WASP-12 b – an exoplanet falling onto its host star?

Gracjan Maciejewski[1]

1. Centre for Astronomy, Nicolaus Copernicus University, Grudziadzka 5, 87–100 Toruń, Poland

With the orbital period as short as 26 hours, the transiting planet WASP-12 b belongs to a group of planets of the tightest orbits. We detected the apparent shortening of its orbital period that could be caused by orbital decay or apsidal precession due to tidal interactions. The reanalysis of available data allowed us to identify an alternative scenario that explains the departure of the transit timing from a linear ephemeris. We found a solution with an additional planet, whose mass is about 17 Earth masses and the orbital period is 3.2 d. We found that this planet can perturb the orbital motion of WASP-12 b that manifests as the apparent orbital decay. Our dynamical model shows that the planet is likely to transit the host star. We plan to acquire precise photometric time series for WASP-12 in the 2017/2018 observing season to confirm the existence of the postulated planet and to determine its parameters.

1 Introduction

The WASP-12 system (Hebb et al., 2009) belongs to a small group of planetary systems with giant planets on extremely tight orbits. The orbital period of the transiting planet WASP-12 b is only 1.09 d long. The planet is a bloated hot Jupiter with an effective radius of $1.90 \pm 0.09\,\mathrm{R_{Jup}}$ (Maciejewski et al., 2013) and a mass of $1.41 \pm 0.10\,\mathrm{M_{Jup}}$ (Hebb et al., 2009). The system architecture has given rise to a number of studies on the planetary atmospheres and star-planet interactions.

Maciejewski et al. (2016) detected the apparent shortening of the orbital period with the method of precise transit timing. This phenomenon could be a manifestation of the orbital decay due to tidal dissipation inside the star (e.g. Levrard et al., 2009; Essick & Weinberg, 2016) or could be a part of the long-term periodic variations produced by apsidal precession of a slightly eccentric orbit (e.g. Ragozzine & Wolf, 2009). The latter scenario is disfavored by new transit and occultation timing (Patra et al., 2017) and gives an upper limit for the orbital eccentricity e_{b} of the order of 10^{-3} (Maciejewski et al., 2016; Patra et al., 2017).

The rate of orbital decay is related to the tidal quality parameter Q'_* that represents the efficiency of tidal dissipation in the host star. Knowledge about the value of this parameter is crucial for predicting the timescales of orbital circularization, axial alignment, and rotational synchronization of binary stars and planetary systems. Unfortunately, it is not well constrained by current observations. To determine its value, binary star systems are often used but they are not relevant for this issue because such quantity is not a fundamental stellar property and depends on the nature of the tidal perturbation. The value of Q'_* is often taken to be 10^6 (Ogilvie & Lin, 2007) but there exist divergent results in the literature. Penev & Sasselov (2011) elaborated theoretical models that predict slower dissipation of the tidal energy inside the host stars, giving Q'_* of the order of $10^8 - 10^9$. Statistical studies on a sample of transiting planet systems detected by ground-based transit surveys suggest $Q'_* > 10^7$ (Penev et al., 2012). On the other hand, Essick & Weinberg (2016) elaborated a more sophisticated model of tidal response (that includes nonlinear interactions and dissipation of tidally driven g-modes), and derived Q'_* between 10^5 and 10^6 for solar-like stars. For WASP-12, we derived $Q'_* = 2.5 \times 10^5$ (Maciejewski et al., 2016). This value is noticeable smaller than the theoretical expectations for the F-type stars that have thinner convective envelopes (thus greater Q'_*), suggesting completely radiative envelopes for the early F types. WASP-12 is 300–500 K hotter than the Sun, so one would expect to find the value of Q'_* rather greater than smaller one.

Patra et al. (2017) discussed other possible explanations of the departure of transit times from the linear ephemeris, including radial acceleration of the system, the Shklovskii effect, and the Applegate effect. All of them are ruled out by Doppler measurements or occultation timing.

Being motivated by intriguing case of the WASP-12 system, we developed an alternative scenario, in which period shrinkage is *de facto* a piece of long-term oscillation induced by a low-mass planetary companion.

2 The alternative scenario

The reanalysis of timing data (transits and occultations) and high precision Doppler measurements from Knutson et al. (2014) and Bonomo et al. (2017), supplemented by over a dozen data points that we have collected with HARPS-N (High Accuracy Radial velocity Planet Searcher for the Northern hemisphere), (Maciejewski et al., in prep.), allowed us to identify the alternative scenario that explains the departure of transit times from the linear ephemeris. We found a unique solution with an additional planet, whose mass is about 17 Earth masses and the orbital period is 3.2 d. This additional planet perturbs the orbital motion of WASP-12 b that manifests as the apparent orbital decay, as shown in Fig. 1. In addition, the existence of the planetary companion is marginally supported by the Doppler measurements with false alarm probability slightly below 1%. Its radial velocity signal has an amplitude of $\sim$9 m s^{-1} and is only 1.5–2.5 times greater than typical uncertainties. Fig. 2 displays the architecture of the system with the additional planet, labelled as WASP-12 c.

Our dynamical model predicts that the system must be almost coplanar and the additional planet transits the host star. The duration of the event is expected to be about 130 min. The transit depth depends on the radius of the planet. Among known exoplanets from a Neptune-like mass regime, there are bodies as compact as rocky BD+20594 b with the radius of $2.23^{+0.14}_{-0.11}\,\mathrm{R}_\oplus$ (Espinoza et al., 2016), and as bloated as Kepler-18 d with the radius of $6.98 \pm 0.33\,\mathrm{R}_\oplus$ (Cochran et al., 2011). This wide range of planetary radii translates into transit depth up to 1.5×10^{-3} normalized flux for the postulated planet.

This finding rises the opportunity for confirmation of the planet c with the transit method. Other detection methods can only provide some clues that betray the existence of the planetary companion. The transit timing method draws attention to this interesting system and can constrain some physical parameters of the additional planet, but observations covering more than 30 years are needed to complete one

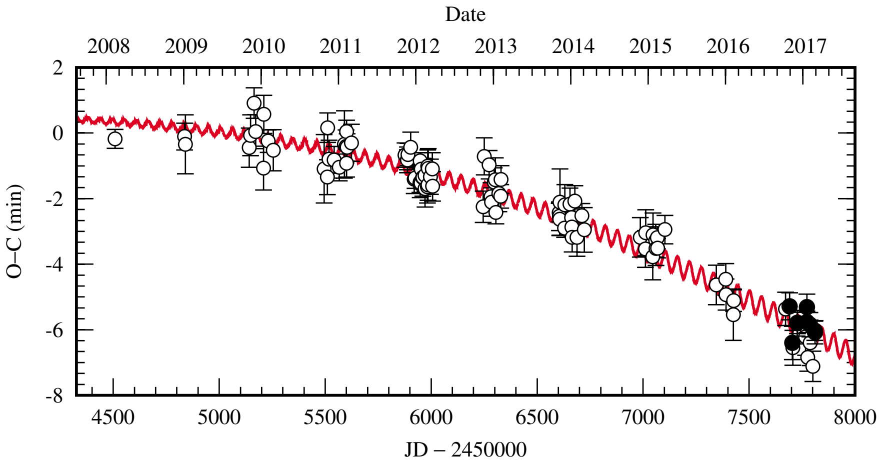

Fig. 1: Transit timing residuals from the constant period ephemeris. The literature data from Maciejewski et al. (2016) and Patra et al. (2017) are marked with open circles. Our new mid-transit times from the 2016/2017 observing campaign (Maciejewski et al., in prep.) are marked with filled dots. The red line sketches transit timing variations predicted by the two-planet model. They mimic orbital decay and cover a portion of a long-period sinusoidal signal.

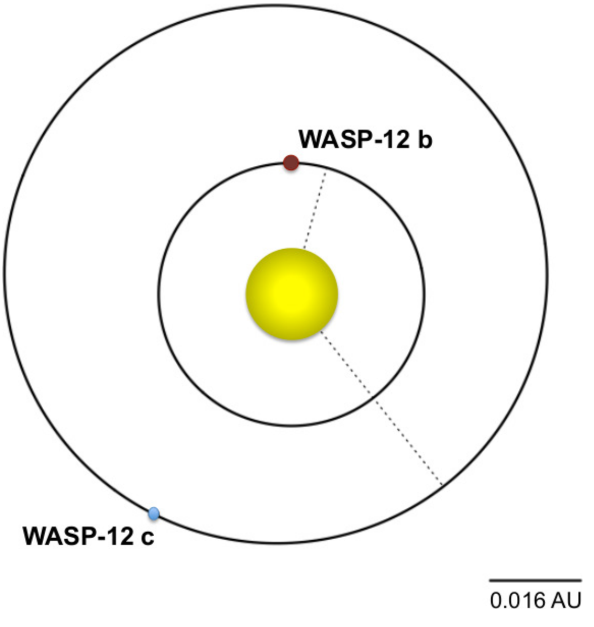

Fig. 2: Possible architecture of the WASP-12 system. The proposed Neptune-mass planet, which can perturb the orbital motion of the known transiting planet WASP-12 b, is labelled as WASP-12 c. Orbits and bodies' sizes are to scale.

cycle of the variation. The Doppler method requires a lot of telescope time to collect a large number of measurements to announce the detection at a high-significance level. With a transit ephemeris calculated from the dynamical model, we plan to hunt for photometric transits of the hypothetical planet in the 2017/2018 observing season.

3 Discussion

Hot Jupiters appear to be usually alone (see e.g. Steffen et al., 2012) or accompanied by other planetary bodies on wide, eccentric orbits (e.g. Schlaufman & Winn, 2016). Numerical simulations show that this picture may be caused by high-eccentricity migration, in which planet's orbital eccentricity is excited to high values by gravitational interactions with other planets or secular perturbations, and then damped by tidal forces with simultaneous shrinkage of the planetary orbit (Rasio & Ford, 1996). This process was found to destabilize and destroy any low-mass inner planets (Mustill et al., 2015). The WASP-47 system is an interesting and so far the only exception from this picture. The hot Jupiter-like planet WASP-47 b (Hellier et al., 2012) is accompanied by two nearby low-mass planets on inner and outer orbits (Becker et al., 2015). Both planets were detected with the transit technique in high precision photometric time series acquired with the Kepler telescope. In addition, the outer planet perturbs the orbital motion of WASP-47 b rising deviations from the strictly Keplerian case. The orbital period is no longer strictly periodic and its variations are observed as a sinusoidal signal in transit times. The case of the WASP-47 system shows that some fraction of hot giant planets must have migrated in early stages of orbital evolution through the interaction with a protoplanetary disk (Lin et al., 1996). Alternatively, such systems could constitute a hot tail of planetary systems with warm Jupiters formed *in situ* (Huang et al., 2016).

The observations of the WASP-47 system with the Kepler telescope have overthrown the paradigm that hot Jupiters do not exist in compact systems, but the question about the occurrence rate of such systems remains open. The population of known hot Jupiters still remains unexplored and high-precision follow-up observations are required to identify more such compact systems. Their properties will place constraints on planet formation and migration theories. WASP-12 is our candidate for a compact planetary system with a hot Jupiter-like planet.

Acknowledgements. The author acknowledges the financial support from the National Science Centre, Poland through grant No. 2016/23/B/ST9/00579. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730890.

References

Becker, J. C., et al., *ApJL* **812**, L18 (2015)

Bonomo, A. S., et al., *A&A* **602**, A107 (2017)

Cochran, W. D., et al., *ApJS* **197**, 7 (2011)

Espinoza, N., et al., *ApJ* **830**, 43 (2016)

Essick, R., Weinberg, N. N., *ApJ* **816**, 18 (2016)

Hebb, L., et al., *ApJ* **693**, 1920 (2009)

Hellier, C., et al., *MNRAS* **426**, 739 (2012)

Huang, C., Wu, Y., Triaud, A. H. M. J., *ApJ* **825**, 98 (2016)

Knutson, H. A., et al., *ApJ* **785**, 126 (2014)

Levrard, B., Winisdoerffer, C., Chabrier, G., *ApJL* **692**, L9 (2009)

Lin, D. N. C., Bodenheimer, P., Richardson, D. C., *Nature* **380**, 606 (1996)

Maciejewski, G., et al., *A&A* **551**, A108 (2013)

Maciejewski, G., et al., *A&A* **588**, L6 (2016)

Mustill, A. J., Davies, M. B., Johansen, A., *ApJ* **808**, 14 (2015)

Ogilvie, G. I., Lin, D. N. C., *ApJ* **661**, 1180 (2007)

Patra, K. C., et al., *AJ* **154**, 4 (2017)

Penev, K., Jackson, B., Spada, F., Thom, N., *ApJ* **751**, 96 (2012)

Penev, K., Sasselov, D., *ApJ* **731**, 67 (2011)

Ragozzine, D., Wolf, A. S., *ApJ* **698**, 1778 (2009)

Rasio, F. A., Ford, E. B., *Science* **274**, 954 (1996)

Schlaufman, K. C., Winn, J. N., *ApJ* **825**, 62 (2016)

Steffen, J. H., et al., *Proceedings of the National Academy of Science* **109**, 7982 (2012)