Tidal disruption-generated exorings of J1407b

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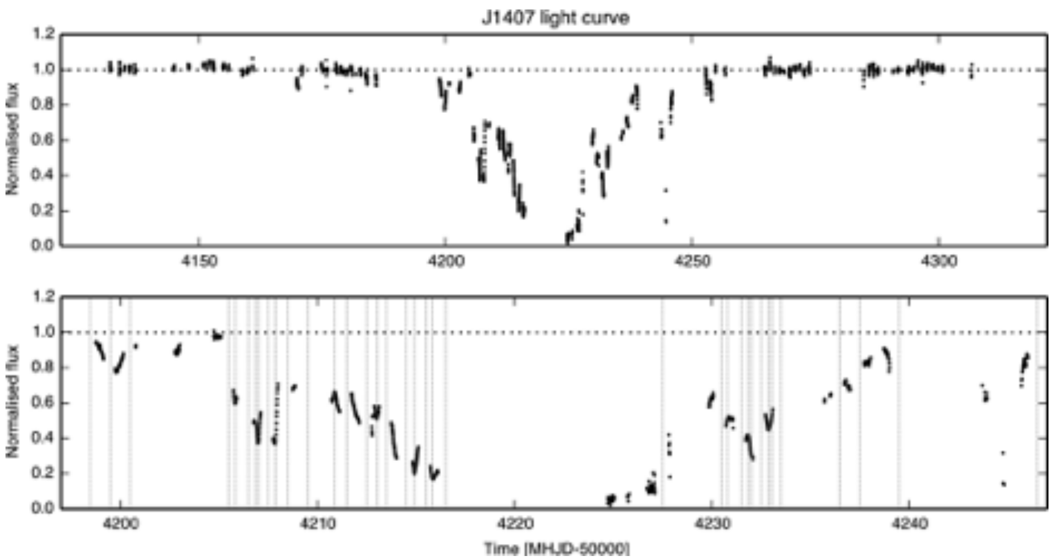
1. Introduction and Literature Review

1.1 Introduction

In April of 2007, astronomers observed a surprising eclipse event around the star 1SWASP J140747.93−394542.6 (‘J1407’). Mamajek and colleagues (2012) noted that this eclipse was remarkably long, deep, and complex, lasting ~56 days and decreasing the star’s light level by more than 3 mag (i.e. >95%). In comparison, Earth’s eclipse would last roughly half a day to a distant observer (Aaron, 2014). The recorded eclipse can be seen in Figure 1.



<u>Figure 1. Recorded light curve of J1407 by SuperWASP telescope (2007)</u> Recordings of the normalized light level of J1407 are shown as black marks (top). The main eclipse event from time 4200 - 4240 is shown in greater detail (bottom). Figure retrieved from Rieder & Kenworthy (2014).

The length and depth of the eclipse already indicate that the transiting object is unusually large. However, another observed characteristic makes the origin of the eclipse of even more interest: the transverse velocity of the transiting object. By recording the rate at which the light level of the star changes during the transit, as well as the radius of the star (J1407 is estimated to be around the size of our Sun), the velocity of any object eclipsing the star can be derived. Kenworthy et al. (2015) found a maximum gradient of ~3 solar luminosities per day for the object transiting J1407, which corresponds to a transverse velocity of 32± 2 km/s (Figure 2). This is similar to Earth’s orbital velocity around the Sun (30km/s; Herman, 1998) and indicates J1407b must orbit relatively close to J1407 (the orbital distance of an orbiting object determines its period and thus its velocity, with a lower distance leading to a higher velocity) .

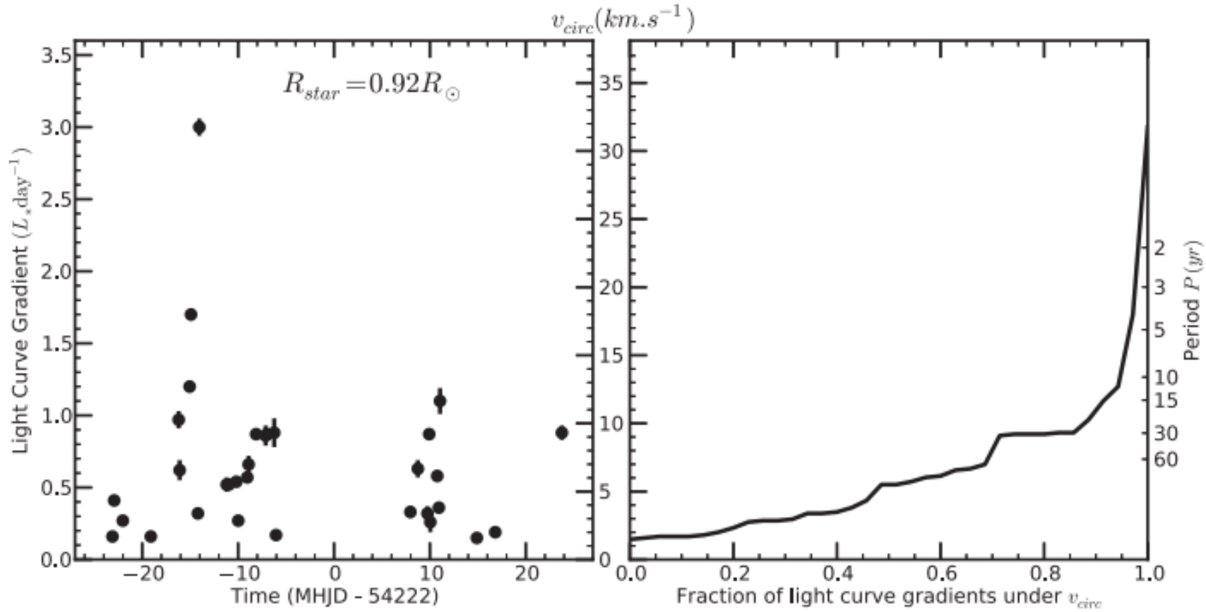


Figure 2a (left). Gradients of the J1407 light curve as a function of time and Figure 2b (right). The transverse velocities required to produce the gradients depicted in Figure 2a. The 'gradient' of a star's light curve describes the rate at which light level changes, which is indicative of how fast an object is transiting across the star's face. A maximum velocity of 32km/s is calculated from the gradient of the observed light curve. Both figures were retrieved from Kenworthy et al. (2015).

In summary, for the transiting object to generate an eclipse of such duration and be moving at these high speeds, it must be both extraordinarily large and orbiting at a close distance to J1407. However, recordings of the movement of the star J1407 show no 'wobble' as might be expected should it be closely orbited by a massive second body (Mamajek et al., 2012). This raises intriguing questions about the origin of the eclipse observed in 2007.

1.2 The current model

Kenworthy and colleagues Mamajek and van Werkhoven are the leading authorities on investigating the origin of these eclipses. They were the first to note that the event was reminiscent of the light curves of the stars Aurigae (Guinan & Dewarf 2002; Kloppenborg et al. 2010; Chadima et al. 2011), and EE Cep (Mikolajewski & Graczyk 1999; Graczyk et al. 2003; Mikolajewski et al. 2005), which have been theorized to be orbited and periodically transited by second bodies possessing an accretion disk (Mamajek et al., 2012). Based on this observation, the researchers speculated that "J1407 is most likely being eclipsed by a low-mass object hosting a disc with significant substructure composed of thin dust debris belts, or 'rings'" (Kenworthy et al., 2015). In other words, they suggested that the star was being eclipsed not by a massive nearby planet or star, but rather by a smaller planet that had extensive rings surrounding it, similar to Jupiter. It was the transiting of this planet and its rings that created the long, strange, eclipse observed. They dubbed this secondary object as 'J1407b'. Their proposal of a ringed-planet would indeed address the expansive size but relatively small mass of the transiting companion. An artistic rendering of J1407b's imagined ring system is shown in Figure 2.

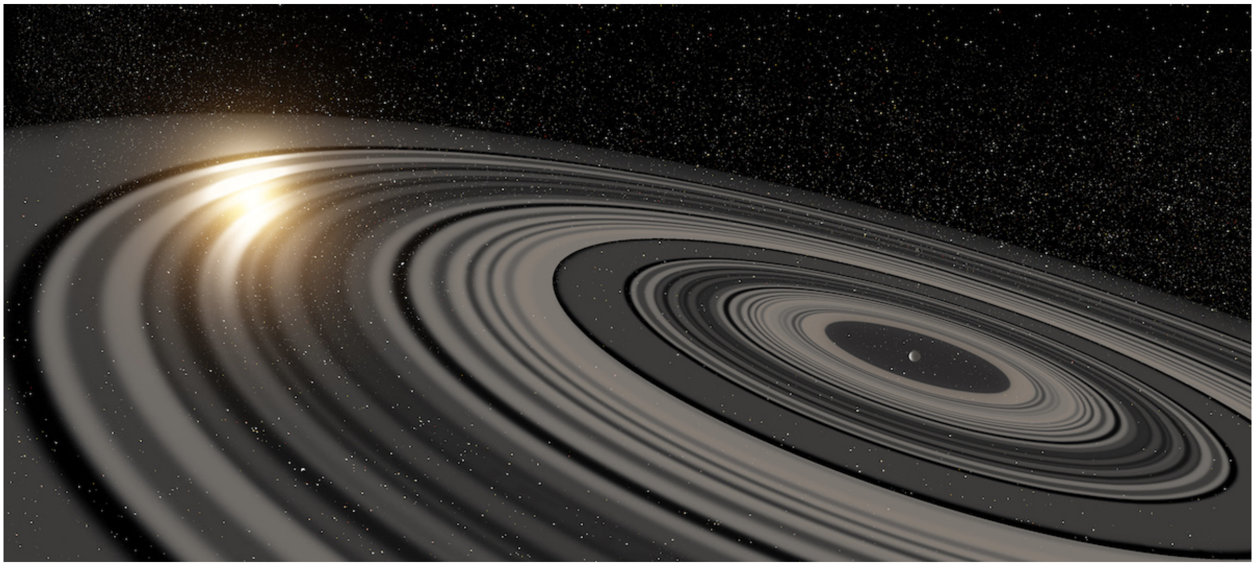


Figure 2. Artistic rendering of J1407b (right bottom) and circumplanetary disk transiting star J1407 (left top). Image by Ron Miller, retrieved from Kenworthy (2022).

Their model of the ring-surrounded J1407b as a candidate for the light curve event has undergone many revisions since its initial proposal in 2012 (Mamajek et al., 2012; van Werkhoven et al., 2014; Kenworthy et al., 2015; Kenworthy & Mamajek, 2015). Its most current version, as proposed in "Constraints on the size and dynamics of the J1407b ring system" (Rieder & Kenworthy, 2016) is considered here.

In their 2016 work, Rieder and Kenworthy tested a variety of orbital arrangements for J1407b and its particle ring, and arrived at the following conditions as being the most probable: J1407b has a mass of around 80-100 $M_{jupiter}$ and orbits in a highly eccentric orbit (~0.7) around J1407 with a period of ~11 years and semi-major axis of 5 AU. The orbital values are set as such so as to fulfill the high observed transverse velocity of the transiting object -- its highly eccentric orbit means that J1407b will be moving at high velocities when it transits at its pericenter (i.e. the point of its orbit at which it is closest to the star).

The authors then add rings of particles, extending up to 0.66 AU, orbiting J1407b in a retrograde direction (i.e. opposite the rotation of the planet) (Rieder & Kenworthy, 2016). The direction of orbit was determined to be retrograde because the researchers found that a retrograde orbit for the rings allowed them to remain stable for a significantly longer period of time than a prograde orbit (i.e. same rotational direction as the planet). These rings of particles account for the length of the observed eclipse, as they would also block the star's light as the planet transits J1407.

Kenworthy and colleagues laid down important foundational work in modeling this intriguing eclipse event, however, their model still possesses several shortcomings.

1.3 Introducing the research gap

There are some notable shortcomings to the current model. Based on the semi-major axis and eccentricity values used by Rieder and Kenworthy (2016), the orbital period of J1407b is 11 years. It has been more than 11 years since the first sighting of the eclipse event in 2007, and should their model hold true we would've expected to see a similar event reoccur within the past few years. However, despite various telescopes constantly watching J1407's area of the sky since its first eclipse, no second eclipse has been observed.

Second, Sutton and colleagues (2022), in a review of Rieder & Kenworthy's (2016) model, criticize that "large eccentricities (e>0.7) were required to account for radial velocity measurements and transit timing, but this resulted in the ring becoming unstable". They analyze the author's research and claim that "the outer region of the ring was found to become unbound from J1407b at large eccentricities" (Sutton et al., 2022). Therefore, the long-term stability of the current model is also an issue that must be addressed.

Finally, Rieder & Kenworthy (2016) leave "the creation and evolution of [the] ring structure [to] future study". In other words, while they explain how a ring-surrounded planet could have resulted in the eclipse, they do not investigate the origin and formation of these rings.

Overall, there appears to be a need for a revised model of the ringed planet J1407b, whose transit of J1407 resulted in the surprising eclipse event observed in 2007. Additionally, the origin of these rings should be explained in order to fill the current research gap.

1.4 Tidal disruption as a mechanism for ring-formation

Rieder & Kenworthy (2016) modeled a retrograde ring-system around J1407b. Sutton et al. (2022) review that retrograde orbits are "generally the result of captured small objects, like many of the Solar System's retrograde moons". Therefore, based on Rieder & Kenworthy's work, they propose that the rings could have been created by "the tidal disruption of a captured smaller [object] in the system" (Sutton et al., 2022).

The concept of tidal disruption was first proposed by Luminet and Carter (1982) in order to describe how stars can be pulled apart by the tidal force of supermassive black holes on close approach. However, it can also be applied to a small object closely approaching a planet, such as the case of the comet Shoemaker Levy-9 passing by Jupiter in 1994 (Boss, 1994). The gravity experienced by the end of the object nearer to the planet is stronger than that experienced by the far end, stretching it in different directions. Eventually, the internal gravity of the object is not enough to hold it together and the object is torn about; Around half its matter escapes the gravitational hold of the planet while the other half is captured and enters a highly eccentric orbit around the planet. This bound matter can form an accretion disk, or series of 'rings' around the planet (Wikipedia, n.d.). It is easy to see how the tidal disruption of a small body (e.g. an asteroid) passing near J1407b could have created a system of rings around the planet.

1.5 Overview

Evidently, the mysterious origins of the series of eclipses underwent by J1407 have yet to be fully explained, although much progress has been made on understanding possible mechanisms. In this paper, I hypothesize that a tidal disruption event around J1407b may have generated a series of rings around the planet that could have resulted in the observed eclipses as the planet transited J1407. I evaluate whether such an event has the potential to have caused the observed eclipses of J1407 by first modeling the aftermath of a tidal disruption event near J1407b and the formation of 'rings', and then plotting a light curve as the planet transits the star J1407. Not only might my project provide a compelling explanation for the interesting eclipse displayed by J1407 in 2007, it will also help astronomers explain any future such events.

2. Methods

2.1 Overview

The primary software used in this project to model any system dynamics is Hanno Rein's open software Rebound (Rein & Liu, 2011). This is the same software used by Rieder & Kenworthy (2016) and Sutton et al. (2022) in their research of the event, and indeed is one of the most widely used integration software employed by astronomers (Rein & Liu, 2011). Rebound allows users to enter initial parameters for *n* number of bodies and then integrates each of their movements over the timescale of interest.

However, despite its wide functionality, Rebound does not easily allow for the actual simulation of a tidal disruption event. For this reason, the first step was to find the initial conditions of all bodies involved immediately following tidal disruption (Section 2.2). Next, these initial conditions were integrated for 5 orbital periods (around 160 years) to model the formation of a ring structure around J1407b (Section 2.3). Finally, the transit of the planet and surrounding ring structure across J1407 was simulated and the resulting light curve was plotted (Section 2.4). These results are compared to the observations discussed in the Introduction in the Results and Discussion sections (Section 3 and 4, respectively).

2.2 Post tidal disruption

The planet J1407b was assumed to be equal in size and mass to Jupiter, based on work by Rieder & Kenworthy (2016), whose model used values on an order of magnitude of Jupiter's. The planet was set on a circular orbit at a distance of 10 AU from J1407, which is also within an order of magnitude to the researchers' values of 5 AU used in their models (Rider & Kenworthy, 2016).

For the tidal disruption event, an asteroid the size and mass of Pluto was assumed to approach within 3 planetary radius of J1407b. This distance is roughly equal to the Roche limit of the planet, which is the distance within which an object will be torn apart by the planet's gravitational field. The asteroid was set to approach at arbitrarily chosen inclination and longitude of pericenter values of 123 degrees and 137 degrees, respectively. These parameters are summarized in Table 2.

Upon approach, this Pluto-sized asteroid would be torn into millions of particles through tidal disruption. Guillochon et al. (2018) lay down a key mathematical relationship describing the energy distribution of an object's particles following tidal disruption, which is used to find the initial conditions of particles in my paper. For simplicity, the energy of particles pre-tidal disruption is set to be 0, and particle energies post-disruption range from E_{min} to E_{max}.

$E_{max} = (m_{planet}/m_{asteroid})^{1/3}\, v_{esc}^{2}$ *J/kg, where* v_{esc} *is the escape velocity of an object on the asteroid's surface.*

$E_{min} = 0 - E_{max}$

For this project, 1 million particles were evenly distributed from E_{min} to 0. These particles are the half of particles that we would expect to remain 'bound' to J1407b following the tidal disruption event (since they lost energy and cannot escape the planet's gravitational field).

From this distribution, the corresponding distribution of the initial semi-major axis of the particles was derived using the following relation:

$a = -1\ (G\ m_{planet})/(2E)$, where a is the semi-major axis, G is the universal gravitational constant, and E is the energy of the particle

However, due to the inverse relationship between a and E, this generated a skewed number of particles with very small semi-major axes. These particles do not contribute to the larger accretion disk formed around the planet but only generate a dense disk in the vicinity of the planet. Therefore, in order to save on computational time, only a subset of these particles were actually integrated (see Table 1) and were weighted to account for the amount of particles they represented.

Notably, a new term is used in Table 1 to describe distances: the "hill radius" of J1407b. The hill radius of a planet is a distance describing the distance within which the planet's gravity (J1407b, in this case) dominates over the gravitational force of the star (J1407). In this paper, J1407b's hill radius is ~0.68 AU and is used as a unit to describe particle distance from the planet, since it provides a useful scale. The movement of particles near the hill radius is heavily influenced by J1407, while those a smaller percentage of the hill radius from J1407b are not.

TABLE 1: Subset of particles used and weighting of each particle

Semi-major axis (% of hill radius of planet)	Number of particles integrated
0 - 5%	1 in 1000
5 - 10%	1 in 100
10 - 15%	1 in 10
15 - 200%	1 in 1

2.3 Formation of rings

The motion of particles was simulated using Hanno Rein's 'Rebound' software (citation). Orbital elements of each particle were inputted as generated in Section 2.2 (see Table 2). Each particle was integrated for 5 orbital periods of the planet (around 160 years). The location of the particle relative to the planet was recorded every period.

TABLE 2: Orbital elements of inputted particles

Orbital element	Abbreviation	Value
Mass	m	0

Semi-major axis	a	See Section 2.1
Eccentricity	e	1 - pericentre/semi-major axis
Inclination	inc	123 degrees
Longitude of pericenter	pomega	137 degrees

Hanno Rein and colleagues' ReboundX (Tamayo et al., 2019) was used to simulate the precession of each particle's orbit caused by the planet's J2 moment. To put it more simply, the J2 moment accounts for the fact that planets are not perfectly spherical and actually bulge out around the equator due to their axial spin. This effect was only considered for particles with semi-major axes of less than 5% of the planet's hill radius, as for particles further away than this cutoff, the precession effect was found to be insignificant, resulting in a pomega change of <1 radian after 5 periods.

Furthermore, for the sake of efficiency, this same set of particles (<5% hill radius) were simulated as a two-body system with just the particle and planet, since at this close distance to the planet the star's gravitational effect was assumed to be negligible. On the other hand, particles further away than 5% of the hill radius might be expected to experience significant deviations to their original orbit over long periods of time, due to J1407's gravitational influence being non-negligible. These were simulated as three-body systems including the particle, J1407b, and J1407. Rieder & Kenworthy (2016) placed the inner limit for using a three-body simulation as being 25% of the planet's hill radius due to "the star's influence [being] smallest for the innermost orbits", so my chosen limit of 5% is well on the safe side.

2.4 Stellar transit

The position of the planet and all the particles around it as it transited across the star from our reference plane was recorded 5000 times over a period of 112 days. Each timestep accounted for around half an hour of movement. Each particle was assumed to have a radius equal to 10% that of the star (corresponding to a 1% decrease in light level). This value was arbitrarily chosen since any result could be scaled by adding more particles/increasing the size of particles. As the planet approached the star, the overlap between the area of each particle and the star was calculated using geometry detailed by Chris Redford (2010). Overlap between two nearby particles was also accounted for, as this would result in a shallower eclipse than two non-overlapping particles. The light level of the star was plotted over those 112 days and is shown in Figure 5.

3. Results

To gain an initial understanding about how the particles of the tidally disrupted body might form ring-like structures around J1407b, I integrated 1 million particles from their initial position within the body over a timespan of five J1407b orbital periods (each period is ~32 years). Below, the position of particles around J1407b are plotted every orbital period (Figure 3).

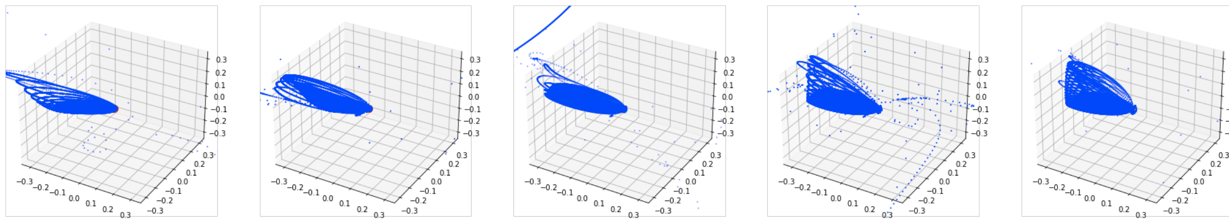


Figure 3. Position of particles around J1407b every orbital period. *All three axes represent each particle's distance from J1407b (located at 0,0,0) in units of AU. The particles from the tidally disrupted body are initially clustered together and can be seen to slowly disperse over the 5 orbital periods (from left to right).*

Although a transit across J1407 could be plotted for any of these periods, we focus primarily on the structure of the particles around J1407b after 5 periods (~160 years). Here, the subplot above (Figure 3, right) is shown in greater detail:

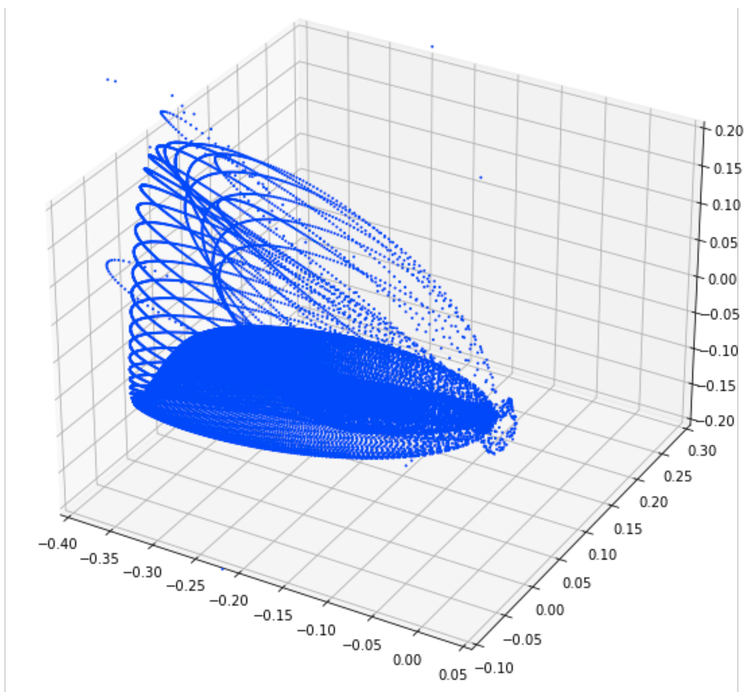
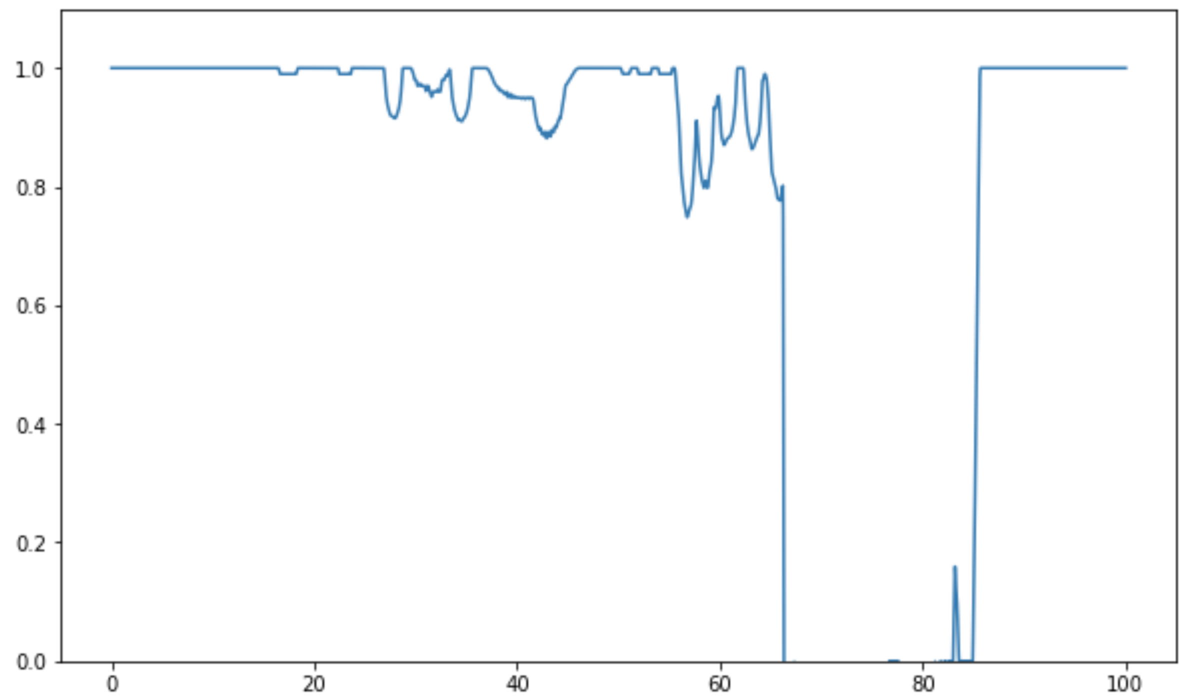


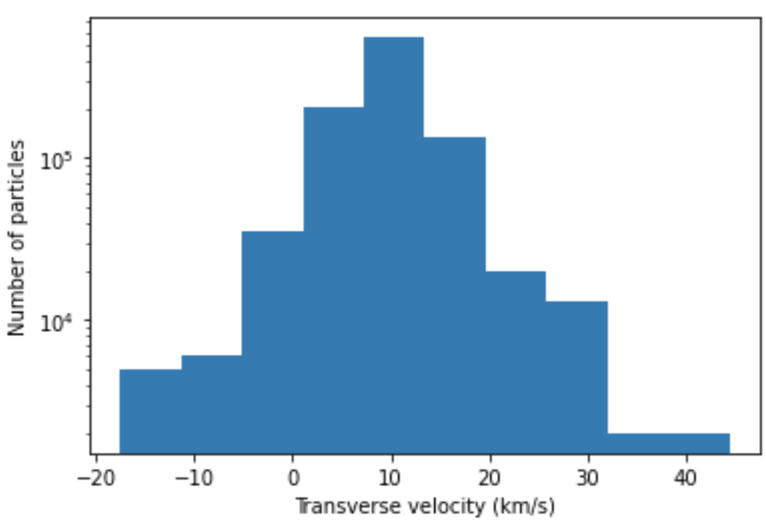
Figure 4. Position of particles around J1407b after 5 orbital periods. *All three axes represent each particle's distance from J1407b (located at 0,0,0) in units of AU. Ring-like structures can be seen to have formed. These rings have processed to generate a 'cloud' around the planet.*

Although this disk structure offers insights of its own, in this paper we are mainly interested in the eclipse event it would cause as J1407b transits J1407. The resultant light curve of J1407 is plotted in Figure 5. Each dip below 1.0 on the y-axis represents some of the star's light being blocked by either the planet or the rings of particles around it. It can be seen that the main dip in light level occurs around days 65-85, which is when the planet itself transits J1407.



<u>Figure 5. Light level of J1407 as J1407b and ring-structure transit.</u> The y-axis represents the percentage light level observed from J1407 while the x-axis represents time in days. A perfect horizontal transit across the midpoint of J1407 is taken. Each particle is assumed to result in a 1% decrease in light level if it transits the star's face from the reference direction (Earth). The transit lasts roughly ~60 days and blocks out all the star's light at its maximum.

Finally, the histogram distribution of particle transverse velocities is plotted in Figure 6. We note that indeed some particles reach the 32km/s transverse velocity needed to match observations. As these particles transit J1407 they could generate the rate of change in light level observed by Kenworthy et al. (2015).



<u>Figure 6. Histogram distribution of all ring particle transverse velocities.</u> The y-velocity of each particle combined with the y-velocity of J1407b is taken as representative of its transverse velocity. Note that the number of particles, as seen on the y-axis of the figure is shown on a logarithmic scale.

4. Discussion

First, a qualitative description of the ring-structure formed by tidal disruption. It can be seen that within the first orbital period (~32 years), all of the particles have spread out from their initial position clustered together (composing the tidally disrupted body) to form multiple rings around J1407b. These rings appear to mostly maintain their initial inclination and lie somewhat flat along a plane. Over the next four periods, this is no longer true, as the 'rings' we see formed precess along the z-axis to form more of a 'cloud' around the planet. This has important implications for our transit photometry, as from the reference direction we imagine (directly along the x-axis from the origin), a perfectly 'flat' ring-structure lying flat along the z-axis would appear simply as a line and could not generate the eclipses observed in Figure 1. Therefore, it is promising that more of a 'cloud' is formed.

Second, a comparison between the modeled light curve as the planet and rings transit J1407 (Figure 5) and the actual light curve (Figure 1). We see that a similar dip pattern is created due to the ring structure, and the length is also around the same, the transit lasting around 60 days instead of 54 days. The main noticeable difference is that while the original recorded light curve is relatively symmetric, due to the high eccentricity of the ring structure in my model the light curve is non-symmetric. However, it is easy to imagine that an alternate transit angle would solve this difference. As can be seen in Figure 6, my model also achieves particles that are able to match the observed transverse velocity (Rieder & Kenworthy, 2015). Therefore, all three important characteristics of the eclipse light curve (pattern, duration, and transverse velocity, as mentioned in section 1.1) are met by my model.

Moving beyond the results seen in the Figures, I also note that my model solves the problems associated with the previous model proposed by Rieder & Kenworthy (2016), as reviewed in section 1.3. Because my model assumes that the tidal disruption event and formation of rings happened relatively recently (i.e. within the last few orbits), instead of around the time of planetary formation, the long-term stability of the rings does not need to be guaranteed. Additionally, because I set J1407b on a circular orbit instead of a highly eccentric one, the planet does not approach J1407 close enough for the ring structure to get ripped away, as was one of the limitations of Rieder & Kenworthy's (2016) model (Sutton et al., 2022). Finally, I set a semi-major axis of 10 AU for J1407b instead of 5 AU as used by Rieder & Kenworthy (2016). This results in an orbital period of ~32 years, leaving ample time for us to observe a second eclipse since the first in 2007.

Overall, the tidal disruption-generated rings around J1407b generate a plausible light curve as the planet transits across the star J1407 (Figure 5) that matches the most important characteristics of the actual light curve recorded in 2007 (Figure 1). Furthermore, my model fulfills the research gap by solving several issues associated with the previous model proposed by Rieder & Kenworthy (2016).

5. Limitations, Future Research & Implications

One limitation of this research project is that only a single combination of initial orbital parameters was modeled. For this reason, my results may not be representative of all tidal disruption events. Future research should consider more parameter combinations (e.g. changing the mass and orbit of J1407b or the point of tidal disruption of the asteroid near the planet).

Another limitation is that the y-velocities of particles in the simulation was assumed to be an accurate representation of each particle's transverse velocity. However, the transverse velocities of the actual observed eclipse were calculated using an alternate method -- the derivative of the light curve was used to calculate the transverse velocity of the rings moving across it. Therefore, a continuation of this project might validate my preliminary results by using this second method to derive the transverse velocity of J1407b's rings as they transit J1407. Furthermore, as mentioned in section 4, future projects should also test alternate transit angles (ex. at various points throughout J1407b's orbit), in order to try and better match the observed light curve from 2007.

Finally, more research into the theoretical frequency of such tidal disruption events throughout the universe is needed. This will be especially important as our astronomical technology improves and we start observing a larger portion of the sky. We are currently only observing a small fraction of the sky and have already witnessed perhaps three such events (J1407, EE Cep, and Aurigae). Should this rate be indicative of the frequency of such tidal disruption-generated eclipses, we might expect to start observing many more similar transits. Regardless of whether the rings of J1407b and resulting light curve of J1407 were indeed generated through tidal disruption, my model will be useful in explaining these other, future sightings.

6. Conclusion

Overall, this research study attempts to fulfill the research gap surrounding the origin of the intriguing series of eclipses underwent by J1407 in 2007. In this study, I hypothesize that a tidal disruption event around the star's orbiting planet J1407b may have generated a series of rings around the planet that could have resulted in the observed eclipses as it transited J1407. I evaluate whether such an event has the potential to have caused the observed eclipses of J1407 by first modeling the aftermath of a tidal disruption event near J1407b and the formation of 'rings', and then plotting a light curve as the planet transits the star J1407. The goal was to compare this modeled light curve (Figure 5) to the actual curve (Figure 1).

I find that the modeled light curve shares many similar features with the actual one, leading to my conclusion that tidal disruption does indeed appear to be a possible mechanism by which the series of eclipses seen by the star J1407 (and other stars such as Aurigae and EE Cep) may have been generated. This result has important implications because it helps us understand how this mysterious event occurred, as well as provides us with valuable tools to help astronomers explain and extract data from similar sightings in the future.

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