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Dynamical delivery of volatiles to the outer main belt

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ABSTRACT

We quantify the relative contribution of volatiles supplied from outer Solar System planetesimal reservoirs to large wet asteroids during the first few My after the beginning of the Solar System. To that end, we simulate the fate of planetesimals originating within different regions of the Solar System – and thus characterized by different chemical inventories – using a highly accurate integrator tuned to handle close planet/planetesimal encounters. The fraction of icy planetesimals crossing the Asteroid Belt was relatively significant, and our simulations show that planetesimals originating from the Jupiter/Saturn region were orders of magnitude more abundant than those stemming from the Uranus and Neptune regions when the planets were just embryos. As the planets reached their full masses the Jupiter/Saturn and Saturn/Uranus regions contributed similar fractions of planetesimals for any material remaining in these reservoirs late in the stage of planetary formation, This implies that large asteroids like Ceres accreted very little material enriched in low-eutectic volatiles (e.g., methanol, nitrogen and methane ices, etc.) and clathrate hydrates expected to condense at the very low temperatures predicted for beyond Saturn's orbit in current early solar nebula models. Further, a large fraction of the content in organics of Ceres and neighboring ice-rich objects originates from the outer Solar System.

1. Introduction

This manuscript addresses the nature of the volatiles that accreted into large wet asteroids, with Ceres as the largest representative of these objects. Volatile composition depends upon the solar nebula temperature. A recent model coupling astrochemistry and astrophysics concluded that large asteroids in the outer Asteroid Belt (hereafter OAB) formed within the snow line and accreted a mixture of water and ammonia hydrates (Dodson-Robinson et al., 2009). The recent detections of water ice at 24 Themis (Campins et al., 2010; Rivkin and Emery, 2010) and 65 Cybele (Licandro et al., 2011) support this model. On the other hand, the Dodson-Robinson et al. model suggests that the conditions of the solar nebula between 2.5 and 3 AU were not suitable for the condensation of a variety of hydrocarbons, while the aforementioned studies also detected organics at 24 Themis and 65 Cybele. This implies that these organics may have been supplied by an external source.

Planetesimal migration across the Solar System is demonstrated by comets and Centaurs. Recent measurements of oxygen isotope ratios indicate that no more than 20% of water found in chondrites comes from the outer Solar System (Alexander et al., 2011), although a recent D/H measurement obtained at comet Hartley 2 by the Herschel Observatory (Hartogh et al., 2011) is consistent with D/H ratios found at Earth and CI chondrites. Hence, the consequences of planetesimal migration in terms of mixing the early Solar System chemistry remain to be understood in greater detail. Mousis and Alibert (2005) suggested that meter-sized planetesimals originating from as distant as the transneptunian region could have been passively transported by gas drag in the turbulent solar nebula. Such migration could have been rapid and adiabatic, so that that mechanism could have delivered clathrate hydrates and low-eutectic species such as methanol hydrates to the inner Solar System. The geophysical implications of such a scenario were highlighted by Castillo-Rogez and McCord (2010) who pointed out that ammonia and methanol hydrates could act as antifreeze and help preserve a deep ocean in Ceres. The preservation of the chemical integrity of that material during delivery toward the inner Solar System remains to be demonstrated though.

In this study we investigate the fate of larger planetesimals ejected from the reservoirs in the gaps between the jovian planets. These planetesimals are expected to be a few km or tens of km (see Mosqueira et al. (2010) for a review on this topic) in diameter. Comets are representatives of these populations and are generally 1–10 km in size. As such, these objects have been relatively less affected by thermal processing than the 10-meter sized planetesimals considered in Mousis and Alibert (2005), see Turner et al. (2012).

The goal of this study is to quantify the relative amount of planetesimals that migrated from different source regions in the

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outer Solar System to the Asteroid Belt – where they could then be accreted by asteroids in the early days of their formation. We simulate the fate of planetesimals traveling across the Solar System during the first 5 My following the formation of the Solar System for two sets of masses: when the giant planets are just cores or embryos, and for full-grown planets. These two "end members," borrowing a term from geology, will help bound the problem by providing a first-order idea on the origin of the volatiles that accreted into the Asteroid Belt.

First we present the modeling approach, which is based largely upon previous work by Grazier et al. (1999a,b) in Section 2. We then track the fate of planetesimals migrating toward the inner Solar System during the first 5 My after the beginning of its formation, while large asteroids are accreting. We present results in Section 3, and discuss their implications in Section 4.

2. Method

The numerical method used in our simulations is a truncation-controlled, roundoff minimized 13th order modified Störmer integrator that employed a roundoff error minimization scheme that we call "significance-ordered computation" (Grazier et al., 2005a,b). Based upon previous test results (Grazier et al., 1999a, 2005b) over the span of a 5 My integration, the expected total system energy error was $\mathcal{O}(10^{-12})$, and the expected position error of the planets was $\mathcal{O}(10^{-8})$ radians.

The integrator uses a time step-varying approach to handle close planet/planetesimal encounters (Grazier et al., 2013). Whenever a planetesimal underwent a close encounter with a jovian planet, entering its gravitational sphere of influence (Danby, 1988), the simulation code stored heliocentric state vectors – from which orbital elements are easily calculated – for the planetesimal as well as all the massive objects in the simulation. The heliocentric state vector for the planetesimal alone was stored upon exit from the sphere of influence. By storing planetesimal entry and exit state vectors for each planetary close encounter, encounters with "interesting" behaviors can readily be examined, re-integrated, even visualized in closer detail. Coupled with both planet and planetesimal state vectors stored at regular intervals, we are able to display the entire orbital history of any particle – or statistics of the ensemble – for the entire simulation. Planetesimals are removed from the simulations by colliding with the Sun or jovian planets, or when they are ejected from the Solar System (Grazier et al., 2013).

We simulated the trajectories of 2000 massless particles in each of the jovian planet and jovian embryo inter-planet gaps. In the case of the embryos, initial masses for Jupiter (Nettelman, 2011) and Saturn (Hubbard et al., 2008) were 15 Earth masses, while those for both Uranus and Neptune were 1 Earth mass (Helled et al., 2011). For the initial particle orbits in each gap the particle semi-major axes were chosen from a normal distribution with mean equal to the average of the semi-major axes of the adjoining planets, and the 3σ points to coincide with the semi-major axes of the adjoining planets. Particle inclinations were also distributed normally, with mean 0 degrees and standard deviation 5 degrees (prograde orbits only). The eccentricities were chosen randomly, between 0 and 1, from a negative exponential distribution with an e-folding constant of 0.1. The remaining orbital elements ranged from 0 to 360 degrees and were chosen from uniform distributions. For a more detailed description of the initial particle distribution, see Grazier et al. (1999a).

We simulated the trajectories and evolution of particles for up to 5 My (unless they were removed from the simulation first): the rationale for this timeframe is that Ceres is believed to have accreted in less than 5 My (Weidenschilling, 2008; see Castillo-Rogez and McCord (2010) for a review), after which the Asteroid Belt surface density decreased significantly. Hence, material implanted in the Asteroid Belt over a longer period could have contributed to replenishing the belt (e.g., Levison et al., 2009), but could not contribute significantly to increasing the asteroid mass. Also, Ceres' differentiated interior – inferred from shape data, (Thomas et al., 2005) – is best explained as the consequence of heat supplied by short-lived radioisotope decay, i.e., during the first My following the accretion of the asteroid (Castillo-Rogez and McCord, 2010). Encounters with comets at a later stage may have contributed in shaping Ceres' surface and geological history, but they probably did not contribute to the overall internal evolution of the object.

The simulations on which we report ignore the role that jovian planetary migration may have had on the evolution of particles in the inter-planet gaps. There is no universal agreement upon the distance that the jovian planets migrated, or even the direction, with some results suggesting the jovians migrated inwards (Franklin et al., 2004; Li et al., 2011), some outwards (Gomes et al., 2005), some both (Walsh et al., 2011). Some of the results reported in these recent studies are, in fact, mutually-exclusive. Clearly planetesimal evolution within the inter-planet gaps would have occurred while the jovian planets were accreting material and increasing in mass. By performing simulations with both full-mass jovian planets, and jovian embryos, the end members of the mass spectrum, we can infer the evolution of any planetesimal swarm for intermediate masses of the jovian planets – assuming that they arrived at their present locations with appreciable planetesimal mass remaining in the inter-planet gaps.

We also ignore the effect of gas drag in these simulations, though, in Section 3, we examine the results of two simulations that integrated identical input particle ensembles – one simulation modeling gas drag and one omitting gas drag. We found that, although there are some interesting differences in the dynamics, the inclusion of gas drag does not impact the qualitative results of this particular study significantly. We also do not model the role of solar radiation pressure—a potentially important, but rarely modeled, effect.

In a previous paper (Grazier et al., 1999a), we developed a kinetic theory that provided a reasonable estimate of how quickly the planetesimal ensembles in each inter-planet gap would evolve. In those simulations we did not model close approaches between planets and planetesimals, the particles were merely removed from the simulation upon entry into a planet's gravitational sphere of influence. While those simulations showed that particle evolution can be driven by resonant effects, and even distant gravitational perturbations by large jovian planets, particle trajectories still evolve most dramatically during close approaches to planets–which we did model in the simulations on which we report here. In the present case, our kinetic theory calculation provides an estimate of the time to first encounter with a planet – an encounter very likely to perturb a planetesimal out of its zone of origin – especially in the case of the Jupiter/Saturn zone – and, in particular, in the full-mass simulations.

In the previous work, we estimated that the average time τ that it took for a particle to be removed from the simulation by collision with a planet was:

$$\tau = \frac{(\Delta v)^3}{\pi n \langle GM \rangle^2},$$

where Δv represents the average velocity difference between particles and bounding planets, and n represents the number density of colliders – estimated using a volume appropriate to our initial planetesimal distribution (for a more detailed description of the method, see Grazier et al., 1999a). $\langle GM \rangle$ is the average GM of the bounding planets and, based upon the equation above, the average