Planetary migration and the Late Heavy Bombardment (better late than never)

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The early history of the Solar System, though still shrouded in mystery, is slowly being pieced together through continuing scientific inquiry. As usual, what at first appeared to be a relatively straightforward physical process, upon deeper analysis has been found to consist of a surprisingly complex sequence of events and processes interacting on a wide range of physical scales. In the last decade, rapid increases in computing power along with the increasing sophistication of dynamic modeling software has been instrumental in revealing processes which act on the largest scales.

1. EVIDENCE FOR THE LHB

The petrology record on the Moon suggests that a cataclysmic spike in the cratering rate occurred ~700 million years after the inner planets formed; this event is known as the Late Heavy Bombardment (LHB). The LHB was discovered in the late 1960s, though it was actually proposed by R. B. Baldwin (1949) before the Apollo dating of lunar rocks conclusively demonstrated it. It is characterized by the impact of around 6×10^{21}g of material onto the moon followed by a precipitous decline in the lunar bombardment rate subsequent to ~3.85 Ga.

The main piece of evidence for a lunar cataclysm comes from the radiometric ages of impact melt rocks collected during the Apollo missions. The majority of these impact melts are believed to have formed during the collision of asteroids or comets tens of kilometers across, forming impact craters hundreds of kilometers in diameter. The Apollo 15, 16, and 17 landing sites were chosen as a result of their proximity to the Imbrium, Nectaris, and Serenitatis basins. Under study on Earth, the ages of impact melts collected at these sites clustered between about 3.8 and 4.1 Ga. This clustering was first noticed by

Tera et al. (1974) who postulated that the ages record an intense bombardment of the Moon. They called it the "lunar cataclysm" and proposed that it represented a dramatic increase in the rate of bombardment of the Moon around 3.9 billion years ago. At the time, the conclusion was considered controversial.

2. MODELS FOR THE LHB

Several models have been proposed to explain the LHB. Though not apparent at first, it is now widely accepted that the population of lunar impactors was in heliocentric rather than geocentric orbit, because Mercury and Mars also show evidence of a primordial heavy bombardment and the relative size distribution of the craters on these planets is similar to that of the Moon. Wetherill (1975) was the first to investigate the possibility that the LHB is simply the tail of the accretion process of the terrestrial planets. The primary objection to this view, however, is that the leftovers of planetary accretion should have a dynamical behavior similar to the Near Earth Asteroids; the latter have a median dynamical lifetime of only 10 Ma, so that the LHB would not have lasted long enough (Gladman et al., 1996, 1997, 2000). In addition, bombardment from continuation of the planetary accretion process should decay monotonically and would therefore require a mechanism to produce the observed spike in the crater record.

Wetherill (1975) suggested that the LHB was a result of the late formation of Uranus and Neptune, which likely were the last planets to accrete and which could have altered the dynamical state of the planetary system more than a half billion years after the formation of the terrestrial planets. Still other models associate the LHB with collisional process in the early asteroid belt. Zappalà et al. (1998) showed that ‘family forming events' (i.e., collisions between large asteroids) near various main-belt mean-motion resonances can produce asteroid showers lasting from 5 to 80 Myr. However, to produce the observed magnitude of cratering, this model requires the disruption of a Ceres-sized asteroid which is highly improbable unless the mass of the belt at 3.9 Ga was still of the order 1M Earth masses (Levison et al. 2001). Conceivably there are other long-term reservoirs, such as the Trojans of various planets, for material that could suddenly be released by collisional or dynamical processes, long after primary accretion was finished in the inner Solar System. Unfortunately, each of these proposals has weaknesses which have precluded general acceptance as the explanation for the LHB.

One constraint on the source of the LHB impactors is that in order to account for the presence of at least 12 lunar basins with diameters greater than 300 km which formed around 3.9 – 3.8 Ga, a large number of ~100 km bodies would have to be stored for half a billion years (Levison et al. 2001). At present there are only about 200 asteroids bigger than 100 km in the entire main asteroid belt. However, the Kuiper Belt and scattered disk beyond Neptune appear to contain thousands of 100 km bodies. This large reservoir of 100 km transneptunian bodies supports the hypothesis that LHB impactors originated in the outer Solar System. However, other evidence seems to suggest impactors consisting of a mixture of transneptunian and asteroidal objects.

In addition, any mechanism for the production of LHB impactors must account for the episodic nature of the LHB, i.e., the sudden increase followed by a sudden decrease in the bombardment rate compared with preceding and following epochs. (The lunar cratering rate appears to have declined to approximately its present rate soon after formation of the late nearside basins.)

3. DYNAMICS OF PLANETARY MIGRATION

Tsiganis, Gomes, Morbidelli, & Levison (2005) proposed a model which could account for a sudden spike of LHB impactors while also naturally reproducing the current orbital parameters of the giant planets, Jupiter's Trojan asteroids, and the Kuiper belt objects. Their model suggested that the LHB was triggered by the rapid migration of the giant planets, which occurred after a long quiescent period. During this burst of migration, the planetesimal disk outside the initial orbits of the planets was destabilized, causing a sudden massive delivery of planetesimals to the inner Solar System. The asteroid belt was also strongly perturbed, with these objects supplying a significant fraction of the LHB impactors.

The consequences of an encounter between two bodies in orbit around the Sun can be computed using the Rutherford two-body scattering formulae. When a planet encounters a much smaller planetesimal, it either accretes the planetesimal or the two bodies scatter off each other, exchanging angular momentum in the process. On the average (averaged over all possible relative orientations), encounters with planetesimals whose z-component of the angular momentum $H = [a(1 - e^2)]^{1/2} \cos i$ is larger than that of the planet, H_p will cause the planet to gain angular momentum and migrate outward while the planetesimal loses angular momentum and is scattered inward. The opposite is true for planetesimals with $H < H_p$. The direction of migration of the planet is therefore determined by the relative populations of planet-crossing planetesimals with $H < H_p$ and $H > H_p$.

The migration for a lone planet embedded in a cloud of planetesimals will be relatively slow since the proportion of interacting planetesimals with $H < H_p$ and $H > H_p$

will be roughly equal*. However, in the case of two planets in close orbits, the inner planet will partially deplete the population of planetesimals with H smaller than the outer planet so that the latter migrates outwards. Similarly, the outer planet partially depletes the population of planetesimals with H larger than the inner planet, so that that planet migrates inwards. This creates a kind of "orbital repulsion". This effect is greater when the two orbits are closer to each other so that there is more overlap of the interacting regions. In addition, migration effects are stronger with a higher density of planetesimals.

*One caveat that should be mentioned are mechanisms such as 'runaway' or 'forced' migration which can cause monotonic or oscillating migration of a lone planet in a massive disk. (Gomes et al. 2004)

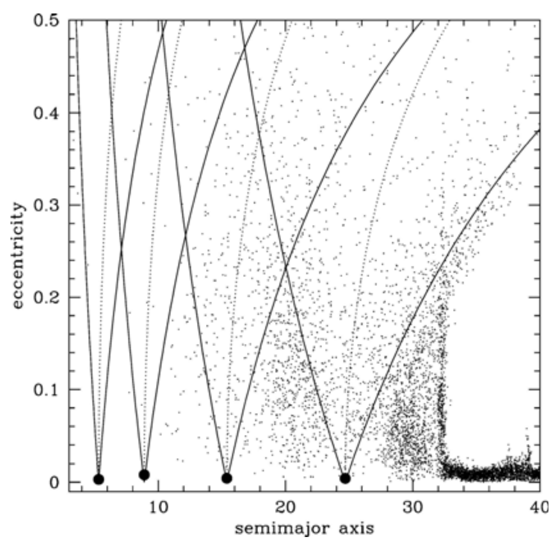

Figure 1

In our Solar System, migration should have had a general trend with Jupiter moving inward and Neptune moving outward. This result was first discovered by Fernandéz and Ip (1984). Figure 1 shows an example of semi-major axis vs. eccentricity distribution of the planets and the planetesimals at one point in time during the migration process. For each planet, the solid curves show the boundaries of the planet-crossing regions for planetesimals and the dotted curves correspond to the condition $H = H_p$ for objects with zero inclination. The overlapping of the Neptune-crossing and Uranus-crossing regions implies a gradual depletion of objects with $H < H_{\text{Neptune}}$ relative to those with $H > H_{\text{Neptune}}$. The consequence of this imbalance induces the outward migration of Neptune. The same reasoning can be applied to the other planets.* (Gomes et al. 2004)

* It should be noted that Jupiter is somewhat of a special case. It is so massive that it rapidly ejects most of the planetesimals that come close to its orbit into interstellar space (or sends a small fraction into the Oort cloud), so that almost all interactions cause it to lose angular momentum and move inwards.

As a planet migrates it encounters new areas of the circumsolar disk which may contain a fresh supply of material with which to interact. Depending on the density, mass, and distribution of the planetesimals it encounters, its migration rate will increase or decrease. As long as the density, etc. of planetesimals is above a critical level, the migration will continue unabated, but if the interactions fall below a critical level, the migration will slow and the planet will interact with less new material which, in turn, causes the migration to slow even further. Eventually the planet will "run out of fuel" and the migration will stop. During the LHB epoch this scenario especially applied to Neptune, which continued to encounter a fresh supply of planetesimals in the outer disk. As a result, the change in its semimajor axis during the LHB was the greatest of the giant planets, almost doubling and sending a massive amount of material into the inner solar system.

But what caused the sudden spike in the rate of migration of the giant planets? Planetesimal-driven migration is probably not important for planet dynamics as long as a gaseous massive solar nebula exists. After the giant planets were formed and the circumsolar gaseous nebula was dissipated, the Solar System was composed of the Sun, the planets and a debris disk of small planetesimals. The planets then started to erode the disk, by either accreting or scattering away the planetesimals. During this epoch, the planets slowly migrated due to the exchange of angular momentum with the disk particles. After the debris disk was depleted, migration continued slowly due to leakage of particles from the outer solar disk. During migration, the eccentricities and mutual inclinations of the planets were damped because of their gravitational interaction with the disk particles, in a process known as dynamical friction. If initially the planets' orbits were sufficiently close to each other, it is likely that they had to pass through low-order mean motion resonances (MMRs), which occur when the ratio between two orbital periods is equal to a ratio of small integers. These resonance crossings would have excited the orbital eccentricities of the resonance crossing planets.

4. JUPITER AND SATURN'S 1:2 MMR AND THE TROJAN ASTEROIDS

Early attempts at modeling the migration of the giant planets assumed that Jupiter and Saturn never reached 1:2 MMR (their strongest resonance). This was based on calculations which showed that should this resonance be crossed, Jupiter's Trojan asteroids would become violently unstable and be ejected from the region. Jupiter and Saturn's 2:1 resonance occurs when the ratio of their orbital periods, P_S/P_J, equals 2. Since the ratio of P_S/P_J is currently slightly less than 2.5 this put severe constraints on the amount of migration which could have occurred while still allowing for the existence of today's jovian Trojans.

Morbidelli et al. (2005) performed migration simulations to determine whether Jupiter's Trojans could survive a Jupiter/Saturn 2:1 resonance crossing. To determine when the Trojans become unstable during the resonance crossing, a migration simulation was performed and P_S/P_J was measured at 40 time steps near the 2:1 MMR crossing. Then for each value of P_S/P_J, the planets were held in non-migrating orbits and 40 simulations were performed using massless test particles placed in the L_4 and L_5 regions under the influence of the Sun, Jupiter and Saturn. The initial distribution of test particles was chosen to mimic the current distribution of Trojans relative to Jupiter. For each simulation, the fraction of test particles that remained in the Trojan region after 2×10^5 years was represented by a single point (shown in the lower plot of Figure 2).

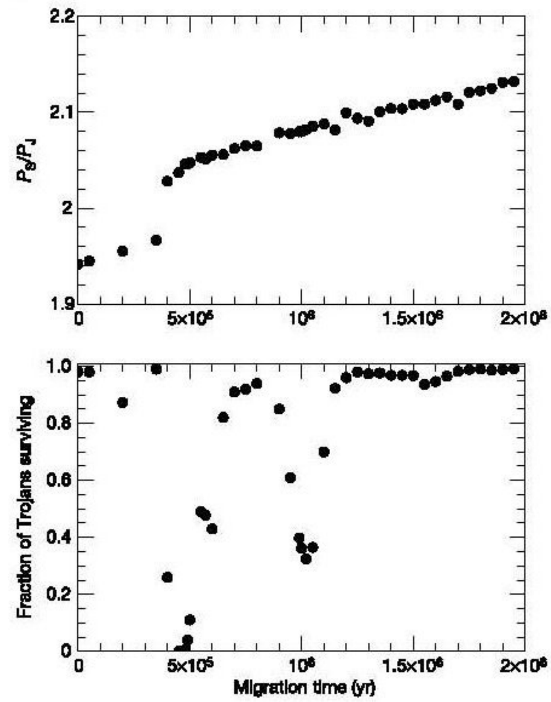

Figure 2

In this simulation, there were two critical planetary configurations that caused a depletion of the Trojans. One occurs just after 2:1 resonance is reached at $P_S/P_J \approx 2.05$

($t = 4.5 \times 10^5$ yr in Figure 2), at which point all resident Trojans escape. This instability is due to a secondary 3:1 resonance between ($1/P_J$ - $2/P_S$) and the oscillation frequency of the Trojans around the Lagrange point. The other critical configuration occurs when $P_S/P_J \approx 2.08$ ($t = 10^6$ yr), which corresponds to a secondary 2:1 resonance between the same two frequencies, and depletes 70% of the Trojans.

The net result was that even with simulations using 1.3 million particles in the Trojan region, none survived the 2:1 MMR crossing. This might appear to eliminate the possibility of Jupiter and Saturn having ever crossed 2:1 MMR since there is clearly a large population of Trojans observed today. However, the dynamical evolution of a gravitating system of objects is time-reversible. Therefore, if objects can escape the Trojan region when it becomes unstable, other bodies can enter the same region and become temporarily trapped. Consequently, a transient Trojan population can be created as long as there is an external source of objects. In this case, the source is constituted by the very bodies that are forcing the planets to migrate, and is of considerable magnitude given how much the planets must move. When Jupiter and Saturn get far enough from the 1:2 MMR that the co-orbital region again becomes stable, the population that happens to be there at that time remains trapped and becomes the population of permanent jovian Trojans still observed today.

Jupiter's Trojans have been hypothesized to be planetesimals that formed near Jupiter and were captured onto their current orbits while Jupiter was growing, possibly with the help of gas drag and/or collisions. This idea, however, has not been able to explain the broad orbital inclination distribution, which ranges up to 40°. When the orbital distribution (inclination, eccentricity, and libration amplitude) of the trapped

Trojans from the Morbidelli simulation are compared to the distribution observed today, the match is quite good.

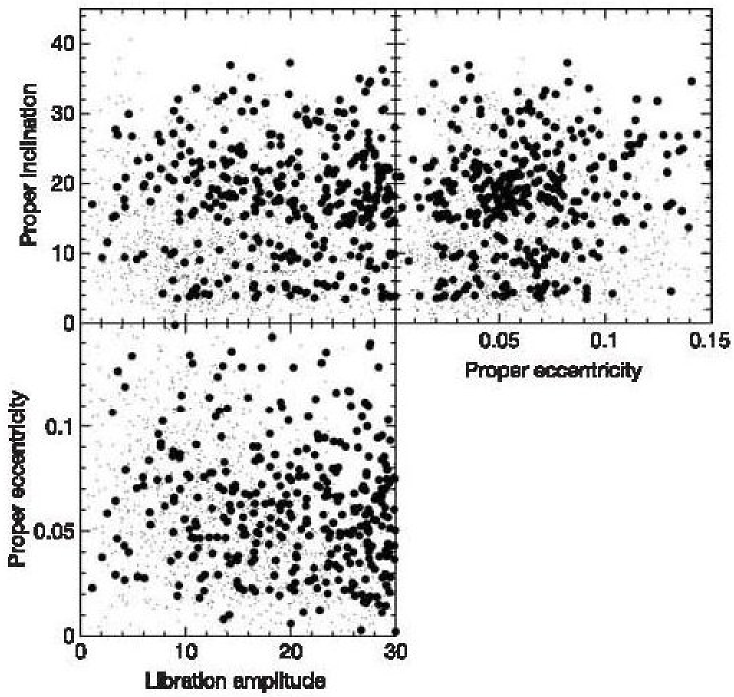

Figure 3

Figure 3 shows a comparison between the model and observations for the orbital distribution of Jupiter's Trojans. The simulation results are shown as filled circles and the observations as dots. (Libration amplitude and proper inclination are measured in degrees.) The distribution of the simulated Trojans is somewhat skewed towards large libration amplitudes relative to the observed population. However, a fraction of the planetesimals with the largest amplitudes would leave the Trojan region during the subsequent 4 Gyr of evolution, leading to a better match. The similarity between the two inclination distributions is strong support for the model. In addition, the mass of the trapped Trojan population is quite consistent with the real population, when scaled to the mass required to move the planets the required distance.

5. MIGRATION THROUGH THE JUPITER:SATURN 1:2 MMR

If it can be assumed that during their migration process, Jupiter and Saturn passed through their 2:1 MMR, a radically different picture of early Solar System history immerges. Tsiganis et al. (2005) performed simulations assuming a massive ($30-50M_E$, where M_E is the mass of the Earth) particle disk, consisting of 1,000–5,000 equal-mass bodies. The disk started just beyond the initial orbits of the planets, ended between 30 and 35 AU, and had a surface density that fell linearly with heliocentric distance. The initial semimajor axis of Jupiter was set to $a_J = 5.45$ AU and Saturn was placed a few tenths of an AU interior to the 1:2 MMR ($a_{1:2} \approx 8.65$ AU). The initial semimajor axes of the ice giants (Uranus and Neptune) were varied in the ranges $11-13$ AU and $13.5-17$ AU, while keeping their initial orbital separation larger than 2 AU. In all cases, the initial orbits of all the giant planets were nearly circular and coplanar (eccentricities, e, and mutual inclinations, i, $\sim 10^{-3}$). Both dynamically 'cold' ($e \approx \sin i \approx 10^{-3}$) and dynamically 'hot' ($e \approx \sin i \approx 0.05$) disks were considered. In all, 43 different configurations were simulated using two different N-body codes, SyMBA and MERCURY, with a time step of $0.25-0.5$ years. In these experiments the self-gravity of the disk was ignored. A typical result of these simulations is shown in Figure 4. The separation between the upper and lower curves for each planet is indicative of the eccentricity of the orbit. The maximum eccentricity over the last 2 Myr is noted to the right of the plot of each orbit.

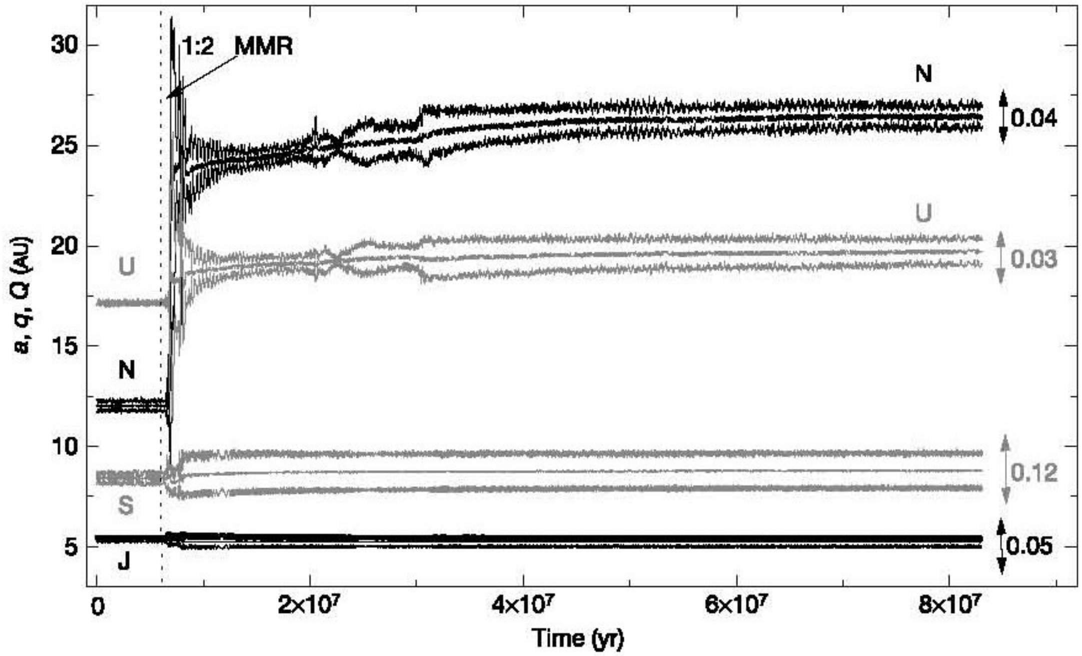

Figure 4

In this simulation, after a period of slow migration on nearly circular orbits, Jupiter and Saturn cross the 1:2 MMR (vertical dotted line), at which point their eccentricities are quickly excited to values comparable to the ones currently observed. These 'kicks' in eccentricity are the result of the planets jumping over the 1:2 MMR without being trapped. The sudden jump in the eccentricities of Jupiter and Saturn has a drastic effect on the planetary system as a whole. The secular perturbations that Jupiter and Saturn exert on Uranus and Neptune force the eccentricities of the ice giants to increase. As a result, the planetary orbits become chaotic and intersect. When this occurs, a short phase of planetary encounters between Saturn, Uranus, and Neptune follows, increasing the inclinations of the orbits by 1°– 7°. During this phase, the eccentricities of Uranus and Neptune can exceed 0.5. Only two cases were found in which no encounters between planets occurred. In 50% of the simulations the two ice giants exchange orbits.

As the ice giants are scattered outward and penetrate the outer disk, a large flux of planetesimals are scattered towards Saturn and Jupiter, hence their rate of migration also increases abruptly. During this fast migration phase, the eccentricities and inclinations of the planets slowly decrease by dynamical friction and the planetary system is stabilized. The planets stop migrating when the disk is almost completely depleted.

Accounting for the observed eccentricities and inclinations of the giant planets has been a problem for theories of planetary formation which suggest that the planets formed on circular and coplanar orbits as a result of gas drag in the early solar nebula which tended to dampen both eccentricities and inclinations of the accreting planetesimals. The observed eccentricities of Jupiter, Saturn and Uranus, however, reach values of 6%, 9% and 8%, respectively. In addition, the inclinations of the orbital planes of Saturn, Uranus and Neptune take maximum values of $2°$ with respect to the mean orbital plane of Jupiter. One of the strong points of the Tsiganis et al. model is that not only the final semimajor axes but also the final eccentricities and inclinations of the giant planets produced in the simulations are close to the observed values as shown in Figure 5. Proper eccentricities and inclinations are defined as the maximum values acquired over a 2-Myr timespan. Inclinations are measured relative to Jupiter's orbital plane. The error bars represent one standard deviation. Values for the real planets are presented with filled black circles. Open grey circles mark the mean values for the runs which produced no encounters for Saturn, while open black circles mark the values for runs where Saturn encountered one or both ice giants. Note that the latter results in a better match of the outer solar system. In these cases, the three orbital elements of all the giant planets have model values that lie within one standard deviation from the actual values.

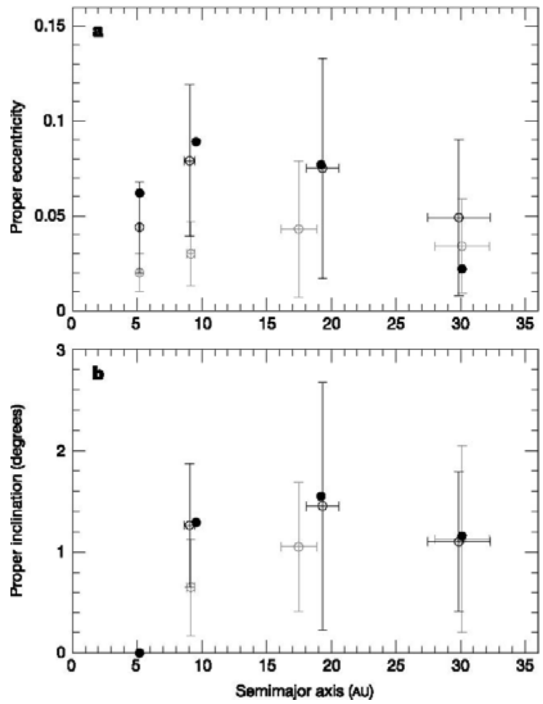

Figure 5

The final semimajor axes of the planets are an important diagnostic of migration models. The final orbital separation of Jupiter and Saturn depends on the amount of mass that they process during the evolution of the system, i.e., on the initial mass of the disk. Although larger disk masses favor the stability of the four-planet system, for disk masses larger than $\sim 35-40M_E$, the final orbital separation of Jupiter and Saturn tends to be larger than is actually observed, and the final eccentricities of the two planets are too small as a result of too much dynamical friction. Disk masses $\sim 35M_E$ seem to produce the closest matches. The initial dynamical state of the disk also affects the final state of the planetary system. 'Hot' disks tend to produce systems where the eccentricities for Jupiter and Saturn are larger than in 'cold' disks. Simulation results tend to support an excited 'hot' disk model.

Survivability of regular satellites of Saturn and the ice giants during encounters of the giant planets was a potential issue with the model. To test the survivability of these moons, eight migration simulations were performed, recording all planetary encounters deeper than one Hill radius (approximately the distance within which the gravity of the planet dominates over the gravity of the Sun). The evolution of the moons were then simulated during each encounter. In half of the simulations, all of the satellite systems survived the entire suite of encounters. Thus, the survivability of the moons was not a problem for the model.

6. THE EFFECTS OF PLANETARY MIGRATION ON THE KUIPER BELT

The Kuiper belt appears to have two major components: a dynamically 'cold' population containing objects on orbits with inclinations i < 4°, and a 'hot' population containing objects whose inclinations can be as large as 30° and possibly larger. (In addition, there is a small population of objects trapped in MMRs with Neptune.) The objects in all three structures have semi-major axes less than 50 AU, at which point the Kuiper belt seems to end abruptly. The Kuiper belt currently contains material totaling less than $0.1M_E$. However, according to accretion models, the objects in the belt would not have grown to their present size unless the Kuiper belt originally contained tens of Earth masses of dynamically 'cold' solids.

Levison and Morbidelli (2003) modeled the effects of Neptune's migration on a primitive dynamically cold Kuiper belt truncated at 30 AU. Truncating the disk at 30 AU provided a natural explanation for why Neptune is where it is – it migrated until it hit the edge of the disk. They suggested that both Kuiper belt populations were formed within ~30 AU. The dynamically hot population was formed by particles which were scattered by Neptune during it's migration and the cold population was formed by particles that became trapped in Neptune’s 1:2 MMR during the migration and were dragged outward along with Neptune. The final cold belt population produced during the numerical simulations consisted of ~1% of the population originally in the massive planetesimal disk, in agreement with the observed small mass of the current population. This offers an explanation of how the Kuiper belt objects were able to accrete in spite of the present low mass of the belt. Originally the belt was much more massive and was located considerably closer to the sun.

A fundamental problem with the model was how the cold population could have been maintained during migration. Standard adiabatic theory predicts that although the inclination of an object trapped in a migrating 2:1 MMR will not be excited, the object’s eccentricity will monotonically increase while the object is pushed outward. Levison and Morbidelli were able to show that many objects trapped in the MMR will have eccentricities that oscillate. Therefore, at any point in time there is always a population of trapped objects with small eccentricity. During the outward migration, some objects will be released from resonance and deposited at various locations corresponding to the present dynamically cold Kuiper belt.

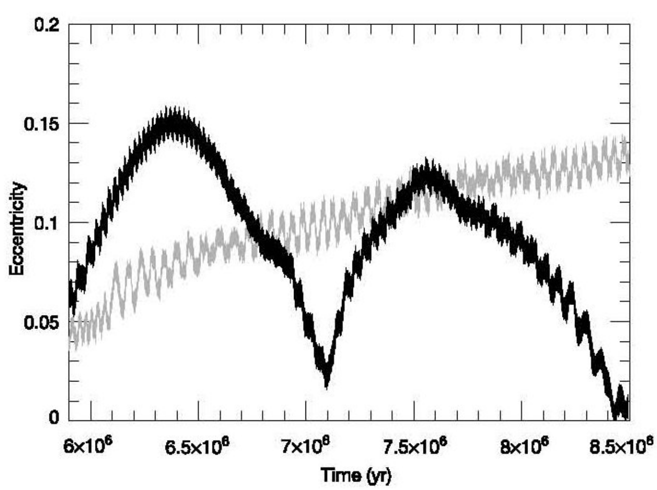

Figure 6

Figure 6 shows the evolution of eccentricity of particles in the 1:2 MMR during Neptune's migration. The grey curve shows the overall monotonic increase in a resonant particle's eccentricity as predicted by adiabatic theory. The black curve shows the actual eccentricity according to the simulation in which large-amplitude secular oscillations temporarily drive the eccentricity down to zero. The difference in the results is due to the simulation using massive particles as opposed to the massless particles assumed in the adiabatic theory.

7. THE EFFECTS OF PLANETARY MIGRATION ON THE ASTEROID BELT

Although dynamic modeling has shown that the migration of Uranus and Neptune would have had little effect on the dynamics of the main-belt asteroids, the migration of Jupiter and Saturn would certainly have had a profound influence on the primordial asteroid belt. During the migration, resonances sweeping through the main belt would have excited the eccentricities and inclinations of a large fraction of main belt asteroids, sending them into Earth crossing orbits or ejecting them from the inner solar system. Today's asteroidal eccentricities and inclinations may be the final product of a process started at the time of planetary migration.

Gomes (1997) using linear theory and numerical simulation analyzed the effects of migration of the giant planets on the primordial main belt asteroids. He showed that although the migration of Jupiter would cause shifts in MMRs, the shifts of secular resonances (ν_6 and ν_{16}) would have a far more profound effect on the orbital parameters of the main belt objects. Secular resonances are more important for two reasons: First, these resonances are usually more effective in pumping up eccentricities and inclinations than MMRs. Second and more importantly, secular resonance position has a much wider variation for a given Δa for Jupiter and Saturn, as compared with the variation of positions of MMRs with Jupiter. Therefore, the sweeping secular resonances would cause perturbations on a much wider range of asteroids than would be caused by MMRs.

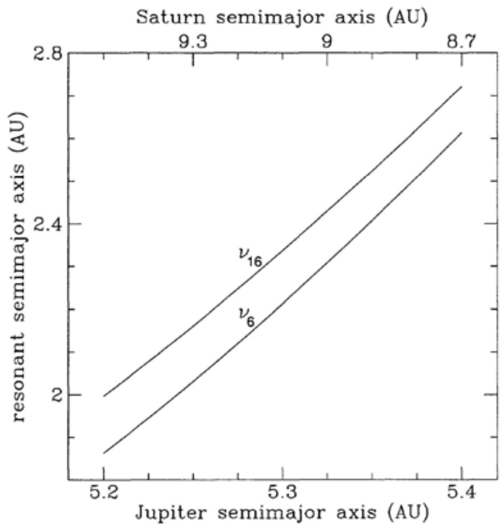

Figure 7

Figure 7 shows the shifts of the two secular resonances, ν_6 and ν_{16}, with a change in Jupiter's semimajor axis from 5.4 to 5.2 AU, and a change in Saturn's semimajor axis from 8.7 AU to 9.5 AU. Recent migration models which take into account a crossing of Jupiter and Saturn's 1:2 MMR, assume an even broader range of semimajor axes for Jupiter and Saturn, using initial values of 5.45 AU and 8.18 AU respectively. This would result in a sweeping of secular resonances throughout the entire primordial main belt.* The degree of excitation of asteroidal eccentricities and inclinations are highly dependent on the rate of migration of Jupiter and Saturn. Lower migration rates cause more perturbation, and consequently a higher depletion of asteroids.

*Gomes showed that the effect of secular resonance on inclinations is only significant for semimajor axes below 2.7 AU. However eccentricities are excited over the entire range of the main belt.

8. SUMMARY

Evidence from dynamic modeling and numerical simulations appear to support a crossing of the 1:2 MMR by Jupiter and Saturn and the subsequent chaotic effects on the orbits of the outer planets as the cause of the Late Heavy Bombardment. As a result of the migration of the four giant planets, a massive number of impactors would have been delivered to the inner Solar System from both the primordial Kuiper Belt and the main asteroid belt. The current orbital parameters of the giant planets, the Trojan asteroids, the main belt asteroids, the Kuiper belt, and the Oort cloud would have been greatly effected during this relatively short but tremendously significant epoch.

9. CONCLUSIONS

The history of our solar region has been punctuated by events and epochs which, although long past, have each left their fingerprints in the petrologic and dynamical structures of the present Solar System. Over the past two centuries, the Geological sciences have developed methodology which has been successfully applied to analysis of the petrologic evidence. We are just now learning to read the record left behind in the Solar System's dynamical structures. To piece together the complete picture, both bodies of evidence must be thoroughly understood. We are now discovering that the emerging story is far more complex than what could have ever been imagined from reading the cover notes.

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