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3D spin-orbit angle of *Kepler*-25 and HAT-P-7

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Abstract. The number of discovered exoplanets now exceeds 1500, mostly due to the *Kepler* space instrument observations. Many of these planet orbit in less than a week around their host stars. This implies that the inward migration of those planets is a basic ingredient of successful theories of planet formation and evolution. Several mechanisms have been proposed to explain the observed periods, which lead to different orbit eccentricity and obliquity distributions. Here we summarise and discuss the results of obliquities for two *Kepler* stars: HAT-P-7 and *Kepler*-25. These are interesting stellar systems as we could carry out a joint analysis using asteroseismology, transit lightcurve and the Rossiter-McLaughlin effect in order to measure the three dimensional obliquity.

1 Introduction

Hundreds of Jupiter-like planets with orbital periods of less than a week have been detected. This indicates that an inward migration mechanism is required in theories of planet formation and evolution. Mostly, two scenario exist. The first one considers that planet migration occurs due to planet–disk interaction, which leads to circular orbits and orbital planes perpendicular to the stellar spin axis. The second invokes a planet-planet scattering mechanism (or Kozai mechanism), which predicts a broad range of eccentric and oblique orbits. Thus, the three dimensional spin–orbit angle between the stellar spin and the planetary orbital axes, ψ, is supposed to be a unique observational probe of the origin and evolution of planetary systems. Measuring it allows us to constrain the ensemble of viable migration models (1; 2).

However, ψ is not easily measured, and proxies are often used instead, such as its projection onto the plane of the sky λ, determined by using the Rossiter–McLaughlin (RM) effect (*e.g.* 1; 3). Nowa-

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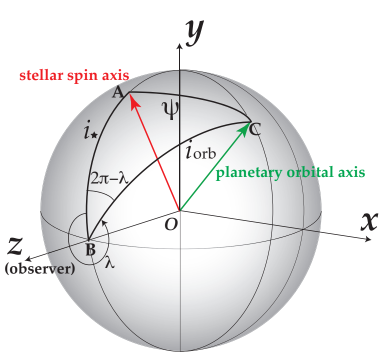

Fig. 1. Relationship between stellar inclination $i_\star$, orbital inclination i_{orb} and projected spin–orbit angle λ for a star–planet system. The coordinates are centered on the star. The XY-plane is in the plane of the sky and $+Z$-axis points towards the observer. Red and green arrows are the angular momentum vectors of the stellar spin and the planetary orbital motion vectors, respectively. The angle AOC, derived from the law of cosines, corresponds to the three dimensional spin–orbit angle ψ.

days, more than 70 transiting planetary systems were observed with the RM effect and among them, more than 30 systems show important misalignment, *i.e.* $|\lambda|$ greater than 22.5° (4). This apparent large diversity of the projected spin–orbit angle is a challenge for existing theories as reported by several authors (*e.g.* 5; 6; 7; 4). Yet, λ suffers from the projection effect that may be responsible of a part of the observed diversity. Measuring ψ is therefore crucial, but requires a prior evaluation of the orbital inclination $i_{\rm orb}$ and of the obliquity of the stellar spin-axis $i_\star$, in addition to λ. The relationship between these quantities is simply due to geometry and is derived from the law of cosines (Figure 1).

In case of transiting planetary systems, it is possible to very precisely determine $i_{\rm orb}$ from the transit lightcurve, as it is in this case close to 90°. However, measurement of $i_\star$ is more difficult, although exist two major independent methods. The simplest technique uses the lightcurve modulation due to a spot at the surface of the star, combined with the rotational velocity of the star, $v \sin i_\star$ in order to evaluate the stellar inclination (8).. This approach relies on at least two critical assumptions. Firstly it assumes that the observed lightcurve periodicity is actually the surface rotation period. This is only accurate if stellar spots live longer than the rotation rate and if all major spots are on the same lobe of the star[1]. Secondly, the latitudinal differential rotation between the line of sight (where the measure of $v \sin i_\star$ is sensitive) and the latitude of the spots is supposed negligible.

A more sophisticated approach uses asteroseismology. As MOST (9), CoRoT (10) and Kepler (11) demonstrated, asteroseismology unveils the internal structure of stars with very high precision, due to the detection of oscillation modes propagating throughout the stars. For a spherically symmetric star, each pulsation mode is characterised by three quantum numbers; the angular degree l, the azimuthal order m ($-l \leq m \leq +l$), and the radial order n. For a non-rotating star, the frequency of each mode are independent of m and show the $(2l + 1)$-fold degeneracy. Thus, the frequency depends on l and n alone and can be directly measured in the Fourier power spectrum computed using the stellar lightcurve. However, the rotation lifts the degeneracy, inducing rotationally split frequency multiplets, characterised by m, that are sensitive to the internal rotation rate and on the stellar inclination between the stellar rotation axis and the line-of-sight $i_\star$ (12). This property has been widely used to infer the internal rotation rate of stars as well as the stellar inclination (*e.g.* 13; 14).

2 Three dimensional spin–orbit angle of HAT-P-7 and *Kepler*-25

HAT-P-7 and *Kepler*-25 are both systems with transiting planets that were observed by *Kepler* during its nominal mission for four continuous years and for which the RM effect is measured. A detailled analysis of these system is given by (15). Here we summarise their results and discuss them. Firstly, the *Kepler* lightcurve was processed in order to measure the stellar pulsations and to derive accurate estimates of the fundamental stellar parameters and the stellar inclination $i_\star$. Secondly, we measured the orbital parameters by combination of a *Kepler* transit lightcurve analysis, the asteroseismic results and the previous data of the RM effect. This allowed us to self consistently evaluate the three dimensional spin–orbit by the means of the law of cosines.

2.1 HAT-P-7

HAT-P-7 is a bright main sequence F6 star of mass $M \simeq 1.6 M_\odot$, radius $R \simeq 2.0 R_\odot$, determined consistently by (15) and (16), and has a Jupiter-size transiting planet in a 2.2-day orbit. The RM effect has been measured independently by three studies: (17, hereafter W09), (18, N09) and (19, A12). Although their results differ quantitatively, possibly due to unknown and non-accounted physical processes, they all indicate strong spin–orbit misalignment. These studies also indicate that the planet is likely in a retrograde orbit, but could be as well in a prograde polar orbit with a much lower probability ($< 0.5\%$).

From asteroseismology, we derived a stellar inclination of approximately 30°. This indicates that the star is nearly seen from its pole. Unfortunately, we cannot definitively rule out the possibly that

[1] For example, in case of two large spots in opposite side of the star, the measured periodicity corresponds twice the actual stellar rotation rate.

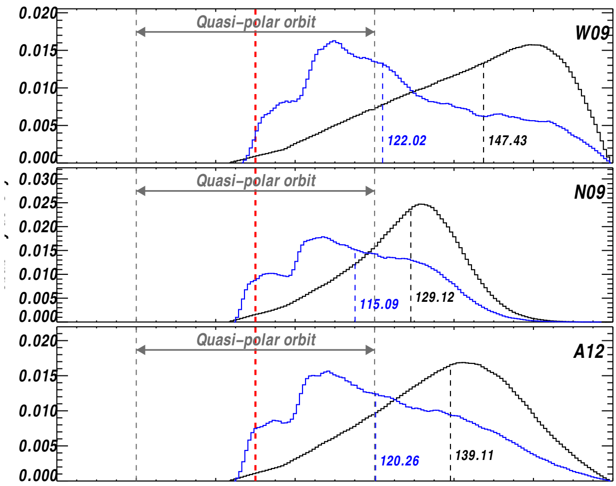

Fig. 2. Probability distributions for the three-dimensional spin–orbit angle ψ of HAT-P-7b for the W09 (top), N09 (middle), and A12 (bottom) data sets. Solid blue lines are the posteriors from the joint analysis. Black dash lines are the posteriors assuming a uniform $\cos i_\star$ distribution but using our derived λ and $i_{\rm orb}$ from the joint analysis. Vertical dash blue and black lines indicate the median values of these distribution. The different datasets lead to compatible probability density distribution by using the joint analysis. In this figure, $\psi = 90°$ (Red vertical dash line) corresponds to a polar orbit while $\psi < 90°$ indicate a prograde orbit and $\psi > 90°$ a retrograde orbit. The quasi-polar orbit range adopted in this study is shown with grey dash lines.

the star is seen from the equator because our measurement is rather imprecise. This is mostly due to the very small frequency spacing between m components and to the rather short lifetime of the pulsation that does not enable us to disentangle the split modes in the power spectrum. Note also that this frequency spacing being an intrinsic measure of the internal rotation, additional photometric seismic analyses are unlikely to improve the precision. Nevertheless, by combining results from asteroseimology, transit lightcurve and RM effect, we confirm that the planet is likely on a retrograde orbit. However, we found that the probability of a prograde orbit is increased from 0.5% to 2.3%[2], when comparing the joint analysis assuming isotropic stellar inclination[3] with the joint analysis that account for the asteroseismically measured stellar inclination. This is mostly because the maximum of probability is shifted from $\psi \simeq 140°$ to $\psi \simeq 110°$ (Figure 2), which indicates that the planet could be in a quasi-polar orbit $\psi \approx 90°$. To be quantitative, defining the quasi-polar orbit as $60° < \psi < 120°$ and using the probability density functions shown in Figure 2, we calculate the posterior probability for the planet to be in a quasi-polar orbit either by using the seismically determined stellar inclination P(quasi-polar | seismic $i_\star$), or by assuming that the stellar inclination is not known, P(quasi-polar | isotropic $i_\star$). Thus, we obtain on average for the three RM effect dataset, P(quasi-polar | seismic $i_\star$) = 52% to be compared with P(quasi-polar | isotropic $i_\star$) = 20%. We conclude that the planet is possibly in a quasi-polar retrograde orbit.

2.2 *Kepler*-25

The *Kepler*-25 system consists of a bright star of mass $M \simeq 1.23 M_\odot$ and $R \simeq 1.34 R_\odot$, with two transiting Neptune-size planets and another one non-transiting planet, deduced from the long-term radial velocity trend. It is one of the few multiple planet systems for which the RM effect is measured (6). For the largest transiting planet, (6) found $\lambda = 7° \pm 8°$ which suggests, assuming coplanarity, that the transiting planets are likely to be orbiting on a plane perpendicular to the stellar spin axis.

To verify this, we proceeded to a joint analysis similar to HAT-P-7 and found $\psi = 26.9^{+7.0°}_{-9.2}$. This precise measurement is due to a very accurate stellar inclination $i_\star = 65.4^{+10.6°}_{-6.4}$. Indeed, contrary to HAT-P-7, the m components do not overlap significantly, ensuring both high precision and accuracy on the stellar inclination. Thus, due to an important projection effect and contrary to what is suggested by λ, ψ does not indicate that the stellar spin axis and the orbital axis are aligned, but rather mildly misaligned.

[2] These are average obtained from our analysis, using the three different RM effect source.

[3] In other words, assuming that the stellar inclination is unknown.

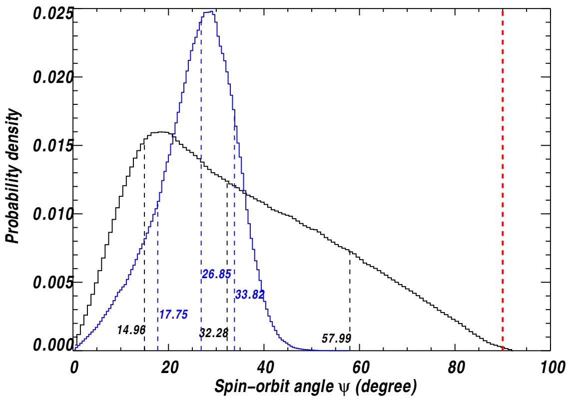

Fig. 3. Probability distributions for the three-dimensional spin–orbit angle ψ of *Kepler*-25c. Solid blue lines are the posteriors from the joint analysis. Black lines are the posteriors assuming a uniform $\cos i_\star$ distribution and using our derived λ and $i_{\rm orb}$ from the joint analysis. Vertical dash lines indicate the median and the confidence interval at 1σ. The vertical red dash line corresponds to a polar orbit.

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