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Position angles and coplanarity of multiple systems from transit timing
(Research Note)

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ABSTRACT

Aims. We compare the apparent difference in timing of transiting planets (or eclipsing binaries) that are observed from widely separated locations (parallactic delay).

Methods. A simple geometrical argument allows us to show that the apparent timing difference also depends on the sky position angle of the planetary (or secondary) orbit, relative to the ecliptic plane.

Results. Our calculation of the magnitude of the effect for all currently known planets (should they exhibit transits) find that almost 200 of them – mostly radial-velocity detected planets – have predicted timing effects greater than 1 s. We also compute the theoretical timing precision for the PLATO mission, which will observe a similar stellar population and find that a 1 s effect will frequently be easily observable. We also find that the sky coplanarity of multiple objects in the same system can be probed more easily than the sky position angle of each of the objects separately.

Conclusions. We show that a new observable from transit photometry becomes available when very high-precision transit timing is available. We find that there is a good match between projected capabilities of the future space missions PLATO and CHEOPS and the new observable. We specify some initial science questions that this new observable may be able to address.

Key words. techniques: photometric – planetary systems

1. Basic principles

We consider a system of one or several eclipsing bodies. These components can be either eclipsing stars or transiting exoplanets, but in the text below we use only transiting exoplanets as a specific example, since similar effects for eclipsing binaries are even stronger. We then assume that a particular transit event on that system was observed from two remote locations simultaneously, and the following was developed with *Kepler* spacecraft (Borucki et al. 2010) and an Earth-bound observer in mind, so the observers are separated by AU-scale distances.

While the existence of transits practically ensures that the inclination angle i is close to 90°, the sky orientation of the systems remains unconstrained. We wish to use the above observational configuration to put such constraints on each transiting member of the system, and if there are more than one, on their sky coplanarity.

We begin by defining all the distances given in the left hand panel of Fig. 1: the orbital distance during transit d_1, the distance to the system d_2, the baseline distance between the two observers b_2 and the corresponding distance projected on the planet's orbit b_1. Important is that one expects that the planet will be seen by the different observers at the same transit phase (e.g., first contact is shown here) at a slight delay, also known as parallactic delay, of $D_{\rm expect} = b_1/V$ where V is the planet's orbital velocity $V = 2\pi d_1/P$ (for circular orbits, where P is the planet's orbital period), and $b_1 = b_2 d_1/d_2$, or

$$D_{\rm expect} = P\frac{b_2}{2\pi d_2} = 0.06666\left[\frac{P}{\rm day}\right]\left[\frac{b_2}{\rm AU}\right]\left[\frac{d_2}{\rm pc}\right]^{-1} \ [{\rm s}]. \quad (1)$$

This can also be read simply as the planetary period times the parallax angle subtended by the two observers from the host star. Low but nonzero eccentricity e would change V by a fractional amount close to e (i.e. $|\Delta V|/V \simeq e$), where the change can be either positive or negative, relative to the circular case, depending on the argument of periastron ω. We note that higher order effects of finite ecentricity, such as orbital precession, are not currently included in the analysis.

This delay is not related, and is actually perpendicular, to the light-time delay between the observers that is caused by different observer positions along the line of sight. If one adds the possibility that the planet's orbit may be tilted at an angle l relative to the line separating the two observers (right panel of Fig. 1), then the effective separation between the two observers, as seen projected on the planet's orbit, is only $b_2\cos(l)$, so

$$D_{\rm observe} = P\frac{b_2}{2\pi d_2}\cos(l). \quad (2)$$

One finds that by dividing $D_{\rm observe}$ by $D_{\rm expect}$ one can measure $\cos(l)$, and this effect will be seen best for long-period planets (if their period is known precisely enough) and for host stars with higher parallactic angle. This measurement is different from the spectroscopic Rossiter-McLaughlin effect (e.g., Ohta et al. 2005) since it bears no relation to the stellar spin axis, which one may assess independently.

Earth-bound observers travel significant distances yearly as they orbit the Sun. A satellite in the L2 Lagrange point, such as PLATO (Rauer & Catala 2011), is similar in that respect. Therefore, the global modeling of multiple transits taken by a

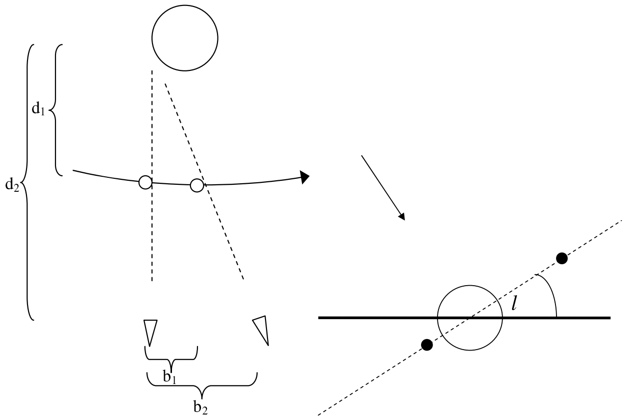

Fig. 1. *Left panel*: top view of the two observers (at the bottom) from above the plane containing the observers and the planet host star. As the planet (empty circle) moves in its orbit, it will appear to transit (here the first contact is shown) at slightly different times for the two observers. *Right panel*: a view along the orbital plane of the planet from infinity. The two observers (filled circles) are on a line that is inclined at an angle l relative to the orbital plane. The *left panel* view was taken from a position illustrated by the arrow.

single observer can produce similar results to the two-observer model above as long as the prediction uncertainty of the linear ephemeris is small relative to the individual timing undertainty. In such a case, the parallactic delay effect will be manifested as residuals to the linear ephemeris that have a 1 yr period and phase such that the maximal residuals occur when the observer's orbit about the Sun, projected on a line perpendicular to the direction of the host star, is maximal. The two separate observations of the same transit are therefore not strictly required but are just more illustrative of the parallactic delay effect. Other timing effects, such as ones caused by orbital precession or dynamical interaction, do not have this particular morphology and can thus be disentangled from the parallactic delay.

In cases where accurate parallax is not known, $\cos(l)$ may not be constrained in this way. However, even in these cases one may compare two eclipsing objects in the same system (when available) – e.g., two transiting planets – for their sky coplanarity even with no information on the system's distance:

$$\frac{\cos(l_1)}{\cos(l_2)} = \frac{D_1}{D_2}\frac{P_2}{P_1}\frac{b_{2,2}}{b_{2,1}}. \quad (3)$$

Here the right hand side of the equation is only made of observable quantities, and the left side is constraining the sky angle between the two transiting planets. We note that at the timing precision required to observe this effect (see next section), the transit timing signal may also become sensitive to planet-planet interaction (Holman & Murray 2005), so these will need to be accounted for as well. We stress again that the parallactic delay effect has a very specific shape (a sine with a pre-determined period and pre-determined phase), and so it should be possible to disentangle this particular effect from other timing effects.

2. Estimating signal significance

2.1. Known systems

To assess the possibility of measuring this effect in already known systems, we calculate $D_{\rm expect}$ using Eq. (1) for all the planets on the NASA Exoplanet Archive[1] using b_2 = 1 AU for all – had they were transiting their host star. For scale, we note that ground-based single-transit timing precision nowadays routinely reaches roughly ten seconds, and sometimes even less than that (e.g., Tregloan-Reed et al. 2013). When sorting the $D_{\rm expect}$ above, exoplanets that have been detected by direct imaging naturally turned out to be prime candidates (they are long-period and close to the Solar System), and these planets form all the top 3 and 14 of the top 19 strongest signals (amplitudes of 19 s or more). However, these planets are too long-period for practical follow-up, and their period is not constrained nearly as well as needed. This is unfortunate since such a configuration could have been use to independently validate this technique from the imaging data.

More important is that all the first 190 planets have $D_{\rm expect}$ in excess of one second, which is not too far from the current state of the art, and most of these planets (>90%) are planets detected by either radial velocity (RV) or transit (the latter of which means they were RV confirmed as well), so they are relatively bright, helping to achieve good timing precision. If found to be transiting, such planets are prime candidates for constraining $\cos(l)$. Of the planets that are already known to transit, the most promising are HD 80606 b and Kepler-22 b, with $D_{\rm expect}$ of 0.127 s and 0.102 s, respectively, so significantly more challenging.

2.2. PLATO and CHEOPS

In the following we give the planned PLATO mission as a specific example, since for this mission the predicted effect may be measured on a large scale, even though suitable isolated cases may already be available in other data (above).

The *Gaia* mission is expected to measure the parallactic angle to all relevant targets to very high precision. Specifically, all PLATO host stars will be brighter than 11th magnitude[2], while all stars brighter than 12th magnitude will be measured by *Gaia* to better than 14 μas[3], so an 11th magnitude Sun-like star will have a distance of $d_2 \approx 171.4$ pc and have d_2 measured to 0.24% or better. Furthermore, the relative errors on P, b_2 are typically several orders of magnitude smaller still, so while distances are notoriously difficult to measure in astronomy, *Gaia* will allow for the error on $D_{\rm expect}$ to be negligible relative to the error in $D_{\rm observe}$.

The times of mid-transit, hence $D_{\rm observe}$, can be measured with an accuracy of $\sigma_{\rm Tc} \simeq (t_{\rm e}/2\Gamma)^{1/2}\sigma_{\rm ph}\rho^{-2}$ (Ford & Gaudi 2006) where $t_{\rm e}$ is the duration of ingress/egress, Γ the rate at which observations are taken, $\sigma_{\rm ph}$ the photometric uncertainty, and ρ the ratio of the planet radius to stellar radius. Since the minimum ingress or egress time is when the transits are central, and since the transit duty cycle for such transits at circular orbits is $q = \frac{R}{\pi a}$, the ingress/egress time $t_{\rm e}$ is

$$t_{\rm e} = 2P\,q\,\rho. \quad (4)$$

For the PLATO mission, star samples P1 and P2 are required to have noise levels ≤34 ppm/h, while for star sample P4 this requirement would be ≤80 ppm/h, and these stars would be observed nearly continuously for two to three years. Assuming white noise, one can scale a given noise level requirement with the ingress/egress time $t_{\rm e}$ for a given orbital period, and compare the expected timing accuracy of single transits to what is expected by $D_{\rm expect}$. This, however, would underestimate

[1] http://exoplanetarchive.ipac.caltech.edu/cgi-bin/ExoTables/nph-exotbls?dataset=planets as of August 28, 2013.

[2] PLATO Definition Study Report (Red Book).

[3] From *Gaia* web page.

PLATO's detection capability since by observing multiple transits events (roughly $N_{\rm tr} = \frac{2\,{\rm yr\ to\ 3\ yr}}{P} Q_{\rm PL}$ events), one would gain a factor of $N_{\rm tr}^{1/2}$ in detectable precision (where $Q_{\rm PL}$ is the PLATO-required duty cycle of 95%).

We computed these detection limits for two planet sizes ($\rho = 0.1$ and $\rho = 0.035$, Jupiter- and Neptune-like, respectively) orbiting a Sun-like star, and three observational scenarios (see Fig. 2): the minimal scenario assumed the P3 star sample requirement of 80 ppm/h collected over the minimal 2 yr (for the long-monitoring phases), the good scenario assumed the P1 and P2 star samples requirement of 34 ppm/h collected over 2.5 yr (for the same phases), and the best-case scenario assumed the bright-star ($m_v \leq 6$) predicted noise level of 10 ppm/h collected over (the PLATO goal of) 3 yr. One finds that short-period giant planets may allow constraining $\cos(l)$ to 1 s or better even in the very minimal scenario presented here (minimal noise requirement, minimal observation time span, minimal ingress/egress time). Given the properties of the known systems above, and the predicted PLATO capabilities outlined here, we conclude that the PLATO mission would be able to constrain $\cos(l)$ on a large number of planets. Figure 2 also includes the calculated $D_{\rm expect}$ value for the known exoplanets – if they were transiting – and one can see that the currently known population largely lies just below PLATO's detection limits. Importantly, since the PLATO target stars are all nearby relative to almost all existing transit surveys, $D_{\rm expect}$ will be, on average, more easily observable in PLATO targets than in the currently known population. Coupled with the large number of targets, we find that a significant number of objects will have an observable $D_{\rm expect}$ using PLATO. We note that even much better detection limits will be availabe for observation of PLATO eclipsing binaries.

We also note that the CHEOPS mission (Broeg et al. 2013) requires a noise level of 150 ppm/min, or ~20 ppm/h, for stars brighter than $V \leq 9$ so it may have comparable performance to the PLATO mission. We did not add it to Fig. 2 to avoid clutter in the figure. The TESS mission is expected to have a performance of ~60 ppm/h, but different stars will be observed for very different durations (from 27 days to 1 year), so while overall performance will vary widely, its best performance will be similar to PLATO's[4].

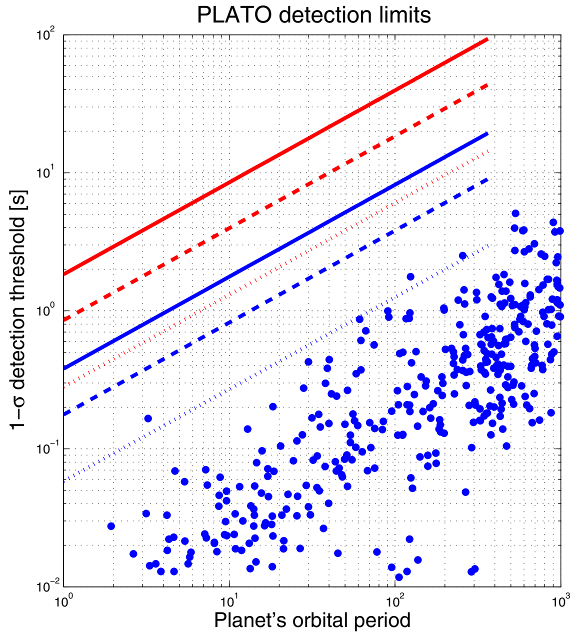

Fig. 2. Solid lines: expected 1σ detection thresholds for PLATO for different scenarios, as a function of the planet's orbital period. Red lines are for Neptune-like planets ($r/R_* = 0.035$) and blue are for Jupiter-like planets ($r/R_* = 0.1$), while the solid, dashed, and dot-dashed line sets (from top to bottom) are for minimal, good, and best-case scenarios, respectively, as described in the text. Dots: $D_{\rm expect}$ of some of the known exoplanets. PLATO planets are likely to have a higher $D_{\rm expect}$ than the current population (see text).

3. Discussion

We have shown that the (cosine of the) sky position angle $\cos(l)$ can be constrained from high-precision transit timing data by comparing the expected and observed parallactic delay if *Gaia*-class parallax angle to the system is available. Moreover, we have shown that sky coplanarity of eclipsing or transiting systems with multiple transiting components can be probed even if the parallax angle is completely unknown. We note that one expects apriori that most multi transiting systems will indeed be aligned because misaligned orbits are less likely to exhibit transits of multiple objects.

Knowledge of $\cos(l)$ can be useful in a number of ways, for example, (I) in young systems that still have disks one may be able to compare the orientation of the planet and the disk; (II) some direct imaging techniques achieve high contrast only on one side of the image plane (e.g., PIAA, Guyon et al. 2012). Knowing $\cos(l)$ will allow aiming such an instrument at the most sensitive angle – increasing sensitivity and allowing the other half of the image plane not to be imaged, reducing on-target time; (III) $\cos(l)$ may also be measured to change in time, hinting of the presence of a multiple systems with strong interaction even if only a single transiting object was previously known; (IV) if the host star (or target binary) has a visual stellar companion, and studies of the relation between the orientation of the planetary (binary) orbit and the stellar companion orbit can be made, perhaps pointing to interaction between the companion and the host natal disk.

Looking forward, we have shown that a large number of known RV-detected planets have parallactic delay in excess of 1 s, so they may well have their $\cos(l)$ constrained by the future CHEOPS mission. Importantly, the PLATO mission (and obviously the CHEOPS mission) is aimed at a stellar population similar to the RV planet host stars above, giving rise to the expectation that PLATO will measure $\cos(l)$ on a large scale. By the time they launch, both of these missions will also benefit from high-precision parallax measurement for their targets from the *Gaia* mission, and both of these missions may allow the investigations proposed here to made routinely.

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References

Broeg, C., Fortier, A., Ehrenreich, D., et al. 2013, Eur. Phys. J. Web Conf., 47, 3005
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Science, 327, 977
Ford, E. B., & Gaudi, B. S. 2006, ApJ, 652, L137
Guyon, O., Kern, B., Belikov, R., et al. 2012, Proc. SPIE, 8442
Holman, M. J., & Murray, N. W. 2005, Science, 307, 1288
Ohta, Y., Taruya, A., & Suto, Y. 2005, ApJ, 622, 1118
Rauer, H., & Catala, C. 2011, IAU Symp., 276, 354
Tregloan-Reed, J., Southworth, J., & Tappert, C. 2013, MNRAS, 428, 3671

[4] No technical publication about TESS is available. We used public data from: https://www.youtube.com/watch?v=mpViVEO-ymc