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Is the Grand Tack model compatible with the orbital distribution of main belt asteroids?

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ABSTRACT

The Asteroid Belt is characterized by the radial mixing of bodies with different physical properties, a very low mass compared to Minimum Mass Solar Nebula expectations and has an excited orbital distribution, with eccentricities and inclinations covering the entire range of values allowed by the constraints of dynamical stability. Models of the evolution of the Asteroid Belt show that the origin of its structure is strongly linked to the process of terrestrial planet formation. The Grand Tack model presents a possible solution to the conundrum of reconciling the small mass of Mars with the properties of the Asteroid Belt, including the mass depletion, radial mixing and orbital excitation. However, while the inclination distribution produced in the Grand Tack model is in good agreement with the one observed, the eccentricity distribution is skewed towards values larger than those found today. Here, we evaluate the evolution of the orbital properties of the Asteroid Belt from the end of the Grand Tack model (at the end of the gas nebula phase when planets emerge from the dispersing gas disk), throughout the subsequent evolution of the Solar System including an instability of the Giant Planets approximately 400 Myr later. Before the instability, the terrestrial planets were modeled on dynamically cold orbits with Jupiter and Saturn locked in a 3:2 mean motion resonance. The model continues for an additional 4.1 Gyr after the giant planet instability. Our results show that the eccentricity distribution obtained in the Grand Tack model evolves towards one very similar to that currently observed, and the semimajor axis distribution does the same. The inclination distribution remains nearly unchanged with a slight preference for depletion at low inclination; this leads to the conclusion that the inclination distribution at the end of the Grand Tack is a bit over-excited. Also, we constrain the primordial eccentricities of Jupiter and Saturn, which have a major influence on the dynamical evolution of the Asteroid Belt and its final orbital structure.

1. Introduction

The Asteroid Belt is challenging to understand but is critical for studies of the formation and early evolution of the Solar System. The orbital configuration of the Asteroid Belt is believed to have been established in two phases. The first phase dates back to the first few million years of Solar System's formation and should be studied in conjunction with the formation of the inner and outer planets, especially Jupiter and Saturn. The second phase occurred when the Asteroid Belt witnessed a Giant Planet instability, long after the damping effects of the gaseous Solar Nebula had dissipated

In general, simulations of the dynamical re-shaping of the Asteroid Belt are made in conjunction with the formation of the inner planets. The first simulations of terrestrial planet formation (Chambers and Wetherill, 1998) included a set of planetary embryos uniformly distributed in the inner region of the Solar System with orbits initially dynamically cold (low eccentricity and inclination). Through numerical integrations of the equations of motion of these embryos, adding a model of accretion by collisions, the system evolves to form planets in the inner region of the Solar System on stable orbits. While early results about the formation of terrestrial planets were promising, one of the problems found in these integrations was related with the final eccentricities of the planets, which were systematically larger than the real ones. The models

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produced more promising results when the presence of a substantial population of planetesimals was also accounted for; in fact, the dynamical friction exerted by the planetesimals acted to decrease the excitation of the planet's final orbits (Chambers, 2001; O'Brien et al., 2006).

An important ingredient was the presence of Jupiter, which should have completed its formation much earlier than the inner planets (Chambers, 2001; Chambers and Wetherill, 1998; Petit et al., 2001). Primarily, the influence of Jupiter on the Asteroid Belt is to promote destructive collisions (fragmentation) rather than constructive collisions (accretion) (Petit et al., 2002). However, Jupiter alone can not excite the eccentricity of planetesimals so much as to explain the current excited orbits of asteroids (Petit et al., 2002). In addition, there is significant diversity in the physical properties of asteroids found in the Main Asteroid Belt, but their main taxonomic classes are found in roughly overlapping distributions – although S-class bodies predominate in the inner regions and C-class bodies in the outer regions (see DeMeo and Carry, 2014). The solution of these issues has been attributed to the original presence of planetary embryos in the Asteroid Belt (O'Brien et al., 2007; Petit et al., 1999). These embryos, once excited by Jupiter, would have scattered the orbits of the planetesimals. In the end, the Asteroid Belt would have been depleted of planetesimals and totally devoid of embryos.

Despite the many successes in the modeling of the terrestrial planets and Asteroid Belt by the simulations described above, systematic problems persisted. The planet formed in the approximate region of Mars systematically showed a much larger mass than the real Mars (see Raymond et al., 2009). An experiment by Hansen (2009) found that if there is sharp outer edge in the initial mass distribution of solids at about 1.0 AU, then the models consistently reproduce the mass of Mars.

Walsh et al. (2011) proposed a mechanism to modify the original mass distribution of solids and produce the truncated disk explored by Hansen (2009), by accounting for the early migration of Jupiter and Saturn when they were still embedded in the gaseous proto-planetary disk. An outcome found in many hydrodynamical models (D'Angelo and Marzari, 2012; Masset and Snellgrove, 2001; Morbidelli et al., 2007; Pierens and Nelson, 2008; Pierens and Raymond, 2011) of the interaction between giant planets and gaseous disks is that the type-II inward migration of a Jupiter-mass planet is halted and even reversed when a second, less massive planet, is formed external to the first one. This provides the explanation for why Jupiter did not migrate to very close the Sun, as is seen for giant planets in many other planetary systems (Cumming et al., 2008; Udry and Santos, 2007). Instead, Jupiter would have migrated first inwards, then outwards. Because of the change in direction of the orbital motion of Jupiter (a "tack" in sailor's jargon), the Walsh et al. (2011) model is named the "Grand Tack". The timing of the formation of Saturn is constrained by the mass distribution of the terrestrial planets, which are best reproduced when Jupiter reverses migration at 1.5 AU and truncates the disk at 1 AU.

The migration of Jupiter would have strongly affected any planetesimals formed in the present-day Asteroid Belt, with a primary consequence of substantially depleting the entire region of small bodies. The inward migration phase primarily pushes the asteroids originally inside of Jupiter's orbit (named "S-class" in Walsh et al., 2011) down to lower semimajor axes (inside of 1 AU), though Walsh et al. (2011) found that about 10% of these bodies are scattered outward onto orbits with semimajor axis a between 4 and 10 AU. During the outward migration of Jupiter and Saturn, these bodies are encountered again, and about 1% are scattered back into the Asteroid Belt. Meanwhile Jupiter and Saturn eventually encounter primitive planetesimals (titled "C-class" in Walsh et al., 2011), and a fraction of a percent of these are also scattered into the Asteroid Belt. This provides, at the time when the gas nebula has dispersed, a final belt which is depleted in mass by a factor of about 1000, that contains two different classes of bodies partially mixed in heliocentric distance and with orbits excited in eccentricities and inclinations (although the final eccentricity distribution does not match well the current one, as discussed below).

Numerous constraints, such as the ages of the last impact basins on the Moon (Bottke et al., 2007), the impact age distribution of HED meteorites (Marchi et al., 2013), and the small total chondritic mass accreted by the Moon since its formation (Morbidelli et al., 2012), point to an epoch of increased bombardment in the inner Solar System about ~400 to 700 Myr after the removal of gas from the proto-planetary disk (whereas the Grand Tack happened before the removal of the gas). This period of increased bombardment is usually called "Terminal Lunar Cataclysm" or "Late Heavy Bombardment" (LHB) (see Hartmann et al., 2000; Chapman et al., 2007, for reviews), and we will adopt the LHB nomenclature here. The origin of the LHB has been linked to a dynamical upheaval in the outer Solar System frequently referred to as the "Nice model" (Tsiganis et al., 2005; Gomes et al., 2005; Levison et al., 2011; Bottke et al., 2012). During this dynamical upheaval the giant planets would have suffered instability and a period of mutual close encounters that radically changed their orbits. In turn, the orbital change of the giant planets would have severely affected the distribution of the asteroids in the main belt (Morbidelli et al., 2010). The best guess on when this instability occurred, from various constraints, is 4.1 Gyr ago (Bottke et al., 2012; Morbidelli et al., 2012).

This is important because the final Asteroid Belt in Walsh et al. (2011) lacks objects with small eccentricities. Indeed, according to the Grand Tack model, the eccentricity distribution expected for the Asteroid Belt at the time when the gas nebula dispersed, some 3–10 Myr after the emergence of first solids and roughly 4.5 Gyr ago, peaks around 0.4. On the other hand, the current distribution of the Asteroid Belt peaks around 0.1 (Morbidelli et al., 2016). It has never been studied whether the Grand Tack final distribution could evolve to one similar to what we see today due to the perturbations caused by the giant planet instability during the Nice Model. The goal of this paper is to present such a study.

In this work, we will study in detail the evolution of the Asteroid Belt orbital structure, from the end of the Grand Tack model to the giant planet orbital instability, through the instability phase, and finally during the last ~4 Gyr until today.

This work will therefore unfold as follows: Section 2 explains our Solar System's configuration and the method used for the numerical simulations. In Section 3 we discuss the dynamical evolution of the Asteroid Belt throughout the various phases of the Solar System's evolution, as well as the influence of the primordial eccentricities of Jupiter and Saturn on the final structure of the Asteroid Belt. Finally, Section 4 summarizes the main conclusions of this paper.

A complementary study, approaching the problem from a different perspective, has been recently presented in Roig and Nesvorný (2015). We will compare our results with theirs at the end of Section 3.2.

2. Methods

Our numerical simulations contain five planets, Venus, Earth, Mars, Jupiter, and Saturn (all with their current masses), plus 10,000 massless particles representing the final outcome of the Asteroid Belt in the Grand Tack simulations (described below). Uranus, Neptune, and the putative extra ice giant invoked in Nesvorný and Morbidelli (2012) are not included in any of our simulations (the same applies for the planet Mercury). These planets are indeed too far from the Asteroid Belt to have any important direct effect on its structure. A caveat, however, is that in some simulations the extra ice giant is sent temporarily onto an Asteroid