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A Fairy Tale About the Formation of Uranus and Neptune and the Lunar Late Heavy Bombardment

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Abstract. It has recently been shown that the standard model for the formation of Uranus and Neptune cannot construct these planets at their current locations. Here we build on a recent model in which Uranus and Neptune form between Jupiter and Saturn. In our new 'fairy tale', the dynamical upheaval that transported the ice giants to their current locations triggered the lunar late heavy bombardment. This scenario also provides a natural explanation for the compositional differences between the ice giants and the gas giants.

1. Introduction

The giant planets in our solar system fall into two distinct classes. Jupiter and Saturn are mainly made of nebular gas (hydrogen and helium) that was directly accreted in the gaseous state. Uranus and Neptune, on the other hand, mainly have the same composition as comets, with only a small amount of nebular gas mixed in. Thus, Uranus and Neptune probably formed from icy solid material (i.e. comets) in a way that was similar to how the terrestrial planets formed. Surprisingly, as we describe in more detail below, it has recently been shown that the standard model for the formation of Uranus and Neptune does not work (Levison & Stewart 2001; Thommes, Duncan, & Levison 2002a, hereafter TDL02). This realization has led to searches for alternatives to the standard model and we present one here. Our model is quite heretical and contains elements that are probably wrong in detail. However, large portions of it may be correct and it illustrates the lengths to which we must go in order to understand the formation of these planets.

Before we describe our new model, we present a brief review of the standard model and why it does not work in the Uranus-Neptune zone. This model, which is based on the model for terrestrial planet formation, envisions three major phases of terrestrial planet formation (eg. Greenberg et al. 1978; Wetherill & Stewart 1993; Lissauer & Stewart 1993; Weidenschilling & Cuzzi 1993). First, within the solar nebula, $1 - 10\,\mathrm{km}$ refractory planetesimals formed from the condensed material in the disk. As the planetesimal population developed, the second stage began and planetary embryos formed via the accretion of these planetesimals in a process known as *runaway growth.* An object of mass M grows at a rate of

$$\dot{M} \;\propto\; \sigma \;\propto\; R^2 \left[1 + \left(\frac{v_{esc}}{v_{rel}}\right)^2\right], \tag{1}$$

where σ is the gravitational cross section of the object, R is its physical radius, v_{esc} is its escape velocity, and v_{rel} is the relative velocity between the object and the bodies it is accreting. The term between the brackets is known as the *gravitational focusing factor* or F_g. During runaway growth the largest embryos contain only a small portion of the mass of the system and thus they do not effect v_{rel}. Thus, the fact that $v_{esc}^2 = 8/3\ \pi\ \rho\ R^2$ implies that $\dot{M} \propto R^4 \propto M^{4/3}$ when $v_{esc} \gg v_{rel}$. An exponent greater than one implies that if two objects were nearly the same mass, the larger of the two would grow faster than its slightly smaller neighbor. So, in each region one object would grow faster than the rest, running away, and thereby dominating its region. See Weidenschilling et al. (1997) for numerical simulations of this process in the terrestrial planet region.

In the standard model, a dominant embryo will eat its smaller neighbors in its so-called *feeding* zone. The size of this zone increases as the mass of its dominant embryo increases, which gives the embryo additional material to accrete. However as the embryo grows, this new material is an increasingly smaller fraction of the total mass of the embryo. Thus, there comes a point where the embryo has grown as much as it can via this process. According to Lissauer (1993), this mass is

$$M_{iso}^2 \approx \frac{\left(8\pi r^2 \Sigma\right)^3}{3^{5/2} M_\odot}, \tag{2}$$

where r is heliocentric distance and Σ is the surface mass density of the particle disk. Assuming a minimum mass solar nebula[1], $M_{iso} \sim 3\,\mathrm{M}_\oplus$ at $20\,\mathrm{AU}$ and $\sim 4\,\mathrm{M}_\oplus$ at $30\,\mathrm{AU}$.

At the end of runaway growth the embryos start to gravitationally perturb one another and excite their eccentricities, e (Kokubo & Ida 1998). These eccentricities increase until their trajectories began to cross. At this time, according to the standard picture, collisions between the planetary embryos began to occur, allowing larger objects to form. This process, which is known as the *late*

[1] The *minimum mass solar nebula* is the disk that we would get if we spread the mass of each of the planets into an annulus and brought the abundance of each annulus to solar composition. Thus, it is the nebula that would be required if the planets formed at their current locations and planet formation was 100% efficient.

stage, continues until all of the available planetesimals in each region are either accreted into larger objects, or dynamically removed. As a corollary, the resulting configuration of planetary embryos that was achieved from this accumulation epoch must have reached a dynamically stable configuration. This final process has been shown to produce reasonable results for the terrestrial planets in our Solar System (e.g. Wetherill 1990, Agnor et al. 1999, Chambers 2001).

The standard model fails in the region outside of Saturn for two reasons. First, as described above, runaway growth only functions if the largest embryos do not affect v_{rel}, i.e. if the embryos are small enough and rare enough that they cannot stir the surrounding planetesimal swarm. When the embryos start to effect v_{rel}, runaway growth breaks down and the accretion rate of the system significantly decreases. This transition between runaway and late-stage growth, which has been come to be called *oligarchic growth*, has only recently been discovered and applied to the Solar System's terrestrial zone (Ida & Makino 1993, Kokubo & Ida 1998, 2000). TDL02 created an oligarchic growth model for the Uranus-Neptune zone and found that the growth rates are so small that the largest objects that grows at 30 AU in the age of the Solar System are significantly smaller than an Earth mass (this will be discussed in more detail in §3.1). These objects are much smaller than Uranus and Neptune, and too small even to allow the late-stage of planet formation to commence.

Even if, however, oligarchic growth could proceed fast enough for large embryos to form, the late-stage of planet formation also fails for the Uranus-Neptune zone (Levison & Stewart 2001). Because of the low number densities in this region, the embryos must grow fast enough so that F_g remains large even though v_{rel} is increasing. However, Levison & Stewart (2001) showed that this does not happen. In particular, in the Uranus-Neptune zone, the system of embryos dynamically excite one another faster than they will collide. As the system dynamically excites itself, F_g becomes small and collisions become rare. Indeed, the system becomes dynamically excited enough that the embryos are fed to Saturn and ejected from the Solar System. Thus, very little growth occurs.

The work of TDL02 and Levison & Stewart (2001) shows that it is unlikely that Uranus and Neptune could have formed at their current locations in the Solar System via the standard model. Thus, it is time to look for alternative models. Although a few have been suggested (for example, see Boss, Wetherill, & Haghighipour 2002), here we put forth an alternative to the standard model involving Thommes et al. (1999)'s idea that Uranus and Neptune formed between Jupiter and Saturn. An interesting element of this scenario is that it also produces the late heavy bombardment (hereafter LHB) of the Moon 3.9 Gyr ago. This scenario also can explain the significant compositional difference between the ice giants (Uranus and Neptune) and gas giants (Jupiter and Saturn) and some of the puzzling aspects of the orbits in the Kuiper belt.

There are a few caveats that readers should note. First, this is not a complete model. We have taken disparate ideas from different research projects and combined them to tell our story (or perhaps it is better described as a fairy tale). Many of these ideas were not intended to be used for the purposes we have applied them to. Thus, there are many holes in our story that still must be filled. So, rather then weaving a complete tapestry of our story, we are patching together a quilt. Second, there are many variants to this story. Rather then present all possible pathways, we decided that it would be clearer to present the simplest and most straightforward of these.

The structure of this paper is as follows. As we alluded to above, our story is tuned toward explaining the lunar LHB. Thus, in §2, we present a brief review of this topic. In §3 we present our story or fairy tale. Finally in §4 we discuss some of the implications of this idea, concentrating on the dynamical structure of the Kuiper belt.

2. A Brief Review of the Lunar Late Heavy Bombardment

The 'Late Heavy Bombardment' or LHB was a phase in the impact history of the Moon that occurred roughly 4.0 to 3.8 Gyr ago. It was during the LHB that the lunar basins with known dates were formed. It marks the final epoch when the dominant surface geology of the Moon was created by large impacts; afterward, mare volcanism dominated for a while, and the subsequent production of larger craters from the end of the LHB to the present time has been relatively very small. The total mass of impactors that struck the Moon during the LHB is estimated to be roughly 6×10^{21} g (Levison et al. 2001, hereafter LHB01) The LHB was recently reviewed in Hartmann et al. (2000). In addition, there is a brief review in LHB01. We make substantial use of the results of LHB01 in this manuscript and adopt the same constraints as they did.

There is an ongoing debate about whether the LHB was either the tail-end of accretion or a spike in the impact rate occurring roughly 3.9 Gyr ago and lasting $\lesssim$ 100 Myr ('terminal cataclysm,' Tera et al. 1974). Although the debate continues, there are some new results that seem to indicate that the LHB was indeed a spike in the Moon's impact rate. Cohen et al. (2000) argue for a spike on the basis of the dating of a small number of lunar meteorites, which apparently came from a wide variety of locations and thus represent an unbiased sample (unlike the Apollo Moon rocks). In addition, Morbidelli et al. (2001) showed that it seems likely that the debris left over from the formation of the terrestrial planets could not have survived the $\sim$ 700 Myr from Solar System origin until the LHB. Thus, LHB01 assumed the LHB was a spike and, following Wetherill (1975), associated it with the formation of Uranus and Neptune.

In particular, using numerical simulations of the dynamical evolution of the planets and small objects in the outer solar system, LHB01 investigated the hypothesis that the LHB was triggered by the formation of Uranus and Neptune. They assumed that Uranus and Neptune formed at their current locations at the time of the LHB. As Uranus and Neptune formed, they scattered neighboring icy planetesimals throughout the Solar System. Some of these objects hit the Moon. LHB01's numerical experiments on the behavior of Uranus-Neptune planetesimals show very good agreement with current constraints on the LHB. Their integrations showed that the Moon would have accreted about 6×10^{21} g, if they assumed that the Uranus-Neptune region initially contained 5 times the current mass of these planets in the form of small solid objects. The influx of Uranus-Neptune planetesimals onto the Moon could have lasted for a time as short as 10 or 20 million years. See LHB01 for a more complete discussion of these models.

Despite the success of LHB01's models, there was one major drawback — LHB01 did not explain in these models where Uranus and Neptune came from. They simply assumed that fully formed Uranus and Neptune suddenly appeared in the trans-saturnian region some 700 million years after the formation of the Earth. In this paper we correct this problem. In particular, our fairy tale includes a phase in which the nearly formed ice giants do indeed start penetrating a trans-saturnian disk at the time of the LHB, thereby triggering an influx of impactors to the Moon.

3. The Fairy Tale

In this section, we present our fairy tale of the origin of the ice giant planets, which includes a source for the LHB on the Moon. This fairy tale has 4 phases. For emphasis we repeat that we make use of several disparate ideas that were not intended to be used for this purpose. Indeed, in some cases the fit is not very satisfactory. However, these models are useful in illustrating our ideas. More detailed models will be presented in future papers.

3.1. Oligarchic growth in the Outer Solar System and the Formation of Giant Planet Cores

Our fairy tale follows the standard model of planet formation until the oligarchic growth phase. For the outer solar system, oligarchic growth has been studied in detail by TDL02. As described above, they found that very little growth occurs beyond $\sim 15\,\mathrm{AU}$ (see Figure 1). So, for the remainder of this section, we will concentrate on the regions between roughly 5 and 10 AU where Jupiter and Saturn are currently found.

Before we proceed, we must briefly discuss how Jupiter and Saturn formed. Most planetary scientists believe (see Wuchterl, Guillot, & Lissauer 2000 for a review, also see Boss 1997 for an alternative view) that Jupiter and Saturn first appeared as $\sim 10 - 15\,\mathrm{M}_\oplus$ giant planet 'cores', which formed as a result of either runaway growth or oligarchic growth. These cores would have formed from the solid material in the Jupiter-Saturn region which consisted of roughly equal parts ice and rock. Thus, these cores are reminiscent of Uranus and Neptune. Indeed, we will argue here, as we did in Thommes et al. (1999), that Uranus and Neptune were members of the same population as the cores of Jupiter and Saturn. After the cores of Jupiter and Saturn formed they accreted the rest of their mass (which consists of mainly hydrogen and helium and constitutes $\gtrsim 90\%$ of their total masses) directly from the solar nebula through a process of hydrodynamic collapse (Pollack et al. 1996).

In order for the final gas accretion phase to occur, the cores of Jupiter and Saturn must become massive enough for hydrodynamic collapse to occur before the solar nebula disperses. This lifetime of the nebula is $\sim 10^7$ years (see Hollenbach, Yorke, & Johnstone 2000 for a review) and so the core must grow on that timescale. The core accretion timescale decreases as the mass of the solar nebula increases. In the oligarchic growth models of TDL02, we find that the solar nebula must have been at least roughly 7 times the minimum mass solar nebula for the core of the giant planets to have formed before the gas

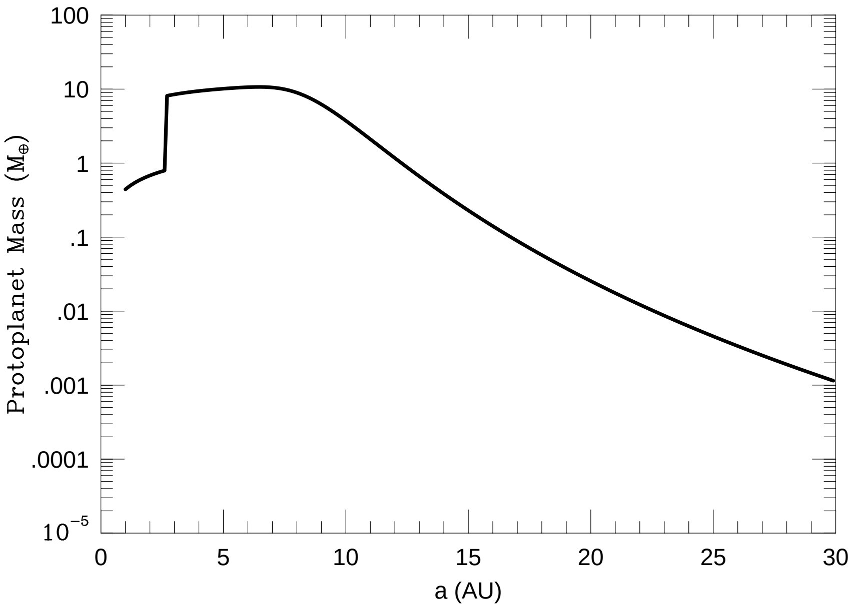

Figure 1. The size of growing protoplanets at 10^7 years as predicted by TDL02's model of oligarchic growth in the outer Solar System. This curve was generated assuming a 7× minimum mass solar nebula.

disappeard. Indeed, Figure 1 shows the size of a growing core at 10^7 years as predicted by TDL02's model for a 7× minimum mass solar nebula.

This value of the mass of the disk is important to our story in two ways. First, recall that in §2 we said that if the LHB came from the Uranus-Neptune region, we would need roughly a 5× minimum mass solar nebula. In addition, a nebula of this mass is consistent with estimates determined by Oort cloud formation models (Dones et al. 2000). So, there are three separate lines of reasoning that lead to roughly the same estimate of the original mass of the solar nebula and our story fits in well with the other estimates.

In addition, it is possible to calculate the number of cores, and their masses, in a region of space and as a function of time once the disk mass is determined. Oligarchic growth predicts that in any given region of the nebula the most massive embryos are all roughly the same mass (although there are statistical deviations of a factor of a few). As the system evolves, the number of embryos decreases as they collide with one another and their masses increase. Given a disk that was 7× the minimum mass solar nebula, TDL02's models predict that there should have been roughly 4 or 5 cores of 10—20 $M_\oplus$ in the Jupiter-Saturn zone at $\sim 10^7$ years, *not* 2 cores. Indeed, according to these models, it is not possible to construct a scenario in which the cores grow fast enough for Jupiter and Saturn to accrete their gas and for only 2 cores to form. There must have been other cores. What happened to them? Following Thommes et al. (1999), in our fairy tale, two of them became Uranus and Neptune.

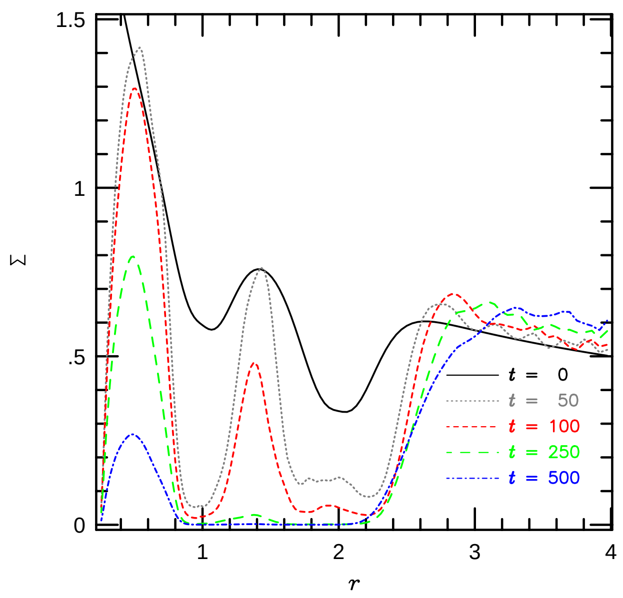

Figure 2. The temporal evolution of the surface density, Σ, of a gas disk, which has two Jupiter-mass planets embedded in it according to the models of Kley (2000). The unit of distance (r) is in terms of Jupiter's semi-major axis and the unit of time (t) is in units of Jupiter's orbital period. In this model, in which two Jupiter-mass planets are located at $r = 1$ and $r = 2$, the gas between the planets is gone in ~ 2500 years.

3.2. Gas Accretion and Evolution

In the simplest version of our fairy tale, the region between roughly 5 and 10 AU contains four 10—15 $M_\oplus$ ice/rock cores embedded in a gas disk. Although oligarchic growth predicts that these cores should all be about the same mass, it also predicts that there should be differences in their masses of the order of a factor of a few. These differences are the result of stochastic events in the growth of the cores. Therefore, the two largest objects could be any of the cores. For simplicity, we assume that the inner and outer cores are the first to cross the boundary in which gas accretion can commence. This occurs when the mass of the cores becomes $\sim 10 - 15\,M_\oplus$. We shall now call the inner and outer cores proto-Jupiter and proto-Saturn, respectively.

The next step in our story has to do with the interaction of the growing gas-giant planets with the surrounding disk. Although the interaction of one planet with the disk has been studied for some time (for example, Papaloizou & Lin 1984), the study of two growing gas-giant planets has only recently been attempted (Kley 2000; Bryden et al. 2000). Both Kley and Bryden et al. numerically studied the interactions between two initially Jupiter-mass planets and a gas disk and found similar results. The basic behavior of this system can be seen in Figure 2 which was reproduced from Kley (2000). Initially disk torques from the planets start to push gas away from the planets' locations, forming the two gaps seen in the figure (the planets are located at $r = 1$ and $r = 2$). This is similar to what has been found in the one-planet case (Papaloizou & Lun 1984; Bryden et al. 1999).

As the individual gaps deepen, the gas between the proto-gas giants leaks away. This process results in a gap in the gas disk that extends from inside the innermost gas-giant to outside the outermost one. This gap forms very quickly, on the order of a few hundred orbital periods of the inner planet (this corresponds to $\sim 1000\,\mathrm{yr}$ for Jupiter). This process is the result of the waves that are generated in the disk by the planets (Bryden at al. 2000). In particular, the inner planet generates waves that propagate through the gas disk between the planets. When these waves hit the inner edge of the outer planet's gap, they force gas into the gap. This gas is then accreted by the outer planet. Likewise, the outer planet generated waves that force inter-planetary gas to the inner planet.

Although Kley's and Bryden et al.'s model did not directly study the Solar System, we believe that it is reasonable to apply their results to it. When we last visited our story, our system contained a growing proto-Jupiter and proto-Saturn with two ice/rock cores between them. Following the models described above, as proto-Jupiter and proto-Saturn accrete their gaseous envelopes, they very quickly clear out the gas between them. Since the cores between proto-Jupiter and proto-Saturn had not yet grown large enough to start to accrete much gas, they are now gas-starved. Even if they continue to grow via the accretion of solid material, there is no nebular gas for them to accrete. This then is a natural explanation for the fundamental compositional differences between the gas giants and ice giants in the Solar System, but it only works if Uranus and Neptune formed between Jupiter and Saturn.

There is one problem with this scenario which we should discuss. (Well, there are probably many problems, but we only discuss this one.) In the hydrodynamic models of Kley and Bryden et al., after the gas between the gas giant planets is gone the planets are pushed together because of the gravitational interaction with the disk. As we will see below, our fairy tale requires that the Jupiter-core-core-Saturn system remain dynamically stable for hundreds of million of years. And yet it seems likely, although this has not been studied, that the system will become unstable as Jupiter and Saturn are pressed together.

We can see three ways to avoid this problem: 1) Jupiter and Saturn could have been formed far enough apart that some migration would not destabilize the core's orbits. 2) As Saturn and Jupiter approach one another they pass through many mutual mean motion resonances. Bryden & Lin (2002) and Kley (2002) have shown that it is possible for these planets to have been trapped in one of these resonances, thereby halting their approach to one another. Indeed, they use this mechanism to explain the resonant structure some of the recently discovered extra-solar planetary systems (e.g. Gliese 876; Marcy et al. 2001). If such a resonant capture did occur, it could have stabilized the Jupiter-core-core-Saturn system. This resonant structure would have been lost in the subsequent dynamical evolution of the system (see below). 3) The gaseous disk beyond Saturn is the main culprit that forces the planets together. So, one way of avoiding our problem is to remove the disk beyond Saturn. Hollenbach et al. (2000) have argued that the disk beyond 10 AU could be destroyed by UV radiation if the Sun formed in an OB association. So, if the Solar System formed in such an environment, there would be no gas disk beyond Saturn and thus the gas giants would not be forced together.

So, at this point in our fairy tale, our system consists of Jupiter and Saturn with two ice/rock cores between them. In addition, there is no gas between Jupiter and Saturn, although there still could be remnants of the disk elsewhere in the system. If so, we assume that the remaining gas dissipates via standard mechanisms (see Hollenbach et al. 2000 for a review).

3.3. The Dynamical Stability of the Jupiter-Core-Core-Saturn System

In our fairy tale, we now have a system that contains Jupiter, Saturn, and two massive cores between them. The next step in our story involves getting the cores (Uranus and Neptune) from between Jupiter and Saturn and delivering them to their current orbits. To do this, we first invoke a dynamical instability which consists of the cores evolving onto orbits that cross the orbits of Jupiter and/or Saturn. In addition, since in the long-run we want to link this instability to the LHB, we want the Jupiter-Core-Core-Saturn to be stable for $\sim 700\,\mathrm{Myr}$ before it goes unstable.

So, just how stable is the Jupiter-Core-Core-Saturn system? It is easy to test this using direct numerical integrations of the orbits of these bodies. Unfortunately, we can only guess at the initial conditions for these simulations because the planets will move around when the system becomes unstable. Even Jupiter and Saturn will move during such an instability (for example see Fernandez & Ip 1981 and Hahn & Malhotra 1999). Given these difficulties, we can only determine if it is reasonable that the system was stable for $\sim 700\,\mathrm{Myr}$. In addition, for the same reasons it only makes sense to perform simple experiments to address this issue. Because, unlike the previous steps of the fairy tale, this step is not published elsewhere, we describe the experiments in some detail.

We performed 16 simulations where Jupiter, the two cores, and Saturn had initial semi-major axes (a) of 5.2, 6.6, 8.3, and 10 AU, respectively. We moved Saturn from its current orbit of $a = 9.6\,\mathrm{AU}$ for two reasons. First, we expect the Saturn will move inward during the instability (Fernandez & Ip 1981 and Hahn & Malhotra 1999). In addition, Saturn and Jupiter are currently near the 5:2 mean motion resonance, which significantly affects their dynamics. We moved Saturn so that the system is further from this resonance because we did not want our stability analysis to be affected by it.

The two cores and Saturn were initially placed on circular, co-planar orbits about the Sun. We varied the initial eccentricity (e) and inclination (i) of Jupiter from run to run. The initial eccentricity of Jupiter was set to a value between 0 and 0.09 and the initial inclination was set to $0.5\,e$. The initial values of the remaining angles of the planets were chosen at random. The method of generating the initial e's and i's of the system is reasonable because the system acts like set of coupled harmonic oscillators and thus Jupiter very quickly distributes its e and i to the other planets. We followed the orbital evolution of this system for up to 10^9 years or until it went unstable using the integrator known as SyMBA (Duncan, Levison, & Lee 1998) which is based, in part, on the Wisdom-Holman mapping (Wisdom & Holman 1991).

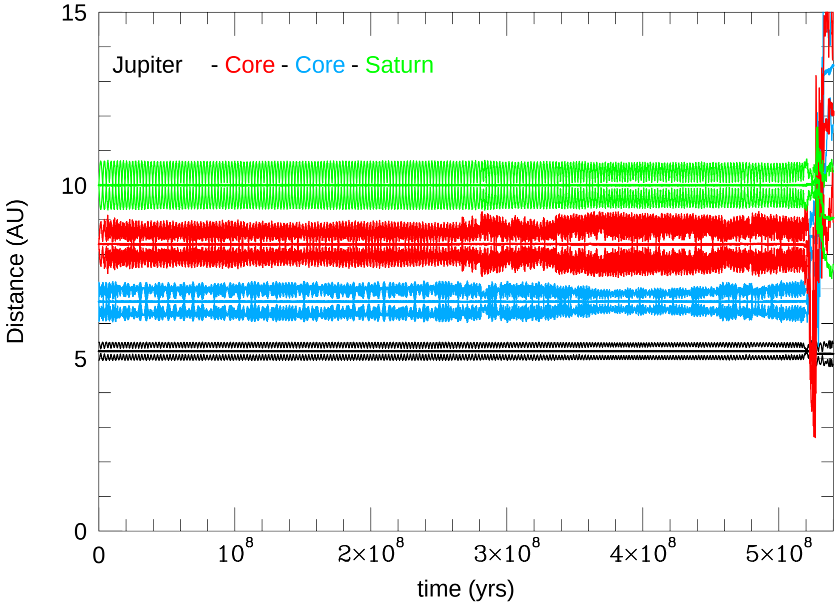

Figure 3. The dynamical evolution of a Jupiter-Core-Core-Saturn system. Each planet is designated by a color, and is represented by three curves. The middle curves follow the semi-major axes of each planet. The bottom curve shows the perihelion distance of each planet while the upper curve shows the aphelion distance. This system remains stable for ~ 520 Myr.

The behavior of a typical system is shown in Figure 3. Each color represents a different planet; the inner curve shows the planet's perihelion distance and the outer curve the aphelion distance. The black and green curves represent Jupiter and Saturn, while the red and blue curves are the two cores. Notice that in this case, the system remains stable for 520 Myr, after which the cores are gravitationally scattered by Jupiter and Saturn.

The dynamical lifetimes of the systems we studied ranged from 143 Myr to longer than the length of the integrations (1000 Myr). Since this spread covers the roughly 700 Myr between the formation of the system and the LHB, we can conclude that it was reasonable that our Jupiter-Core-Core-Saturn system was stable for 700 Myr and then went unstable.

3.4. The System's Dynamical Evolution After the Instability

Finally, we need to address what happens after the Jupiter-Core-Core-Saturn system goes unstable. To answer this question, we turn to the simulations of Thommes et al. (1999, 2002b). In these papers, we directly addressed the issue of the dynamical evolution of a Jupiter-Core-Core-Saturn after it goes unstable. In particular, the physical situation that we studied was slightly different from the one which we are employing here — one in which Jupiter and Saturn were in their *current* orbits and we placed the cores on circular orbits between them. As a result of these differences, the instability occurred immediately in the original simulations. We do not expect, however, that the small differences in the initial

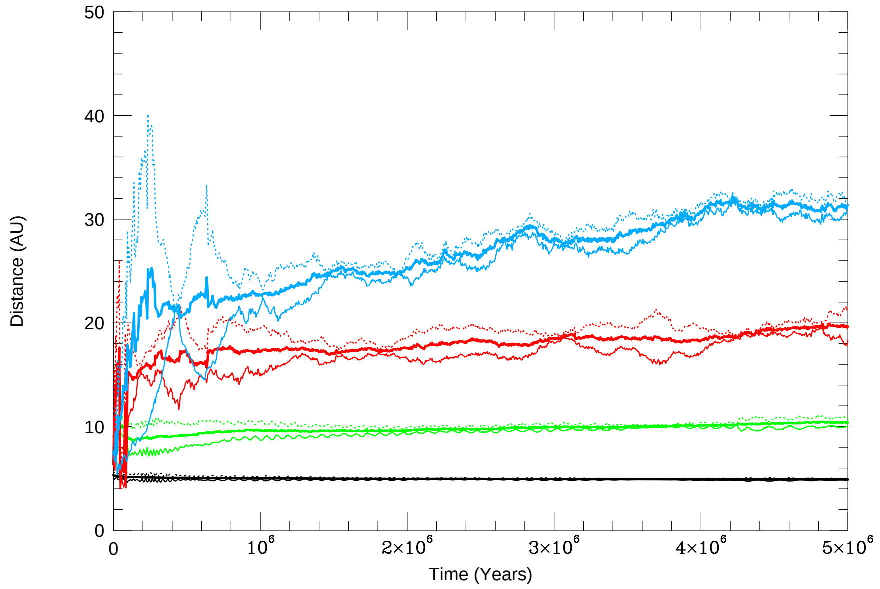

Figure 4. The temporal evolution of one of Thommes et al. (1999)'s simulations of an unstable Jupiter-Core-Core-Saturn system. Depicted are Jupiter (black), Saturn (green), and the two 'failed cores' (red and blue) in the run which, at its endpoint of $5\,Myr$, most closely resembles the present Solar System. Shown are the semi-major axes (thick solid) as well as the instantaneous perihelion (thin solid) and aphelion (dotted) distances of the orbits.

conditions will measurably affect the evolution of the system after the instability occurs. Thus, we can apply the integrations in Thommes et al. (1999) and Thommes et al. (2002b) to our fairy tale.

In addition to Jupiter, the two cores, and Saturn, Thommes et al. placed a massive particle disk beyond the orbit of Saturn. This massive disk, which was consistent with a $4\times$ minimum mass solar nebula, must have been present in the early solar system in order to explain the large objects observed in the Kuiper belt (Stern & Colwell 1997; Kenyon & Luu 1999). However, as described above, we do not expect Uranus- or Neptune-sized objects to form there.

Figure 4 shows the temporal evolution of a run from Thommes et al. (1999) that produced a successful Solar System analog. Depicted are Jupiter (black), Saturn (green), and the two 'failed cores' (red and blue). Shown are the semi-major axes (thick solid) as well as the instantaneous perihelion (thin solid) and aphelion (dotted) distances of the orbits. Just after the instability the cores suffered multiple gravitational scatterings with Jupiter and Saturn. However, when the cores plowed into the trans-Saturnian disk particles, the disk particles were scattered around the solar system (which are not shown in the figure). The cores, on the other hand, felt a drag force due to their gravitational interaction with the disk particles, which acted to circularize their orbits. As a result the cores became decoupled from Jupiter after 9×10^4 years and from Saturn after 2.5×10^5 years. They underwent close encounters with each other

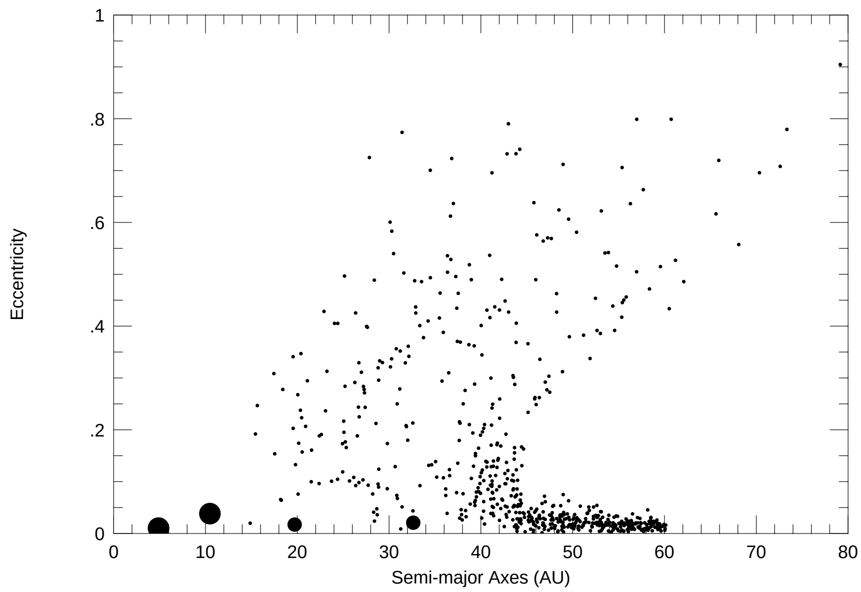

Figure 5. The state of Thommes et al. (1999)'s system shown in Figure 4 at the end of the simulation at 5 million years. The locations of the two large dots represent the semi-major axes and eccentricities of Jupiter and Saturn, respectively. The medium dots are the two cores, and the small dots are the disk particles.

until 8×10^5 years. Eventually, the dynamical drag due to small disk objects decoupled them from each other and damped their eccentricities until they were on nearly circular orbits. After this time, they slowly migrated outward due to the interactions with disk particles. Such a migration has been invoked to explain the structure of the Kuiper belt observed in the real Solar System (Malhotra 1995). An animation of the behavior of this system can be found at `http://www.boulder.swri.edu/~hal/un-scat.html`.

The structure of the system at 5 Myr can be seen in Figure 5. At this time, the inner core has a semi-major axis, a, of $19.7\,AU$, an eccentricity, e, of 0.05, and an inclination of 0.2°. For comparison, Uranus currently has $a = 19.2\,AU$, $e = 0.05$, and $i = 0.8°$. The outer core has $a = 31.1\,AU$, $e = 0.006$, and $i = 0.2°$, while Neptune currently has $a = 30.1\,AU$, $e = 0.01$, and $i = 1.7°$. We believe though that such an amazingly strong correspondence between this model and the real system is largely a coincidence. However, in Thommes et al. (1999, 2002b) we studied dozen of systems and in roughly half the cases we produced a system that looks roughly like our solar system.

Before the instability, the trans-saturnian disk particles are nearly in circular, co-planar orbits. As soon as the cores penetrate this disk, they start to scatter the disk particles around the solar system. Most of these objects either end up in the Oort cloud or are ejected from the solar system entirely. However, some of these objects were scattered into the the inner solar system by Jupiter and struck the Moon and terrestrial planets. In our fairy tale, this is the cause of the LHB on the Moon (as described in §2).

4. Summary and Concluding Remarks

We have presented a new scenario for the formation of Uranus and Neptune that includes an explanation of the LHB on the Moon and terrestrial planets. Although there are many variations to our theme, its most basic form entails the following steps:

- 4 ice/rock giant-planet cores of 10 – 15 $M_\oplus$ grow in the Jupiter-Saturn zone due to oligarchic growth.
- The innermost and outermost cores start to accrete gas and open gaps. These are proto-Jupiter and proto-Saturn.
- Waves generated at resonances in the gas ring between proto-Saturn and proto-Jupiter forces that gas into gaps. The ring between the gas planets is removed. As a result, the cores between the gas giants cannot accrete gas.
- The resulting Jupiter-core-core-Saturn system is stable for 700 Myr and then goes unstable. The cores (Uranus and Neptune) are ejected from between the gas giants.
- Uranus and Neptune get scattered outward. Interactions with the trans-Saturnian particle disk leads them to evolve to their current locations. During this process disk particles are scattered throughout the solar system. Some of these strike the Moon. This event is the Lunar LHB.

Although this fairy tale is heretical, it nicely explains some of the more puzzling aspects of the solar system. For example, the compositional differences between the ice giants and the gas giants are a natural consequence of our story. In addition, it also inherently explains why the deuterium-to-hydrogen ratios (D/H) of the ice giants (Feuchtgruber et al. 1999) are lower than those of the Oort cloud comets Halley (Eberhardt et al. 1995), Hyakutake (Bockelée-Morvan et al. 1998) and Hale-Bopp (Meier et al. 1998) by a factor of approximately three (a difference large compared to the uncertainties of the measurements). In the standard model the ice giants form from the the same population that eventually forms the Oort cloud, so we might expect their D/H ratios to be similar. In our fairy tale, the ice giants and Oort cloud comets form in different regions of the solar nebula and thus there is no reason to believe they should have the same D/H ratio. Finally, the interaction between the cores and the trans-Saturnian disk can explain many of the dynamical features of the Kuiper belt (see Thommes et al. 2002b for more detail).

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