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Magnetic winding and turbulence in Hot Jupiters

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INTRODUCTION

Hot Jupiters (HJs) are gas giants orbiting very close to their host stars, with orbital periods of a few days, corresponding to distances within about 0.1 AU. Due to the high irradiation from their host stars and the tidal locking of the rotational and orbital periods, strong temperature differences persist between the dayside and the nightside. This triggers strong thermal zonal jets that tend to redistribute the heat, as shown in global circulation models (GCMs).
Most HJs have inflated radii, up to double of what cooling models for planetary evolution predict. A strong correlation with the irradiation is observed, with inflation starting to appear for equilibrium temperatures above about Teq = 1000 K. However, the effects of irradiation alone are not quantitatively sufficient to explain the large radii inflation, given the shallowness of the absorbing layer of the radiation. Therefore, the most probable explanation is the continuous deposition of some additional heat.
Among the possible physical mechanisms, one of the most popular is Ohmic heating due to the dissipation of currents induced by the magnetic field which is produced by the zonal winds composed of ionized material. The Ohmic mechanism fits the inferred efficiency trend above: as the irradiation increases, the conductivity and the induced currents increase monotonically, until the generated magnetic fields are strong enough to slow down the global zonal winds via magnetic drag, thus self-regulating the system and limiting the overall efficiency of the mechanism

Most existing studies considered semi-analytical estimates within the linear regime of the induction, i.e. when the atmospheric dynamics produces a small perturbation over the background magnetic field generated in the interior. This approach is valid for relatively low conductivities, corresponding to temperatures T < 1500 K. For higher temperatures, the induced magnetic field is locally so high that the linear approximation fails. Our project focuses on simulations that can connect both regimes.

OHMIC DISSIPATION STUDY

As a first step, in our first work we focused on the non-linear regime, i.e. when the induced magnetic fields are comparable or larger than the internal ones. We presented local ideal MHD simulations of a narrow atmospheric column in the dayside radiative layers of a HJ upper atmosphere (1 mbar-10 bar), which can be seen as an extension of the earlier non-magnetic studies. We included realistic, parametrized profiles for the wind velocity, mimicking the steepest profiles of GCMs and turbulent perturbations. We found that, under conditions that are typical of ultra hot Jupiters (T > 3000 K), a strong toroidal field (of the order of several hundred gauss) is created in the shear layer, confined by meridional currents. Moreover, turbulent small-scale structures induce further currents in deeper regions, but more detailed simulations were needed to assess this clearly.

In this second work, we go a step further to quantify such dissipation, we study the combined effect of winding and atmospheric turbulence. We use realistic profiles for the wind velocity and pressure, obtained from GCM simulations, for different exoplanets. We also include realistic conductivity, which depends on temperature and pressure and can be approximated by classical formulae for the potassium contribution, dominant for the typical HJ. We consider the modelling of four concrete exoplanets, as an application: two moderately irradiated (HD209458b, HD189733b), and two highly irradiated (WASP18b, WASP121b).

RESULTS AND CONCLUSIONS

In our simulations we observed modifications to the profiles and intensities of magnetic fields and currents, compared to both the ideal MHD scenario and the linear regime, especially for intermediate T of about 1500-2000 K, where the bulk of observed HJs lies, due to the winding effect. Such profiles change within the same planet, having a more extreme profiles (in terms of shear of the zonal wind) close to the substellar point, and being more mild at different latitudes and longitudes.

On the other hand, 1D simulations give us information about the winding effect and the amplification of the magnetic field as seen before, however full 3D simulations are very important, since they provide us with information about the amount of currents that can eventually penetrate the convective region below the radiative-convective boundary (RCB) for different cases due to perturbations. These simulations have found that the extremely strong electrical currents generated can be sufficient to account for the observed inflation of

HJs' radii, provided these currents reach the inner layers. Furthermore, magnetic fields in the hottest planets can reach up to kilogauss levels locally around shear layers, with significant variability in induced currents influenced by local planetary temperatures. This work lays the groundwork for future studies on the radio detectability of these features.

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