Hot Spot Offset Variability from Magnetohydrodynamical Thermoresistive Instability in Hot Jupiters

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A thermoresistive instability possible in hot Jupiters

- The thermoresistive instability operating in hot Jupiters was first described by Menou 2012.
  - Uncontrollable thermal runaway.
- The thermoresistive instability was further studied by Hardy et al. 2022 and 2023.
  - The temperature runaway is kept under control with dynamics.

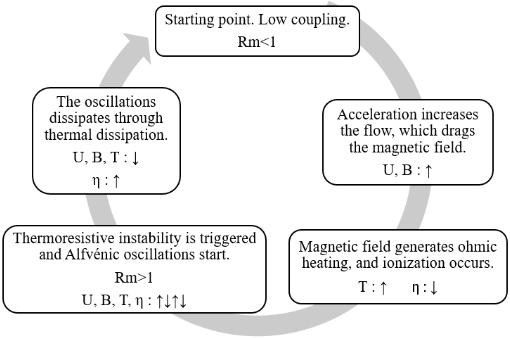

Figure: Flow chart of the instability workings. The oscillation between low coupling (Rm<1) and high coupling (Rm>1) between the field and flow is key.

Instability domains of previous works

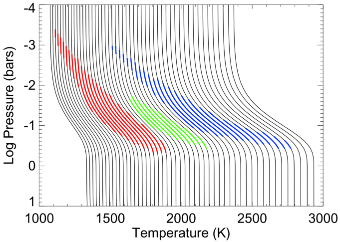

Figure: Thermoresistive instability domains superposed on temperature-pressure profiles representative of the dayside of a typical hot Jupiter. The colors represent different input parameters. Taken from Menou 2012b.

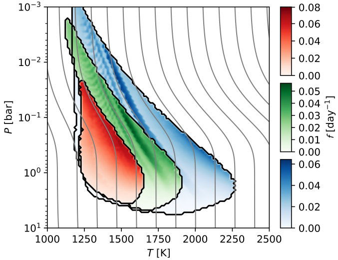

Figure: Thermoresistive instability domains. The colours represent different input parameters similar to the ones used in Menou 2012b. Taken from Hardy et al. 2022.

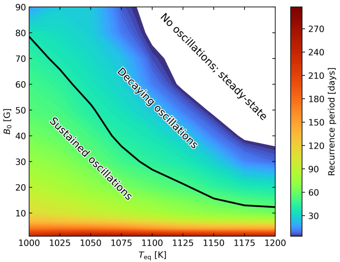

Figure: Thermoresistive instability domain. Y-axis is the radial magnetic field strength instead of pressure. Taken from Hardy et al. 2023.

Goals of the Longitudinal Expansion

- Follow the evolution of the hot spot during TRI.
- Predict the temperature contrast between day and night sides.
- Have better observational predictions.

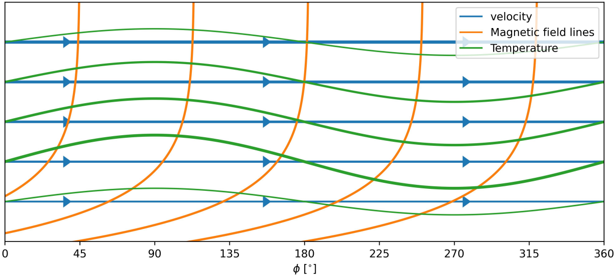

Figure: Cartoon of the magnetic field interacting with the atmosphere in the equatorial plane, with a sinusoidal temperature profile.

Equations and parameters

$$\frac{\partial u_x}{\partial t} = \boxed{\frac{B_0}{\mu_0 \bar{\rho}} \frac{\partial B_x}{\partial x}} + \boxed{\frac{\bar{\mu}}{\bar{\rho}} \frac{\partial^2 u_x}{\partial x^2}} + \boxed{a_x}$$

$$\frac{\partial B_x}{\partial t} = \boxed{B_0 \frac{\partial u_x}{\partial x}} + \boxed{\frac{\partial \eta}{\partial x} \frac{\partial B_x}{\partial x} + \eta \frac{\partial^2 B_x}{\partial x^2}}$$

$$\frac{\partial T}{\partial t} = -\boxed{u_x \frac{\partial T}{\partial x}} + \boxed{\frac{\bar{\mu}}{\bar{\rho}\bar{c}_p} \left[\frac{\partial u_x}{\partial x}\right]^2} + \boxed{\frac{\eta}{\mu_0 \bar{\rho}\bar{c}_p} \left[\frac{\partial B_x}{\partial x}\right]^2} + \boxed{\frac{1}{\bar{\rho}\bar{c}_p} \frac{\partial \bar{\chi}}{\partial x} \frac{\partial T}{\partial x} + \frac{\bar{\chi}}{\bar{\rho}\bar{c}_p} \frac{\partial^2 T}{\partial x^2}} + \boxed{\frac{1}{\bar{\rho}\bar{c}_p} \frac{\partial F_{\mathrm{irr}}}{\partial x}}$$

$$T(\phi) = T_0 + T_1 \sin\phi + T_2 \cos\phi$$

$$\eta(\phi) = \eta_0 + \eta_1 \sin\phi + \eta_2 \cos\phi$$

Where the colors represent Lorentz force and Induction, source terms, Viscous stress/heating, Ohmic diffusion/heating, thermal diffusion and advection. The barred variables ($\bar{x}$) come from the background structure and are not updated in time.

Spatiotemporal Evolution

- Alfvénic oscillations and temperature runaway occur at depth in the atmosphere.
- The hottest point can extend beyond the terminators but does so when the atmospheric temperature is almost uniform in longitude.
- The last panel shows the key to TRI, with Rm<1 before and after the instability and Rm>1 during.

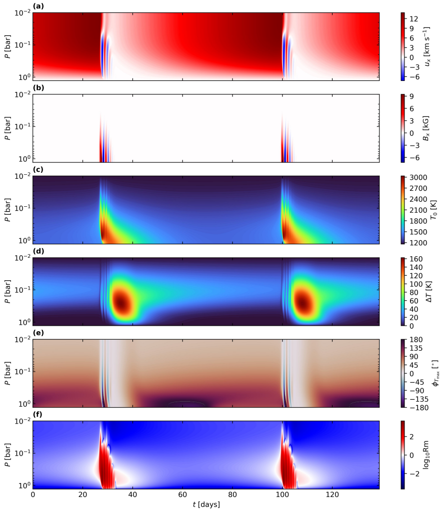

Figure: Spatiotemporal evolution of the velocity, magnetic field, temperature, the peak-to-peak temperature at every layers, hot spot offset and magnetic Reynolds number in P-t. The

Heat Flux and Hot Spot Offset

- The thermal runaway from TRI alters thermal flux at the upper boundary, artificially amplified by the constant temperature boundary condition.
- TRI and following Alfvénic oscillations lead to significant longitudinal variations in hot spot position, which could be observed.
- Magnetic field strength influence recurrence periods and oscillation amplitudes.
- The time variability effects from these oscillations would require many transits to characterize. (In red: bursts sequences have a period of 73 days. Alfvén oscillations have a period of 2 days.)

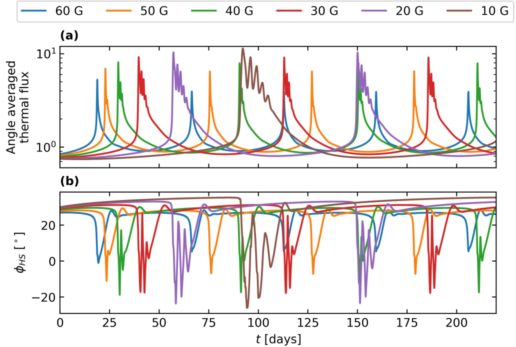

Figure: Angle averaged thermal flux on the dayside of the planet for different values of magnetic field, and the offset of the peak of the thermal flux; the hot spot.

Chaotic behavior

We applied the longitudinal expansion to the dimensionless local model of Hardy et al. 2022. While general motions are the same, chaotic behavior was found!

- A perturbation near machine precision is enough to change the outcome.
- The exponential growth with positive Lyapunov coefficient (λ) is true to chaos theory.
- Different initial conditions solutions all converge to the same strange attractor.

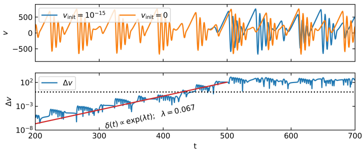

Figure: Decorrelation between unperturbed and perturbed solutions with the associated Lyapunov coefficient.

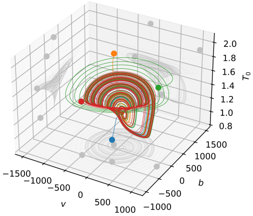

Figure: 3D phase space of chaotic solution with different initial conditions, converging onto the attractor.

Main take-aways

- Temperature dependent η lead to interesting non-linear dynamical behaviors.
- The periods of our oscillations range from a few days to a few hundreds of days.
- In some area of parameter space, we predict westward motions during the Alfvénic oscillations.
- For all this to work, we need a temperature sensitive electric conductivity, hence the importance of alkali metals in HJs.
- The local model is susceptible to chaotic behavior under the longitudinal expansion.