

Solar System Dynamics: Planet V and Lunar Late Heavy Bombardment

Abstract

Using the SWIFT simulator on the Swinburne Supercluster, I conducted a series of experiments to evaluate Chambers and Lissauer's hypothesis that a fifth terrestrial planet, Planet V, was responsible for the 200 Myr period of bombardment that took place in the inner Solar System ~4 Gyr ago—the so-called late heavy bombardment (LHB). The first series of experiments modeled the Solar System with 9 planets and the inner asteroid belt (IAB); the second series modeled the Solar System after the addition of Planet V in order to determine its putative effect on the dynamic stability of the Solar System. The final series determined the effect that Planet V would have had on the orbits of the bodies of the IAB. Since these experiments failed to produce a population of Earth-crossing impactors, they present no supporting evidence for the Chambers-Lissauer hypothesis. I evaluate potential weakness in the simulation design and suggest further avenues of investigation.

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Introduction

Approximately 4 billion years ago, the Moon underwent a series of large-scale impacts that lasted for about 200 million years. These impacts appear to have created some of the larger basins, including Imbrium (1,160 km in diameter) and Orientale (930 km). Based on samples returned by Apollo 15, Imbrium formed about 3.85 billion years ago. Although no direct measurements have been made, Orientale is thought to be slightly younger (Kiefer, 1998).

Several models have been proposed to explain this so-called Late Heavy Bombardment (LHB). In 1975, Wetherill found that the last members of the population of leftover planetesimals could have been responsible for the LHB (Wetherill, 1975). Others, based on the calculations of Evans and Tabachnik (1999), have posited the existence of a band of asteroids between Earth and Mars that could have been a source of LHB impactors (Chambers & Lissauer, 2002). Researchers have also proposed two methods by which the formation of Uranus and Neptune might have perturbed planetesimals into Earth-crossing orbits (Levison et al., 2001) (Levison, Thommes, Duncan, & Dones, 2002).

The idea that a fifth terrestrial planet once orbited between Mars and Jupiter is not new, although it has fallen out of favor since the discovery that the combined mass of all the main belt asteroids is less than the Earth's moon (Bennett, Schneider, Donahue, & Voit, 2000). Chambers and Lissauer's recent hypothesis that a so-called "Planet V" could have been in an unstable orbit that perturbed some inner main belt asteroids into Earth-crossing orbits merits additional investigation.

Leftover Planetesimals

One attractive LHB theory is that the early Solar System contained a number of planetesimals that were "left over" from the formation of the planets. In order to be responsible for the LHB, these leftovers must have been located somewhere in the Solar System that kept them from impacting the planets until the 200 Myr period during which the LHB took place.

In the mid-1970s, researchers found a number of potential "storage places" within the early Solar System (Wetherill, 1975). Among the ways that significant amounts of matter could be preserved for the required time were:

- Mars-crossing orbits
- Earth-crossing orbits
- Orbits entirely within the perihelion of Venus
- Orbits in the vicinity of Uranus and Neptune

Of these four sources, Wetherill (1975) believed that only those planetesimals from the vicinity of Uranus and Neptune could account for both the required storage time and the

observed frequency and distribution of the LHB. Planetesimals in orbits near Uranus would eventually be perturbed into short-period orbits due the influence of Neptune, much the same way that Saturn helps perturb objects orbiting in the region of Jupiter (Everhart, 1973). As a result, these planetesimals would have been responsible for the LHB impacts.

Asteroids between Mars and Earth

The past decade has seen the discovery of several minor planets in stable orbits in the outer Solar System, including those orbiting in the Kuiper belt as well as the Centaur asteroids. In 1999, researchers described results from numerical simulations of zones of orbital stability in the inner Solar System in which they found two possible long-lived belts of asteroids (Evans & Tabachnik, 1999).

The first region lies between the Sun and Mercury. These so-called Vulcanoids should orbit between 0.09-0.21 AU and may survive for the age of the Solar System. The second region of stability is between Earth and Mars (1.08-1.28 AU), where a population of bodies that are on near-circular orbits may survive. The current catalogue of near-Earth objects reveals an abundance of minor planets with low inclinations and eccentricities (Evans & Tabachnik, 1999).

A team of researchers, led by Morbidelli, found that by the end of the main accretional period of the terrestrial planets, a small percent of the initial planetesimal population between 1 and 2 AU would have had highly inclined orbits. They believe that “the final depletion of this leftover population would cause an extended bombardment of all of the terrestrial planets” (Morbidelli, Petit, Gladman, & Chambers, 2001).

Formation of Neptune and Uranus

Another hypothesis is that the LHB was triggered by the formation of Uranus and Neptune. As Uranus and Neptune formed, they scattered neighboring icy planetesimals throughout the Solar System, some of which eventually hit the Moon. Mathematical integrations show that the Moon would have accreted about 6×10^{21} g, assuming that the Uranus-Neptune region initially contained 5 times the current mass of these planets in the form of small solid objects (Levison et al., 2001).

The numerical experiments Levison’s team performed on the behavior of Uranus-Neptune planetesimals show very good agreement with current constraints on the LHB. According to their models, the influx of Uranus-Neptune planetesimals onto the Moon could have lasted for as little as 10 to 20 million years (Levison et al., 2001). This model appears to explain the LHB well, but it requires that fully formed Uranus and Neptune not appear in the trans-Saturnian region until some 700 million years after the formation of the Earth.

Although Levison’s early model ignored the anomalous appearance of Uranus and Neptune in trans-Saturnian space 700 Myr after the formation of the Earth, his team has

recently proposed a new model for the formation these two planets that includes a phase in which “the nearly formed ice giants do indeed start penetrating a trans-Saturnian disk as the time of the LHB, thereby triggering an influx of impactors to the Moon” (Levison et al., 2002).

Planet V

The idea that the Solar System might be “missing” a planet between Mars and Jupiter is hardly new. In the eighteenth century, scientists were trying to find a mathematical formula that accurately described the distances of all the planets from the Sun. One such formula, now called the Titus-Bode Law, described the observed Solar System with uncanny accuracy.

However, there was a major problem with the Titus-Bode Law. No one had observed a planet where it predicted one should be, between the orbits of Mars and Jupiter at 2.8 AU. On the first night of the 19th century, Father Giuseppe Piazzi discovered a small new planet, which he named Ceres. Ceres orbits the Sun at 2.77 AU and was thought to be new proof for the Titus-Bode Law. However, the discovery of other such minor planets at roughly the same orbital distance turned out to be a major problem for the proponents of Titus-Bode (Hoskin, 1999).

It was once believed that what we now refer to as the asteroid belt was composed of the debris of a larger planet that was somehow destroyed in some sort of major catastrophe. Numerous science fiction writers later picked up this theme, and Robert Heinlein even went so far as to name this ruined planet *Lucifer* (Heinlein, 1948). Today, however, it is commonly thought that the gravitational influence of Jupiter itself prevented planet formation between it and Mars.

Two hundred years after Piazzi discovered Ceres, two NASA astronomers, John Chambers and Jack Lissauer, have resurrected the idea that a fifth terrestrial planet may have once orbited between Mars and Jupiter. Unlike Heinlein’s *Lucifer*, their hypothetical Planet V was not the source of the asteroids, but instead might have been responsible for the LHB (Chambers, Lissauer, & Morbidelli, 2001 and Chambers & Lissauer, 2002).¹

According to this hypothesis, Planet V formed in a low-eccentricity orbit just outside the orbit of Mars at approximately 1.9 AU. Computer models detailed in CL02 showed that its orbit would be unstable on a timescale of ~ 600 Myr. Approximately 3.9 Gyr ago, Planet V was perturbed into a highly eccentric orbit that eventually crossed the inner asteroid belt, where it in turn perturbed a large percentage of these minor planets into orbits that temporarily increased the number of Earth-crossing objects and hence the lunar impact rate (Chambers & Lissauer, 2002). In this paper, I examine the CL02 models in detail and describe my attempt to duplicate their results.

¹ Hereafter referred to as CL02.

Procedures and Techniques

In order to account for the late heavy bombardment of the Moon approximately 3.9 Gyr ago, any devised hypothesis must provide a mechanism by which the impactors were stored for 600 Myr. This storage mechanism must be stable over long periods of time, preventing the impactors from entering Earth-crossing orbits. The hypothesis must also include a method by which the stored materials could be placed into impacting orbits. Many models have been proposed to date, including leftover planetesimals, asteroids between Mars and Earth, and byproducts of the formation of Neptune and Uranus.

Chambers and Lissauer have proposed a new model in which the Solar System originally contained a fifth terrestrial planet, which they dubbed Planet V, with an orbit between Mars and the asteroid belt. Initially, Planet V had a stable orbit, but after approximately 600 Myr, perturbations from the other planets drove it onto an unstable orbit that crossed the asteroid belt. These close encounters with Planet V scattered many asteroids into the inner Solar System via resonances, temporarily enhancing the flux of impactors on the Moon until Planet V was itself removed by a resonance (Chambers et al., 2001).

In order to evaluate CL02, I created a number of simulations in an attempt to duplicate their work using a different integration method. A series of experiments were run using the SWIFT simulator on the Swinburne Supercluster computers. These experiments were designed to evaluate the validity of each portion of CL02. After analyzing the results of these experiments I am unable to confirm any portion of Chambers and Lissauer's hypothesis. Planet V remained in a stable orbit over the total integration time period. When explicitly placed into an orbit that entered the inner asteroid belt, Planet V failed to perturb even a single asteroid into an Earth-crossing orbit.

In this section, I detail the simulation software used, along with the series of experiments conducted to evaluate the CL02 results.

The Swift Simulator

In order to evaluate the CL02 models, the SWIFT Solar System simulator code was used. SWIFT is a subroutine package written by Hal Levison and Martin Duncan and is designed to integrate a set of mutually gravitationally interacting bodies together with a group of test particles which experience the gravitational influence of the massive bodies but do not affect each other or the massive bodies (Levison, 2002).

SWIFT was run on the Swinburne Centre for Astrophysics and Supercomputing's "Supercluster" in Melbourne, Australia. The Centre provided a web-based interface that allowed me to submit experiments to the SWIFT simulator remotely. This same web interface was also used to retrieve the results of each experiment and to plot the results in a number of formats and relationships.

Adjusting the Models

Chambers and Lissauer's model included three events that must occur to explain the lunar LHB:

1. Planet V must form in a stable orbit between Mars and Jupiter
2. Its orbit must be perturbed into a highly eccentric one that crosses the inner asteroid belt
3. Its passage through the asteroid belt must perturb a large number of asteroids into Mars- and Earth-crossing orbits.

In CL02, the authors describe a series of 36 N-body integrations that were conducted using a variety of starting conditions and parameters. Two of the most important parameters were their integration step size, which was set to seven days, and total integration time, which was 1 Gyr.

Initial experiments using the SWIFT simulator showed that it would not be possible to duplicate even one of the CL02 1-Gyr experiments. Simulations of a 10-planet Solar System with 1000 massless test particles (TPs) with an integration timestep of seven days and a total integration time of 100,000 years required approximately 30 hours of computer time to complete. Completing even a single 1-Gyr simulation would take approximately 300,000 hours, or about 34 years! Since there were bound to be significant differences between their N-body simulation code and that of the Swift simulator, I planned to make adjustments to my models in order to successfully evaluate theirs, evaluating the validity of each event separately, if necessary.

It quickly became obvious that each of the events listed above must be completed separately, due to computing restraints already mentioned. This led to the development of three experiment series:

1. Modeling the early Solar System
2. Addition of Planet V
3. Introduction of the inner asteroid belt

Each of these series is described below. The output of each experiment will be discussed in detail in the "Results" section.

Series 1: Modeling the Early Solar System

My first goal was to build a mathematical model of the early Solar System and evaluate its behavior and stability over a timescale of ~600 Myr. It was crucial to characterize the behavior of this "base" model in order to correctly evaluate what changes are caused by the introduction of a fifth terrestrial planet.

	<i>e</i>	<i>a</i> (AU)	<i>i</i>	Mass (M_{Jupiter})
Sun				1046.84210526
Mercury	0.20563069	0.38709893	7.00487	0.00017368
Venus	0.00677323	0.72333199	3.39471	0.00256263
Earth	0.01671022	1.00000011	0.00005	0.00314316
Mars	0.09341233	1.52366231	1.85061	0.00033799
Jupiter	0.04839266	5.20336301	1.3053	1.00000000
Saturn	0.0541506	9.53707032	2.48446	0.29894737
Uranus	0.04716771	19.19126393	0.76986	0.04570000
Neptune	0.00858587	30.06896348	1.76917	0.05393158
Pluto	0.24880766	39.48168677	17.14175	0.00000668

Table 1. Planetary and Orbital Parameters of the Solar System. Adapted from <http://seds.lpl.arizona.edu/nineplanets/> & http://ssd.jpl.nasa.gov/elem_planets.html

A series of experiments was conducted utilizing the orbital and planetary parameters listed in Table 1. In addition to the nine planets listed above, 1000 test particles were added, representing the inner asteroid belt. Their orbital parameters were set as follows:

Eccentricity (e) = 0.01-0.2 (range)

Semi-Major Axis (a or SMA) = 1.9-3.3 AU (range)

Inclination (i) = 0.1

Twelve short-duration simulations were run in order to test the simulator output and make sure that the simulations were well behaved and returned meaningful results. After the 12 test runs were complete, two 500 Kyr simulations were run, each requiring approximately 30 hours of computer time to complete. CL02 was based on a total integration time of 1 Gyr with an integration timestep of 7 days. Due to hardware limitations and limited time availabilities, I was unable to run any experiments with a total integration time similar to those achieved in CL02. All simulation runs were conducted with an integration timestep of 7 days (0.01965 years), matching CL02.

Series 2: Addition of Planet V

Once the overall stability of the early Solar System model was established, a new series of experiments were run, adding Chambers and Lissauer's Planet V.

Based on the simulations reported in CL02, the following planetary and orbital parameters were used for Planet V:

$e = 0.001$

$a = 1.9 \text{ AU}$

$i = 0.001$

Mass = $0.0017 M_{\text{Jupiter}}$ ($1/2 M_{\text{Mars}}$)

This setup initializes Planet V in a flat circular orbit past Mars and at the inner boundary of the IAB.

Three short-period test runs were conducted to make sure that the model parameters were valid. After the validation runs were complete, two sets of three simulations each were run for a period of 5.0×10^6 and 5.0×10^7 years respectively, each of which took approximately 40 hours to process. These models were able to run for significantly longer times, since the models did not contain any test particles (aside from 2 placed in the Kuiper belt to keep the simulations running). The reduced complexity allowed the calculations to proceed at an accelerated rate.

Series 3: Introduction of the Inner Asteroid Belt

Once Planet V had been added to the Solar System, two sets of three 200 Kyr simulations were run to determine what, if any, effect that it would have on the 1000 TPs that represented the inner asteroid belt (IAB).

In the first set, Planet V's semi-major axis was set to 1.9, 2.1 and 2.3 AU, while the 1000 TPs representing the IAB were placed into flat, circular orbits whose SMA ranged from 1.9 to 3.3 AU. By placing Planet V into orbits at the edge of, just inside of, and in the middle of the IAB, I was able to test the robustness of the CL02 hypothesis, in terms of initial orbital conditions.

In the second set, Planet V's semi-major axis was set to 1.8, 1.85 and 1.9 AU, while the 1000 TPs representing the IAB were placed into flat, circular orbits whose SMA ranged from 2.2 to 2.7 AU. This second series of simulations was optimized so as to closely duplicate the optimal solution presented in CL02.

Results

In this section, I detail the results from the three series of experiments conducted with the SWIFT simulator.

The 9-planet Solar System

Two simulations were run in order to determine the validity of using SWIFT to model the Solar System. The nine traditional planets and 1000 test particles representing the IAB were allowed to run for a total integration time of 5×10^5 years. The results of these simulations are shown here:

```
Run 1:
864 particles out of 1000 still active after 500 Kyr
Planet Information:
#         a         e         i
1         0.3872      0.1891      13.3747
2         0.7236      0.0243       2.0603
3         1.0004      0.0342       2.5392
4         1.5243      0.0533       4.5835
5         5.1988      0.0069       0.6254
6         9.5803      0.0934       3.1190
```

7	19.3612	0.0835	1.1259
8	30.1150	0.0120	1.0514
9	39.5628	0.2551	17.5568

Discarded Test Particles:
136 ==> Too close to Mars

Run 2:
814 particles out of 1000 still active after 500 Kyr

Planet Information:			
#	a	e	i
1	0.3872	0.1565	9.3008
2	0.7236	0.0146	0.9242
3	1.0004	0.0380	2.6736
4	1.5244	0.0388	3.9355
5	5.2007	0.0433	1.1011
6	9.5025	0.0630	2.7517
7	19.0594	0.0658	1.6623
8	30.2707	0.0064	0.8649
9	39.9140	0.2547	16.3846

Discarded Test Particles:
186 ==> Too close to Mars

Comparing the orbital parameters at the end of the simulations to their initialization values shows that these 9-planet Solar Systems are stable over a timescale of 5.0×10^5 years. The loss of 136-186 asteroids from the IAB is most likely indicative of a resonance with Jupiter, and should provide a good baseline for comparing the effects of adding Planet V to the Solar System.

The 10-planet Solar System

In the first set of three simulations, Planet V was placed in a flat, circular orbit at 1.9 AU. Each simulation was run for a total integration time of 5.0×10^6 years. The results were as follows:

Planet Information:			
#	a	e	i
1	0.3873	0.2143	6.4233
2	0.7237	0.0249	2.9916
3	1.0002	0.0501	3.1906
4	1.5832	0.0860	4.8317
5	1.7321	0.0927	1.1572
6	5.1948	0.0302	1.8543
7	9.6612	0.1010	1.2273
8	19.1524	0.0431	2.2846
9	30.2969	0.0387	1.0385
10	39.7030	0.2869	15.4753

Planet Information:			
#	a	e	i
1	0.3872	0.3649	15.8522
2	0.7236	0.0332	4.0709
3	1.0004	0.0327	2.7452
4	1.5432	0.0487	2.5014
5	1.8421	0.2202	15.7906
6	5.1982	0.0231	1.0267
7	9.6060	0.0795	2.9401
8	19.2719	0.1014	0.6788
9	30.2700	0.0202	1.4833
10	39.6488	0.2362	18.7270

Run #3:			
1	0.3873	0.1833	9.1174
2	0.7236	0.0332	1.2058
3	1.0004	0.0353	2.1887
4	1.5243	0.0585	4.5474
5	1.9012	0.0840	10.1650
6	5.2005	0.0468	1.5383
7	9.4848	0.0619	2.2077
8	19.1657	0.0571	0.5304
9	29.9842	0.0156	1.4405
10	39.3759	0.2206	18.0128

Comparing the orbital parameters at the end of the simulations to the initialization shows that the three 10-planet Solar Systems are stable over a timescale of 5.0×10^6 years. None of the planets have wandered significantly, although Planet V has drifted slightly sunward. It is interesting to note however, that its eccentricity and inclination have increased to values similar to Pluto's in #2, and it became highly inclined in #3.

In the second set, the simulation was allowed to run for 5.0×10^7 years. The results were as follows:

Run #1:			
Planet Information:			
#	a	e	i
1	0.5285	0.6560	117.8123
2	1.1466	36949.5850	77.2321
3	0.4256	*****	37.0910
4	3.8747	20372.5694	34.1883
5	2.2294	20877.1853	97.6258
6	8.4498	0.6326	31.2071
7	122.2456	604.0492	153.3726
8	23.3608	1980.3977	64.3961
9	30.5389	0.4603	124.2499
10	95.7815	0.8467	59.6055

Run #2:			
1	157.6838	1144.4916	175.0902
2	1.3154	4783.1053	137.2955
3	231.1560	280.2420	125.7876
4	73.7713	9333.6658	35.2598
5	14.3461	326.9889	89.8366
6	5.0016	0.8538	76.8695
7	8.4482	693.4121	92.0751
8	93.7669	48.6729	91.8296
9	31.0676	0.1214	94.3237
10	40.1876	0.3190	26.3610

Run #3:			
1	0.3873	0.2843	6.9420
2	0.7236	0.0511	0.4332
3	1.0004	0.0160	2.1463
4	1.5247	0.0640	3.2944
5	1.8996	0.0939	11.6697
6	5.1995	0.0446	0.7550
7	9.5384	0.0626	3.0735
8	19.2316	0.0630	0.5247
9	29.9786	0.0198	1.7328
10	39.1562	0.2029	18.9083

It is obvious that the simulated Solar System stability becomes unstable over a timescale of 5.0×10^7 years when using the SWIFT simulator. In #1 & #2, all the planets underwent significant chaotic changes in their orbital parameters.

10-Planets plus the IAB

The first set of three experiments conducted with all ten planets and 1,000 test particles representing the IAB were initially run for 200 Kyr with an integration timestep of 7 days.

```
Run #1: Planet V's initial a=1.9 AU
639 particles out of 1000 still active after 200 Kyr
Planet Information:
#           a           e           i
1           0.3873       0.2390       7.4905
2           0.7236       0.0333       3.6265
3           1.0004       0.0271       1.0123
4           1.5243       0.0961       2.1980
5           1.9008       0.0988       11.1603
6           5.2008       0.0443       0.7676
7           9.5474       0.0526       2.7225
8           19.2117      0.0815       1.3634
9           30.0579      0.0152       2.6181
10          39.0226      0.2574       16.4808
```

```
Discarded Test Particles:
7 ==> Too close to Mars
354 ==> Too close to Planet V
```

```
Run #2: Planet V's initial a=2.1 AU
360 particles out of 1000 still active after 200 Kyr
Planet Information:
#           a           e           i
1           0.3873       0.2019       17.4839
2           0.7236       0.0435       2.8153
3           1.0004       0.0154       0.2811
4           1.5243       0.1020       3.9986
5           2.1009       0.1509       5.2891
6           5.2008       0.0265       0.9582
7           9.5420       0.0823       2.6042
8           19.2193      0.0381       2.2613
9           30.3224      0.0123       2.0105
10          43.4186      0.3534       14.1885
```

```
Discarded Test Particles:
13 ==> Too close to Mars
627 ==> Too close to Planet V
```

```
Run #3: Planet V's initial a=2.3 AU
301 particles out of 1000 still active after 200 Kyr
Planet Information:
#           a           e           i
1           0.3872       0.1869       2.8847
2           0.7236       0.0293       2.1450
3           1.0004       0.0253       2.0938
4           1.5244       0.0890       3.4152
5           2.3012       0.0555       4.0991
6           5.2006       0.0399       0.7701
7           9.4985       0.0714       2.8461
8           19.2458      0.0360       1.0010
9           30.3627      0.0134       2.3841
10          39.5273      0.2605       16.9984
```

```
Discarded Test Particles:
15 ==> Too close to Mars
684 ==> Too close to Planet V
```

This first set of experiments was conducted with parameters designed to test a fairly broad range of orbital parameters for both Planet V and the IAB. A second set of experiments were conducted using parameters taken from CL02 in order to more closely

evaluate their results. The IAB was reduced to a narrow annulus, and Planet V's orbital parameters were constrained as well.

```
Run #1: Planet V's initial a=1.8 AU
512 particles out of 1000 still active after 200 Kyr
Planet Information:
#         a         e         i
1         0.3873      0.2445      4.3150
2         0.7236      0.0310      2.2089
3         1.0004      0.0313      1.1753
4         1.5242      0.0827      3.7763
5         1.8004      0.1066      6.1083
6         5.1995      0.0163      1.3466
7         9.5413      0.0941      1.6857
8        19.2919      0.0359      2.8154
9        29.9302      0.0097      2.7462
10       39.0794      0.2442      17.6755
Discarded Test Particles:
7 ==> Too close to Mars
481 ==> Too close to Planet V
```

```
Run #2: Planet V's initial a=1.85 AU
985 particles out of 1000 still active after 200 Kyr
Planet Information:
#         a         e         i
1         0.3872      0.1830      4.0022
2         0.7236      0.0690      2.4225
3         1.0004      0.0590      1.2008
4         1.5268      0.1020      3.5646
5         1.8432      0.1350      7.6160
6         5.1998      0.0475      1.3134
7         9.6114      0.0608      2.4454
8        19.2350      0.0515      2.1426
9        30.0706      0.0149      0.7139
10       39.4443      0.2572      16.9200
Discarded Test Particles:
2 ==> Too close to Mars
13 ==> Too close to Planet V
```

```
Run #3: Planet V's initial a=1.9 AU
993 particles out of 1000 still active after 200 Kyr
Planet Information:
#         a         e         i
1         0.3873      0.1480      9.7352
2         0.7236      0.0411      2.9499
3         1.0004      0.0286      1.8822
4         1.5243      0.1142      1.3885
5         1.9008      0.0953      17.3112
6         5.2015      0.0446      1.3235
7         9.5756      0.0548      2.4758
8        18.9793      0.0958      0.6610
9        30.4658      0.0289      1.7042
10       36.1667      0.2504      15.4170
Discarded Test Particles:
2 ==> Too close to Mars
5 ==> Too close to Planet V
```

Both sets of simulations showed that a 10-planet Solar System with an IAB would be fairly stable over a time period of 2×10^5 years. It is interesting to note that the IAB-planet interactions are much lower in the second set.

Analysis: SWIFT vs. Chambers-Lissauer

In this section, I analyze the results presented above and discuss whether or not they support the hypothesis offered by CL02. The first comparison that can be made between my results and those of CL02 is the stability of Planet V once it had hypothetically formed.

According to CL02, the planets remained on non-crossing orbits, but gravitational perturbations gradually increased the eccentricity of Planet V until its orbit crossed both that of Mars and the IAB at approximately 400 Myr.

The three figures below summarize the results of one series of simulations for comparison with CL02.

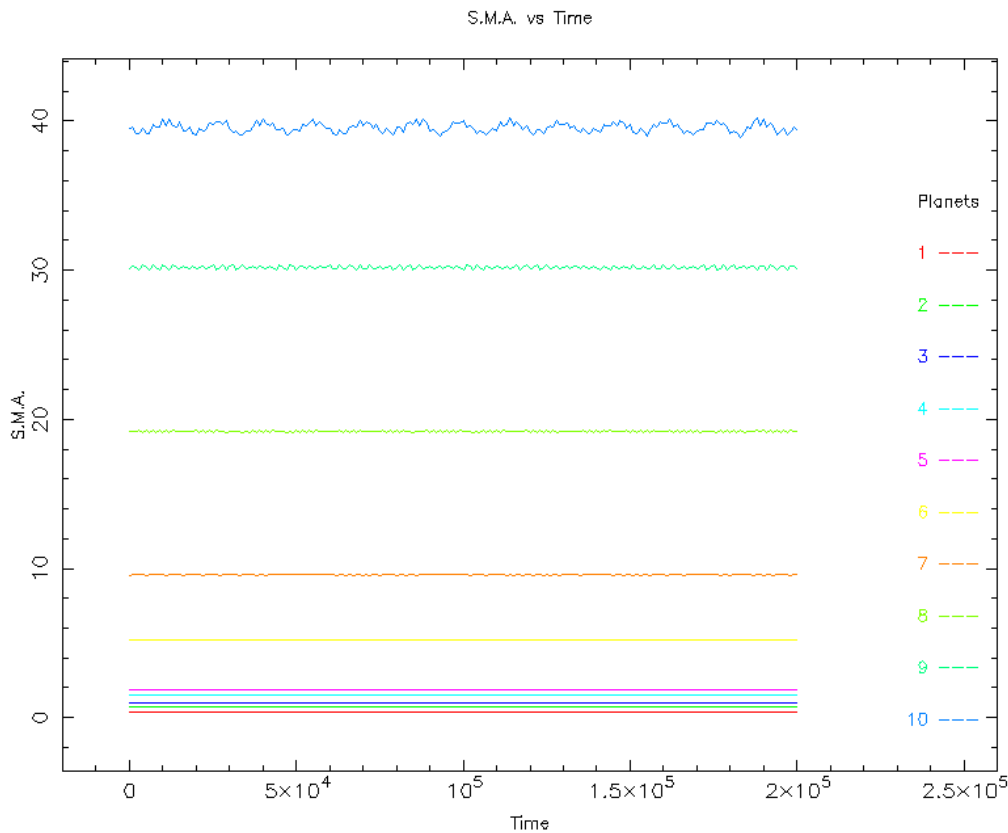


Figure 1. Semi-Major Axis vs. Time for Series 3, Set 2, Run #2

The planets are represented by the numbers and colors along the right side, from Mercury (1) to Pluto (10). The value for Planet V (5) is constant, along with the rest of the inner Solar System, indicating that its orbit is quite stable in the parameter.

As one can see in Figure 1, the semi-major axis (SMA) for the terrestrial planets remained constant. The only noticeable variations are in the outer planets, which are both minor and cyclical. Figure 2 illustrates the changes in eccentricity (e) over the extent of the simulation. One can see that there were significant changes to the eccentricity of both Mars and Planet V during this simulation.

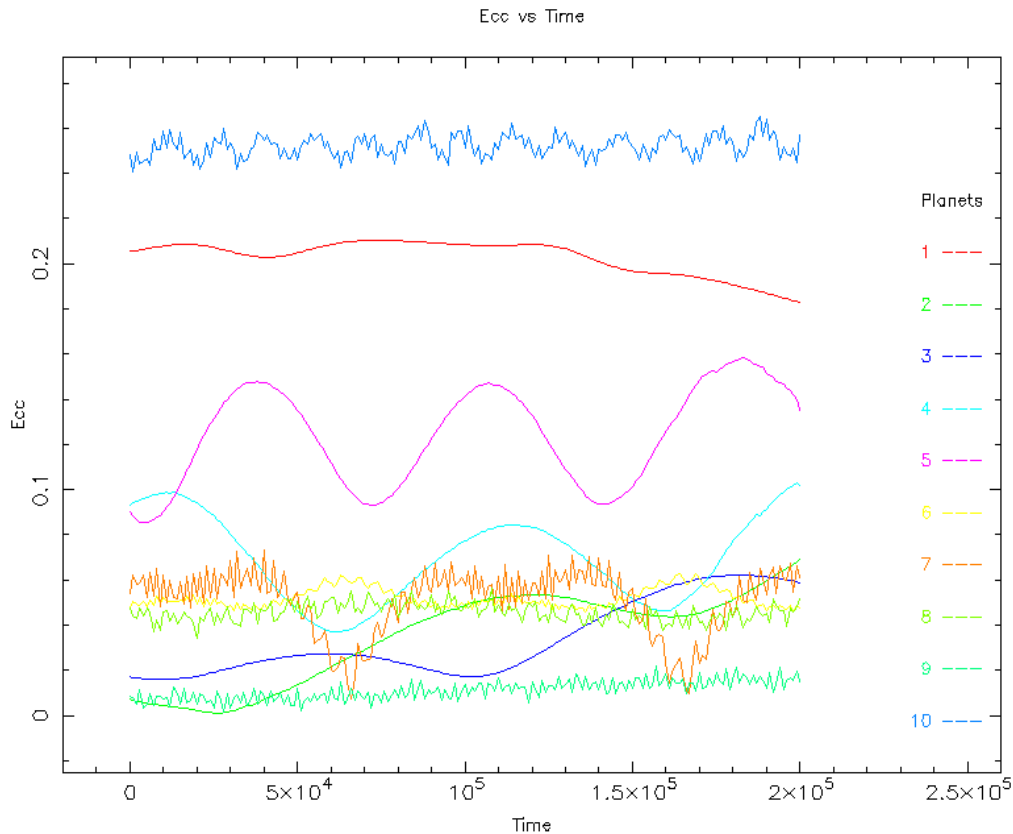


Figure 2. Eccentricity vs. Time for Series 3, Set 2, Run #2

The curves reported for each planet in the Solar System show that eccentricity (e) is changing as the simulation evolves.

Figure 3 shows that the changes in a and e over time resulted in very minor differences in each planet's periastron distance—certainly not enough to result in planet-crossing orbits.

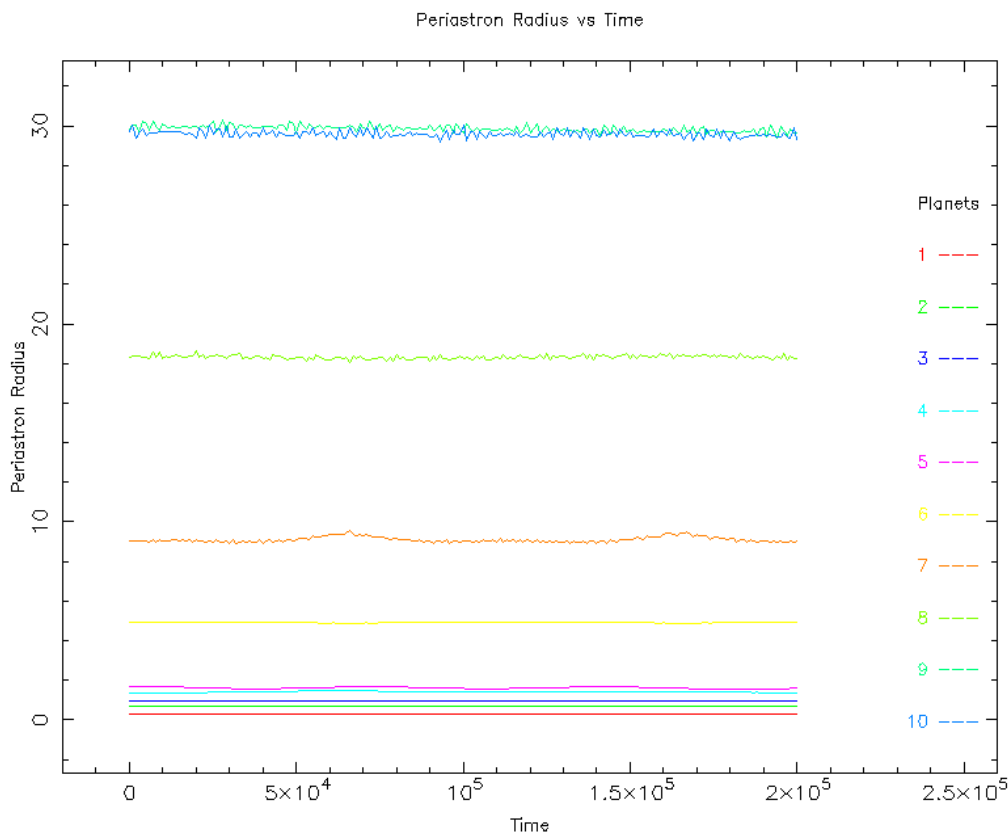


Figure 3. Periastron Radius vs. Time for Series 3, Set 2, Run #2

The periastron radius indicates the minimum distance from the Sun on each orbit. By comparing the periastron of one planet to the orbital elements of another, especially a and e , one can determine if it is on a planet-crossing orbit.

While it is true that these simulations only ran for 200 Kyr, as opposed to the 1 Gyr in CL02, there doesn't seem to be any evidence that the addition of Planet V entered a Mars- or IAB-crossing orbit.

The Fate of Planet V

In CL02, the authors indicated that Planet V's orbit increased in both e and inclination (i) until it entered the ν_6 resonance in the IAB, later falling into the Sun at approximately 600 Myr.

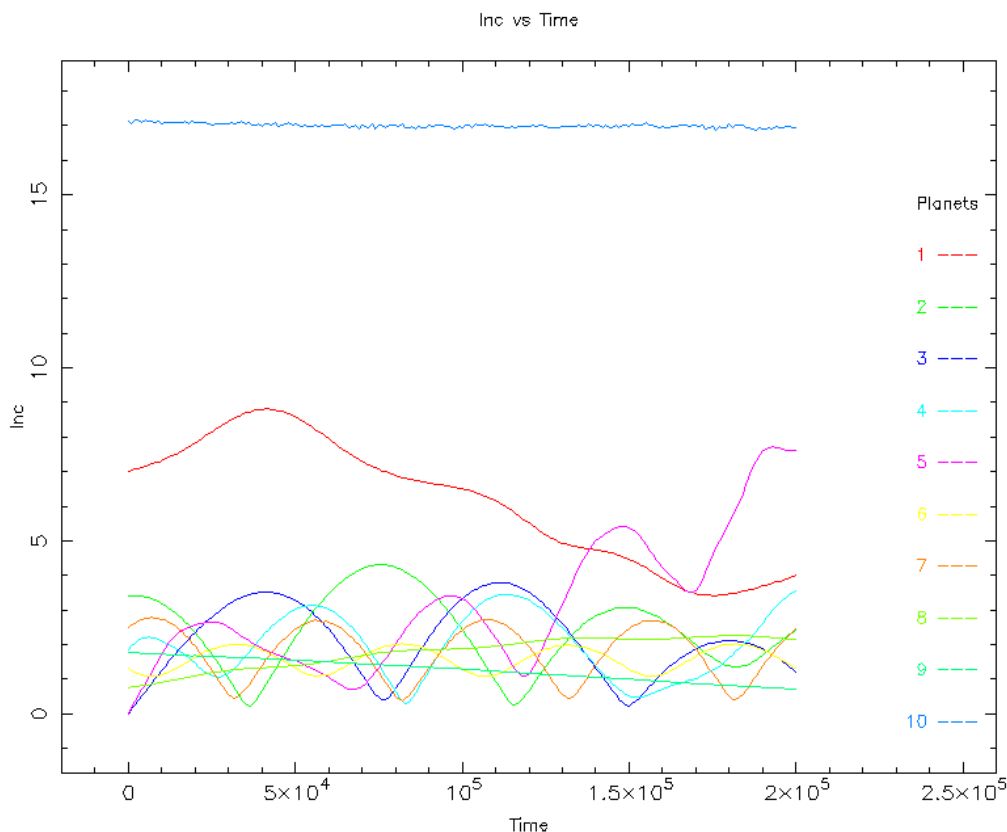


Figure 4. Inclination vs. Time for Series 3, Set 2, Run #2
In this simulation, Planet V (5) undergoes a cyclical and cumulative increase in inclination.

The results in this case are not quite as clear. While the a , e , and periastron results indicated that Planet V's orbit remains fairly stable over the simulation's total integration time, the inclination results shown in Figure 4 show no such stability. Over the 200 Kyr of the simulation, Planet V's inclination undergoes a cyclical but ever-increasing change, going from 0 to approximately 8 degrees.

It may be the case that Planet V would eventually enter the ν_6 resonance and be perturbed into the Sun, but there is no clear evidence of this in my simulations.

IAB Perturbations & Earth-crossing Asteroids

The crux of CL02 is their argument that the changing orbit of Planet V would eventually perturb members of the IAB into the inner solar system, thus increasing the lunar impact rate during the LHB.

Since no confirmation Planet V's stability or ultimate fate could be made from the results of my simulations, it was necessary to place Planet V into the orbits that Chambers and

Lissauer described, with a set to 1.8, 1.85, and 1.8 AU respectively for the three simulation runs detailed below.

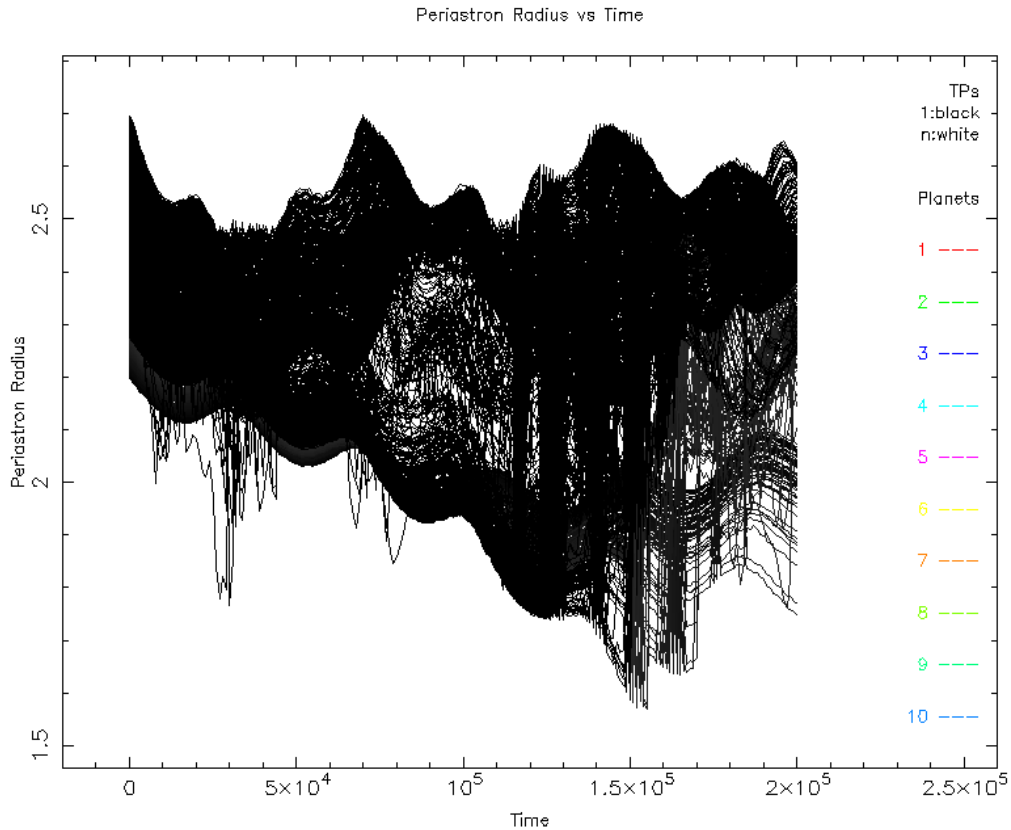


Figure 5. IAB Periastron Radius for Series 3, Set 2, Run #1

This figure illustrates the periastron radii for the population of 1000 IAB bodies. Note that none of these asteroids penetrate closer than 1.5 AU, well outside Earth's orbit.

Figures 5-7 illustrate the changes in periastron radius that the simulated IAB underwent during the three 200 Kyr simulations that were conducted. According to these, none of the asteroids entered Earth-crossing orbits, nor were they perturbed into the inner solar system, since the minimum observed periastron distance was ~ 1.6 AU. Since no asteroids evolved into Earth-crossing orbits, they could not have been responsible for the LHB.

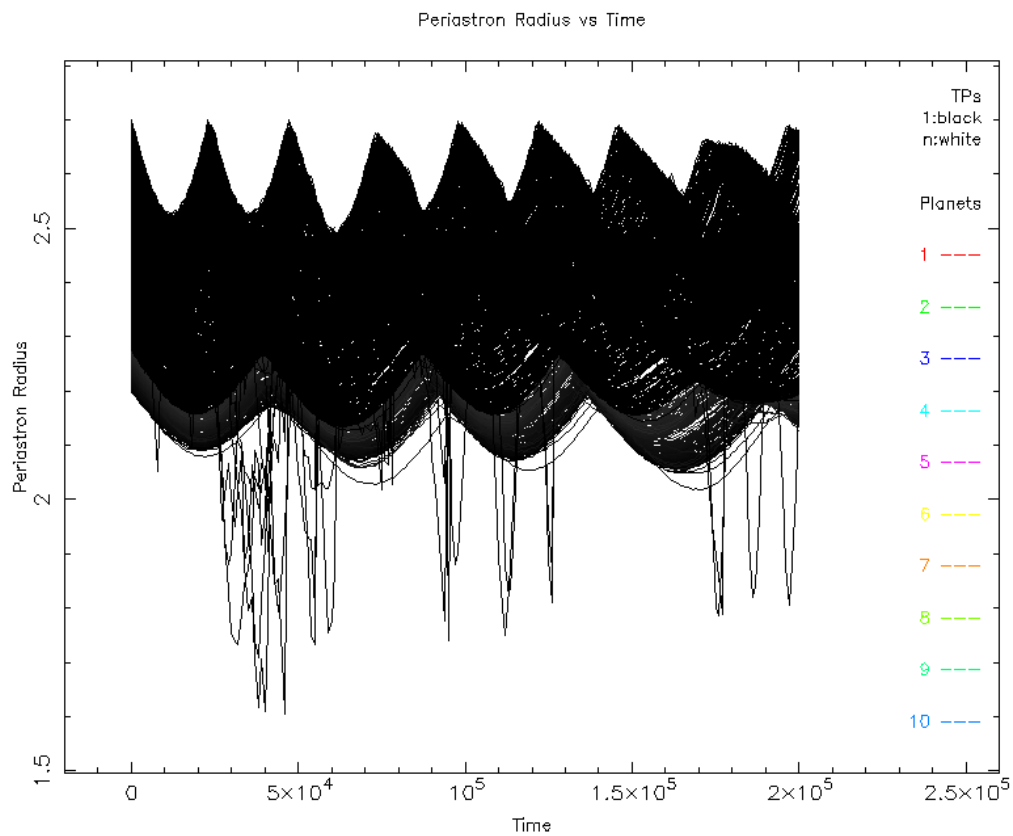


Figure 6. IAB Periastron Radius for Series 3, Set 2, Run #2
 This experiment resulted in only a few asteroids getting closer than 2 AU, which explains why Mars (at 1.52 AU) had such a low encounter rate, as detailed in Table 2.

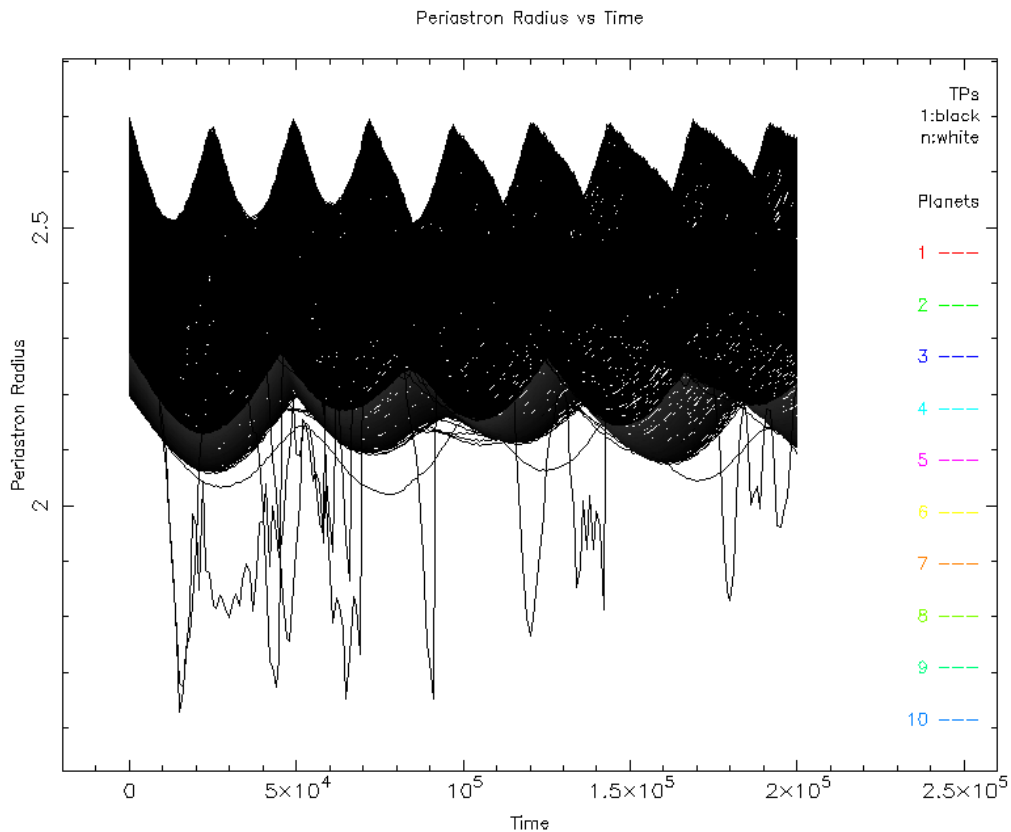


Figure 7. IAB Periastron Radius for Series 3, Set 2, Run #3

This experiment resulted in a low number of Mars encounters as well. Only 15 asteroids came within the Hill radius for Mars.

Table 2 contains a summary of planetary encounters reported by SWIFT for each of the five long-duration simulations that were reported above. Just as we have seen that no asteroids were perturbed into Earth-crossing orbits, the SWIFT simulator confirmed this by explicitly reporting that no asteroids entered Earth's Hill radius of 0.1016 AU.

Simulation	Duration	Planet V	Mars	Earth
9 planets #1	500 Kyr	n/a	136	0
9 planets #2	500 Kyr	n/a	186	0
10 planets #1	200 Kyr	354	7	0
10 planets #2	200 Kyr	627	13	0
10 planets #3	200 Kyr	684	15	0

Table 2. Summary of Planetary Encounters by IAB Members

In order to support CL02, the three 10-planet simulations should have resulted in a non-zero Earth impact rate.

Conclusion: Evaluating Chambers-Lissauer

In order to account for the LHB, a hypothesis must provide a mechanism by which the impactors were stored for ~600 Myr as well as a method by which the stored materials could be placed into impacting orbits. Chambers and Lissauer proposed a new model in which the Solar System originally contained a fifth terrestrial planet, Planet V, with an orbit between Mars and the asteroid belt. Initially, Planet V had a stable orbit, but after approximately 600 Myr, perturbation effects drove it onto an unstable orbit that crossed the asteroid belt. Close encounters with Planet V scattered many asteroids into the inner Solar System via resonances, temporarily enhancing the flux of impactors on the Moon until Planet V was itself removed by a resonance (Chambers et al., 2001). In order to evaluate CL02, I created a number of simulations in an attempt to duplicate their work using a different integration method. A series of experiments were run to evaluate the validity of each portion of CL02. After analyzing the results of these experiments I am unable to confirm any portion of Chambers and Lissauer's hypothesis. Planet V remained in a stable orbit over the total integration time period. When explicitly placed into an orbit that entered the inner asteroid belt, Planet V failed to perturb even a single asteroid into an Earth-crossing orbit.

It is entirely possible that my inability to duplicate any portion of CL02 is due to fundamental differences between SWIFT and the hybrid symplectic integrator used by Chambers and Lissauer. Clearly more research is needed before CL02 can either be accepted or rejected as a viable explanation for the lunar LHB.

One such approach would be to reproduce the three series of SWIFT experiments run, allowing each to run for the full 1 Gyr used by CL02. This approach was not available to me, owing to time and resource restrictions. Another would be to set up a series of experiments by which each subsequent set of model parameters were optimized based on the previous set so that the orbits might then "evolve" into those proposed by CL02. Other integrators could also be utilized—SWIFT might not be appropriate for duplicating CL02, but there are other integrators available. The Planet V hypothesis is certainly intriguing and is worth further research.

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