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Evolution of angular-momentum-losing exoplanetary systems

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Abstract

We assess the importance of tidal evolution and its interplay with magnetic braking in the population of hot-Jupiter planetary systems. We show that the long-term evolution of planets orbiting F- and G-type stars is significantly different owing to the combined effect of magnetic braking and tides. Angular momentum loss has to be taken into account when constraining tidal evolution in close planetary systems.

1. Introduction

One of the long-standing problems in the field of exoplanets is understanding how short-period giant planets, usually called hot Jupiters, have reached their current orbit. According to the prevailing theory, giant planets must form beyond the snow line of a protoplanetary disk, which is typically located at a few astronomical units from the star. Hot Jupiters have a semi-major axis $\lesssim 0.1$ AU, so they must have undergone some kind of migration.

Several migration theories are considered and they involve different halting mechanisms that can be tested by comparing their predictions with the observed orbital properties of exoplanets. However, further secular changes in the orbits of exoplanets can still be induced by tidal interaction between the planet and the star, even when the primordial migration mechanism is no longer effective. The tidal torque scales as the inverse of the sixth power of the semi-major axis a^{-6}, consequently it is especially important in the case of hot Jupiters. To test the migration scenarios, it is thus crucial to estimate the efficiency of tidal dissipation and its effects over the evolutionary lifetime of the star. But it is difficult to reach definite conclusions due to the limitations in our knowledge of the actual mechanism responsible for tidal dissipation, its efficiency, and the effects of angular momentum loss (AML) of the host through magnetic braking.

2. Magnetic braking and tides

Even without a detailed knowledge of the AML law or tidal dissipation mechanisms, there is a way to assess the general outcome of tidal evolution, using energy considerations only. Using the method of Lagrange multipliers we can characterise the minima of the total energy under the constraint that the total angular momentum shall be some unknown function of the stellar angular velocity only [2]. In this way we are considering that the total angular momentum of the star-planet system is not conserved, because magnetic braking exerts a torque on the star.

Thus we show that a stationary state can exist, and that it is characterized by circularity of the orbit, alignment between the spin of the planet, the star and the normal to the orbital plane, but not by co-rotation. The orbital mean motion of the planet at equilibrium is equal to the stellar angular velocity reduced by a factor β that depends on the AML rate through the stellar wind. The equilibrium is pseudo-stable if

$$\beta > 4 - \frac{1}{C_p + C_\star} \frac{M_\star M_p}{M_\star + M_p} a^2 \qquad (1)$$

and

$$\beta > 0 \qquad (2)$$

where a is the semi-major axis, C_p and $C_\star$ are the momenta of inertia of the planet and the star respectively and M_p and $M_\star$ are their masses. This result is valid whatever the tidal dissipation mechanism may be and is independent of any tidal theory framework.

3. Characteristic time-scales

The resulting orbital evolution can be broken down into three limit regimes. They correspond to configurations in which the wind torque either dominates, is comparable to, or is dominated by, the tidal torque. We use a formulation of the tidal torque obtained in the framework of the equilibrium tide braking [1] assuming a constant $Q' = 10^7$. Magnetic braking is modelled with a Skumanich-type law and a torque

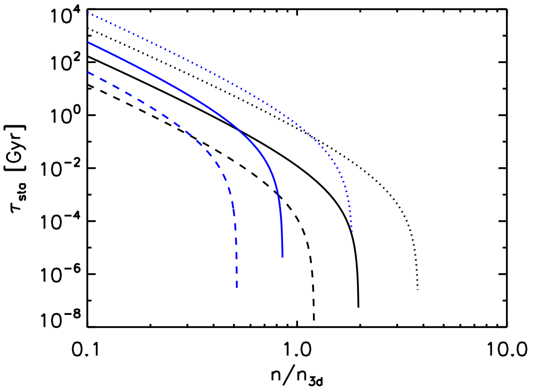

Figure 1: Estimates of the maximum possible duration of the stationary state as a function of the orbital mean motion in units of $n_{3d} = 2\pi/(3\text{days})$. The computations are done for a G-type star (black) or F-type star (blue) and planetary masses of 0.1 (dashed), 1 (solid), 10 (dotted) Jupiter masses.

of magnitude $\Gamma_w = -\alpha_{\rm mb} C_\star \Omega^3$, where the value of $\alpha_{\rm mb}$ is estimated from observed rotational velocities of stars in clusters of different ages. We take $\alpha_{\rm mb} = 1.5 \times 10^{-14} \gamma$ yr where $\gamma = 1.0$ for G stars and $\gamma = 0.1$ for F stars.

When the wind torque is much larger in amplitude than the tidal torque, we can consider that the stellar spin sets the pace of evolution. This is the case for typical stellar rotation rates of young stars and planets not closer than the 2:1 mean motion resonance. Depending on the initial rotation period of the star, this regime would last for about 50 My to 1 Gyr respectively for G-type stars (10 times longer for F-type stars).

When the wind torque is comparable to the tidal torque, the system can enter a stationary state where tidal evolution proceeds at almost constant stellar spin frequency, which allows to slow down the migration of the planet. A necessary condition for the establishment of the stationary state is that the tidal torque be opposite in sign and comparable in magnitude to the wind torque, and this can be maintained as long as there is enough orbital angular momentum compared to the stellar rotational angular momentum to maintain the torque balance. The duration of the stationary state as a function of the initial mean motion when a system enters into the stationary state is given in Fig. 1 for different stellar and planetary masses. Stars loosing less angular momentum through their wind (F-type stars) can generally maintain the stationary state longer than stars with a more efficient wind. For a given orbital distance, more massive planets can remain in the stationary state longer than less massive planets. In some cases, the stationary state can be maintained for a timescale longer than the main-sequence lifetime of the star. For example, this would be the case of a Jupiter-sized planet entering the stationary state with an orbital period of 12-15 days.

When the tidal torque is much greater than the wind torque, tidal dissipation sets the characteristic time of in-spiral time τ_a. This implies $\tau_a \leq 100$ Myr for a Jupiter-mass planet and of the order of Myr for planets of more massive than 5 $\rm M_J$. There is thus a very low probability to observe massive planets in this phase of evolution. On the other hand, low-mass planets can have an in-spiral time that is longer than the main-sequence lifetime of their host star.

4. Summary and Conclusions

We have shown that when the magnetic braking of the star is considered, a tidal pseudo-stable equilibrium state can exist. For the known transiting exoplanets, we find that the distributions of angular momentum in systems with F and G-type stars display a statistically significant difference, and it is possible that most of the transiting planets in circular and aligned orbits be close to their stationary state. The distribution of angular momentum between the orbit and the stellar rotation gives information not only about the future evolution of a given system, but also on its possible initial angular momentum distribution at the beginning of binary tidal interaction. More detailed studies could help putting constraints on tidal dissipation efficiency, magnetic braking and migration scenarios.

References

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