# Asteroid Belt History and Terrestrial Bombardment

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ABSTRACT

The main asteroid belt spans $\sim$ 2–4 AU in heliocentric distance and is sparsely populated by rocky debris. The dynamical structure of the main belt records clues to past events in solar system history. Evidence from the structure of the Kuiper belt, an icy debris belt beyond Neptune, suggests that the giant planets were born in a more compact configuration and later experienced planetesimal-driven planet migration. Giant planet migration caused both mean motion and secular resonances to sweep across the main asteroid belt, raising the eccentricity of asteroids into planet-crossing orbits and depleting the belt. I show that the present-day semimajor axis and eccentricity distributions of large main belt asteroids are consistent with excitation and depletion due to resonance sweeping during the epoch of giant planet migration. I also use an analytical model of the sweeping of the $\nu_6$ secular resonance, to set limits on the migration speed of Saturn.

After planet migration, dynamical chaos became the dominant loss mechanism for asteroids with diameters $D \gtrsim 10$ km in the current asteroid belt. I find that the dynamical loss history of test particles from this region is well described with a logarithmic decay law. My model suggests that the rate of impacts from large asteroids may have declined by a factor of three over the last $\sim 3$ Gy, and that the present-day impact flux of $D > 10$ km objects on the terrestrial planets is roughly an order of magnitude less than estimates used in crater chronologies and impact hazard risk assessments.

Finally, I have quantified the change in the solar wind $^6$Li/$^7$Li ratio due to the estimated in-fall of chondritic material and enhanced dust production during the epoch of planetesimal-driven giant planet migration. The solar photosphere is currently highly depleted in lithium relative to chondrites, and $^6$Li is expected to be far less abundant in the sun than $^7$Li due to the different nuclear reaction rates

of the two isotopes. Evidence for a short-lived impact cataclysm that affected the entire inner solar system may be found in the composition of implanted solar wind particles in lunar regolith.

# CHAPTER 1

# DYNAMICAL HISTORY OF THE MAIN ASTEROID BELT

## 1.1 Introduction

The main asteroid belt spans the $\sim$ 2–4 AU heliocentric distance zone that is sparsely populated with rocky planetesimal debris. Strong mean motion resonances with Jupiter in several locations in the main belt cause asteroids to follow chaotic orbits, cross the orbits of the major planets, and be removed from the main belt (Wisdom, 1987). These regions are therefore emptied of asteroids over the age of the solar system, forming the well-known Kirkwood gaps (Kirkwood, 1867). In addition to the well known low-order mean motion resonances with Jupiter that form the Kirkwood gaps, there are numerous weak resonances that cause long term orbital chaos and transport asteroids out of the main belt (Morbidelli and Nesvorny, 1999). A very powerful secular resonance that occurs where the pericenter precession rate of an asteroid is nearly the same as that of one of the solar system's eigenfrequencies, the $\nu_6$ secular resonance, lies at the inner edge of the main belt (Williams and Faulkner, 1981).

The many resonances found throughout the main asteroid belt are largely responsible for maintaining the Near Earth Asteroid (NEA) population. Non-gravitational forces, such as the Yarkovsky effect, cause asteroids to drift in semimajor axis into chaotic resonances whence they can be lost from the main belt (Öpik, 1951; Vokrouhlický and Farinella, 2000; Farinella et al., 1998; Bottke et al., 2000). The Yarkovsky effect is size-dependent, and therefore smaller asteroids are more mobile and are lost from the main belt more readily than larger ones. Asteroids with $D \lesssim 10$ km have also undergone appreciable collisional evolution over the age of the solar system (O'Brien and Greenberg, 2005; Cheng, 2004; Bottke et al., 2005a), and collisional events can also inject fragments into chaotic resonances (Wetherill, 1977;

Gladman et al., 1997). These processes (collisional fragmentation and semimajor axis drift followed by injection into resonances) have contributed to a quasi steady-state flux of small asteroids ($D \lesssim 10$ km) into the terrestrial planet region and are responsible for delivering the majority of terrestrial planet impactors over the last $\sim 3.5$ Gy (Bottke et al., 2000, 2002a,b; Strom et al., 2005).

In contrast, most members of the population of $D \gtrsim 30$ km asteroids have existed relatively unchanged, both physically and in orbital properties, since the time when the current dynamical architecture of the main asteroid belt was established: the Yarkovsky drift is negligible and the mean collisional breakup time is $> 4$ Gy for $D \gtrsim 30$ km asteroids. Asteroids with diameters between $\sim$ 10–30 km have been moderately altered by collisional and non-gravitational effects. However, as I show in Chapter 2, the asteroids with $D \gtrsim$ 10–30 km are also subject to weak chaotic evolution and escape from the main belt on gigayear timescales. By means of numerical simulations, the loss history of large asteroids in the main belt has been computed, as described in Chapter 2. I also computed the cumulative impacts of large asteroids on the terrestrial planets over the last $\sim 3$ Gy.

The orbital distribution of large asteroids that exist today must have been determined by dynamical processes in the early solar system, because large asteroids do not uniformly fill regions of the main belt that are stable over the age of the solar system (Minton and Malhotra, 2009, see also Chapter 3). The present study is therefore additionally motivated by the need to understand better the origin of the present dynamical structure of the main asteroid belt. The Jupiter-facing boundaries of some Kirkwood gaps are more depleted than the sunward boundaries, and the inner asteroid belt is also more depleted than a model asteroid belt in which only gravitational perturbations arising from the planets in their current orbits have sculpted an initially uniform distribution of asteroids. In Chapter 3 I show that the pattern of depletion observed in the main asteroid belt is consistent with the effects of resonance sweeping due to giant planet migration that is thought to have occurred early in solar system history (Fernandez and Ip, 1984; Malhotra, 1993, 1995; Hahn and Malhotra, 1999; Gomes et al., 2005), and that this event was the last major dynamical depletion event experienced by the main belt. The last major dynamical depletion event in the main asteroid belt likely coincided with the so-called Late Heavy Bombardment (LHB) $\sim$ 3.9 Gy ago as indicated by the crater record of the inner planets and the Moon (Strom et al., 2005).

## 1.2 Planet migration and the Late Heavy Bombardment

Early numerical simulations of the formation of the outer ice giants, Uranus and Neptune, produced an unexpected result. In the simulations of Fernandez and Ip (1984), the ice giants were grown from embryos 20% their present mass by accretion within a massive planetesimal disk, with Jupiter and Saturn at their present masses. They discovered that gravitational interactions between the gas giants, the ice giant embryos, and the planetesimal disk caused the orbits of the gas giants and ice giant embryos to migrate, with Jupiter migrating inward toward the Sun, and the outermost four large bodies migrating outward. This effect is called planetesimal-driven giant planet migration, and it can occur even if Uranus and Neptune have their present mass, but only if there is a massive planetesimal disk beyond the orbits of the giant planets. Planetesimal-driven planet migration can be understood in the following way.

A close encounter between a planetesimal and a giant planet can either increase or decrease the orbital angular momentum of the planetesimal and inversely that of the planet. Whether the planetesimal experiences an increase or a decrease in orbital angular momentum depends on details of the encounter, such as impact parameter and encounter angle. Due to the relatively small sizes of the ice giants, a planetesimal that experiences a close encounter with an ice giant is more likely to remain gravitationally bound to the Sun than escape. Because the planetesimal has experienced a close encounter with a planet, its orbit is strongly coupled to that planet and it will likely experience future close encounters with it. If a single ice giant were the only planet in the solar system, this would mean that any given planetesimal would encounter it over and over again, until chance would allow for an encounter that sent the planetesimal out of the solar system completely. If this process were repeated by large numbers of planetesimals, this would result in a net decrease in the ice giant's angular momentum, and its orbit would migrate sunward. However, the real solar system contains two ice giants, Uranus and Neptune, and two gas giants, Jupiter and Saturn. Planetesimals which have their angular momentum reduced by a close encounter with Neptune can potentially begin to encounter Uranus. Such a close encounter with Uranus can decouple the planetesimal from Neptune, reducing the chances for further close encounters with the outermost ice giant. In this way Uranus acts as a "sink" of planetesimals, and Neptune experiences a net increase in angular momentum and its orbit grows as it passes planetesimals inward toward Uranus.

A similar process occurs at Uranus, but in this case both Neptune and Saturn acts as planetesimal sinks. Because Saturn is larger than Neptune, Saturn is a more effective sink, and Uranus experiences a net increase in angular momentum after encounters with numerous planetesimals. And again at Saturn, Jupiter acts as a more effective sink than Uranus, so Saturn also migrates outwards. Therefore as the icy planetesimals interact with the giant planets, they tend to be passed down from one giant planet to its inward neighbor until they ultimately begin encountering Jupiter. There are no more giant planets inward of Jupiter to act as effective sinks. Also, because of Jupiter's large size, a planetesimal is much more likely to escape from the Sun on a hyperbolic trajectory after an encounter with Jupiter than with any of the other three giant planets. Jupiter therefore experiences a net decrease in angular momentum as it tosses planetesimals onto hyperbolic orbits sending them forever out of the solar system.

Evidence in the structure of the Kuiper Belt suggests that the early solar system experienced just such a phase of planetesimal-driven migration (Fernandez and Ip, 1984; Malhotra, 1993, 1995; Hahn and Malhotra, 1999; Levison et al., 2008). In particular, both the large eccentricity of Pluto and its location within the 3:2 mean motion resonance with Neptune are well explained by resonance capture during the outward migration of Neptune (Malhotra, 1993). The existence of populations of

Kuiper Belt Objects in the 3:2, 2:1, and other low order mean motion resonances with Neptune were predicted as an outcome of planetesimal-driven planet migration before these populations of resonant objects were discovered observationally (Malhotra et al., 2000).

A natural outcome of planetesimal-driven planet migration is to enhance the impact flux everywhere in the solar system. In the terrestrial planet region, planet migration can enhance the impact flux in two ways. First, the scattering of icy planetesimals by the giant planets would have resulted in many of those planetesimals crossing the orbits of the terrestrial planets. Second, because the dynamical structure of the main asteroid belt is dominated by the influence of the giant planets (most importantly Jupiter and Saturn), any change in the orbital properties of these planets in the past should have gravitationally disturbed the asteroid belt. As the giant planets migrated, locations of mean motion resonances as well as secular resonances would have swept across the asteroid belt, raising the eccentricities of asteroids to planet-crossing values. This period of planet migration has been suggested as a cause of the so-called Late Heavy Bombardment (LHB), assuming the onset of migration was sufficiently delayed (Gomes et al., 2005).

The Late Heavy Bombardment has long remained a puzzling and controversial topic in solar system chronology. The radiometric ages of ancient highland representing impact melt rocks returned during the American *Apollo* and Soviet *Luna* missions showed an apparent clustering at $\sim 3.9$ Gy ago (Turner et al., 1973; Tera et al., 1973, 1974; Ryder, 1990). One interpretation of the clustering of impact melt rock ages was that the collected samples represented the tail end of a long period of intense impact bombardment that began with the initial accretion of solids in the inner solar system 4.57 Gy ago (Hartmann, 1975; Russell et al., 2006). Hartmann (1975) suggested that the lack of ancient rocks (those with impact resetting ages $\gtrsim 4$ Gy) on the Moon is the result of a "stone-wall" effect, that is that prior to 4 Gy ago the impact rate was so high that all older impact melt rocks were obliterated into micron-size dust by subsequent impacts. The samples returned in the lunar missions of the late 1960s and early 1970s helped to calibrate crater counting-based age estimates of lunar surface features, which suggest that lunar cratering rapidly declined from a rate several orders of magnitude above the present value down to within a factor of two or three above the present value at ∼ 3.8–3.9 Gy ago (Ryder, 1990; Stöffler and Ryder, 2001; Hartmann et al., 2000; Ryder, 2002; Neukum et al., 2001). Under the stone-wall hypothesis, all ancient impact melt rocks have been destroyed beyond any ability to date, and the only remaining fragments are those produced at the end of this period of intense bombardment, ∼ 3.9 Gy ago. The crater densities of several ancient lunar terrains along with estimates of their absolute ages determined by radioisotope dating of samples returned by the *Apollo* and *Luna* missions is shown in Fig. 1.1.

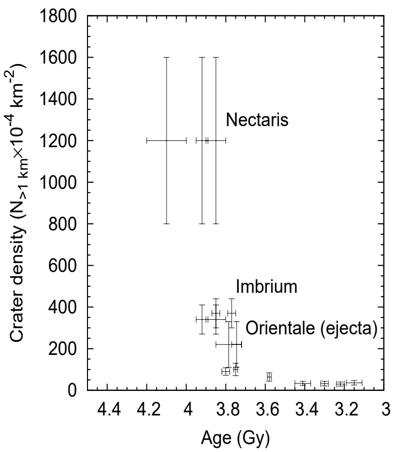


Figure 1.1: Crater densities vs. age for select lunar terrains. A rapid decline in the cratering rate at ∼ 3.9 Gy is observed. The age of Nectaris basin is controversial, and several proposed ages are shown here. Data taken from Stöffler and Ryder (2001).

Based on the resetting ages of several isotopic systems (U-Pb, K-Ar, and Rb-Sr) from lunar rock samples of ancient heavily cratered terrains, an alternative hypothesis, dubbed the “terminal lunar cataclysm,” was suggested by members of the Caltech Lunatic Asylum. In this model, the Moon experienced a sudden and intense spike in its impact rate at ∼ 3.9 Gy ago (Tera et al., 1974, 1973). Under this hypothesis, the lack of impact melts older than $\sim 4.0$ Gy is taken as evidence that the impact rate was relatively low in the interval between planetary accretion and 4 Gy ago (Chapman et al., 2007). In particular, unique characteristics of the U-Pb isotopic system suggest a cataclysmic event at $\sim 4$ Gy ago from the lunar samples, rather than simply the last stages of a monotonically declining impact rate stretching back to the beginning of the solar system. The lead isotope $^{207}$Pb is a daughter product of the decay of $^{235}$U, and $^{206}$Pb is a product of the decay of $^{238}$U, with different half lives for each. When a mineral assemblage becomes closed (that is, whatever lead or uranium exists in the rock or is subsequently produced by radioactive decay remains in the rock until it is analyzed), then a plot of $^{207}$Pb/$^{206}$Pb vs. $^{238}$U/$^{206}$Pb falls on a curve called the concordia, and the position on the curve is a function of the closure age (see Fig. 1.2). If at any point in the rock's history the system is reopened (that is, either uranium or lead is allowed to escape or accumulate within the rock) and then closed again, the resulting values of $^{207}$Pb/$^{206}$Pb vs. $^{238}$U/$^{206}$Pb will fall along a discordant line that intersects the concordia at the initial closure age and again at the age corresponding to the isotope mobilization event. Lead is a more volatile element than uranium, and therefore loss or accumulation of lead during heating of minerals drives the minerals to the discordant line. By measuring a variety of minerals that had varying amounts of either loss or accumulation of lead during a single heating event, the discordant line can be constructed, as shown in Fig. 1.2.

Tera et al. (1974) showed that a variety of *Apollo* samples show discordant U-Pb ratios that intersect the concordia at both $\sim 4$ Gy and $\sim 4.45$ Gy ago. Their interpretation for this result is that the lunar rocks became isotopically closed to U and Pb after the Moon formed around $\sim 4.45$ Gy ago. Then, a major global thermal event occurred at $\sim 4$ Gy ago that then opened the rocks to lead, allowing both radiogenic and non-radiogenic lead to escape some minerals and accumulate in others. The rocks have then remained closed to lead since this event. This scenario formed the basis of their lunar cataclysm argument, in which the impact rate on the Moon was low after its formation but then suddenly underwent a spike at $\sim 4$ Gy.

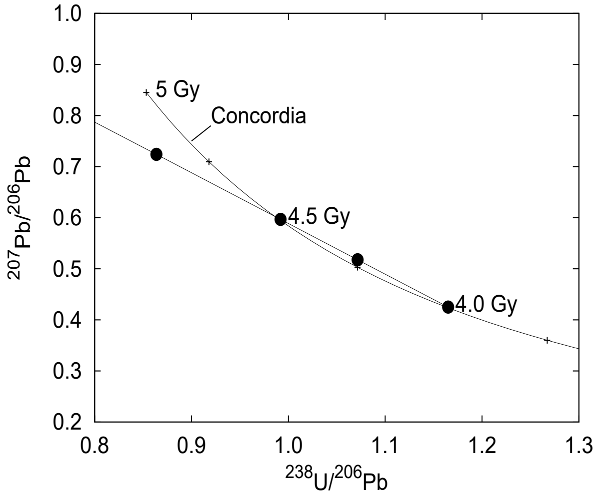


Figure 1.2: Illustration of a discordant U-Pb system. The points show measurements of a hypothetical assemblage of minerals in a rock that were closed to uranium and lead at 4.5 Gy ago and then reopened at 4 Gy ago. Radiogenic lead was depleted from some minerals and added to others, and the resulting data points plot along a discordant line that intersects the concordia at 4.5 Gy and 4 Gy. Compare with Fig. 3 of Tera et al. (1974) which shows data from Apollo samples.

However, the *Apollo* and *Luna* samples were obtained over a relatively small area of the lunar near side, and Haskin et al. (1998) has argued that the apparent clustering of ages seen in these samples results from ejecta from a single basin impact event, namely the formation of the Imbrium basin. Imbrium is the largest near side lunar basin. In contrast, Norman et al. (2006) have identified at least four separate heating events that cluster around 3.75–3.96 Gy ago on the basis of $^{40}$Ar–$^{39}$Ar dating of a variety of *Apollo 16* impact melt breccias. They argue that each event seems to have unique petrological characteristics that correlate with each other in time, which implies that the clustering of ages is not the result of a single basin impact, but several over a relatively short period of time.

One way to determine whether the apparent cluster of ages is simply an artifact of the limited sampling area of lunar samples is analyze lunar meteorites. Lunar meteorites presumably originate from nearly anywhere on the Moon, and impact melts from several lunar meteorites show a lack of ages older than 3.92 Gy (Cohen et al., 2000, 2005). However, rather than clustering at 3.9 Gy, the lunar meteorites impact melts show ages as young as 2.5 Gy. The meteorite record may also provide some insights into the bombardment rate of within the main asteroid belt. The class of meteorites called the H-chondrites record impact events in the $^{40}$Ar-$^{39}$Ar system suggesting impact events within the first $\sim$ 100 My of the solar system (the era of planetary accretion), 3.6–4.1 Gy ago (the end of the LHB), but nothing in-between Swindle et al. (2009).

The hypothesis that the lunar cratering record represents a cataclysmic spike in the cratering rate on all the terrestrial planets (or perhaps even the entire solar system) of $\lesssim$ 100 My in duration, rather the tail end of the planetary accretion era that began with the condensation of the first solids 4.57 Gy ago, has remained a very controversial idea (Hartmann et al., 2000; Chapman et al., 2007). The differing hypotheses have very different implications for the early history of Earth. The Earth would have received an even higher rate of impacts than the Moon, due to its larger geometric and gravitational cross-sections. The end of the LHB at $\sim$ 3.8 Gy corresponds to the end of Earth's Hadean eon. The Hadean is the name given to the period of time on Earth between its formation at $\sim$ 4.5 Gy ago and the oldest known rocks at $\sim$ 3.9 Gy ago. The Hadean was so named because it was assumed that the Earth must have been a hellish place under such intense bombardment, where scarcely would the ocean begin to condense when a giant impact would vaporize it back into the atmosphere again (Sleep et al., 1989; Chyba, 1990; Nisbet and Sleep, 2001). Recently, however, evidence has emerged to contradict this picture. Small numbers of zircon crystals have recently been discovered that have U-Pb ages well within the Hadean. Zircon is an unusually hard mineral and can survive the intense heat and pressure that rocks experience as they undergo processing due to Earth's plate tectonics. Several of these zircon crystals suggest that continental crust and oceans were extent as early as 4.3 Gy ago (Harrison, 2005; Mojzsis et al., 2001).

Under the declining impact hypothesis, Earth should not have had continental crust nor liquid water oceans at this time, as the impact rate would have been far too high (e.g., Ryder, 2002). In addition, some Hadean zircons which have formation ages older than 4 Gy ago show metamorphic overgrowths that date to 3.9 Gy (Trail et al., 2007). These overgrowths have been interpreted as representing short-lived heating events that reset the U-Pb system in the rim of the crystal, leaving the cores intact. These metamorphic overgrowths with ages of 3.94–3.97 Gy were seen in at least three separate crystals, however all crystals were collected at the same site and may represent a local event rather than a global one.

The hypothesis that LHB was simply the tail end of the initial accretion of the terrestrial planets is also problematic in light of post-*Apollo* era studies of terrestrial planet formation. Numerical modeling of formation of the terrestrial planets and the isotopic composition of the bulk Earth indicates that the accretion of the terrestrial planets happened on a very short timescale—on the order of a few tens of millions of years (Greenberg et al., 1978; Halliday et al., 2003; Kenyon and Bromley, 2006), and that the remnants of accretion should have been removed very quickly from the inner Solar System (in tens of millions of years rather than hundreds of millions) due to dynamics and collisional evolution (Bottke et al., 2007a). Thus it is very difficult to connect the intense bombardment observed in the rock record of the Moon some 700 My after the formation of the planets with planetary accretion itself. Both the evidence of the existence of Hadean continents and oceans, and the short timescale for the depletion of accretion remnants from the inner Solar System, imply that the Earth's bombardment rate was likely much lower during most of the Hadean than is implied by a steadily decaying bombardment rate. Therefore the LHB may indeed have been a cataclysmic event that took place over a relatively short duration ending at about 3.8–4.0 Gy ago.

Strom et al. (2005) showed that the heavily cratered terrains on the Moon, Mars, and Mercury that are presumed to date to the time of the LHB all have size-frequency distributions that are consistent with impactors originating in the main asteroid belt. This evidence suggests that, at least by the end of the LHB, the impactors that dominated the cratering record on the terrestrial planets were ejected into terrestrial planet-crossing orbits from the main asteroid belt by a size-independent mechanism. Resonance sweeping by planetesimal-driven giant planet migration is a compelling mechanism for exciting main belt asteroids into planet-crossing orbits in a size-independent way. A problem with the hypothesis that giant planet migration caused the LHB is that the timing of the LHB puts the event 600–800 My after the formation of the solar system. The timing and duration of planet migration is uncertain, but one successful model of planet migration, the so-called "Nice model" has, through a suitable choice of initial conditions of the solar system, demonstrated the ability to delay the onset of migration until up to $\sim 1$ Gy after the formation of the solar system (Gomes et al., 2005). The Nice model therefore provides a plausible mechanism for delaying giant planet migration such that it coincides with the LHB, but the exact timing of the destabilizing trigger at $\sim 700$ My after planet formation is not a necessary outcome. As I will show in Chapter 5, planet migration itself likely took place over a very time span ($\lesssim 10^7$ yr), and therefore any model which proposes to link planetesimal-driven planet migration with the LHB must include a mechanism to delay the onset of migration for several $10^8$ yr. Regardless of the controversies surrounding the cause and duration of the LHB, the hypothesis that the giant planets experienced a phase of planetesimal-driven migration is well supported by observations, and in Chapter 3 I show that patterns of depletion observed in the asteroid belt are consistent with the effects of sweeping of resonances during the migration of the outer giant planets.

## 1.3 Overview of the present work

Motivated by the compelling link between planetesimal-driven planet migration, the dynamical history of the asteroid belt, and the LHB, I seek to quantify the dynamical effects that planet migration produced on the early asteroid belt. I begin by looking for clues in the present-day structure of the observed asteroid belt, using observations to infer the post-LHB dynamical history of asteroids. I describe in detail the dynamical models of the present-day asteroid belt in Chapter 2. These models are constrained by the observed orbital distributions of large asteroids in the main belt. I use these models to explore the dynamical mechanism by which large asteroids have been lost from the main belt over the last 4 Gy, and show that the impact rate of large ($D > 10$ km) asteroids onto the terrestrial planets may be significantly underestimated. In Chapter 3 I use the results of the asteroid belt models developed in Chapter 2 to show that asteroids currently do not uniformly fill all of the stable regions of the asteroid belt. Much of Chapter 3 has been published as Minton and Malhotra (2009).

Asteroid eccentricity excitation by the sweeping of the $\nu_6$ resonance is the primary mechanism by which most asteroids were removed from the asteroid belt and placed onto planet-crossing orbits during the epoch of planetesimal-driven planet migration. In order to better understand the process by which asteroid depletion occurred during planet migration, I have developed an analytical model of the sweeping $\nu_6$ secular resonance. In Chapter 4 I show how the secular dynamics of the solar system is changed when Jupiter and Saturn are displaced from their current semi-major axes. I use the method of Fourier analysis of long-term integrations of the two giant planets to show how the magnitude of the $g_6$ eigenfrequency (which determines the position of the $\nu_6$ resonance) changed as a function of the giant planets' migration history. I also show that a relatively simple secular theory is an adequate model of the change in the $g_6$ eigenfrequency as a function of Saturn's position for the majority of Jupiter and Saturn's migration history. The secular theory is based on the Laplace-Lagrange linear secular theory with the correction due to the proximity of Jupiter and Saturn to their 2:1 mean motion resonance that was developed by Malhotra et al. (1989). I use results derived in Chapter 4 as inputs to a model of the excitation of asteroids by the sweeping $\nu_6$ resonance, in Chapter 5. The analytical model of the sweeping $\nu_6$ resonance explicitly relates an asteroids change in eccentricity excitation to its initial eccentricity and the migration rate of Saturn. I use the results of the analytical model to set an upper limit on the rate of migration of Saturn. I also show that a peculiar feature of the eccentricity distribution of asteroids in the main belt is consistent with the effects of the sweeping $\nu_6$, and may help further constrain the migration rate of Saturn.

Establishing a link between the epoch of planet migration and the Late Heavy Bombardment may require further observational tests. In Chapter 6 I explore whether "pollution" of the solar atmosphere by lithium may have left its trace in the lunar rock record. Lithium is an element that is more rare in the Sun than in planetesimals because lithium is destroyed by thermonuclear fusion at relatively low temperatures. I model the abundance of solar lithium and the ratio of two isotopes of lithium, $^6$Li and $^7$Li, under a variety of assumptions. These models may also help observationally identify exosolar systems experiencing their own versions of the LHB.

I include here a table of all symbols used and their basic definitions.

Table 1.1: Symbols and their definitions

| Symbol | Definition |
|---|---|
| | Dynamics and orbital elements |
| $G$ | Universal gravitational constant |
| $a$ | Semimajor axis |
| $e$ | Eccentricity |
| $i$ | Inclination |
| $\varpi$ | Longitude of pericenter |
| $\Omega$ | Longitude of the ascending node |
| $\lambda$ | Mean longitude |
| $J$ | Conjugate momentum $\sqrt{a}(1-\sqrt{1-e^2})$ |
| $\tau$ | e-folding timescale |
| $g_i$ | Secular eigenfrequency of planet $i$ |
| $\beta_i$ | Phase of the eigenmode of planet $i$ |
| $E_j^{(i)}$ | Amplitude of the $j^{th}$ eigenmode in planet $i$ |
| | Projectile and crater physical properties |
| $D$ | Diameter (of projectile in the context of cratering) |
| $D_c$ | Final crater diameter |
| $H$ | Absolute visual magnitude |
| $m$ | Mass |
| $\rho$ | Density |
| $\rho_v$ | Geometric visual albedo |
| $\theta$ | Impact angle |
| $N$ | Number |

# CHAPTER 2

# DYNAMICAL EROSION OF THE ASTEROID BELT

## 2.1 Introduction

Knowledge about the distribution of the asteroids in the main belt just after that last major depletion event may help constrain models of that event. Quantifying the dynamical loss rates from the asteroid belt also help us understand the history of large impacts on the terrestrial planets. Motivated by these considerations, in this chapter I explore the dynamical erosion of the main asteroid belt, which is the dominant mechanism by which large asteroids have been lost over the last $\sim 4$ Gy.

I have performed a series of n-body simulations of large numbers of test particles in the main belt region over long periods of time (4 Gy and 1.1 Gy). I derive an empirical functional form for the population decay and loss rate of main belt asteroids. Finally, I discuss the implications of my results for the history of large asteroidal impacts on the terrestrial planets.

## 2.2 Numerical simulations

My long term orbit integrations of the solar system used a parallelized implementation of a second-order mixed variable symplectic mapping known as the Wisdom-Holman Method (Wisdom and Holman, 1991; Saha and Tremaine, 1992), where only the massless test particles are parallelized and the massive planets are integrated in every computing node. My model included the Sun and the planets Mars, Jupiter, Saturn, Uranus, and Neptune. All masses and initial conditions were taken from the JPL Horizons service[1] on July 21, 2008. The masses of Mercury, Venus, Earth, and the Moon were added to the mass of the Sun.

[1]see http://ssd.jpl.nasa.gov/?horizons