Classification of magnetized star-planet interactions: bow shocks, comet-like tails, and in-spiraling streams

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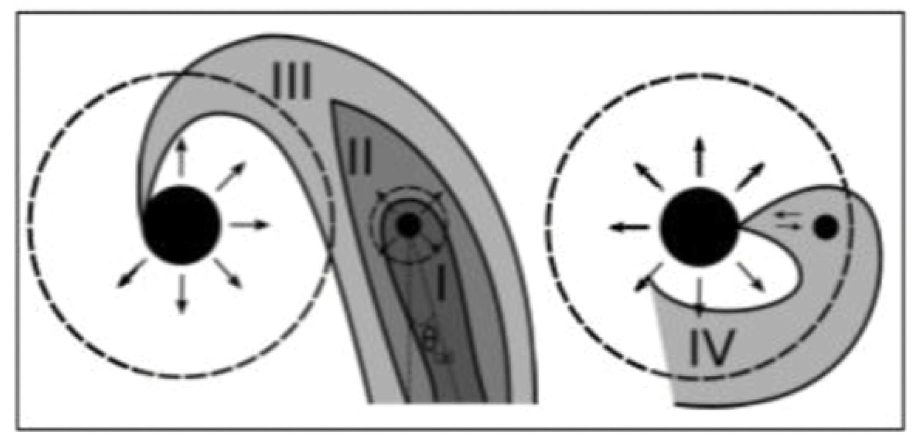

Abstract

Stellar irradiation is believed to drive outflows from the surface of close-in exoplanets, a phenomenon that is supported by transit observations of Hot Jupiters. Assuming planetary magnetospheres similar to those of our solar system, such outflows are expected to be magnetized. Moreover, the environment of short period orbits consists of the sweeping stellar wind plasma that is known to attain super-sonic velocities. This framework suggests the manifestation of complex magnetized star-planet interactions in systems harboring Hot Jupiters. In this work, we perform a series of parameterized 3D magneto-hydrodynamic numerical simulations in order to provide a classification for the different types of interactions that may occur (Matsakos et al. 2014). We incorporate stellar and planetary outflows that are consistent with detailed physical models and investigate case by case the exhibited dynamics.

Numerical setup

For the simulations we use PLUTO, a numerical code for computational astrophysics (Mignone et al. 2007). We integrate the magneto-hydrodynamic (MHD) equations in a 3D cartesian box that spans 30 stellar radii (R_*) along each dimension.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0\,,$$
$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} + \frac{1}{4\pi\rho}\mathbf{B}\times(\nabla\times\mathbf{B}) + \frac{1}{\rho}\nabla P = \mathbf{g} + \mathbf{F}_{\rm in}\,,$$
$$\frac{\partial P}{\partial t} + \mathbf{v}\cdot\nabla P + \gamma P \nabla\cdot\mathbf{v} = 0\,,$$
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla\times(\mathbf{B}\times\mathbf{v}) = 0\,.$$

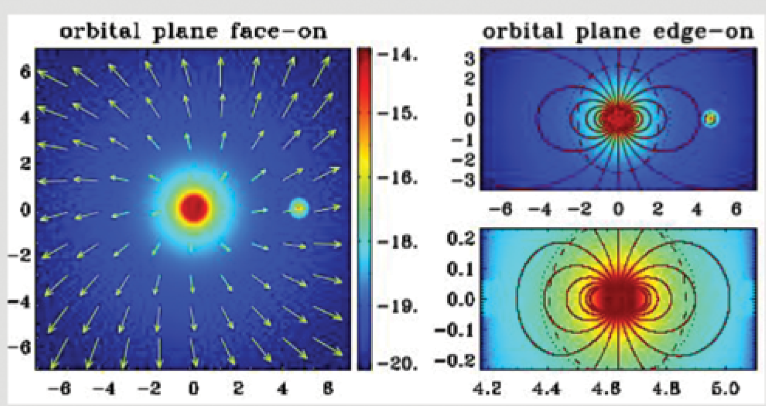

Fig. 1: The MHD equations (left) and the initial conditions on the right. The 2D slices show the logarithmic density contours (in units of g cm^{-3}) for z = 0 (x-y plane; left panel) and for y = 0 (x-z plane; right panels). The top right panel is focused on the star and the bottom right on the planet. Solid lines represent the magnetic field, arrows show the velocity field, dashed lines the poloidal Alfvén surface, and dotted lines the sonic surface. The axes are in units of 0.01 AU.

The star is placed in the center of the domain and the planet on a circular orbit around it (see right panel of Fig 1. The computational domain is resolved by a static, multiply refined grid of 424 × 320 × 320 cells. Due to the different sizes of the two bodies, the resolution of the planet and its vicinity is higher than the stellar by an order of magnitude (Δx, Δy, $\Delta z \simeq 0.008\ R_*$ or 128^3 cells). The physical duration of the simulation is 4 days, in a fraction of which the system attains a quasi steady state.

We adopt highly accurate numerical schemes to compensate for the resolution limits imposed by the three-dimensional character of the simulations. We use the HLLD Riemmann solver and we apply third order accuracy in space (piecewise parabolic interpolation) and time (3rd order Runge-Kutta). Finally, the condition $\nabla \cdot \mathbf{B} = 0$ is ensured with the divergence cleaning method.

Each numerical simulation required 50 000 hours of computational time in Midway of RCC, whereas each data file saved at specified time intervals was 3GB.

Results

The left panel of Fig. 2 displays the final steady state of a star-planet simulation for a Hot Jupiter (mass 0.5 M_J, radius 1.5 R_J) 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, is channeled backwards, and forms a comet-like tail that is blown away by the stellar wind. The right panel of Fig. 2 shows a model of a similar Hot Jupiter that orbits at 0.025 AU (period of 1.2 days), i.e. within the critical surface of the stellar wind. Here there are no shocks, material from the planet and its tail accretes onto the star along their common flux tubes.

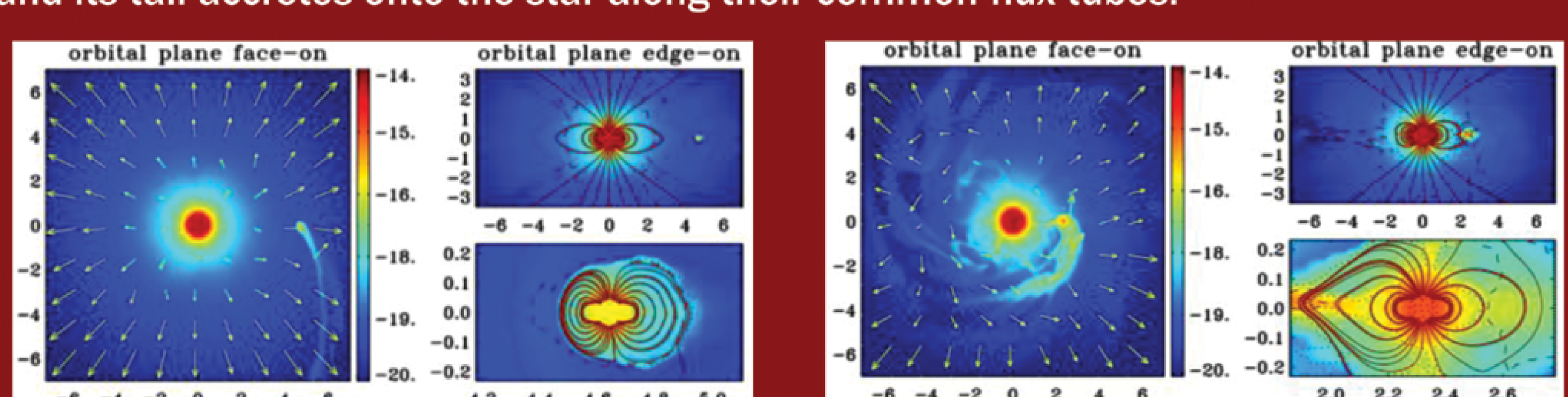

Fig. 2: Logarithmic density contours (g cm^{-3}) for a close-in Hot Jupiter (right panel), and one for a further out planet (left panel). Solid lines represent the magnetic field, vectors show the velocity field, dashed lines the Alfvén surface and dotted lines the sonic one. The unit length is 0.01 AU. Top panels focus on the star and bottom on the planet.

Results

Figure 3 displays a simulation for a similar Hot Jupiter located at 0.05 AU, but for a younger host star (high UV flux regime). A strong planetary wind develops and the flow becomes super-Alfvenic 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 the low density stellar plasma give rise to Kelvin-Helmholtz and Rayleigh-Taylor instabilities in both the in-spiraling and the trailing streams.

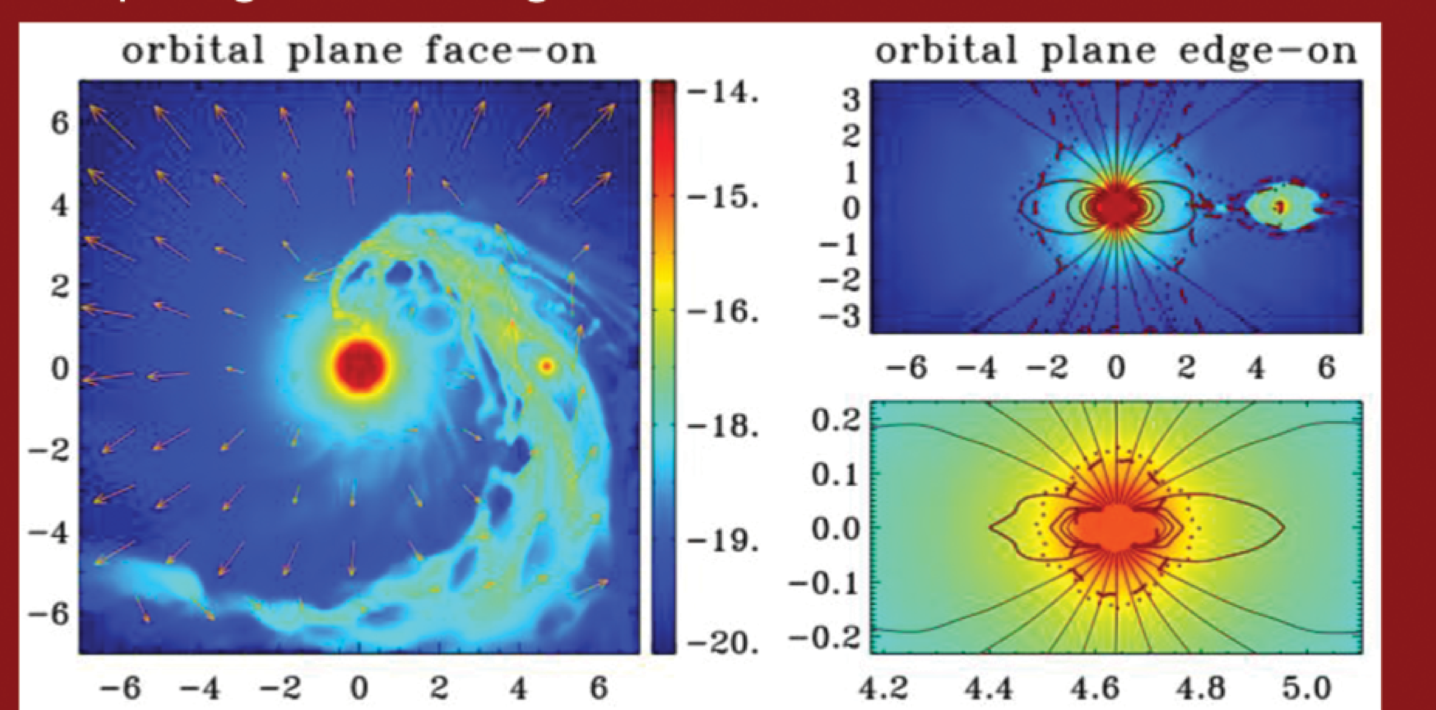

Fig. 3: Same as Fig. 2 but for the case of a Hot Jupiter with a strong outflow.

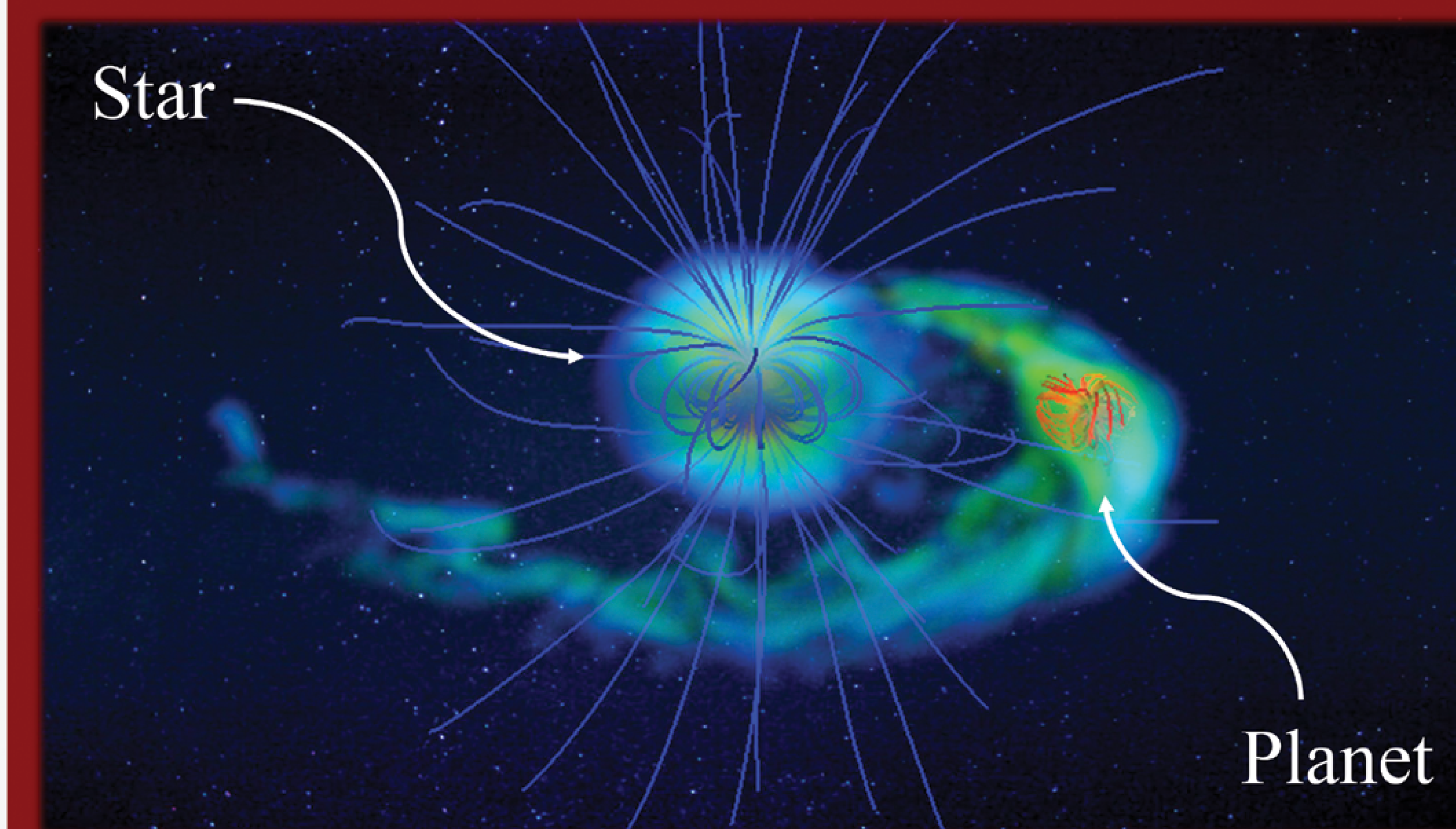

Fig. 4: 3D representation of the star-planet interaction shown in Fig. 3. The colored flow highlights the density of the plasma and the blue/red lines the magnetic field. This is the final steady state of the simulation.

Our analysis led to the following conclusions:

1. Star-planet interactions may be classified into four categories I, II, III, and IV (see sketch on top). Cases I, II, and III have the Hot Jupiter outside the critical surface of the stellar wind, and case IV within.
2. Type I interactions exhibit a bow shock ahead of the planet, due to the plasma of the environment that impacts onto the planetary magnetosphere. A comet-like tail develops in the trail of the orbit, and is being blown away by the stellar wind (e.g. left panel of Fig. 2).
3. Cases II/III develop a planetary outflow that opens up the magnetosphere and collides with the stellar wind. The shocked plasma is dragged backwards forming a wide tail, which is then fragmented by dynamical instabilities. Interactions of type III show additionally an accreting stream of planetary origin that spirals in and impacts onto the stellar surface (e.g. Fig. 3).
4. Class IV interactions are expected to have plasma flowing directly from the planetary surface to the star via magnetic flux tubes that connect the two bodies (e.g. right panel of Fig. 2). These structures are expected to be time-dependent because the magnetic field topology changes in time due to the reconnection induced by the orbital motion.

Acknowledgements

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References

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