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ASTR 419 Final Paper: Exomoon Detection

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1. INTRODUCTION

In our solar system, there are over a hundred confirmed moons, but we have yet to confirm the existence of any outside of our solar system. These evasive bodies are known as 'exomoons' and are sought after for their potential to support life and to better our understanding of solar system and planetary formation. Astronomers are interested in detecting exomoons because it is speculated they have a higher chance of being habitable than exoplanets as they do not have to be within a star's habitable zone to have the energy needed for a thick atmosphere(Kipping et al. 2009). Rather, tidal heating caused by the gravitational interaction between a moon and its host planet can generate a significant amount of energy that can make up for and even exceed the decreased stellar radiation received by the moon due to its distance from its star(Dobos et al. 2022). Tidal heating occurs in our own solar system between Jupiter and Io (Noyola et al. 2014). There are several methods of detecting exomoons that are able to yield confirmation of their existence, two of the most promising being transit photometry and transit time variation. Both have been used to detect exomoons and extensive research has been done showing they can be applied to the search for exomoons (Heller et al. 2014). In fact, earlier this year an exomoon candidate dubbed Kepler-1708 b-i was found using transit photometry, though the authors urge it be met with great skepticism as it requires further observations to confirm or reject it (Kipping et al. 2022). Other promising methods of detection include direct imaging and observing radio emissions. The former is particularly promising in the case of tidally heated exomoons because they can be far more luminous than their host planet regardless of their distance from their star (Limbach & Turner 2013). Exoplanets may also be directly imaged with current technology and an eclipse of its moon may be observed (Limbach & Turner 2013). As for the latter, radio emissions are induced by Io on its host planet, Jupiter, due to the Io's motion in Jupiter's magnetosphere (Noyola et al. 2014). It is thought that this interaction may be present in other planet-moon systems and simulations show that current technology is able to detect the emitted radio waves (Noyola et al. 2014). In this paper I will further discuss the aforementioned methods of exomoon detection and their feasibility with current and future technology.

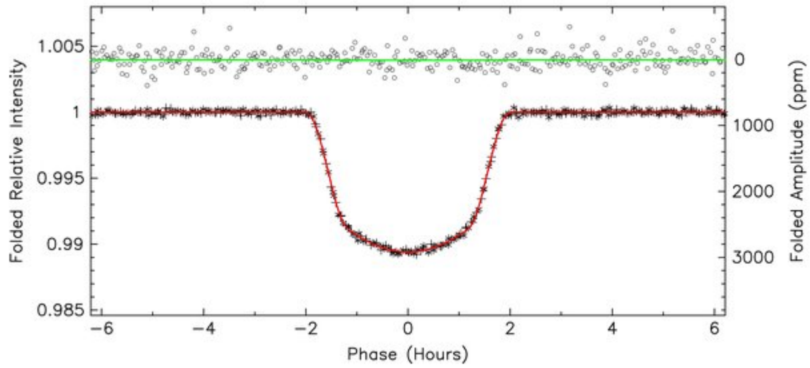

Figure 1. Figure from Dunham et. al (2010). The photometry of Kepler-6b folded by the 3.234723-day period. The model fit to the primary transit is overplotted in red (vertical axis on the left), and an attempt to fit a corresponding secondary eclipse is shown in green with the expanded and offset scale on the right

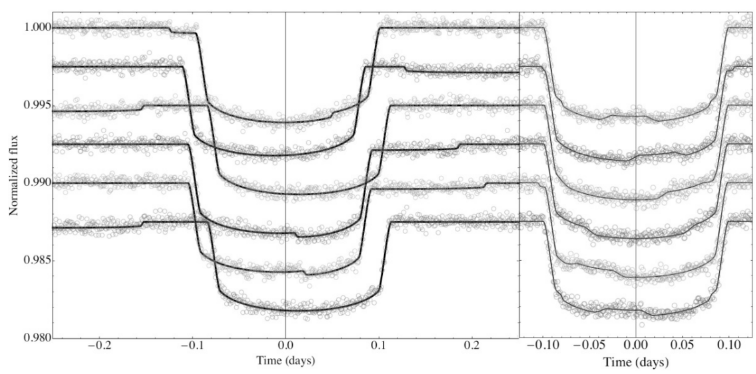

Figure 2. Figure from Heller et. al (2014).(Left) Six simulated transits using LUNA (Kipping 2011) of a Habitable Zone Neptune around an M2 star with an Earth-like moon on a wide orbit. (Right) Same as left, except the moon is now on a close-in orbit, causing "mutual events". Both plots show typical Kepler noise properties for a 12th-magnitude star observed in short-cadence.

2. TRANSIT PHOTOMETRY

Transit photometry involves observing the brightness of a star over time. When an object such as a planet passes in front of the star, light is occulted resulting in the aperture receiving less flux. For example, Figure 1 shows the light curve produced by the transit of Kepler-6b around its host star Kepler-6 (Dunham et al. 2010).

The difference in the unoccoculted flux and occulted flux is the depth of transit and is directly proportional to the ratio between the planet and star radii (Carter et al. 2008). Since moons are significantly smaller than their host-planets, the depth of the moon's transit is also significantly smaller than its planet's, so it can be difficult to distinguish between their contributions to a light curve. A simulated light curve produced by a planet-moon system is shown in Figure 2 where the difference in transit depths from the two objects is apparent(Heller et al. 2014). Exomoons with the potential to host life are likely to be found within the range of 0.1 - 0.5 $M_{\oplus}$ (Heller et al. 2014). Considering how small these objects can be, the amount of occulted flux is expected to be quite small, but thankfully Kepler-class photometry is capable of detecting occultations down to 0.2 $M_\oplus$ (Kipping et al. 2009). Therefore, considering we have technology proven capable of detecting exomoons with transit photometry, this method of detection is quite promising.

3. TRANSIT TIME VARIATION (TTV) & TRANSIT DURATION VARIATION (TDV)

The orbit of a planet around a star is non-Keplerian if a third body is present in the system because the gravitational pull of the third body causes the planet to wobble and orbit its barycenter with the third object. In the case where the third body in question is a moon and there are no other perturbing bodies in the system, the gravitational pull of the moon causes the planet to wobble about the planet-moon barycenter (Kipping 2009). The planet orbits the planet-moon barycenter in an ellipse and its velocity changes depending on where it is on its orbital path. This change in velocity causes the planet's orbital period around its star to vary, and therefore the time between observed stellar transits to vary. This variation is known as transit timing variation (TTV). Also, the planet can experience transit duration variation (TDV) for the same reason: the planet may be moving faster or slower during transit depending on its position relative to its moon (Kipping 2009). The TTV and TDV are dependent on the masses of the objects and the geometry of their orbits (Simon et al. 2007). More precisely, Kipping (2009) derived the rms TTV amplitude δ_{TTV} of an exoplanet as proportional to the exomoon mass M_m and semi-major axis a_m:

$$\delta_{TTV} \propto M_m a_m \tag{1}$$

Kipping (2009) also derived the relationship between the rms TDV amplitude δ_{TDV}, M_m, and a_m:

$$\delta_{TDV} \propto M_m \cdot a_m^{-\frac{1}{2}} \tag{2}$$

With the assumption supported by Domingos et. al (2006) that the eccentricity of the moon's orbit $e_s \simeq 0$, Kipping (2009) gives the ratio between TTV and TDV η as approximately:

$$\eta = \frac{\delta_{TDV}}{\delta_{TTV}} \simeq \frac{2\pi\bar{\tau}}{P_p} \cdot \frac{\sqrt{3}}{\chi^{3/2}} \tag{3}$$

where τ is the ratio between the distance in kilometers the planet has to cross to complete its transit and the radial component of the velocity $v_{B\perp}$ given by Kepler's 3rd law, and χ is some fraction of the Hill radius d_{max} which is the radius defining the spherical region over which the gravitational effects of the planet dominates satellites. It is given by:

$$d_{max} = a_p \cdot (\frac{M_p}{3M_\bigstar})^{v_{B\perp}} \tag{4}$$

Where a_p is the semi-major axis of the exoplanet's orbit around its star that has mass $M_\bigstar$.

For an exomoon to be detected by the TTV method, the telescope used must achieve a timing accuracy of significantly less than δ_{TTV}, and to be detected by TDV it must have a duration error of significantly less than δ_{TDV}.

Suppose a $1M_{\oplus}$ exomoon on a circular orbit with $\chi = 0.25$ and a period of $P_s \simeq 2.5$ days is orbiting around an exoplanet identical to GJ436b with $a_p = 0.0291$ AU and a planet-star mass-ratio of $1.54 \cdot 10^{-4}$, but with an orbital period $P_p = 35.7$ days. In this case, $\delta_{TTV} = 138$s and $\delta_{TDV} = 60$s.The telescope with which Alonso et al. (2008) observed GJ436b was the 1.52m Telescopio Carlos Sánchez (TCS), and it had a timing accuracy of $\sim$ 13s and a duration error of $\sim$ 50s. TCS would therefore be able to detect this hypothetical exomoon by the TTV method, but unlikely with the TDV method (Kipping 2009). Considering TCS is a ground based telescope, detecting exomoons with the TTV and TDV methods is possible and promising with the newer, more precise instrumentation of today.

4. DIRECT IMAGING

The gravitational interaction between a large planet and a small moon causes the moon's structure to expand and contract throughout its orbit, causing internal friction within the moon that heats its interior. The lost gravitational and rotational energy is converted into thermal radiation. In some cases, tidal heating can cause exomoons to be up to 0.1% brightness of their primary star in thermal wavelengths, even at distances far outside the habitable zone(Limbach & Turner 2013). The vast amount of heat generated allows for exomoons to be well outside the habitable zone of their system primary and still have the necessary energy to have an atmosphere and be considered habitable.

The combination of high brightness and distance from their system primary make exomoons possible to directly image with current and near-future instruments. The ground-based telescope, Warm Spitzer, for example, is able to detect a $\approx 600K$ exomoon the size of Earth at a distance of up to 5 pc away. Considering tidal heating can cause exomoons to be up to 1000K and the upper limit of their radius is predicted to be close to $M_{\oplus}$ (Heller et al. 2014), Warm Spitzer would be able to detect this exomoon if it exists(Limbach & Turner 2013). Furthermore, the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) scheduled to launch in 2032 and the James Webb Space Telescope's Mid Infrared Instrument (JWST-MIRI) will be able to detect tidally heated Earth-sized exomoons down to $\approx$300K as far as 4 pc from the Sun (Limbach & Turner 2013). Ground-based telescopes including the Giant Magellan Telescope (GMT), the Thirty Meter Telescope (TMT), and the European Extremely Large Telescope (E-ELT) will also be sensitive enough to use direct imaging(Limbach & Turner 2013), making the future of this method very promising.

5. RADIO EMISSIONS

Radio waves have been observed to emit due to the interaction between Io's ionosphere and Jupiter's magnetosphere (Mauk et al. 2001). This interaction is predicted to occur in other planet-moon systems (Heller et al. 2014), hence why this method of detection warrants discussion. Since radio wavelengths are A telescope with sensitivity in the tens of μJy, for example, would be able to detect radio frequencies from a $\leq 1R_{\oplus}$ up to 15 light years away. At present, there are no telescopes with such high sensitivity, but the Square Kilometer Array (SKA) telescope is set to launch in the 2020s and will be sensitive enough to detect exomoons down to the size of Mars with this method (Noyola et al. 2014).

6. FUTURE WORK

This paper sought out to discuss some of the most promising methods of exomoon detection. The most promising of which include transit photometry, TTV and TDV, and direct imaging as they are all methods able to be employed with current technology. Transit photometry is particularly promising because data taken by Kepler has been shown to be sensitive enough to detect an exomoon if one exists in the systems explored. TTV and TDV also offer high potential for exomoon discovery because the effect an exomoon has on the transit of its host planet around the system primary is strong enough to be detected by current instruments. So, if we observed many transits of a known exoplanet, we would be able to detect an exomoon based on the TTV and TDV. Direct imaging is also very promising because tidally heated exomoons can be arbitrarily large distances from a star and still be habitable and very bright, so distinguishing between the star's light and the moon's light is much less difficult than when we directly image exoplanets closer to the star in the habitable zone. Current technology can be used for direct imaging, but future technology such as JWST-MIRI makes the method even more promising. Detecting radio emissions from Io-Jupiter-like interactions, on the other hand, will have to wait until higher sensitivity telescopes are available, such as SKA, due to the vast length of radio waves. As the next generation of telescopes and instruments are deployed, it seems data taken with them will inevitably return the first detection of an exomoon.

REFERENCES

Carter, J. A., Yee, J. C., Eastman, J., Gaudi, B. S., & Winn, J. N. 2008, ApJ, 689, 499, doi: 10.1086/592321

Dobos, V., Haris, A., Kamp, I. E. E., & van der Tak, F. F. S. 2022, MNRAS, 513, 5290, doi: 10.1093/mnras/stac1180

Dunham, E. W., Borucki, W. J., Koch, D. G., et al. 2010, The Astrophysical Journal, 713, L136, doi: 10.1088/2041-8205/713/2/l136

Heller, R., Williams, D., Kipping, D., et al. 2014, Astrobiology, 14, 798, doi: 10.1089/ast.2014.1147

Kipping, D., Bryson, S., Burke, C., et al. 2022, Nature Astronomy, 6, 367, doi: 10.1038/s41550-021-01539-1

Kipping, D. M. 2009, MNRAS, 392, 181, doi: 10.1111/j.1365-2966.2008.13999.x

—. 2011, MNRAS, 416, 689, doi: 10.1111/j.1365-2966.2011.19086.x

Kipping, D. M., Fossey, S. J., & Campanella, G. 2009, MNRAS, 400, 398, doi: 10.1111/j.1365-2966.2009.15472.x

Limbach, M. A., & Turner, E. L. 2013, The Astrophysical Journal, 769, 98, doi: 10.1088/0004-637x/769/2/98

Mauk, B. H., Williams, D. J., & Eviatar, A. 2001, J. Geophys. Res., 106, 26195, doi: 10.1029/2000JA002508

Noyola, J. P., Satyal, S., & Musielak, Z. E. 2014, The Astrophysical Journal, 791, 25, doi: 10.1088/0004-637x/791/1/25

Simon, A., Szatmá ry, K., & Szabó, G. M. 2007, Astronomy &amp Astrophysics, 470, 727, doi: 10.1051/0004-6361:20066560