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Planet-star tidal interactions with precise transit timing

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Abstract. Theoretical calculation and some indirect observations show that massive exoplanets on the tightest orbits – so-called hot Jupiters – must undergo orbital decay due to tidal dissipation within their host stars. This orbital evolution could be observationally accessible through precise transit timing over the course of decades. Meter-class telescopes are recognised as excellent instruments for such follow-up observations. They usually provide photometric time series of millimagnitude or even sub-millimagnitude precision for stars brighter than ∼12 mag. Such observations allow us to determine individual mid-transit times with errors between 20 and 40 s, and when they are combined together, the averaged timing precision down to or even below 10 s can be achieved over time scales of months. The rate of planetary in-spiralling may not only help us to understand some aspects of evolution of planetary systems, but can also be used as a probe of the stellar internal structure. Since 2017 we have run a regular observing campaign aimed at transit timing for a sample of best candidates for in-falling planets. Among them there is WASP-12 b, transits of which exhibit a pronounced departure from a linear ephemeris. New observations allow us to confirm the rapid decay rate for that planet, and to place constraints on the tidal dissipation efficiency in other systems.

Key words: planet-star interactions – stars: individual: HAT-P-23, WASP-12 – planets and satellites: individual: HAT-P-23 b, WASP-12 b

1. Introduction

The tidal force, which is raised by one body on the other, is proportional to the mass of the body rising the tide, and inversely proportional to the cube of the distance between both bodies. Thus, massive exoplanets on the tightest orbits, with orbital separations as small as several stellar radii, are recognised as great laboratories for studies of star-planet tidal interactions outside the Solar Sytem. Such planets, called hot Jupiters, are expected to be spiralling towards host stars because of the dissipative nature of tides, caused by the friction of the tidally induced fluid flow (Levrard et al., 2009). In such systems, the host star usually rotates slower than the orbital period of the planet. There is a phase lag in the tidal response that results in transferring the orbital angular momentum into the star – the orbit shrinks and the star spins up. The dissipation of energy, which is stored in the equilibrium tides, is thought to occur in stellar zones where the viscosity is induced by the turbulent convective motions (Zahn, 1966; Goldreich & Nicholson, 1977). The tidal dissipation can be boosted by radiative damping of the dynamical tides that are produced near radiative-convective boundaries (see Goldreich & Nicholson, 1989, for further references).

The efficiency of tidal dissipation in the host star can be characterised with the dimensionless tidal quality parameter $Q'_\star = \frac{3}{2}Q_\star/k_2$ (Goldreich & Soter, 1966), where $Q_\star$ is the inverse of the phase lag between the tidal potential and the tidal bulge (or the ratio of energy stored in tidal distortion to energy dissipated in one tidal cycle), and k_2 is the second order tidal Love number. A smaller value of $Q'_\star$ translates into a stronger or more efficient tidal dissipation and vice versa. Theoretical studies of turbulent damping of equilibrium tides predict $Q'_\star$ of 10^8–10^9 for main-sequence stars (Penev & Sasselov, 2011). The studies of binary stars in stellar clusters show that $Q'_\star$ might be of order 10^6 (e.g. Meibom & Mathieu, 2005). A statistical analysis of the destruction rate of hot Jupiters yields $Q'_\star > 10^7$ (Penev et al., 2012). In other studies, Jackson et al. (2008) and Husnoo et al. (2012) obtained $Q'_\star \sim 10^{6.5}$, while Hansen (2010) found $10^7 < Q'_\star < 10^9$. An investigation of orbital parameters for a sample of hot planets allowed Bonomo et al. (2017) to conclude that Q'_* must exceed 10^6–10^7. Penev et al. (2018) studied hot-Jupiter systems with known stellar rotation periods and found that the tidal quality parameter may also depend on the amplitude and frequency of the tidal excitation, and it must be in the range of 10^5 to 10^7.

Orbital decay can be detected through transit timing over a course of decades. Following the formalism of Goldreich & Soter (1966), the cumulative shift in transit times $T_{\rm shift}$ after time T can be estimated by the formula

$$T_{\rm shift} = -\frac{27}{4}\frac{\pi}{Q'_\star}\frac{1}{P_{\rm orb}}\left(\frac{M_{\rm p}}{M_\star}\right)\left(\frac{a}{R_\star}\right)^{-5} T^2 \,, \tag{1}$$

where $P_{\rm orb}$ is the orbital period, $M_{\rm p}$ is the planet's mass, $M_\star$ and $R_\star$ are the host star's mass and radius, and a is the semi-major axis of the planet's orbit. For some planets, the predicted value of $T_{\rm shift}$ is of order 100 s after ten years if $Q'_\star = 10^6$ is assumed (e.g., Birkby et al., 2014).

So far, the only candidate for a spiralling-in exoplanet is WASP-12 b (Hebb et al., 2009). The planet has a mass of $\sim 1.4\ M_{\rm Jup}$ (Jupiter mass) and a bloated radius of $\sim 1.9\ R_{\rm Jup}$ (Jupiter radius). It orbits its F/G host star with a period of 1.09 d. Maciejewski et al. (2016) employed the method of precise transit timing to detect the apparent shortening of the orbital period. Departure from a linear transit ephemeris by ∼5 minutes was observed in the course of 8 years. This finding translates into the rate of orbital period shortening of $\sim 2.6 \times 10^{-2}$ s yr^{-1}, giving $Q'_\star = 2.5 \times 10^5$. Although transit times were found to follow the quadratic ephemeris very well, there is still an alternative scenario in which the observed period shrinkage is *de facto* part of a long-period cycle caused by either a tidally induced apsidal precession of a slightly eccentric orbit (Ragozzine & Wolf, 2009) or dynamical interactions with a planetary companion (Maciejewski, 2018).

Being motivated by the case of the WASP-12 system, we have initiated a systematic transit timing monitoring programme for a sample of hot giant exoplanets for which period shrinkage could be detected in the course of a decade (Maciejewski et al., 2018). In this note, we announce results obtained for the WASP-12 system. We place them in a wider context by comparing them to results obtained for another system of our sample – HAT-P-23, in which there is a 2.1 $M_{\rm Jup}$ planet orbiting an early G dwarf star with a period of 29 hours (Bakos et al., 2011).

2. Results

New mid-transit times were determined from photometric time series acquired between March 2016 and September 2018 with 0.6–2.0 m telescopes located in Spain, Germany, Bulgaria, and Poland (see Maciejewski et al., 2018, for details). The transit timing residuals against the linear ephemerides in the form:

$$T_{\rm mid}(E) = T_0 + P_{\rm orb} \times E \,, \tag{2}$$

where E is a transit number from the reference epoch T_0, are shown for both planets in Fig. 1. The new transit times for HAT-P-23 b reveal no departure from the linear ephemeris. To place a constraint on the rate of the orbital decay for HAT-P-23 b , and hence on $Q'_\star$, a quadratic ephemeris in the form was fitted:

$$T_{\rm mid} = T_0 + P_{\rm orb} \times E + \frac{1}{2}\frac{dP_{\rm orb}}{dE} \times E^2 \,, \tag{3}$$

where $\frac{dP_{\rm orb}}{dE}$ is the change in the orbital period between succeeding transits. The best-fit parameters and their uncertainties were derived from the posterior probability distributions of those parameters generated with the Markov Chain Monte Carlo algorithm. We employed 100 chains, each of which was 10^4 steps long after discarding the first 1000 trials. The value of $Q'_\star$ was calculated after rearranging Eq. (1) to the form

$$Q'_\star = -\frac{27}{2}\pi \left(\frac{M_{\rm p}}{M_\star}\right) \left(\frac{a}{R_\star}\right)^{-5} \left(\frac{dP_{\rm orb}}{dE}\right)^{-1} P_{\rm orb} \,. \tag{4}$$

Since the value of $\frac{dP_{\rm orb}}{dE}$ was found to be indistinguishable from 0 within 2σ, we found that $Q'_\star$ of HAT-P-23 must be greater than 5.6×10^5 at the 95% confidence level (Maciejewski et al., 2018).

The new transit times for WASP-12 b were found to follow the quadratic ephemeris very well. The best-fit model has the reduced χ^2 of 0.9 and yields

$$\frac{dP_{\rm orb}}{dE} = (-9.67 \pm 0.73) \times 10^{-10} \quad \text{days per epoch}^2 \,. \tag{5}$$

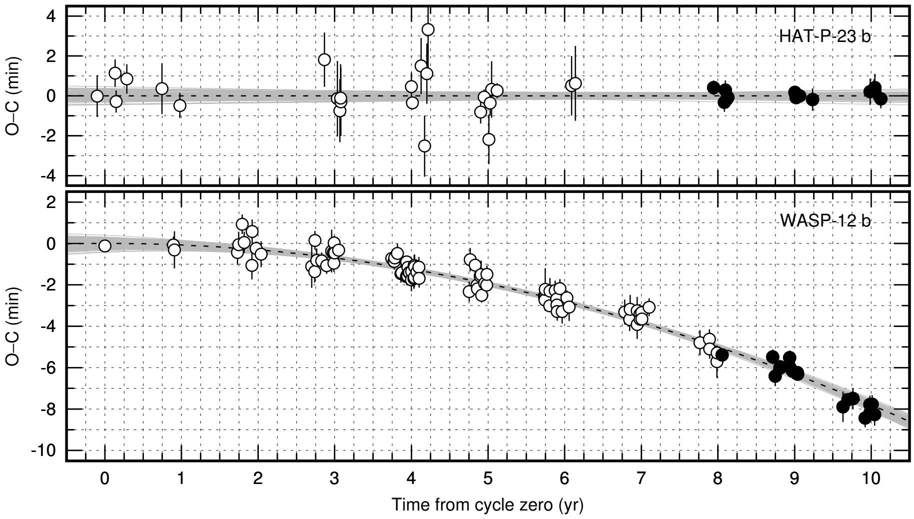

Figure 1. Upper panel: timing residuals against the linear ephemeris for HAT-P-23 b. Values from the new observations, which are taken from Maciejewski et al. (2018), are marked with dots, while the literature values are plotted with open circles. A dashed line marks the zero value. The ephemeris uncertainties are illustrated by grey lines that are drawn for 100 sets of parameters, randomly chosen from the Markov chains. Bottom panel: the same as in the upper panel but for WASP-12 b with the difference that the dashed line in the bottom panel displays the best-fit quadratic trend in transit times, and the grey lines sketch the uncertainties of the quadratic ephemeris.

This value is consistent within error bars with and more precise than values of $(-8.9 \pm 1.4) \times 10^{-10}$ and $(-10.2 \pm 1.1) \times 10^{-10}$ days per epoch^2 reported by Maciejewski et al. (2016) and Patra et al. (2017), respectively. Following eq. (4), we obtained

$$Q'_\star = (1.82 \pm 0.32) \times 10^5 \,. \tag{6}$$

3. Concluding discussion

Chernov et al. (2017) demonstrated that the rate of the orbital shrinkage of WASP-12 b might be consistent with theoretical predictions which assume the host star is a dwarf. In this scenario, the WASP-12 system would be nowadays observed in the final stage of its existence, which appears to be unlikely (Patra et al., 2017). On the other hand, Weinberg et al. (2017) found that the observed rate of orbital decay could only be explained if WASP-12 were a subgiant – a star during the transition phase between the end of the main-sequence stage and the beginning of stable hydrogen burning in a shell on the red-giant branch. This scenario is supported by the stellar properties, which are consistent with a $\sim$1.2 $M_\odot$ subgiant star. Models of the internal structure of subgiants predict that the efficiency of the tidal dissipation is boosted by several orders of magnitude due to nonlinear wave-breaking of the dynamical tide near the star's centre (Barker & Ogilvie, 2010). If this mechanism operates in WASP-12, the calculations of Barker & Ogilvie (2010) yield $Q'_\star \approx 1.9 \times 10^5$ that is in an excellent agreement with our empirical $Q'_\star \approx 1.8 \times 10^5$. The high value of $Q'_\star \approx 10^8$ would have prevented the planet from spiralling inward over the course of $\sim$4 Gyr of WASP-12's evolution on the main sequence. The evolutionary changes in the star's interior structure would then trigger a rapid orbital decay that is observed nowadays (Barker & Ogilvie, 2010; Weinberg et al., 2017).

For the HAT-P-23 system, the model of Essick & Weinberg (2016) predicts $Q'_\star \approx 6.7 \times 10^5$, which is not rejected by our empirical constraint of $Q'_\star > 5.6 \times 10^5$. On the other hand, Penev et al. (2018) obtained $Q'_\star \approx 3 \times 10^6$ assuming that HAT-P-23, with its rotational speed observed nowadays, has been spun up by tides being raised by its hot giant planet. Further precise transit timing data are expected to empirically verify the proposed models.

A mechanism that drives the rapid orbital decay of WASP-12 b still remains a puzzle. New transit times follow the quadratic ephemeris very well, making the alternative scenarios, such as the apsidal precession or dynamical perturbations from a planetary companion, less likely.

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