Magnetohydrodynamical torsional oscillations from thermo-resistive instability in hot Jupiters

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Why are magnetic fields important for hot Jupiters (HJs)?

- Hot Jupiters temperature ranges cause partial ionization of the atmosphere.

$$\boxed{\eta = 0.023 \frac{\sqrt{T}}{\chi_e} \mathrm{m}^2\ \mathrm{s}^{-1}}$$

- Possible strong non-linear interaction between the magnetic field and the flow (Rm>1).

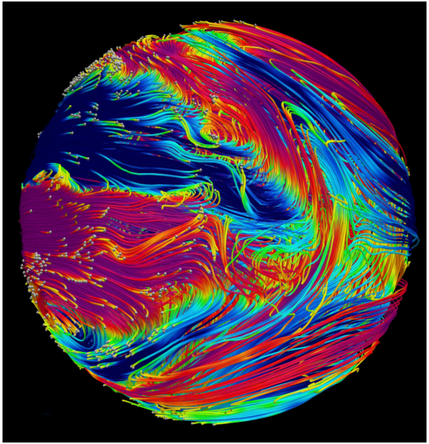

Figure: Magnetic field lines in the atmosphere of a hot Jupiter simulation. Taken from Rogers (2017).

A thermo-resistive instability possible in hot Jupiters

- The thermo-resistive instability described by Menou 2012.
  - Constant velocity shearing the system.
  - No Lorentz force on the flow.
- The thermo-resistive instability described by Hardy, Cumming, and Charbonneau 2022.
  - Constant velocity forcing term.
  - By adding dynamics to the system, we show behaviours that were missed before.

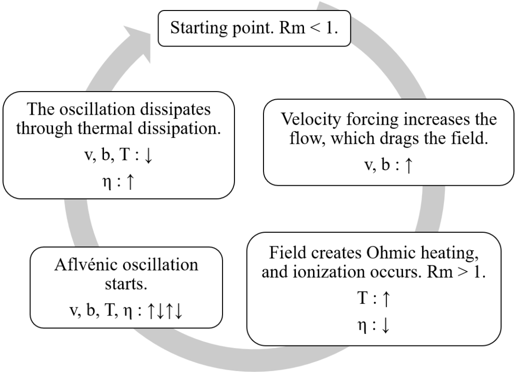

Figure: Flow chart of the instability workings. The oscillation between low coupling (Rm<1) and high coupling (Rm>1) between the field and flow is key.

Menou's instability domains

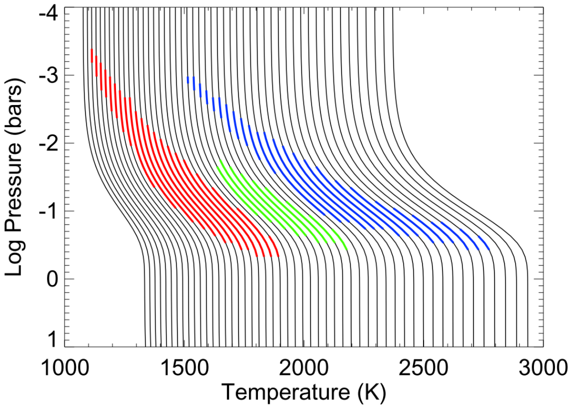

Figure: Thermo-resistive instability domains superposed on temperature-pressure profiles representative of the dayside of a typical hot Jupiter. The colours represent different input parameters. Taken from Menou 2012.

Our instability domains

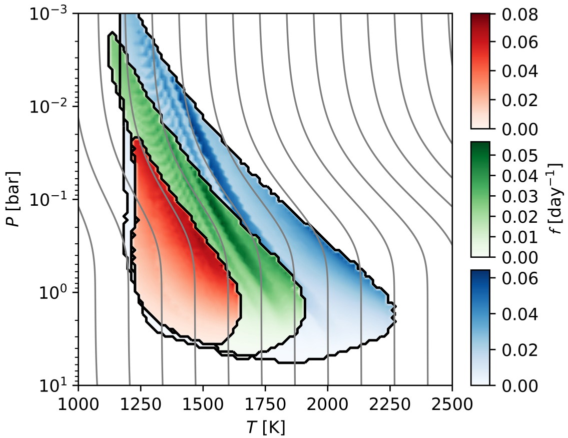

Figure: Thermo-resistive instability domains. The colours represent different input parameters similar to the ones used in Menou 2012. Taken from Hardy, Cumming, and Charbonneau 2022.

Goals of the One Dimensional Model (1DM)

- Have a radial structure within the system.
  - Pressure,
  - Density,
  - Temperature profile,
  - Diffusion coefficients.
- See the effect of phase mixing and the boundary conditions.
- Have better observational predictions.
- Get (a bit) closer to reality.

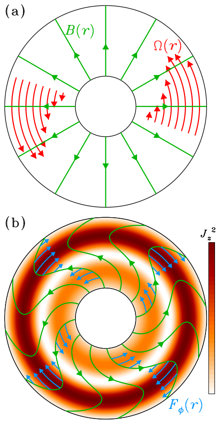

Figure: Cartoon of the magnetic field interacting with the atmosphere in the axisymmetric equatorial plane.

Equations and parameters

$$\frac{\partial u_y}{\partial t} = \frac{B_0}{\mu_0 \bar{\rho}} \frac{\partial B_y}{\partial x} + \frac{\bar{\mu}}{\bar{\rho}} \frac{\partial^2 u_y}{\partial x^2} + a_{u_y}$$

$$\frac{\partial B_y}{\partial t} = B_0 \frac{\partial u_y}{\partial x} + \frac{\partial \eta}{\partial x} \frac{\partial B_y}{\partial x} + \eta \frac{\partial^2 B_y}{\partial x^2}$$

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

$$\eta = 0.023 \frac{\sqrt{T}}{\chi_e} \mathrm{m}^2 \, \mathrm{s}^{-1}$$ (Perna et al. (2010))

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

Impacts of the magnetic diffusivity

- The temperature dependence of the magnetic diffusivity can totally change the behaviour of the system if taken into account or not.
- Often neglected, the spatial dependence of the magnetic diffusivity in the induction equation ($-\nabla\eta \times (\nabla \times \mathbf{B})$) also drastically changes the behaviour of the system.

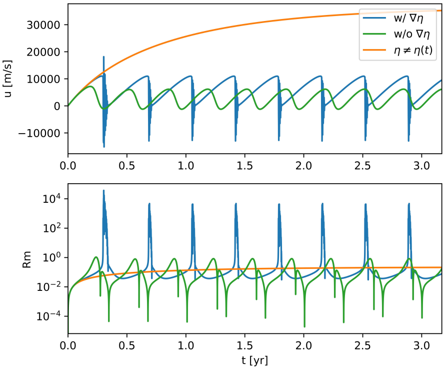

Figure: Impact of different treatments of η shown by the mid-point of simulations with the same parameters. In blue is the complete equation. In green we neglected the spatial gradient of η in the induction equation. In orange we did not update η with the changes of temperature.

Oscillating system: an example

All oscillating simulations have similar behaviour:

- Cold and slow with no B_y;
- Quick rise in temperature and field once the instability is reached;
- Decaying Alfvén waves subjected to phase mixing;
- Return to small velocities while cooling;
- Repeat.

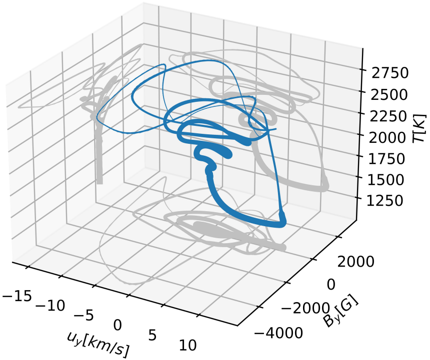

Figure: Phase space trajectory of a simulation at the central point of the radial domain. The thinner the line, the faster the system is going through phase space.

Impacts on observations

The time variability effects from these oscillations would require many transits to characterize. For example, the simulation shown in the previous slide has the following periods.

- Bursts sequences have a period of 135 days;
- Alfvén oscillations have a period of 2.2 days.

The simulation has a background magnetic filed of $B_0 = 30$ G and an irradiation temperature of $T_{irr} = 1000$ K.

Main take-aways

- Temperature dependent η lead to interesting dynamical behaviours.
- The period 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 oscillations.
- For all this to work, we need a temperature sensitive electric conductivity, hence the importance of alkali metals in HJs.
- We're still surveying the parameter space, but we already see that we can reach super-sonic velocities, meaning we need more physics in the model.

The content of this presentation was taken from Hardy, Cumming, and Charbonneau 2022 and Hardy, Cumming, and Charbonneau (in prep).