Is High-Eccentric Tidal Migrations a Plausible Pathway to Explain Hot Jupiter’s Short Orbital Periods?

Student Dissertation

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Is High-Eccentric Tidal Migrations a Plausible Pathway to Explain Hot Jupiter’s Short Orbital Periods?
A Report submitted as the examined component of the Project Module SXP390

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Not including:

- Title page
- Abstract
- Contents
- Equations & Tables
- References
- Glossary
- Acknowledgements
Abstract

Hot jupiters are uniquely defined by their high mass and short orbital periods. This has led to many questions on how these gas giants could form under such extreme conditions. In this literature review, I analyse one such theory of hot Jupiter formation known as highly eccentric tidal migration.

Tidal migration is the theory of gas giants forming at the outskirts of their host star system, often beyond the snow line as a small planetary core. It is here where the planet develops a highly eccentric orbit via a perturbation event. This highly eccentric orbit leads to the planet having close orbital passes to their host star. These nearby passes lead to tidal forces with the host star creating a loss of momentum and a circularisation of their orbit with a much smaller orbital period.

For my literature review, I highlight the uniqueness of hot jupiters, followed by briefly highlighting in situ formation pathways via gravitational instability and accretion. I explain and critically analyse evidence for two pathways of tidal migration, known as planet-planet scattering and Kozai-Lidov cycles. Additionally I highlight observations of hot jupiters and propose which pathway they might have formed from.

Overall, I conclude both planet-planet scattering and Kozai-Lidov cycles are viable pathways for hot Jupiter formations. But which pathway is more dominant still remains unclear. Additionally there is less research for Kozai-Lidov cycles connected to hot jupiters compared to planet-planet scattering in part due to direct observational challenges. I also propose future research should focus on finding more observational evidence, especially obliquities and orbit inclinations, to narrow down which pathway is more common for tidal migration – these observations can add more supporting evidence to tidal migration.

[Words: 281 including “Abstract” title]
# Abbreviations

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<tr>
<td>PPS</td>
<td>Planet-Planet Scattering</td>
</tr>
<tr>
<td>KL Cycles</td>
<td>Kozai-Lidov Cycles</td>
</tr>
<tr>
<td>G.I</td>
<td>Gravitational Instability</td>
</tr>
<tr>
<td>TESS</td>
<td>Transiting Exoplanet Survey Satellite</td>
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Glossary

Acknowledgements
Chapter 1 Introduction

1.1 Background

With modern science and technology, we can now attempt to answer our curiosities about the universe. One of the more fascinating fields of astronomy is the search and discovery of exoplanets. One such category of exoplanets is known as hot jupiters. These are gas giants found orbiting very close to host stars. One of the first hot jupiters discovered in 1995 is known as 51 Pegasi B (Mayor and Queloz, 1995). These gas giants experience some of the most extreme physics of all exoplanets, puzzling astronomers on how they could have formed.

In this literature review, I summarise the properties of hot jupiters to understand what makes them unique to other exoplanets. I highlight theories for their formations that led to their unique orbits. I analyse and evaluate current literature for one such theory known as tidal migration, via two main pathways, planet-planet scattering and Kozai-Lidov cycles. Finally, I provide a conclusion on the theory and provide my view on its plausibility whilst suggesting what research needs to be done in future.

1.2 Objectives

1. Give an overview of the uniqueness and characteristics of hot Jupiters, in particular their peculiarly short orbital periods and rarity.

2. Briefly compare and contrast the alternative mainstream theories of planet formation (in situ accretion and in situ gravitational instability) to high-eccentric tidal migration.

3. Outline and describe each step of the evolution of high-eccentric tidal migration that a hot Jupiter undergoes to form its short orbital periods.

4. Discuss the merits of the theory known as high-eccentric tidal migration, and any recent research of models and observations that support or oppose the theory.

5. Give an overall conclusion of the theory’s plausibility. Highlight any limitations to the theory, and suggest what can be done to fill in gaps of understanding.
1.3 Scope of Work

This literature review focusses on the formation of hot jupiters and how they achieve their short orbital periods via tidal migration. The properties of hot jupiters are also highlighted and an overview of other formation pathways are briefly covered to highlight the differences between the theories.

1.4 Methodology

I have used

- PROMPT to evaluate papers that are relevant for the literature review.
- Papers typically less than 5 years old so that we the literature review is relevant and in line with current research.
- Search terms: hot jupiters, tidal migration, gas giant formation, planet-planet scattering, Kozai-Lidov cycles
Chapter 2 Overview of Hot Jupiters

2.1 Hot Jupiter Properties

Classification of hot jupiters shares common properties making them distinct from other exoplanets. The main distinctive properties of hot jupiters are their large mass and short orbit periods.

2.1.2 Hot Jupiter Masses

Hot jupiter masses classify them as gas giants. Whilst no lower limit for mass has been officially defined, an upper limit exists. The upper limit is around $13.6M_J$, at which point gasses begin to experience high pressure and temperatures resulting in deuterium fusion causing hot jupiters to become brown dwarfs (Spiegel, Burrows and Milson (2011), Albrow et al. 2018 and Etans and Lissauer, 2022). However $60M_J$ was chosen by The Exoplanet Encyclopaedia (Observatoire de Paris, 2015) when factoring multiple formation scenarios.

2.1.2 Hot Jupiter Orbits

Although no true range has been defined for their orbit periods, most are less than Mercury’s (87.91 days). Contemporary literature considers orbital periods less than 10 days to be good criteria due to ease of detection via transit and radial velocity surveys. Examples for short orbital periods are NGTS-6b, displaying an orbital period of just 21.17h (Vines et al, 2019) and 51 Pegasi B with an average of around 4 days (Mayor and Queloz, 1995).
2.2 Hot Jupiter Populations

Hot jupiters are rare exoplanets. Occurrence rates suggest they have a tendency to form around metal rich stars.

Osborn and Bayliss (2019) investigated this correlation with a sample of 217 hot jupiters, mass ranges of \(0.1 M_J\) to \(13 M_J\) with orbital periods less than 10 days. The metallicity \(\frac{Fe}{H}\) of the host stars was calculated using a power law equation:

\[
f \left( \frac{Fe}{H} \right) \propto 10^{\beta \left( \frac{Fe}{H} + c \right)} \quad \text{Equation 2.1}
\]

(Osborn and Bayliss, 2019)

Where \(\beta\) is a chosen index of the power law

c is a chosen offset value to correct for metallicity inaccuracies

The results highlighted preference for hot jupiters to form with stars containing a higher metallicity ratio.

*IMAGE REDACTED FOR COPYRIGHT REASONS*

Figure 2.1 Probability density of hot jupiters (light blue) compared to a simulated model (red) against metallicity of host stars (Osborn and Bayliss, 2019).

Boley et al. (2021) investigated 11,125 hot jupiters from a TESS survey orbiting stars of low metallicity \(-2.0 \leq \frac{Fe}{H} \leq -0.6\). The sample set agreed with previous literature, finding occurrence rates between 0.04% and 0.36% with an average of 0.18%:
From table 2.1, sample size from Boley et al. (2021) is half the size of other surveys using the transit method (right column). I find this might impact the accuracy of occurrence rate. Larger sample sizes on par with previous studies would help give the findings greater accuracy. However, even with the smaller sample, occurrence rates still suggest hot jupiters mostly form around metal rich stars.

Additionally, comparing detection methods (table 2.1) to occurrence rate $f_p$, transit surveys often find occurrence rates that are half that of radial velocities.

Moe and Kratter (2021) highlighted binary star systems suppress the formation of close in giant planets which could explain the bias between the two survey methods.

Radial velocity surveys have higher precision for identifying binary systems than transit method surveys (Moe and Kratter, 2021). This results in radial velocity surveys routinely omitting binary systems from their samples due to false positives. Using compiled radial velocity surveys, an overall average occurrence rate was calculated to be $1.09\% \pm 0.1\%$, this was compared against transit method samples from Kepler and TESS surveys.

**Table 2.1** Occurrence rates of hot jupiters. With N as total sample size, $f_p$, the average occurrence rate, Fe/H metallicity of host star. (Boley et al. 2021)
Figure 2.2 *Comparison of occurrence rates of transit method by Kepler and TESS surveys, with an average radial velocity across multiple surveys (Moe and Kratter, 2021).*

Figure 2.2 shows lower occurrence rates for Kepler and TESS transit surveys (dashed blue and greens lines) compared to averaged radial velocity surveys (red). By omitting binary systems (solid blue and green lines), occurrence rates increased by $\approx 0.8\%$. This is similar to the occurrence rates of known star systems with a difference of $0.1\% \pm 0.2\%$ (Moe and Kratter, 2021).

So the removal of binary systems from transit surveys provides a more accurate picture. I suggest for future transit surveys, binary systems be removed to get more accurate results.

Since hot jupiters are typically found around metal rich stars, I also think they could become extinct as host stars leave the main sequence and become red giants engulfing the planet. Given red giants have lower metallicity; this might explain the high rates of hot jupiters around metal rich stars.
Chapter 3 Other Formation Theories

3.1 Gravitational Instability

Gravitational instability (G.I) involves stellar disk collapsing via gravitation alone. From this, sufficient material conglomerates near a host star of sufficient mass to form a hot jupiter.

G.I theories for hot jupiters have generally fallen out of favour in literature. For hot jupiters to form from G.I, the criterion known as the Toomre Criterion (Equation 3.1) has to be met:

\[
Q = \frac{2\sqrt{\frac{kT}{\mu}}}{GP\Sigma_{gas}} \leq 1 \quad \text{Equation 3.1}
\]

(Dawson and Johnson, 2018)

Where \( T \) is the temperature of the gas
\( \mu \) the mean molecular weight
\( k \) is the Boltzmann constant
\( P \) orbital period
\( G \) is the universal gravitational constant
\( \Sigma_{gas} \) is the gas surface density

Rafikov (2005), highlighted that G.I alone cannot guarantee the formation of a giant planet. They require efficient cooling times for the stellar disks to clump together and hot temperatures counter gravitational conglomeration. Additionally if the cooling is too slow insufficient gas disk material may collapse to form a gas giant. So, in order for hot jupiters to form by G.I, they must meet a minimum temperature \( T_{\text{min}} \) and a minimum gas density \( \Sigma_{\text{min}} \).
\[ \Sigma_{\text{min}} \approx 6.6 \times 10^5 \text{g cm}^{-2} a_{\text{AU}}^{-21/10} (Q^6 \mu^{6/5} \zeta)^{-1/5} \left( \frac{M_*}{M_\odot} \right)^{7/5} \]  
*Equation 3.2*

\[ T_{\text{min}} \approx 5800 \text{K} a_{\text{AU}}^{-6/5} \mu^{3/5} (Q \zeta)^{-2/5} \left( \frac{M_*}{M_\odot} \right)^{3/5} \]  
*Equation 3.3*

(Rafikov, 2005)

Where \( a \) is the semi major axis

\( Q \) is the Toomre Criteria

\( M_* \) is the mass of the host star

\( M_\odot \) the solar mass

\( \mu \) is the mean molecular weight relative to atomic hydrogen

\( \zeta \) is cooling time function

This gave the minimum limits for planets forming at semi major axis \( a \leq 1 \text{AU} \):

\[ \Sigma > \Sigma_{\text{min}} = 5.7 \times 10^5 \text{ g cm}^{-2} \]  
*Equation 3.4*

\[ T > T_{\text{min}} = 5.2 \times 10^3 \text{ K} \]  
*Equation 3.5*

These limits, requires stellar disk mass of \( \approx 0.6 M_\odot \) which is in disagreement with observations of most stellar disks. Additionally such high temperatures would prevent the planet from being bound to the star.

However, using equation 3.1, Dawson and Johnson (2018) found temperatures \( T = 1500\text{K} \), gas density \( \Sigma_{\text{gas}} \approx 2 \times 10^5 \text{ g cm}^{-2} \) and period \( P = 3 \text{ day} \) to be plausible conditions for the stellar disk to collapse into a hot Jupiter.

Because gas density scales with the period of an orbit, a proportionality ideal to form hot Jupiters was found to be \( \Sigma_{\text{gas}} \propto P^{-7/6} \) (Dawson and Johnson, 2018). However, observations of stellar disks indicate proportionalities closer to \( \Sigma_{\text{gas}} \propto P^{-1} \) (Andrews, 2015) confounding doubts into the plausibility of G.I.

The requirements needed for G.I to form hot Jupiters do not match observations. I agree with current literature, that G.I is an implausible formation pathway.
3.2 Core Accretion

Core accretion typically starts with a small core forming in the stellar disk via accreting material. For hot jupiters to form, this core is theorised to migrate inwards via losses to angular momentum whilst accumulating mass. This accumulation forms sufficient mass to become a gas giant and orbital periods similar to hot Jupiter.

![Core Accretion pathway](Image 3.1)

*Image 3.1 Core Accretion pathway (Fortney. J, Dawson. R and Komacek T., 2021)*

It has been long accepted for accretion to predominate, a core mass of approximately 10 earth masses ($10M\oplus$) (Pollack et al, 1996 and Suzuki et al, 2018) is required to obtain sufficient gravitational influence and angular momentum to exchange via accumulating mass.

![Mass accretion runaway](Figure 3.2)

*Figure 3.2 Mass accretion runaway begins at around $10M\oplus$. Where $M_p$, $M_{XY}$ and $M_z$ are different solar mixtures of elements. (Pollack, et al, 1996)*
The hurdle for core accretion is the time scale for a core to accumulate sufficient mass before stellar gas dissipates. Previous research found stellar gas lifetimes varied by stellar mass density (Ribas, Bouy and Merin, 2015). For low density stellar mass (<2\(M_\odot\)), 60% to 70% of the simulations ended within 3 million years. And 5% to 20% ended within 11 million years. For higher mass densities (\(\geq 2M_\odot\)), 80% ended within 1 million years and 35% to 40% ended within 3 million years, with the remaining simulations failing to dissipate at all.

Figure 3.3 *Lifetimes of protoplanetary discs against low and high density stellar mass (Ribas, Bouy and Merin, 2015)*

Podolak *et al.* (2020), investigated accretion rates of proto-jupiter cores to see if they could form within the lifetimes of stellar gas disks. They found the accretion times to be within acceptable time frames but insufficient mass was accreted to reach the masses of gas giants. For the first 1.5 million years \(4M_\oplus\) to \(5M_\oplus\) of mass was accreted followed by a rapid gas accretion of \(\approx 10M_\oplus\). After this time period, mass accretion reduces to \(0.3M_\oplus\) and \(0.4M_\oplus\) over the next 1 million years.
Figure 3.4: Mass accretion over time. Mass accreted by a previous study (Lozovsky et al., 2017) in red. Accretion rates with no orbit inclination (solid black). Random inclinations between 0° and 0.003° (dashed black). Podolak et al. (2020).

Figure 3.4 demonstrates an inability for accretion to accumulate sufficient mass to form a gas giant. Hot jupiters typically have masses much higher ($30M_\oplus$) as a minimum. This suggests accretion could be a better pathway for super earths but not hot jupiters. One obvious reason being the closer the core forms to the host star, the smaller the orbit sweep pathway there is to accumulate mass.

However, the study did not include pebble accretion in the model which is the accumulation of larger solid masses, instead only gas was modelled. Bitsch et al. (2019), ran a similar simulation including pebble accretion. Their study found that sufficient mass can be accumulated with pebbles present in the stellar medium within an acceptable timeframe for typical stellar lifetimes of up to 3 million years.

Overall it seems core accretion is a possible pathway for hot jupiter formation compared to G.I. providing pebble accretion occurs to form within the disk lifetimes.
Chapter 4 High Eccentric Tidal Migration

4.1 What is Tidal Migration?

Tidal migration is a multi-stage formation theory. The first stage requires a gas giant to form in the outer regions of the planetary system. For the second stage, a perturbation event occurs causing the orbit of the planet to destabilise and create an eccentric excitation. This eccentricity inevitably results in a perihelion that is closer to the host star. The amount of eccentricity required is heavily dependent on the mass of the planet and host star and initial semi major axis. The small perihelion results in stronger gravitational tugging from the host star resulting in a loss of angular momentum and smaller orbital radius. The third and final stage is the eventual circularisation of the orbit via loss of angular momentum preventing any further inward migration.

4.2 Pathways of Tidal Migration

For tidal migration, an eccentric excitation event needs to occur. The pathways for this event to occur fall into two processes:

1. **Planet-planet scattering (PPS):** A passing perturbing body kicks a planet into a higher eccentric orbit by impact or flyby slingshot. (Marzari, 2014).

2. **Kozai-Lidov (KL) cycles:** Caused by a perturbing companion body. The perturber causes an oscillation of companion’s pericentre causing an exchange between eccentricity and orbit obliquity (Wu & Murray, 2003).

![Kozai-Lidov Cycles](Batygin, n.d)
4.2.1 Planet-Planet Scattering

Gong and Ji (2017) did an analysis on Kepler-413b to explain the origins of its short orbital period. They theorised its eccentric orbit $e \approx 0.118$ came from tidal migration due to PPS. Simulations showed a common pattern of PPS leading to one planet being ejected from the system. This ejection typically depended on differences in masses between the two planets in the system.

Table 4.1: Mass ratio $q$ the planets with the probabilities of ejection from the inner $E_{\text{ej}in}$ and outer $E_{\text{ej}out}$ planets (Gong and Ji, 2017).

<table>
<thead>
<tr>
<th>Mass ratio</th>
<th>Ejection Preference</th>
<th>$E_{\text{ej}in}$</th>
<th>$E_{\text{ej}out}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q = 1$</td>
<td>[0.2$M_\oplus$, 0.2$M_\oplus$]</td>
<td>0.52</td>
<td>0.19</td>
</tr>
<tr>
<td>$q = 0.5$</td>
<td>[0.1$M_\oplus$, 0.2$M_\oplus$]</td>
<td>0.55</td>
<td>0.06</td>
</tr>
<tr>
<td>$q = 0.3$</td>
<td>[0.2$M_\oplus$, 0.1$M_\oplus$]</td>
<td>0.37</td>
<td>0.26</td>
</tr>
<tr>
<td>$q = 0.15$</td>
<td>[0.06$M_\oplus$, 0.2$M_\oplus$]</td>
<td>0.69</td>
<td>0.02</td>
</tr>
<tr>
<td>$q = 0.15$</td>
<td>[0.2$M_\oplus$, 0.06$M_\oplus$]</td>
<td>0.35</td>
<td>0.32</td>
</tr>
<tr>
<td>$q = 0.03$</td>
<td>[0.03$M_\oplus$, 0.2$M_\oplus$]</td>
<td>0.72</td>
<td>0.01</td>
</tr>
<tr>
<td>$q = 0.03$</td>
<td>[0.2$M_\oplus$, 0.03$M_\oplus$]</td>
<td>0.29</td>
<td>0.41</td>
</tr>
<tr>
<td>$q = 0.03$</td>
<td>[0.006$M_\oplus$, 0.2$M_\oplus$]</td>
<td>0.70</td>
<td>0.00</td>
</tr>
<tr>
<td>$q = 0.03$</td>
<td>[0.2$M_\oplus$, 0.006$M_\oplus$]</td>
<td>0.00</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Figure 4.1 The eccentricity distribution for the surviving outer planet. With $m_{\text{in}}$ the inner planet’s mass, $m_{\text{out}}$ is the outer planet’s mass (Gong and Ji, 2017).
For most simulations ≈ 25% (figure 4.1) resulted in eventual eccentricities similar to Kepler-413b (e ≈ 0.118) occurring when the inner planet had initial mass ratio q of 0.03 to the outer planet and only the outer planet survives.

Frelikh et al, (2019) did analysis on ensembles of systems to see how PPS may affect eccentricity. The results also depended on the mass of the planets, highlighting it could be divided into two groups of mass ranges. For \( m < 1.17 M_J \) fewer planets achieved high eccentricity (\( >0.4e \)) compared to planets with mass \( m > 1.17 M_J \).

**Figure 4.2** Highly eccentric orbits form from planets with semi major axis \( a > 10^0 \text{ AU} \) with masses \( m > 1.17 M_J \) (red) compared with \( m < 1.17 M_J \) (purple) (Frelikh et al, 2019).

As mentioned (Chapter 2.2), hot jupiters are found around metal rich stars. Frelikh et al, (2019) also highlighted that planets around metal rich stars had a higher chance of exhibiting highly eccentric (\( >0.4e \)) orbits from PPS.
Figure 4.3 Planets around metal rich stars (blue) had higher eccentricities than metal poor stars (red) (Frelikh et al, 2019).

I find the connection between metal rich stars and high eccentricities provides strong support for hot jupiters to migrate via PPS since many are found around metal rich stars. But it’s evident the mass ratio of the planets also add a risk factor of ejection where less than 25% appear to avoid ejection (figure 4.1 & table 4.1).

Carrera, Raymond and Davies, (2019) ran 500 N-body simulations involving 3 planet systems over a 10 million year timespan to determine if PPS could explain how planets achieve extreme eccentricities e > 0.99. Extreme eccentricities have been considered unstable for PPS (Chambers, Wetherill and Boss, 1996). However simulations disproved this instability, highlighting there is no upper limit for the eccentricity via PPS (Carrera, Raymond and Davies, 2019).
Figure 4.4 demonstrates higher eccentricities can be achieved if two planets collide versus if one gets ejected. Additionally impacts occur more frequently than ejection. I find this could indicate many hot jupiters are found in systems with a companion planet.

Hord et al, (2021) performed a search of confirmed systems known to have hot jupiters using survey data from the Transiting Exoplanet Survey Satellite (TESS). They searched 184 systems with the criteria, radius $R_p > 8R_\oplus$ and orbital period $P < 10$ days. The survey of transit data was tested against simulations of transits involving a hot jupiter and a virtual companion. The simulations were then compared to TESS data to find similarity.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>$0.3 \leq R_p \leq 4 , R_\oplus$</th>
<th>$2.0 \leq R_p \leq 4 , R_\oplus$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>7.2%</td>
<td>4.2%</td>
</tr>
<tr>
<td>68%</td>
<td>11.8%</td>
<td>6.8%</td>
</tr>
<tr>
<td>90%</td>
<td>22.0%</td>
<td>13.3%</td>
</tr>
<tr>
<td>95%</td>
<td>27.8%</td>
<td>17.1%</td>
</tr>
<tr>
<td>99%</td>
<td>39.4%</td>
<td>25.0%</td>
</tr>
</tbody>
</table>

Table 4.2 Rate of companions for hot jupiters. Percentage rate of hot jupiters having a companion between radii $0.3R_\oplus \leq R_p \leq 4R_\oplus$ and $2.0R_\oplus \leq R_p \leq 4 \, R_\oplus$. With simulation confidence level (left column). (Hord et al, 2021).
From table 4.2, less than half of hot jupiters appear to have a companion planet. I find this does not strongly correlate with figure 4.4. Table 4.2 suggests companions are less likely with hot jupiters which might suggest ejection is more common than believed.

During PPS, gravity will inevitably fluctuate in unpredictable ways due to companion interaction. Planets experiencing these fluctuating gravitational instabilities can result in their obliquities to fluctuate (Petrovich, Tremaine and Rafikov, 2014).

Li (2021) ran 500, 2-body system simulations to investigate obliquity of planets undergoing PPS. 80.2% of the planets had non zero obliquity, and planets with semi major axis ($a < 1\text{au}$), 97.8% experienced angles > 10°. For planets with a larger semi major axis ($a > 1\text{au}$), only 66.0% experienced angles > 10°. This suggests that if a hot jupiter formed in the outer regions of the system undergoing PPS before migrating inwards, there is a high chance they have high obliquity.
Figure 4.6 Planet obliquity experiencing PPS (blue) and no PPS (red), showing non zero obliquity for PPS in majority of simulations, Li (2021).

Hong et al (2021) also ran 5,500 simulations of 2-body simulations to determine the percentage of planets that experienced obliquities > 40° and > 90° for three sets of planetary distances (1 au, 0.3 au, 5 au). Simulations showed the inner planet closest to the host star (0.3 au) had highest probability of its outer companion experiencing high obliquities at 31.98% for > 40° and 21.46% for > 90° with the inner planet being ejected.

<table>
<thead>
<tr>
<th>Set</th>
<th>Obliq &gt; 40° (%)</th>
<th>Obliq &gt; 90° (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (1 au)</td>
<td>17.86</td>
<td>5.07</td>
</tr>
<tr>
<td>2 (0.3 au)</td>
<td>31.98</td>
<td>21.46</td>
</tr>
<tr>
<td>3 (5 au)</td>
<td>10.43</td>
<td>3.21</td>
</tr>
<tr>
<td>All</td>
<td>19.51</td>
<td>8.77</td>
</tr>
</tbody>
</table>

Table 4.3: Obliquities of outer planet (Hong et al, 2021)

Figure 4.7: Evolution of obliquity for inner (blue) and outer (yellow) planet over 2 million years (Hong et al, 2021).
Table 4.3 adds weight to the findings of figure 4.6. PPS increases the likelihood of planets having high obliquity. But this occurred when one planet is ejected. But as previously highlighted planet impacts are more probable than ejections for PPS (figure 4.1). I find there is no clear agreement on which is more probable between impacts and ejection pathway for PPS with current research.

I suggest more investigations into obliquities of hot jupiters would help resolve this unknown. If there is many hot jupiters with high obliquities, then maybe they experienced PPS with ejection of their companion, if they have low obliquities, perhaps they experienced PPS by impacts.
4.2.2 Kozai-Lidov Cycles

Rodet, Su and Lai (2021) investigated a number of simulations to see if an outer companion perturber could lead to KL cycles. The outer companions had variable distances (10au to 500au). The simulation was also given an eccentricity limit that could lead to tidal migration (equation 4.1).

\[
1 - e_{lim} \approx 10^{-3} \left( \frac{k_{2,j}}{0.37} \right)^{2} \left( \frac{R_{j}}{1 \text{R}_{\text{Jup}}} \right)^{10} \left( \frac{a_{p,eff}}{40 \text{au}} \right)^{10} \left( \frac{m_{p}}{5 \text{M}_{\text{Jup}}} \right)^{2} \left( \frac{m_{j}}{1 \text{M}_{\text{Jup}}} \right)^{-2} \left( \frac{M_{1}}{1 \text{M}_{\odot}} \right)^{4} \left( \frac{a_{j}}{5 \text{au}} \right)^{16/9} \text{ Equation 4.1}
\]

(Rodet, Su and Lai, 2021)

Where \( a_{p,eff} = a_{p} \sqrt{1 - e_{p}^{2}} \) of the outer perturbing planet

\( k_{2,j} \) is the Love number of the inner planet

\( R_{j} \) is the radius of the inner planet

\( m_{j} \) and \( m_{p} \) is the mass of the inner planet and outer perturbing planet respectively

\( a_{j} \) is the semi major axis of the inner planet

\( M_{1} \) is the mass of the host star

The results showed varying probabilities of inward spiral by the inner planet.

![Figure 4.8](image)

**Figure 4.8:** Probability distribution that led to inward spiral of inner planet against varying initial eccentricities for the perturbing body. With closest approach \( \bar{q} = q / a_{p} \) where \( a_{p} \) is the semi major axis and \( q \) is the planet’s periastron (Rodet, Su and Lai, 2021).
The occurrence rate of migration via KL cycles was between 5% and 10%. The simulations were simplified however by setting the host star mass to $1M_\odot$. I find this simplification is not a great reflection of systems that likely exist since equation 4.1 depends on mass. I think more simulations of different host star masses would also help to determine how much the eccentricities depend on stellar mass.

Muñoz and Petrovich (2020), investigated a hot jupiter WD1856 D belonging to a triple star system to see if KL cycles could explain the tidal migration pathway for its orbit.

Table 4.4: Parameters of the WD 1856+534 System (Muñoz and Petrovich, 2020).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD Mass ($M_{\text{WD}}$)</td>
<td>0.518 ± 0.05 $M_\odot$</td>
</tr>
<tr>
<td>WD cooling age ($T_{\text{cool}}$)</td>
<td>5.85 ± 0.5 Gyr</td>
</tr>
<tr>
<td>Planet orbital period</td>
<td>1.407 days</td>
</tr>
<tr>
<td>Planet semimajor axis ($a_p$)</td>
<td>0.0204 ± 0.00012 au</td>
</tr>
<tr>
<td>Planet radius ($R_p$)</td>
<td>10.4 ± 1 $R_\odot$</td>
</tr>
<tr>
<td>Mass G 229-20 A ($M_A$)</td>
<td>0.346 ± 0.007 $M_\odot$</td>
</tr>
<tr>
<td>Mass G 229-20 B ($M_B$)</td>
<td>0.331 ± 0.004 $M_\odot$</td>
</tr>
<tr>
<td>$M_{\text{tot}} = M_A + M_B$</td>
<td>0.677 ± 0.031 $M_\odot$</td>
</tr>
<tr>
<td>A-B binary semimajor axis ($a_{\text{AB}}$)</td>
<td>5.8 ± 0.4 au</td>
</tr>
<tr>
<td>Outer semimajor axis ($a_{\text{out}}$)</td>
<td>150 ± 10 au</td>
</tr>
<tr>
<td>Outer eccentricity ($e_{\text{out}}$)</td>
<td>0.3 ± 0.1</td>
</tr>
</tbody>
</table>

To determine if KL cycles could explain the orbit, initial conditions had to consider the host star was not likely a white dwarf but rather a red giant. This means WD1856 D had to have a semi major axis larger than it was today or it would’ve been engulfed; this limitation was determined by equation 4.2:

$$a_p^{(\text{RGB})} \leq a_{\text{eng}} = 2\text{au} \left(\frac{M_p}{1M_j}\right)^{\frac{1}{3}} \quad \text{Equation 4.2}$$

(Muñoz and Petrovich, 2020)

Where $a_p^{(\text{RGB})}$ is the semi major of the planet during the hosts star’s first giant branch (RGB) $M_p$ is the mass of the planet.

Equation 4.2 provided a maximum initial separation for the hot jupiter before migration occurred. However the derivation comes from an old model (Nordhaus et al, 2010). I find this could reduce the accuracy of the findings since the model might not be using up to date knowledge from literature.
Figure 4.9 The survival and migration viability of WD1856 D. Areas in red resulted in a hot jupiter that didn’t match WD1856 D. The blue curves represent the limits where migration could occur. Black area represents possible values of hot jupiters from simulations. (Muñoz and Petrovich, 2020).

Figure 4.9 shows it was possible for the planet to undergo KL cycles and experience tidal migration. But the window of opportunity is very small (middle and right graphs) and also shows stellar mass plays a role. I find this highlights that the results depicted in figure 4.8 might be unreliable due to using a simplified model of host star mass set to $1M_\odot$ for all simulations.

Angelo et al. (2022) ran a study on Kepler-1656b, a giant planet with a highly eccentric orbit ($e \approx 0.8$) experiencing KL cycles. The investigation looked into whether these KL cycles would lead to tidal migration. The inclination of Kepler-1656b’s orbit was $(i = 89.31° \pm 0.51°)$. This inclination is close to being perpendicular to the host stars orbital normal, which made it ideal for KL cycles to occur.
Simulations were divided into two sets with varying initial conditions and were evaluated to determine if Kepler-1656b migrated to its current orbit period of 31.562± 0.011 days.

In set 1, the virtual planets began with similar conditions to Kepler-1656b from observations with some margin of variability. In set 2, all planets were set to the same semi major axis for the starting condition ($a_b = 0.197\text{au}$).
Figure 4.10: Simulation results from both sets depicting different outcomes. Simulated planet reaches host star’s Roche limit and becomes engulfed (bright red dot). Becomes tidally locked (black dot), undergoes PPS leading to ejection from the system or collision with companion planet (blue dot). Planet survives (mauve dot). The black rectangle outline depicts the region of planets that are similar in eccentricity and semi major axis to Kepler-1656b (Angelo et al. 2022).
Figure 4.11: Example of 3 simulations with different results. Initial conditions, left: \(M_c = 1.52M_{\text{jup}}, a_c = 2.52\text{au}, e_c = 0.64, i_{bc} = 112.96^\circ\), tidally locked after \(1.2 \times 10^6\text{yr}\). Middle: \(M_c = 1.28M_{\text{jup}}, a_c = 1.88\text{au}, e_c = 0.51, i_{bc} = 76.93^\circ\) with engulfment occurring after \(5 \times 10^6\text{yr}\). Right: \(M_c = 1.09M_{\text{jup}}, a_c = 2.09\text{au}, e_c = 0.014, i_{bc} = 121.65^\circ\) leading to eccentric orbit after \(6.3 \times 10^9\text{yr}\) (Angelo et al. 2022).

From figure 4.10, the results matching observations (black rectangle outline) highlights an eccentric orbit occurs without leading to tidal locking. Instead eccentricity oscillated (figure 4.11; right) leading to a stable orbit. This shows KL cycles occurred but did not lead to tidal migration.

This suggests not all KL cycles lead to tidal migration even though high eccentricity occurs. However the study of KL cycles is not as heavily studied compared to PPS. I think KL cycles is a possible pathway for tidal migration, but requires more observations and investigations to develop strong evidence. I suggest more surveys be carried out to find candidates in systems with a companion and a high orbit inclination (\(i \approx 90^\circ\)) capable of experiencing KL cycles. Observations could be carried out to see if KL cycles occur and migration takes place. Since hot jupiters have short orbital periods, observation times are feasible. For KL cycles, radial velocities would be a suitable choice to measure orbit periods since their inclination would make transit measurements difficult.
4.3 Observational Evidence

Adams, Millholland and Laughlin (2019), studied a handful of hot jupiter obliquities via phase curves. These were HD 149026 b, WASP-12 b and CoRoT-2 b. It was shown for HD 149026 b there was no indication of an obliquity, which might suggest it did not form via PPS but could form via KL cycles or in situ. CoRoT-2 b however had an obliquity of approximately (45.8° ± 1.4°) which could indicate PPS. WASP-12 b phase curves were undergoing strong tidal forces by the host star making obliquity measurements too difficult to form a conclusion.

Montet, *et al* (2020) investigated DS Tuc ab, a hot jupiter with an orbit period of 8.138 days and of a relatively young age ≈ 5 million years. The obliquity was found to be around 12° ± 13°. The authors suggest the likely pathway was in situ via accretion but did not investigate PPS. I find its non-zero obliquity and lack of companion planet, could suggest that PPS via ejection is possible and a model should be tested to confirm plausibility.

Dong, *et al* (2021) discovered a proto hot jupiter TOI-3362b, with an eccentricity $e = 0.815^{+0.002}_{-0.003}$, mass of $5M_j$ and orbital period of 18.1 days, with an F-type host star having high metallicity $Fe/H = 0.017^{+0.057}_{-0.049}$.

The data suggests, PPS and KL cycles could be viable pathways for tidal migration due to the star’s metallicity in the case of PPS and the orbit inclination of $89.140°^{+0.584}_{-0.668}$ in the case of KL cycles.

However the obliquity has yet to be measured, so it is unclear which pathway is more likely. Given the orbit period is only 18.1 days, I suggest more observations and measurements be made to calculate its obliquity – this might highlight the most probably pathway.

A hot jupiter known as XO-3b with mass $11.70 ± 0.42M_j$ and orbit period of 3.19 days was observed by transit methods (Yang and Wei, 2022). Data showed the planet was experiencing tidal forces by its host star due to its eccentric orbit ($e = 0.27587^{+0.00071}_{-0.00067}$).

With orbit inclination around $70° ± 15°$ and no obliquity, I find this could indicate KL cycles as the cause of its non-circular orbit. The lack of obliquity rules out PPS.
Dalba, et al (2021) discovered a gas giant, Kepler-1704 b, that has eccentricity $e = 0.921^{+0.010}_{-0.015}$. Its orbital period at 988.88 days suggests the planet has not managed to migrate inwards. I find the eccentricity likely occurred due to PPS due to non-zero obliquity but the lack of orbit inclination measurements cannot rule out KL cycles. The periastron for the orbit didn’t allow the planet to experience strong tidal forces to migrate inwards (Dalba, et al 2021).

I find these observations add weight to the tidal migration theories being plausible pathways. It is evident many planets require more detailed observation for obliquity and orbit inclination to get a clearer picture on whether PPS or KL cycles are the more likely pathway.
Chapter 5 Conclusion

5.1 Summary

This review has described the basic properties that give hot jupiters their uniqueness. And their populations and occurrence rates have been highlighted to demonstrate their rarity.

In situ formation via G.I and accretion theories has also been highlighted to show other possible formation pathways for hot jupiters. I find literature has largely disproven G.I as a viable pathway but core accretion likely does permit formation of hot jupiters if pebble accretion is involved.

Two pathways for tidal migration was analysed, PPS and KL cycles. PPS is a more heavily researched pathway than KL cycles due to the theory being older. But I find both pathways likely can form hot jupiters, though it is not clear if PPS or KL cycles is more common. It is also unclear if PPS via impacts or ejection is more likely to result in hot jupiters.

5.2 Future Research

Given tidal migration is a likely pathway, there is no clear consensus on which pathway is more likely. More direct observations should be carried out to measure hot jupiter eccentricities, companions, orbit inclinations and obliquities. This data is vital in order to determine which pathway they may have under taken. Additionally models used to run simulations were sometimes found to use old or outdated models which may impact how likely these pathways occur. Iteration on improving these models would highlight possible new patterns and relations besides obliquity and orbit inclinations – allowing us to make new observations and new insights into pathway histories.
5.3 Objectives

This literature review has fully met its objectives:

1. Give an overview of the uniqueness and characteristics of hot Jupiters, in particular their peculiarly short orbital periods and rarity – Chapter 2

2. Briefly compare and contrast the alternative mainstream theories of planet formation (in situ accretion and in situ gravitational instability) to high-eccentric tidal migration. – Chapter 3

3. Outline and describe each step of the evolution of high-eccentric tidal migration that a hot Jupiter undergoes to form its short orbital periods. – Chapter 4, Section 4.1

4. Discuss the merits of the theory known as high-eccentric tidal migration, and any recent research of models and observations that support or oppose the theory - Chapter 4, Section 4.2 & 4.3

5. Give an overall conclusion of the theory’s plausibility. Highlight any limitations to the theory, and suggest what can be done to fill in gaps of understanding – Chapter 5
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Glossary

- **Accretion**
  - The action of obtaining mass from a stellar disk via gravitational forces and impacts from a larger massive body travelling through the stellar disk medium.

- **Gravitational Instability**
  - Random perturbations and non-uniform temperatures in stellar medium results in a runaway effect and a conglomeration of mass to create planetary cores via gravitational forces alone.

- **Kozai-Lidov Cycles**
  - When two planets have orbit inclinations perpendicular to one another around a host star, oscillations lead to the orbit of one planet’s inclination to align with its companion. This oscillation also creates a highly eccentric orbit.

- **Planet-Planet Scattering**
  - A perturbation event either by impacts or close fly-bys of two planets leading to excitations in orbit eccentricity. This leads to one of the planets ejected, destroyed or in a large wide orbit far from the host star.

- **Tidal Migration**
  - When a planet has an eccentric orbit that results in a close pass of its host star, the gravitational forces from the host star creates a loss of angular momentum to the planet. This loss of angular momentum reduces the eccentricity and semi major axis for the planet resulting in a smaller orbital period.

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