


Could star-planet magnetic interactions lead to planet migration and influence stellar rotation?

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Abstract. The distribution of hot Jupiters, for which star-planet interactions can be significant, questions the evolution of exosystems. We aim to follow the orbital evolution of a planet along the rotational and structural evolution of the host star by taking into account the coupled effects of tidal and magnetic torques from *ab initio* prescriptions. It allows us to better understand the evolution of star-planet systems and to explain some properties of the distribution of observed close-in planets. To this end we use a numerical model of a coplanar circular star-planet system taking into account stellar structural changes, wind braking and star-planet interactions, called ESPeM (Benbakoura *et al.* (2019)). We find that depending on the initial configuration of the system, magnetic effects can dominate tidal effects during the various phases of the evolution, leading to an important migration of the planet and to significant changes on the rotational evolution of the star. Both kinds of interactions thus have to be taken into account to predict the evolution of compact star-planet systems.

Keywords. stellar evolution, solar-type stars, stellar rotation, magnetism, star-planet interactions

1. Introduction

The discovery of more than 4000 exoplanets during the last two decades has shed light on the importance of characterizing star-planet interactions. Indeed, a large fraction of these planets have short orbital periods and are consequently strongly interacting with their host star. In particular, several planetary systems, like 55 Cancri, WASP-18 or HD 189733 (cf. Figure 1 to see the architecture of those systems), are likely to host exoplanets undergoing a migration due to tidal and magnetic torques. We consider here the joint influence of stellar wind, tidal and magnetic star-planet interactions on the star's rotation rate and planetary orbital evolution. We focus our study on the relative influence of tidal and magnetic torques on the system evolution. Our objective is to take into account simultaneously *ab initio* prescriptions of tidal and magnetic torques in exosystems, so as to improve our understanding of close-in star-planet systems and their long-term evolution.

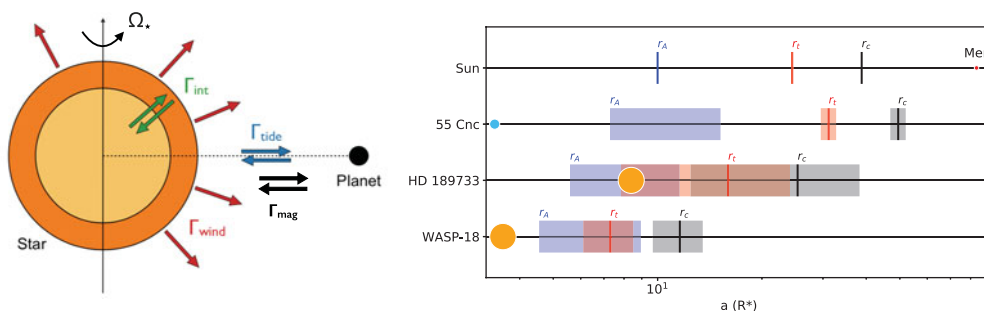


Figure 1. On the left: schematic view of the system and its interactions (adapted from Benbakoura *et al.* 2019). The various Γ quantities (int, wind, mag, tide) illustrate the various angular momentum transfer mechanisms taken into account in our study. On the right: architecture of the inner Solar System, 55 Cancri, HD 189733 and WASP 18. The semi-major axis a is expressed in stellar radii R_* . Red dots: Sub-Earths. Blue dots: Super-Earths. Orange dots: jovian planets. In black: co-rotation radius r_c , with error bars. In red: transition equilibrium-dynamical tide r_t , with error bars. In blue: Estimates of the sub-alfvénic region transition r_A for realistic stellar magnetic fields.

2. Stellar rotation and planetary migration

ESPEM (French acronym for Planetary Systems Evolution and Magnetism; Benbakoura *et al.* 2019) is a 1D numerical model of a coplanar circular star-planet system allowing us to follow the joint secular evolution of the semi-major axis of the orbit and the stellar rotation. We consider in this model a solar-type star with a bi-layer internal structure following MacGregor & Brenner 1991, whose changes are monitored along the evolution of the system by relying on grids provided by the 1D stellar evolution code STAREVOL (Amard *et al.* 2016). The companion is considered a punctual mass.

A global schematic view of the different interactions involved in the system is given in Figure 1. The yellow disk depicts the stellar radiative core and the orange shell the convective envelope. The red arrows account for the angular momentum extraction by the stellar wind (Schatzman 1962, Weber & Davis 1967; see Ahuir *et al.* 2019 for the interdependencies between magnetism, wind and stellar rotation). The green arrows correspond to internal angular momentum exchanges between the core and the envelope of the star, which in absence of external disruptions evolve towards synchronization of their rotation (MacGregor & Brenner 1991). Such a coupling also takes into account the growth of the radiative zone during the Pre-Main Sequence, resulting in an angular momentum transfer from the envelope to the core (MacGregor 1992). The blue arrows account for exchanges between the stellar envelope and the planetary orbit due to both equilibrium and dynamical tidal effects (Hansen 2012, Ogilvie 2013, Mathis 2015, Bolmont & Mathis 2016).

3. Two-body magnetic interaction

Along with wind braking and tidal effects, magnetic interactions (black arrows in Figure 1) occur because of the relative motion between the planet and the ambient wind at the planetary orbit. If the planet is in a sub-alfvénic region (where the wind velocity is smaller than the local Alfvén speed), a magnetic torque applied to the planet can be associated to an efficient transport of angular momentum between the planet and the star through the so-called *Alfvén wings* (Neubauer 1998). Several regimes then appear according to the magnetic properties of the planet, at least as a first approximation. If the planet is able to sustain a magnetosphere, Alfvén waves generally do not have enough

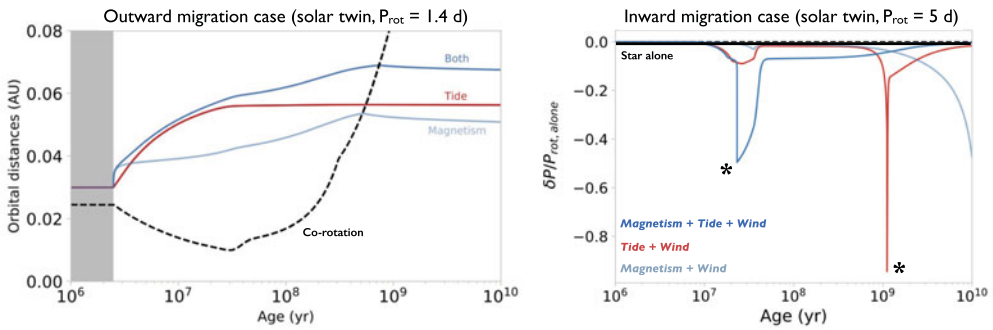


Figure 2. On the left: orbital evolution of a Jupiter-like planet, initially at $a = 0.03$ AU, orbiting a fast rotating solar twin ($P_{\text{rot}} = 1.4$ d) in the open-field configuration. The black dashed line corresponds to the co-rotation radius of the star without any planet. On the right: evolution of the relative difference of rotation periods between a mildly rotating solar twin ($P_{\text{rot}} = 5$ d) hosting a Jupiter-like planet initially at $a = 0.03$ AU and a similar star without planet. Mark * corresponds to the planetary destruction. In black: case of a star without planet.

time to go back and forth between the star and the planet. In this case, two unique Alfvén wings form around the planet, leading to the so-called *dipolar* interaction (Saur *et al.* 2013, Strugarek *et al.* 2015, Strugarek 2016). In the opposite case, when the ambient wind pressure is too strong or if the planetary dynamo sustains a too weak magnetic field, propagating Alfvén waves can overlap and the interaction becomes *unipolar* (Laine *et al.* 2008, Laine & Lin 2012). (Strugarek *et al.* 2017) have performed a first study on planetary migration taking into account simultaneously tidal and magnetic torques, by computing the migration timescale of the planet for both contributions. Their study reveals that both effects could play a key role depending on the characteristics of the star-planet system considered. A self-consistent secular evolution of star-planet systems under the influence of magnetic and tidal torques is thus needed to properly disentangle the importance of the two physical mechanisms.

4. Influence of the tidal and MHD torques on the orbital evolution and the stellar rotation

To assess the relative contributions of the tidal and magnetic torques on the star-planet secular evolution, we will assume in the following section that the planet is located in an open-field region to maximize magnetic interactions (for example in the equatorial plane of a star with a quadrupolar magnetic field). The stellar magnetic field is then assumed to be radial ($B_{\star} \sim 1/r^2$).

The left panel of Figure 2 shows the evolution of the semi-major axis of a Jupiter-like planet, initially at a distance $a = 0.03$ AU, orbiting around a fast rotating solar twin ($P_{\text{rot}} = 1.4$ d). The coupled action of the tidal and magnetic torques (in dark blue in Figure 2) shows an outward migration acting at the beginning of the evolution and an evolution of the semi-major axis deviating significantly from the case where tidal effects alone are acting on the system (in red in Figure 2). The orbital evolution of the planet taking into account star-planet magnetic interactions without tidal effects (in light blue in Figure 2) also presents an important outward migration at the beginning of the simulation, then a less pronounced evolution than in the purely tidal case.

The magnetic and tidal torques lead to angular momentum exchange between the orbital motion of the planet and the rotating star. Because of the conservation of the total angular momentum of the system, stellar rotation is also affected by those interactions. The right panel of Figure 2 shows a case of planet destruction, for which a Jupiter-like

planet located initially at $a = 0.03$ AU orbits a mildly rotating solar twin ($P_{\text{rot}} = 5$ d). The influence of planetary migration on stellar rotation is quantified by

$$\delta P = P_{\text{rot}} - P_{\text{rot,alone}}, \quad (4.1)$$

where $P_{\text{rot,alone}}$ is the rotation period of the star without a planet. In the case of a planetary destruction (mark * in Figure 2), the star presents a sharp spin-up when the planet falls down in the central body. This corresponds to the transfer of its orbital angular momentum to the host-star. The presence of magnetic torques (in dark blue in Figure 2) changes the survival time of the planet, making its destruction happen earlier than in the purely tidal-case. In the case of Figure 2 the planet falls during the PMS, which is at the origin of a briefer and less intense spin-up than for the tide-only case (in red in Figure 2). An evolution only driven by magnetic effects (in light blue in Figure 2) leads to a potential destruction of the planet after the end of the simulation, which is at the origin of a monotonous decrease of the stellar rotation rate. In those three configurations, an overestimated stellar rotation rate due to planetary migration, compared to what it is expected from gyrochronology (Skumanich 1972, Barnes 2003), can last several billions of years.

5. Conclusions

We presented some preliminary results obtained with the ESPEM model comparing the relative importance of tidal and magnetic torques for exosystems' evolution. Depending on the initial configuration of the system, magnetic effects can dominate tidal effects along the evolution of the system, which is in agreement with Strugarek *et al.* (2017). Furthermore, the planet has a significant influence on stellar rotation, especially in the case of an efficient inward migration and a collision during the MS. First statistical studies performed with ESPEM tend to show that initial fast stellar rotation result in the excitation of tidal inertial waves and of a stronger magnetic field, that leads to intense tidal-magnetic effects and therefore to more efficient planetary migration (Teitler & Königl 2014). Studying the evolution of a synthetic population of exoplanets may allow us to explain some features of the distribution of close-in planets (McQuillan *et al.* 2014). We intend to explore such statistical approaches in the near future. With a similar wind prescription as the one used in ESPEM we find that 20% of the exoplanets detected so far are likely to lie in a sub-alfvenic region. The dissipation of tidal gravity waves (Zahn 1975, Goodman & Dickson 1998, Terquem *et al.* 1998) will be also taken into account in future work.

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