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NUMERICAL AND ANALYTIC RESEARCH INTO THE FORMATION OF THE HD 80606B PLANETARY SYSTEM

A thesis submitted in partial satisfaction of the
requirements for the degree of

BACHELOR OF SCIENCE

in

PHYSICS

by

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10 June 2009

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2009

Abstract

Numerical and Analytic Research into the Formation of the HD 80606b Planetary System

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Numerical simulations of the formation and evolution of the planetary system HD 80606b were tested using a simplified four-body code written in C++ by myself and Michael Sebastian. HD 80606b is in a binary star system, and has the highest eccentricity of the known extrasolar planets of $e = 0.9321$. To reach this eccentricity without interaction with other planets, it is expected that it would have had to form at an inclination of 84.8° to the binary plane. We tested to see whether or not high eccentricities could be reached with two planets initially in the system. With an extra planet, we theorize that the initial inclination would not need to be $\sim 84^\circ$, but could be $\sim 60^\circ$ and still produce high eccentricities. Out of twenty runs, 35% of those ended up with an eccentricity higher than 0.95, and all but one run had a max eccentricity of 0.8 or higher. These initial results provide strong support for our hypothesis, but are not conclusive. Further test will be conducted using a full four-body code.

Contents

Acknowledgements

I would first like to thank my advisor Jonathan Langton for giving me the opportunity to work on a great project such as this. Even before he was my thesis advisor, he took the time to help me learn C++, which was greatly beneficial. His dedication to helping me learn the theory is also much appreciated. Thanks to Michael Sebastian for his help and insight while writing the computer programs. I would also like to thank Greg Laughlin for overseeing the entire project, and helping me with any questions I had about it. Finally, I would like to thank my family and friends for their support and encouragement not only during my thesis, but throughout my five years of college, without whom I would have not have made it this far.

1 INTRODUCTION

The question of whether or not planets existed outside our solar system was unknow until 1992 when the first extrasolar planet was discovered. Aleksander Wolszczan and Dale Frail confirmed that the pulsar PSR B1257+12 contained two planets, PSR B1257 +12 B, C (Wolszczan & Frail, 1992). Both planets are about 4 times as massive as Earth. They were discovered using the pulsar timing method, which uses the fact that pulsars rotations are so regular, any difference in their rotational period is detectable. However, some argue that this was not technically the first discovery of an extrasolar planet because in 1988, it was suspected that there was a planet orbiting Gamma Cephei. Then in 1989, HD 114762 b was discovered but could not be confirmed to be a planet until 1996. In 1995, Michel Mayor and Didier Queloz discovered the first extrasolar planet to orbit a main sequence star, 51 Pegasi (Mayor & Queloz, 1995). The planet was named 51 Pegasi b. These are the "firsts" of many planets outside of our Solar System to be discovered. As of May 4, 2009, there are 347 known extrasolar planets.

Many of the extrasolar planets have orbital characteristics which significantly differ from the planets in our Solar System. The eccentricities can be much higher, and a large fraction orbit very closely to their host star. According to recent data, $\sim 25\%$ of these high eccentricity planets are orbiting a star which is in a binary star system (Takeda & Rasio, 2005). This suggests that the planets possibly formed differently than the ones in our Solar System, or formed farther out and migrated inward. In 2001, the planet HD 80606b was discovered (Naef et al., 2001), having the highest eccentricity of all extrasolar planets of 0.9321. During its periastron passage, it comes as close as 0.029 AU, which, for comparison, is about 7 solar radii. HD 80606 b's mass is ~ 3.68 Jupiter masses (M_J). It has an orbital period of 111.4 days, and a semi-major axis of 0.432 AU. It orbits HD 80806, which is in a binary system with HD 80607. They are both main sequence, yellow dwarf stars, similar to ours, and are separated by a distance of ∼1000 AU. The system is located in Ursa Major, approximately 200 light-years away.

Much research has been done on the subject of extrasolar planets, from detection of them, to simulating the dynamics of the upper atmosphere (Langton & Laughlin, 2008). This thesis focuses on the evolution of HD 80606b and how it achieved such a high eccentricity, similiar to the work done by Wu & Murray (2003). We also use many of the same values and assumptions they used. In addition, some parameters were used from Ford (2000), in which numerical integrations for the dynamical evolution of planetary systems containing two identical planets were tested. A few of the parameters used by Ford were that the two planets formed in nearly cicrular orbits, and orbited very close to the dynamical stability limit. Also, the initial relative inclination of the two planets ranged from 0 to 5°, and the remaining angles were randomly chosen between 0 and 2π. One thing that differed from Ford's values in our runs was that we chose the initial eccentricity to be between 0 and 0.1 insead of 0 and 0.01.

In Chapter 2 I discuss the theory of the Kozai mechanism, and how it could be responsible for the current orbit of HD 80606b. The initial setup and parameter distributions are discussed in Chapter 3, along with assumptions that are made. Finally, I discuss the data and results in Chapter 4.

2 THEORY

A planet orbits a star under Newton's equation:

$$d^2\mathbf{r}/dt^2 = -GM\mathbf{r}/r^3 \tag{2.1}$$

where G is the gravitational constant ($6.673 \times 10^{-11} m^3 kg^{-1} s^{-2}$), M is the mass of the star, $\mathbf{r} = x\hat{x} + y\hat{y} + z\hat{z}$ and $r = |\mathbf{r}| = \sqrt{x^2 + y^2 + z^2}$. This equation is used to describe the motion of a single body in three dimensions. It has been established that the motion of two bodies can also be described by equation 2.1. However, for three or more bodies, the equation of motion must contain a term for the mutual gravitational attraction of each pair of bodies. For example, the x-component of the acceleration for body 2 in a three-body system is:

$$a_{2,x} = -G((m_1(x_2)/r_{12}^3) + m_3(x_3 - x_2)/(r_{23}^3) + m_1 m_3(x_3)/(r_{13}^3)) \tag{2.2}$$

In this equation, m_1 is taken to be at the origin of the system, r_{12} is the separatoin between bodies 1 and 2, r_{23} is the separation bedween bodies 2 and 3, and r_{13} is the separation between bodies 1 and 3. Using this simple equation of motion, and considering different configurations of bodies, one sees that interesting things can happen. For example, it is well known that many extrasolar planets have eccentricities much higher than the planets in our Solar System, and at least a quarter of these reside in binary star systems (Takeda & Rasio, 2005). Could the fact that they are in a binary star system have anything to do with their high eccentricities? It is more than likely, and is the basis for a theory proposed by Wu & Murray (2003) which explains this phenomena.

2.1 The Kozai Mechanism

In 1962, Yoshihide Kozai developed a theory that is now known as the Kozai mechanism. In his original paper he studied how inclined asteroids are perturbed under the influence of the Sun and Jupiter, when the asteroid is much less massive than Jupiter. This same concept can be applied to extrasolar planetary systems if instead of an asteroid, a Jupiter size planet is considered. Also, used in place of Jupiter for the second perturbing object would be another star that is the binary companion of the host star. The Kozai mechanism can cause a planet's eccentricity to be increased to values near unity if its initial inclination is inclined enough relative to the binary plane. This mechanism has been used to explain the unusually high eccentricities in extrasolar planets, most notably in the case HD 80606b (see next section), which has the highest eccentricity of all known extrasolar planets.

The Kozai mechanism requires some conditions to be met for it to work. First of all, it requires the planet's host star to have a binary companion. Even if this companion is far away, as long as the planet's orbit is initially inclined to the binary plane by more than $39.2°$ (Kozai, 1962), it can have a significant effect which will perturb the planetary orbit. If the inclination is lower than this, then the periapse argument rotates very fast through all the angles and the torque exerted on the planet averages essentially to zero. Also, the Kozai oscillations must be shorter than the age of the system, otherwise there will not be enough time for the eccentricity to grow to large values. With these requirements met, and enough time, cyclical angular momentum is exchanged between the planet and the distant companion causing long periods of oscillation in the eccentricity and inclination. These long-period oscillations are known as “Kozai oscillations” (Kozai, 1962), and usually last ∼20 Myr. During the transfer of angular momentum, orbital energies remain almost unchanged. Orbital parameters such as the mass and semimajor axis of the planet and star do not affect the eccentricity or inclination; they only affect the period of the Kozai cycles. During Kozai oscillations, the semimajor axis of the planet remains roughly constant. It is up to other processes to bring the planet in closer to its host star. Assuming that the planet formed in a nearly circular orbit, it is shown (Innanen et al., 1997) that the maximum eccentricity is given by:

$$e_{max} = \sqrt{1 - \frac{5}{3}\cos{i_0}^2} \tag{2.3}$$

The Kozai mechanism is quite sensitive in that it doesn’t take much to either reduce it, or break it completely. Kozai oscillations can be broken by things such as non-spherical stars (Soderhjelm 1980; Innanen et al. 1997), planet-planet interactions over long time-scales (Innanen et al., 1997), and general relativistic effects (Ford et al. 2000). All these processes can effect the precession of the pericenter argument of the planet, hence reducing the average Kozai torque. If the perturbations cause precession faster than the Kozai precession rate, then Kozai oscillation is destroyed (see WM03, Eqn. 2).

2.2 Kozai Migration of HD 80606b

With the highest known eccentricity, HD 80606b’s life history is an interesting topic to investigate, and is the focus of this thesis. There has been much research done on the planet since its discovery in 2001 (Naef et al. 2001). In 2003, Wu and Murray proposed an idea that could explain how the planet obtained such an eccentric orbit, using the theory of Kozai (1962).

Because HD 80606 has a companion located roughly 1000 AU away, a new theory was developed which involved the companion star being responsible for the high eccentricity and small orbit of the planet. There are two main components to this theory. First, the planet is assumed to have been born at a distance of a few AU from its star, while its orbital plane was inclined relative to the stellar binary plane. The theory is that the companion star will induce an eccentricity oscillation due to the Kozai mechanism (Kozai, 1962). This is where the planet trades orbital inclination for eccentricity. When the relative inclination between the orbital planes is above the critical angle ($I > 39.2°$), long term cyclic angular momentum exchange occurs between the planet and the companion star (Takeda & Rasio, 2005). The second component to the theory is tidal circularization. This is most effective during times of high eccentricity in the Kozai cycle. This dissipative tidal process irreversibly draws the planet inward. This process is known as "Kozai migration." While the companion star is far from the planet, it still has a significant effect in that it will perturb the planetary orbit as long as the planets orbit is inclined more than 39.2° to the binary plane. As a result of angular momentum exchange with HD 80607, the planet's eccentricity and inclination could go through large cyclic variations, increasing greatly over time. Because the mass and semimajor axis of the companion star is much greater than that of HD 80606b, effects on the companion's orbit can be neglected. Using this approximation, the z-component j_z of the planet's angular momentum is conserved.

$$j_z = \sqrt{GMa_p}M_p\sqrt{1-e^2}\cos I \tag{2.4}$$

The z-axis is normal to the plane, and the subscript p denotes the planet. Here, a_p is the semi-major axis of the planet, I is the inclination, and e is the eccentricity, where

$$e = \sqrt{1 + 2h^2 E/\mu^2} \tag{2.5}$$

While the planet is undergoing Kozai oscillations, the Kozai integral

$$H_K = \sqrt{1 - e^2} \cos I \tag{2.6}$$

is conserved. A maximum in e occurs during the time when I is at its minimum, and vice versa. This can be seen in Fig. 2.1 and 2.2. The Kozai cycle will last tens of millions of years. During these cycles, the Kozai integral remains constant, which yields $I \geq 84.8°$ for an initial $e = 0.1$ (Wu & Murray, 2003). This means that the planet must have formed nearly perpendicular to the binary plane. As of today, this is one of the leading theories that explains why Jupiter sized extrasolar planets have such high eccentricities. Although this theory seems to explain the highly eccentric orbits of extrasolar planets in binary systems, it can't be the only one, or be 100% complete. There could be other factors that play a part that are unknown at the present time. The problem with the Wu-Murray theory is that (a) it requires an extremely improbable initial configuration of the system and (b) it requires that there be no other planets in the HD 80606 system, which would be unexpected for a star of HD 80606's high metallicity. Thus, we strive to explain this phenomenon using a slightly modified version of this technique.

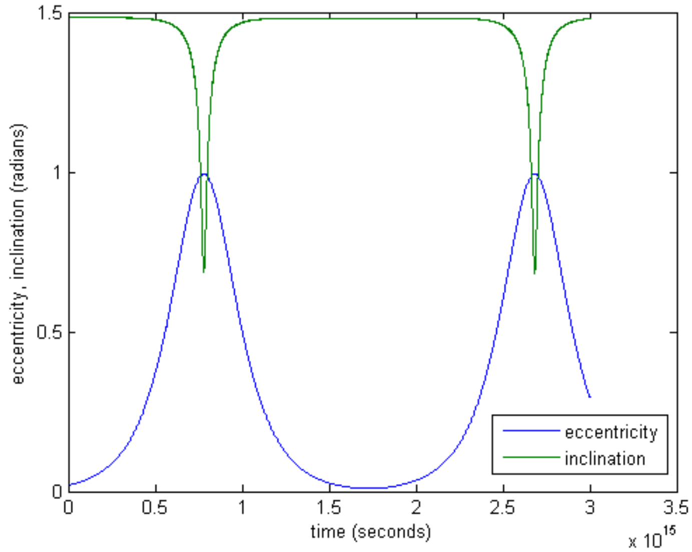

Figure 2.1: **Eccentricity and Inclination vs Time** Because the Kozai integral is conserved, when either the inclination or eccentricity goes up, the other must go down. This plot nicely shows that happening for a single planet in a binary star system.

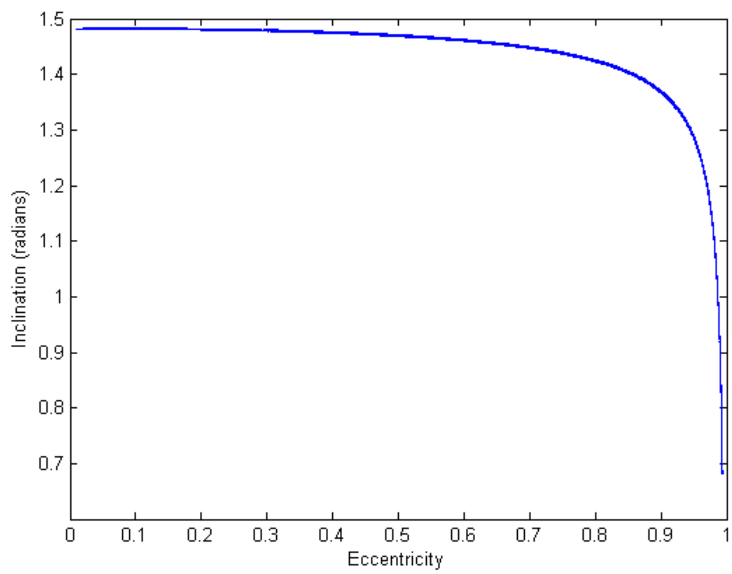

Figure 2.2: **Eccentricity vs Inclination** This plot is just another way of showing that the inclination and eccentricity are inversely proportional to each other.

3 METHODS AND ASSUMPTIONS

The purpose of this thesis is to simulate the evolution of the HD 80606b planetary system, in hopes of reproducing the planets high eccentricity under different initial conditions than those proposed by Wu & Murray (2003). We also strive to explain some unresolved issues with the Wu-Murray Theory. The HD 80606b planetary system is in a binary star system containing two yellow dwarf stars like our Sun, with the planet HD 80606b orbiting HD 80606. Although there are only three bodies, as discussed in the Theory section we hypothesize that adding a second planet to the system will allow high eccentricities to be reached without such extreme initial conditions. Thus, we now have a four body system, which required a four body code to be written. The journey to get to the final four-body code that is used for our simulations has been a long one. There were many other smaller codes that were written first and tested to make sure they worked correctly. Once we had all our separate codes working, we were able to put them together to make one code encompassing all the different aspects needed to properly run simulations and test our theory. In §3.1, an overview of the steps taken to reach the final production code is given. With the code completed and ready for performing tests, §3.2 will cover what initial conditions each object started out with, and what assumptions were made. Finally, §3.3 will talk about how our test runs were set up and performed.

3.1 Brief Overview to Making Final Working Code

The first few codes were fairly simple, and were mainly to help us get used to using programming to solve scientific problems. Once this was accomplished, we wrote a 2-dimensional two-body code. This involved just one planet orbiting a star in a keplerian orbit. After we were sure this was working properly, we made the code more realistic by making it 3-dimensional (3D). With the 3D code up and running, we added a third body to the system (HD 80607). With the second star now part of our code, we were able to test to make sure that the planet underwent Kozai migration, as it should in a binary system with the correct initial conditions. Figure 3.1 shows that the planet underwent Kozai migration. Confident that Kozai migration was indeed happening, we added one more planet which orbited the same star as the first planet, being that we ultimately needed a four-body code to simulate our theory of the evolution of the HD 80606b planetary system. However, our code is not a true four-body code. We are assuming that the stars' orbit is Keplerian (i.e., a perfect ellipse), so the planets do not affect the stars' motion. It is beneficial to use this kind of code for our simulations because it will run faster, and will also demonstrate that our approach is clearly feasible. With our final production code ready, we began to start running tests. For a more thorough and complete discussion of steps leading to the final code, and how the code itself works, see Sebastian (2009).

3.2 System Parameters and Constraints

The masses of the stars and planets stayed the same throughout every run, along with the initial semimajor axes. The initial orbital parameters were randomly generated. The system parameters are described below, and summed up in table 3.1.

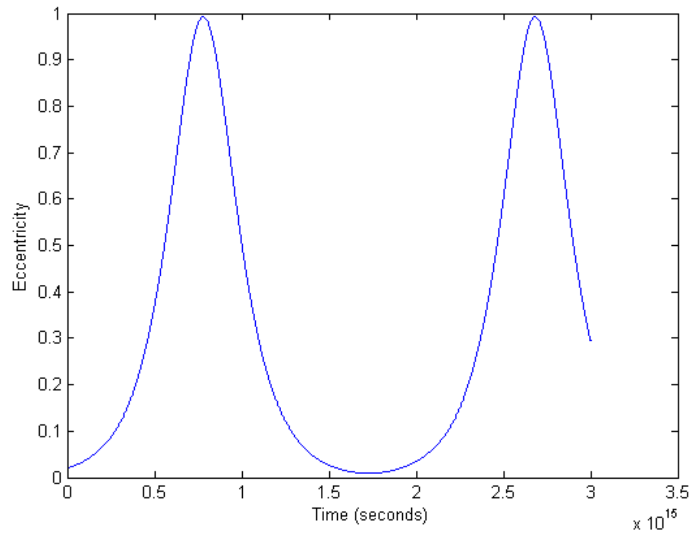

Figure 3.1: **Kozai Oscillations** This graph shows Kozai oscillations for a 4 M_J planet in a binary star system. The initial inclination was set at 80°, and the planet's orbital evolution ran for $\sim$ 95 Myr.

Mass of host star (m_1, HD 80606). - The mass of the primary star is slightly less massive than our sun at 0.9 $M_{\odot}$, where a solar mass is 1.98×10^{30} kg. This seems to be about average among stars with orbiting planets. According to the California and Carnegie Planet Search, about 60% of stars with discovered planets are 0.9-1.1 solar masses.

Mass of binary star (m_3, HD 80607). - The mass of the binary companion is similar in spectral type and metallicity to HD 80606, and is therefore assumed to be the same as the primary star at 0.9 $M_{\odot}$.

Mass of planet 1 (m_2, HD 80606b). - While the exact mass of the planet is hard to determine, we know that it is approximately $4 \pm 0.3 M_J$. The planet's inclination has been constrained by transit observations (Laughlin et al. 2009, Fossey et al. 2009), so RV measurements determine that mass $m_2 = 4.0 M_J$. We therefore adopt the planets mass to be 4 M_J.

Table 3.1: **System Parameters**

Parameter	Value
M_1	$0.9 \times 1.98 \times 10^{30}$kg
M_3	$0.9 \times 1.98 \times 10^{30}$kg
M_2	$4 \times 1.89 \times 10^{27}$kg
M_4	$4 \times 1.89 \times 10^{27}$kg
i_2	$60°$
i_4	$60° \pm 5°$
e_2	0-0.1
e_4	0-0.1
a_2	5 AU
a_4	7.6 AU
Ω, ω	0-2π

Mass of planet 2 (m_4, HD 80606c). - The fact that the second planet is further out from the star than the first planet means that it can not be larger than the other planet. This is because there is less material (dust, gas, rocks, etc.) the farther out you go. Most of the matter is closer in towards the star where the gravity is larger. This in turn means that a planet further out will not be able to grow larger than a planet closer inward, and in our case that limit is 4 M_J. The mass of the second planet is thus set to 4 M_J.

Initial inclination of planet 1 (i_2). - According to the theory of Kozai, a planet must have a minimum initial inclination of $\sim 40°$ in order for the Kozai mechanism to take place. In the case of HD 80606b, the inclination must be $\geq 84.8°$ (Wu & Murray, 2003). Since we are trying to achieve the same high eccentricity with a lower initial inclination by adding a second planet, we run the test at an initial inclination of $60°$.

Initial inclination of planet 2 (i_4). - We assume that both planets formed in nearly coplanar orbits, thus having approximately the same inclination. We therefore start the second planet out at an inclination within $\pm 5°$ of the first planet.

Initial eccentricity of planet 1 (e_2). - Our theory assumes that a planet would form in a nearly circular orbit. We therefore randomly choose a value between 0 and 0.1, the same as used by Wu & Murray (2003).

Initial eccentricity of planet 2 (e_4). - The theory of how planets form tells us that not only does the material exist in approximately the same plane, but it also should be spinning with about the same eccentricity. It is therefore appropriate to assume that the second planet formed with the same initial eccentricity as the first planet. Thus we use the same initial eccentricity as the first plane which is between 0 and 0.1.

Initial semimajor axis of planet 1 (a_2). - In staying within close accordance to the values used by Wu & Murray (2003) Wu and Murray (2003), a semimajor axis of 5 AU is used to start out with. This value of the semimajor axis is chosen because 5 AU is a reasonable distance for a 4 M_J planet to form.

Initial semimajor axis of planet 2 (a_4). - A value of 7.6 AU is chosen for the second planet. This is because it is just inside the edge of the instability zone. Any further out and the planet is likely to be stable; any further in and it's not likely that a second planet could have lasted long enough to reach 4 M_J. Figures 3.2 and 3.3 show this stability and instability over a period of about 100 Myr. It is assumed that after this amount of time, either the planets' orbits would not change, or one planet would be ejected from the system.

Initial orbital elements (Ω, and ω). - The initial values for the longitude of the ascending node Ω, and argument of periapsis ω were randomly generated to have a value between 0 and 2π.

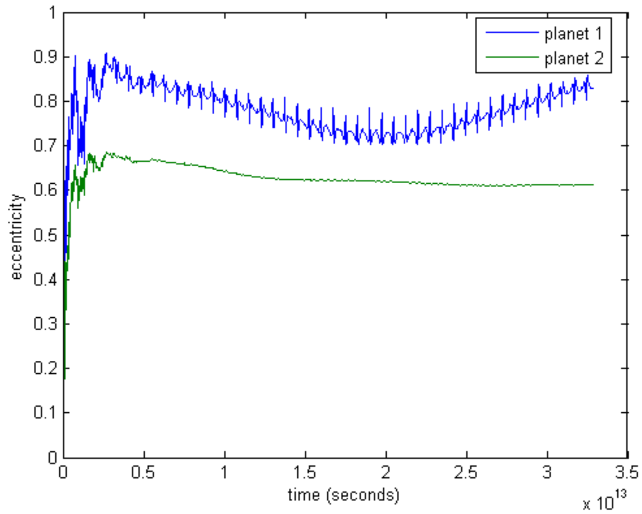

Figure 3.2: **Orbital Instability with Planet Closer** A test run was performed with the second planet at a distance of 7.4 AU. As can be seen, inside 7.6 AU, the planets interact with each other very quickly, which would not allow a second planet to form.

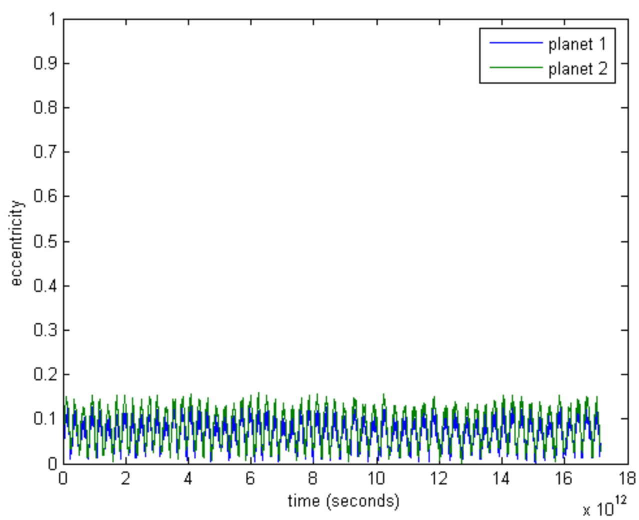

Figure 3.3: **Orbital Stability with Planet Farther** At a distance of 7.8 AU, both planets remain stable in their orbits, interacting little with each other.

3.3 Numerical Simulations

Our simulations were run using a computer code written by myself and Michael Sebastian. We are studying the orbital evolution of planetary systems containing two planets in binary star systems. Both planets are identical, with a mass of 4 M_J, and orbit a 0.9 $M_\odot$ star with semimajor axes of 5 and 7.6 AU. The binary companion is also a 0.9 solar mass star which orbits the main star with an eccentricity of 0.5, and has a semimajor axis of 1000AU. After randomly generating the values for the orbital elements, we integrated the equations of motion described in the theory section (Eq. 2.2 but with four bodies). The positions of the planets are integrated using the Fourth Order Runge-Kutta method (RK4). The RK4 method numerically solves ordinary differential equations, using four evaluations per time-step to give fourth order accuracy. For further explanation, see Sebastian (2009). The code also has another important aspect to it, and that is adaptive time steps. This basically determines where an object is in its orbit, and adjusts the time step accordingly. If the planet is close to the star, such as during its periastron passage, the code will make the time steps smaller, and vice versa if the planet is at apastron (farthest distance away from the star). This is important because during periastron passage the planet is moving very fast, so we want a small time-step which gives us more data points during that part of its orbit. During apastron the planet is moving much slower, so we want the time-steps to be larger since we are not as interested in what is happening there. Also, if the time-steps were to stay the same throughout the whole orbit, our data files would be extremely large, containing a lot of unnecessary data. It is therefore crucial that our code have adaptive time-stepping.

There are a few things that we neglected to incorporate into our code, such as general relativistic effects (GR precession), tidal effects, and rotational bulges on the planet. Leaving things such as tidal effects out will affect the results of our runs. For example, Kozai migration alone can only account for bringing the planet in so close to the star. For further migration, things like tidal circularization are required. However, our models will only hope to show that high eccentricities can be achieved with two planets in the system. We are not trying to obtain actual values for the final semimajor axis of the planet, and are assuming processes such as tidal circularization will occur later on in the planets life, thus bringing the planet in closer to the star. We also ignored the effects of the force on the binary star due to the planets. Because the binary companion is so far away, and both planets are very small compared to it, we assumed the force to be negligible. With this assumption, the motion of the binary will not be completely accurate, thus the force it exerts on the planet during Kozai migration will not be accurate either. Another thing that will affect our results is the range we chose for the eccentricities of the planets. We chose e to be between 0 and 0.1, which is too large a range, and should have been between 0 and 0.01. This is not that big of a deal however, and should not affect our results too much. Finally, there is an error in our code in that we set the ecentricity of both planets to be the same. There is no reason to assume this though, but since the eccentricities are generally lower than 0.1, we do not expect it to make a big difference in our results.

4 RESULTS

The objective of this thesis was to test whether or not high eccentricities could be reached in a system which initially contained two planets that formed at a lower inclination than $\sim 84°$. Wu and Murray (2003) determined that for the case of HD 80606b, the planet had to have formed at an inclination $> 84.8°$ to the binary plane to reach its current eccentricity of 0.9321. However, we theorized that with a second planet, high eccentricities could still be achieved. Twenty simulations were run to test this theory, with the initial inclination being $60°$. Table 4.1 shows the max eccentricity obtained for each run. Also, Fig. 4.2 is a histogram that was made to show the distribution of max eccentricities. While we do not state which planet was ejected from the system because it does not matter, the outer planet we ejected most of the time. Due to conservation of energy, once either planet is ejected, the one still in orbit would be left with a semimajor axis of $a_{final} \approx a_1 a_2/(a_1 + a_2) \approx 3.01$ AU. For a derivation of this equation see Ford (2000). A good example that the Kozai mechanism can still take place, and high eccentricities can be reached is shown in Fig 4.1. The first part of the graph shows when the two planets are still in the system. Both orbits are highly chaotic, until finally one of the planets gets ejected from the system. At this point, it can be seen that the planet left in the system has an increase in eccentricity and oscillates around $e = \sim 0.92$, going through two and a half Kozai cycles and obtaining a maximum eccentricity of $e = 0.9566$. This run is evidence that an initial inclination of 84° is not necessisarily needed for the Kozai mechanism to work, and that it can happen even at 60°.

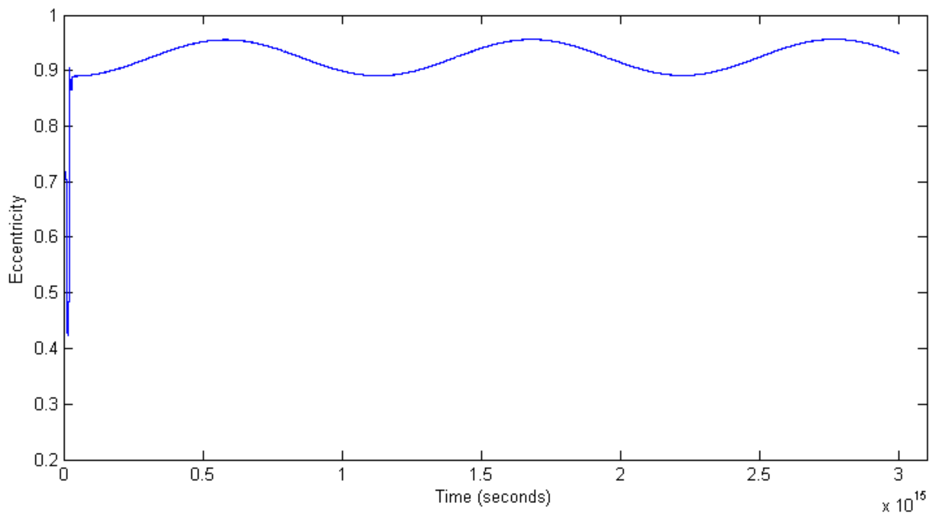

Figure 4.1: **Kozai Cycles** Both planets are initially in the system, as shown by the first part of the graph, then after one gets ejected, the planet left in orbit undergoes Kozai cycles, reaching a maximum eccentricity of 0.9566.

Out of all the runs, 35% had a max eccentricity > 0.95, 50% > 0.9, 75% > 0.85, and 95% > 0.8. The highest eccentricity was 0.9982, and the lowest was 0.6188, which is still very high for a planet. In comparison, Mercury has the highest eccentricity in our Solar System of 0.2056. We are interested in eccentricities that are higher than ∼0.95 because during processes like tidal circularization, which will draw the planet in closer, some eccentricity will be lost. Therefore it is important for the planet to have an eccentricity higher than 0.9321, so after the planet comes to a stable orbit, it will have an eccentricity as high as HD 80606b, which is the purpose of these tests. According to Wu & Murray (2003), HD 80606b would have had to reach an eccentricity of 0.993 during the Kozai cycle in order to produce the periastron currently observed; this is also assuming the planet had a semimajor axis of 5 AU.

Table 4.1: **Max Eccentricities**

Run	Max e	Run	Max e
1	0.8649	11	0.6188
2	0.8962	12	0.9174
3	0.9982	13	0.9612
4	0.8698	14	0.9158
5	0.9924	15	0.9053
6	0.8249	16	0.9765
7	0.8667	17	0.9924
8	0.9917	18	0.8064
9	0.8460	19	0.9566
10	0.8247	20	0.8906

While plotting the eccentricity versus time for one of the test runs, I noticed something interesting. During the Kozai cycles, smaller oscillations were taking place. This can be seen in Fig. 4.3.

This effect is however probably due to errors caused by our assumptions. The smaller oscillations go away if a full four-body code is used instead of the modified version we used, and also if Jacobi coordinates were used. This is where you calculate the orbital elements of a body relative to the center of mass of all bodies interior to that body. For our next project (see next Chapter), these will be taken into account and hopefully correct this effect.

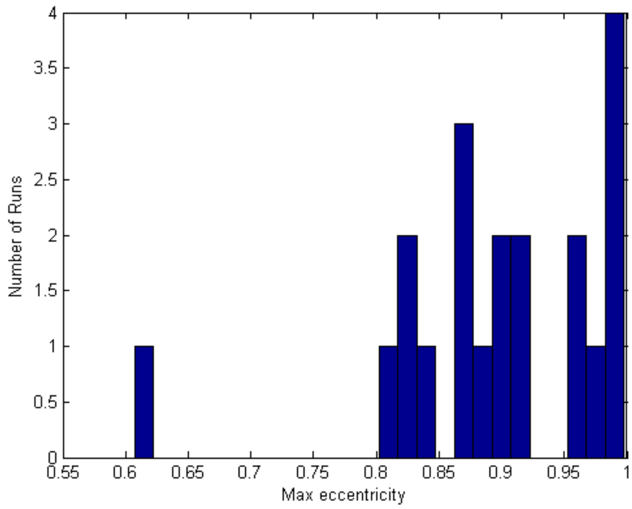

Figure 4.2: **Histogram of max eccentricities**

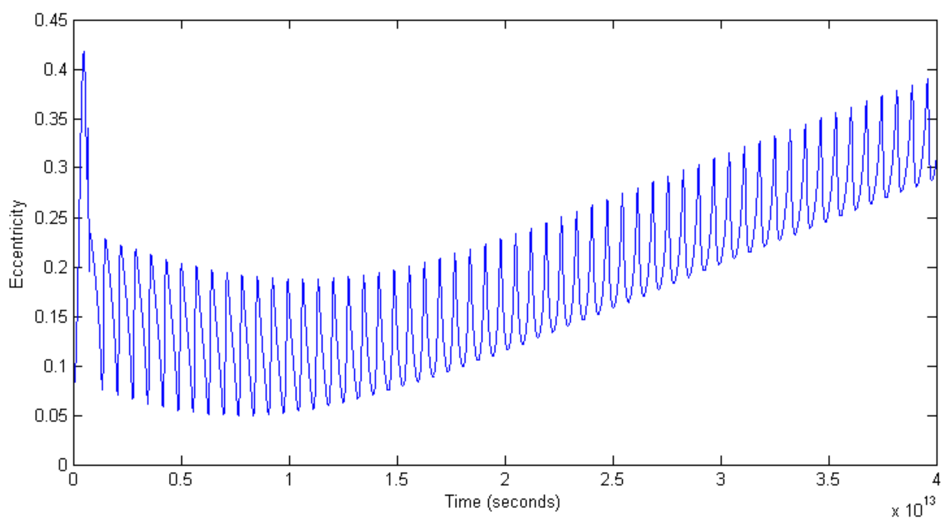

Figure 4.3: **Oscillations in Kozai cycles** Smaller oscillations can be seen within each full Kozai cycle. However, this is probably due to errors in our code, and has no real significance

5 CONCLUSION

The evolution of a two-planet system within a binary star system was tested. We theorized that with two planets initially in the system, one planet could reach high eccentricities through the Kozai mechanism (Kozai, 1962) with the ejection of the other planet . With the second planet in the system, we proposed that this could happen with an initial inclination of only 60° to the binary plane, and not 84.4° as determined by Wu & Murray (2003). Our tests show that high eccentricities can be reached, with 35% of the runs achieving $e > 0.95$. In every case, one planet got ejected from the system, leaving the other one with a higher eccentricity and smaller semimajor axis. Many of the runs would look like this when plotted. Some end up with a high eccentricity like 4.1, and some would only reach $e = \sim 0.8$. This just shows that it is possible for high eccentricities to be reached without such extreme initial conditions. Being that many extrasolar planetary systems have planets with large eccentricities, these results look promising. However this does not prove our theory, it just provides strong evidence for it. It should be noted that these results are just preliminary because we did not use a full four-body code, but they do however support our hypothesis.

The Work that was done for this thesis will not be the end. Our next goal is to use a full four-body code and test our theory again. This means the new code will account for the force exerted on the binary companion by the two planets, as well as the main star, making its orbital path more realistic. We will also take into account the fact that the planets would probably have had slightly different eccentricities to begin with, and will make our initial values range from 0 to 0.01. Also, many more tests will be run, probably up to 100 or more. The tests will cover a wider range of initial inclinations, all the way from 60° to 80° with 5° increments in between. Overall, the next code will be more accurate to real life situations, and will hopefully help us to better understand extrasolar planets, and how they might have evolved.

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