The migration of single hot Jupiters

Balance of evidence tips towards dynamical and tidal evolution

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Abstract

In this thesis, we revisit the seventeen year old question of how hot Jupiters got to their short period orbits, given that gas-giant planet building is supposed to take place beyond the ice-line at about 3 AU. Two major theories are generally used to explain this mystery. Firstly, exchange of energy and angular momentum between the newly-built planet and the progenitor dust and gas disk could result in planetary migration to a short period. This is generally believed to result in planets on circular orbits, with orbital angular momenta that are aligned with the host star spin. The competing theory which has gained more support in recent years, is that gravitational interactions leading to planet-planet scattering and/or Kozai interactions with massive and distant objects caused the planets to migrate violently (scattering) or slowly (Kozai) to short period, eccentric and misaligned orbits. These orbits are then expected to circularise and align under tidal interactions with the host star. In addition, the host star is expected to show evidence of spin-up if the tide on the star is strong enough.

Our contribution to this field is to provide additional support for the scenario involving dynamical interaction and tidal damping. We present observational evidence in the form of 158 new radial velocity measurements for 12 planets and a reanalysis of existing radial velocity data and photometric constraints from the literature for a total of 64 planetary systems. We also critically consider a further 30 newly announced planets from the literature. We show that there is no evidence for a finite eccentricity in several cases that were previously claimed to be "exceptions" to the observed trend that *close-in planets are on circular orbits* and the generally accepted reason that *they underwent strong tidal interactions*. We also show that the dissipative effect of tides raised in the planet by the star and vice versa explain all the eccentricity and spin-orbit alignment measurements available for transiting planets. We find evidence for excess rotation of the star in 6 systems, showing that heavy and close-in objects can exert strong tidal effects on the star. Hot Jupiters on circular orbits clump on the mass-period relation, which thus appears to be related to the stopping mechanism of orbital migration for hot Jupiters.

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Author's declaration

The work described in this thesis was done in collaboration with other researchers at several different institutions. The research problem itself ("Is correlated noise affecting the observational support for tidal effects in the sample of transiting exoplanets?") was the idea of Frédéric Pont.

The work in Section 3.5 is my own work, with only supervisor oversight from Frédéric Pont. I adapted the approach as described by Sivia (2006), keeping in mind the importance of red-noise as described by Pont, Zucker, and Queloz (2006).

Chapter 4 contains material covered in the paper by Husnoo et al. (2011), which I wrote by expanding a 2 page template that my supervisor Frédéric Pont provided me, along with a lot of advice, into the final 9 page paper. I performed the analysis myself, but I received a lot of advice on the details of the writing-up through extensive discussions with the other co-authors, especially from Tsevi Mazeh (Tel Aviv University), Claire Moutou (Laboratoire d'Astrophysique de Marseille), Guillaume Hébrard (Institut d'Astrophysique de Paris) and François Bouchy (Institut d'Astrophysique de Paris). The radial velocity measurements for the orbits of WASP-12 and WASP-14 were obtained by several members of the SOPHIE team (Anne Eggenberger, Isabelle Boisse, Rodrigo Díaz and Luc Arnold) and reduced by Guillaume Hébrard on behalf of Frédéric Pont. The data for the Rossiter-McLaughlin sequence were captured by the SOPHIE Consortium team on behalf of Elaine Simpson (Queens University Belfast).

Chapters 5 and 6 contain material covered in the paper by Husnoo et al. (2012). Again, I performed all the analysis and wrote the paper myself, but benefited from extensive discussions with the co-authors Frédéric Pont, Tsevi Mazeh and Daniel Fabrycky on the details of the presentation of the paper. The initial results in this paper were originally published in a paper by Pont et al. (2011), which my supervisor wrote and to which I contributed the initial results. This latter paper benefited from discussions in Tel-Aviv with Tsevi Mazeh, and Daniel Fabrycky (Harvard-Smithsonian Centre for Astrophysics). The SOPHIE data in these latter two papers were reduced by Guillaume Hébrard on behalf of Frédéric Pont, while the HARPS data was obtained on behalf of Tsevi Mazeh by ESO. All three papers benefited hugely from the detailed and careful reports of the anonymous referees. I am also grateful to Gilles Chabrier and Tim Naylor for their enthusiastic comments at various points, on tidal effects and Bayesian data analysis, respectively.

The code used to model the Rossiter-McLaughlin effect in Section 3.1.2 was initially implemented by Frédéric Pont using the equations of Giménez (2006) in Python, but the code was too slow for interactive use. I ported this code to C, profiled it, implemented several improvements to speed up the code, and wrote wrapper functions so that the faster version could be called from Python. The code for modelling the transit lightcurve (Section 3.2) was implemented by Suzanne Aigrain following Mandel and Agol (2002), and I used this as is. The code for the MCMC and radial velocity analysis (Section 3.1) was initially implemented by Frédéric Pont in Python, but I have re-implemented it from scratch in Python to include multiple datasets, and ported the slower subroutines to C to speed them up.

The summaries in Sections 7.1.1 and 7.1.2 refer to my own work, whenever they refer to this thesis. The only input from the co-authors at that stage was to ask questions about the procedure to ensure I wasn't doing anything obviously wrong. The work in Section 7.1.3 is where the co-authors Frédéric Pont, Tsevi Mazeh, and Daniel Fabrycky contributed most, by helping with the interpretation of the Figure 6.1 in terms of the Roche limit, and suggesting the reference to Ford and Rasio, 2006. The actual comparison with the works of Winn et al. (2010) was my own work, although the division of "aligned" and "misaligned" at $\lambda = 30^o$ is the suggestion of Frédéric Pont. The Figures 6.2, 6.3 and 6.4 were my own idea, although Frédéric Pont suggested that I use colours to differentiate between "normal" (circular/aligned/normal rotation) and "interesting"(eccentric/misaligned/fast rotation) rather than symbols. The latter suggestion improved the prevention enormously.

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