Atmospheric Outflows from Hot Jupiters: 2D MHD Simulations

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Abstract. Recent observations of stellar hydrogen Ly-α line absorption during transits of some hot Jupiter exoplanets suggest the presence of a dense, fast wind that is blowing from planetary atmosphere (Vidal-Madjar et al. 2003; Ben-Jaffel 2007). Modeling efforts include 1D hydrodynamic models (Murray-Clay et al. 2009; Yelle 2004; García Muñoz 2007) and 2D isothermal magnetized wind models (Trammel et al. 2014), among others. In this work, we model the 2D structure of the irradiated upper atmosphere of a hot Jupiter planet and its interaction with the planetary magnetic field. We calculate self consistently the heating by stellar UV radiation and the cooling of the atmosphere by Ly-α emission. We solve for the ionization structure assuming a 100% hydrogen atmosphere, accounting for the radiative ionization, recombination and advection of the gas. We show the effect of stellar tides and planetary magnetic field on the planet outflow and calculate the Ly-α transmission spectra of the resulting atmosphere.

1. Numerical Setup

We perform 2D hydro- and magnetohydrodynamical (HD /MHD) simulations of the extended upper atmosphere of a hot Jupiter with semi-major axis of $a = 0.05AU$. The planet mass is $M_p = 0.7M_J$, the radius is $R_p = 1.35R_J$, and the planet orbits a solar type star. The code solves the ideal MHD equations in cylindrical coordinates (r, z), with the domain $0 < r/R_p < 12$ and $0 < z/R_p < 4$. The planet is subject to the gravitational potential of the star, which is formulated in the corotating frame. The energy equation is solved by including source terms for the heating by UV stellar light at energies of 20 eV and cooling by Ly-α emission after collisional excitation by free electrons. The ionization balance is calculated for hydrogen, accounting for UV excitation, recombination and ion advection. Simulations are performed with the PLUTO code (Mignone et al. 2007). We use a modified version of the Simplified Non-Equilibrium Cooling (SNeq) module to integrate the energy equation.

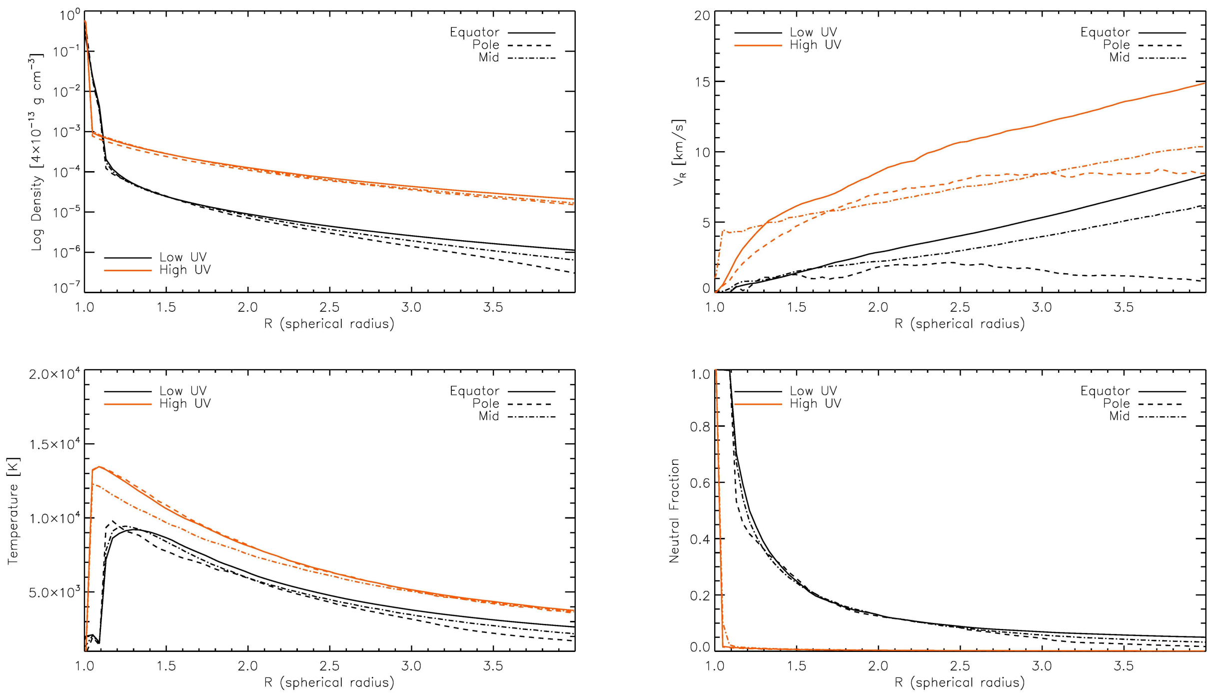

Figure .1: Radial structure of the extended atmosphere of the planet for low UV flux (i.e. solar value) and high UV flux (i.e. 1000X solar value).

2. Hydrodynamic Winds

Figure .1 shows the radial profile of the atmospheric outflow. The temperature rises to $\sim 10^4$ K near the $\tau = 1$ surface at $1.1R_p$ for all latitudes. The warm base drives a supersonic outflow in the equatorial region. In the polar region, the negative vertical stellar gravity quenches the outflow, which remains sub-sonic. For high UV fluxes, the atmosphere is 100% ionized at the base of the wind, while for low UV fluxes $\sim$ 20% of hydrogen remains neutral at $1.5R_p$.

3. Magnetized Winds

Figure .2 shows the poloidal velocity and temperature for a magnetized outflow in a dipolar field with surface amplitudes of $B = 0.1G$ and $B = 2G$ at the equator. The outflow with weak field is flow-dominated by the thermal pressure, and resembles the non-magnetized case. Density and temperature are approximately spherical near R_p, while the poloidal velocity is dominated by v_r (cylindrical). For larger magnetic fields, the flow around the equator is suppressed, resulting in a dead zone with zero poloidal velocity. Gas accumulates in the dead zone creating an over-dense bubble that is heated by irradiation to larger temperatures than at larger latitudes, and where the cooling by advection away from the planet is suppressed. As was observed in the non-magnetized case, the outflow remains subsonic in the polar region, and the field lines are bent towards the star due to the tidal interaction.

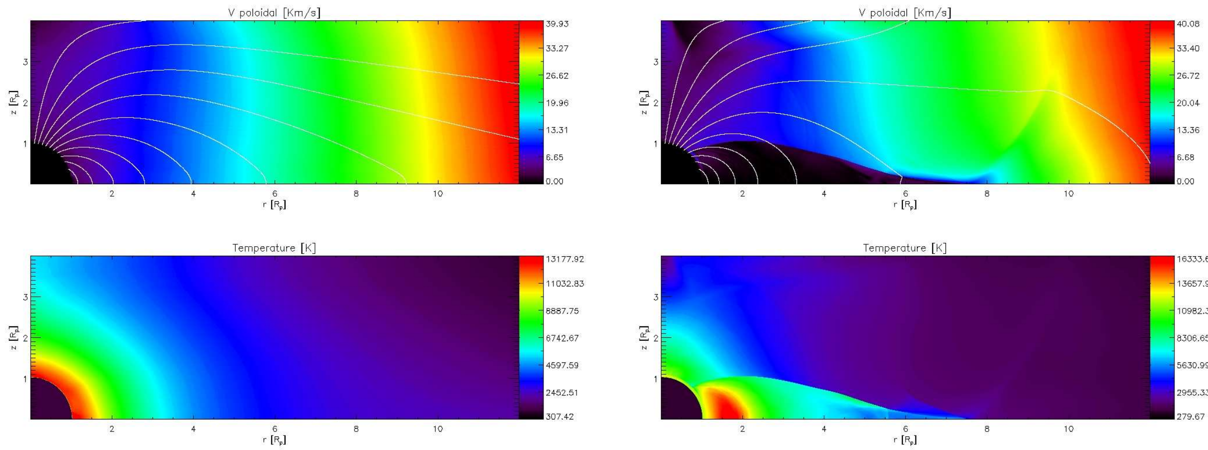

Figure .2: Structure of the magnetized outflow for high UV flux. Top: v_r for $B = 0.1G$(left) and $B = 2G$(right). Bottom: T for $B = 0.1G$(left) and $B = 2G$(right)

4. Transmission Spectra

We calculate the fraction of stellar light (H Ly-α line) absorbed by the atmosphere of the planet during transit for the magnetized models described above. The line transmission spectra are shown in Figure .3 for the high-flux models. Low-flux models have larger absorption due to increased neutral column densities, even though velocities are smaller than in the high-flux case. The warm dead zone in a magnetized atmosphere absorbs around the line center, where the ISM absorption dominates, preventing it from being probed by Ly-α. Between 30km/s and 60km/s, magnetic models begin to differ from unmagnetized ones, with higher field strengths leading to higher absorption. Uribe et al. (2014) will address the magnetized outflows in the low-flux case.

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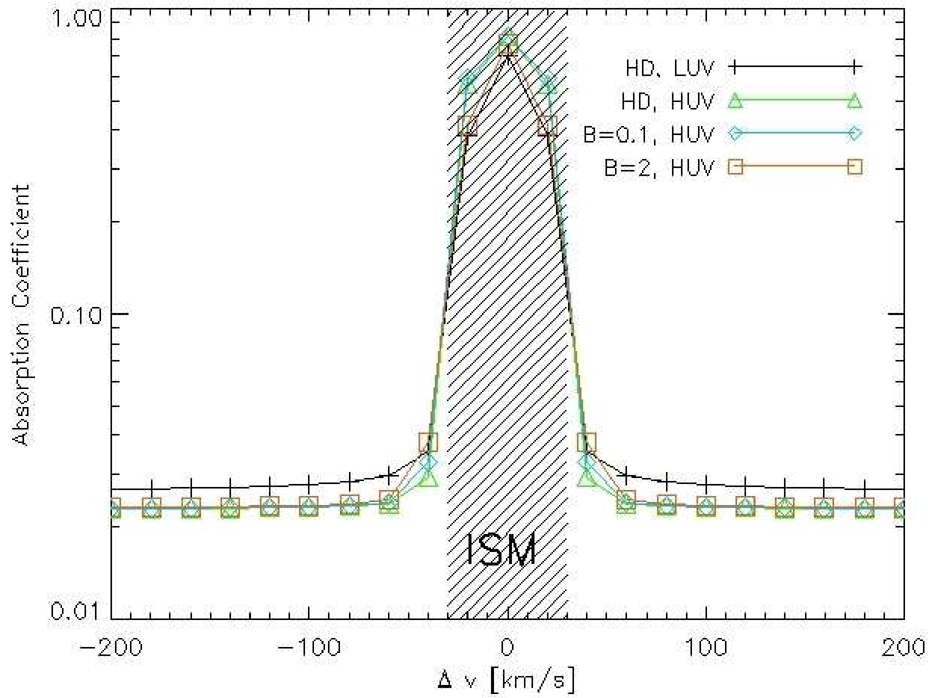

Figure .3: Stellar Ly-α line absorption by the planetary atmosphere.

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