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Dynamical evolution of the Earth–Moon progenitors – Whence Theia?

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ABSTRACT

We present integrations of a model Solar System with five terrestrial planets (beginning ~30–50 Myr after the formation of primitive Solar System bodies) in order to determine the preferred regions of parameter space leading to a Giant Impact that resulted in the formation of the Moon. Our results indicate which choices of semimajor axes and eccentricities for Theia (the proto-Moon) at this epoch can produce a late Giant Impact, assuming that Mercury, Venus, and Mars are near the current orbits. We find that the likely semimajor axis of Theia, at the epoch when our simulations begin, depends on the assumed mass ratio of Earth–Moon progenitors (8/1, 4/1, or 1/1). The low eccentricities of the terrestrial planets are most commonly produced when the progenitors have similar semimajor axes at the epoch when our integrations commence. Additionally, we show that mean motion resonances among the terrestrial planets and perturbations from the giant planets can affect the dynamical evolution of the system leading to a late Giant Impact.

1. Introduction

Significant effort has been placed in determining the origins of the bodies within our Solar System. One of the most perplexing areas of study is the formation of Earth's moon, and more generally, of the Earth–Moon system. Several theories have been explored, including five scenarios that have garnered serious study by the scientific community over the past few decades. These scenarios include a fission wherein the Moon split from a rapidly rotating Earth, co-accretion of the Earth and Moon as a binary pair, capture of the Moon as a renegade planet, precipitation of the Moon from the Earth caused by a intense bombardment of small planetesimals, and a Giant Impact resulting from a collision of a Mars-sized or larger object with the Earth.

The reigning explanation is that the Moon comes from a Giant Impact on the Earth from a Mars-sized (Hartmann and Davis, 1975; Cameron and Ward, 1976) or larger object (Cameron, 1997, 2000; Canup, 2012), although a smaller impactor may also be possible (Ćuk and Stewart, 2012). This theory rises to the top as it provides a sufficient explanation to many characteristics of the Earth–Moon system, most notably the amount of angular momentum residing in their mutual orbit and in the Earth's rotation, differences in mean densities of the two bodies together with compositional similarities between the Moon and the Earth's mantle (cf. Herwartz et al., 2014), and variations in comparative radioisotopic ratios that all suggest a formation during the late stage of planetary accretion. During this late stage, it is very likely that the terrestrial region was fairly clear of large objects based upon numerical models of the duration of terrestrial planet growth (Chambers, 2013). Chambers (2013) demonstrated that 3–5 terrestrial planets could have formed in the Solar System based on a new framework considering the effects of fragmentation and hit-and-run collisions. Specifically, Chambers shows that a 5 terrestrial planet system can persist through a full planetary growth simulation (Fig. 3 of Chambers, 2013). Other works (Jacobson et al., 2014; Izidoro et al., 2014; Walsh and Morbidelli, 2011; Brasser and Morbidelli, 2011; Chambers, 2007; O'Brien et al., 2006) have also shown that the number of terrestrial planets possible is consistent with the 3–5 estimate. In the case of a 5 planet model, the extra planet could have formed between the orbits of present day Venus and Mars.

Theories on the details of the Giant Impact hypothesis continue to be innovated and investigated further. Recent scenarios include: a hit-and-run scenario wherein a 30°–40° collision angle is preferred (Reufer et al., 2012), variations on the angular momentum of the Earth–Moon system following the impact (Ćuk and Stewart, 2012), and variations upon the scaled impact parameter (Canup, 2012). The newest scenarios (Ćuk and Stewart, 2012; Canup, 2012) invoke special conditions that allow for a Moon-forming impact, but the conditions to arrive at these scenarios may prove constraining. Ćuk and Stewart (2012) requires that the proto-Earth be nearly formed (~0.99 $M_\oplus$) and spinning at a rate near the breakup threshold to allow a smaller projectile to produce the protolunar disk. The alternate scenario proposed by Canup

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(2012) invokes a collision between similar-sized progenitors and requires that the impact angle to be less oblique than previously indicated.

Other previous inquiries (Wetherill, 1986; Chambers and Wetherill, 1998; Chambers, 2001) suggest that planetary accretion is largely completed in a few tens of millions of years, with the early heavy bombardment lasting about 100 Myr. The effects of giant impacts are largely stochastic and typically produce a large rotational angular momentum (Safronov, 1966; Lissauer and Safronov, 1991; Lissauer et al., 2000, and references therein). Terrestrial planet formation and the consequences of large impacts have been active areas of inquiry that have produced interesting and ingenious solutions to specific problems (Agnor et al., 1999; Kokubo et al., 2006; Kokubo and Ida, 2007; Kokubo and Genda, 2010; Raymond et al., 2006, 2009; Morishima et al., 2008, 2010; Hansen, 2009; Elser et al., 2011; Walsh and Morbidelli, 2011). Early simulations with a SPH (smooth particle hydrodynamics) code to characterize the impact suggested a mass ratio of the colliding bodies of 7:3 (Cameron, 1997, 2000). More recent studies using SPH simulations indicate a wider range of impacts could lead to successful Moon forming events (Canup and Asphaug, 2001; Canup, 2004; Canup et al., 2013).

Several studies based upon radiogenic dating (Brandon, 2007; Halliday, 2008; Borg et al., 2011; Bottke et al., 2014; Jacobson et al., 2014) suggest that the Moon-forming impact was late in the accretionary sequence, implying that at least five terrestrial planets persisted for tens of millions of years prior to a collision reducing the number. The best known observable to constrain the possible solutions is the dating of lunar samples. We place special emphasis on this constraint as the early estimates of this indicate the age of the lunar melt at 60–120 Myr (Taylor, 1975) after the formation of Calcium Aluminum Inclusions (CAIs) in the Solar System asteroids and updated measurements that obtain an age of 70–110 Myr (Touboul et al., 2007; Brandon, 2007; Halliday, 2008; Borg et al., 2011). However, other works (Yin et al., 2002; Jacobsen, 2005; Yu and Jacobsen, 2011) argue for a Moon-forming event earlier than 40 Myr. On the other hand, recent works (Jacobson et al., 2014; Bottke et al., 2014), which coupled dynamical simulations with geochemical constraints and impact age distributions on meteorites, concluded that the Moon formed 70–130 Myr after the CAIs.

Terrestrial planet formation simulations through the growth of planetesimals (Chambers, 2001, 2013) show that most planetary embryos are cleared in 30–50 Myr after the CAIs, typically leaving of 3–5 terrestrial bodies surviving. Radiometric dating of the Earth using ^{182}Hf–^{182}W suggests the bulk Earth to have formed $\sim$30–50 Myr after the CAIs (Kleine et al., 2009). While it is possible that more than five terrestrial planetary embryos were present during this time, dynamical formation simulations show this to be unlikely (Chambers, 2001, 2013; Raymond et al., 2006). Simulations also show that a total mass of 0.02–0.2 $M_\oplus$ in (small) planetesimals could be expected $\sim$30–50 Myr after CAIs (Jacobson and Morbidelli, 2014). Thus, from all these considerations it is likely that there was a significantly long timespan before the Moon-forming event, during which the inner Solar System contained five planetary bodies and a planetesimal population with a small total mass.

Following Rivera (2001, 2002), we model the late stage formation of the Solar System with five inner terrestrial planets and four outer giant planets whose dynamical evolution leads to a Giant Impact. Based on the dating of early Solar System events discussed above, we favor simulations that lead to a Giant Impact after 20–80 Myr have elapsed. This relative time window of 20–80 Myr considers the maximum range that is consistent with both the estimate of 30–50 Myr for our starting epoch (after the inner Solar System is reduced to five planetary bodies and a population of leftover planetesimals of negligible mass) and the 70–110 Myr range as the expected timing of the Giant Impact (Fig. 1).

The Solar System epoch that we are considering is subsequent to the dissipation of the gaseous component of the protoplanetary disk (which is estimated to have occurred a few million years after the beginning of planet formation), so we consider neither gas drag nor planetary migration in our simulations. However, in the Nice model, the Giant Impact occurs prior to the rearrangement of the giant planets induced by interactions with the disk of planetesimals in the Kuiper belt. Therefore, we perform some of our integrations using a configuration of the giant planets commensurate with the Nice model. Through these considerations, we seek to determine likely masses and orbital properties of the Earth–Moon progenitors at the epoch when our simulations begin. We outline our methodology in Section 2, present and interpret our results in Section 3, and provide our conclusions in Section 4.

2. Methodology

2.1. Starting parameters

In most of our integrations, the major planets (excluding the Earth–Moon system) begin with orbital elements from a well-defined recent epoch. Following Rivera (2002), we use the orbital elements given in Table 1. Our Nice model simulations use different parameters for the giant planets. We make the following assumptions about certain properties of the proto-Earth and proto-Moon:

1. The sum of the masses of the proto-Earth and proto-Moon is equal to the present Earth–Moon system. The sum of angular momenta of the proto-Earth and proto-Moon (primarily in their motions about the Sun) is equal that of the current Earth–Moon system.
2. A relationship of equipartition of orbital excitation energy exists to describe the eccentricities of the Earth–Moon progenitors.
3. The proto-Moon originated from the general neighborhood of the proto-Earth. Specifically, in most of our simulations we place the starting orbit of the proto-Moon between the orbit of Venus and slightly exterior to the orbit of Mars. However, we also present some simulations in which the proto-Moon begins as close to the Sun as 0.44 AU and as distant as 2.18 AU.

These assumptions are driven by observational evidence (e.g., dating of Apollo lunar samples and isotopic ratios) and current theories pertaining to the formation of the Solar System. The most general set of possible parameters is large, and we investigate only a small fraction in order to determine the general trends and processes present. We use the work of Rivera (2002) to begin our investigation, and we expand his results by considering much larger regions of parameter space for the semimajor axis and eccentricity

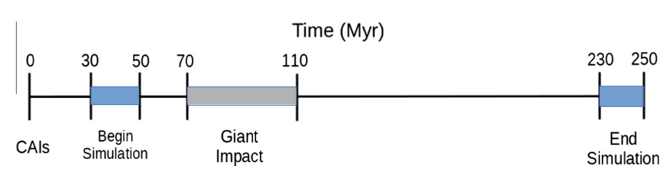

Fig. 1. Timeline illustrating our windows of interest with respect to the beginning of the Solar System. Our simulations begin subsequent to the bulk formation of the terrestrial planets, which is indicated to be at 30–50 Myr. The time range from 70 to 110 Myr represents the timing of the Giant Impact (from other studies), and the window of 20–80 Myr from the beginning of our simulations corresponds to the full range of allowed times of the bulk formation of proto-Earth and the Giant Impact.