Magnetic winding in non-ideal MHD atmospheres of Hot Jupiters

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Hot Jupiters are expected to develop magnetic fields induced by atmospheric winds. Here, we perform 1D magnetohydrodynamic (MHD) simulations of atmospheric columns using wind and T profiles from global circulation models (GCM) of various exoplanets. We explore magnetic field winding and Ohmic dissipation, and include the effects of Hall drift and ambipolar diffusion. Our results show that strong azimuthal magnetic fields can form in the non-linear regime, reaching values around 100 G at pressures near 1 bar. The meridional currents are dissipated through Ohmic heating, with local efficiencies up to 10^{-3}. Hall and ambipolar effects also play a role in shaping the magnetic field, especially in the hottest planets. Although our model uses a, plane-parallel geometry and does not include magnetic drag, it highlights the complexity and non-linearity of induction in HJ atmospheres.

Hot Jupiters 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**. Such radii can reach up to 2 R_J, which cannot be accounted for within standard cooling models, 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 strong zonal **winds**, or in deeper regions, where conductivity is given by pressure ionization. Here we focus on the atmospheric region, in which we study **(1)** how the winding effect may amplify the local magnetic field and affect the local amount of Ohmic dissipation produced in the planet and **(2)** if the Hall and ambipolar terms contribute in the induced field.

Numerical model

We simulate the outermost (from 100-1000 bar to p ~ 10^{-3}-10^{-2} bar), radiative layers of a HJ atmospheric column at the substellar point. The concept and the code are similar to the 3D turbulent simulations by [4], where we focused on very simple wind and hydrostatic, isothermal profiles, using ideal MHD. Here we use a 1D version, considering only the vertical variations with a plane-parallel approximation, but we expand on our previous investigation in several aspects:

- Release the ideal MHD approximation, incorporating the Ohmic, Hall and ambipolar non-ideal terms

$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \frac{\mathbf{J}}{\sigma} + \frac{\mathbf{J}\times\mathbf{B}}{en_e} - \frac{(\mathbf{J}\times\mathbf{B})\times\mathbf{B}}{\nu_{in}\rho_i}$$

- Adopt as background profiles P(T) and wind profiles from GCM simulations of [5], [6] and [7] for different planets under hydrostatic equilibrium (table and Fig.1).

Model	M_p $[M_J]$	R_p $[R_J]$	$T_{\rm eq}$ [K]	$F_{\rm irr}$ [MW/m^2]	$B_{\rm d}$ [G]
WASP 76b-d0	0.92	1.83	2160	4.9	0
WASP 76b	0.92	1.83	2160	4.9	3
HD 189733b	1.13	1.13	1191	0.32	3
HD 209458b	0.73	1.36	1484	1.1	3
WASP 18b	10.2	1.24	2413	7.7	20
WASP 121b	1.16	1.75	2358	7.0	3

Table 1: List of the main properties of the input profiles used in this work: name of the model, mass, radius, equilibrium temperature, irradiation, and background magnetic field value Bd used in the drag term in the GCM

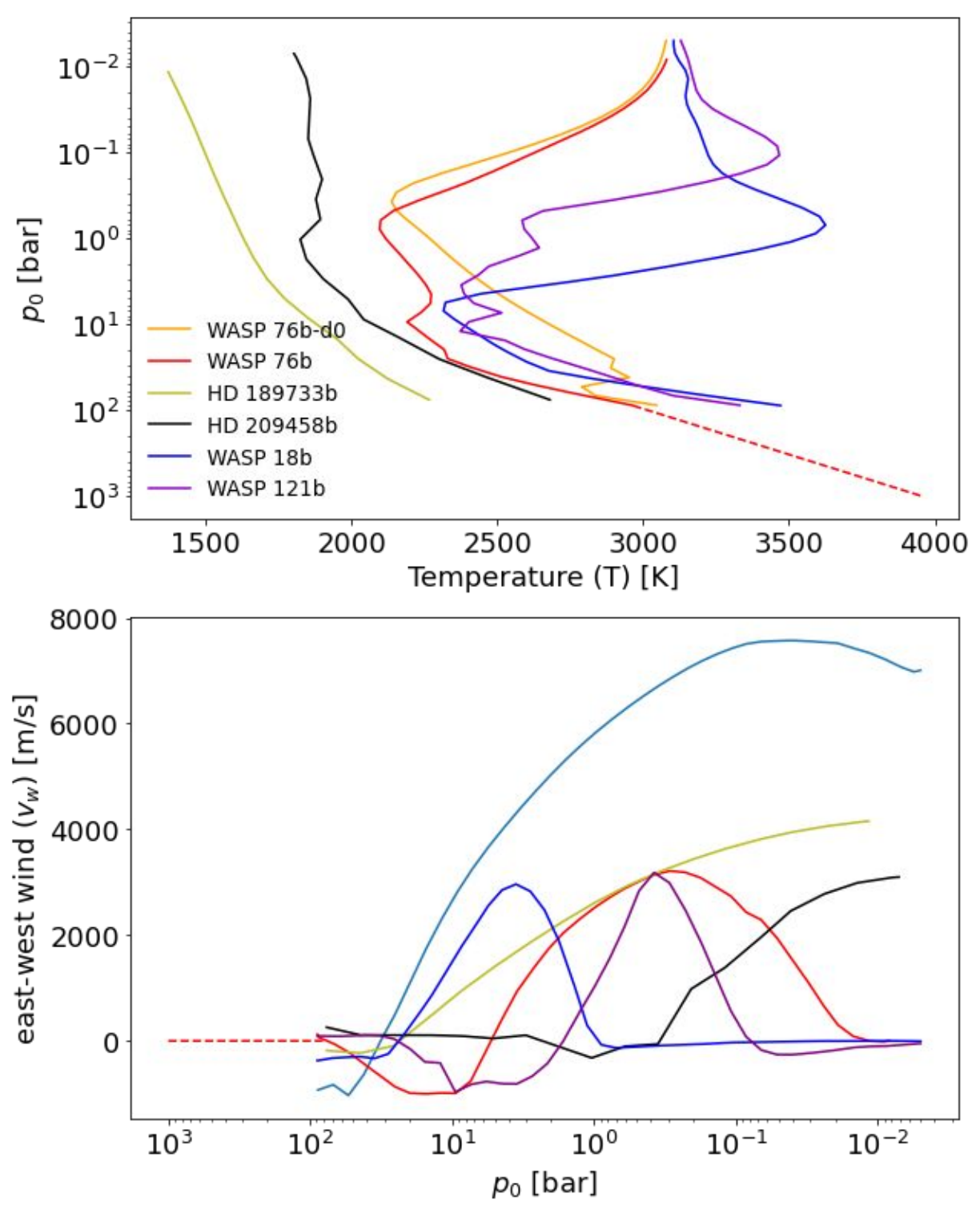

Figure 1: Substellar profiles for the different models shown in Table 1. p(T) (top) and zonal winds (bottom). We show the extension to deeper pressures for WASP 76b with a dashed line.

In order to quantify the OD we need to know:

- The induced currents (from simulations)
- The conductivity using the classical formula given by [8]:

$$\sigma(T,p) = \frac{x_e}{\langle\sigma v_{en}\rangle_e}\frac{e^2}{m_e}$$

Infrastructure

The simulations are performed by Simflowny [9], a user-friendly platform that generates codes for partial differential equations. It employs the SAMRAI infrastructure for 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 RK 4th-order scheme for the time advance

Results

GENERAL BEHAVIOUR IN DIFFERENT PLANETS

- Strong Bx (equilibrium advection and Ohmic)
- Most effective close to the shear region
- For different planets there are two competing effects: (1) hotter planet → stronger T → faster winds winds to amplify Bx, (2) counteracting B_{drag}, which slows down the wind
- WASP 121b highest induction (|Bx|max ~ 1550 G)

EFFECT OF NON-IDEAL TERMS

- Hall and ambipolar << winding and Ohmic (Fig.2)
- Noticeable in the outermost layers of the hottest planets where the Bx is modified
- Hall effect generates a By

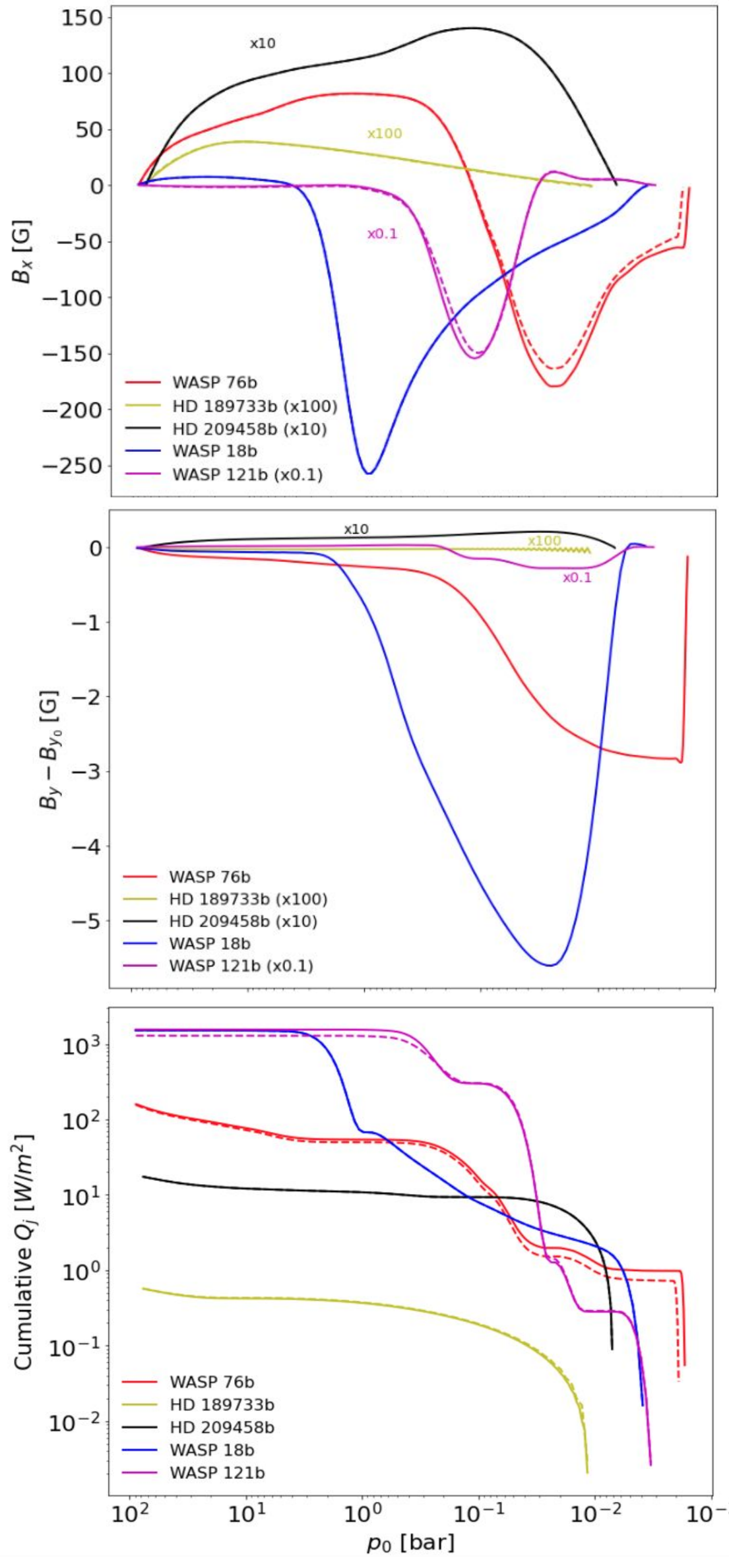

Figure 2: Bx, By and cumulative Qj for all the studied planets. The dashed lines purely winding+Ohmic cases, with no Hall and ambipolar terms included

CONNECTION WITH OBSERVATIONS: ION-NEUTRAL VELOCITY

- [10] presented a novel method to constrain B by comparing the velocities of heavy ions and neutral gas using HR spectroscopy
- Our domain deeper than the photosphere, where the predictions could be tested
- Our velocities, Fig. 3, match with the predicted in [10] (planet with local B= 150 G)

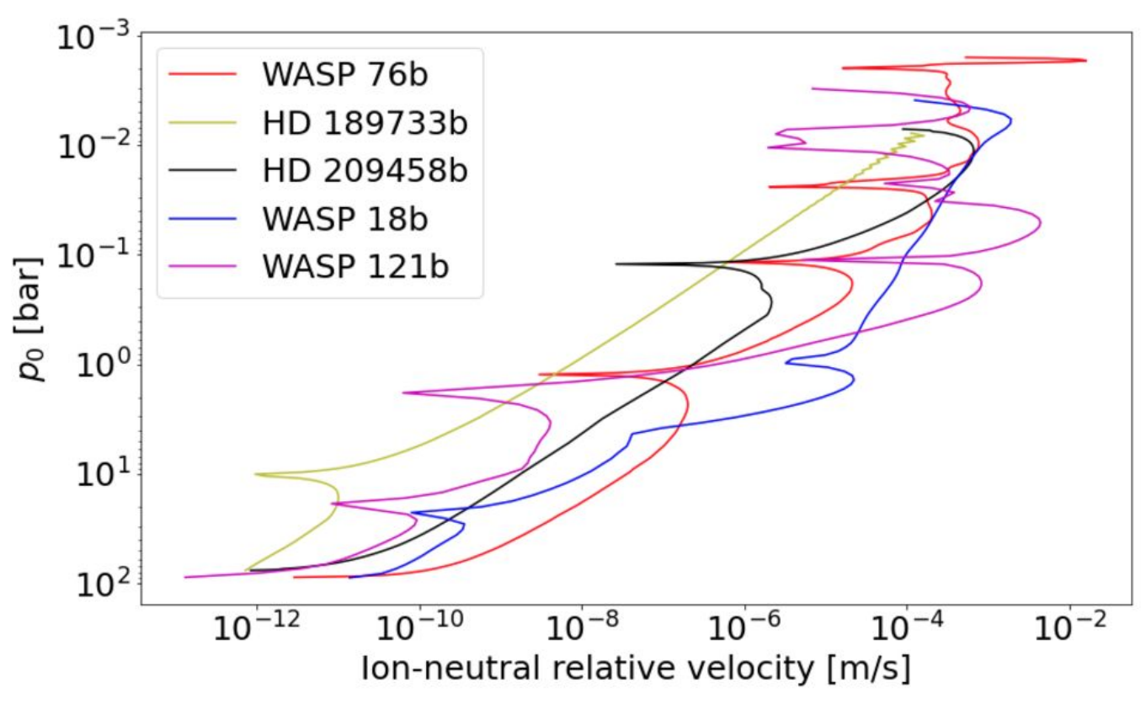

Figure 3: Relative velocity between ions and neutrals inferred from the solutions of the different models

SENSITIVITY ON THE MAXIMUM DEPTH

- Increase of Bmax when reaching deeper layers (BC)
- Dissipation
  - Main contribution at a few bars
  - The total deposited energy is similar for all

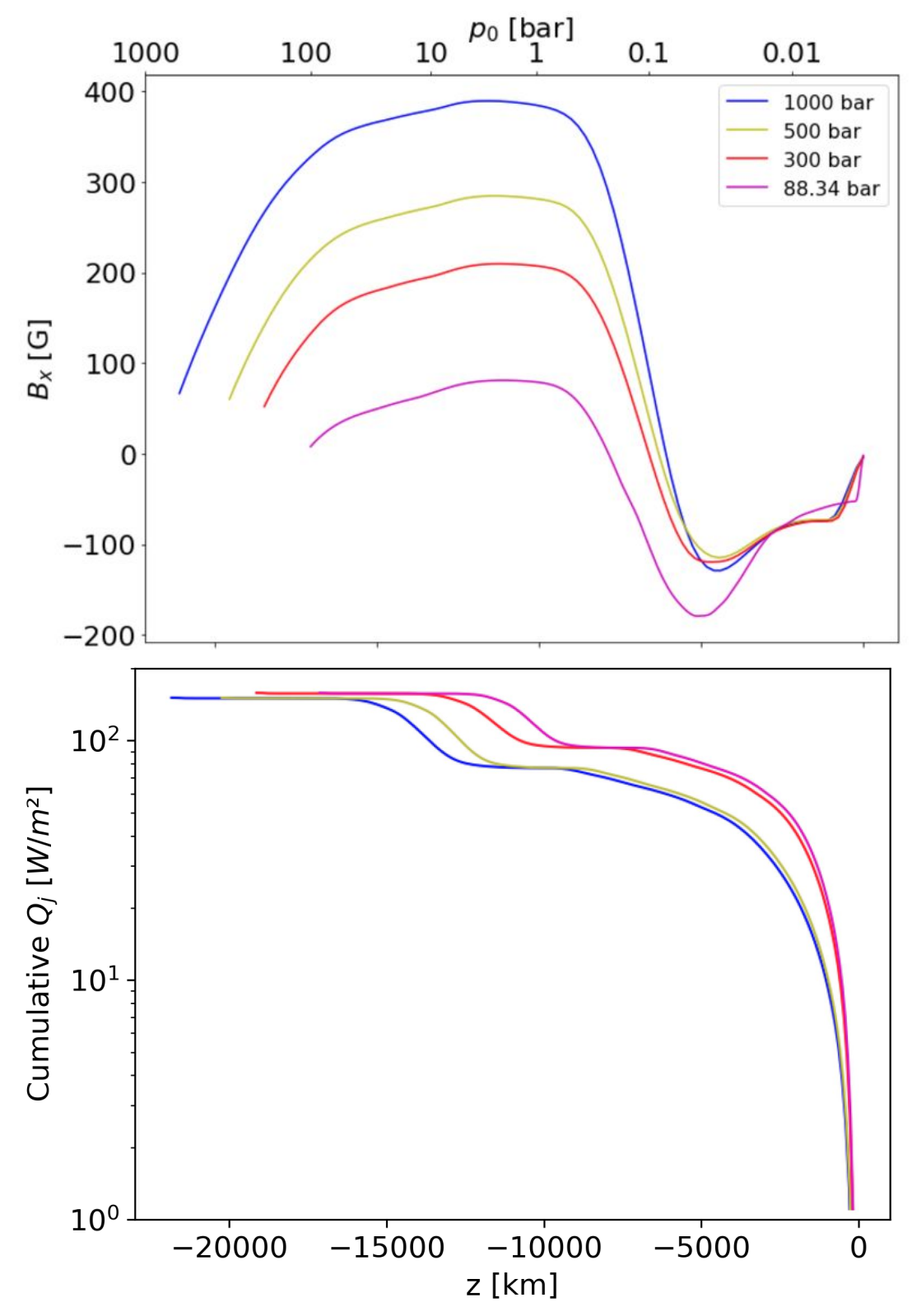

Figure 4: Bx and cumulative Qj considering different extensions of the domain.

SENSITIVITY ON THE MAGNETIC FIELD STRENGTH

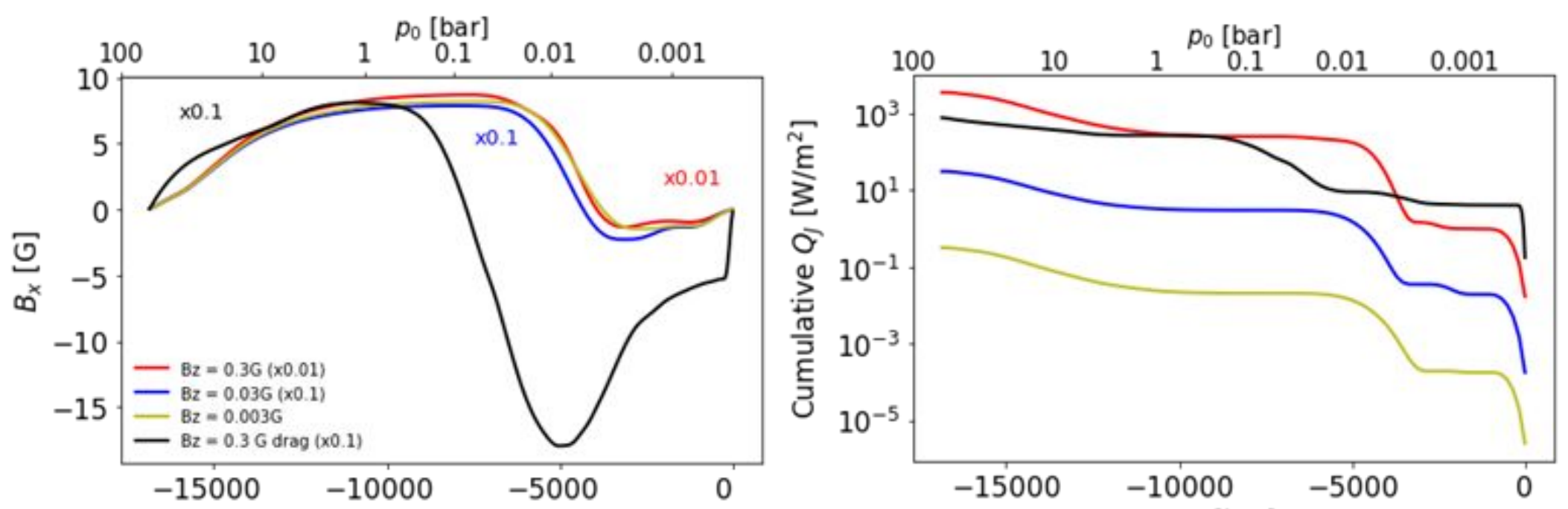

Figure 5: Bx and cumulative Qj for different initial Bz

- No drag
- Max. values of the induced Bx three orders of magnitude greater than initial field (Fig.5)
- Linearity of the winding

Future work

- 1D MHD simulations:
  - Consider other points which are not the sub-stellar
  - Inclusion of simple radiative transfer scheme
  - Extension to shallow layers
- 3D: Evaluation of the perturbative effects in the magnetic field for different planets (Soriano-Guerrero et al. 2025b in preparation)

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Full paper (Soriano-Guerrero et al. 2025a)