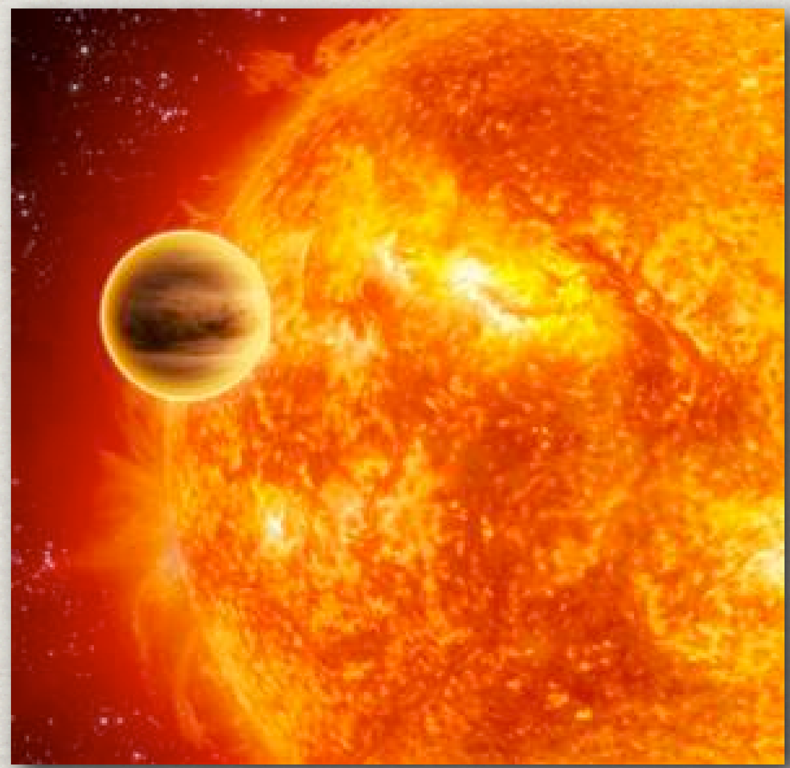
Inflating Hot Jupiters With Ohmic Dissipation



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The Problem

Detection of first transiting planet, HD 209458b

↓

Radius anomaly - planet too puffy
(expect radius to shrink significantly in less than a Gyr)

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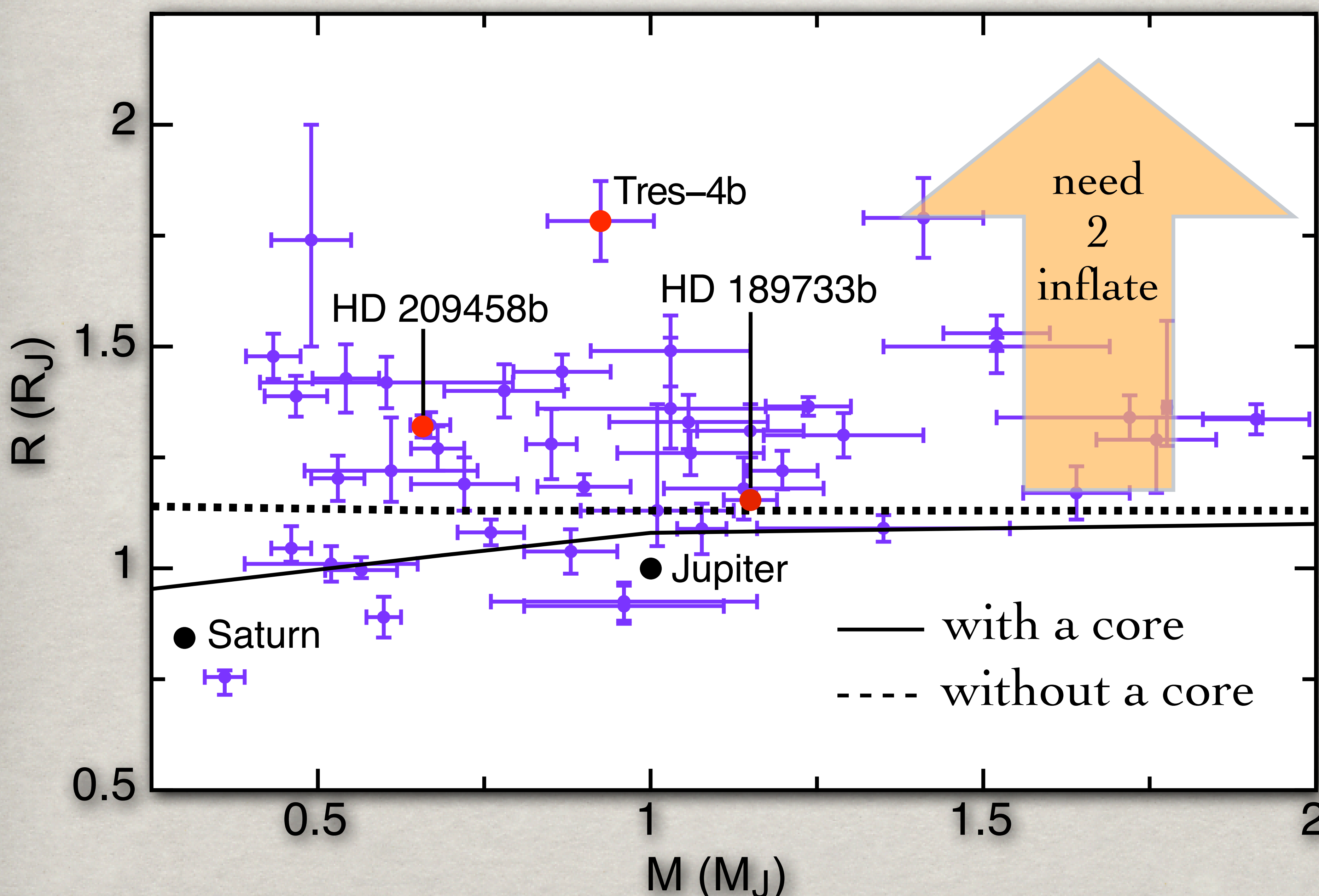
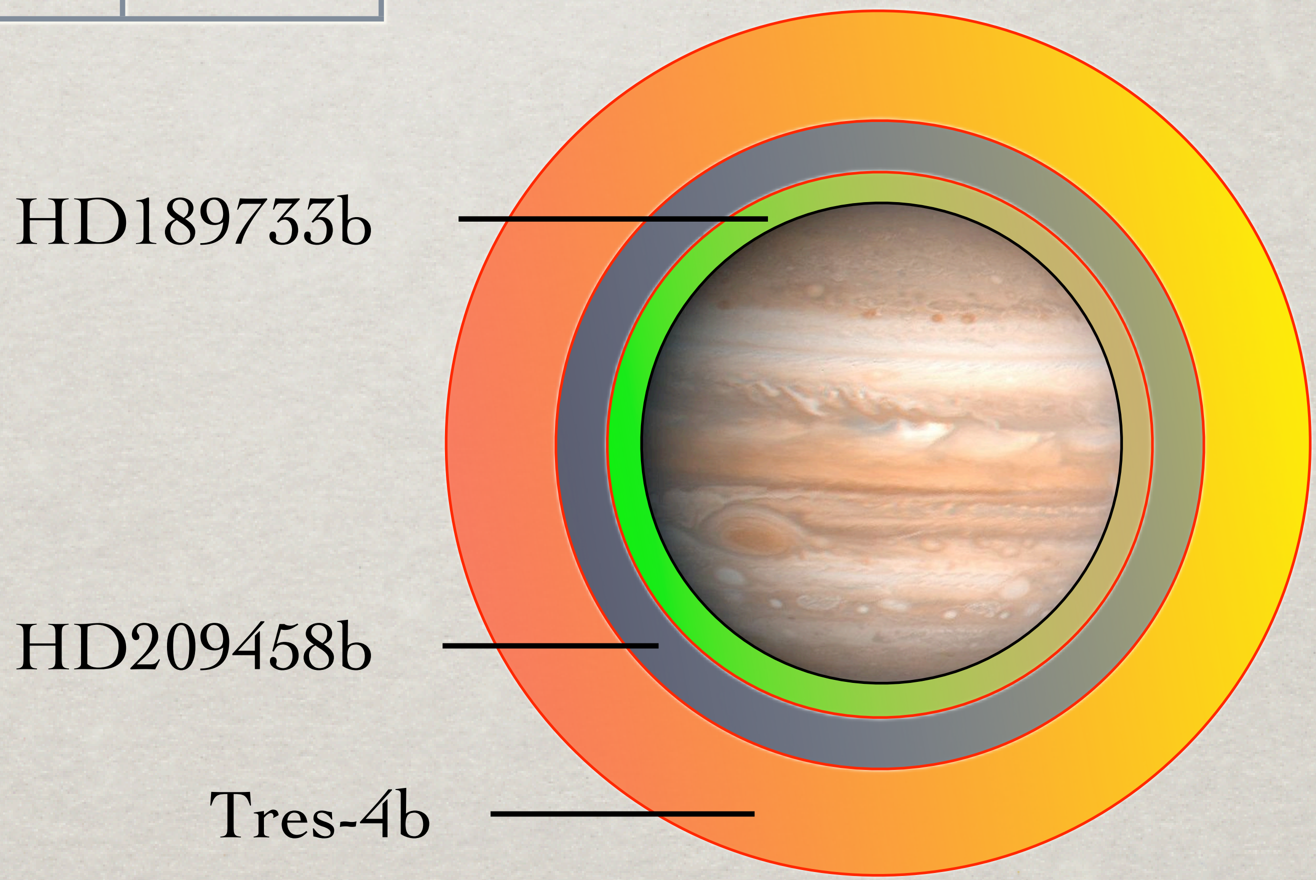
Other transit detections: puffy hot Jupiters are common!
What's going on?

R-M diagram



(Models from Bodenheimer et al 2003)

Planet	R (R_j)	M (M_j)	T_{eff} (K)
HD189733b	1.14	1.13	1117
HD209458b	1.35	0.69	1130
Tres-4b	1.8	0.92	1782



Some Proposed Solutions

I) Current eccentricity tides
(Bodenheimer et al 2001/2003, Mardling 2007, Liu et al 2008)

II) Strong early tidal heating
(Ibgui & Burrows 2009, Miller et al 2009, Laconte et al 2010)

$$\frac{\partial L}{\partial m} = \dot{\epsilon} - T\frac{\partial S}{\partial t}$$

$\dot{\epsilon}$: power per unit mass

m is enclosed mass

III) Breaking gravity waves
(Showman & Guillot 2002, Guillot & Showman 2002)

IV) Enhanced opacity
(Burrows et al 2007)

V) Double diffusive convection
(Chabrier & Baraffe 2007)

etc...

Our Solution

Winds on hot Jupiters are fast (~ few km/s)

+

Atmospheres of hot Jupiters are hot (T > 1500K)

↓

Thermal ionization, which results in electical conductivity + fast wind allows for emf

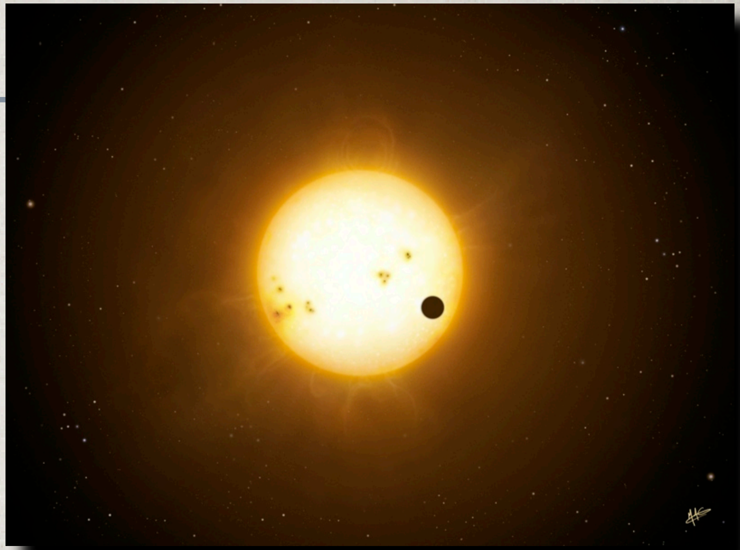
↓

Electrical currents through the interior

↓

Ohmic Dissipation prevents secular cooling and therefore the contraction of the planet.

Outline



The mechanism is generic.

Here, we apply it to HD 209458b, HD189733b, Tres-4b

- Electrical conductivity profile
- Zonal flow and the magnetic field.
- Kinematic MHD model and Ohmic dissipation
- Conclusion, future work

Ionization

Atmosphere: thermal ionization of alkali metals

Interior: thermal and pressure ionization of H and He

$$\frac{n_j^+ n_e}{n_j - n_j^+} = \left(\frac{m_e k_b T}{2\pi\hbar^2}\right)^{\frac{3}{2}} \exp\left(-I_j/k_b T\right)$$

H and He ionizations are given in the Saumon et al (1995) equation of state.

Element	Abundance (f)	I (ev)
Na	$10^{-5.5}$	5.14
K	$10^{-6.5}$	4.34
Li	$10^{-8.5}$	5.39
Rb	$10^{-9.5}$	4.18
Cs	$10^{-10.9}$	3.89
Ca	$10^{-5.5}$	6.11
Ti	10^{-8}	6.83
Cr	10^{-6}	6.77
Fe	$10^{-4.2}$	7.9

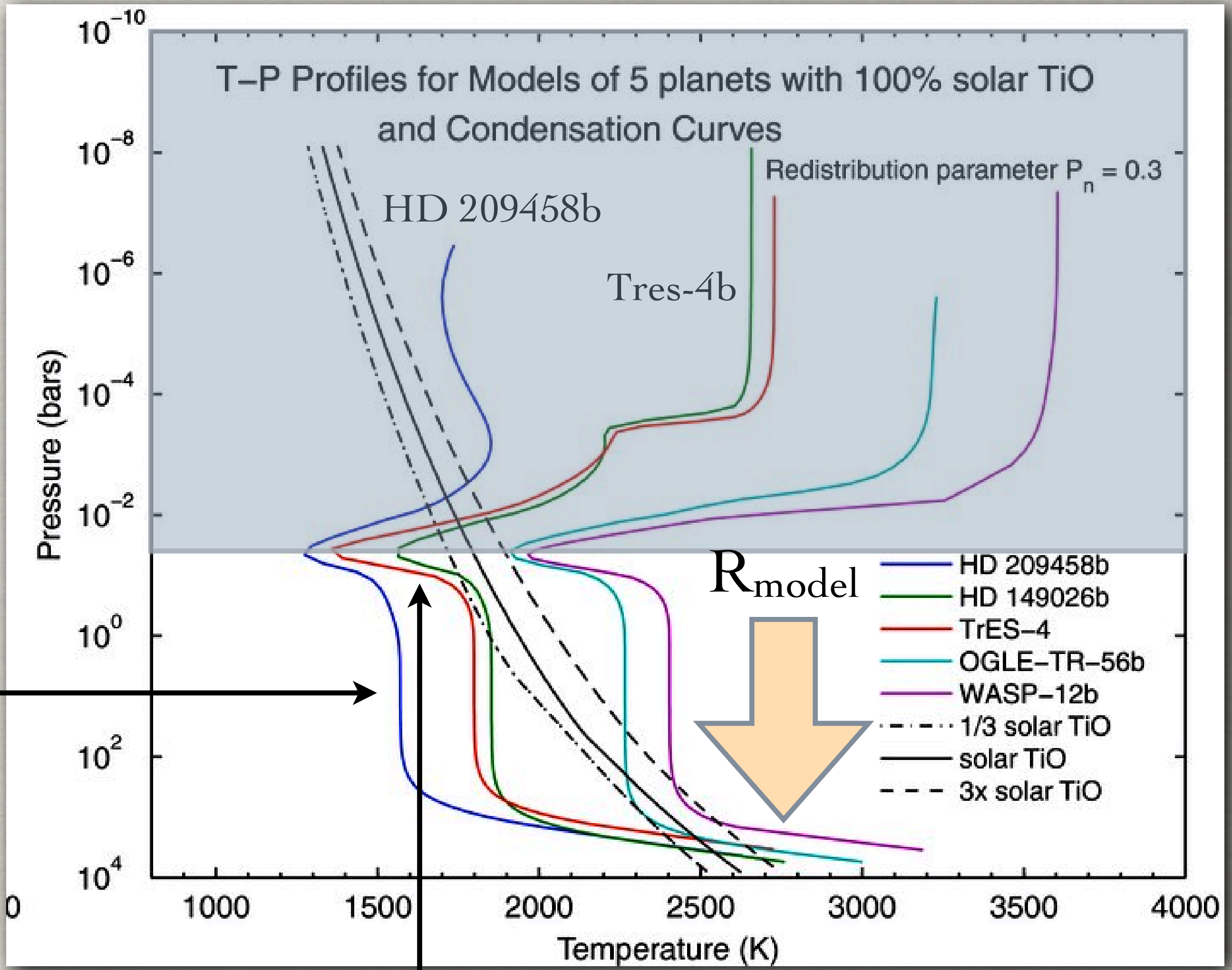
from Lodders et al '99

Ionization in hot Jupiter atmospheres

If $T = const.$ and ionization is far from complete ($n_j^+ \ll f_j n$)

Ionization is exponential:

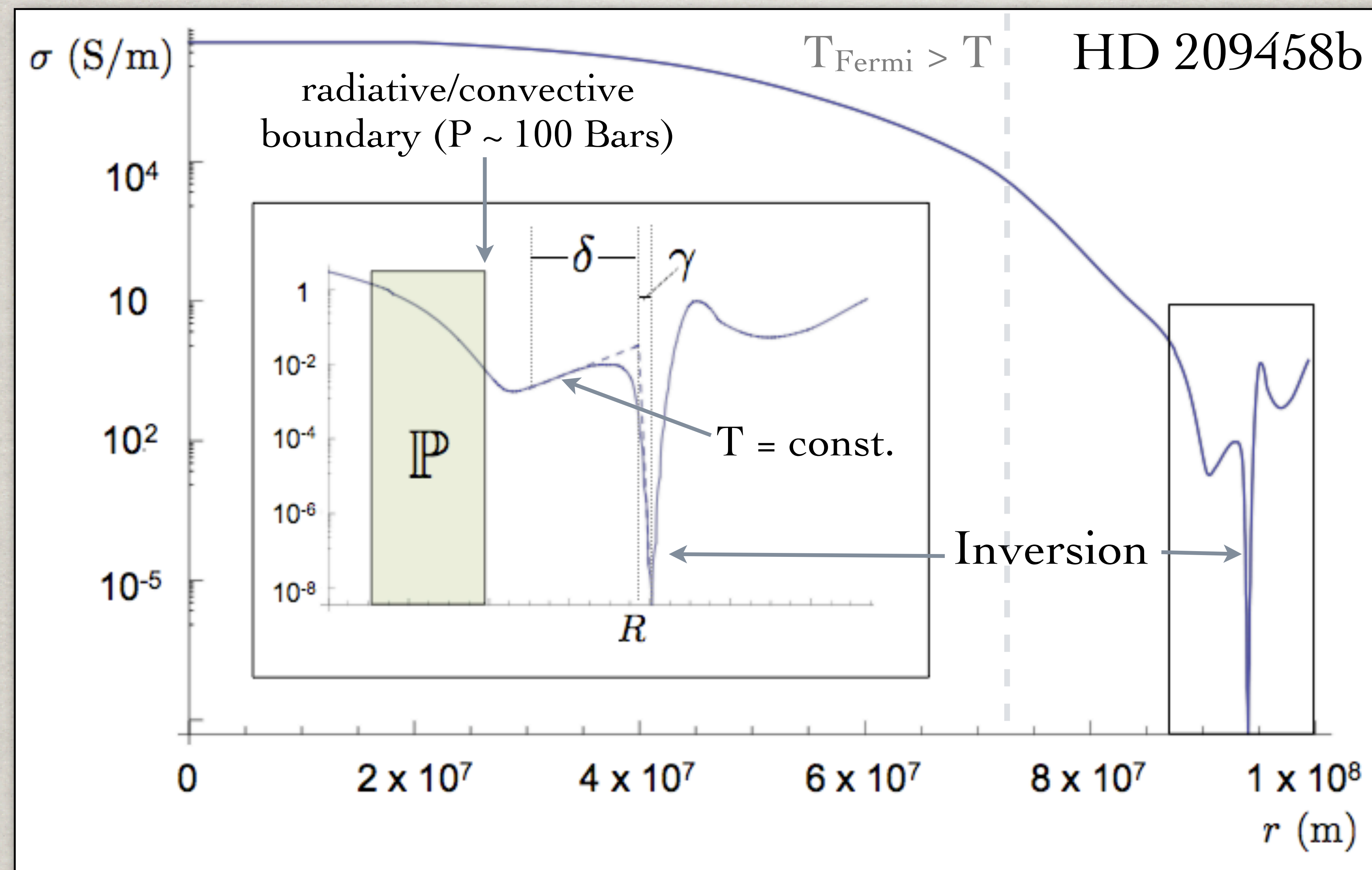
$$n_e = n_0 \sqrt{\sum_{i=1}^{N} f_i \chi_i e^{\frac{r_0 - r}{2H}}}$$



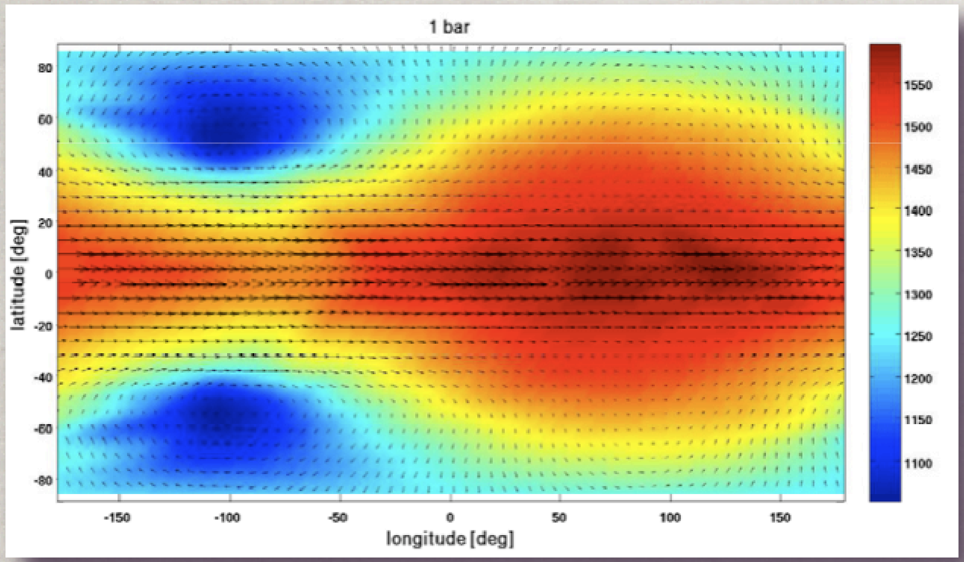
from Spiegel et al '09

Temperature inversions cause the conductivity to drop by orders of mag!

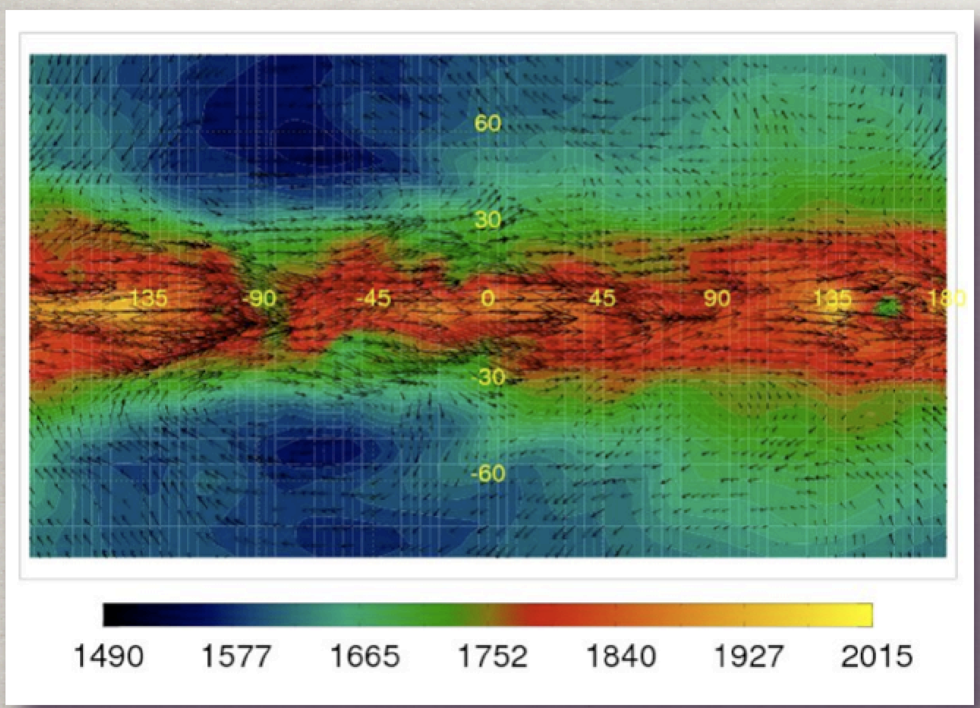
Electrical Conductivity Profile



Zonal Flow



Showman et al 2009



Rauscher & Menou 2009

GCM's show development of strong (~1km/s) zonal jets in the lower atmosphere

The jets generally penetrate to P ~ 10 Bars. Between 10 and 100 Bars, velocities are smaller i.e. ~ 100 m/s.

Approximations / Assumptions

Single zonal jet, of thickness δ
with a parabolic radial dependence

$$\vec{v} \propto \sin(\theta)\ \hat{\phi}$$

We assume a maximum wind speed of 1 km/s.
Rigid rotation at P = 10Bars

Magnetic field: dipole aligned
with the rotational axis

$$\vec{B}_{dip} = \vec{\nabla} \times k\left(\frac{\sin\theta}{r^2}\right)\hat{\phi}$$

At the surface, $||B|| = 10^{-3}$ T ($||B|| = 4.2 \times 10^{-4}$ T).

Boundary condition: zero radial current across the inversion,
so all current is confined to the interior.

Induction Equation

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla} \times \lambda \vec{\nabla} \times \vec{B} + \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right)$$

seek a steady-state solution

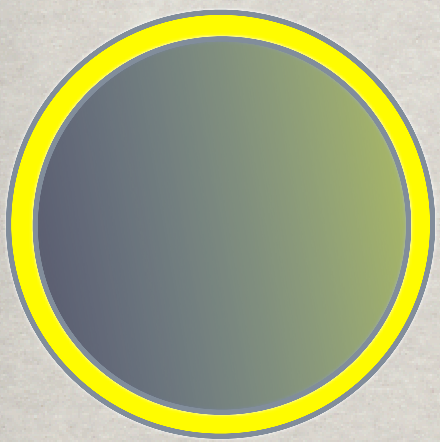
assume background field is a dipole field

assume the (v x B) term is dominated by the background field

$$\vec{\nabla} \times \lambda \left(\vec{\nabla} \times \vec{B}_{ind} \right) = \vec{\nabla} \times \left(\vec{v} \times \vec{B}_{dip} \right)$$

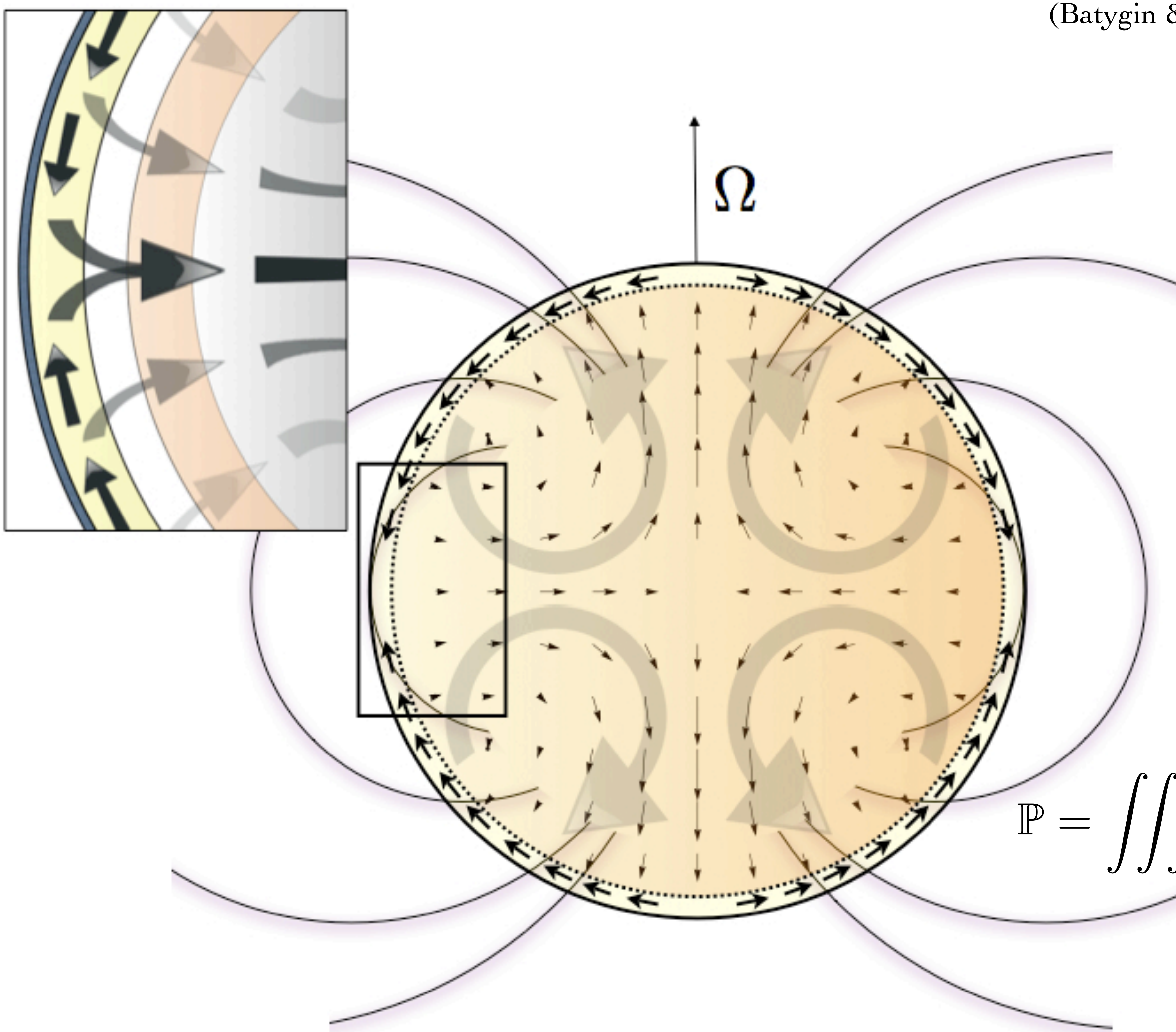
electric field

$$\overrightarrow{J}_{ind} = \sigma \left(\overrightarrow{v} \times \overrightarrow{B}_{dip} - \vec{\nabla} \Phi \right)$$



$$\overrightarrow{\nabla} \cdot \sigma \overrightarrow{\nabla} \Phi = \overrightarrow{\nabla} \cdot \sigma \left(\overrightarrow{v} \times \overrightarrow{B}_{dip} \right)$$

(Batygin & Stevenson 2010)



$$\mathbb{P} = \iiint \frac{\vec{J}^2}{\sigma(r)} dV$$

Some Scalings

$$\left.\begin{array}{l}\mathbb{P} \propto \sqrt{Z} \\ \boxed{\mathbb{P} \propto \exp(T)}\end{array}\right\} \quad \mathbb{P} \propto \sigma$$

Changing Y (core vs. no core) has little effect.

Also, <u>to leading order</u>,

$$\mathbb{P}_{atm} \propto \delta \qquad \mathbb{P}_{int} \propto \delta^2$$

$$\boxed{\mathbb{P} \propto v^2} \quad \boxed{\mathbb{P} \propto B^2}$$

Generally,

$$\mathbb{P}_{int} \sim \text{few} \times 10^{-2}\ \mathbb{P}_{atm}$$

Results: HD 209458b

In order to maintain HD 209568b's radius, 4×10^{18} W is needed.

In our model, this dissipation is attained at P ~ 90 Bars i.e. *at* the radiative/convective boundary.

Majority of the interior dissipation is between P = 100 Bars and P = 3 kBars.

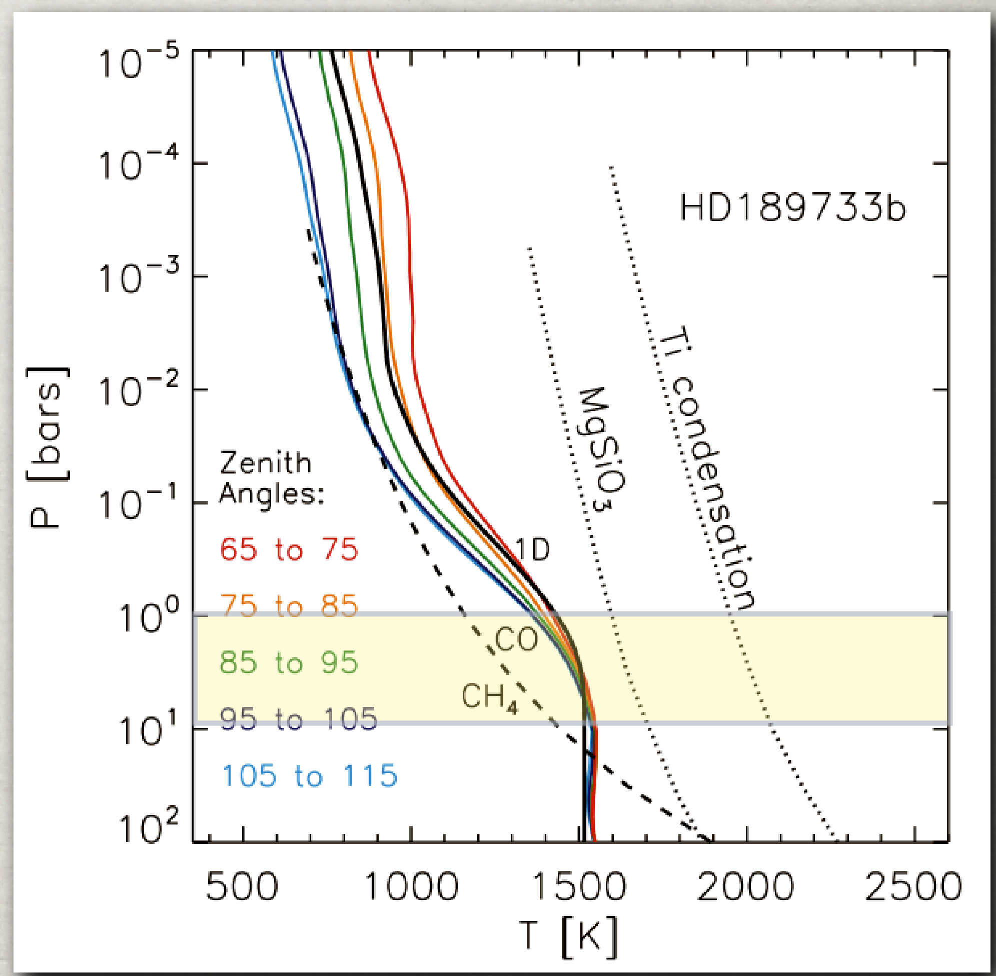
Ohmic heating in the atmosphere is small (~ few % of the insolation)

Results: HD 189733b

Explanation of radius requires no interior heating

Our model predicts a negligible (~10^{16} W) interior heating rate

A very thin layer of the atmosphere is sufficiently ionized



Fortney et al 2009

Results: Tres-4b

In order to maintain Tres-4b radius, 5×10^{19} W is needed.

Our model suggests Ohmic heating of 1.4×10^{20} W below P=100Bars, and significant heating in the atmosphere.

However, $Re_m \sim 15$ (a violation of the kinematic assumption).

Perhaps ionic drag reduces the velocity by a factor of ~ 3. If so, we're in the right ballpark.

Summary

A new MHD mechanism for inflation of extrasolar gas giants.

Required power naturally emerges, given conservative estimates of wind speed and magnetic field strength.

The mechanism, while still at play, has negligible effect for planets whose atmospheres are not hot enough for sufficient ionization to take place.

Hot, but smaller exoplanets are attributed to heavy element enrichment.

Future Work

We considered kinematic flows, but Lorentz force (JxB) may act to significantly modify the flow.

How does the induced current affect the interior dynamo?

Field generation in the atmosphere?

What about the stellar magnetic field? Linking of field lines?

10^5

10^3

$$Re_m = \frac{VL}{\lambda} \gtrsim 1$$

$$\frac{1}{\mu_0 \sigma}$$

10^{-6}

only need
10^{-2} S/m !

Thank You

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