HOW TO DETERMINE AN EXOMOON’S SENSE OF ORBITAL MOTION

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ABSTRACT

We present two methods to determine an exomoon’s sense of orbital motion (SOM), one with respect to the planet’s circumstellar orbit and one with respect to the planetary rotation. Our simulations show that the required measurements will be possible with the European Extremely Large Telescope (E-ELT). The first method relies on mutual planet–moon events during stellar transits. Eclipses with the moon passing behind (in front of) the planet will be late (early) with regard to the moon’s mean orbital period due to the finite speed of light. This “transit timing dichotomy” (TTD) determines an exomoon’s SOM with respect to the circumstellar motion. For the 10 largest moons in the solar system, TTDs range between 2 and 12 s. The E-ELT will enable such measurements for Earth-sized moons around nearby Sun-like stars. The second method measures distortions in the IR spectrum of the rotating giant planet when it is transited by its moon. This Rossiter–McLaughlin effect (RME) in the planetary spectrum reveals the angle between the planetary equator and the moon’s circumplanetary orbital plane, and therefore unveils the moon’s SOM with respect to the planet’s rotation. A reasonably large moon transiting a directly imaged planet like β Pic b causes an RME amplitude of about 100 m s−1, about twice the stellar RME amplitude of the transiting exoplanet HD209458 b. Both new methods can be used to probe the origin of exomoons, that is, whether they are regular or irregular in nature.

Key words: eclipses – methods: data analysis – methods: observational – planets and satellites: individual (β Pic b) – techniques: photometric – techniques: radial velocities

1. CONTEXT

Although thousands of extrasolar planets and candidates have been found, some as small as the Earth’s Moon (Barclay et al. 2013), no extrasolar moon has been detected. The first dedicated hunts for exomoons have now been initiated (Pont et al. 2007; Kipping et al. 2012; Szabó et al. 2013), and it has been shown that the Kepler or PLATO space telescopes may find large exomoons in the stellar light curves (Kipping et al. 2009; Heller 2014), if such worlds exist.

The detection of exomoons would be precious from a planet formation perspective, as giant planet satellites carry information about the thermal and compositional properties in the early circumplanetary accretion disks (Canup & Ward 2006; Heller & Pudritz 2014). Moons can also constrain the system’s collision history (see the Earth–Moon binary; Hartmann & Davis 1975) and bombardment record (see the misaligned Uranian system; Morbidelli et al. 2012), they can trace planet–planet encounters (see Triton’s capture around Neptune; Agnor & Hamilton 2006), and even the migration history of close-in giant planets (Namouni 2010). Under suitable conditions, an exomoon observation could reveal the absolute masses and radii in a star–planet–moon system (Kipping 2010). What is more, moons may outnumber rocky planets in the stellar habitable zones (Heller & Barnes 2014) and therefore could be the most abundant species of habitable worlds (Williams et al. 1997; Heller et al. 2014).

A moon’s sense of orbital motion (SOM) is crucial to determine its origin and orbital history. About half of the techniques have been proposed to find an extrasolar moon (Heller 2014), but none of them can determine an exomoon’s SOM with current technical equipment (Lewis & Fujii 2014). We here identify two means to determine an exomoon’s SOM relative to the circumstellar orbit and with respect to the planet’s direction of rotation. In our simulations, we use the European Extremely Large Telescope5 (E-ELT) as an example for one of several ELTs now being built.

2. METHODS

2.1. An Exomoon’s Transit Timing Dichotomy (TTD)

For our first new method to work, the moon needs to be large enough (and the star’s photometric variability sufficiently low) to cause a direct transit signature in the stellar light curve (Sartoretti & Schneider 1999). Depending on the moon’s orbital semi-major axis around the planet (a_p), on the orbital alignment, some stellar transits of the planet–moon pair will then show mutual planet–moon eclipses. These events have been simulated (Cabrera & Schneider 2007; Sato & Asada 2009; Kipping 2011a; Pál 2012), and a planet–planet eclipse (Hirano et al. 2012) as well as mutual events in a stellar triple system (Carter et al. 2011) have already been found in the Kepler data.

Figure 1 illustrates the difficulty in determining a moon’s SOM. Panels (a) and (b) visualize the two possible scenarios of a prograde and a retrograde SOM with respect to the circumstellar motion. Panel (c) presents the four possible ingress and egress locations (arbitrarily labeled I, II, III, and IV) for a mutual planet–moon event during a stellar transit. Panel (d) shows the projection of the three-dimensional moon orbit on the two-dimensional celestial plane. If the moon transit is directly visible

5 Construction of the E-ELT near the Paranal Observatory in Chile began in 2014 June, with first light anticipated in 2024.
before a mutual event (I and II). However, this inspection cannot enter the stellar disk first and then performs a mutual event with in the stellar light curve, then events I and II can be distinguished a time delay speed of light, an Earth-bound observer witnesses events I and IV with a positive transit timing dichotomy of mutual planet–moon events. Due to the finite eclipses. (d) Edge view (as seen from Earth) of a circumplanetary moon orbit. Roman numbers I to IV denote the ingress and egress of mutual planet–moon (e) Transit timing dichotomy of mutual planet–moon events. Due to the finite (a) Top view of the system’s orbital motion. The moon’s circumplanetary orbit is prograde with respect to the circumstellar orbit. (b) Similar to panel (a), but now the moon is retrograde. (c) Top view of the moon’s orbit around the planet. (d) Transit timing dichotomy of mutual planet–moon events. Due to the finite speed of light, an Earth-bound observer witnesses events I and IV with a positive time delay \( \Delta t \) compared to events II and III, respectively.

Figure 1. Orbital geometry of a star–planet–moon system in circular orbits. (a) prograde orbit (b) retrograde orbit

\[ \delta \Delta t = \frac{\Delta P_{ps}}{c} \left( 1 - \cos(\alpha) \right) = \frac{\Delta P_{ps}}{c} \left( 1 - \cos \left( \arcsin \left( \frac{R_p}{\Delta P_{ps}} \right) \right) \right) \ll \Delta t, \]

with \( c \) being the speed of light, \( R_p \) the planetary radius, and \( \alpha \) defined by \( \sin(\alpha) = R_p/\Delta P_{ps} \) as shown in Figure 1(e). For a moon at 15 \( R_p \) from its planet, such as Ganymede around Jupiter, \( \alpha \approx 3.8 \) and \( \delta \Delta t \approx 0.005 \) s, which is completely negligible. Orbital eccentricities could also cause light travel times different from the one shown in Figure 1. However, even for eccentricities comparable to Titan’s value around Saturn, with 0.0288 the largest among the major moons in the solar system, TTDs would be affected by <5%, or fractions of a second. Significantly larger eccentricities are unlikely, as they will be tidally eroded within a million years (Porter & Grundy 2011; Heller & Barnes 2013).

2.2. The Rossiter–McLaughlin Effect (RME)
in the Planetary Emission Spectrum

In the solar system, all planets except Venus (Gold & Soter 1969) and Uranus rotate in the same direction as they orbit the Sun. One would expect that the orbital motion of a moon is aligned with the rotation of the planet. However, collisions, gravitational perturbations, capture scenarios, etc. can substantially alter a satellite’s orbital plane (Heller et al. 2014). Hence, knowledge about the spin–orbit misalignment, or obliquity, in a planet–exomoon system would be helpful in inferring its formation and evolution.
Figure 2. Theoretical emission spectra of a hot, Jupiter-sized planet (orange, upper) and a Sun-like star as reflected by the planet at 10 AU (blue, middle) and 100 AU (light blue, lower). For the planet, a Jupiter-like bond albedo of 0.3 is assumed.

(A color version of this figure is available in the online journal.)

Figure 3. Transit timing dichotomies of the 10 largest moons in the solar system. Moon radii are symbolized by circle sizes. The host planets Jupiter, Saturn, Neptune, Uranus, and Earth are indicated with their initials. Note that the largest moons, causing the deepest solar transits, induce the highest TTDs.

Contamination of the planetary spectrum by the star via direct stellar light on the detector and stellar reflections from the planet might pose a challenge. Consequently, observations need to be carried out in the near-IR, where the planet is relatively bright and presents a rich forest of spectral absorption lines. Figure 2 shows that contamination of the planetary spectrum by reflected star light becomes negligible beyond several 10 AU, with no need for additional cleaning.

3. RESULTS AND PREDICTIONS

3.1. Transit Timing Dichotomies

We computed the TTDs of the 10 largest moons in the solar system, yielding values between about 2 and 12 s (Figure 3). Most intriguingly, the largest moons (Ganymede, Titan, and Callisto), which have the deepest solar transit signatures, also have the largest TTDs. This is owed to the location of the water ice line in the accretion disks around jovian planets, which causes the most massive icy satellites to form beyond about 15 $R_{\text{Jup}}$ (Heller & Pudritz 2014). Figure 3 indicates that timing precisions of 1–6 s need to be achieved on transit events with depths of only about 10$^{-4}$, corresponding to the transit depth of an Earth-sized moon transiting a Sun-like star.

Precisions of 6 s in exoplanet transit mid-times have been achieved from the ground using the Baade 6.5 m Telescope at Las Campanas Observatory in Chile (Winn et al. 2009). On the one hand, the planet in these observations (WASP-4b) was comparatively large to its host star with a transit depth of about 2.4%. On the other hand, the star was not particularly bright, with an apparent visual magnitude $m_V \approx 12.6$. The photon collecting power of the E-ELT will be $(39.3 \, \text{m}/6.5 \, \text{m})^2 \approx 37$ times that of the Baade Telescope. And with improved data reduction methods, timing precisions of the order of seconds should be obtainable for transit depths of $10^{-4}$ with the E-ELT for very nearby transiting systems.

We calculate the probabilities of one to four mutual events ($P_i, \ i \in \{1, 2, 3, 4\}$) during a stellar transit of a coplanar planet–moon system. The distance of the moon traveled

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6 So far, 80 exoplanets have had their spin–orbit alignment measured via the RME, see R. Heller’s Holt–Rossiter–McLaughlin Encyclopaedia (http://www.physics.mcmaster.ca/~rheller).

7 Models were provided by T-O. Hasser (2011, private communication), based on the spectral library by Hasser et al. (2013) available at http://phoenix.astro.physik.uni-goettingen.de/.
on its circumplanetary orbit during the stellar transit \( s = 2R_\oplus P_\text{ph} d_{ps}/(P_{ps} a_{ph}) \), with \( a_{ph} \) denoting the circumstellar orbital semi-major axis of the planet–moon barycenter and \( P_{ps} \) being its circumstellar orbital period. We analyze a Jupiter-like planet at 1 AU from a Sun-like star and simulate \( 10^6 \) transits for a range of possible moon semi-major axes, respectively, where the moon’s initial orbital position during the stellar transit is randomized. As the stellar transit occurs, we follow the moon’s circumplanetary orbit and measure the number of mutual events (of type I, II, III, or IV) during the transit, which can be 0, 1, 2, 3, or even 4.

For siblings of Io, Europa, Ganymede, and Callisto we find \( P_1 = 21\% \), 13\%, 8\%, and 5\% as well as \( P_2 = 50\% \), 24\%, 11\%, and 5\%, respectively (Figure 4). Notably, the probabilities for two mutual events (purple long-dashed line) are higher than the likelihoods for only one (red solid line) if \( d_{ps} \lesssim 1.6 \times 10^6 \) km. For moons inside about half-way between Io and Europa, the probability of having no event (black solid line) is <50\%, so it is more likely to have at least one mutual event during any transit than having none. Moons inside 200,000 km (half the semi-major axis of Io) can even have three or more events, allowing the TTD method to work with only one stellar transit. Deviations from well-aligned orbits due to high transit impact parameters or tilted moon orbits would naturally reduce the shown probabilities. Nevertheless, mutual events could obviously be common during transits.

A single stellar transit with \( \geq 3 \) mutual events contains TTD information on its own. A two-event stellar transit only delivers TTD information if the events are either a combination of I and II or of III and IV. Moons in wide orbits cannot proceed from one conjunction to the other during one stellar transit. Hence, the contribution of TTD-containing events along \( P_2 \) is zero beyond about \( 10^6 \) km. In close orbits, the fraction of two-event cases with TTD information is \( P_{L, \text{TDD}} \approx P_\text{ph}(a_{ps} \tau)^{-1} \). For Io, as an example, \( P_{L, \text{TDD}} = (6.1 \times \pi)^{-1} \approx 5\% \). So even for very close-in moons, two-event cases with TTD information are rare.

3.2. The Planetary Rossiter–McLaughlin Effect due to an Exomoon

We simulated the RME in the near-IR spectrum of a planet similar to \( \beta \) Pic b assuming a planetary rotation speed of 25 km s\(^{-1}\) (Snellen et al. 2014) and a Jovian planetary radius (\( R_\text{Jup} \)). The moon was placed in a Ganymede-like orbit (\( a_{ps} = 15 R_\text{Jup} \)) and assumed to belong to the population of giant moons that form at the water ice lines around super-Jovian planets, with a radius of up to about 0.7 Earth radii (\( R_\oplus \); Heller & Pudritz 2014). Using the code of Albrecht et al. (2007, 2013), we simulated absorption lines of the rotating planet as distorted during the moon’s transit with a cadence of 15 minutes. Focusing on the same spectral window (2.304–2.332 \( \mu m \)) as Snellen et al. (2014), we then convolved the planetary spectrum (Figure 2) with these distorted absorption lines. Employing the CRIRES Exposure Time Calculator and incorporating the increase of \( 39.3 \text{ m}/\text{s}^2 \approx 23 \) in collecting area for the E-ELT, we obtain a signal-to-noise ratio of 75 per pixel for a 15 minutes exposure—the same values as obtained by Snellen et al. (2014) for a similar calculation. The resulting pseudo-observed spectra are finally cross-correlated with the template spectrum, and a Gaussian is fitted to the cross-correlation functions to obtain RVs.

Pro- and retrograde coplanar orbits are clearly distinguishable in the resulting RME curve (Figure 5). In particular, the RME amplitude of \( \approx 100 \text{ m/s}^{-1} \) is quite substantial. In comparison, the RME amplitude of HD 209458 b is \( \approx 40 \text{ m/s}^{-1} \) (Queloz et al. 2000), and recent RME detections probe down to 1 m s\(^{-1}\) (Winn et al. 2010).

4. DISCUSSION AND CONCLUSION

We present two new methods to determine an exomoon’s SOM. One method, which we refer to as the TTD, is based on a light traveling effect that occurs in subsequent mutual planet–moon eclipses during stellar transits. For the 10 largest moons in the solar system, TTDs range between 2 and 12 s. If the planet–moon orbital period can be determined independently (e.g., via TTV and TDV measurements) and with an accuracy of \( \lesssim 1 \) hr, or if a very close-in moon shows at least three mutual events during one stellar transit, then TTD can uniquely determine the sequence of planet–moon eclipses. To resolve the TTD effect, photometric accuracies of \( 10^{-4} \) need to be obtained along with mid-event precisions \( \lesssim 6 \) s, which should be possible with the E-ELT. If an exomoon is self-luminous, e.g., due to extreme tidal heating (Peters & Turner 2013), and shows...
regular planet–moon transits and eclipses every few days, its TTD might be detectable without the need of stellar transits. Eccentricities as small as 0.001 can trigger tidal surface heating rates on large moons that could be detectable with the James Webb Space Telescope (Peters & Turner 2013; Heller et al. 2014). However, TTD measurements do not require such an extreme scenario, which does not support the conclusion of Lewis & Fujii (2014) that mutual events can only be used to determine an exomoon’s SOM if the moon’s own brightness can be measured. In general, TTDs can be used to verify the prograde or retrograde motion of a moon with respect to the circumstellar motion.

The second method is based on measurements of the IR spectrum emitted by a young, luminous giant planet. We present simulations of the RME imposed by a transiting moon on a planetary spectrum. The largest moons that can possibly form in the circumplanetary accretion disks, halfway between Ganymede and Earth in terms of radii, can cause an RME that will be comfortably detectable with an IR spectrograph like CRIRES mounted to an ELT. A larger throughput or larger spectral coverage than the current non-cross-dispersed CRIRES will make it possible to determine the SOM of smaller moons, maybe similar to the ones we have in the solar system. A moon-induced planetary RME can determine the moon’s orbital motion with respect to the planetary rotation.

Combined observations of an exomoon’s TTD, its planetary RME as well as the moon’s stellar RME (Simon et al. 2010; Zhuang et al. 2012) and the inclination between the moon’s circumplanetary orbit and the planet’s circumstellar orbit (Kipping 2011a) can potentially characterize an exomoon orbit in full detail.

We conclude by emphasizing that a moon’s transit probability in front of a giant planet is about an order of magnitude higher than that of a planet around a star. A typical terrestrial planet at 0.5 AU from a Sun-like star has a transit probability of $R_p/0.5 \text{AU} \approx 1\%$. For comparison, the Galilean moons orbit Jupiter at distances of about 6.1, 9.7, 15.5, and 27.2 $R_{\text{Jup}}$, implying transit probabilities of up to about 16%. With orbital periods of a few days, moon transits occur also much more frequently than for a common Kepler planet. Permanent, highly accurate IR photometric monitoring of a few dozen directly imaged giant exoplanets thus has a high probability of finding an extrasolar moon.

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