Atmospheric turbulence and magnetic field amplification in hot Jupiters

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Abstract

Hot Jupiters (HJs) are gas giants orbiting very close to their host stars. These planets have inflated radii that cannot be accounted for standard cooling models. Various mechanisms have been proposed, among which is Ohmic dissipation based on the dissipation of currents induced by the magnetic field stretching due to the flow motion. This work in progress focuses on the effect of atmospheric turbulence on magnetic fields and Ohmic dissipation in the upper atmosphere of HJs. Box simulations representing tiny atmospheric columns are used to evaluate where electrical currents are induced by the shear layer and the turbulence and quantify them. We perform ideal magnetohydrodynamic (MHD) simulations applicable for very Hot Jupiters. We find strong magnetic fields (up to kG locally) and currents at equilibrium, induced by enforcing the local effects of zonal jets and, at a lesser extent, turbulent perturbations. These models will be used to quantitatively assess the radius inflation, by calculating the (high) conductivity profile.

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1. HJs and Ohmic dissipation

Hot Jupiters have high irradiation from their host star and strong temperature differences between the dayside and the nightside, which generate strong zonal jets that try to redistribute the heat.

For equilibrium temperatures $T_{eq} \gtrsim 1000$ K, there is a clear trend between T_{eq} (i.e., the irradiation) and their **inflated radii**, see Fig. 1. Such radii can reach up to 2 R_J, which cannot be accounted for within standard cooling models for planetary evolution at $\sim$ Gyr ages, even when irradiation is taken into account. Either a cooling slowing down, or a persistent extra heat is needed to explain the observed radii. We focus on the **Ohmic dissipation** (OD) scenario, based on the dissipation of currents induced by the magnetic field stretching due to the flow motion. Such currents are a natural outcome of the strong winds due to the presence of ionized Alkalin metals. Quantifying the amount of such atmospheric OD requires a prescription for both the conductivity and currents profiles.

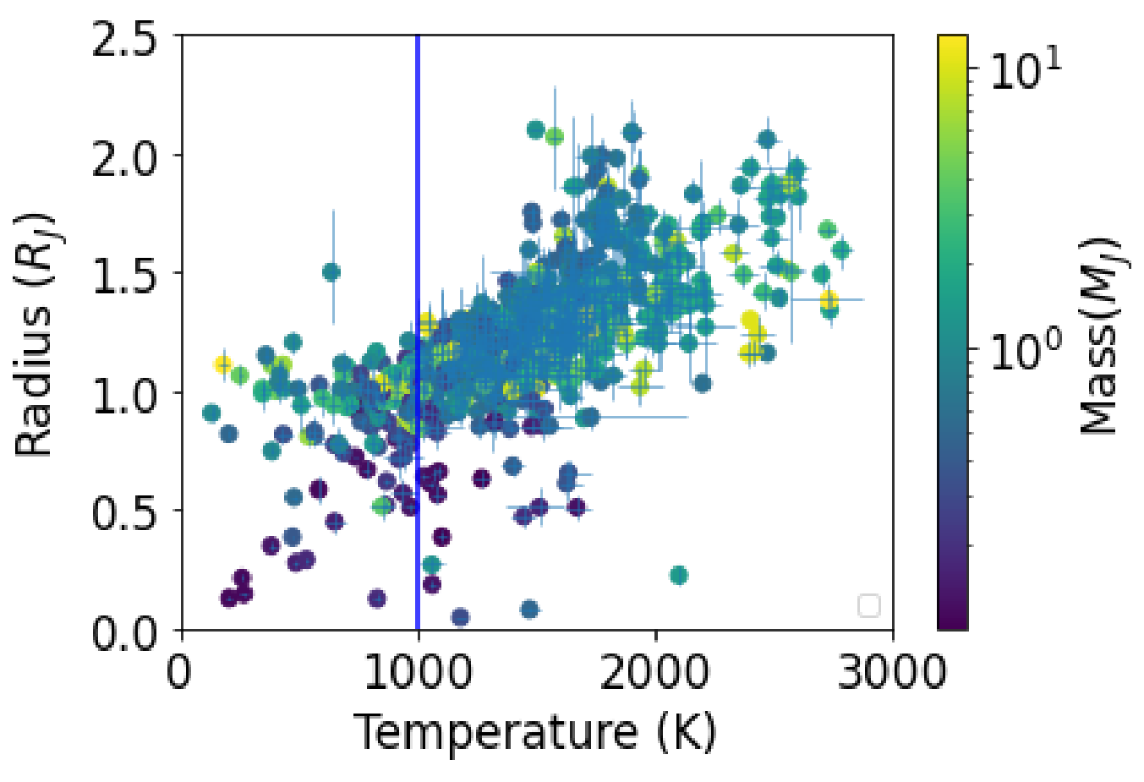

Figure 1. Radius versus temperature scatter of 740 Jupiter-like exoplanets available in the NASA Exoplanet Database. The blue line is at T=1000K, where the radius increase approximately starts.

4. Applicability

We here neglect the resistivity, which is acceptable if the conductivity is high enough. Where does it apply? We calculated the conductivity due to ionized Potassium (the main source of charges for $T \lesssim 3000$ K, and we found that our approximation is valid as long as the equilibrium temperature is larger than $\sim 2000-2500$ K (Fig. 5). When the resistivity is evaluated a posteriori, we can estimate the amount of OD. If the radiative-convective boundary is close enough to the shear layer, then OD can relatively easily lead to relevant HJ radii inflation.

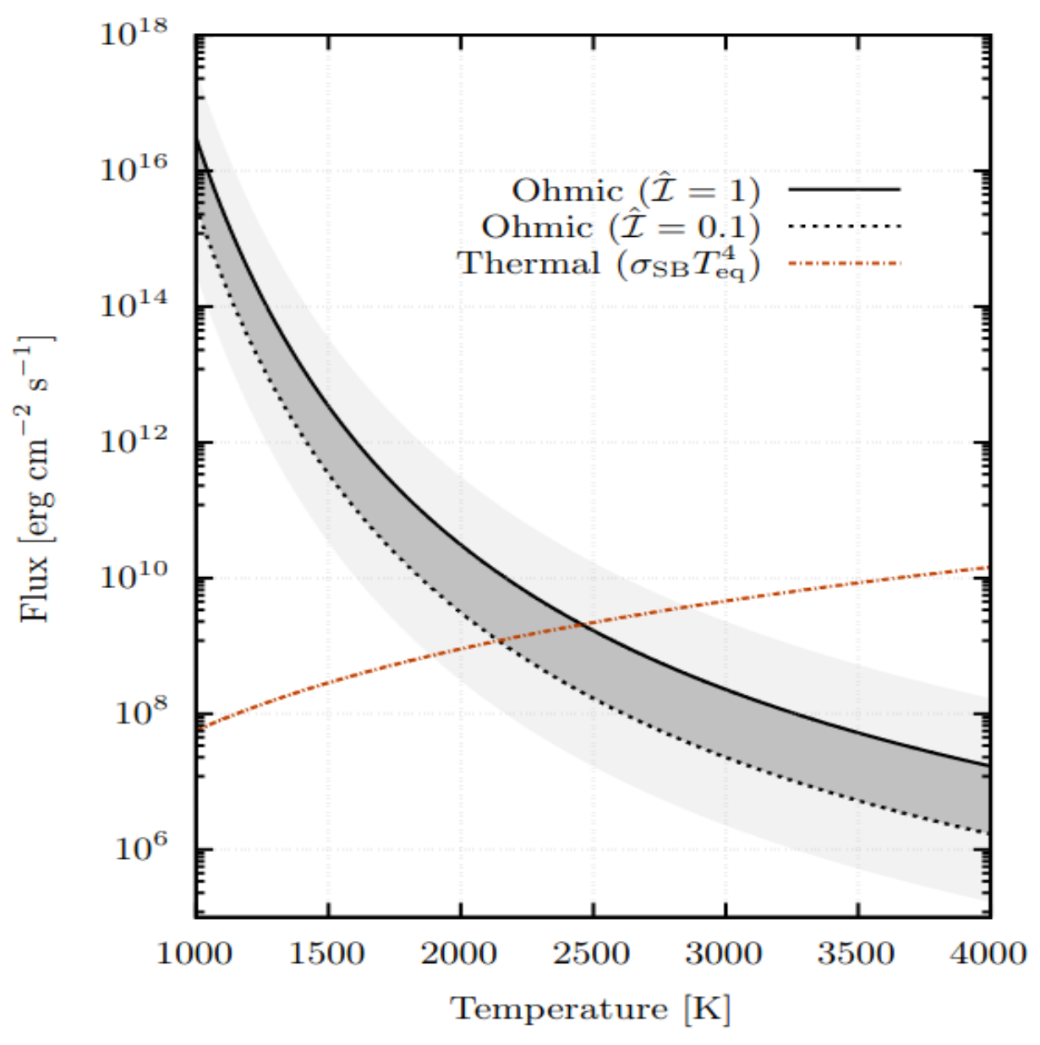

Figure 5. The integrated Ohmic rate $\int_V \frac{J^2}{\sigma}$ (black lines, with the typical values found in our simulations depicted as a dark gray area) has to be less than the irradiation density on the column $\sigma_{sb} T^4$ (red line).

2. Atmospheric model and numerical setup

We perform **3D MHD simulations** in a box, representing a tiny (less than a degree in latitude and azimuth) column of the outer HJ's atmospheres, where the zonal jet (wind) intensity increases, reaching typically the speed of sound in the outermost layers. We prescribe as a forcing a wind profiles $w(z)$ qualitatively similar to the ones calculated by global circulation models, taking into account especially the ones at the sub-stellar point. Such shear ($\partial_z w$), and further additional turbulent perturbations we enforce, cause a magnetic field amplification, up to a saturation value. We use ideal MHD, neglecting resistivity, which is applicable to high enough conductivities, i.e for very Hot Jupiters ($T \gtrsim 2000$ K). We assumed an isothermal regime and a 3D domain $\hat{x}, \hat{y} \in [0,5]$, and $\hat{z} \in [0, L]$, located below 10 bar.

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.

3. Results

We have explored different wind profiles. 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 (Fig. 2, density perturbations). 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). At equilibrium, regardless of the small initial field prescribed, the magnetic field is predominantly toroidal with values up to kG, due to the winding induced by the wind $w(z)$. Additional small-scale structures are provided by turbulence. Most of the magnetic field is again located in the shear layer (Fig. 3). In Fig. 4 we show the average electric current (right) and the magnetic field (left) generated inside the box as a function of height. They both have a maximum in z $\approx$ 1.6 which corresponds to the region where the shear layer is located. The currents flow meridionally (y-axis), and there is no clear sign of a penetration at deeper layers.

This study is a first of its kind to have a more quantitative evaluation of currents, to be used in OD modeling in HJs. Future developments will include the resistivity and the thermal diffusion, rising also the resolution used.

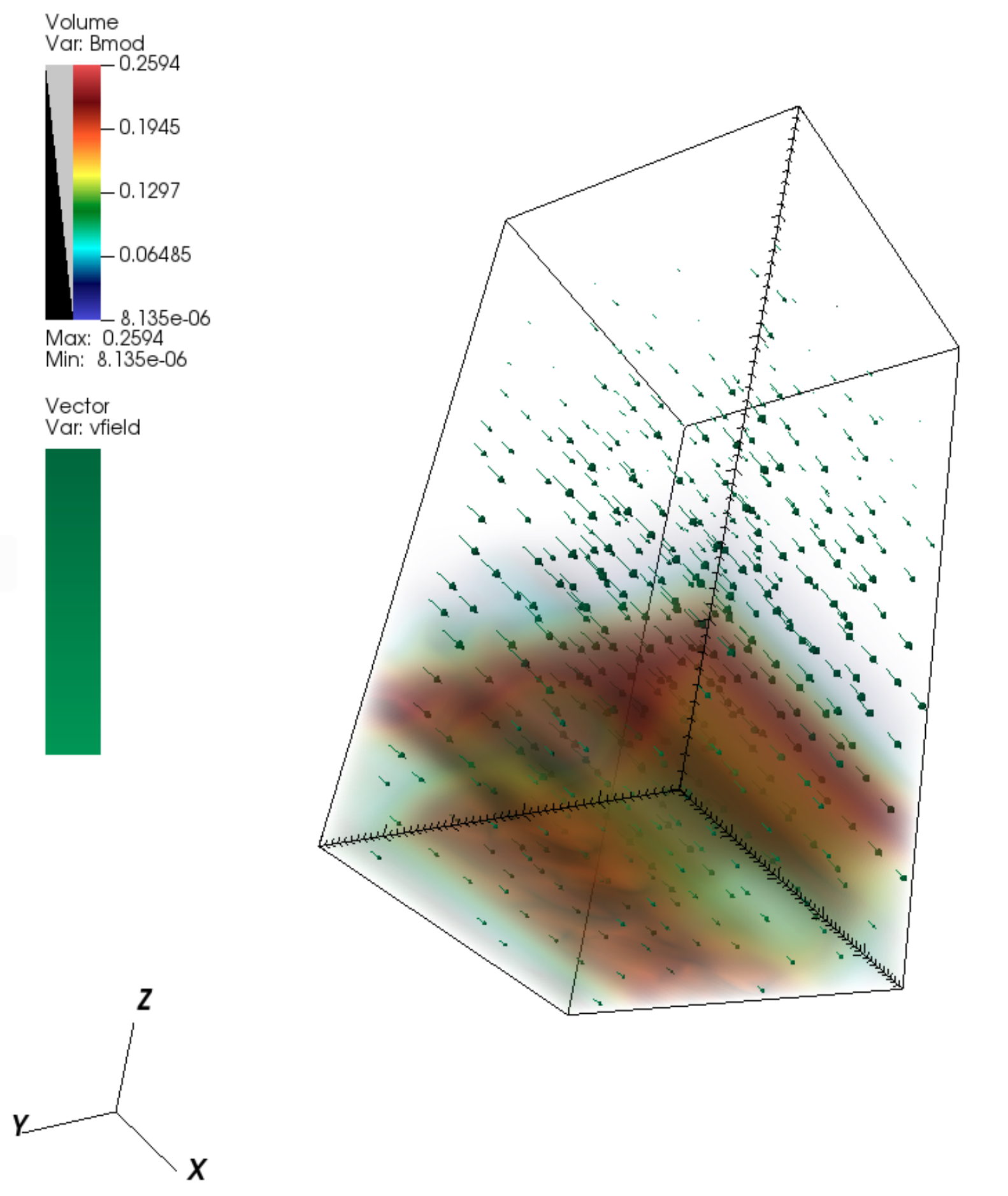

Figure 3: 3D box. Green arrows are the velocity and the colors the intensity of the magnetic field.

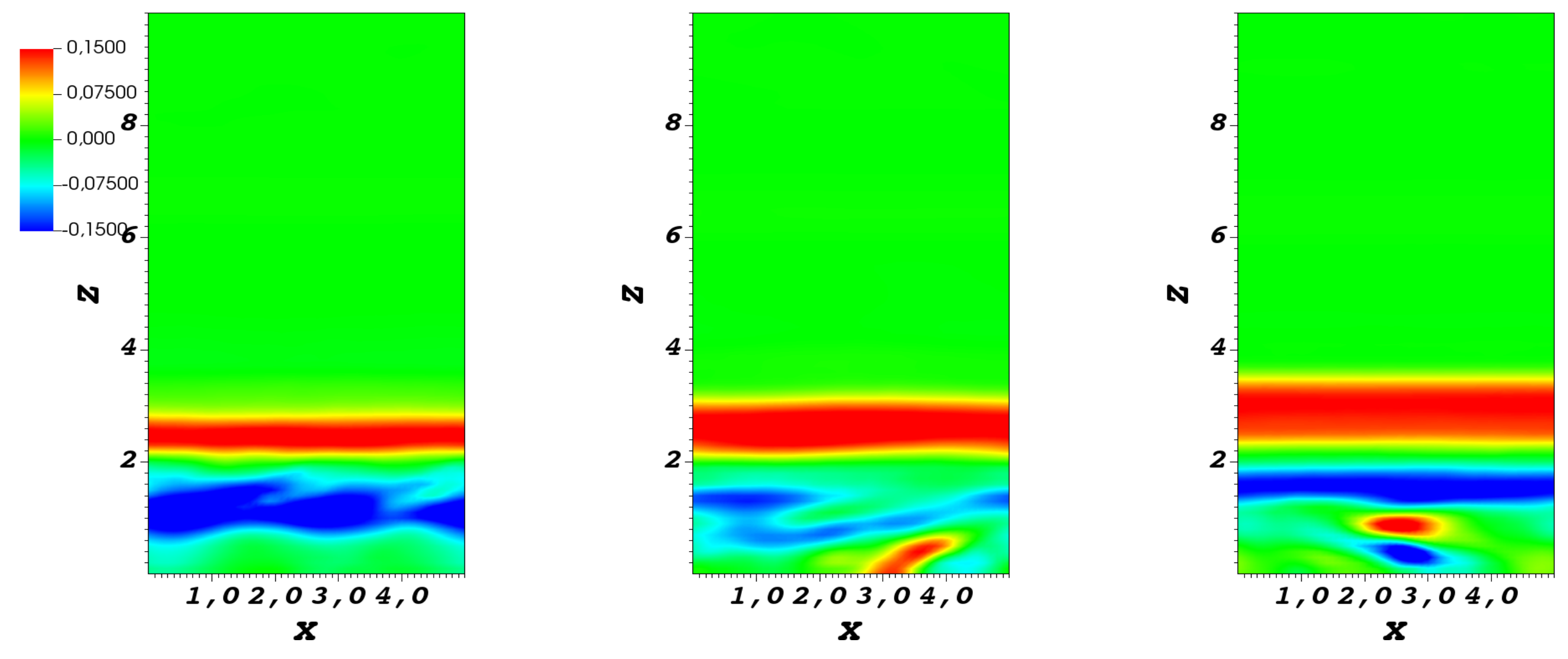

Figure 2. xz slice of the perturbed density $\delta\rho$ at t_*=100 (left), t_*=1200 (center) and t_*=1500 (right), where t_* is the crossing time for a scale-height H_*.

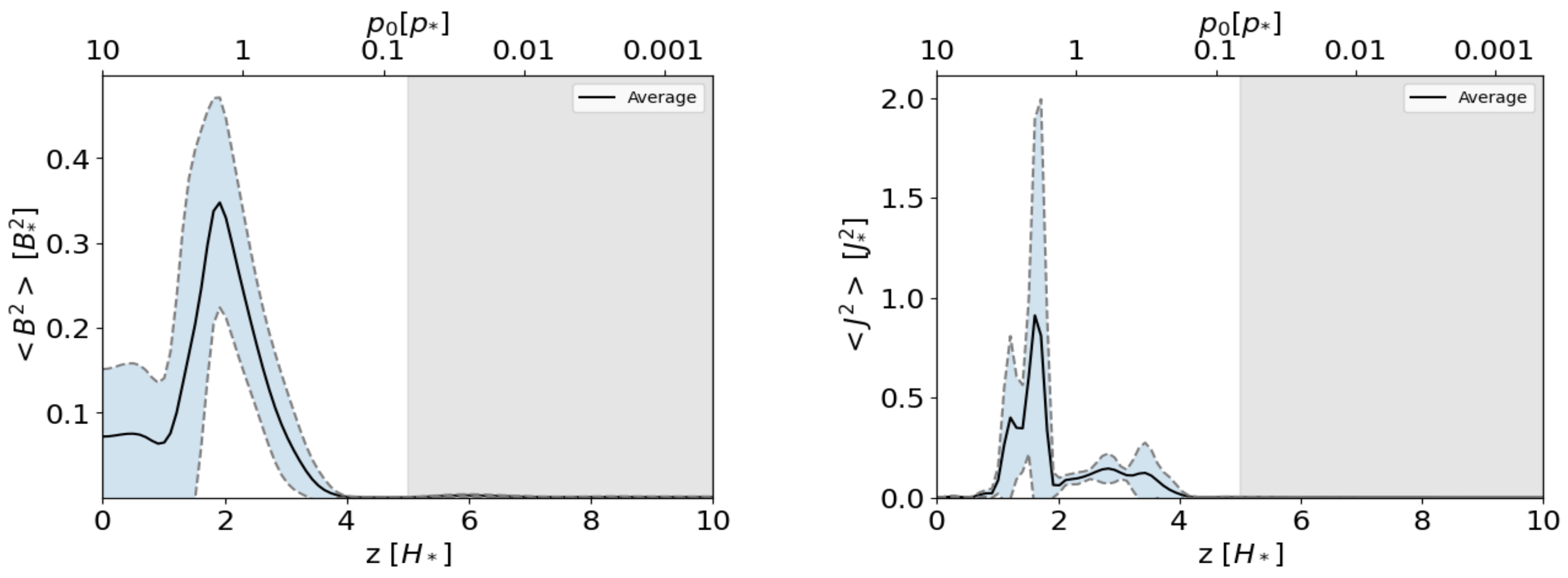

Figure 4. Averaged (in the $x-y$ plane and over a few snapshots) profiles of $B^2(z)$ and J^2(z). The units are $B_* = 0.35$ T, $J_* = \frac{0.218 \frac{\mathrm{A}}{\mathrm{m}^2}}{(T_{eq}/2000K)}$, for gravity $g = 10$ m s^{-2} and a given T_{eq}.