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Tidal dissipation in the host star of short-period exoplanetary systems

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Abstract

With the successes of the space missions CoRoT, *Kepler*, and K2 and of the large ground-based surveys, we are living a revolution for our knowledge of planetary systems. As of today, more than 2950 confirmed exoplanets have been discovered. They orbit a broad diversity of host stars with different masses and evolutionary stages.

In this context, many systems have a compact orbital architecture with planets orbiting very close to their star. Such systems, which will be explored by CHEOPS, TESS and SPIRou, are the seat of strong tidal (and magnetic) interactions. They modify the orbits of the planets and the stellar and planetary rotation angular velocity and inclination. In the case of stable binary systems, they lead to the orbit circularisation and to the spins synchronisation and alignment; in the case of unstable systems they drive the spiraling of the planet towards the central star. In short-period systems, this is the dissipation of tidal flows and waves excited in the host star that drive these processes.

In this work, we review the efforts that we have achieved to model stellar tides and their dissipation in the convective envelope of low-mass stars. We show how this tidal friction is intrinsically driven by the structural and rotational evolution of stars and how it strongly impacts the evolution of their planetary system. We also discuss the perspectives of this work to take into account the dissipation of tides in stellar radiation zones and the effects of differential rotation and magnetic fields.

1. General motivation

The broad diversity of the orbital architecture of discovered short-period exoplanetary systems stimulates a lot of studies of their dynamical evolution and stability. In this framework, tidal interactions are one of the key physical mechanisms that must be understood and coherently modeled. Indeed, the dissipation of the kinetic energy of tidal large-scale flows and waves in the host star of short-period exoplanetary systems drives the evolution of the semi-major axis and the eccentricity of the orbits, of their rotation, and of the spin-orbit inclination. In this framework, a large number of studies proposed to use the simplified so-called tidal quality factor Q to parametrize the efficiency of this dissipation and the related friction. Using the phenomenology of forced damped oscillators, the dissipation is strong and the evolution is rapid when the quality factor is small and vice-versa. Two ways are then used to prescribe a value for Q: i) one can choose to calibrate it on observations or on formation scenario ; ii) one choose to compute it using ab-initio hydrodynamical models of dissipative mechanisms acting on tidal flows (e.g. Ogilvie & Lin 2007, Ogilvie 2013). In the second case, tidal dissipation becomes a complex function of the internal structure of stars, of their dynamical properties (their rotation, stratification, viscosity and thermal diffusivities, etc.) and of the forcing frequency. Such dependences have a strong impact on the dynamical evolution of systems.

To obtain a coherent picture of the dynamics of exoplanetary systems it is thus necessary to have a correct evaluation of tidal dissipation in their host stars along their evolution. From now on, stellar mass range spreads from M red dwarfs to intermediatemass A-type stars. In this context, tidal friction in the rotating turbulent convective envelopes of these low-mass stars has been proposed to explain the orbital and rotational properties of hot-Jupiter systems (e.g. Albrecht et al. 2012, Valsecchi & Rasio 2014, and references therein for hot-Jupiter systems). In stellar convective layers, tidal flows are constituted of large-scale non-wavelike/equilibrium flows driven by the adjustment of the hydrostatic structure of stars because of the presence of the planetary companion and the dynamical tide constituted by inertial waves, which have the Coriolis acceleration as restoring force (e.g. Ogilvie & Lin 2007). In addition, both the structure and rotation of stars strongly vary along their evolution (e.g. Amard et al. 2016) while observations of star-planet and binary-star systems show that tidal dissipation varies over several orders of magnitude. Therefore, the key questions that must be addressed for dynamical studies is how does the tidal friction in the convective envelope of low-mass stars vary as a function of stellar mass, evolutionary stage, and rotation?

2 Results

Combining the formalism derived for the frequency-averaged dissipation of tidal inertial waves propagating in convective regions of stars (Ogilvie 2013) with state-of-the-art grids of stellar rotating models (Amard et al. 2016), we show that:

- the stellar tidal friction is a complex function of the mass, metallicity, age, and rotation (Mathis 2015, Gallet et al. 2017, Bolmont et al. 2017);
- it varies over several orders of magnitude as a function of these physical parameters;
- it is driven by the evolution of the stellar structure during the pre-main-sequence and by the evolution of rotation during the main-sequence;
- the predicted orbital migration and planet survival rate obtained using such an ab-initio modeling is strongly different that the one assuming a constant tidal quality factor (Bolmont & Mathis 2016);
- tidal dissipation cannot explain the dichotomy observed for the exoplanetary spin-orbit angles (Damiani & Mathis 2018).

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