Chapter 1

Introduction

The year 1609 saw two landmark discoveries in the field of planetary science. The observational breakthrough was made by Galileo Galilei who that year turned a telescope to the skies for the first time in human history. His new tool led to the first major discoveries of planetary science: the phases of Venus, the moons of Jupiter, mountains on the Moon, and the rings of Saturn. The theoretical breakthrough was made by Johannes Kepler, who published in *Astronomia Nova* his new theory of planetary motion. Included in this theory was the empirical observation that the planets orbit the Sun in fixed elliptical orbits and that their rate of orbital motion swept out equal areas in equal times. These are now known as Kepler's first and second laws of planetary motion (the third law would come in 1619). Four hundred years later, planetary scientists are still making discoveries based on these two breakthroughs. The results presented in this thesis used telescopes about ten thousand times stronger than Galileo's original refractor, along with powerful analytical tools, originally developed by Isaac Newton, that mathematically codify Kepler's empirical laws.

These observational and theoretical tools are applied to various problems in orbital dynamics. The main goal of orbital dynamics or celestial mechanics is to explain the motion of bodies in space due to their mutual (gravitational) interactions. The simplest non-trivial dynamical system is the orbital motion of two point-masses in space. This two-body problem has a straightforward analytical solution: each object orbits the center of mass in a fixed elliptical orbit. In honor of Johannes Kepler's empirical discovery of this elliptical motion, such orbits are called Keplerian.

Anything more complex than the two-body problem will execute non-Keplerian motion. When attempting to solve these complex dynamical problems, the first goal is to identify the most important aspect that has not yet been included in the solution. Each of the four subsequent chapters in my thesis represents a problem that is slightly more complicated than the two-body problem; in each case, my work was to characterize the dominant non-Keplerian aspect of the problem that had not yet been considered.

1.1 Chapter 2: Extra-Solar Planet Interiors

Chapter 2 studies the orbital motion of planets orbiting other stars. Over 300 such extra-solar planets have been discovered in the last fifteen years; Marcy et al. (2005) estimate that ∼12% of stars possess gas giant planets within about 20 AU. Originally, most extra-solar planets were discovered through measuring the stellar radial velocities. When the radial velocity motion matched the Keplerian motion of a star around the center-of-mass of a star-planet system, the presence of the planet could be indirectly inferred. The radial velocity technique had its first major successes beginning in 1995, with the discovery by (Mayor and Queloz, 1995) of a planet orbiting the star 51 Pegasi. Planets like 51 Pegasi b were totally unexpected: it is a Jupiter-like planet in a surprisingly un-Jupiter-like orbit with an orbital period of only 4 days. Planets like 51 Pegasi b are called "hot Jupiters" to emphasize that they orbit their parent stars at a radius ∼100 times closer than Jupiter in our solar system.

Since the orbits of hot Jupiters are so compact, there is a ∼10% chance that these planets will pass in front of their parent star as seen from Earth (as compared to a ∼0.1% chance for a planet in a Jupiter-like orbit). As a consequence, the star will diminish in brightness as the dark planet occults a portion of the bright star. The depth of the photometrically observed transit is proportional to the ratio of areas of the planet and star. The first observation of such a transiting planet around HD 209458 (Charbonneau et al., 2000) proved that these objects were similar to Jupiter, because the ∼1% depth of the transit corresponds to an object the size of Jupiter (since $\left(\frac{R_{\rm Jup}}{R_{\rm Sun}}\right)^2 \approx 0.01$). Using the *Hubble Space Telescope* (HST), precise photometry at the 10^{-4} level can be achieved allowing for a detailed description of many properties of the planetary and stellar system (Winn, 2009). Planets transiting bright stars are the most information-rich planetary objects outside our solar system.

Many transiting planets have radii that are much larger than can be explained by interior models (e.g., Guillot et al., 2006; Burrows et al., 2007), resulting in anomalously tiny densities (as low as $\sim$0.3 g cm^{-3}). Other planets have surprisingly high densities, indicative of very large solid cores (Sato et al., 2005). For both kinds of planets, it may be very difficult or even impossible to determine the correct modifications needed to align planetary interior models with the wide range of observed planetary densities.

Our contribution to this problem was to suggest a model-independent measure of interior structure that would be valuable in order to begin disentangling otherwise unconstrained physics. The interior density distribution of a planet affects the size of rotational and tidal bulges caused by the planet's spin and the nearby star's gravitational field, respectively. These effects can all be captured with a single number, k_{2p}, the planetary Love number, which ranges from 0 for a perfectly rigid planet to 1.5 for a fluid totally homogeneous planet. The Love numbers of Jupiter ($k_{2J} \simeq 0.49$) and Saturn ($k_{2S} \simeq 0.32$) differ because Saturn has a relatively larger core of solid elements. The value of k_{2p} reflects the amount of central condensation of a body and thus, a measurement of k_{2p} is a model-independent probe of planetary interiors. (It is equivalent to measuring J_2 of an extra-solar planet.)

It has been known for decades that a non-zero value of k_2 creates a non-Keplerian orbital precession, i.e., a rotation of the normally-fixed orbital ellipse (Russell, 1928; Cowling, 1938; Sterne, 1939a,b). This subtle non-Keplerian effect can be measured with precise light curve measurements over a long time baseline. In fact, measuring orbital precession in eclipsing binary systems gave the first model-independent indication that stars were highly centrally condensed ($k_2* \approx 0.03$). However, until our work in Chapter 2, no one had applied this method to extra-solar planets with the goal of measuring planetary interiors.

One of the surprising conclusions about orbital precession in extra-solar planetary systems is that the planet is actually the dominant source of precession, with the much more massive star contributing a factor of ∼10 less. The huge tidal bulge raised on the planet by the star, sometimes reaching over 2000 km in size, creates a significant modification to Keplerian motion. The rate of orbital precession is strongly dependent on the star-planet distance, so we focused on planets that were extremely close to their parent stars, known as very hot Jupiters, which have semi-major axes of only ∼0.02 AU and orbital periods of 1-2 days. For such planets, the orbital precession due to the planetary interior is nearly 100 times more powerful than precession caused by the star or general relativity.

This prominent effect and its usefulness for obtaining model-independent measurements of planetary interiors had not been recognized in the extra-solar planet community. Therefore, we chose to extend our study beyond the theoretical orbital dynamics and to demonstrate that actual measurements of orbital precession of transiting planets were possible. The most powerful photometric tool for measuring k_{2p} in the short-term is NASA's *Kepler* mission, which successfully launched on March 6, 2009 and started taking high quality science data on May 13, 2009. To achieve its main goal of detecting transiting Earth-radius planets in Earth-like orbits, *Kepler* will also obtain exquisite photometry of over 100000 stars, about 30 of which are expected to host hot Jupiters with periods less than 3 days (Beatty & Gaudi, 2008). Chapter 2 contains a full model of *Kepler* photometry on transiting planets in order to demonstrate the ability to detect orbital precession of very hot Jupiters.

By investigating the full photometric signal of orbital precession, Chapter 2 demonstrates that *Kepler* can realistically detect apsidal precession with the accuracy necessary to infer the presence or absence of a massive core in very hot Jupiters with orbital eccentricities as low as $e \simeq 0.003$. Furthermore, the signal due to k_{2p} creates unique transit light curve variations that are generally not degenerate with other parameters or phenomena. In this chapter, we discuss the plausibility of measuring k_{2p} in an effort to directly constrain the interior properties of extra-solar planets. This chapter is about to be published in the *Astrophysical Journal* under the title, "Probing the Interiors of Very Hot Jupiters Using Transit Light Curves."

1.2 Chapter 3: The Haumea Family

The remainder of my doctorate research focused on the orbital dynamics of minor planets within our own solar system orbiting beyond Neptune. These icy bodies are called Kuiper belt objects (KBOs) in honor of Gerard Kuiper's prediction of a distant population of small bodies similar to the asteroid belt (Edgeworth, 1949; Kuiper, 1951). Throughout this thesis, the term KBOs is synonymous with transneptunian objects and refers to the entire population of solar system small bodies with semi-major axes greater than Neptune's ($a \gtrsim 30$ AU).

The properties of the ~1000 known KBOs orbiting beyond Neptune have already changed our understanding of the formation of the outer solar system. For example, the orbital distribution of these bodies point to a past dynamical excitation event during a chaotic episode in solar system history (e.g., Malhotra, 1995; Gomes et al., 2005; Chiang et al., 2007; Levison et al., 2008a) as well as significant orbital migration of the outer planets (e.g., Fernandez and Ip, 1984; Malhotra, 1993; Gomes et al., 2005b). Studying the orbital dynamics of KBOs improves our understanding of the early formation and evolution of the solar system.

For several years, Prof. Michael Brown has led a major observational effort to discover and characterize new KBOs. One of the major aspects of this research was the spectroscopic survey of near-infrared spectra of bright KBOs, summarized by Barkume et al. (2008). These authors found that KBOs fell into three major spectroscopic categories: methane-rich dwarf planets (Eris, Pluto, and Makemake), KBOs with strong water ice spectra (Haumea and others), and KBOs with featureless near-IR spectra (the majority of KBOs). The difference between the methane-rich and featureless categories can be explained by the model of Schaller and Brown (2007), who show that only the largest KBOs are massive enough to prevent a methane atmosphere from escaping.

An explanation of the objects with strong water ice spectra was not as clear. These objects spanned a wide range of sizes and had atypical optical colors (blue or gray gradients, instead of the strong red gradient observed for most KBOs). The key to understanding these objects was in their orbital parameters: they were all clustered within a small region of semi-major axis, eccentricity, and inclination. The only viable hypothesis that can explain a clustering in both surface and orbital properties is that these objects were all once part of the same parent body. In other words, these icy bodies are a collisional family.

A sufficiently energetic collision can impart enough velocity to gravitationally eject many of the impact fragments. These fragments go into nearby orbits and together form a collisional family. Dozens of these families have been identified in the asteroid belt since Hirayama's original identifications of groups of asteroids nearly a century ago (Hirayama, 1918). Recent modeling has shown that these groups of asteroids with similar orbits and spectra are very well explained by collisional formation (e.g., Durda et al., 2007).

Families in the Kuiper belt are unique, even compared to asteroid families, because they are direct fingerprints of ancient collisions. In the asteroid belt, the Yarkovsky effect and other perturbations degrade the coherence of asteroid families after hundreds of millions of years (Farinella & Vokrouhlicky, 1999; Milani & Farinella, 1994). Kuiper belt families stay mostly coherent over the age of the solar system and can provide a direct view of processes present at the beginning of the solar system.

In Brown et al. (2007), we showed that the dynamical clustering of objects with strong water ice spectra was well explained by a collisional family. The largest remnant of this family is the dwarf planet Haumea, the largest object with a strong water ice spectrum. Our discovery of the first known Kuiper belt family around the dwarf planet Haumea (formerly known as 2003 EL61) has already been called a "milestone" in the study of the Kuiper belt (Morbidelli, 2007), because families are a unique testbed for theories of the dynamical, collisional, and surface properties of KBOs.

The dwarf planet Haumea is, perhaps, the most interesting object in the Kuiper Belt. Early in solar system history (Levison et al., 2008), Haumea experienced a massive collision that imparted its ultra-fast rotation (Rabinowitz et al., 2006), created two moons (Brown et al., 2006; Chapter 4), and shattered its icy mantle, sending fragments into nearby heliocentric orbits (Brown et al., 2007). As discussed above, these fragments were discovered after the largest spectroscopic survey of Kuiper belt objects (Barkume et al., 2008) revealed that six KBOs had remarkably deep water ice absorptions, including Haumea and its brightest satellite (Barkume et al., 2006) and four other KBOs in nearby heliocentric orbits.

The spectroscopic survey that identified the original Haumea family members was limited to the $\sim$40 brightest KBOs. The vast majority of KBOs cannot be studied spectroscopically which significantly limits the ability to find new family members observationally. We therefore turned to a dynamical analysis of the Haumea family in an attempt to identify new candidate family members and to characterize the Haumea family in more detail. The results of this work are presented in Chapter 3.

The ejection of orbits from a collision can be simulated dynamically by giving objects an isotropic non-Keplerian velocity "kick" of magnitude Δv from a single collision location in space. This instantly changes the orbital elements of the ejected bodies and creates a unique pattern of semi-major axes, eccentricities, and inclinations. In Chapter 3, we model the orbital element spread of the original Haumea family members to estimate the original collision location. We then take all known KBOs and calculate their proximity to the collision through the estimated value of Δv needed to reach their current orbits. The objects with the lowest value of Δv are good candidates for membership in the Haumea family. This and other techniques used in Chapter 3 were based on similar techniques used for asteroid families, adapted for application in the Kuiper belt.

Two KBOs, predicted to be family members by the dynamical analysis of Chapter 3, have recently been observed spectroscopically by Schaller & Brown (2008). These authors find that the predicted family members indeed share the same deep water ice spectra characteristic of Haumea family members. Additional Haumea family members will be identified in the future by observing more of the candidates identified in Chapter 3 as well as the discovery of additional KBOs near the center of the family.

Performing this Δv analysis yielded one very unusual result: Haumea is not at the center of the collision. This is surprising, since it is by far the largest family member and also has clearly experienced a giant collision in the past as inferred from its high density, ultra-fast rotation, and two small moons. As discussed in Brown et al. (2007) and modeled in Chapter 3, the reason Haumea is not at the center of the collisional family is that it has diffused from its original orbital location as the result of a weak mean-motion resonance with Neptune. Haumea's heliocentric orbital period is exactly 12/7 times larger than Neptune's orbital period. Orbital diffusion within mean-motion resonances had been demonstrated before (it is the origin of the Kirkwood gaps in the asteroid belt, for example). We found empirically that such diffusion nearly conserves the Tisserand parameter $T \approx \cos i\sqrt{1-e^2}$. The current eccentricity (inclination) of Haumea is higher (lower) than the expected collision center in a way that is consistent with conservation of the Tisserand parameter. Hence, allowing for the non-Keplerian effect of resonance diffusion, the current location of all the known family members are consistent with a tight dynamical cluster ($\Delta v \lesssim 150$ m s^{-1}).

Though chaotic in nature, resonance diffusion has an associated timescale. Using the estimated initial location of the center of the Haumea family, Chapter 3 also describes how the age of the Haumea family can be estimated by calculating the time Haumea needs to diffuse to its current location. Through n-body dynamical simulations of the giant planets and objects in the 12:7 resonance, we showed that the Haumea family must be at least 1 Gyr old, with 90% confidence. That is, only 10% of simulated particles moved from the center of the collision to the current location of Haumea within 1 GYr. Our estimate for the age of the Haumea family is 3.5 $\pm$ 2 Gyr. The lack of precision is due to the chaotic nature of resonance diffusion. In Chapter 3, we show that the precision can be increased with the discovery of more resonant Haumea family members. I estimate that future surveys of the Kuiper belt, such as Pan-STARRS and LSST (Trujillo, 2008), will provide enough family members to date the age of the Haumea collision with a precision of 0.5 GYr by the year 2020. An absolute age determination of the Haumea family will be extremely valuable for constraining models of outer solar system formation.

The ancient nature of the Haumea family fits in well with the general understanding of the formation of the Kuiper belt. Most successful models of outer solar system formation predict that the primordial Kuiper belt was about 100 times more massive than the Kuiper belt seen today. In the current Kuiper belt, the probability of the collision needed to form the Haumea family is very low, less than 1%. There is a significant increase in collision probability obtained by forming the Haumea family early in the history of the Kuiper belt when the number densities were much higher. The formation of the Haumea family was studied in detail by Levison et al. (2008), who conclude that the most probable origin of the Haumea family is an ancient collision between two scattered-disk objects.

Chapter 3 was published as Ragozzine & Brown (2007) in the *Astronomical Journal* under the title, "Candidate Members and an Age Estimate of the Family of Kuiper Belt Object 2003 EL_{61}."

1.3 Chapter 4: The Satellites of Haumea

The giant impact that formed the collisional family of Haumea (Chapter 3) also presumably formed the two small satellites discovered by Brown et al. (2005) and Brown et al. (2006). These two satellites share the spectral features of Haumea and the other Haumea family members (Barkume et al., 2006; Fraser and Brown, 2009) and it is certainly possible for a single giant impact to produce both satellites and a collisional family, though the Haumea collision has not yet been modeled in detail. Hence, it is likely that the two satellites, named Hi'iaka and Namaka, were formed in a giant collision billions of years ago.

As a result of Kepler's third law (published in 1619), measurements of the orbital period and semi-major axis of a binary system can be combined to yield the total mass. By determining the orbit of the outer brighter satellite Hi'iaka, Brown et al. (2005) found the mass of Haumea to be about 4.2×10^{20} kg or 1/3 the mass of Pluto. These authors also found that the orbit of Hi'iaka had a relatively large semi-major axis ($a \simeq 49000$ km) and a non-zero eccentricity ($e \simeq 0.05$). This orbit is moderately inconsistent with simple tidal models that would predict a smaller separation and a nearly circular orbit for a satellite that tidally evolved outwards after its initial formation near the Roche lobe of Haumea (Brown et al., 2005).

Determining the orbit of the inner fainter satellite, Namaka, was much more difficult. Non-Keplerian perturbations from Hi'iaka and the J_2 of the elongated Haumea (Rabinowitz et al., 2006) are so strong, that it is impossible to fit a reasonable Keplerian model to the observations spanning more than about a month. Over the course of three years and several nights of observation, we eventually asked for and received time on HST to observe the triple system 5 times over the course of 8 days. This was enough to determine a preliminary Keplerian orbit whose parameters could then be used in a fully interacting three-point mass model to determine the orbits of both satellites and the masses of all three bodies. The astrometric data was sufficient to fully characterize the orbits of Hi'iaka and Namaka as well as the masses of Haumea and Hi'iaka, with values given in Chapter 4.

However, the mass of Namaka was only marginally detected and Haumea's J_2 was too degenerate with the mass of Hi'iaka to measure separately.

Even before the full solution was determined, we realized that Namaka's orbit was nearly edge-on, which was confirmed by our solution of the orbital motion. In an analogy to transiting extra-solar planets (Chapter 2), Namaka's orbit currently takes it in front of and behind Haumea as seen from Earth. That is, according to the orbit solution, the Haumea system is currently undergoing mutual events (Fabrycky et al., 2008).

Using the known orbit, the angle between Namaka, Haumea, and the Earth (in the case of occultations) or the Sun (in the case of shadowing) falls well below the $\sim$13 milliarcseconds ($\sim$500 km) of the projected shortest axis of Haumea. Observing multiple mutual events can yield accurate and useful measurements of several system properties as shown by the results of the Pluto-Charon mutual event season (e.g. Binzel & Hubbard, 1997). The depth of an event where Namaka occults Haumea leads to the ratio of albedos and, potentially, a surface albedo map of Haumea, which is known to exhibi,t color variations as a function of rotational phase, indicative of a variegated surface (Lacerda et al., 2008; Lacerda, 2008). Over the course of a single season, Namaka will traverse several chords across Haumea allowing for a highly accurate measurement of Haumea's size, shape, and spin pole direction (e.g., Descamps et al., 2008). The precise timing of mutual events will also serve as extremely accurate astrometry, allowing for an orbital solution much more precise than reported in Chapter 4. Our solution also predicts two satellite-satellite events, one in February 2009 and one in July 2009 — the last such event until the next mutual event season begins around the year 2100.

Our knowledge of the state of the Haumea system will improve significantly with the observation and analysis of these events. See `http://web.gps.caltech.edu/~mbrown/2003EL61/mutual` for up-to-date information on the Haumea mutual events. To date (May 29, 2009), there are no secure detections of any of the Haumea-Namaka mutual events, though some of our observations are highly suggestive. We also applied for and received HST observations of the February 2009 satellite-satellite event. The accurate resolved photometry show significant variability that it still being interpreted.

Although the mutual events are very interesting for the future, the actual orbits themselves show unexpected implications for Haumea's past. Throughout the solar system, all multiple satellite systems with well-known tidally-evolved orbits have very low eccentricities and inclinations. With an eccentricity of 0.25 ± 0.02 and mutual inclination of $13^\circ \pm 1^\circ$, Namaka's orbit is most unusual. The excitation of Namaka's orbit is almost certainly due to the also unique combination of massive interacting satellites and extensive tidal evolution (e.g., Canup et al., 1999). As the satellites tidally evolved outwards, they passed through mean-motion resonances that excited their eccentricity and inclination. For a detailed qualitative description of this model, see Chapter 4. It is interesting to note that the satellites are highly tidally-evolved, implying that they, like the Haumea family, were not formed in recent geologic history.

Chapter 4 was published as Ragozzine & Brown (2009) in the *Astronomical Journal* under the title, "Orbits and Masses of the Satellites of the Dwarf Planet Haumea (2003 EL_{61})".

1.4 Chapter 5: The Changing Orbits of Kuiper Belt Binaries

Haumea is not the only Kuiper belt object with satellites. Dozens of KBOs are known to be binary (Noll et al., 2008b) and it is already clear that these binaries are giving us unique clues into the evolution of the outer solar system (Noll et al., 2008a). For example, Brown et al. (2006) found that the binary fraction of large KBOs is significantly higher than the binary fraction of smaller KBOs and Noll et al. (2008b) recently reported that the binary fraction of non-resonant KBOs with low heliocentric inclinations ($29.3\pm^{7.2}_{6.3}$%) is strikingly different from the binary fraction of high inclination KBOs of similar sizes ($2.9\pm^{6.5}_{2.4}$%).

In light of these recent results, it seems clear that a major goal of the KBO community will be to use the orbital distributions of KBO binaries to constrain theories on the formation of the Kuiper belt. Achieving this goal will require many observational and theoretical studies of KBO binaries.

One major difficulty in connecting the observations to formation theories is that the current orbital properties of KBOs may not represent the initial orbital distribution. Without a clear understanding of the processes that can modify KBO binary orbits, there is no sure way to extrapolate the present-day observational trends backwards in time in order to gain insights into binary formation mechanisms. As a result, we must begin addressing mechanisms that can modify KBO binary orbits since their initial epoch of formation.

Two mechanisms that may modify the orbits of KBO binaries on geologic timescales are perturbations from the Sun and tidal evolution (Greenberg & Barnes, 2008; Perets & Naoz, 2008). In Chapter 5, we study these non-Keplerian effects using a model developed specifically for KBO binaries. Since this is one of the first major attempts to calculate the orbital and tidal evolution of KBO binaries, the techniques of Chapter 5 are not applied to specific binary systems; instead, general results are sought.

We find that perturbations from the Sun (in the form of Kozai oscillations and Cassini states) combined with tidal evolution at high eccentricities can significantly modify the semi-major axes, eccentricities, inclinations, spin rates, and obliquities of KBO binaries. In particular, orbital and tidal evolution can change binary properties from those indicative of formation by gravitational capture (Goldreich et al., 2002) to those indicative of formation by giant impact (Canup, 2005). The Orcus-Vanth binary is used as a test case to show that solar perturbations and tidal evolution complicate the interpretation of binary orbital properties.

Though potentially adverse to the goal of inferring the original orbital distribution of KBO binaries, these effects do leave unique observational signatures, which are also discussed in Chapter

5. Future theoretical and observational studies will clarify the importance of these effects.

Though dynamics is arguably the oldest branch of planetary physics, there is still theoretical and observational progress being made over 400 years after its birth. This thesis represents my minor contribution to planetary science in a study of the orbital dynamics of Kuiper belt object satellites, a Kuiper belt family, and extra-solar planet interiors.

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