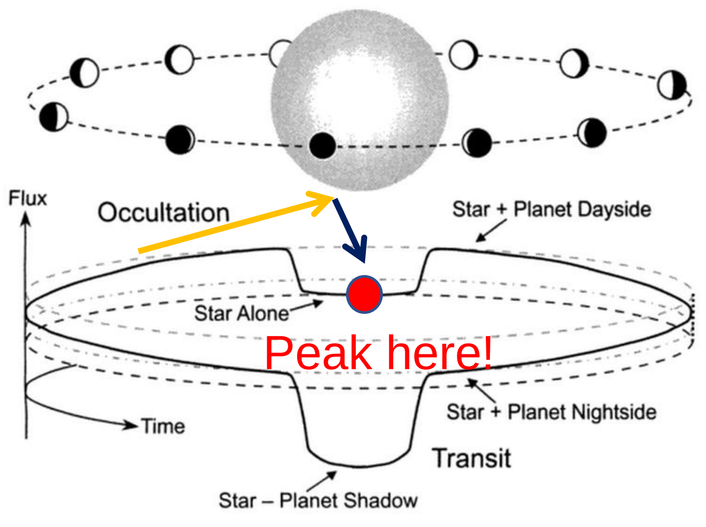
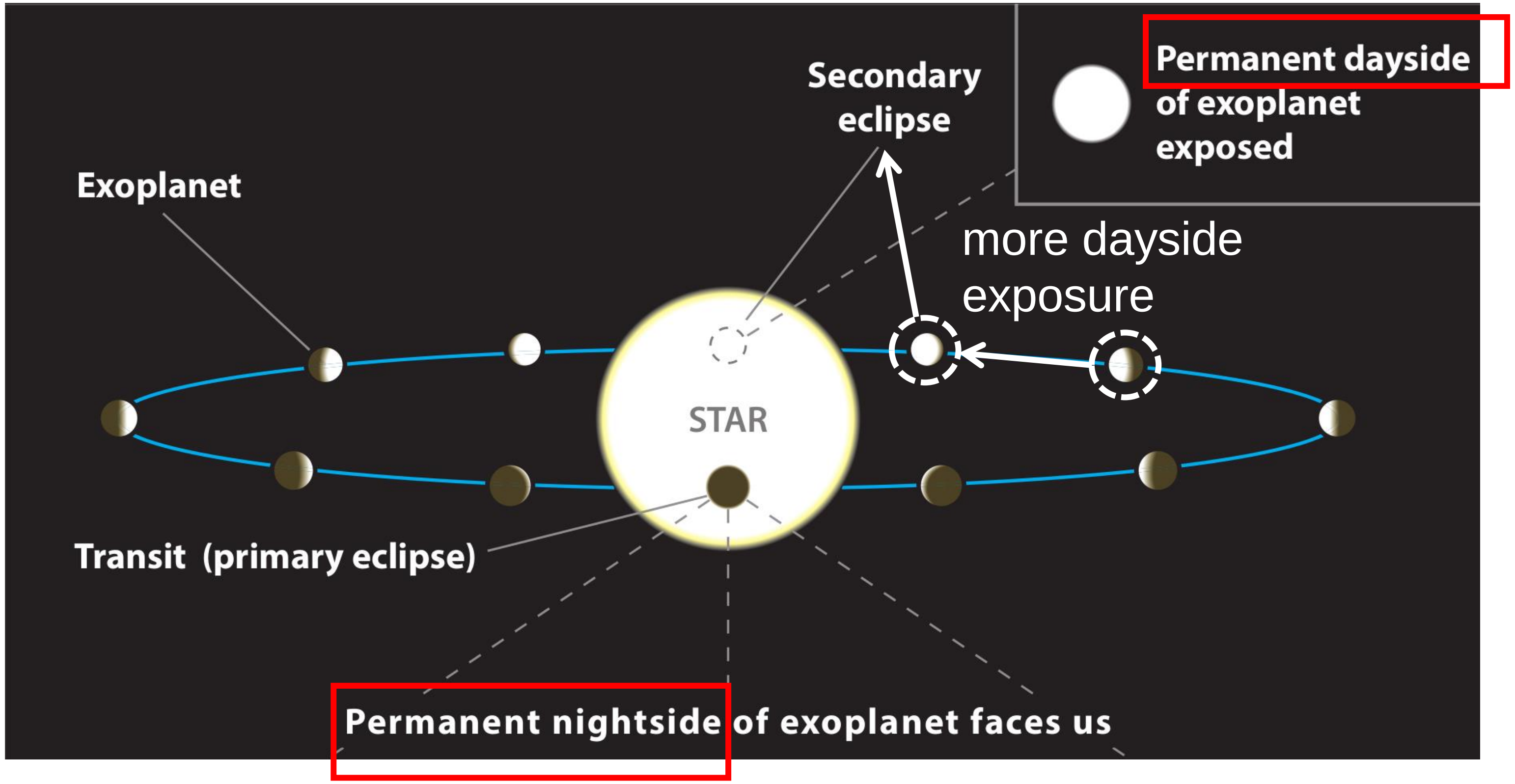
2021/04/16

Tidally-locked Hot Jupiters and Transit Method



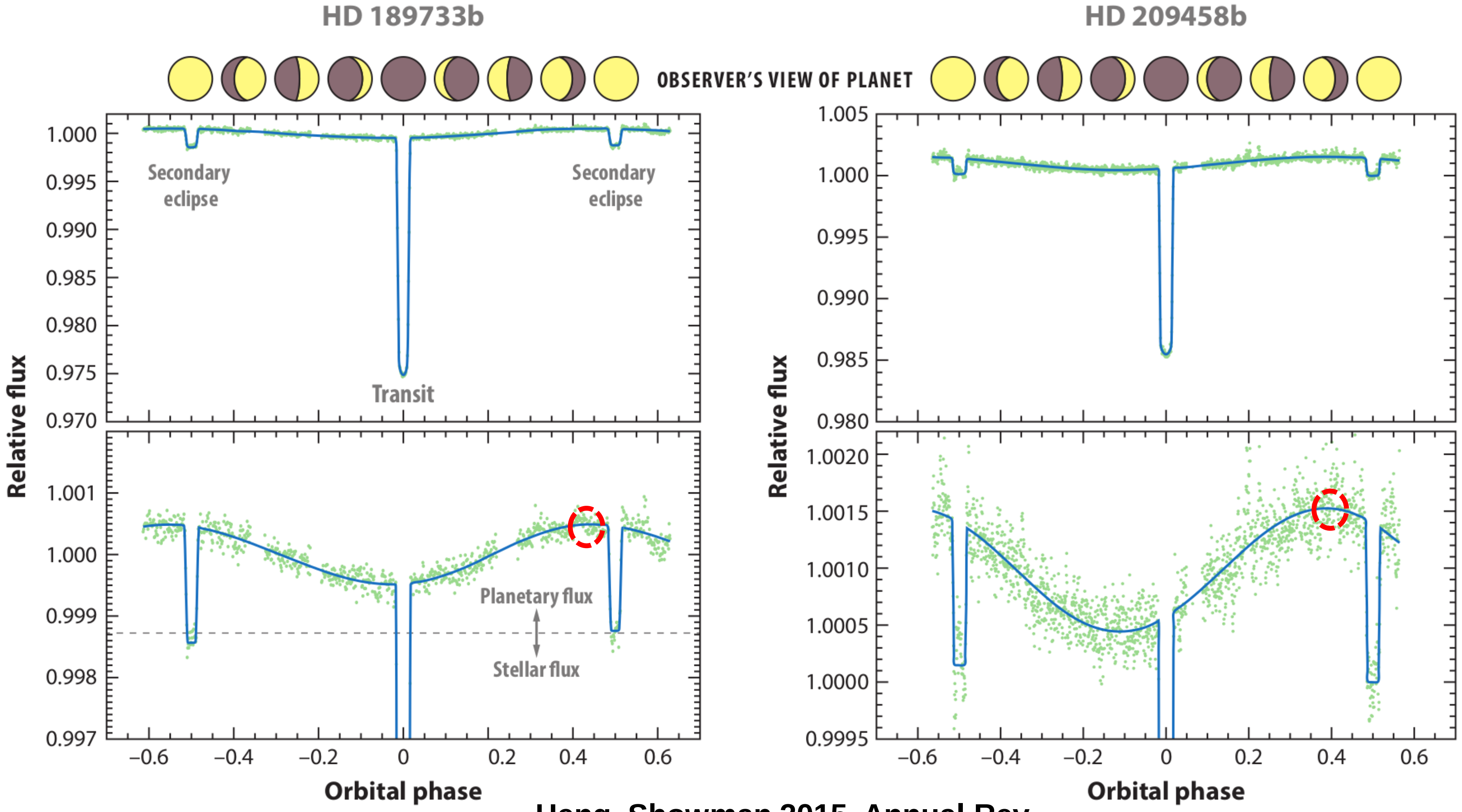
astrobites.org



Heng, Showman 2015, Annual Rev

If we assume a tidally-locked planet with rocky, dry surface, then the brightest place (**hotspot**) on it should the position where sun shines directly (**Substellar Point**), which means from light curve we should find planet's flux's peak **concide** with the Secondary eclipse.

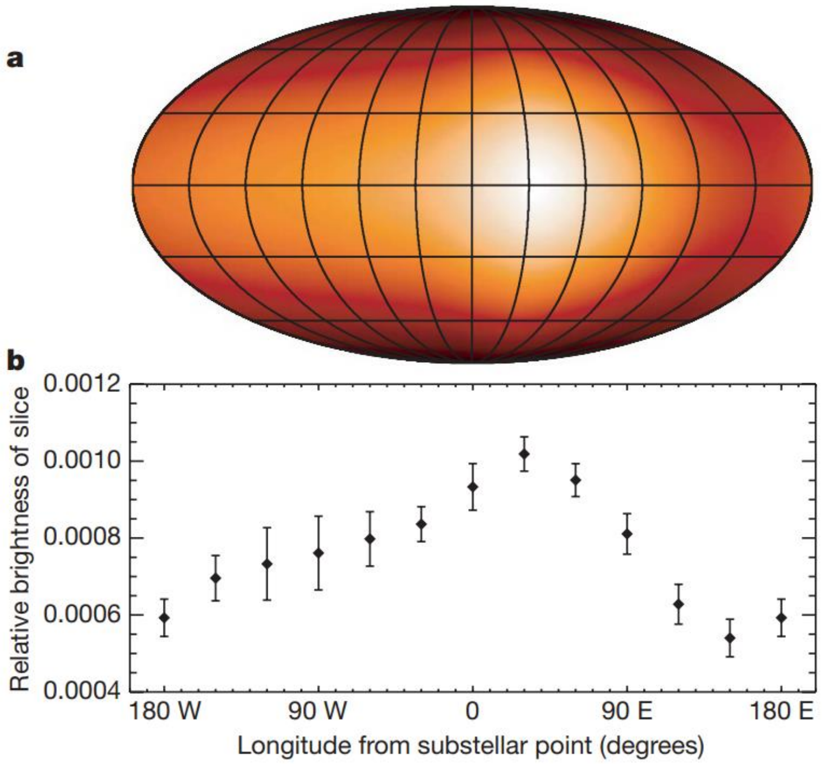
Phase Curve of 2 HJs



Heng, Showman 2015, Annual Rev

Flux's peak position is ealier than the secondary eclipse. ->hotspot not at substellar point

HJ Atmosphere & Eastward Hotspot



Knutson et.al 2007, nature
2D temperature mapping of HD 189733b's atmosphere. Hotspot is shifted **eastward** of the substellar point

What causes this feature?
Why in solar Jupiter we don't have this?

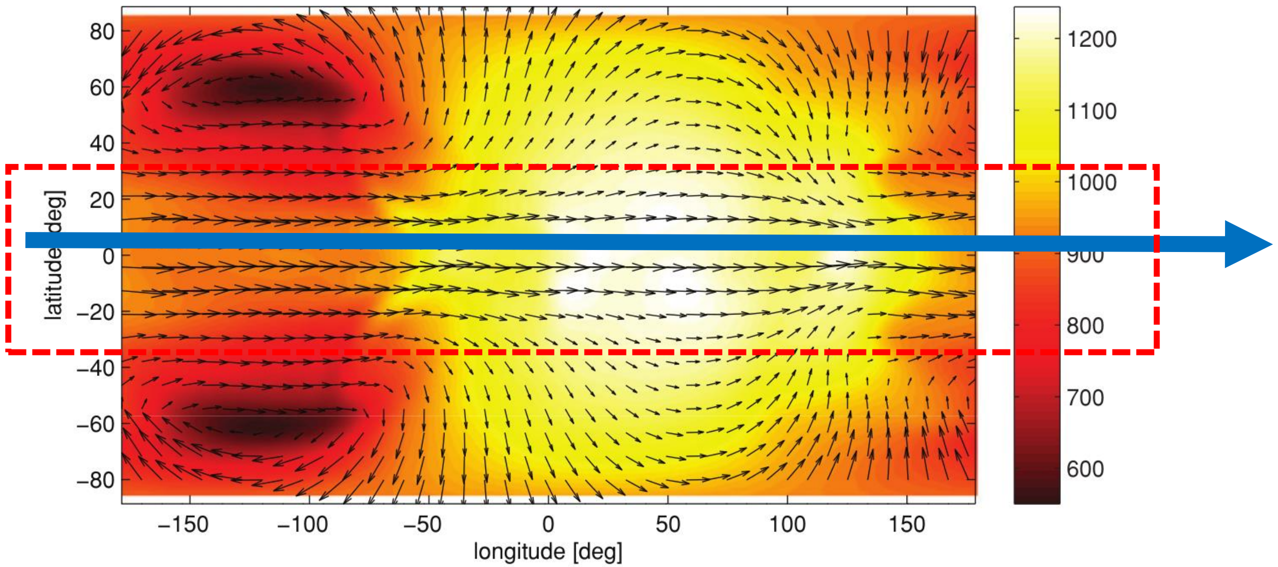
- ☐ Rotation
  Due to tidal damping, Hot jupiter rotates much slower.....
  Jupiter: 10 hrs / Hot Jupiter: 3-5 days

- ☐ Intense Day-Night heating gradient
  Equator-pole heating gradient much dominating in solar system planets.

- ~~☐ Internal heating~~
  ~~Comparable to stellar irradiation on Jupiter, but tiny on Hot Jupiter.~~

- ☐ Highly-irradiated
  ~100 k on Jupiter, ~ 2000K on Hot Jupiter.
  Potentially ionized atmosphere.

Superrotation



showman et.al 2009, ApJ
GCM simulation of HD 189733b's atmosphere

A **common feature** in all simulations:

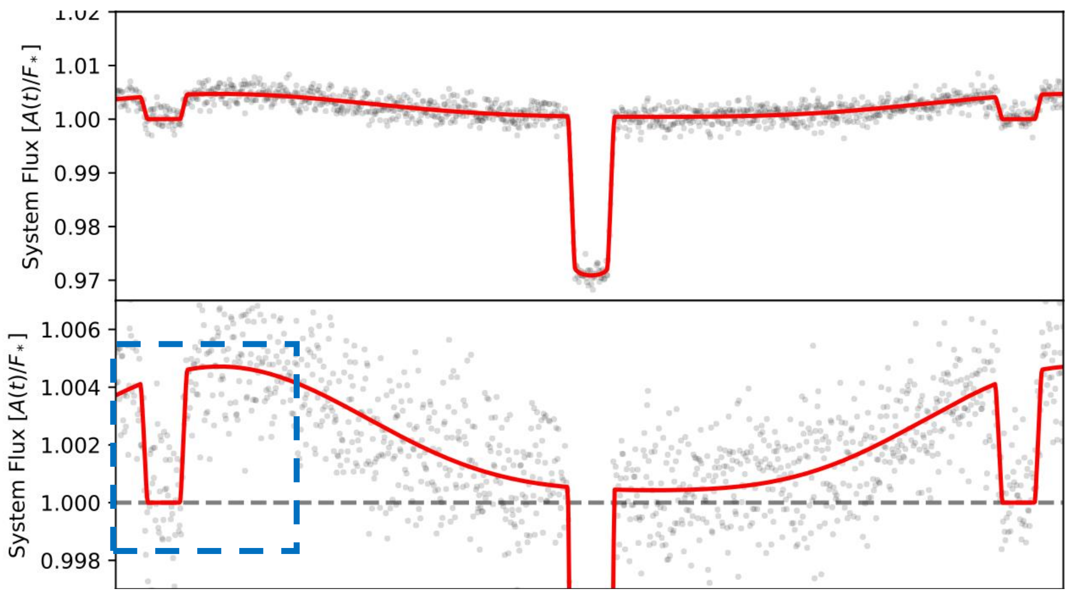
eastward hotspot together with a strong eastward equatorial **zonal wind,** we call it **Superrotation.**

Also been observed in HD209458b ~ 2km/s (ref: Snellen et al.2010)

Do all hot Jupiters have an eastward hotspot and eastward equatorial superrotation?

No

Westward Hotspot: Diversity



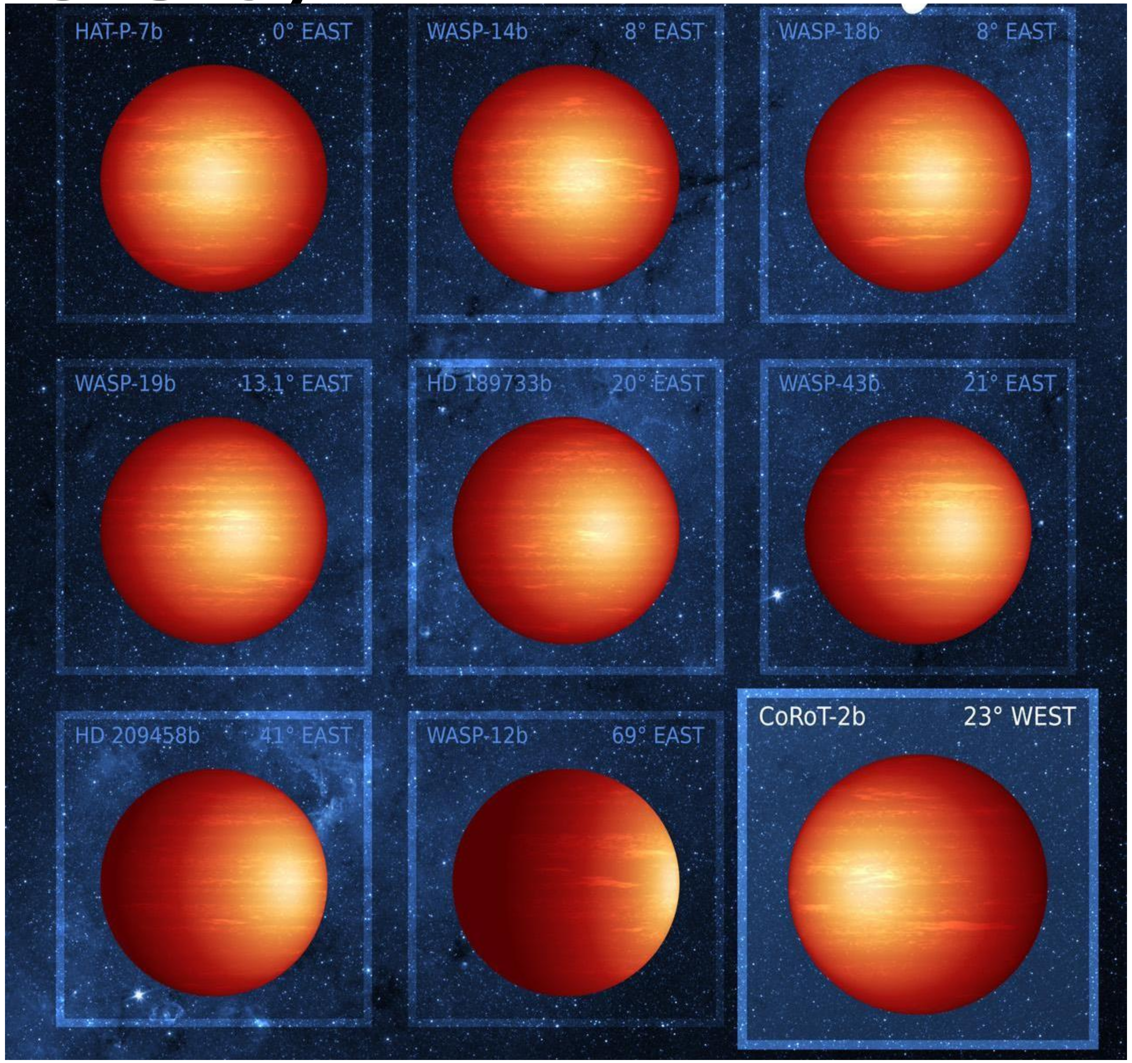
Lisa Dang et. al, 2018, Nature astro.

Phase curve peaks **after** the secondary eclipse.

-> Westward hotspot.

Why? New mechanism?

Published results



Lisa Dang, Future of Space Astronomy in Canada, Nov 6-7 2018 Université de Montréal, QC

Westward Hotspot: Implications

Possible explanations:

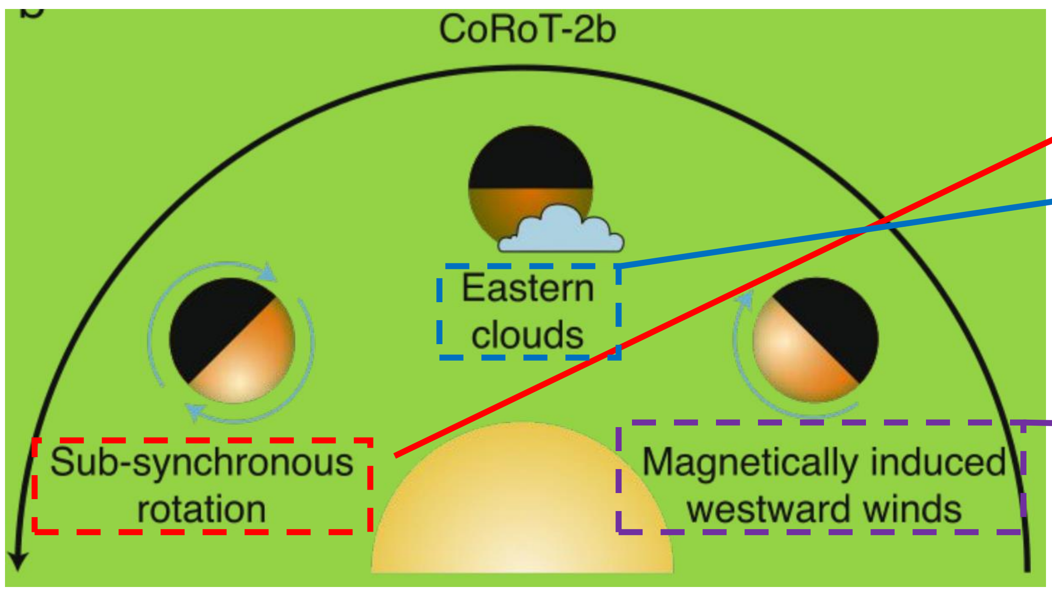


Illustration from Barstow (2018), Lisa Dang

Not totally tidally locked:
Frequent planet-star angular momentum exchange?Why? Wrong understanding of tidally locked timescale?

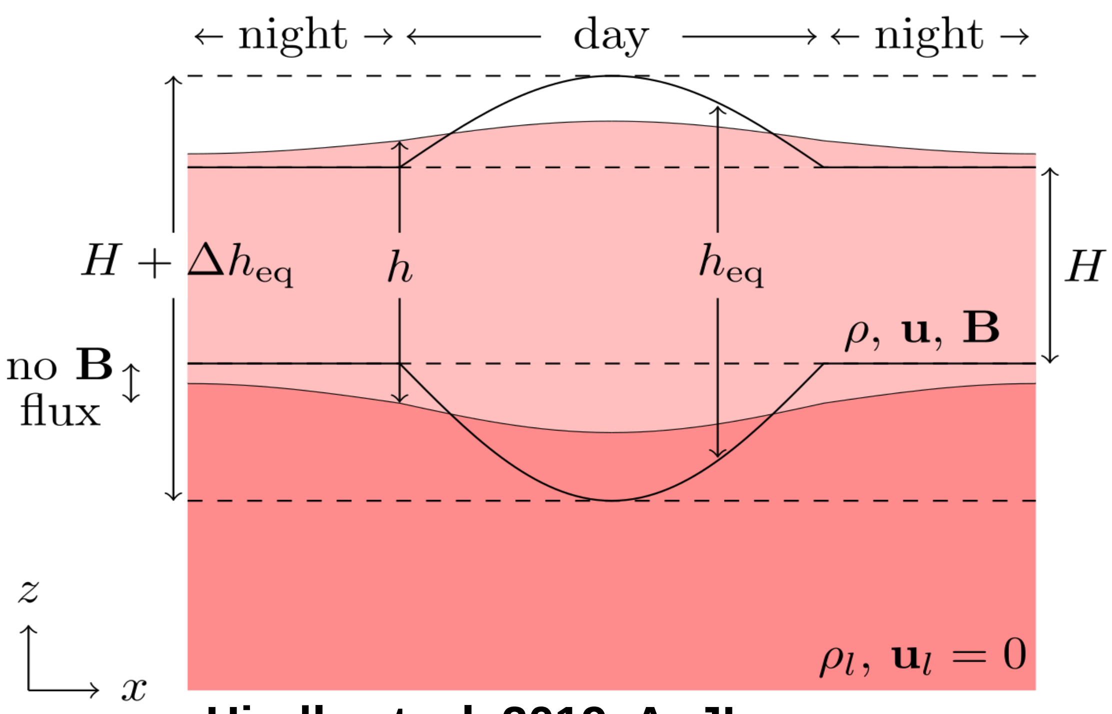
Formation mechanism? What's the impact on obeservations?

Magentically driven westward wind, unknown mechanism.

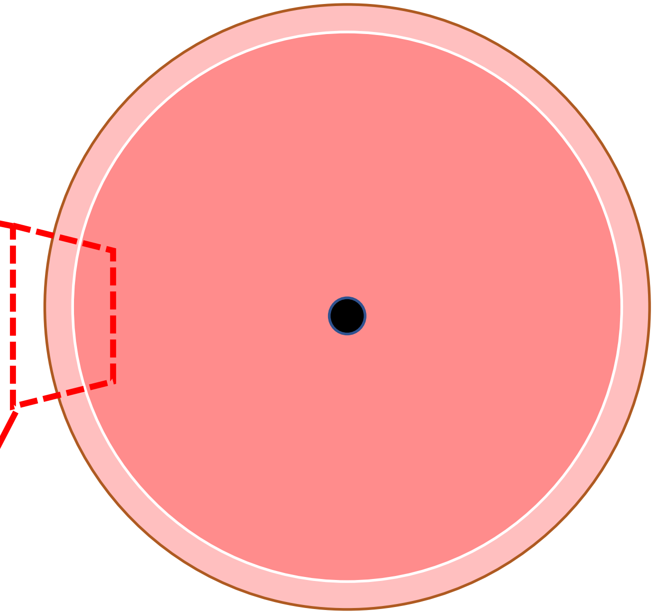
High irradiation implies weekly ionized atmosphere.

What we are interested in.

Simplified Model



Hindle et. al, 2019, ApJL



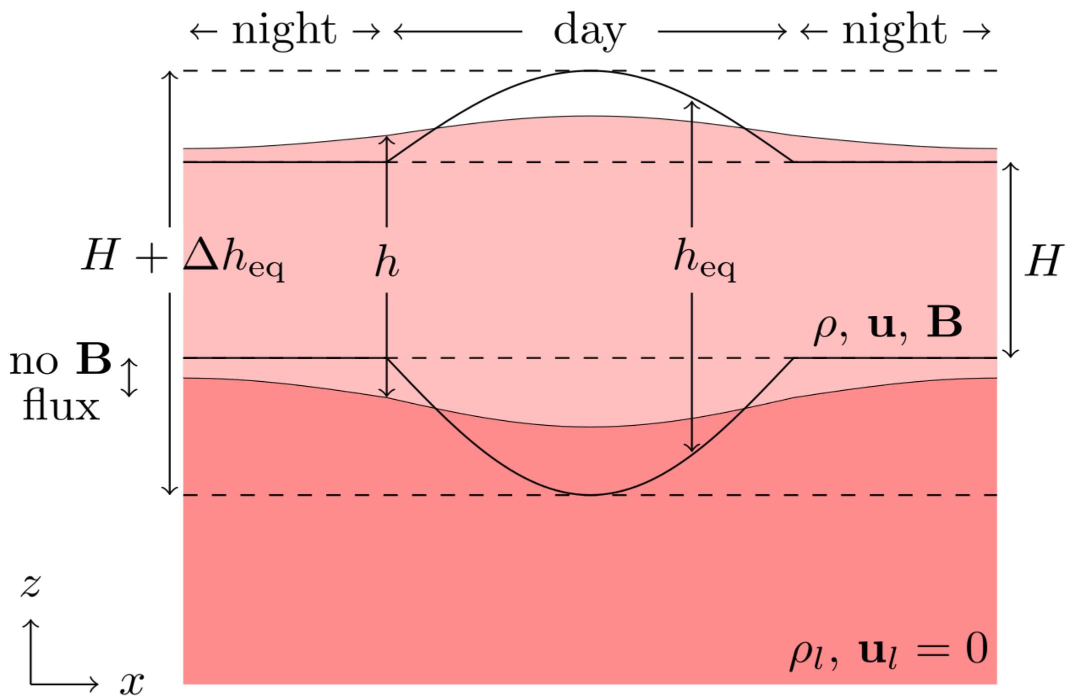
Pink: shallow, active upper layer

Red: deep, quiescent lower layer

- Each layer has a constant density.
- Magnetic field can not go across the layer surface.

Horizontal scale **>>** vertical scale -> neglecting vertical variations -> column-integrated Euler equations -> 2D shallow water equation

Shallow water approximation



Hindle et. al, 2019, ApJL

Vertical momentum transport

Magnetic tension

Drag term

Coriolis

$$\frac{d\mathbf{v}}{dt} + g\nabla h + f\mathbf{k}\times\mathbf{v} = \mathbf{R} - \frac{\mathbf{v}}{\tau_{\rm drag}} + (\mathbf{B}\cdot\nabla)\mathbf{B}$$

$$\frac{\partial h}{\partial t} + \nabla\cdot(\mathbf{v}h) = \frac{h_{\rm eq}(\lambda,\phi) - h}{\tau_{\rm rad}} \equiv Q,$$

Newtonian relaxation type Thermal forcing

- All quantities 2D. e.g. h(x,y)
- h: Water Height ~ Pressure strength. (P ~ ρgh) ~ to mimic Temperature
- h_{eq}: Guassian / Cosine type. To mimic radiation equilibrium temperature.

Hydrodynamic Mechanism: Free Waves

$$\frac{d\mathbf{v}}{dt} + g\nabla h + f\mathbf{k}\times\mathbf{v} = \mathbf{R} - \frac{\mathbf{v}}{\tau_{\mathrm{drag}}}$$

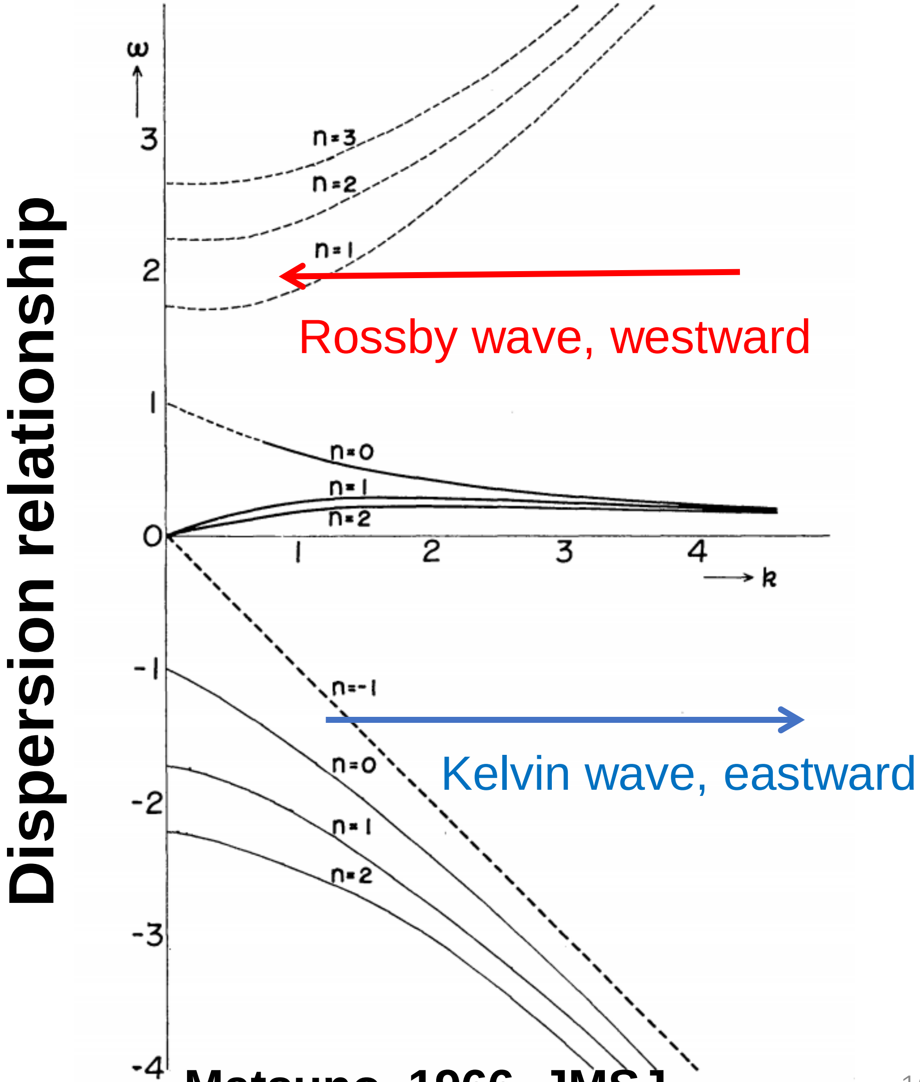
$$\frac{\partial h}{\partial t} + \nabla\cdot(\mathbf{v}h) = \frac{h_{\mathrm{eq}}(\lambda,\phi) - h}{\tau_{\mathrm{rad}}} \equiv Q,$$

W/O thermal forcing, free system, we can do perturbations to gain wave modes.

e.g., $h = H + \eta\exp[\mathrm{i}(\omega t + kx)]$

➡ dispersion relationship

$$\omega^2 - k^2 + \frac{k}{\omega} = 2n+1 \quad (n=0,\ 1,\ 2,\ \ldots)$$



Matsuno, 1966, JMSJ

HD Mechanism: Forced solution

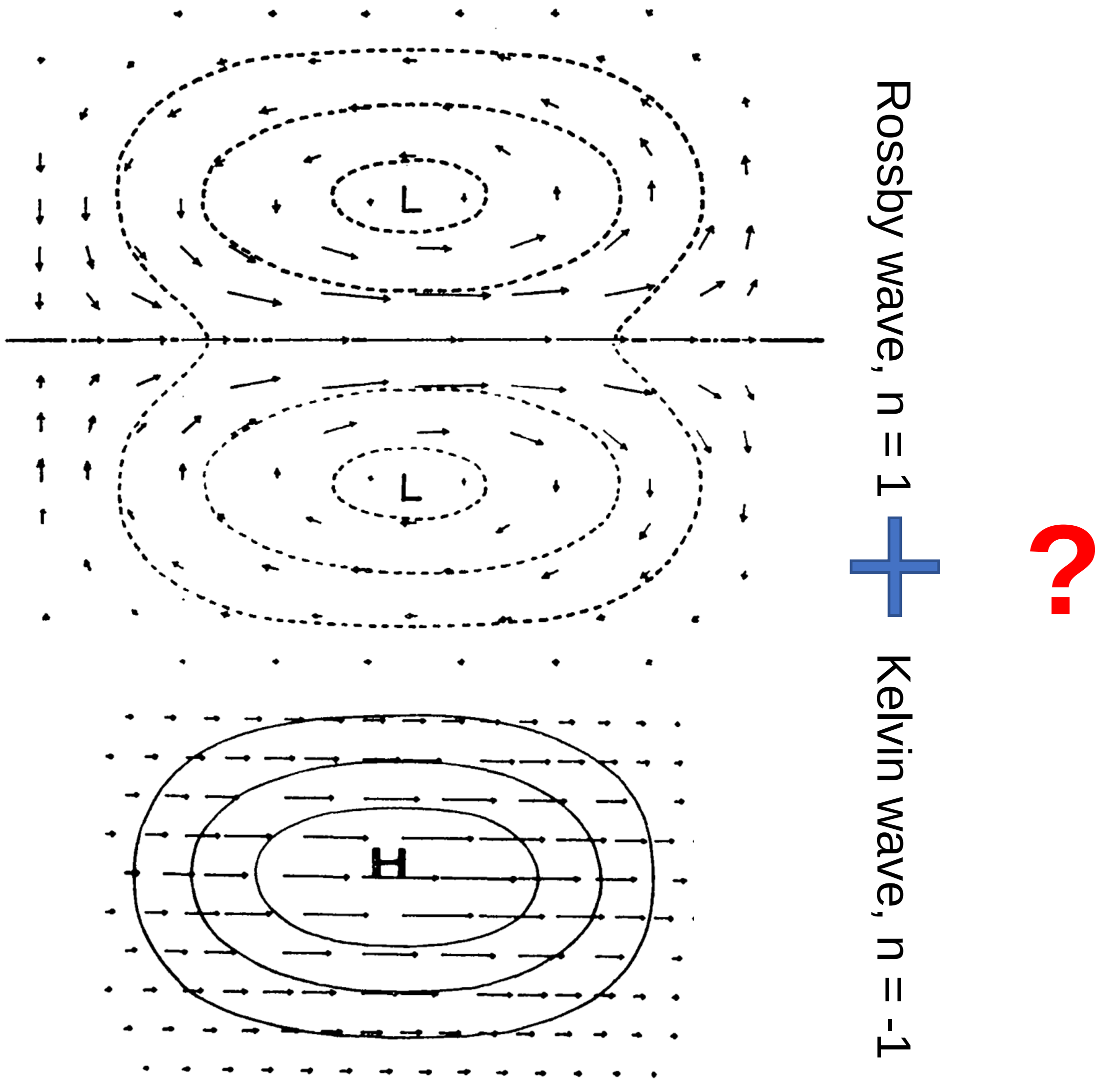
$$\frac{d\mathbf{v}}{dt} + g\nabla h + f\mathbf{k}\times\mathbf{v} = \mathbf{R} - \frac{\mathbf{v}}{\tau_{\text{drag}}}$$

$$\frac{\partial h}{\partial t} + \nabla\cdot(\mathbf{v}h) = \frac{h_{\text{eq}}(\lambda,\phi) - h}{\tau_{\text{rad}}} \equiv Q,$$

With thermal forcing, forced system, **We solve for steady state** of the perturbation.

Forced solution can be expanded by free wave modes.

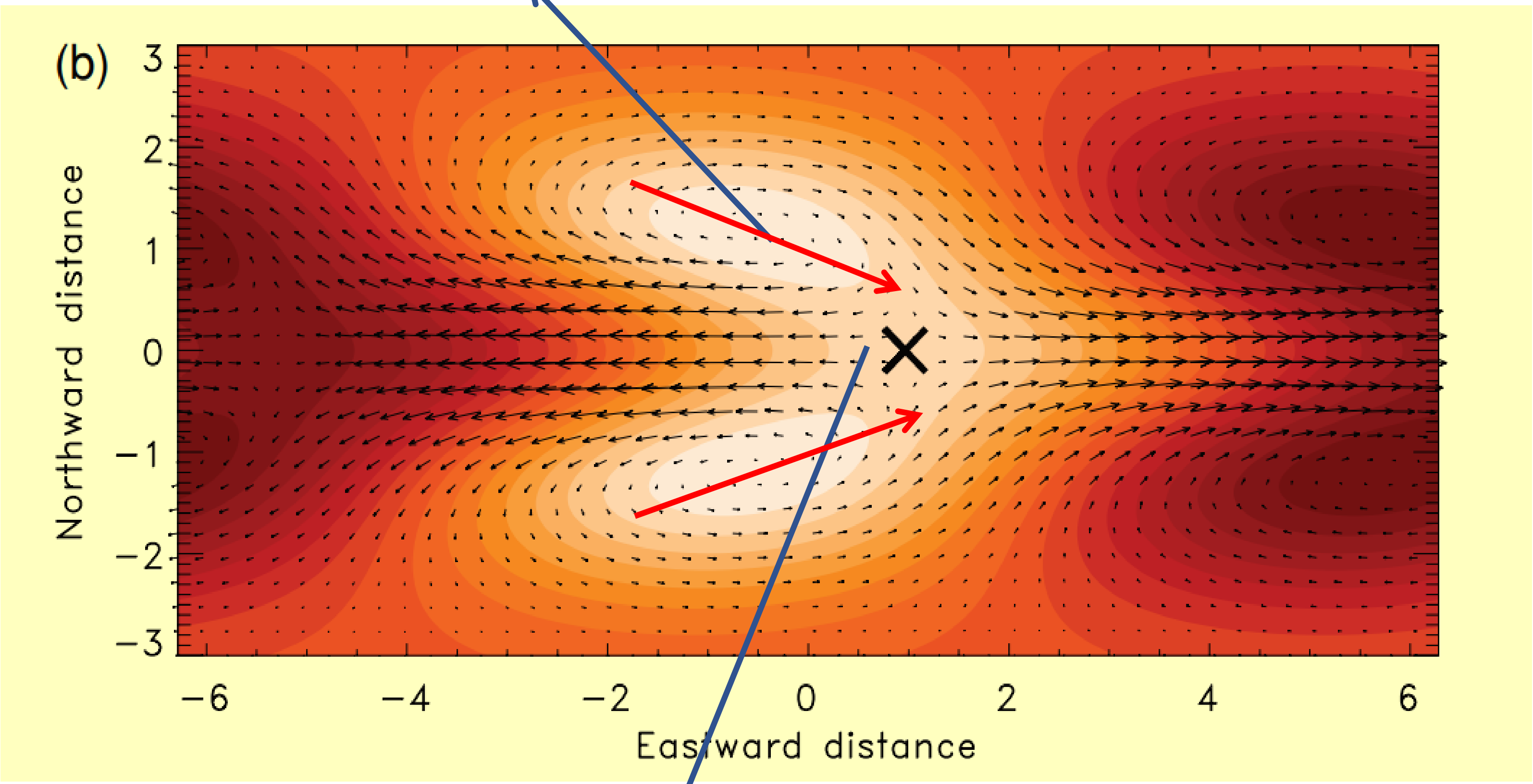
On Hot Jupiters, driving force is the intense day-night heating gradient.



Matsuno, 1966, JMSJ

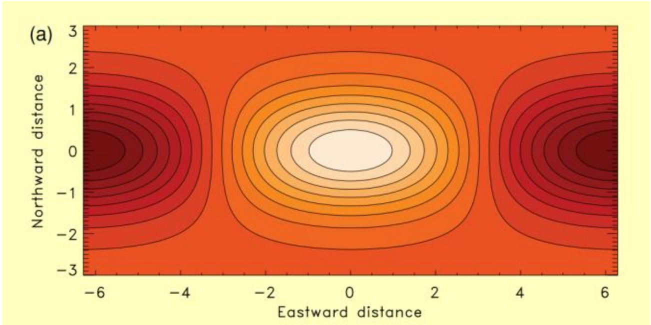
HD Mechanism: Momentum transport

Westward propagating Rossby wave



Showman & Polvani, 2011, ApJ

Eastward propagating Kelvin wave → eastward hotspot



Guassian thermal forcing

Velocity Tilting

↓

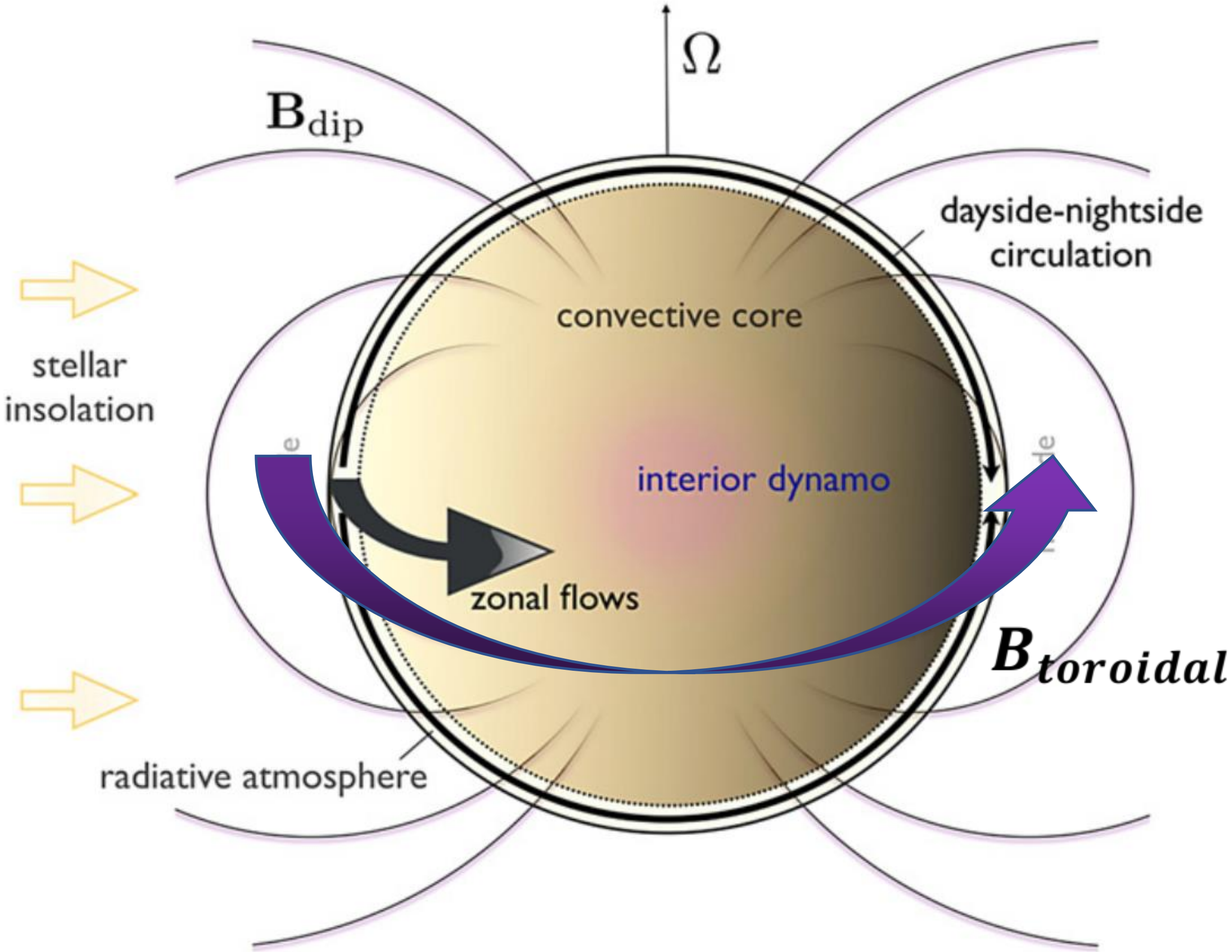
Momentum tranport from high latitude to equator

↓

Superrotation

Magnetohydrodynamic: Magnetic field

An analogy to solar Jupiter.



Batygin, 2013, ApJ

Deep-seated dynamo in Hot Jupiters, which contributes to a dipole magnetic field.

⬇

Strong Zonal flow interacts with the dipole magnetic field.

⬇

Induce another toroidal magnetic field

$$\boldsymbol{B_{toroidal}} \propto \boldsymbol{cos\theta sin\theta}$$

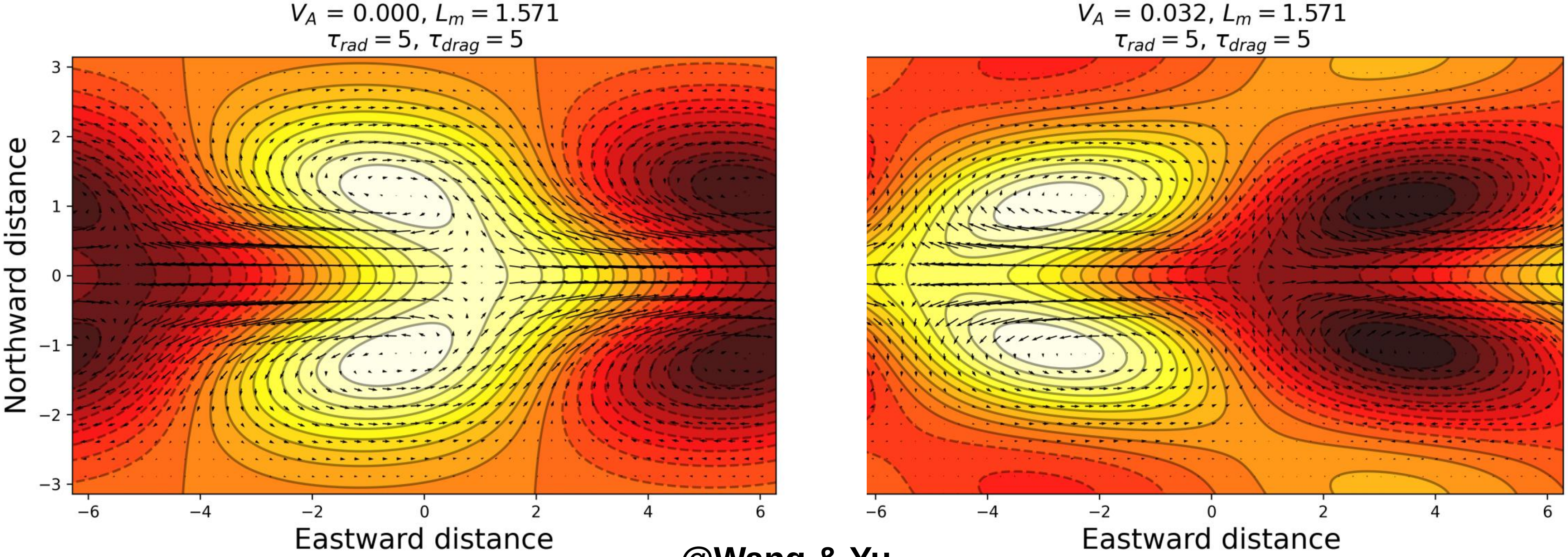
$\boldsymbol{B_{toroidal}} \gg \boldsymbol{B_{dip}}$ when temperature is sufficiently high (>1600K)

⬇

What we use in practice:

$$B_y = 0$$
$$B_{x0} = e^{1/2} V_A \frac{y}{L_m} e^{-y^2/2L_m^2}$$

MHD: result



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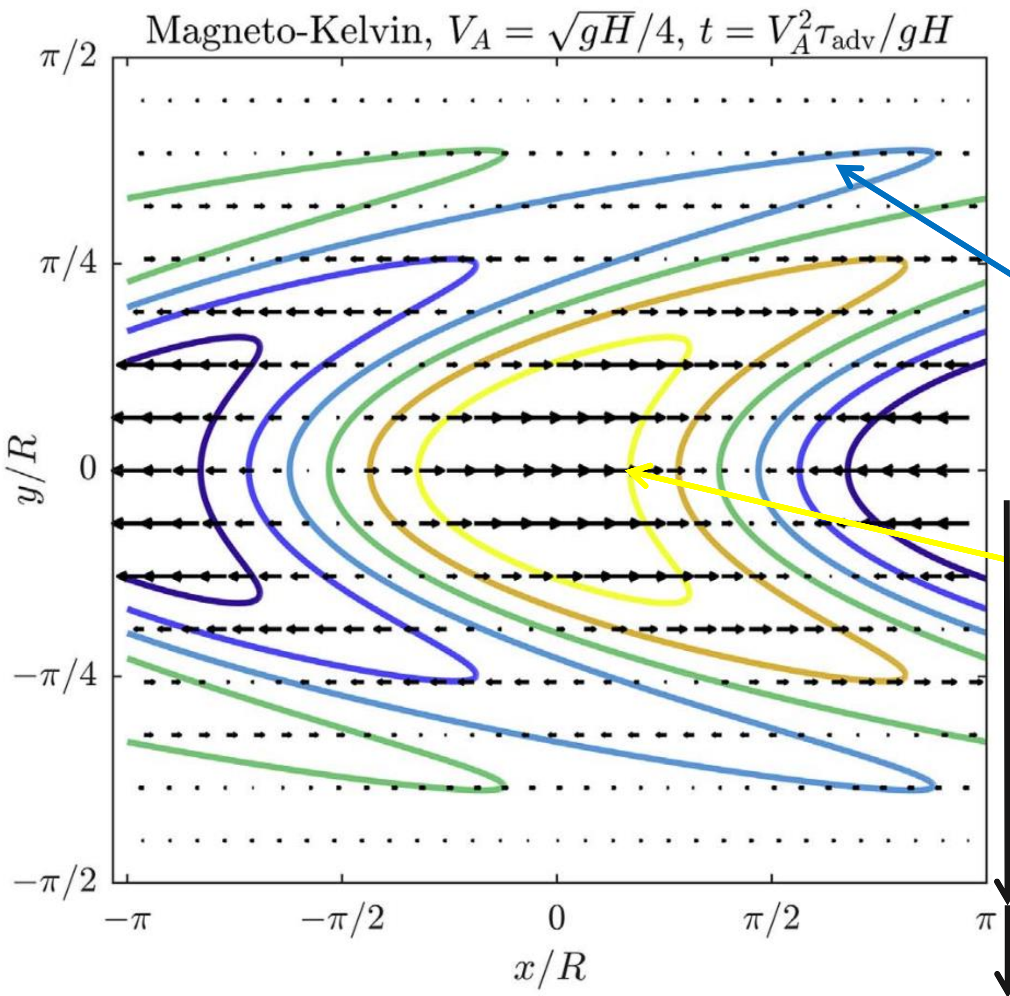
$$B_y = 0$$
$$B_{x0} = e^{1/2} V_A \frac{y}{L_m} e^{-y^2/2L_m^2}$$

Variable:
V_A: Alfven speed, the strength of magnetic field
L_m: the scale of the magnetic field

MHD: Deformed Kelvin wave



Hindle et.al, 2019, ApJL

Magnetic field modifies the dispersion relationship

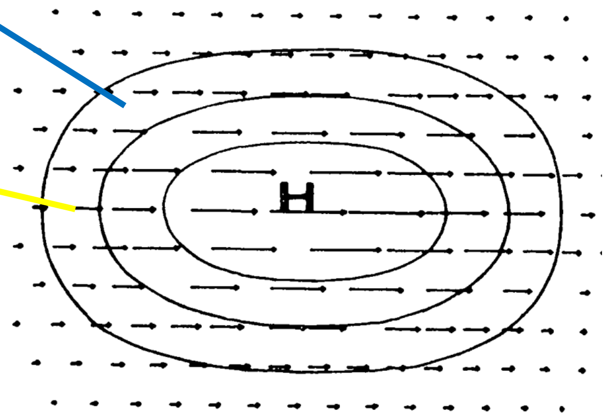
$$\omega = \sqrt{c^2 + v_{A0}^2 \frac{y^2}{R^2}}\, k_x$$

y dependency

Zaqarashvili, 2018, ApJ

Move faster

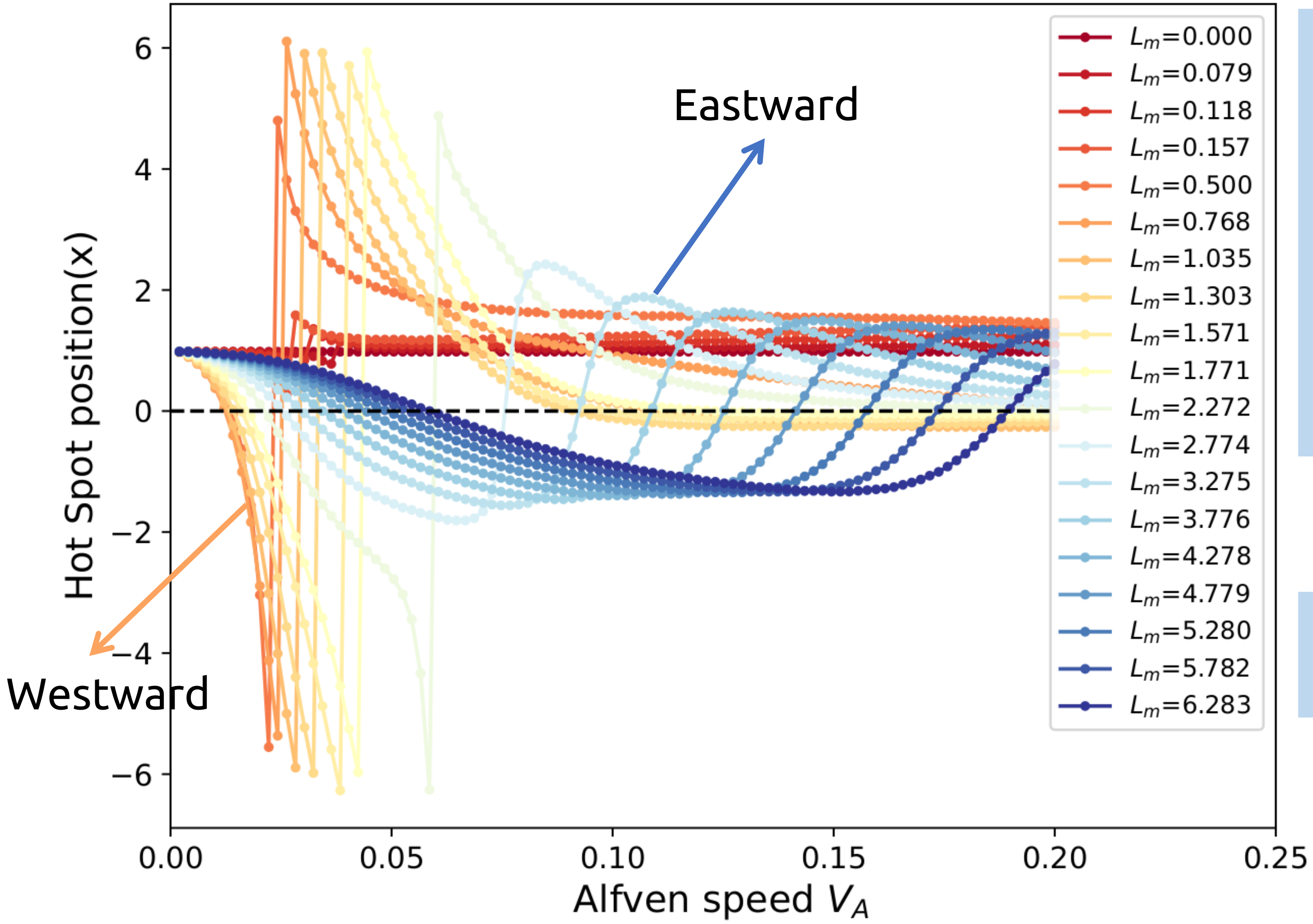
Move slower



Deformed tilting (Northeast - Southwest)

Reversal of wind direction

MHD: Parameter dependency



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Red curve region:
L_m too small, no westward shift ~ Purely HD case

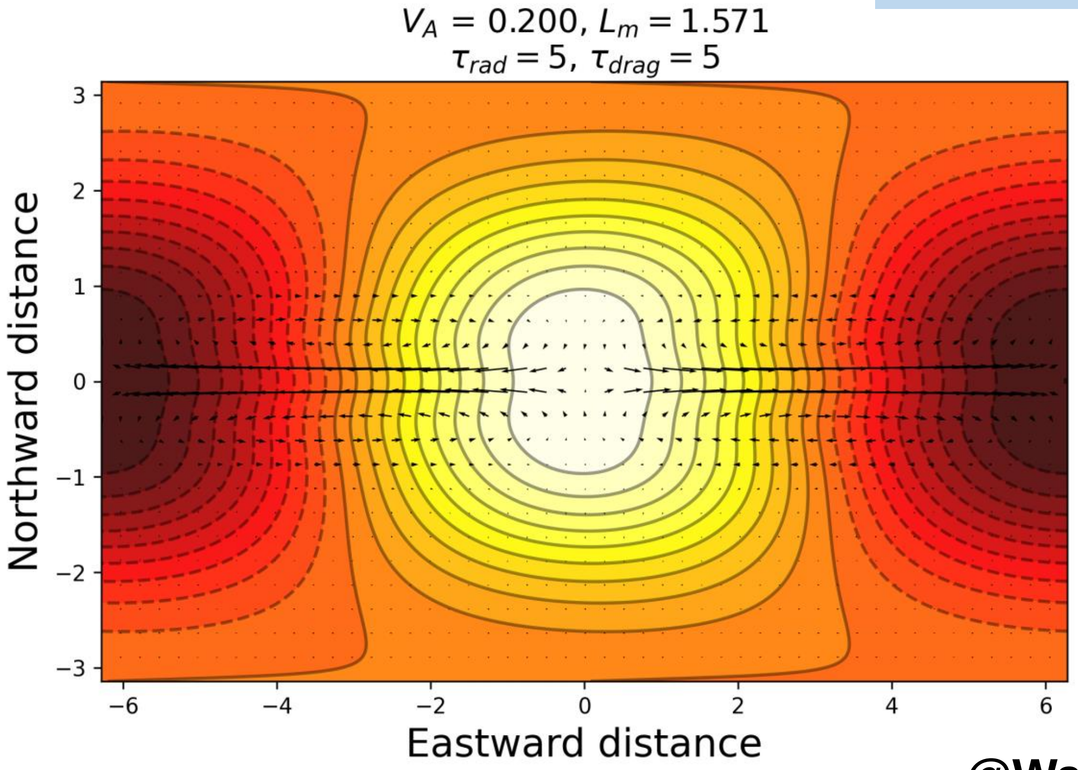
Yellow and Blue curve region:
L_m moderate, westward shift when V_A moderate, eastward shift when V_A very strong

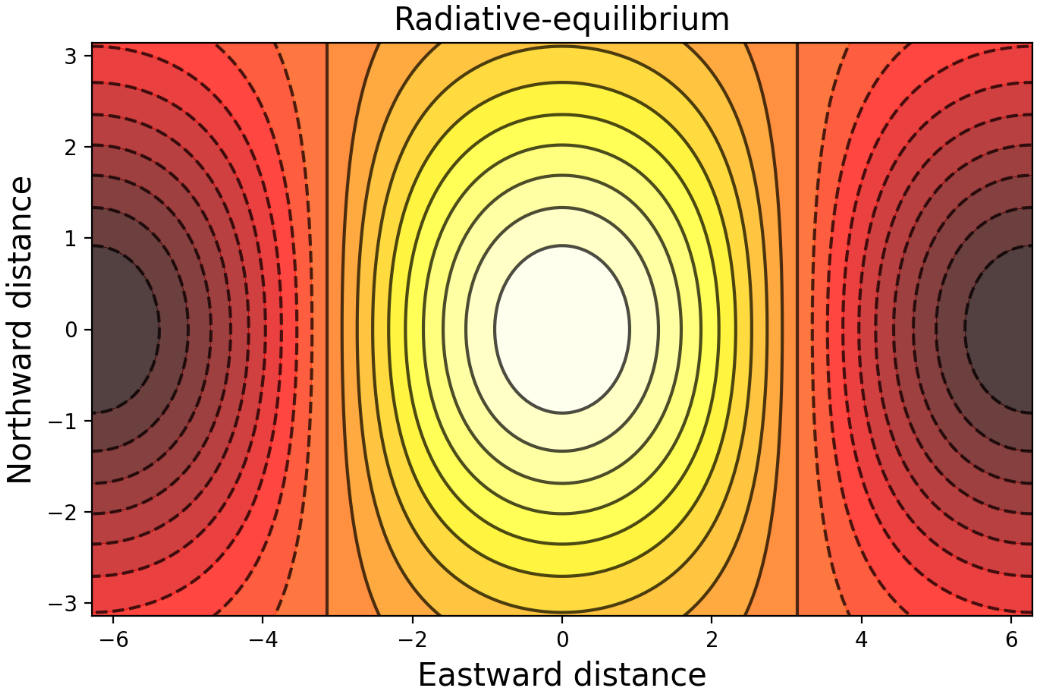
Weak magnetic field:
Deformed Kelvin wave reverse the wind.

MHD: Parameter dependency

Strong magnetic field:
Magnetic drag dominate, waves can hardly propagate. → approach radiative-equilibrium pattern

Hotspots don't really shift.





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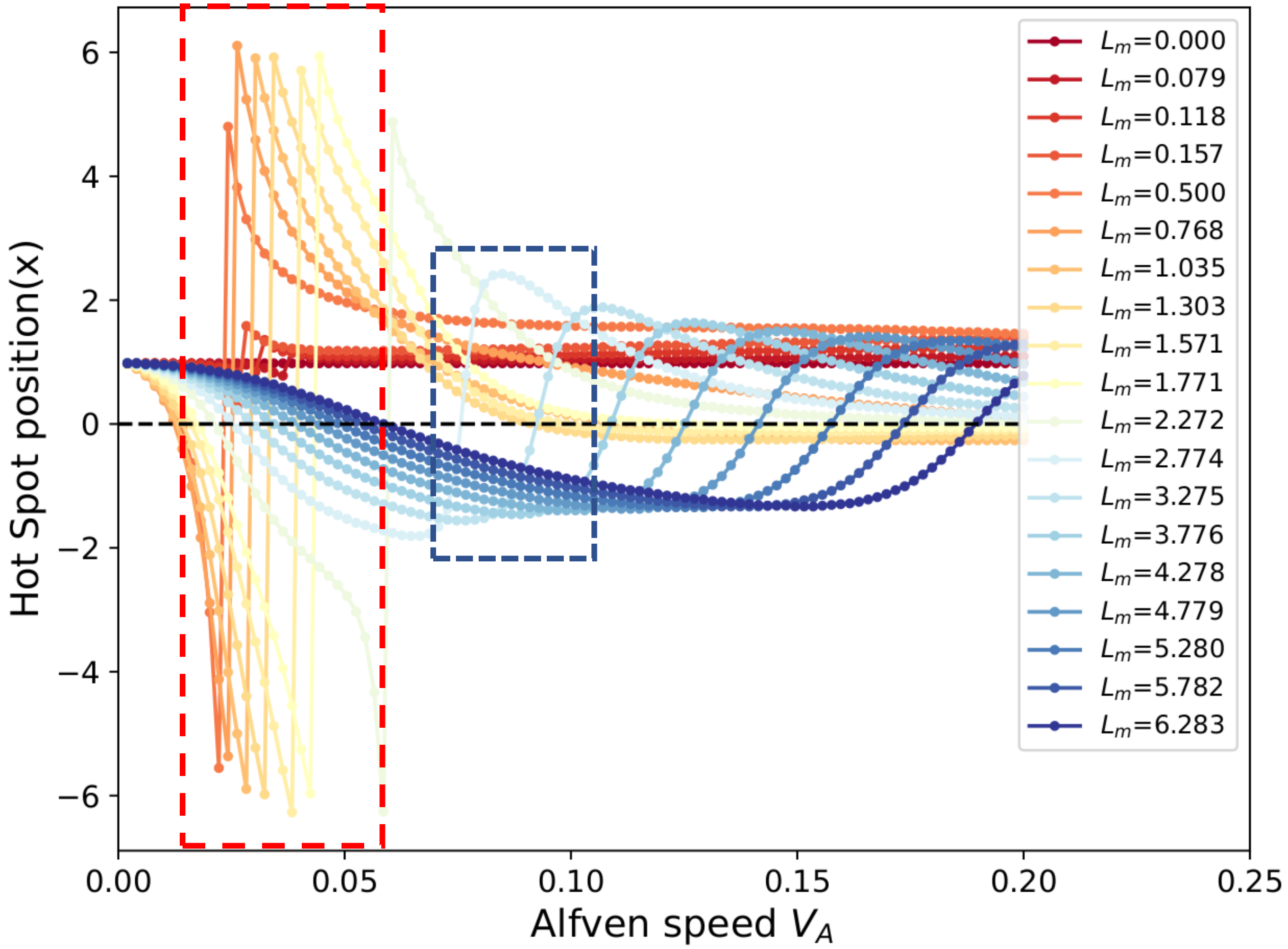
MHD: Parameter dependency



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Rapid transition in hotspot position, Why?

Unknown yet...

Possible idea:
Dominate wave mode jumps.

Open to any ideas!

Future work

- Try to explain the mechanism from wave mode spliting.

- We don’t consider the impact that equatorial zonal flow may react on waves in turn. (wave-mean flow interaction.) Linking the mean flow to the strength of magnetic field would give a more realistic scenario. (Ref: Hammond 2018, wave-mean; Menou 2012, magnetic scaling law)

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Thanks for listening