

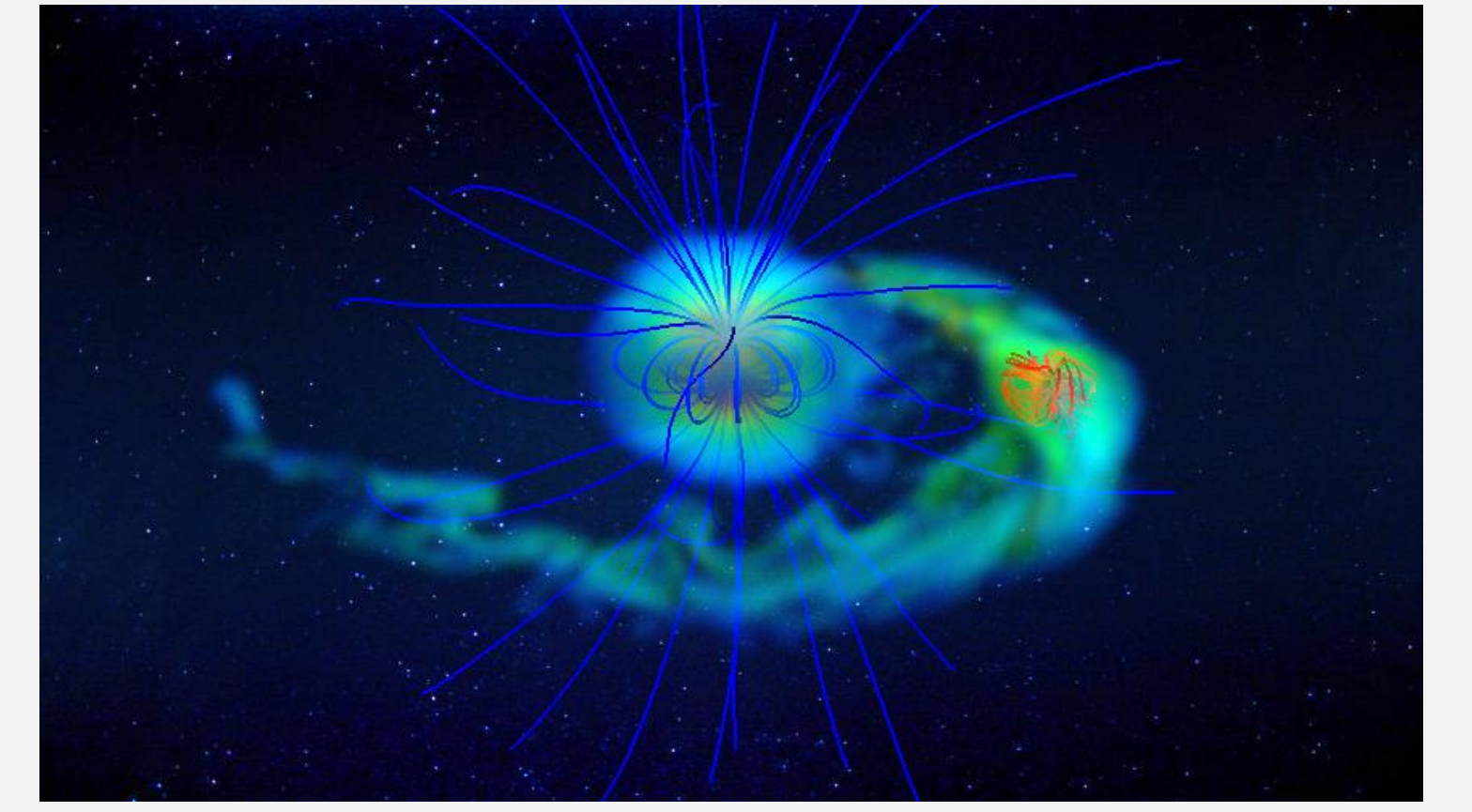
Classification of magnetized star-planet interactions: bow shocks, comet-like tails, and in-spiraling streams



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Abstract

Stellar irradiation is believed to drive outflows from the surface of close-in planets, 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. On the other hand, 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. 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 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 for both 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 further investigate both the low ($5 \cdot 10^2 \text{ erg cm}^{-2} \text{ s}^{-1}$) and the high ($5 \cdot 10^5 \text{ erg cm}^{-2} \text{ s}^{-1}$) regimes of the 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:

Parameter	Symbol	Stellar value	Planetary value	Units
Radius	R_*, R_p	$1 R_\odot$	$1-1.5 R_J$	$R_J \approx 10^{-1} R_\odot$
Mass	M_*, M_p	$1 M_\odot$	$0.5-1 M_J$	$M_J \approx 10^{-3} M_\odot$
Surface temperature	T_*, T_p	10^6	$6 \cdot 10^3-10^4$	K
Surface density	ρ_*, ρ_p	$5 \cdot 10^{-15}$	$7 \cdot 10^{-17}-3 \cdot 10^{-13}$	g cm^{-3}
Equatorial surface magnetic field	B_*, B_p	2	0.1-1	G
Escape speed at the surface	$v_{\text{esc}*, v_{\text{esc}p}}$	620	36-62	km s^{-1}
Sound speed at the surface	$c_{\text{snd}*, c_{\text{snd}p}}$	130	9-13	km s^{-1}
Surface speed ratio $(v_{\text{esc}}/c_{\text{snd}})^2/2$	λ_*, λ_p	11.5	3.8-23	-
Surface plasma beta $P/(B^2/8\pi)$	β_*, β_p	5	0.002-400	-
Rotation period	$\mathcal{P}_*, \mathcal{P}_p$	12	1.2-3.7	days
Stellar UV flux	F_{UV}	$5 \cdot 10^2-5 \cdot 10^5$	-	$\text{erg cm}^{-2} \text{ s}^{-1}$
Orbital radius	R_{orb}	-	0.02-0.05	AU
Orbital period	\mathcal{P}_{orb}	-	1.2-3.7	days
Orbital speed	v_{orb}	-	138-195	km s^{-1}

Results

The left panel of Fig. 1 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. 1 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.

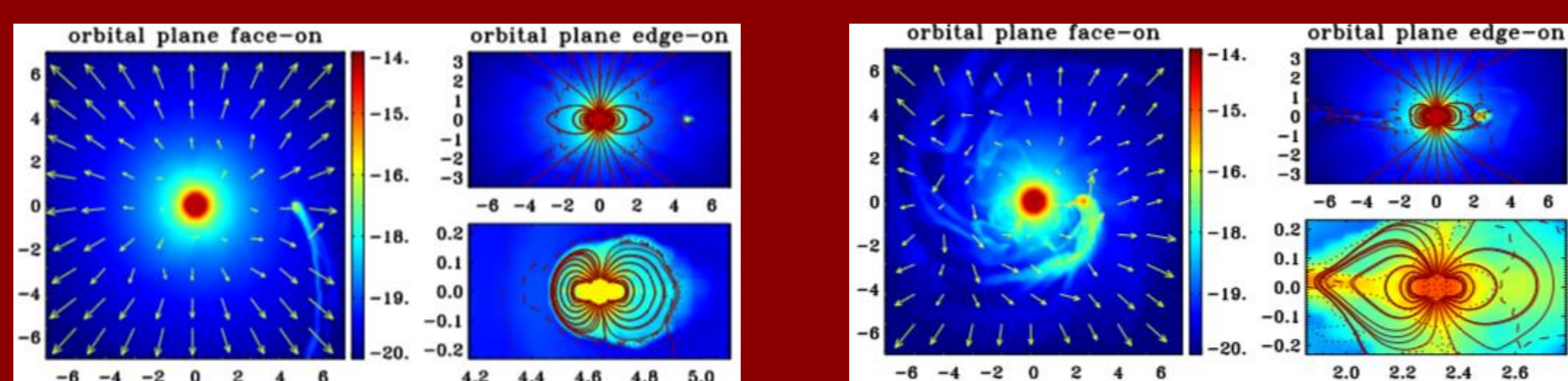


Fig. 1: Logarithmic density contours (g cm^{-3}) for a close-in Hot Jupiter (right panel), and one for a further out planet (left panel). Solid lines represent the magnetic field, vectors show the velocity field, dashed lines the Alfvén surface and dotted lines the sonic one. The unit length is 0.01 AU. Top panels focus on the star and bottom on the planet.

Results

Figure 2 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-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 the low density stellar plasma give rise to Kelvin-Helmholtz and Rayleigh-Taylor instabilities in both the in-spiraling and the trailing streams. The accreting flow and its impact might have an observable signature similar to what Pillitteri et al. (2010, 2011, 2014) have found (see Pillitteri+ poster).

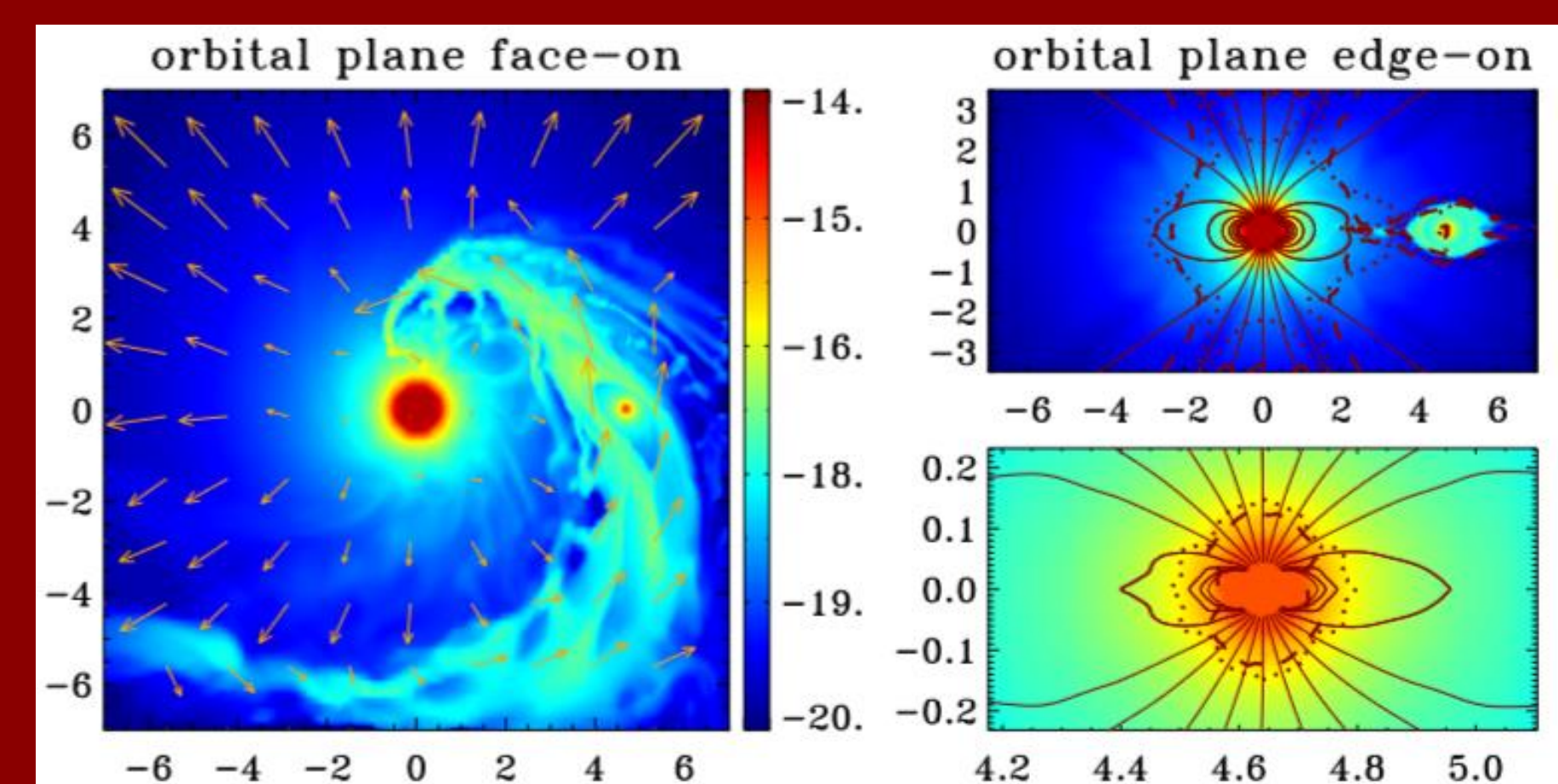


Fig. 2: Same as Fig. 1 but for the case of a Hot Jupiter with a strong outflow.

Our analysis led to the following conclusions:

1. Star-planet interactions may be classified into four categories I, II, III, and IV (see Fig. 3). 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. 1).
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. 2). The presence of the stellar wind and magnetosphere slow down the plasma, thus preventing it from forming a torus.
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. 1). 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.

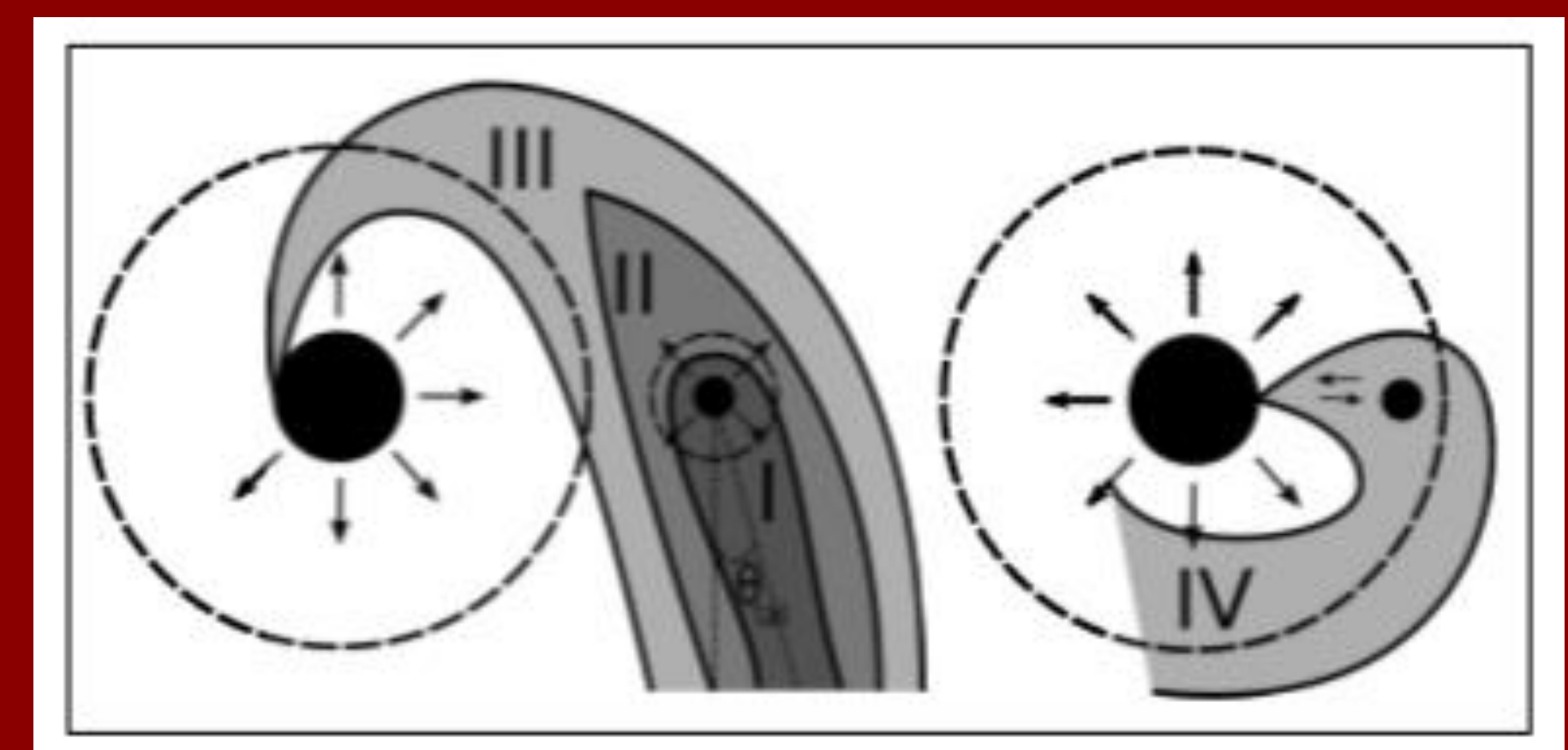


Fig. 3: Sketch of the orbital plane face-on that classifies the four types of star-planet interactions. The large solid circle is the star and the small the Hot Jupiter. The dashed lines show the critical surfaces of the flows, which is indicated with arrows. The gray areas highlight the material escaping from the planet. The different possible configurations are denoted with the latin numbers I, II, III, IV. The left panel groups together the cases where the Hot Jupiter is beyond the critical surface of the stellar wind, and the right panel when it is within.

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