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ROTATIONAL AND ORBITAL EVOLUTION OF STAR-PLANET SYSTEMS. IMPACT OF TIDAL AND MAGNETIC TORQUES.

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Abstract. 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 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. To this end, we have developed a numerical model of a circular and coplanar star-planet system taking into account stellar structural changes, wind braking and star-planet interactions, called ESPEM (Evolution of Planetary Systems and Magnetism). We present synthetic populations of star-planet systems and compare their distribution in orbital period and in stellar rotation period to the *Kepler* satellite data. We find that star-planet magnetic interactions significantly modify the distribution of super-Earths around slowly rotating stars, which improves the agreement between synthetic populations and observations. Tidal effects, on the other hand, shape the distribution of giant planets.

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

1 Introduction

Over the past two decades, many close-in exoplanets have been detected around a wide variety of host stars. These planets are likely to undergo migration throughout the evolution of the star-planet system, from their formation within a protoplanetary disk to the end of the host star's life. Once the disk is gone, the migration of a planet in close orbit can be triggered by two complementary physical mechanisms. On one hand, the presence of the planet induces tidal effects within the star. These lead to a deformation of the star in the direction of the companion which generates a large scale flow, the equilibrium tide (Zahn 1966a; Remus et al. 2012a), dissipated by tubulent friction in the stellar convective zone. The planet can also excite waves within its host star that will then be dissipated in the radiative (e.g., Zahn 1975; Goodman & Dickson 1998; Ahuir et al. 2021b) and the convective zone (e.g., Ogilvie 2013; Mathis 2015): this is the so-called dynamical tide. The dissipation of these flows induces an angle between the deformation of the star and the line connecting the planet to the center of the star, at the origin of a torque that can induce a planetary migration. On the other hand, the planet feels a drag force from the ambient stellar magnetized wind. This results in the propagation of Alfvén waves between the planet and the star, whose superposition forms stationary structures called *Alfvén wings* (Neubauer 1980). Such a connection between the two celestial bodies is conducive to exchanges of energy and angular momentum (e.g., Saur et al. 2013; Strugarek et al. 2015; Strugarek 2016; Strugarek et al. 2017). These two types of mechanisms then define characteristic orbits playing a determining role in the evolution of the system considered. Thus, a planet located below the co-rotation orbit (for which the orbital period is equal to the stellar rotation period) migrates towards its host star, whose rotation accelerates. Beyond this orbit, the planet moves away from the star, whose rotation slows down. We aim in this work to predict the orbital evolution of a planet throughout the structural, rotational and magnetic evolution of its host star, simultaneously taking into account tidal and magnetic torques, in order to understand the distribution of close-in planets observed.

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2 The ESPEM code

To account for the secular evolution of star-planet systems under the action of magnetic and tidal interactions, we use ESPEM (French acronym for Evolution of Planetary Systems and Magnetism ; see Benbakoura et al. 2019; Ahuir et al. 2021a), which is a numerical code computing the secular evolution of a star–planet system by following the semi-major axis of the planetary orbit as well as the stellar rotation rate. We assume a coplanar and circular orbit, and a synchronized planetary rotation, as the reservoir of angular momentum of the planet is less important than the one in its orbit (Guillot et al. 1996). The companion is considered as a punctual mass. We consider a two-layer solar-type star composed of a radiative core and a convective envelope, whose changes are monitored along the evolution of the system by relying on grids provided by the 1D stellar evolution code STAREVOL (e.g., Amard et al. 2019). Tidal dissipation is only considered in the stellar envelope in this work as a first step (Hansen 2012; Ogilvie 2013; Mathis 2015). The core is interacting with the envelope through internal coupling (MacGregor & Brenner 1991; MacGregor 1991), and the latter exchanges angular momentum with the orbit through tidal and magnetic interactions. Moreover, the whole system loses angular momentum through magnetic braking by the stellar wind (e.g., Weber & Davis 1967; Matt et al. 2015; Ahuir et al. 2020). Hence, the angular momentum of the planetary orbit, L_{orb}, the stellar convective zone, L_c, and radiative zone, L_r, are evolved by the following system of equations:

$$\frac{dL_{orb}}{dt} = -\Gamma_{\text{tide}} - \Gamma_{\text{mag}} \tag{2.1}$$

$$\frac{dL_c}{dt} = \Gamma_{\text{int}} + \Gamma_{\text{tide}} - \Gamma_{\text{wind}} + \Gamma_{\text{mag}} \tag{2.2}$$

$$\frac{dL_r}{dt} = -\Gamma_{\text{int}}, \tag{2.3}$$

where Γ_{int} is the internal torque, coupling the core and the envelope of the star, Γ_{wind} is the wind-braking torque, Γ_{tide} and Γ_{mag} are the tidal and magnetic torques between the star and the planet, respectively. A schematic global view of the system studied by ESPEM is provided in Figure 1.

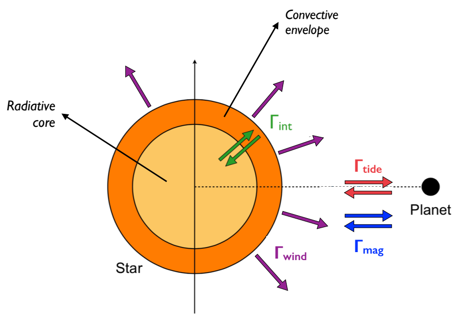

Fig. 1. Schematic view of the system and its interactions (adapted from Benbakoura et al. 2019). The radiative core (in yellow) and the convective envelope (in orange) exchange angular momentum (green arrows). Stellar wind carries away angular momentum from the envelope and spins the star down (purple arrows). Stellar rotation and planetary orbit are coupled through tidal (red arrows) and magnetic effects (blue arrows).

3 Secular evolution and planetary populations

We now seek to generate a synthetic population of star–planet systems from ESPEM, and then compare the resulting distributions with observations from the *Kepler* mission. To this end, we design a sample comprising 7000 ESPEM simulations that covers the set of possible configurations of compact star–planet systems. As we assume a bi–layer structure for the star, we consider stellar masses between 0.5 and 1.1 $M_\odot$ with a step of 0.1 $M_\odot$. Furthermore, to account for the rotational distribution of stars in open clusters (Gallet & Bouvier 2015) in our synthetic populations, we consider five initial rotation periods uniformly distributed between 1 and 10 days. The age of the system is sampled between 1 Myr and 10 Gyr to obtain 2000 uniformly distributed instants. Then to create our distribution only stellar ages corresponding to the main sequence phase are considered. Stellar masses, initial rotation periods and ages are then biased to reproduce the distribution in effective temperatures and rotation periods from the McQuillan et al. (2014, MMA14) sample, constituting until very recently the largest homogeneous database on the rotation of stars in the *Kepler* field involving F- to M-type stars. We then include various planets by choosing 40 initial semi-major axes between 5×10^{-3} and 0.2 AU, uniformly distributed in logarithm, as well as five planetary masses between 0.5 Earth masses and 5 Jovian masses, evenly spaced in logarithm. The corresponding initial orbital periods then range between 0.12 and 46 days, which allows to initially populate all orbital distances for which star–planet interactions can act effectively. From these initial conditions, we can generate three different populations of star-planet systems by evolving them by tidal effects only, or by taking into account magnetic effects for a planetary magnetic field B_p assumed equal to 1 and 10 G. Each planetary mass is weighted to reproduce the planetary radius distribution of the McQuillan et al. (2013, MMA13) sample, one of the very few studies to date combining the orbital period of detected exoplanets and the stellar rotation period of their host star. To do so, we rely on the probabilistic mass–radius relations proposed by Chen & Kipping (2017). For the sake of consistency, since our model does not deal with multi-planet interactions, we filter out multi-planetary systems from the MMA13 database, thus excluding 106 systems out of the 737 *Kepler* systems of interest (KOI) of the sample. We then compare the ESPEM-predicted orbital period and stellar rotation period distributions with observations of KOIs from the filtered MMA13 sample.

We find that that star-planet interactions shape the orbital distribution of exoplanets by depopulating low orbital periods. More precisely, magnetic interactions significantly affect the distribution of super-Earths around stars whose rotation period $P_{\rm rot}$ is higher than about 5 days. Compared to tidal-only simulations, this improves the agreement between synthetic populations and observations at orbital periods lower than $P_{\rm orb} = 1$ d (corresponding to an orbital distance of around 4.3 solar radii in the solar case, see Figure 2). Tidal effects, on the other hand, shape the distribution of giant planets. Hence, star–planet magnetic interactions play a key role in the migration of the less massive planets. Overall, the simultaneous consideration of magnetic and tidal effects shows a better agreement between synthetic populations and observations. The planetary magnetic field thus plays an important role in shaping the distributions. Indeed, an increase of B_p leads to an enhanced depopulation of the shortest orbital periods, bringing the ESPEM predictions closer to the *Kepler* distributions (see the left panels of Figure 2). Moreover, while values close to those observed in the Solar System (between 1 and 10 G) lead to an excess of planets at low orbital periods for the synthetic distributions, intense fields up to 4000 G have been predicted for hot Jupiters orbiting young stars, which significantly enhances the efficiency of the magnetic interactions (e.g., Hori 2021). Therefore, considering planetary fields stronger than 10 G may lead to an even better agreement. However, a large uncertainty about the value of the magnetic field of exoplanets remains to this day. Moreover, additional star-planet interactions, such as the dynamical tide in the stellar radiative zone (e.g., Guillot et al. 2014; Barker 2020; Ahuir et al. 2021b) or magnetic interactions in the unipolar regime (Laine et al. 2008; Laine & Lin 2012), could further depopulate short orbital periods. It is also possible that some of the planets we considered at the beginning of the evolution are simply not formed in the protoplanetary disk. These two avenues will be investigated in future work to account for the distribution of close-in planets observed in the *Kepler* field.

4 Conclusions

We designed synthetic populations of star-planet systems based on *Kepler* stellar distributions by taking into account for the first time magnetic and tidal effects simultaneously in their secular evolution. We found that magnetic interactions, after disk dissipation, significantly affect the distribution of super-Earths around slow rotators, improving the agreement between synthetic populations and observations, while tidal effects shape the distribution of giant planets. Our work shows that the observed populations must be carefully studied to derive constraints on planetary formation, because migration within the disk (not considered here) as well as magnetic and tidal interactions (post-disk) influence the evolution of close-in planets. Conversely, the observed distributions do not directly constrain the planetary distributions following the dissipation of the disk. This new description of the secular evolution of these systems is thus essential for instruments and missions to study exoplanets such as CHEOPS, TESS, PLATO, JWST and ARIEL.

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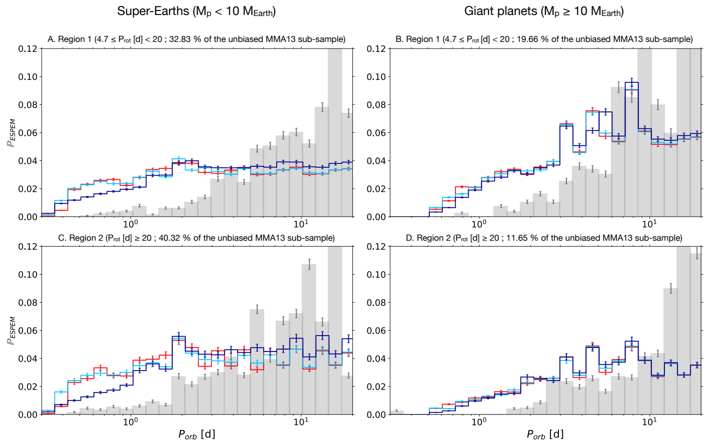

Fig. 2. Distribution of orbital periods for super-Earths (left column) and giant planets (right column). Each row corresponds to a population of middle-aged (Region 1, for which $4.7 \leq P_{\rm rot}\ [d] < 20$), and old (Region 2, $P_{\rm rot} \geq 20$ d) star–planet systems. The letter d stands for days. The gray histogram corresponds to the distributions obtained with the unbiased MMA13 sample. The ESPEM distributions with $B_p = 0, 1, 10$ G are shown in red, light blue and dark blue respectively.

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