3D Modelling of Magnetized Star-planet Interactions: Cometary-type Tails and In-spiraling Flows

T. Matsakos[1,2], **A. Uribe**[1], **A. Königl**[1]

[1]*Department of Astronomy & Astrophysics, The University of Chicago, Chicago, IL 60637, USA*

[2]*LERMA, Observatoire de Paris, Université Pierre et Marie Curie, Ecole Normale Supérieure, Université Cergy-Pontoise, CNRS, France*

Abstract. Close-in exoplanets interact with their host stars not only gravitationally but also through magnetized plasma outflows. Here, we identify the different types of such interactions based on the physical parameters that characterize the system. We perform 3D magneto-hydrodynamic (MHD) numerical simulations to model the evolution of a variety of possible star-planet configurations, incorporating realistic stellar and planetary outflows. We explore a wide range of parameters and analyze the flow structures and magnetic topologies that develop.

1. Context and Aims

One notable finding of transit observations that probe the atmospheres of close-in planets has been the evidence for escaping material from Hot Jupiters and Neptunes. Their atmospheres are heated by photoionization and the energy input is large enough that it may drive magnetized winds with mass-loss rates on the order of 10^{10}-$10^{12}\,\mathrm{g\,s^{-1}}$ (Murray-Clay et al. 2009; Adams 2011). Such outflows are not isolated; their study has to be extended to take into account their environment, which consists of the stellar wind plasma propagating at velocities of a few hundred of $\mathrm{km\,s^{-1}}$. In this context, the star and planet are expected to interact via their outflows and/or their magnetic fields. In both cases, whether the stellar wind collides with the planetary outflow or its magnetosphere, the interaction can have a potentially observable signature. For example, there might be a detectable bow shock in front of the planet, or a cometary-type tail that trails the orbit, both of which could contribute to the absorption of the stellar radiation of a transiting Hot Jupiter. Cohen et al. (2011) carried out simulations of the star-planet interaction and found the formation of in-spiraling flows that originate from the planet and accrete onto the host. In this work (Matsakos et al. 2014), we perform a series of 3D MHD simulations in order to address the following questions:

1. What are the different types of star-planet interaction that arise in a system of a Hot Jupiter orbiting a solar analog?

2. What is the impact of this interaction on the planet and its outflow?

3. What is the feedback on the stellar wind and the host star?

2. Numerical Setup

For the initial conditions of the two outflows, we adopt a simplified approach along the lines of Matt & Pudritz (2008). We initialize isothermal Parker-type winds, as well as dipolar magnetospheres, both for the star and the planet. The temporal evolution of such configurations opens up the magnetospheres and leads to self-consistent steady-state winds. We use PLUTO (Mignone et al. 2007) to integrate the MHD equations in a 3D box that spans 30 stellar radii along each dimension. We explore a wide range of planetary and orbital parameters to cover the rich parameter space of Hot Jupiters. In particular, we consider two types of planets, one that is Jupiter-like in terms of its mass and radius, and another that is less massive but larger in size. We investigate both the low ($5 \cdot 10^2\,\mathrm{erg\,cm^{-2}\,s^{-1}}$) and the high ($5 \cdot 10^5\,\mathrm{erg\,cm^{-2}\,s^{-1}}$) regimes of incident EUV flux using the classification of Murray-Clay et al. (2009). This determines the density and velocity profiles of the planetary outflows, which we have matched with 1D sophisticated numerical simulations (Uribe et al. 2014). Two additional parameters are the distance of the Hot Jupiter from the host star and the strength of the planetary magnetic field. The following table lists the values we have considered in our simulations:

3. Results

Figure 1 displays the final steady state of a star-planet simulation for a Hot Jupiter (mass $0.5\,M_\mathrm{J}$, radius $1.5\,R_\mathrm{J}$, magnetic field 0.1 G) that orbits a solar analog (low UV flux) at 0.05 AU (period of 3.7 days). The planetary outflow is weak and cannot overcome the (projected along the orbit) ram pressure of the stellar wind. The impact leads to a bow shock that keeps the magnetosphere compressed and closed. The atmospheric plasma is trapped within the dead zone and is channeled backwards, trailing the orbit. The cometary-type tail that forms is blown away by the stellar wind.

Figure 2 displays a simulation for a similar Hot Jupiter in terms of the planetary and orbital parameters, but for a younger host star (high UV flux regime). A strong planetary wind develops and the flow becomes super-Alfvénic within a few planetary radii. Its collision with the environment leads to the formation of shocks. Part of the accumulated material accretes onto the host, and the rest forms a dense tail. The velocity shear and the push from

Table .1: The range of parameters considered in the simulations.

Parameter	Stellar value	Planetary value	Units
Radius	$1\,R_\odot$	1–1.5 R_J	$R_\mathrm{J} \simeq 10^{-1}\,R_\odot$
Mass	$1\,M_\odot$	0.5–1 M_J	$M_\mathrm{J} \simeq 10^{-3}\,M_\odot$
Temperature	10^6	$6 \cdot 10^3$–10^4	K
Magnetic field	2	0.1–1	G
Escape speed	620	36–62	$\mathrm{km\,s^{-1}}$
Sound speed	130	9–13	$\mathrm{km\,s^{-1}}$
$(v_\mathrm{esc}/c_\mathrm{snd})^2/2$	11.5	3.8–23	–
Plasma beta	5	0.002–400	–
Rotation period	12	1.2–3.7	days
Stellar UV flux	$5 \cdot 10^2$–$5 \cdot 10^5$	–	$\mathrm{erg\,cm^{-2}\,s^{-1}}$
Orbital radius	–	0.02–0.05	AU
Orbital period	–	1.2–3.7	days
Orbital speed	–	138–195	$\mathrm{km\,s^{-1}}$

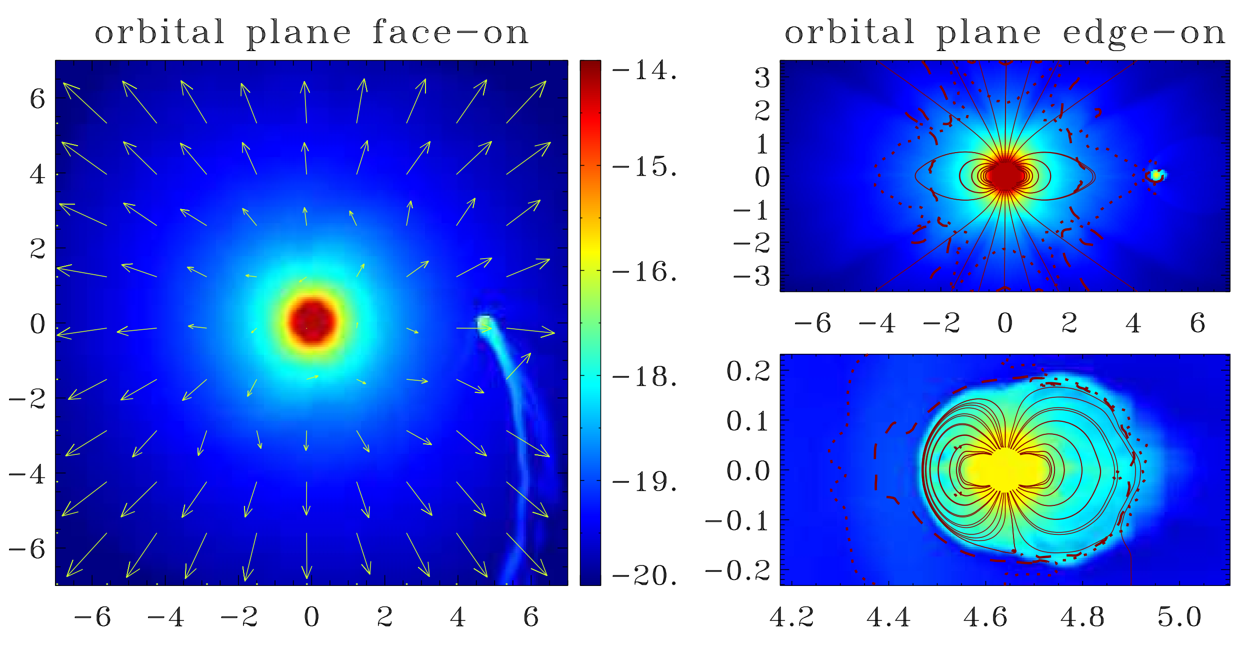

Figure .1: Logarithmic density contours (in units of $\mathrm{g\,cm^{-3}}$) are shown for a Hot Jupiter with a weak prescribed outflow (the unit length is 0.01 AU). Left panel: orbital plane face-on. Right panels: orbital plane edge-on, focused on the star (top) and on the planet (bottom). Solid lines represent the magnetic field, vectors show the velocity field, dashed lines the poloidal Alfvén surface and dotted lines the sonic one.

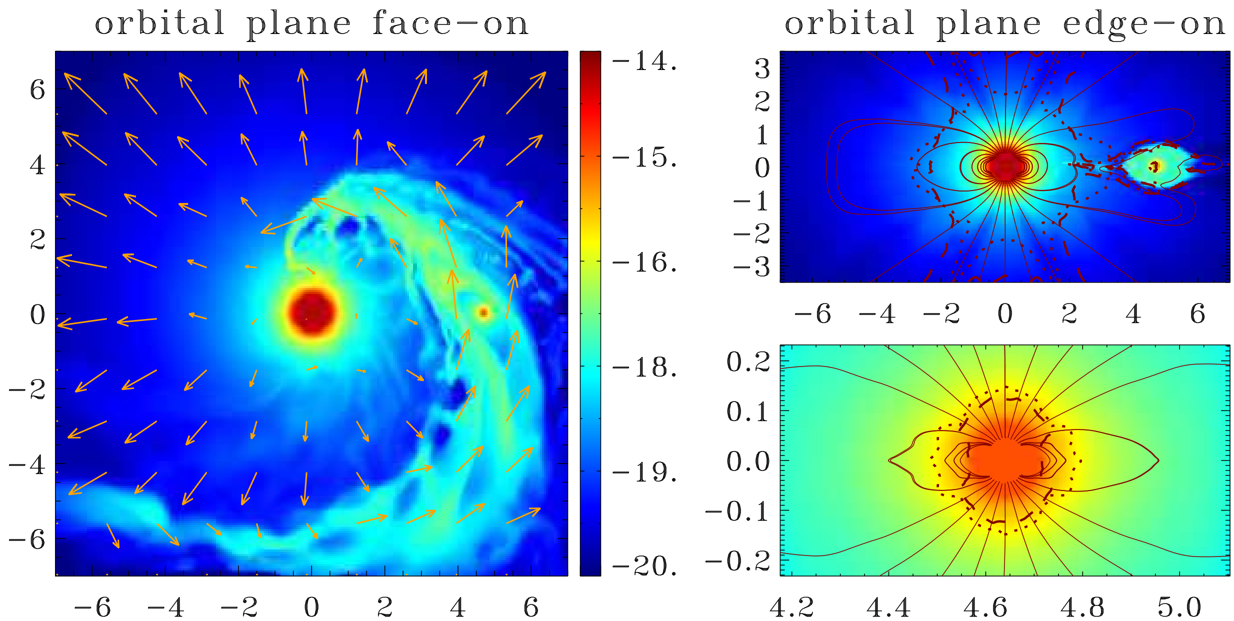

Figure .2: Same as Fig. 1 but for the case of a Hot Jupiter with a strong outflow.

the low density stellar plasma give rise to Kelvin-Helmholtz and Rayleigh-Taylor instabilities in both the in-spiraling and the trailing streams. Such dense features might have an observable signature during transits.

Acknowledgements. We thank Sean Matt for his helpful guidance in the implementation of the stellar wind models, as well as S. Wolk, I. Pillitteri, K. Poppenhaeger, O. Cohen, J. Turner, A. Strugarek, S. Brun, V. Reville, A. Vidotto, A. Lanza, F. Adams, and F. Rasio for fruitful discussions. This work was completed with resources provided by the University of Chicago Research Computing Center, and was supported by NASA ATP grant NNX13AH56G and NSF grant AST-0908184.

References

Adams, F. C. 2011, Apj, 730, 27

Cohen, O., Kashyap, V. L., Drake, J. J., et al. 2011, ApJ, 733, 67

Matt, S. & Pudritz, R. E. 2008, ApJ, 678, 1109

Matsakos T., Uribe A., Königl A. 2014, preprint, to be submitted to A&A

Murray-Clay R., Chiang E., Murray N. 2009, ApJ, 693, 23

Mignone A., Bodo G., Massaglia S., Matsakos T., Tesileanu O., et al. 2007, ApJS, 170, 228

Uribe A., Matsakos T., Königl A., 2014, preprint, to be submitted to ApJ