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Forming terrestrial planets and delivering water

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Abstract. Building models capable of successfully matching the Terrestrial Planet's basic orbital and physical properties has proven difficult. Meanwhile, improved estimates of the nature of water-rich material accreted by the Earth, along with the timing of its delivery, have added even more constraints for models to match. While the outer Asteroid Belt seemingly provides a source for water-rich planetesimals, models that delivered enough of them to the still-forming Terrestrial Planets typically failed on other basic constraints - such as the mass of Mars.

Recent models of Terrestrial Planet Formation have explored how the gas-driven migration of the Giant Planets can solve long-standing issues with the Earth/Mars size ratio. This model is forced to reproduce the orbital and taxonomic distribution of bodies in the Asteroid Belt from a much wider range of semimajor axis than previously considered. In doing so, it also provides a mechanism to feed planetesimals from between and beyond the Giant Planet formation region to the still-forming Terrestrial Planets.

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1. Introduction

Increasingly models are finding that the numerous mysteries surrounding the formation of the Terrestrial Planets and the Asteroid Belt are intertwined. One of the biggest issues in Terrestrial Planet Formation has been the large Earth/Mars mass ratio – where the Earth is 10× the mass of the Mars – the "Small Mars" problem (see Raymond *et al.* 2009). Meanwhile, the Asteroid Belt is dynamically excited, vastly depleted in mass and contains overlapping distributions of very different types of Asteroids (see Demeo and Carry 2014). Complicating these two problems is the strong link between the C-type asteroids, predominate in the outer Asteroid belt (beyond ∼2.8 au), Carbonaceous Chondrite meteorites and the water on Earth (see Morbidelli *et al.* 2012). The formation of the Terrestrial Planets is closely linked with the formation and evolution of the Asteroid Belt.

The formation of the Terrestrial Planets presents a modeling challenge with a dynamic range problem so severe that it is necessarily modeled piece-wise. The gaseous solar nebula surrounding the Sun initially condenses dust, and 100 Myr later a system of four rocky planets is left. The first stages of dust growth are understood through laboratory analysis (see Blum and Wurm 2008) and statistical modeling of growth and fragmentation (see Dullemond and Dominik 2005, Ormel *et al.* 2007). Through nebular and physical processes still not fully understood a population of planetesimals form from the dust — with the expectation of forming in sizes up to or exceeding 100 km (see Johansen *et al.* 2015).

With most solid mass turned into planetsimals, pairwise accretion of planetesimals can proceed – though it is notable that works such as Lambrechts and Johansen (2012) have explored ideas on "pebble accretion" where planetesimals can accrete primarily from leftover dust and pebbles, rather than on each other. If planetesimals are primarily feeding off planetesimals the stages of growth are well explored. First, “Runaway” growth is dominant, where gravitational focusing can significantly enhance the growth rate of the largest bodies owing to the low relative velocities due to the damping affects of the solar nebula (see Kokubo and Ida 2000). As the largest bodies grow in size the combination of their increased ability to perturb local orbits combined with the decreasing damping affects of a dissipating gas-disk, the orbits of the small bodies begin to get excited and relative velocities increase. This eliminates the advantages of gravitational focusing and the local region enters “Oligarchic growth”, where the growth rate of the largest bodies slow. Meanwhile, in distant regions of the disk Runaway growth continues until an oligarch, or planetary embryo appears — this leads to the development of a bi-modal size distribution where planetary embryos reach similar sizes and are surrounded by a sea of smaller planetesimals (see Kokubo and Ida 1998).

Eventually, the orbits of the planetary embryos begin to cross and giant impacts ensue in the “Giant impact” stage of growth (see Chambers 2001). This final stage can take up to 100 Myr defined somewhat by the last giant collision, which is commonly thought to be the collision between the Earth and a Mars-sized body that produced the Earth’s Moon.

Models that attempt to put these pieces together have struggled to match all of the constraints at the same time. Getting a correct Earth/Mars mass ratio was only a high-probability event when the giant planet orbits were highly eccentric - not at all expected (see Raymond *et al.* 2009). For example, in these cases, Raymond *et al.* (2009) found that outer-belt asteroids, here the presumed source of water on Earth, were not delivered in high enough quantities to explain the water content of Earth.

A fundamental aspect, and mystery, for Solar System evolution is that the giant planets must have been fully formed prior to the dissipation of the solar nebula in order to explain their large gaseous envelopes. Meanwhile, in the context of these inner Solar System models, the Asteroid Belt’s origin and evolution was due to the frustrated growth and dynamical excitement caused by the growth of the giant planets. With disk lifetimes expected to be around 2–10 Myr (Haisch *et al.* 2001), the giant planets therefore form much faster than the expected accretion timescales for the Earth (Kleine *et al.* 2004). So the growth and behavior of the giant planets has the potential to strongly affect the growth of the terrestrial planets and the growth in the Asteroid Belt.

Matching the total mass depletion, orbital excitement and taxonomic mixing in the Asteroid Belt requires some substantial pertubrations. Distant resonant interactions with the giant planet only affect relatively small regions in the asteroid belt and can’t stir the entire population. However, embedded planetary embryos — formed by the same growth process as needed to form the rocky planets at 1 au — can be excited by the giant planets and then stir and deplete the entire population of small bodies in the Asteroid Belt region (Petit *et al.* 2001, Obrien *et al.* 2007). While this process can deplete and stir the Asteroid Belt, the embryos prefentially eject planetesimals on low-inclination orbits due to low relative velocity encounters producing a skewed orbital distribution with far more high inclination bodies produce than observed in today’s Asteroid Belt. This does provide a way to move water-rich asteroids from the outer Asteroid Belt, and also a mechanism to capture iron meteorites into the Asteroid Belt that originate from the terrestrial planet forming region Bottke *et al.* (2006).

Thus, problems exist within classical scenarios for both matching critical constraints for both the planets and the Asteroid Belt.

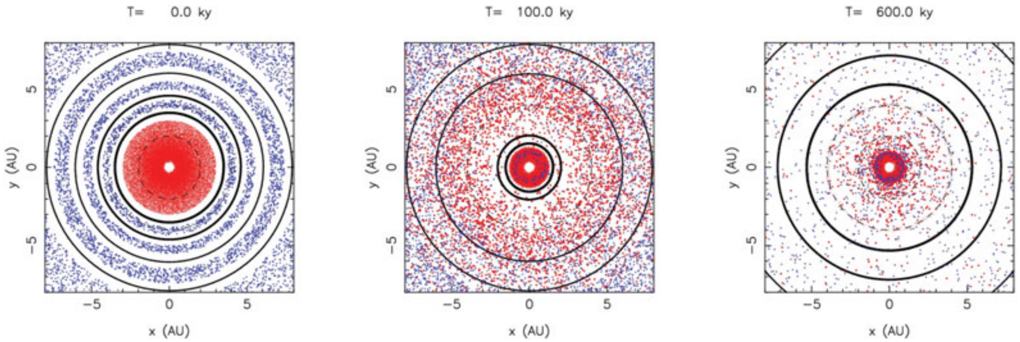

Figure 1. Diagram showing the proposed movement of the giant planets during the "Grand Tack" along with the the paths of different types of small bodies across the inner Solar System. The red dots represent particles initially interior to Jupiter (where the innermost solid black circle is the orbit of Jupiter, followed by Saturn, Uranus and Neptune), and the blue dots represent the particles forming beyond the snow-line between and the beyond the giant planets.

2. Migrating Giant Planets

A new work, dubbed the "Grand Tack", found considerable success in both matching the properties of the terrestrial planets, but also in satisfying the constraints posed by the asteroid belt and the delivery of water to Earth (Walsh *et al.* 2011, Walsh *et al.* 2012, O'brien *et al.* 2014). This model earned its moniker because it relies on an inward-then-outward migration of Jupiter to severely alter the distribution of solid material in the early Solar System (similar to a sailboat "tacking" – making a series of sharp turns to sail upwind). The result of the migration is to create an outer edge to the solids at 1.0 AU, which helps in creating a small Mars with a short accretion time (Figure 1).

This model has met with success because its truncation of the inner disk of planetesimals and embryos provides good conditions to form a small Mars, as a sharp edge of material at 1 au leads to the scattering and isolation of a Mars (Hansen 2009). It addresses the Asteroid Belt constraints through the depletion and re-filling of the population owing to the inward-then-outward migration of Jupiter. The final population is emplaced due to gravitational scattering affects, leading to widely excited orbits, and a low mass. The relative mass of the volatile poor population (think "S-type", or bodies forming inside the snow line), is anchored by their source from the same disk that formed the terrestrial planets and thus is not a tunable parameter. Likewise, the planetesimal population that is scattered into the out Asteroid Belt (think "C-types", or bodies forming beyond the snow line), have a total mass limited by that required to deliver water to the terrestrial planets. Thus, both populations are anchored by constraints related to the formation of the planets.

This model also does not rely on the formation of planetary embryos in the Asteroid Belt. The excitement of the Asteroid Belt and the delivery of water is done by the migration of the Giant Planets. New models of Runaway and Oligarchic growth are finding that the timescale for growing planetary embryos is vastly different at 1 and 3 au, such that embryos may never have time to grow at 3 au before the gaseous nebula dissipates (Minton and Levison 2014, Carter *et al.* 2015). Thus, a model that does not require embryo growth at 3 au may be necessary to avoid this problem.

Similarly, the migration of the Giant Planets serves as a mechanism to replenish the supply of planetesimals into the Terrestrial Planet region. Models showing the slow embryo growth at 3 au, also show rapid depletion of planetesimals inside of 1 au, which can be problematic as planetesimals are critical for damping the orbits of the terrestrial planets through the last stages of their growth (O'brien *et al.* 2006). This replenishment of planetesimals provided by giant planet migration can help to damp the orbits of the forming planets, that might otherwise be far too dynamically excited to match the constraints of our current system (see Brasser *et al.* 2013).

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