MIXING OF THE ASTEROID BELT DUE TO THE FORMATION OF THE GIANT PLANETS.

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Introduction: The asteroid belt is observed to be a mixture of objects with different compositions, with volatile-poor asteroids (mostly S-complex) dominant in the inner asteroid belt while volatile-rich (mostly C-complex) asteroids dominate the outer asteroid belt. While this general compositional stratification was originally thought to be an indicator of the primordial temperature gradient in the protoplanetary disk, there is growing evidence that that meteorites believed to originate from those different types of asteroids appear to come from very distinct reservoirs, with distinct isotopic and elemental signatures [1,2,3]. This is suggestive, but by no means guaranteed, that the ordinary and carbonaceous chondrites originated in well separated locations in the Solar System.

A few years ago, it was suggested that a dramatic migration of Jupiter into the inner Solar System may provide a way to implant outer Solar System material into the asteroid belt [4,5]. However, this model was missing an important earlier piece of physics, how the giant planets actually formed. This is because, at the time, there was no dynamically self-consistent model for forming the giant planets.

In recent years, theories surrounding the formation of small-bodies and planets have been undergoing a radical shift. Particles with stopping times comparable to their orbital times, often called “pebbles” (although may they range from sub-centimeter to decimeter sizes), interact with gaseous protoplanetary disks in very special ways. Gas drag can first concentrate the pebbles, allowing them to gravitationally collapse and directly produce the planetesimal building blocks [6], and then drag will cause them to be efficiently accreted on to these planetesimals, rapidly producing larger planetary embryos and even gas giant cores [7]. Full dynamically self-consistent models can now show that giant planet can form in two stages, first pebble accretion can rapidly form 10-20 Earth mass rocky-icy cores large enough that they can efficiently accrete disk gas, and form the final gaseous planets [8].

Armed with this dynamically self-consistent model of planet formation we can investigate, how the process of giant planet formation will impact the surrounding planetesimal population, without requiring a dramatic migration of the giant planets.

Methods: We use the planet formation code LIPAD (the Lagrangian Integrator for Planetary Accretion and Dynamics) [9] to model to collisional and dynamical evolution of a solar system forming under these conditions. LIPAD is based upon the N-Body integrator SWIFT [10] but uses novel algorithms to statistically follow bodies that are too small and numerous to be handled in a traditional N-body integrator. This allows us to model how our system may have evolved starting from pebbles and planetesimals all the way to a mature planetary system.

To test the effect of giant planet formation in the asteroid belt we placed a population planetesimals in outer Solar System and allow them to accrete pebbles. To speed up runs and increase the number of runs we could carry out we began with 4 larger near Mars-sized planetesimal seeds to serve as the initial location of the giant planet cores. We place these seeds in positions expected to approximate the location of the giant planets before the late instability, i.e. either in their pre-Nice 2 initial conditions [11] or a bit more widely spaced. These compact initial conditions are consistent with where planets form in our comprehensive planet formation models [8]. We note that even if we begin the planetesimals in the pre-Nice initial conditions they tend to move due to their interactions with the other planetesimals and even with the pebbles, therefore the planets do not end up in the same positions.

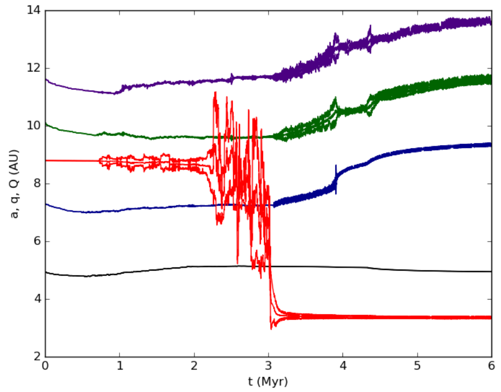
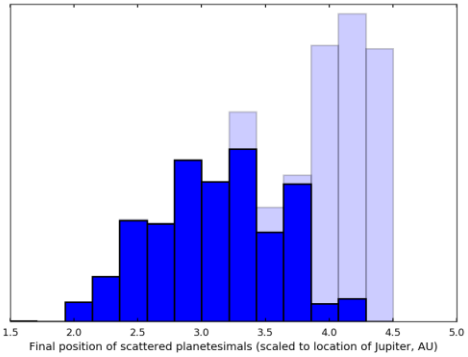


Figure 1: The semi-major axis, perihelion and aphelion of an outer Solar System body scattered into the asteroid belt (red) the planets (dark blue, dark green, indigo).

Results: As the giant planets cores grow via by pebbles accretion, they scatter surrounding planetesimals both inwards and outwards. In figure 1 we show the orbital evolution of an example asteroid. As the planetary embryos accrete pebbles (and later gas) then begin to dynamically excite and scatter nearby planetesimals. Once the giant planets grow large enough, the planetesimals chaotically diffuse, scattering from one planetary core to another.

Additionally, the giant planet cores move modestly because of interactions with the surrounding planetesimals as well as with interaction with the other growing cores. This can cause additional outer-Solar Systems asteroid to be scattered inwards. This is a very stochastic process with large variations between then runs. The planetesimals detach from Jupiter either due to small movements of Jupiter or due to gas drag or, more rarely, due to chaotic interactions with the asteroids already present within the asteroid belt. In figure 2 we show the distribution of remaining planetesimals scattered inwards, scaling the runs to the final location of Jupiter.



Additionally, we ran the resulting distribution in the presence of the current Juipter/Saturn locations to observe what would be stable in the current Solar System.

Figure 2: The distribution of planetesimals, scaled to the final location of Jupiter. In light blue show the original distribution of implanted planetesimals, dark blue shows those objects that are stable for 1 Myr for Jupiter/Saturn in their present day configuration.

Notes on the formation of Ceres. Of particular interest in this system is Ceres. Ceres is observed to have ammonia on its surface, a material believed to be from the very distant outer Solar System [12]. In our model, we have two possible explanations for Cere's observed composition. First, as we observe particles transported into the inner Solar System from the entire giant planet forming area (although it is less likely to occur from the more distant regions), it is possible that Ceres is simply a member of that population. In this case, we should find many other small bodies in the asteroid belt with similar compositions. An alternative, and we believe more likely option, is that as Ceres, as the largest body in the asteroid belt, underwent a small amount of pebble accretion before being scattered inwards. The efficiency of pebble accretion strongly depends upon the planetesimal's size; therefore a Ceres sized body could accrete these pebbles that formed in the very distant parts of the Solar Nebula much more efficiently that the smaller counterparts [13,7]. Under this scenario, Ceres (and possibly the other large asteroids) would have compositional differences from the bulk of the asteroids.

Conclusions: We find that the pebble accretion model can successfully explain many attributes of the Solar System: an outer Solar System with a few giant planets and ice giants and a Kuiper belt [8], an inner Solar System with terrestrial planets, a small Mars, and a low mass asteroid belt [13] which, as described in this abstract consists of material mixed from the inner and outer Solar System. Furthermore, the asteroid belt can be excited after formation by excitation from embryos scattered from the terrestrial planet system, or by excitation by chaotic interactions between the giant planets [14]. This could potentially provide an alternative non-Grand Tack [3] solution to the origin of many C-complex bodies, including Ceres.

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