Project Notes:

Project Title: Modelling Exomoons
Name: Julia Rasmussen

Note Well: There are NO SHORT-cuts to reading journal articles and taking notes from them. Comprehension is paramount. You will most likely need to read it several times so set aside enough time in your schedule.

Contents:

Knowledge Gaps:

This list provides a brief overview of the major knowledge gaps for this project, how they were resolved and where to find the information.

Knowledge Gap	Resolved By	Information is located	Date resolved
What methods have been tried to locate exomoons?	**The Hunt For Exomoons With Kepler (Hek). Ii. Analysis Of Seven Viable Satellite-Hosting Planet Candidates**	Abstract	10/20/19
How can an exomoon be confirmed?	**The Transits of Extrasolar Planets with Moons**	Transit timing effects due to an exomoon	9/12/19
Why weren't these exomoons confirmed?	**The Hunt For Exomoons With Kepler (Hek). Ii. Analysis Of Seven Viable Satellite-Hosting Planet Candidates**	Discussion and Conclusions	10/20/19

Literature Search Parameters:

These searches were performed between 9/12/2019 and 2/13/2020.
List of keywords and databases used during this project.

Database/search engine	Keywords	Summary of search
George C. Gordon Library Website	exomoons	I found articles 1, 2, 3, and 11.
George C. Gordon Library Website	exomoon (there is a difference)	I found article 10.
George C. Gordon Library Website	tidal heating	I found article 6.
George C. Gordon Library Website	pegasi 51b	I found article 9.

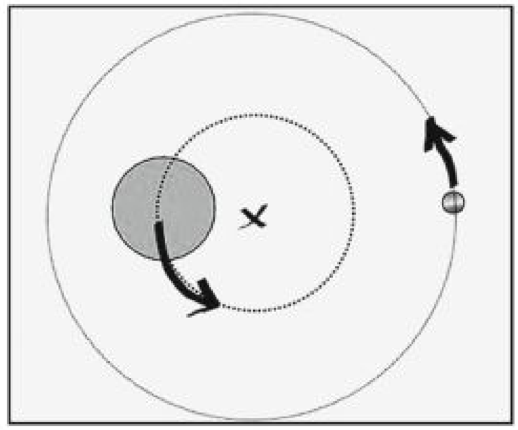
Article #1 Notes: The Transits of Extrasolar Planets with Moons

Article notes should be on separate sheets

Source Title	Springer Thesis Book Series (2011)
Source Author	Kipping, David M.
Source citation	Kipping, D. M. (2011). *The Transits of Extrasolar Planets with Moons* (dissertation). Springer-Verlag Berlin Heidelberg.
Original URL	https://link-springer-com.ezproxy.wpi.edu/book/10.1007%2F978-3-642-22269-6
Source type	Dissertation
Keywords	Transits, exomoons, exoplanets, photometry, TOA (time of arrival) - changes in the time that a pulsar's signal is observed, presumably based off of an exomoon, radial velocity (RV)
Summary of key points	A transiting exomoon could be detected by the perturbations in the time of the exoplanet's occultation of its sun, due to its gravitational effects. This is called TTV, however, to calculate TTV exactly, a 3-body model would have to be used, which is impractical because it has not been solved. Instead, a series of approximations are used to approximate the theoretical value of a planet's TTV.

Important Figures

Fig. 1.2 Cartoon illustrating the reflex motion of a star in the inertial frame of the barycentre. The planet's presence gives rise to variations in the position (used for astrometry and pulsar timing) and the velocity (used for radial velocity) of the host star, which may used to detect an exoplanet



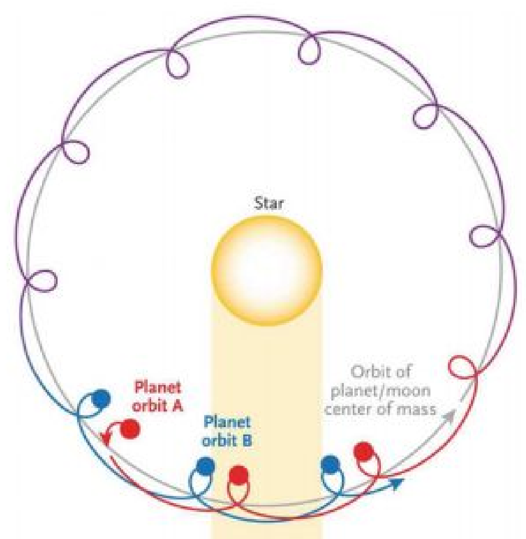
The variation in the sky position, α, of a star of mass M_* at a distance d from the Earth, hosting a planet[2] of mass M_P and semi-major axis a_P, can be estimated by Eq. (1.1). The equation reveals that ~10^{-7} as, or ~0.1 μas is a reasonable estimate for the required precision in astrometry, which outlines just how challenging detecting an exoplanet truly is with this method.

$$\begin{aligned} M_P a_P &= M_* a_* \\ \alpha &\simeq \frac{a_*}{d} \\ &= (94.''5 \times 10^{-9}) \left(\frac{a_P}{\mathrm{AU}}\right) \left(\frac{10\ \mathrm{pc}}{d}\right) \left(\frac{M_P}{M_J}\right) \left(\frac{M_\odot}{M_*}\right) \end{aligned} \tag{1.1}$$

This figure uses the formula $m_1 a_1 = m_2 a_2$, a formula commonly used that relates the masses (m) of star 1 and 2 to their maximum distance from the barycentre (a). It then uses the formula for parallax, $\alpha = \frac{1}{d}$, where d is the distance from the star in pc and α is the parallax angle of the star. In this case, Kipping is solving for the largest angle that the system could be looked at and you could still potentially find the planet from the star's wobble, based on the distance that the star orbits from the barycenter.

$$\begin{aligned} \Delta(\mathrm{TOA}) &\simeq \frac{a_*}{c} \sin i_P \\ &= \frac{a_P M_P}{M_* c} \sin i_P \\ &= (4.74 \times 10^{-4}\ \mathrm{s}) \sin i_P \left(\frac{a_P}{\mathrm{AU}}\right) \left(\frac{M_P}{M_J}\right) \left(\frac{M_\odot}{M_*}\right) \end{aligned} \tag{1.2}$$

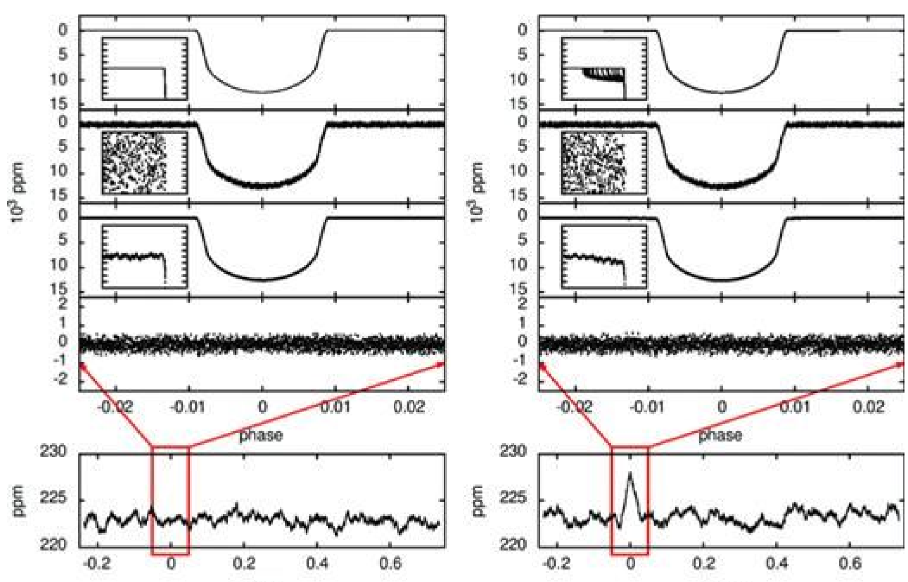
The equation for changes in the TOA (time of arrival) for a pulsar's bursts, based off of c (speed of light), a_* (the distance of the star from the barycenter), a_p (the distance of the planet from the barycentre), M_P (the mass of the planet), and i_P (the orbital inclination of the planet, relative to earth and its star). This is really effective, because pulsar timing is usually really precise, most of the time even more precise than the clocks that we have here on Earth. Any perturbation,

	or TOA, is really noticeable, and indicative of something irregular orbiting the pulsar. $$\begin{aligned} M_P v_P &= M_* v_* \\ K_* \simeq v_* \sin i_P &= \frac{M_P \sin i_P}{M_*} \frac{2\pi a_P}{P_P} \\ &= M_P (2\pi G)^{1/3} M_*^{-2/3} P_P^{-1/3} \\ &= (28.4\ \mathrm{m/s}) \sin i_P \left(\frac{M_P}{M_J}\right) \left(\frac{M_*}{M_\odot}\right)^{-2/3} \left(\frac{P_P}{\mathrm{years}}\right)^{-1/3} \qquad (1.3) \end{aligned}$$ Kipping assumes that, in a two-body system, (angular?) momentum (p=mv) will be conserved in the system, and because there are only two bodies that can possibly act within the system, they must have equal momentum. The variables are self-explanatory. **Fig. 6.1** Cartoon illustrating the composite motion of a planet in orbit of a star with an unseen exomoon companion. Unless the period of the moon happens to be resonant to the planet's orbital period (which there is no reason to expect) then orbit B will exhibit a different shift in position than orbit A at the time of inferior conjunction. These changes in position give rise to the TTV effect  Shows how a planet's orbit changes over time because of the moon that orbits it. This change in orbit/the time it will transit over its sun is how exomoons could potentially be detected by the transiting method.
Reason for interest	Directly correlates to what I want to do; it talks about how one could possibly use transiting to detect exomoons.
Notes	Uses a lot of math. Kipping doesn't really talk about his research/approach to the problem until chapter 6. In 2011, about 80% of the approximately 500 exoplanets that had been discovered were with the radial velocity (RV) technique. This may mean that when Kipping talks about
Follow up Questions	What other objects can cause TTV?

	Is there a way I could model this on a computer? If so, would it be more or less accurate? Is there a way to account for the planet and moon as being a blob of mass at their barycenter relative to their sun, but also model how their dynamics would create a transit for both the moon and planet?

Article #2 Notes: Signals of Exomoons in Averaged Light Curves of Exoplanets

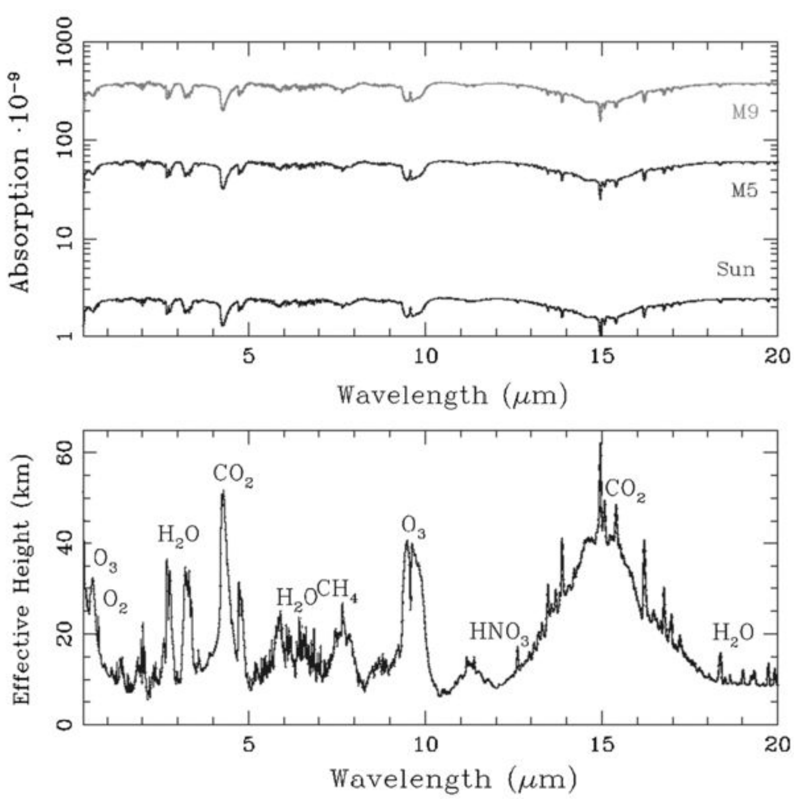
Article notes should be on separate sheets

Source Title	Royal Astronomical Society (2011)
Source Author	A. E. Simon, Gy. M. Szabo, L. L. Kiss, K. Szatmary
Source citation	Simon, A. E., Szabó, G. M., Kiss, L. L., & Szatmáry, K. (2011). Signals of exomoons in averaged light curves of exoplanets. *Monthly Notices of the Royal Astronomical Society*, *419*(1), 164–171. doi: 10.1111/j.1365-2966.2011.19682.x
Source type	Article
Keywords	Transits, exoplanets, oscillations, cadence, detection limit
Summary of key points	In order to find an exomoon, the available transiting data must first be processed so that objects that could cause TTV, one of the main theoretical methods, can be eliminated. This can be done by recentering the data, making a graph based on the difference between the observational and median light curves, and then trying to find a possible pattern that could be an exomoon.
Important Figures	 This shows the light curve of two simulated stars, the one to the left with a Jupiter-sized planet but no moon, the one to the right with that same planet, and an Earth-sized moon. As you can see, in the left-most model, the noise (the graph at the bottom of the figures) is

	relatively even, compared to the noise of the right-most model. The sudden increase in the amount of light that is being blocked is due to the moon, which is also seen on the top right-most graph, in the close-up to the left. This figure is important because it illustrates how an exomoon could change the transit curve of a star and thus potentially be detected.
Reason for interest	Directly correlates to what I want to do; it involves exomoons and transiting and thoughts on how to do it.
Notes	This paper models it out using math. On one hand, the authors probably know much more math than I do, so it's probably pretty accurate modeling-wise, but on the other, they can't account for all the gravitational phenomena/perturbations that happen in a system with multiple bodies. Computers might not be able to either, especially because I don't know how to use higher level mathematics, and thus probably won't know how to teach the computer that either, but I think they can potentially be better at modeling because of their computational power.
Follow up Questions	Is there a case where the exomoon is so large that its impact on the star's brightness is part of the median curve? How can this method be improved upon? How heavily does this rely on computer modeling?

Article #3 Notes: Characterizing Habitable Exomoons

Article notes should be on separate sheets

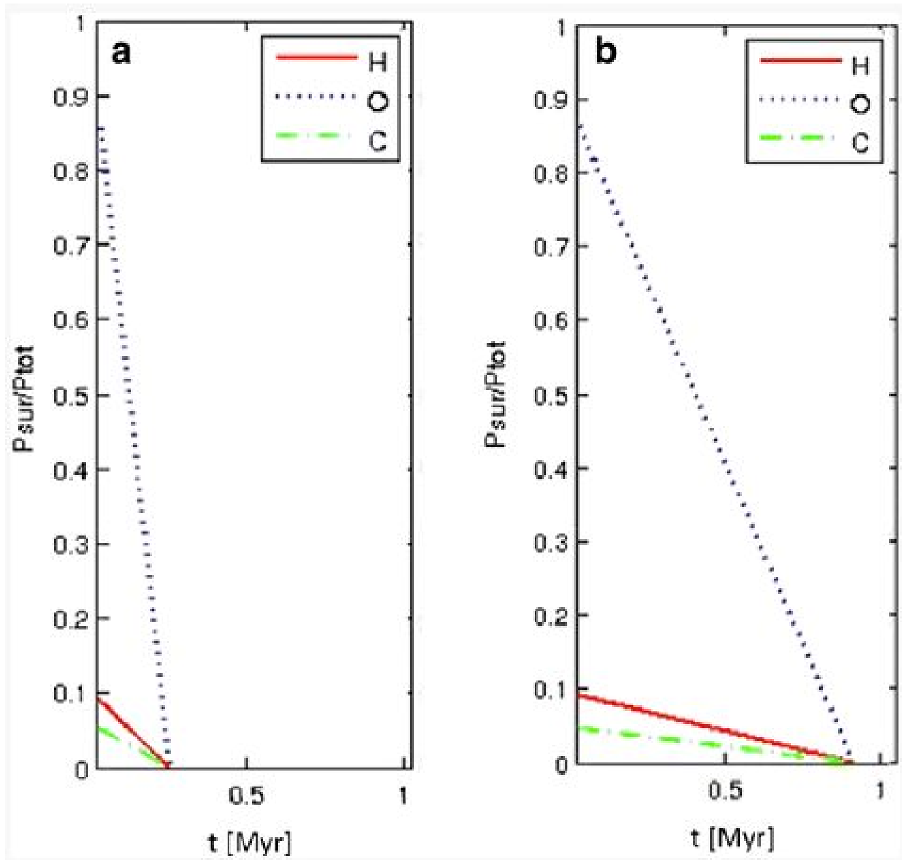
Source Title	The Astrophysical Journal (2010)
Source Author	L. Kaltenegger
Source citation	Kaltenegger, L. (2010). Characterizing Habitable Exomoons. *The Astrophysical Journal*, *712*(2). doi: 10.1088/2041-8205/712/2/l125
Source type	Article
Keywords	Transits, Hill's Radius, tidal locking.
Summary of key points	The stability of an exomoon relies on multiple factors, including its maximum orbital separation and how that relates to the Hill's radius of the planet. The atmospheric spectroscopy of a exomoon could be found if that exomoon orbited a couple of stellar radii away from a transiting planet, as the moon would transit at a different time than the planet.
Important Figures	

	This figure shows a sample spectrum of an exomoon compared to that of its host star. If you know the spectrum of the host star, and sample its light while only the exomoon is transiting it, you can find the spectrum of the exomoon’s atmosphere, which can then help tell you whether or not that exomoon might be habitable.
Reason for interest	So far I’ve looked at articles that relate directly to my project. This one still focuses on exomoons, but is less math-heavy and doesn’t really focus on modelling anything, relying on theory instead.
Notes	Not math-heavy, no modelling; focuses on theory instead. Maybe not too much new info.
Follow up Questions	How is an exomoon orbiting its planet multiple solar radii away feasible? Wouldn’t the gravitational attraction be too weak for it to be a moon anymore? Couldn’t you find the spectrum of a moon much in the same way you find the spectrum for an exoplanet; if the orbital time is short enough (which admittedly, would have to be extremely short), couldn’t you look at the primary and secondary eclipses of the moon on the planet and star?

Article #4 Notes: Origin and Stability of Exomoon Atmospheres: Implications for Habitability

Article notes should be on separate sheets

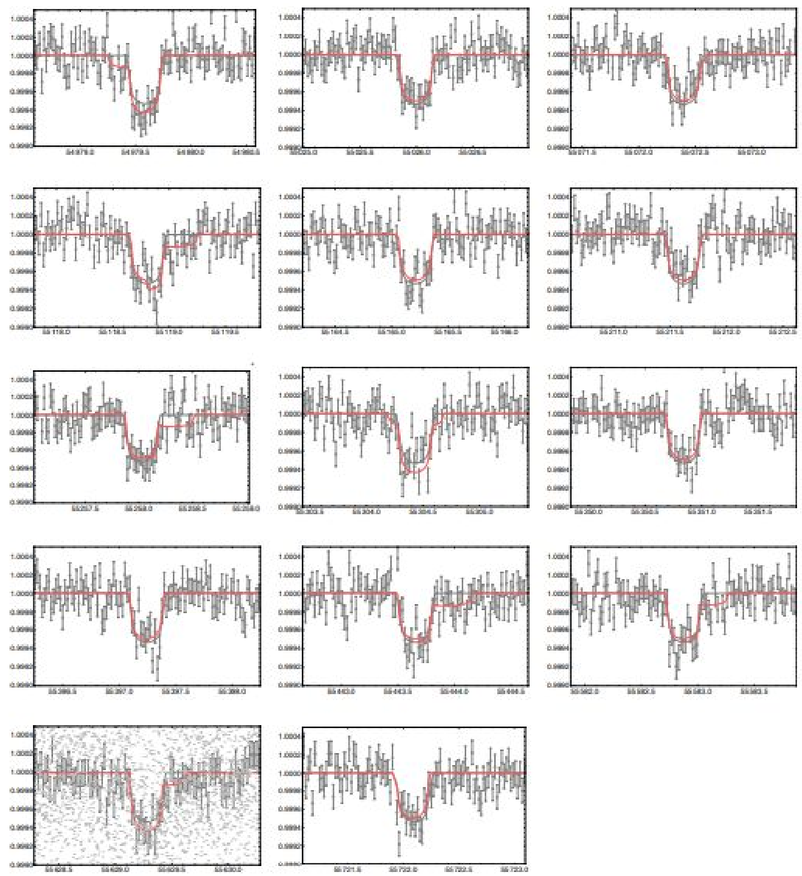
<table>
<tr><td>Source Title</td><td>Springer Link (2014)</td></tr>
<tr><td>Source Author</td><td>H. Lammer, S. Schiefer, I. Juvan, P. Odert, N. Erkaev, C. Weber, K. Kislyakova, M. Güdel, G. Kirchengast, A. Hanslmeier</td></tr>
<tr><td>Source citation</td><td>Lammer, H., Schiefer, S. C., Juvan, I., Odert, P., Erkaev, N. V., Weber, C., … Hanslmeier, A. (2014). Origin and stability of exomoon atmospheres: implications for habitability. Origins of life and evolution of the biosphere : the journal of the International Society for the Study of the Origin of Life, 44(3), 239–260. doi:10.1007/s11084-014-9377-2</td></tr>
<tr><td>Source type</td><td>Article</td></tr>
<tr><td>Keywords</td><td>TTV (variations in a transit’s timing), TDV (variations in a transit’s overall duration), Habitable Zone, Habitable Edge (HE)</td></tr>
<tr><td>Summary of key points</td><td>When an exomoon is created along with the star, it is exposed to high levels of xray and uv radiation. This must be taken into account to model whether or not an exomoon could potentially be habitable. The purpose of this article is to try to estimate how early xray and uv radiation would affect exomoons with 0.5, 1.0, and 1.5 earth masses. The heating of the exomoon would most likely result in the moon being differentiated, much like the formation of terrestrial planets, and a magma ocean then being formed, the steam from which would create the atmosphere of the exomoon.</td></tr>
<tr><td>Important Figures</td><td>
<table>
<tr><th>Exomoon</th><th>P_{H_2O} [bar]</th><th>P_{CO_2} [bar]</th></tr>
<tr><td>$0.1 M_\oplus$ | $0.46 R_\oplus$</td><td>~30–120</td><td>~7–25</td></tr>
<tr><td>$0.5 M_\oplus$ | $0.8 R_\oplus$</td><td>~50–300</td><td>~10–65</td></tr>
<tr><td>$1.0 M_\oplus$ | $1 R_\oplus$</td><td>~75–460</td><td>~35–100</td></tr>
</table>
This table shows the projected range of partial atmospheric pressures for either water or carbon dioxide given the mass and radius of an exomoon and assuming initial conditions close to that of Mars. Two graphs showing how the partial pressure would evolve over time are shown, the first showing the lower bound, and the second showing the higher values.</td></tr>
</table>

	
Reason for interest	This article looks at the idea that even if an exomoon exists, it isn't necessarily habitable. This doesn't directly tie to how to find an exomoon, but rather looks at the potential habitability. This may tie into my project later on, but right now my interest in this article is to see how much the subject of exomoons have been expanded on in scientific literature.
Notes	"In addition, these signals, which have similar amplitudes, also show a 90°-phase difference which provides a unique exomoon signature and as a result, a combination of TDV and TTV can confirm the presence of an exomoon": What makes finding these, TDVs and TTVs together so difficult? Moons can enhance their parent planet's magnetic field through radio waves, which can then in turn protect them.
Follow up Questions	How massive does an exomoon have to be in order to potentially be habitable? Is it possible for an exomoon to be habitable but not be in the habitable zone? Is there any way to do this other than tidal locking? Does an exomoon's planet shield it at all from its star's radiation? What about exomoons hat orbit red dwarfs?

Article #5 Notes: The Hunt For Exomoons With Kepler (Hek). Ii. Analysis Of Seven Viable Satellite-Hosting Planet Candidates

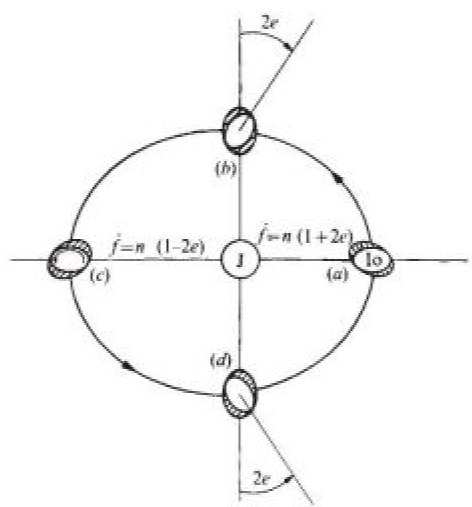
Article notes should be on separate sheets

Source Title	The Astrophysical Journal (2013)
Source Author	Kipping, D. M., Hartman, J., Buchhave, L. A., Schmitt, A. R., Bakos, G. Á., & Nesvorný, D.
Source citation	Kipping, D. M., Hartman, J., Buchhave, L. A., Schmitt, A. R., Bakos, G. Á., & Nesvorný, D. (2013). The Hunt For Exomoons With Kepler (Hek). Ii. Analysis Of Seven Viable Satellite-Hosting Planet Candidates. *The Astrophysical Journal*, *770*(2), 101. doi: 10.1088/0004-637x/770/2/101
Source type	Article
Keywords	$\eta_{☾}$ - frequency of moons around viable host planets, KOI (Kepler Object of Interest), TSO (Target of Opportunity), TSA (target selection algorithm), S/N signal to noise ratio
Summary of key points	Seven planets that possibly have moons were analysed. A range of possible masses for a moon was found for each planet, but no moons were confirmed, or had strong evidence. Additionally, this analysis did not support the idea that super-Earths/mini-Neptunes would have a high frequency of large moons.

Important Figures	 Multiple transit curves for the exoplanet KOI-722.01 that show possible curves of best fit with a possible exomoon.
Reason for interest	First systematic search for exomoons.
Notes	For Kepler data, the lower limit to the radius and mass of a possible exomoon is approximately an Earth mass and Earth radius.
Follow up Questions	Have there been any other subsequent HEKs? Does the lower limit for the possible radius and mass of a detectable exomoon change with more data? Does the lower limit for the possible radius and mass of a detectable exomoon change when looking at the data for TESS compared to that of Kepler?

Article #6 Notes: How Tidal Heating in Io Drives the Galilean Orbital Resonance Locks

Article notes should be on separate sheets

Source Title	Nature (1979)
Source Author	Charles F. Yoder
Source citation	Yoder, C. F. (1979). How tidal heating in Io drives the galilean orbital resonance locks. *Nature*, *279*(5716), 767–770. doi: 10.1038/279767a0
Source type	Article
Keywords	Orbital resonance, tidal heating, Io, dissipation, Q
Summary of key points	Io's volcanic activity is caused by tidal heating through orbital resonance and dissipation of the energy in tidal bulges. Io, Ganymede, and Europa only came into orbital resonance as of a couple hundred million years, but they probably were pretty close to their current 2:1 resonance. Yoder found that, over time, moons close to Io, Europa, and Ganymede's initial conditions tend to settle into a 1:1 resonance.
Important Figures	 **Fig. 1** Location of tidal bulge of a synchronously rotating satellite at different points in its orbit. The tide lags behind at pericentre (*a*) where the orbital angular velocity $\dot{f}$ is greatest. The optical libration of the permanent bulge has the opposite phase and is $2e$ radians behind a point (*b*) and ahead at point (*c*). An illustration of where the tidal bulges for a moon are over the

	course of its orbit. F represents the orbital angular velocity.
Reason for interest	This is a paper that talks about orbital resonance, which I may look into once I take a look at the radius-mass-semi-major axis stuff.
Notes	The Q value is a measure of a body’s response to tidal distortion; Q=energy in orbit/energy lost in orbit due to internal friction.
Follow up Questions	

Article #7 Notes: The Detection and Characterization of a Nontransiting Planet by Transit Timing Variations

Article notes should be on separate sheets

Source Title	Science (2012)
Source Author	David Nesvorný, David M. Kipping, Lars A. Buchhave, Gáspár Á. Bakos, Joel Hartman and Allan R. Schmitt
Source citation	Nesvorný, D., Kipping, D., Buchhave, L., Bakos, G., Hartman, J., & Schmitt, A. (2012). The Detection and Characterization of a Nontransiting Planet by Transit Timing Variations. *Science,336*(6085), 1133-1136. doi: 10.1126/science.1221141
Source type	Journal Article
Keywords	Dynamical Modeling, TTV, TTD, visual transit anomalies, Bayesian
Summary of key points	Basically, they tried to find an exomoon by looking at the system's TTVs and TDVs. They couldn't find an exomoon, because the TTV that could have been an exomoon got weaker as TDVs were added, which is uncharacteristic of an exomoon, so they disregarded it. They did find multiple other planets in the system though.
Important Figures	The top graph shows the periodic dips in brightness experienced by the star, and clearly shows a significant TTV. The bottom graph shows the changes in TTV and TDV over a

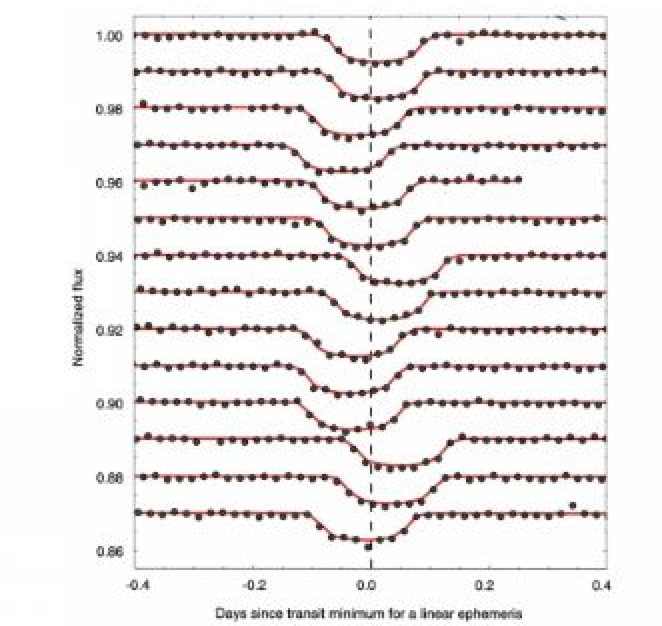


Fig. 1. Maximum-likelihood transit model (red line) overlaid with the long-cadence Kepler offsetted data for KOI-872b. The large TTVs are evident visually from the light curve. The ramp-affected transit is excluded here (see fig. S2).

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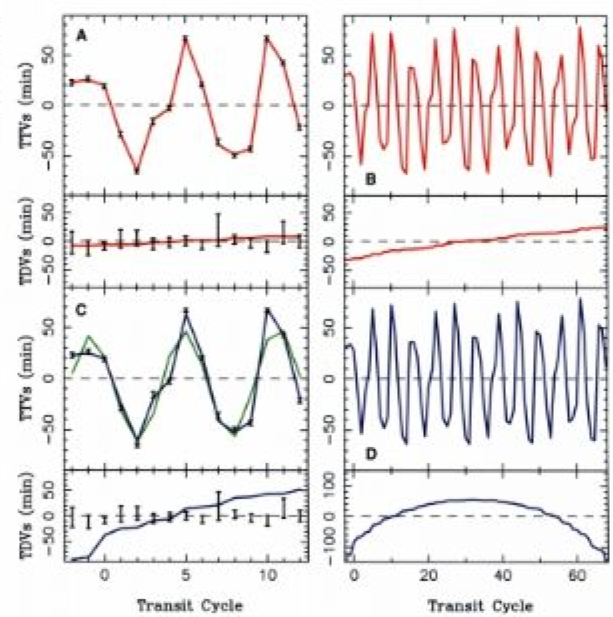
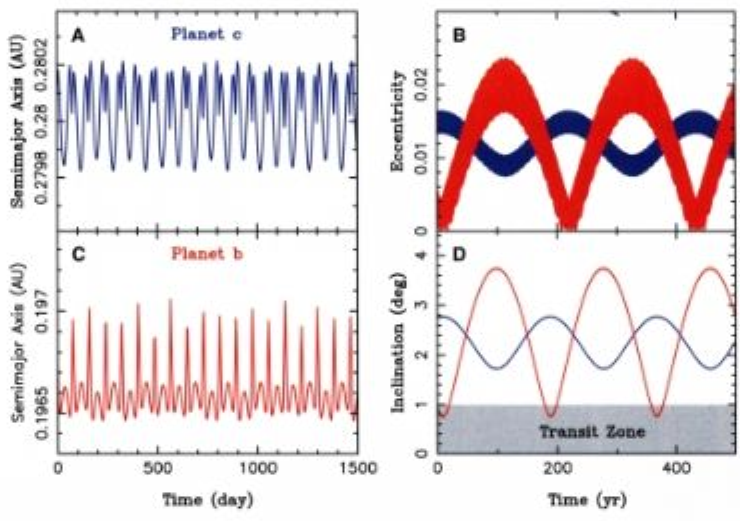


	
Reason for interest	This is the first analysis of a system for exomoons
Notes	The system they looked at was one with two confirmed planets, one planet candidate, with one of the planets having a really large TTV value. The planets are described as having nearly circular and coplanar orbits, similar to our solar system (which is important for modelling because otherwise you get weird physics stuff). The planet candidate could potentially host a moon (transit anomalies, dynamics).
Follow up Questions	How many other analyses have there been of specific systems since?

Article #8 Notes: Three Classes of Newtonian Three-Body Planar Periodic Orbits

Article notes should be on separate sheets

Source Title	Physical Review Letters (2013)
Source Author	Milovan Šuvakov, V. Dmitrašinović
Source citation	Šuvakov, M., & Dmitrašinović, V. (2013). Three Classes of Newtonian Three-Body Planar Periodic Orbits. *Physical Review Letters*, *110*(11). doi: 10.1103/physrevlett.110.114301
Source type	Article
Keywords	Jacobi relative coordinate vectors, orthogonal axes, Schubart orbit
Summary of key points	There have been three main families of solutions to the three-body problem: the Langrange-Euler, Broucke-Henon-Hadjidemetriou, and Figure-8 families. These researchers sought to find some more models of periodic, collisionless, solutions to the three body problem, in a system in four dimensional space starting with zero angular momentum. They found 13 additional families that are solutions to the three-body problem.

Important Figures

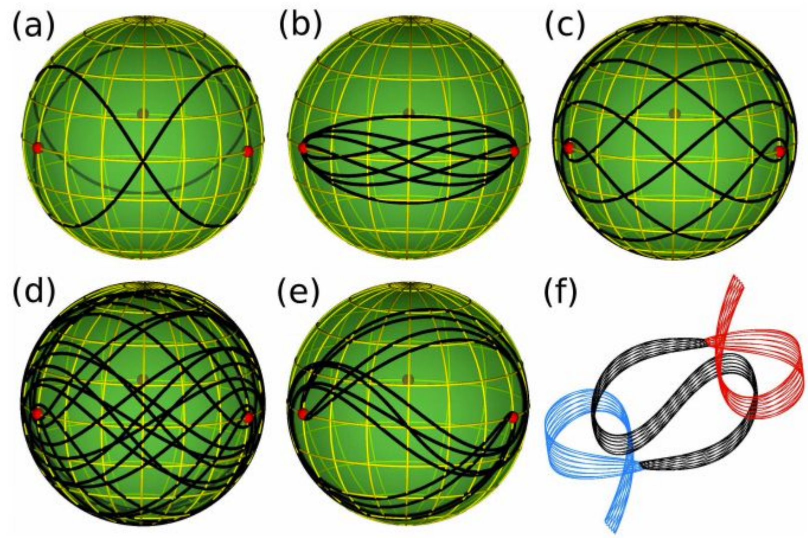


FIG. 1: The (translucent) shape-space sphere, with its back side also visible here. Three two-body collision points (bold red circles) - punctures in the sphere - lie on the equator. (a) The solid black line encircling the shape sphere twice is the figure-8 orbit. (b) Class I.A butterfly I orbit (I.A.1). Note the two reflection symmetry axes. (c) Class I.B moth I orbit (I.B.1) on the shape-space sphere. Note the two reflection symmetry axes. (d) Class II.B yarn orbit (II.B.1) on the shape-space sphere. Note the single-point reflection symmetry. (e) Class II.C yin-yang I orbit (II.C.2) on the shape-space sphere. Note the single-point reflection symmetry. (f) An illustration of a real space orbit, the "yin-yang II" orbit (II.C.3a).

The figures above show the solutions to the three-body problem in 3-D space. A is the already-discovered figure-8 family, but the other four are the four main classes (Ia, Ib, IIb, and IIc) shown in the table below. The thirteen distinct families are presented in the table below. The table details the starting particle positions for each individual case, as well as its period.

TABLE I: Initial conditions and periods of three-body orbits. $\dot{x}_1(0), \dot{y}_1(0)$ are the first particle's initial velocities in the x and y directions, respectively, T is the period. The other two particles' initial conditions are specified by these two parameters, as follows, $x_1(0) = -x_2(0) = -1$, $x_3(0) = 0$, $y_1(0) = y_2(0) = y_3(0) = 0$, $\dot{x}_2(0) = \dot{x}_1(0)$, $\dot{x}_3(0) = -2\dot{x}_1(0)$, $\dot{y}_2(0) = \dot{y}_1(0)$, $\dot{y}_3(0) = -2\dot{y}_1(0)$. The Newton's gravity coupling constant G is taken as $G = 1$ and equal masses as $m_{1,2,3} = 1$. All solutions have "inversion partners" (mirror images) in all four quadrants, i.e. if $\dot{x}_1(0), \dot{y}_1(0)$ is a solution, so are $\pm\dot{x}_1(0), \pm\dot{y}_1(0)$. Some of these partners are exactly identical to the originals, others are identical up to time reversal, and yet others are related to the originals by a reflection; we consider all of them to be physically equivalent to the originals. Note that two pairs of initial conditions in the same quadrant (II.C.2a and II.C.2b; and II.C.3a and II.C.3b) specify only two independent solutions; see the text for explanation.

Class, number and name	$\dot{x}_1(0)$	$\dot{y}_1(0)$	T	Free group element
I.A.1 butterfly I	0.30689	0.12551	6.2356	$(ab)^2(AB)^2$
I.A.2 butterfly II	0.39295	0.09758	7.0039	$(ab)^2(AB)^2$
I.A.3 bumblebee	0.18428	0.58719	63.5345	$(b^2(ABab)^2A^2(baBA)^2ba)(B^2(abAB)^2a^2(BAba)^2BA)$
I.B.1 moth I	0.46444	0.39606	14.8939	$ba(BAB)ab(ABA)$
I.B.2 moth II	0.43917	0.45297	28.6703	$(abAB)^2A(baBA)^2B$
I.B.3 butterfly III	0.40592	0.23016	13.8658	$(ab)^2(ABA)(ba)^2(BAB)$
I.B.4 moth III	0.38344	0.37736	25.8406	$(babABA)^2a(abaBAB)^2b$
I.B.5 goggles	0.08330	0.12789	10.4668	$(ab)^2ABBA(ba)^2BAAB$
I.B.6 butterfly IV	0.350112	0.07934	79.4759	$((ab)^2(AB)^2)^6A((ba)^2(BA)^2)^6B$
I.B.7 dragonfly	0.08058	0.58884	21.2710	$(b^2(ABabAB))(a^2(BAbaBA))$
II.B.1 yarn	0.55906	0.34919	55.5018	$(babABabaBA)^3$
II.C.2a yin-yang I	0.51394	0.30474	17.3284	$(ab)^2(ABA)ba(BAB)$
II.C.2b yin-yang I	0.28270	0.32721	10.9626	$(ab)^2(ABA)ba(BAB)$
II.C.3a yin-yang II	0.41682	0.33033	55.7898	$(abaBAB)^3(abaBAbab)(ABAbab)^3(AB)^2$
II.C.3b yin-yang II	0.41734	0.31310	54.2076	$(abaBAB)^3(abaBAbab)(ABAbab)^3(AB)^2$

Reason for interest

This article is the article detailing 13 new cases to solve the 3-body problem.

Notes

These cases all assume zero angular momentum, with all three bodies being of equal mass.

Follow up Questions	Are there other solutions to the three-body problem? Is there one unifying solution? Can the three-body problem ever be solved? Can some n-body problems ever be solved in a similar way, in a single case?

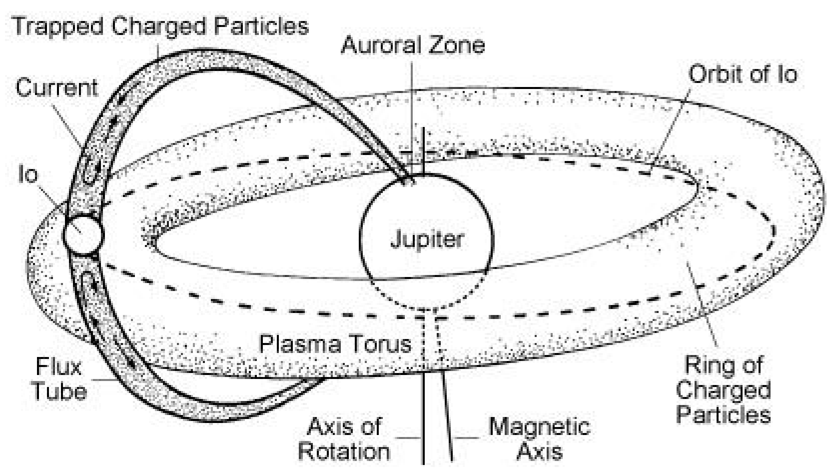
Article #9 Notes: The Planet around 51 Pegasi

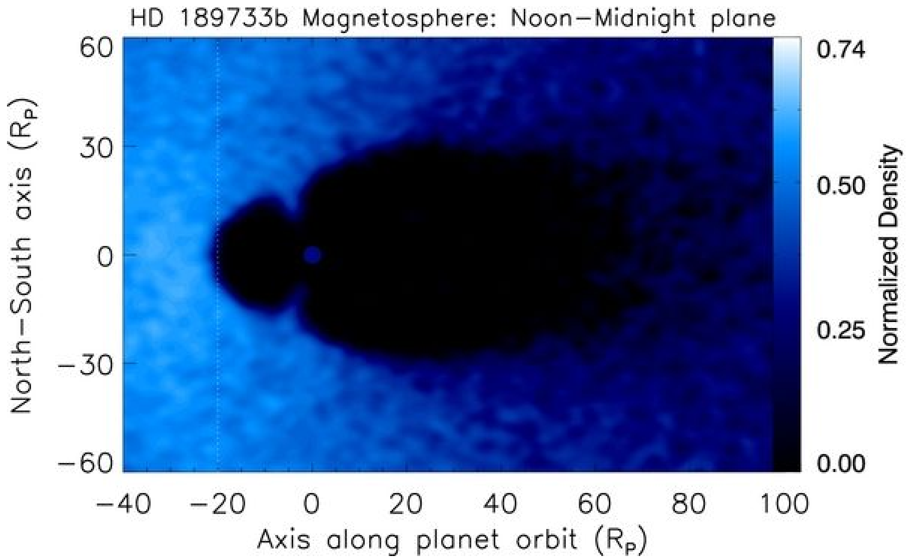
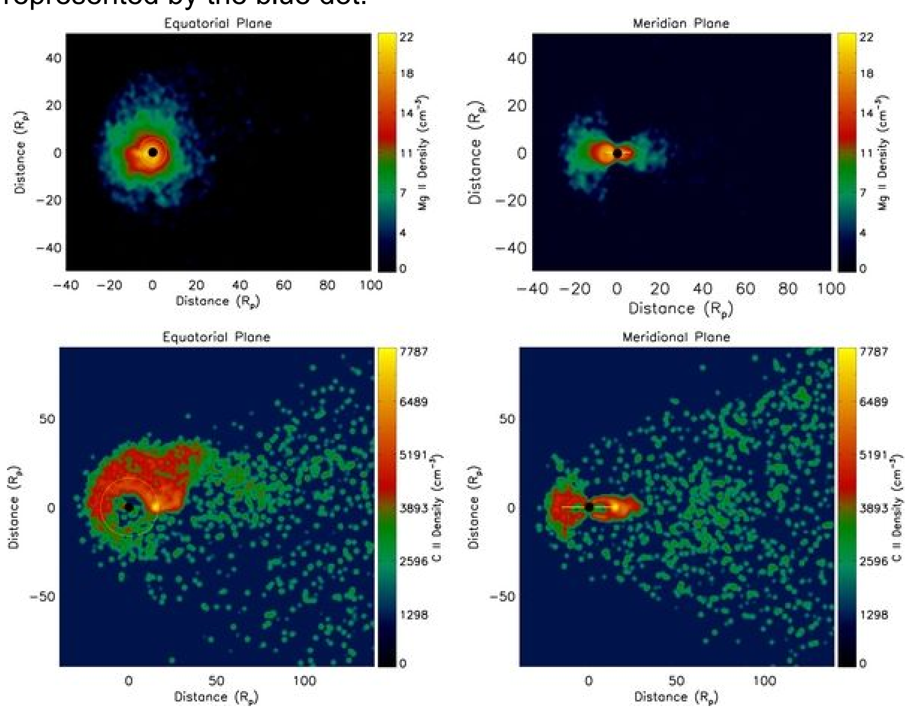
Article notes should be on separate sheets

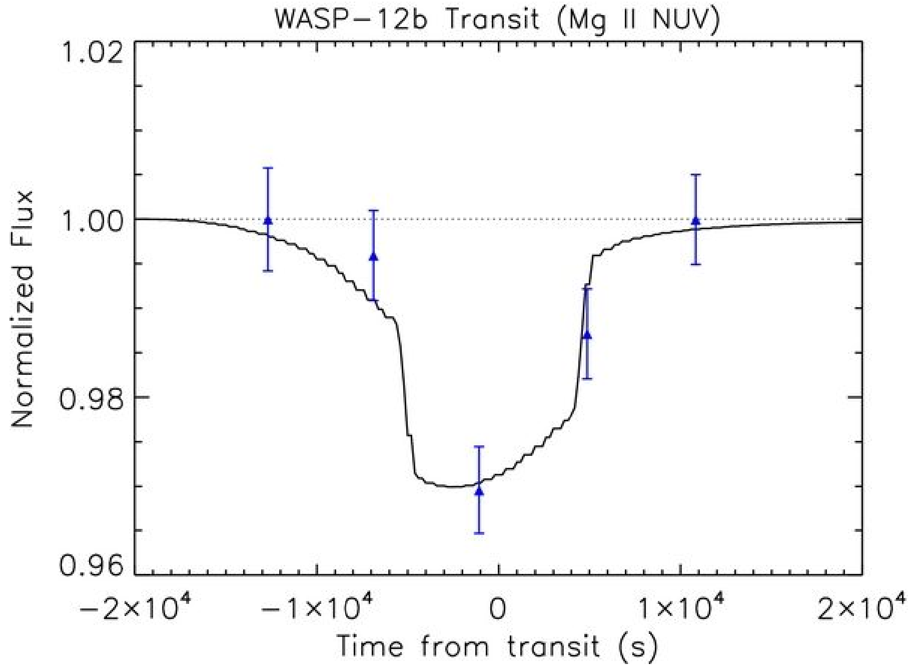
Source Title	The Astrophysical Journal (1997)
Source Author	Marcy, Geoffrey W. ; Butler, R. Paul ; Williams, Eric ; Bildsten, Lars ; Graham, James R. ; Ghez, Andrea M. ; Jernigan, J. Garrett
Source citation	Marcy, G. W., Butler, R. P., Williams, E., Bildsten, L., Graham, J. R., Ghez, A. M., & Jernigan, J. G. (1997). The Planet around 51 Pegasi. *The Astrophysical Journal*,*481*(2), 926–935. doi: 10.1086/304088
Source type	Article
Keywords	51 Pegasi, spectroscopy, S/N (signal to noise ratio), Doppler effect
Summary of key points	Pegasi 51b was the first exoplanet discovered orbiting around a sun-like star. It was discovered by finding the Doppler shifts in the sun's spectrum caused by the planet-induced wobble.
Important Figures	
Reason for interest	Pegasi 51b was the first planet discovered orbiting around a sun-like star. This is the article that first has conclusive evidence that Pegasi 51b is a planet.
Notes	Doppler velocity errors are typically 5m/s for observations with a signal-to-noise ratio (S/N) of 70, and better for higher S/N. Randomist thing ever, but it might be useful. Basically, the higher the S/N ratio is, the better, because you literally cannot find some planets/moons with a low enough S/N.
Follow up Questions	

Article #10 Notes: Transit of Exomoon Plasma Tori: New Diagnosis

Article notes should be on separate sheets

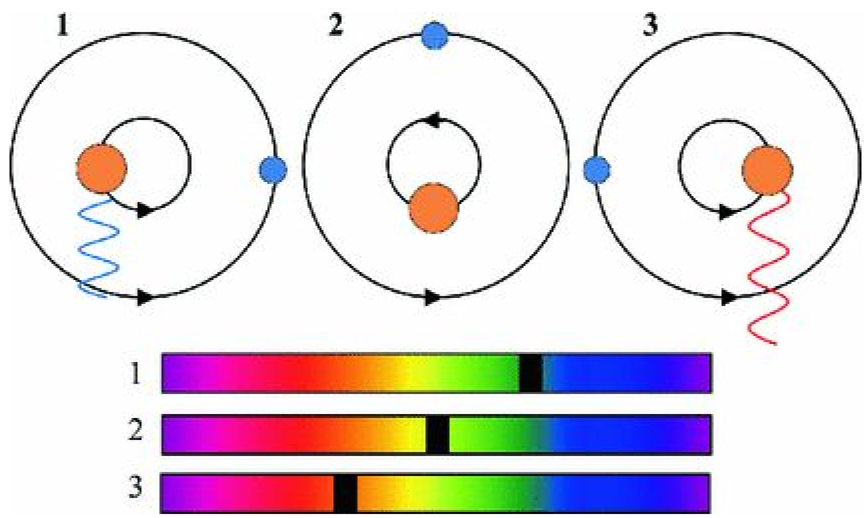
Source Title	The Astrophysical Journal (2014)
Source Author	Lotfi Ben-Jaffel and Gilda E. Ballester
Source citation	Ben-Jaffel, L., & Ballester, G. E. (2014). Transit Of Exomoon Plasma Tori: New Diagnosis. *The Astrophysical Journal*, *785*(2). doi: 10.1088/2041-8205/785/2/l30
Source type	Paper
Keywords	Plasma torus, ions, absorption
Summary of key points	 (http://ase.tufts.edu/cosmos/view_picture.asp?id=1174) In our solar system, Io is constantly spewing atmospheric gas, which, due to its orbit, takes on a toroidal shape. This gas is then ionized by ions from the sun, superheating this gas to plasma (http://vega.lpl.arizona.edu/iotorus/torus-description.html), which then emits ultraviolet rays, which we call the plasma torus. As all this gas absorbs incoming light, this could lead to detection through realization that the absorption cannot be coming from either the planet or the sun, and then could be coming from the plasma torus. In particular, in the two systems HD 189733 and WASP-12b, Mg II and C II absorption lines were found that weren't thought to be from either the sun or planet, and were thought to be the result of absorption by the plasma torus.

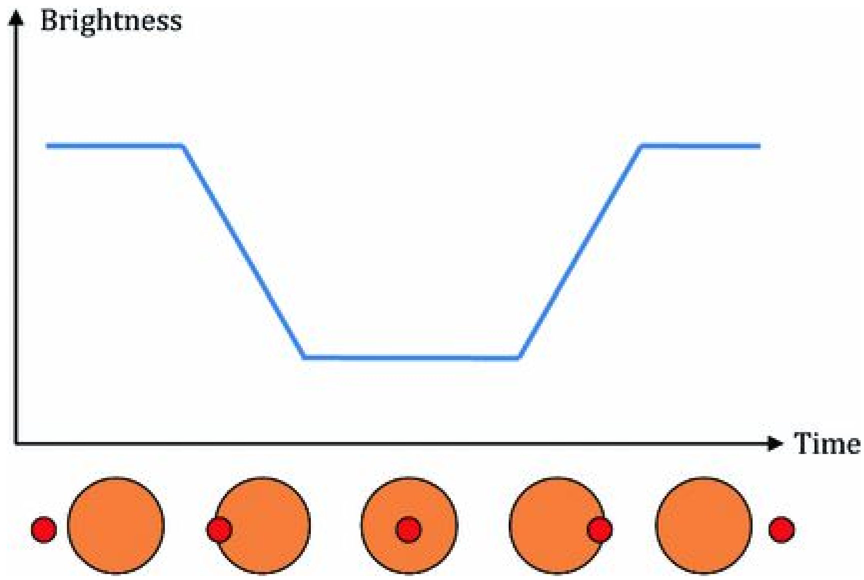
Important Figures	 Shows the PIC simulation of the magnetosphere of the planet, with the solar wind flowing from left to right, and the planet at (0, 0), represented by the blue dot.  The PIC models for WASP-12b (top) and HD 189733 (bottom). The left side shows the view from the equatorial plane (or the view from the top of the model), whereas the right side shows the view from the meridional plane (or the side of the model). The black dot in the middle, centered around (0, 0), is the planet. The orange dot going around it is the planet. The green and red particles are the ions.

	 The transit curve for WASP-12b. It looks really smooth, with slight dips before and after the transit.
Reason for interest	Concerns a different way to find exomoons. Also, it's an interesting phenomenon that I haven't heard about before, which is cool.
Notes	- Exomoons could make a plasma torus with their planet much in the same way that Io does with Jupiter - Plasma tori are thought to form from volcanic material spewed out from volcanic moons, and as such, shouldn't be that widespread. - Researchers used PIC (particle-in-cell) code to model the plasma torus - The models had very specific orbital parameters, given that they had specific systems in mind when modelling the plasma tori. As such, their results shouldn't be taken as universal truths but rather as something that might be true for two specific systems.
Follow up Questions	Why is this phenomena more widespread? What is the probability that the potential exomoons discovered in the paper (around HD 189733 and WASP-12b) actually exist? Could these exomoons be further looked at with transiting/TTV/TDV methods (i.e. my project) in order to be confirmed? If two exomoons that had the potential to make plasma tori were to orbit close enough to each other, could the plasma torus extend around both of them?

Article #11 Notes: Exomoons to Galactic Structure: High Precision Studies with the Microlensing and Transit Methods

Article notes should be on separate sheets

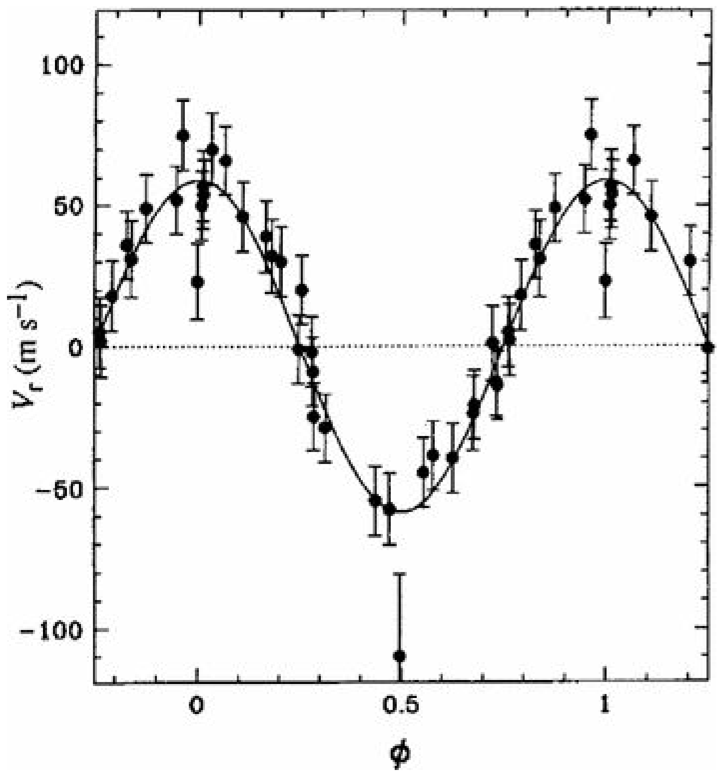
Source Title	Springer Book Theses (2018)
Source Author	Supachai Awiphan
Source citation	Ben-Jaffel, L., & Ballester, G. E. (2014). Transit Of Exomoon Plasma Tori: New Diagnosis. *The Astrophysical Journal*, *785*(2). doi: 10.1088/2041-8205/785/2/l30
Source type	Thesis
Keywords	 Image showing how an exoplanet can be detected by looking at shifts in the star’s radial velocity, due to changes in spectral lines because of the Doppler shift.



An image illustrating how transit curves are formed, based on how the planet transits the face of the star.

$$K_* = \frac{M_p \sin i_p}{M_*} \frac{2\pi a_p}{P_p}$$

Where K_* is the amplitude of the radial velocity signal, M_p is the mass of the planet, M_* is the mass of the sun, a_p is the semi-major axis of the planet's orbit, P_p is the period of the planet, and i_p is the inclination of the planet to the star, relative to the observer.

	 Original data of 51 Pegasi b's impact on the radial velocity of 51 Pegasi.
Summary of key points	
Important Figures	
Reason for interest	
Notes	- Since the discovery of 51 Pegasi b in 1995, over 700 exoplanets have been discovered using the radial velocity method. - Transiting is biased to find exoplanets with large radii, short periods, and that are close to their host star (due to orbital inclination). - Gravitational microlensing is the only technique known to potentially find exoplanets at truly large distances. -
Follow up Questions	