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Populating the asteroid belt from two parent source regions due to the migration of giant planets—"The Grand Tack"

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Abstract–The asteroid belt is found today in a dramatically different state than that immediately following its formation. It is estimated that it has been depleted in total mass by a factor of at least 1000 since its formation, and that the asteroids' orbits evolved from having near-zero eccentricity and inclination to the complex distributions we find today. The asteroid belt also hosts a wide range of compositions, with the inner regions dominated by S-type and other water-poor asteroids and the outer regions dominated by C-type and other primitive asteroids. We discuss a model of early inner solar system evolution whereby the gas-driven migration of Jupiter and Saturn brings them inwards to 1.5 AU, truncating the disk of planetesimals in the terrestrial planet region, before migrating outwards toward their current locations. This model, informally titled "The Grand Tack," examines the planetary dynamics of the solar system bodies during the final million years of the gaseous solar nebula lifetime—a few million years (Myr) after the formation of the first solids, but 20–80 Myr before the final accretion of Earth, and approximately 400–600 Myr before the Late Heavy Bombardment of the inner solar system. The Grand Tack attempts to solve some outstanding problems for terrestrial planet formation, by reproducing the size of Mars, but also has important implications for the asteroid population. The migration of Jupiter causes a very early depletion of the asteroid belt region, and this region is then repopulated from two distinct source regions, one inside the formation region of Jupiter and one between and beyond the giant planets. The scattered material reforms the asteroid belt, producing a population the appropriate mass, orbits, and with overlapping distributions of material from each parent source region.

INTRODUCTION

The broad view of early solar system chronology has evolved as observations and theory have uncovered the potentially critical role played by planetary migration (Armitage 2007; Kley and Nelson 2012). Models of solar system evolution must now consider the possibility that our planets may have undergone substantial radial migration. Below, as we discuss two major epochs that shaped the solar system, we will cover two entirely distinct means of giant planet migration—first by interactions with the gaseous solar nebula, and later by interactions with small planetesimals and other planets. Current results, including those discussed here, suggest that planets in our solar system underwent both types of planet migration at very distinct times in its history.

The time period of interest for understanding the large-scale radial redistribution of material in the solar system extends from the condensation of the first solids ≈4.568 Gyr ago (Amelin et al. 2002; Bouvier and

Wadhwa 2010), up to the "late" bombardment of the Moon and inner solar system some 4.1–3.9 Gyr ago (Tera et al. 1974; Chapman et al. 2007; Bottke et al. 2012). Interestingly, the gaseous solar nebula was only present for the first about 4–5 Myr of the solar system's history (Kita et al. 2005; see also Haisch et al. [2001] for lifetimes of disk around other stars). In these first about 4–5 Myr it is expected that the giant planets grew to their final sizes and rocky planetesimals grew to be lunar to Mars-sized planetary embryos (Weidenschilling et al. 1997; Kokubo and Ida 2000). It is in the following 30–100 Myr that the terrestrial planets finished accreting (Kenyon and Bromley 2006; Kleine et al. 2009; also see Morbidelli et al. 2012), and approximately 400–600 Myr later that the orbits of the giant planets experienced an instability that resulted in the restructuring of the outer solar system and the bombardment of the inner solar system (the "Nice Model"; Gomes et al. 2005; Morbidelli et al. 2005; Tsiganis et al. 2005; Levison et al. 2011; Bottke et al. 2012).

Overall, we are left with a curious planetary system where the close-in, smaller planets took much longer to form than the much more massive and more distant giant planets. Our entire solar system, nearly everything from planets down to km-sized asteroids, did not reach its final configuration until 400–600 Myr after the very first solids formed. This is exciting in that it tells us that our system may share some traits with extra-solar planetary systems discovered in recent years, many of which show evidence for large-scale planet migration and even planet–planet scattering (Adams and Laughlin 2003; Armitage 2007; Juric and Tremaine 2008; Raymond et al. 2010). However, it also changes how we interpret and compare physical properties of bodies found throughout the solar system. The take away lesson will be that bodies in the solar system were not necessarily formed where we find them today.

THE GRAND TACK

Models of terrestrial planet formation attempt to track the growth of planetesimals from a large swarm of asteroid-sized bodies up to a few planets. This growth progresses through a few distinct stages as bodies collide and accrete. First, with low relative velocities due to dynamically cold orbits (low eccentricity and inclination), growth is favored for larger bodies owing simply to their gravitationally enhanced cross-sections (Safronov and Zvjagina 1969; Greenberg et al. 1978; Ida and Makino 1993; Rafikov 2003). This is referred to as "runaway growth," and occurs on 10^5 year time scales resulting in the rapid production of bodies up to lunar sizes, depending on nebular surface densities. Once the largest bodies reach lunar sizes they are large enough to gravitationally perturb their neighbors, which increases the smaller neighbors' eccentricities and hence their relative velocities. These large bodies enter a phase of "oligarchic growth" in which their growth rates slow owing to the higher relative velocities, which allows those slightly smaller to catch up in mass (Kokubo and Ida 1998, 2000). However, the very small planetesimals never grow larger as their high relative velocities allow them to accrete only on larger oligarchs and not with each other. The outcome of this stage, on a roughly million-year time scale, is a population of planetary embryos of lunar to Mars mass, and a population of much smaller planetesimals (Kenyon and Bromley 2006). This bimodal distribution, typically modeled to have roughly equal mass in each component, is the starting point for many modern terrestrial planet formation models, including the Grand Tack (see Morbidelli et al. [2012] for a review).

The final stages of terrestrial planet formation then find the planetary embryos accreting into a stable system of planets. This stage, the "giant impact" stage, takes anywhere from 30 to 100 Myr. These models have had success creating systems with 3–4 terrestrial planets on orbits similar to those observed in the solar system (O'Brien et al. 2006; Raymond et al. 2006, 2009; Morishima et al. 2008, 2010). However, models of terrestrial planet formation have consistently struggled to match the small mass of Mars relative to Earth (see Raymond et al. 2009).

In traditional models of terrestrial planet formation described above, the "small Mars" problem exists due to its accretion from the substantial amount of material between the orbit of Earth and the inner edge of the asteroid belt. Recent work by Hansen (2009), pointed to a possible solution relying on a variant of the typical initial conditions (see also Wetherill 1978). Simulations in which the disk of planetesimals was confined to an annulus between 0.7 and 1.0 AU produced a close match for the orbits and mass distribution of the planets, including the Earth/Mars mass ratio. However, still missing was a mechanism to produce this truncation of the planetesimal disk at 1.0 AU. Similarly, if the planetesimal disk simply ended at 1.0 AU, the existence of the asteroid belt between 2.0 and 3.5 AU would be problematic.

The disparity in growth time scales between the giant planets (a few million years) and the Earth (a few *tens* of millions of years) allows for substantial interaction between the fully grown giant planets and the precursors of the terrestrial planets. Thus, the Grand Tack model presents a scenario in which the growing, or fully grown, giant planets could have briefly migrated into the inner solar system during the gas-rich phase of the solar nebula, drastically altering the distribution of planetesimals and planetary embryos. There are substantial unknowns about the growth mechanisms and time scales of the giant planets, although their formation necessarily completed in the presence of the nebular gas-disk and predated the terrestrial planets.

Evidence of giant planet migration in extra-solar planetary systems is inferred from the observed orbital distributions of discovered giant planets, while it has also been extensively modeled in hydrodynamic simulations of giant planets interacting with gaseous disks (see Kley and Nelson [2012] for a review). In our own solar system, evidence for past planet migrations can be found in the orbit of Pluto (Malhotra 1995), the orbits of the giant planets (Tsiganis et al. 2005), the structure of the asteroid belt around the Kirkwood gaps (Minton and Malhotra 2009), and the secular properties of the giant planet's orbits (Morbidelli et al. 2009).

Numerical simulations performed over the last 20 years robustly demonstrate that Jupiter-mass planets in gaseous protoplanetary disks create annular gaps in the disk and migrate inward; a process called type II migration (Lin and Papaloizou 1986; Ward 1997; see Kley and Nelson 2012). However, a different evolution is found for two planets locked in a mean motion resonance. Specifically, hydrodynamic simulations show that Saturn is eventually captured in the 2:3 mean motion resonance with Jupiter (Masset and Snellgrove 2001; Crida and Morbidelli 2007; Pierens and Nelson 2008; Pierens and Raymond 2011). This resonant configuration changes the net torques on the planets from the gas-disk and leads to a migration reversal; both planets migrating outwards instead of inwards (this migration reversal depends on the two planet's mass ratio—where Jupiter's larger mass results in outward migration). This evolution continues while the planets remain in resonance until the gas-disk dissipates.

The possibility of Jupiter migrating into the inner solar system, before Saturn halts and reverses their migration, can dramatically affect terrestrial planet formation. Given the vast uncertainties in the understanding of both giant planet formation and gas-disk evolution, one cannot estimate a priori the precise time scales or turning point for the inward-and-outward migration of the giant planets. Rather it is necessary to examine the evidence left behind, by way of the terrestrial planets and asteroid belt, to build and test a model. Hansen (2009) found that an outer edge to the planetesimal disk at 1 AU could solve the small Mars problem. Simple tests showed that if Jupiter migrated inward to 1.5 AU before reversing its migration, the inner disk of planetesimals and embryos would have been truncated at 1 AU. Matching these ideal initial conditions for terrestrial planet formation provides the location for the migration reversal (or where the "tack" happened). However, given that the giant planets must traverse the asteroid belt region twice in such a scenario, the existence and properties of the asteroid belt today pose a key constraint.

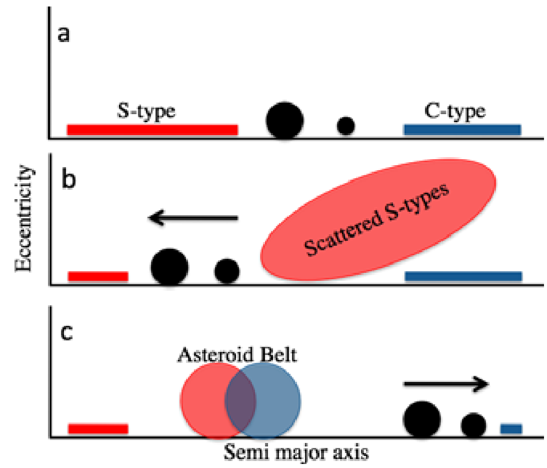

Fig. 1. A schematic of the Grand Tack, where the large black circle is Jupiter and the outer, smaller, circle is Saturn. The "S-type" planetesimal disk (red) is representative of the diverse population of volatile-poor, or dry, asteroids. The "C-type" disk, between and beyond the giant planets (blue), is representative of the more primitive populations of asteroids. The arrows show the inward (a), then outward migration (b) of Jupiter and Saturn, and the resultant scattering of the two distinct population of planetesimals (c). The final configuration is a truncated inner disk of planetesimals needed to reproduce the Earth/Mars mass ratio, and an asteroid belt repopulated with bodies from both the S-type and C-type parent populations.

Walsh et al. (2011) present and test this idea, now informally called the "Grand Tack." Given that the location of the migration reversal was anchored by the results of simple tests and previous terrestrial planet simulations (Hansen 2009; and tested again in Walsh et al. 2011), the numerical models focused on the fate of the small-body population and the existence/properties of bodies in the asteroid belt. As the actual formation location of Jupiter is unknown, it is tested at a range of values, but nominally set at 3.5 AU due to estimates of the snow line location (Ciesla and Cuzzi 2006; Lecar et al. 2006; Garaud and Lin 2007). Any populations of small bodies inside, or outside, the formation location of Jupiter will then be subject to its gravitational influence during its migration inward and then outward.

The simulations start with two separate populations of asteroids (Fig. 1). Inside the orbits of the giant planets there is a planetesimal disk between about 0.7 and 3.0 AU. Between and beyond the giant planets is a second population of asteroids, which is likely to be more primitive and water-rich. We label the inner population "S-types" and the outer "C-types." However, this is not to imply that there are only two specific types of asteroids—rather compositional variations within each group would account for a large variety of asteroid taxonomic classes and meteorite groups (Burbine et al. 2002; Bus et al. 2002; DeMeo et al. 2009).

As Jupiter migrates inward it scatters about 15% of the planetesimals from the inner disk (the "S-types") onto more distant orbits beyond about 4 AU. After the "tack," when Jupiter and Saturn begin their outward migration, they first encounter this population of scattered S-type material. Only later during their outward migration do Jupiter and Saturn begin encountering the C-type bodies that are initially located between and beyond the giant planets. A fraction (0.5%) of the "S-type" material is scattered back inward onto stable orbits in the asteroid belt. A similar fraction of the "C-type" material is scattered later and also reaches stable orbits in the asteroid belt. The numerical models varied the giant planet migration speed, the nominal size of the planetesimals (affecting their gas-drag properties), the existence/behavior of Uranus and Neptune, the starting point of Jupiter, and growth and evolution of Saturn (see the supplementary material of Walsh et al. 2011). While making minimal changes to the overall results, no single parameter other than the migration of Jupiter fundamentally changed the outcome.

The final asteroid belt in the simulations is composed of material from both parent populations. The simulations reproduce the constraint that S-type material dominates the inner belt (interior to 2.8 AU) and that C-type material dominates the outer belt (Fig. 2). This outcome is a result of the giant planets first encountering, and scattering, the previously scattered S-type bodies during their outward migration, while only later encountering the primitive disk of planetesimals. This timing is important as bodies scattered earlier are more likely to be trapped in the inner part of the asteroid belt, and those encountered later are more likely to reach the outer belt. Ordinary and carbonaceous chondrites are thought to come from these broad S- and C-classes of asteroids, respectively, and they are substantially different petrologically, chemically, and isotopically. These physical differences are not easily accounted for in a cooling nebula (Warren 2011) and therefore origin at different locations in the disk is a potential solution.

The orbital eccentricities of the simulated asteroid belt are elevated when compared with today's observed orbits. However, the subsequent instability of the giant planet's orbits (the Nice Model, discussed in the next section) has been shown to produce a reshuffling of asteroid orbital eccentricities (Minton and Malhotra 2009). The orbital inclinations of the asteroid belt are a much stronger constraint, as they are less susceptible to later changes. The simulation results produce a range of 0–25°, which is very similar to what is found today.

Thus, at the conclusion of the Grand Tack the gas-disk has dissipated, the giant planets are parked in the outer solar system in a compact configuration with Jupiter and Saturn in resonance at about 5.4 AU and about 7 AU (despite uncertainties about the formation of Uranus and Neptune, they are also expected to be in resonance with Saturn and each other; see Levison et al. 2011). The asteroid belt is depleted and dynamically excited. The terrestrial planets have tens of millions of years left to finish their accretion from a truncated disk of planetesimals and lunar to Mars mass embryos.

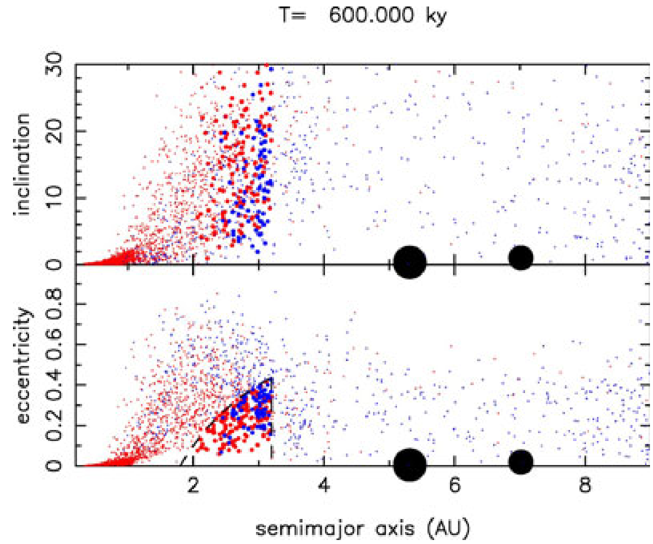

Fig. 2. The orbital inclinations (top) and eccentricities (bottom) of the planetesimals remaining following the Grand Tack as a function of their semimajor axis. The large black circles are final locations of Jupiter and Saturn. The dotted line in the bottom panel is the rough outline of today's asteroid belt. The planetesimals that are within the asteroid belt boundaries are enlarged in both the inclination and eccentricity panel. The red dots, representing the S-type bodies, dominate the inner part of the asteroid belt region, while the blue dots representing the C-type population dominate the outer region of the asteroids belt.

THE NICE MODEL AND THE LATE HEAVY BOMBARDMENT

The Grand Tack scenario described above provides some solutions to planetary formation problems, and also results in a very early (about 4–5 Myr) depletion and excitation of the asteroid belt. However, the solar system does not yet match that found today. There is a final restructuring of the solar system—the events surrounding the so-called "Late Heavy Bombardment" (LHB)—remaining to finalize the orbits of giant planets and redistribute some small body populations. The Nice Model is currently the most studied model describing the reshuffling of giant planets' orbits, which is also a likely trigger for the "late" bombardment of the inner of the solar system (Gomes et al. 2005; Morbidelli et al. 2005;

Tsiganis et al. 2005; Levison et al. 2011; Bottke et al. 2012). The essential characteristics of the Nice Model are quite different from the Grand Tack, as the migration of the giant planets during the Grand Tack is caused by interactions with the gas-disk, while migration during the Nice Model is driven by the gravitational scattering of planetesimals from a massive primordial Kuiper Belt. The Nice Model is also temporally distinct from the Grand Tack, as its link to the Late Heavy Bombardment (LHB) anchors it around about 400–600 Myr after the formation of the solar system (Bottke et al. 2012) while the Grand Tack migration would have occurred within the first about 5 Myr in the presence of the gaseous solar nebula.

The scattering of giant planets in a violent instability is thought to have occurred in the majority of known systems of giant extra-solar planets (Chatterjee et al. 2008; Ford and Rasio 2008; Juric and Tremaine 2008; Raymond et al. 2010). A similar version of this mechanism is also at the heart of the Nice Model, whereby, after a long quiescent period in a close and compact configuration, the exchange of angular momentum between the massive primordial Kuiper Belt (30–50 Earth masses) and the planets breaks the planets out of resonance (Levison et al. 2011). This leads to a violent phase of crossing orbits and planet–planet scattering. When Neptune is scattered outward into the primordial Kuiper Belt, the resident planetesimals are rapidly scattered. The net result of the scattering, due to angular momentum exchanges between planetesimals and planets, is that Jupiter moves inwards slightly to its current location (about 5.2 AU) while Saturn, Uranus, and Neptune are pushed onto larger and more eccentric and inclined orbits as we find them today (9.5, 19.6, and 30 AU), respectively (Levison et al. 2011). The primordial Kuiper Belt plays an important role of damping the planet's orbital eccentricities, helping to stabilize the giant planet system, while itself being dynamically excited and also substantially depleted of mass. Its current orbital structure bears the signs of its violent past, with the orbit of Pluto being a result of Neptune's incursion into the primordial Kuiper Belt (Malhotra 1995).

The global solar system-wide effects of the Nice Model are vast. First, the short time period over which the close encounters and planet–planet scattering events occur allows for both the Trojans at Jupiter and the irregular satellites of all the giant planets to be captured from the scattered population of the primordial Kuiper Belt (Morbidelli et al. 2005; Nesvorný et al. 2007). The scattering of Neptune into the primordial Kuiper Belt quickly excites and ejects material from the region, leaving today's dynamically excited Kuiper Belt (Levison et al. 2008; Batygin et al. 2011). The large movement of the giant planets causes powerful orbital resonances to sweep across the asteroid belt, creating large regions of instability in the asteroid belt, causing a rapid depletion that removes ½ to ¼ of its mass, much of which is destined to bombard the terrestrial planets (Gomes et al. 2005; Minton and Malhotra 2009; Morbidelli et al. 2010; Bottke et al. 2012). Similarly, the asteroid belt is found to capture some scattered primordial Kuiper Belt objects that may account for the D- and P-type population of bodies in the outer reaches of the asteroid belt (Levison et al. 2009). The connection to the bombardment of the inner solar system provides the temporal link to the increase in impacts on Earth known as the Late Heavy Bombardment, believed to have occurred around 4.1–3.9 Gyr ago (Bottke et al. 2012).

The Nice Model is the last major dynamical event to shape the solar system. For the 4 billion years to follow planetary orbits are unchanged and only minor changes are made to the various small body populations.

CONCLUSIONS AND DISCUSSIONS

The Grand Tack and the Nice Model are intimately linked in a few ways. First, the end state of the Grand Tack provides the initial conditions for the Nice Model. For Jupiter and Saturn to migrate outward in the Grand Tack model they must be so close that their annular gaps in the gaseous disk overlap (Masset and Snellgrove 2001). In hydrodynamic simulations Jupiter and Saturn are consistently trapped in 3:2 resonance, triggering outward migration during which Uranus and Neptune are expected to be trapped in a resonant chain (as in Morbidelli et al. 2007). This compact configuration is stable for billion-year time scales and is the starting point for the giant planets in the Nice Model. Similar closely packed, resonant or near-resonant configurations appear to be a common occurrence among the planetary systems discovered by the Kepler mission (Lissauer et al. 2011).

Following the Grand Tack, the asteroid belt will be altered 400–600 Myr later by the Nice Model. Walsh et al. (2011) found that the asteroid belt immediately after the Grand Tack has enough mass to account for the further depletion caused by the sweeping resonances found in the Nice Model. These sweeping resonances also reshuffle the eccentricity distribution in the asteroid belt without dramatically altering the inclination distribution. As discussed above, the asteroid's orbits have elevated eccentricities at the end of the Grand Tack, while the more constraining inclination distribution is a solid match to today's asteroid belt. This further reshuffling is expected to push some asteroids to lower eccentricity orbits, a simple solution to this discrepancy (Minton and Malhotra 2009; Morbidelli et al. 2010; Walsh et al. 2011).

Standing alone, each model helps solve problems for both the inner and outer solar system. A combination of the two models provides a coherent picture of the evolution of the solar system from just a few million years after the formation of the first solids—until the giant planets finished migrating throughout the solar system.

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