Internal and atmospheric Ohmic dissipation in Hot Jupiters

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1. Hot Jupiter and Ohmic dissipation

Hot Jupiters (HJs) are gas giants orbiting very close to their host stars. They have high irradiation from their star and strong temperature differences between the dayside and the nightside, which generate strong zonal jets that try to redistribute the heat. These planets have **inflated radii**: for equilibrium temperatures $T_{eq} > 1000$ K, there is a clear trend between T_{eq} and R (Fig. 1). Such radii can reach up to 2 R_J, which cannot be accounted for within standard cooling models for planetary evolution at ~ Gyr ages, even when irradiation is taken into account. Either a delayed cooling or a persistent internal heat deposition [1] is needed to explain the observed radii. We focus on the Ohmic dissipation (OD) scenario, the most promising mechanism initially proposed by [2] and [3]. Electrical currents can be generated either in the outermost layers, carried by the electrons of ionized Alkaline metals and induced by the zonal strong **winds**, or in deeper regions, where conductivity is given by pressure ionization. Additionally, we explore how the turbulence can drag the currents into deeper convective regions, where heat is effective in inflating the planets. Quantifying the amount of OD requires a prescription for both the conductivity and currents profiles.

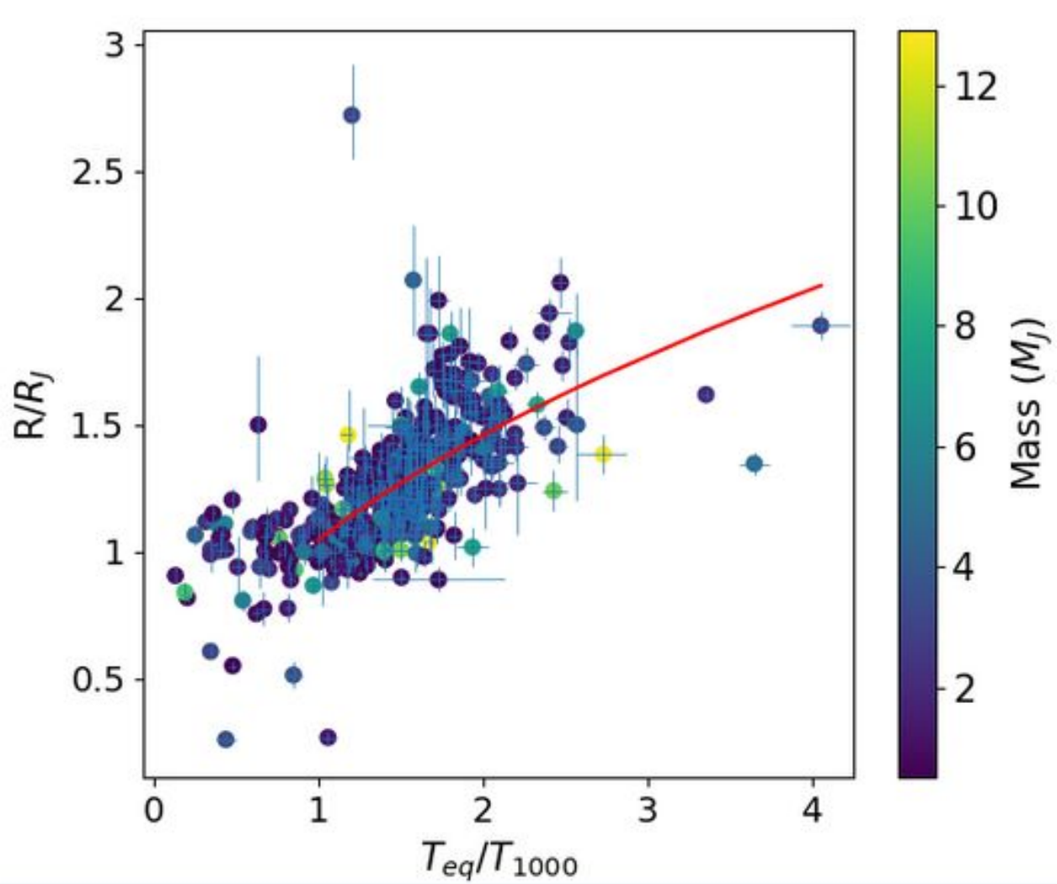


Figure 1. Radius versus equilibrium temperature scatter of 397 giant (0.5-13 M_J) exoplanets in the NASA Exoplanet Archive database with available masses, ages, radii and equilibrium temperatures, selecting only those with radius relative error <25%. The red line quantifies the T_{eq}-R trend above 1000 K, with a best-fitting power-law model given by: $\log(R/R_J) = (0.481 \pm 0.035) \log(T_{eq}(/1000\ K) + \log(1.044 \pm 0.020)$.

2. Internal Ohmic Heating (Akgün et al. submitted [4])

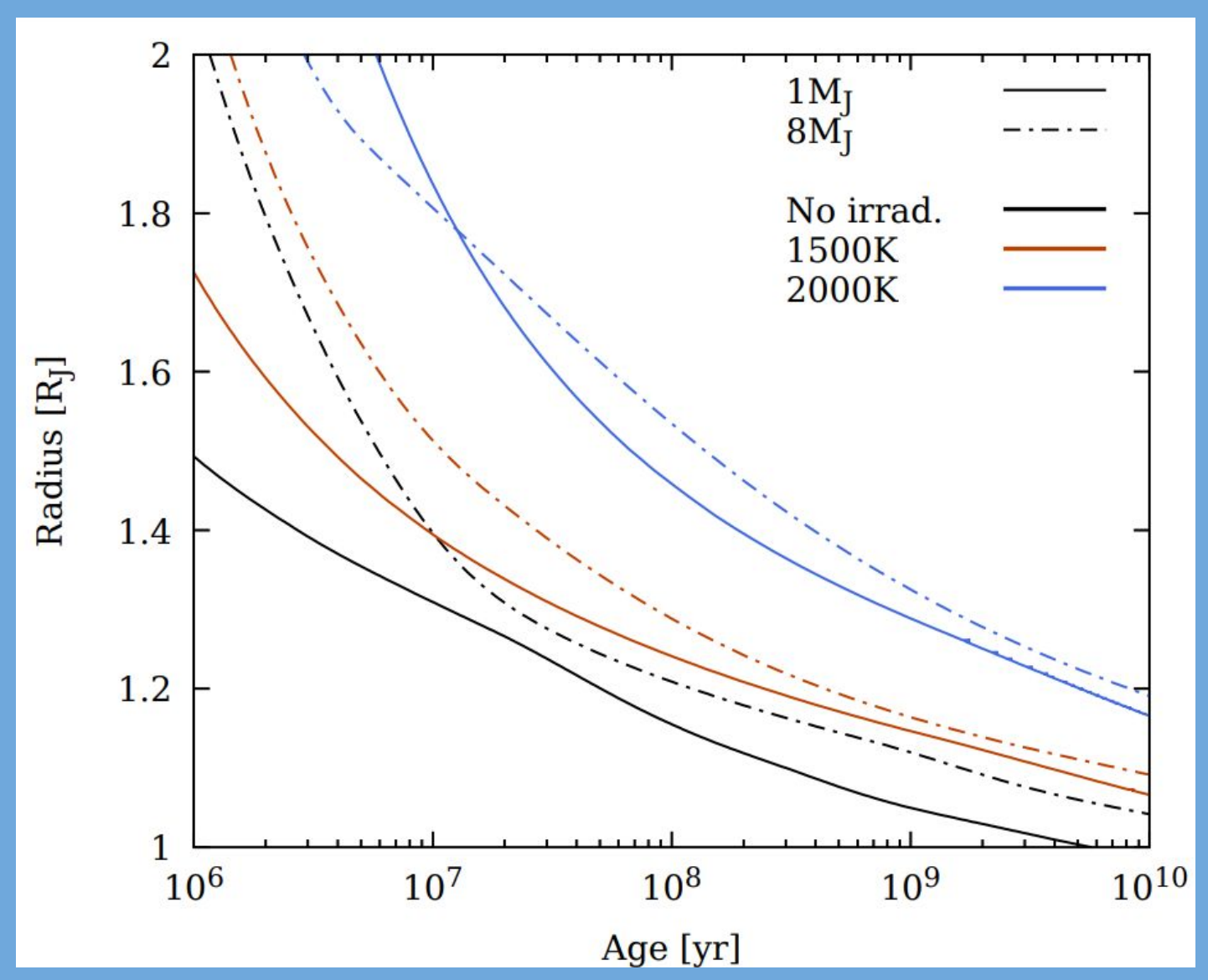
- Using the evolutionary code MESA, we simulate the evolution of irradiated giant planets, spanning the range 1 to 8 M_J, incorporating an internal source of Ohmic dissipation located beneath the radiative-convective boundary (RCB). We have parameterized the currents by the value of B and ℓ, the only free parameter in our effective model, interpreted as the typical radius of curvature of the field lines:

$$Q_J = \frac{J^2}{\sigma} = \left(\frac{c}{4\pi}\right)^2 \frac{B^2}{\ell^2 \sigma}$$

- We implemented a conductivity $\sigma(P)$ which mimic both the Alkaline thermal ionization [2] and metallic Hydrogen deep contributions [5], and the magnetic field evolution through widely-used scaling laws [6][7]:

$$B = 4.8 \times 10^3 \left(\frac{ML^2}{R^7}\right)^{1/6} G$$

- Compared to the little inflation obtained with irradiation alone (Fig. 2), this internal Ohmic dissipation model can broadly reproduce the range of observed radii (Fig. 3), by using values of radius of curvature up to about two orders of magnitude smaller than what we estimated from the Juno measurements of the Jovian magnetosphere and from MHD dynamo simulations presented herein ($\ell = (0.01 - 0.1)\ R_P$). The observed trend with equilibrium temperature can be explained if the highly-irradiated planets have more intense and more small-scale magnetic fields (small values of ℓ).
- We argue that such small values of ℓ are consistent with the presence of a turbulent field which becomes more and more important as T_{eq} increases. The existence of turbulence and its effect on radius inflations had been proposed in the past by [8] and [9], but without the inclusion of magnetic field, which we test then with box simulations (see next section).



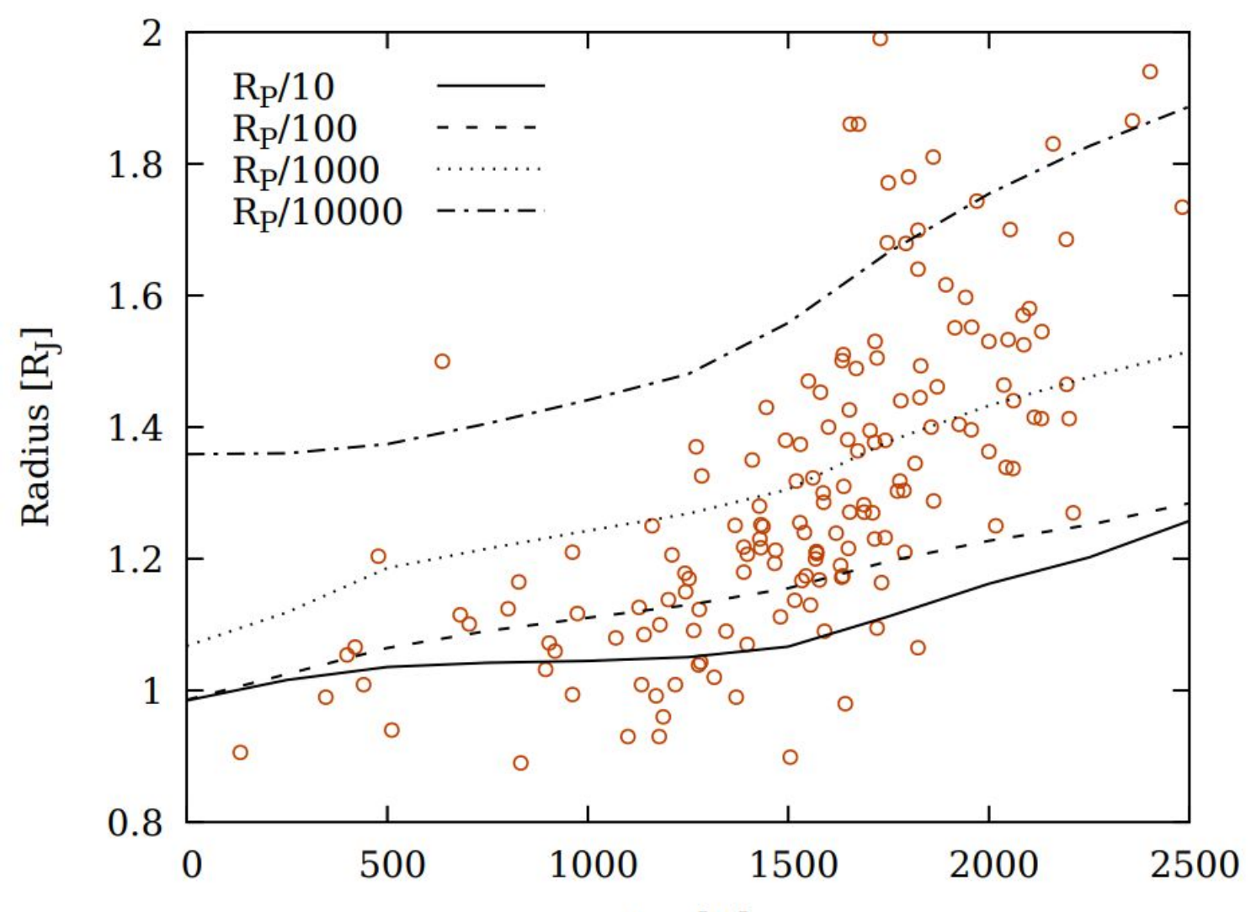


Figure 2 (left): Evolution of the radii of planets with masses 1 M_J (solid lines) and 8 M_J (dash-dotted lines), up to an age of 10 Gyr when no Ohmic heating is present. Three sets of curves are shown: black lines are for no irradiation; red lines are for T_{eq}=1500 K; and blue lines are for T_{eq} =2000 K. Here we show the cases for relatively high temperatures, as the inflation for T_{eq}<1000 K remains relatively moderate (close to the black lines). Note that the maximum inflation for the models shown here is approximately 20%, as expected [1].
Figure 3 (right): Asymptotic planetary radius (at Gyr) versus T_{eq} for models with Ohmic heating for a 1 M_J planet and various values of ℓ. The cases with $\ell > 0.1\ R_p$ is practically the same as the no Ohmic case. The HJ data for planets of mass $0.8 < M_P/M_J < 2$ (close to the range of the simulated curves) are shown as red circles.

References

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3. MHD atmospheric box simulation: winding and turbulence

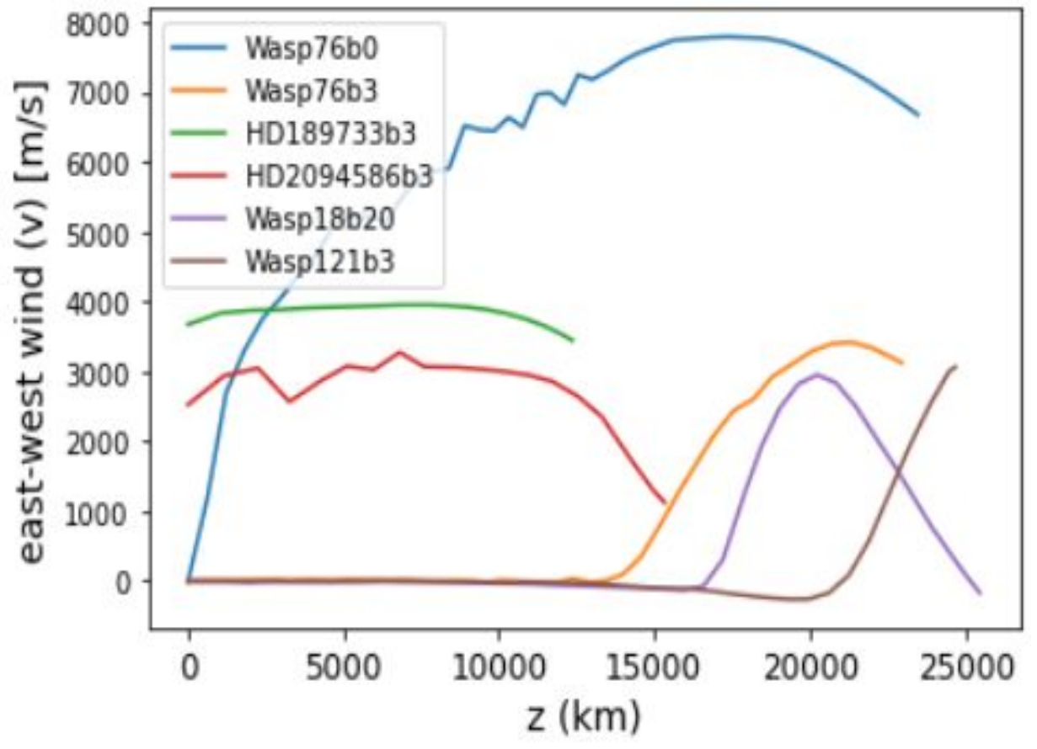
In order to explore the effects of winding and turbulence and the consequences for OD, 1D and 3D MHD box simulations of atmospheric columns. The simulations are performed by Simflowny (https://hub.docker.com/r/iac3/simflowny), a user-friendly platform that generate codes for any partial differential equations. It employs the SAMRAI infrastructure for the management of the parallelization, mesh refinement and output writing. We employ high resolution shock-capturing method MP5 for the spatial discretization, using a splitting flux scheme, and a Runge-Kutta 4th-order scheme for the time advance.

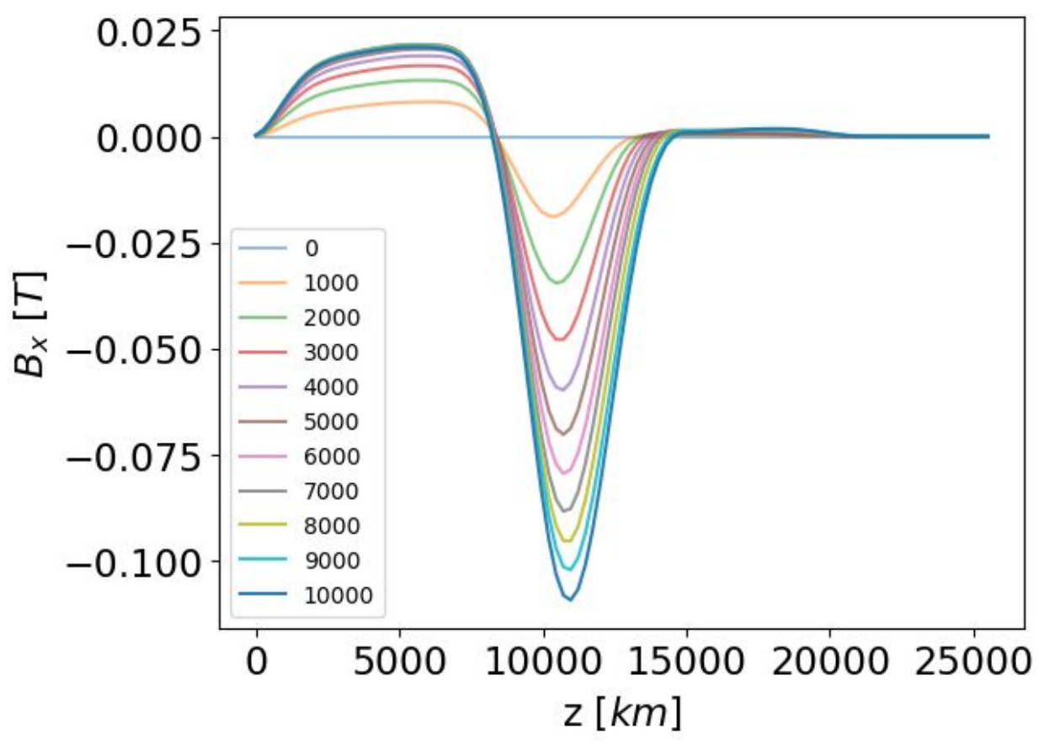
1D winding effect

- Under the presence of a background component of the magnetic field (generated in the interior of the planet), the most relevant effect is its winding, due to the shear of the wind. Previous works [2] [3] focused on estimates under the assumption of linear perturbation. However, for $T_{eq} > 1500$ K the conductivity is large enough to induce magnetic fields stronger than the background. This non-linearity requires full MHD simulations. The induced field will be the balance between the induction and the resistive term, where the conductivity is given by [2]:

$$\frac{\partial B}{\partial t} = \nabla \times \left(v \times B - \frac{J}{\sigma}\right)$$

- A background P(T) profile in hydrostatic equilibrium has been considered to study 1D MHD equations of a narrow (less than a degree in latitude and azimuth) column of the outer HJ's atmospheres, below 100 bar, where the zonal jet (wind) intensity increases, reaching typically the speed of sound in the outermost layers. Different wind profiles $v_x(z)$ and P(T) for different known exoplanets have been obtained from GCM from Dr. Hayley Beltz (Fig. 4).
- Several simulations have been performed and they show a common behaviour. Due to the presence of the shear layer (vertical changes of wind speed), a strong toroidal field is created in the same direction of the wind as observed in Fig. 5 and 6 for GCM profiles from setups applied to Wasp-18b and HD 209485b.
- However, if these intense but very localized currents circulate only in these radiative layers, the heat deposition is not effective in inflating the planet. We then explore 3D turbulent effects below.





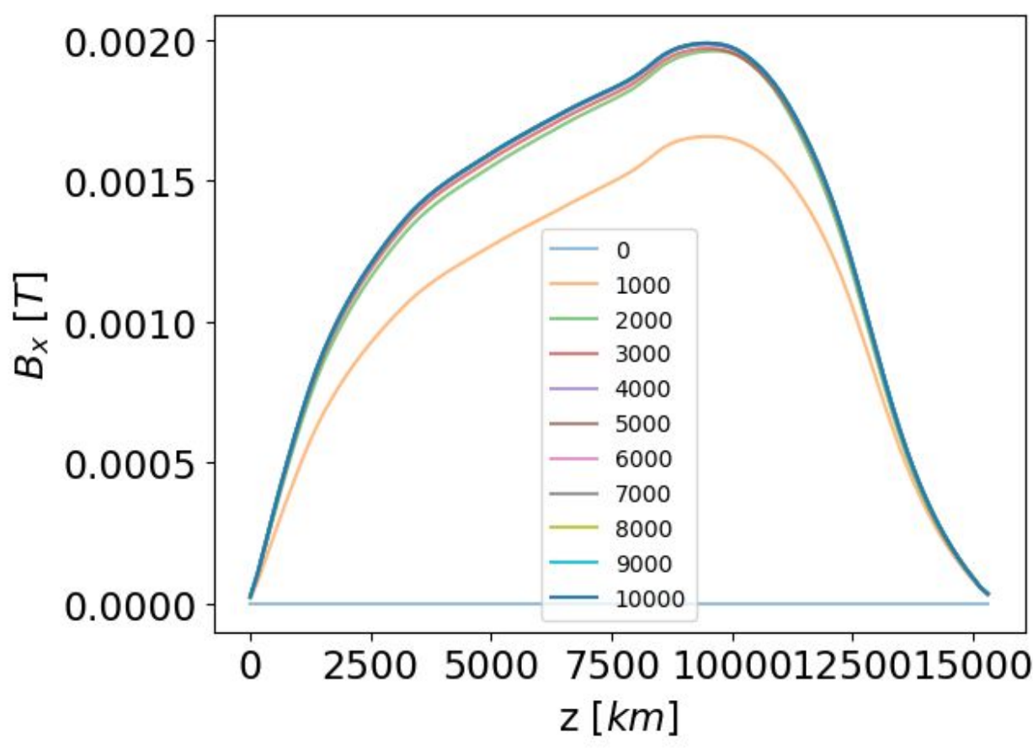
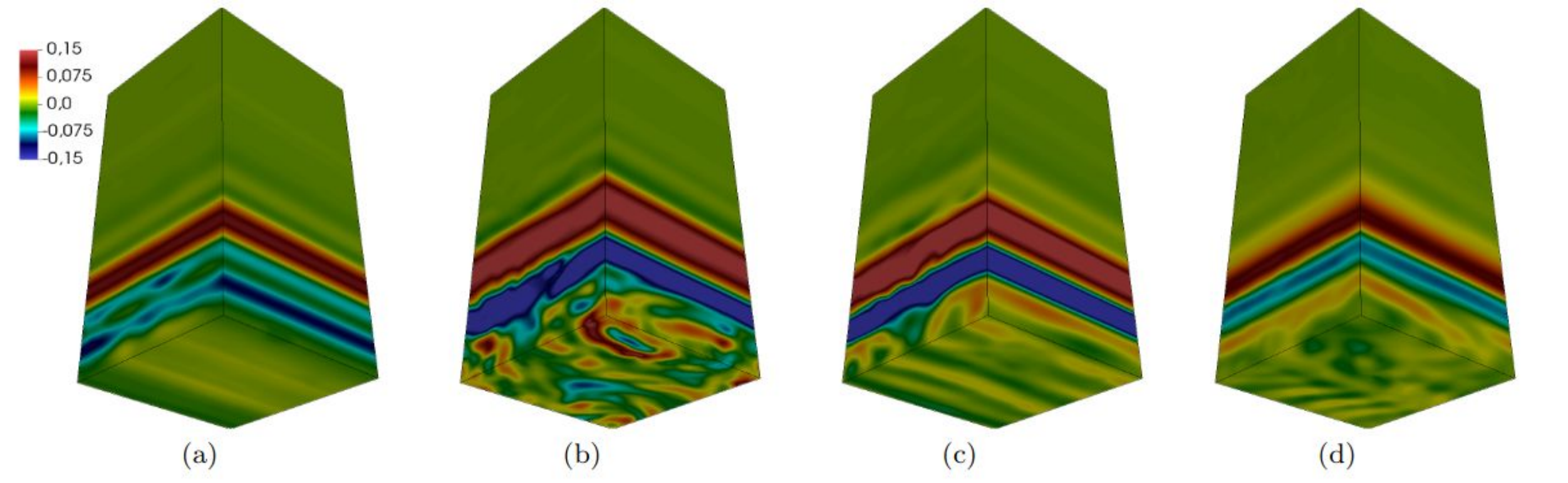


Figure 4 (left). Wind profiles obtained from Beltz' GCMs, applied to different exoplanets.
Figure 5 (center). Magnetic field amplification due to winding effect for the wind profile resulting at the sub-stellar point in Beltz' GCM applied to Wasp-18b with a T_{eq} =2413 K. The different colour lines indicate the different times needed by the code to approach the equilibrium configuration, starting from Bx=0.
Figure 6 (right). Same as Fig. 5 for HD 209458b T_{eq} =1484 K: the resistivity is much higher, and Bx lower.

3D MHD turbulence

- We performed 3D MHD simulations with the same configuration mentioned before but adding small random forced perturbations in the momentum equation (white noise in space and time, 1% amplitude wrt wind).
- In general, after hundreds of crossing timescales the system reaches a saturated state, with small relative variations in density, pressure and temperatures over the stable background stratification. Such perturbations are created mostly at the shear layer and below it, while in the upper part they escape away (we have a damping region in our numerical domain).
- The dominant component of the magnetic field is still the azimuthal (x direction). Coherent smaller magnetic structures appear. They elongated in the x direction due to the winding and they show a certain complexity in the y-z plane, reflecting the curling and twisting effect of MHD turbulence (Fig 8).
- The presence of small structures in lower region of the domain may indicate a penetration of the currents at deeper layers, Fig. 7 which would be relevant to help the currents penetrate to deeper layers to inflate the planet from the convective region. We have seen this effect for a wide range of prescribed conductivity profiles and simulation parameters.



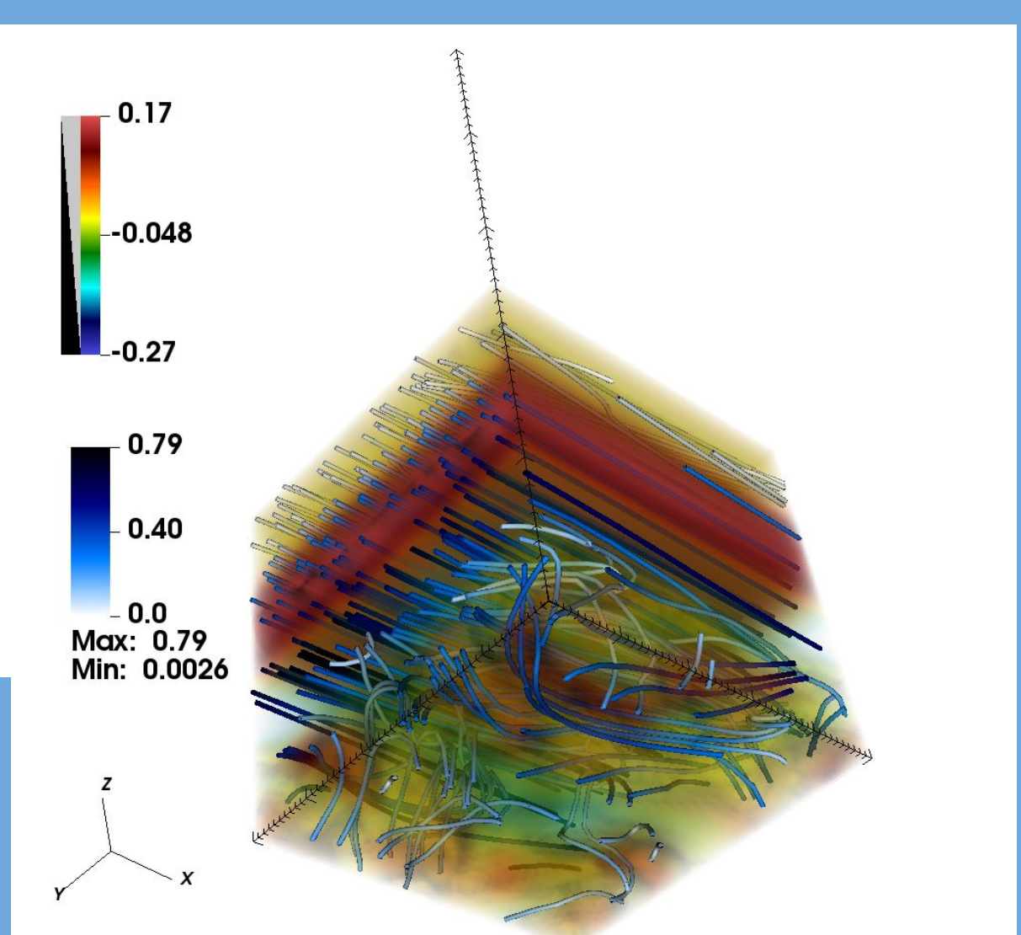


Figure 7 Vertical 3D snapshots of the perturbed density, at four different times t/t_*=500(a), 2000 (b), 3000 (c) and 6000 (d), for a simulation.
Figure 8 Representative 3D snapshot of a simulation. The rainbow color scale represents the value of density perturbation, while the magnetic field lines are colored with the intensity of the magnetic field.

4. Conclusions

- 1D long term evolution simulations of irradiated planets, including OD based on realistic conductivities, suggest the possibility of small-scale magnetic fields rising from the atmospherically induced currents.
- Our MHD simulations in a box representing a narrow atmospheric column (typically below 100 bar) show that winding can create locally very intense magnetic fields, but localized to the shear regions of the winds.
- Turbulent forcing allow the creation of vortices and small-scale magnetic structures, which are dragged at deeper layers, where they can be dissipated. This is compatible with the type of Ohmic heat that our evolutionary models of irradiated giant planets need to explain inflated radii.
- Future works will refine further the conductivity prescriptions and will perform a statistical comparison of the population, constraining the OD parameters.
- Further MHD simulations will be performed at deeper layers, to study the turbulent effects in the relevant regions of heat deposition.

This work is a compilation of three different works. Soriano-Guerrero C. et al 2024 has been published by MNRAS (Volume 525, Issue 1, October 2023, Pages 626–641), Akgün T. et al al. 2024, submitted to A&A, arXiv:2403.11501 and Soriano C. et al 2024 is under preparation. All projects are funded by ERC Starting Grant IMAGINE (948582, PI D. Viganò) and María de Maeztu (CEX2020-001058-M). April 2024