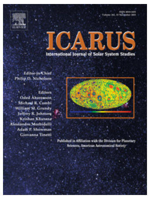
Icarus 275 (2016) 239–248

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Dynamical sequestration of the Moon-forming impactor in co-orbital resonance with Earth

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ARTICLE INFO

Article history:
Received 5 August 2015
Revised 1 April 2016
Accepted 3 April 2016
Available online 20 April 2016

Keywords:
Moon
Planetary formation
Planetary dynamics

ABSTRACT

Recent concerns about the giant impact hypothesis for the origin of the Moon, and an associated "isotope crisis" may be assuaged if the impactor was a local object that formed near Earth. We investigated a scenario that may meet this criterion, with protoplanets assumed to originate in 1:1 co-orbital resonance with Earth. Using *N*-body numerical simulations we explored the dynamical consequences of placing Mars-mass companions in various co-orbital configurations with a proto-Earth of 0.9 Earth-masses ($M_\oplus$). We modeled 162 different configurations, some with just the four terrestrial planets and others that included the four giant planets. In both the 4- and 8-planet models we found that a single Mars-mass companion typically remained a stable co-orbital of Earth for the entire 250 million year (Myr) duration of our simulations (59 of 68 unique simulations). In an effort to destabilize such a system we carried out an additional 94 simulations that included a second Mars-mass co-orbital companion. Even with two Mars-mass companions sharing Earth's orbit about two-thirds of these models (66) also remained stable for the entire 250 Myr duration of the simulations. Of the 28 2-companion models that eventually became unstable 24 impacts were observed between Earth and an escaping co-orbital companion. The average delay we observed for an impact of a Mars-mass companion with Earth was 102 Myr, and the longest delay was 221 Myr. In 40% of the 8-planet models that became unstable (10 out of 25) Earth collided with the nearly equal mass Venus to form a super-Earth (loosely defined here as mass $\geq 1.7\,M_\oplus$). These impacts were typically the final giant impact in the system and often occurred after Earth and/or Venus has accreted one or more of the other large objects. Several of the stable configurations involved unusual 3-planet hierarchical co-orbital systems.

1. Introduction

A conflict exists between dynamical models of very early solar system evolution and measurements of isotopic compositions of available solar system material. Dynamical models of recent decades have suggested that the first 50–100 Myr of terrestrial planet formation involved km-size planetesimals and large lunar- to Mars-mass protoplanets (Wetherill and Stewart, 1989,1993; Chambers and Wetherill, 1998; Chambers, 2001, 2013). During this period extensive scattering and mixing of these objects may have occurred, both within and between the inner and outer solar system. The prevailing theory for the formation of the Moon suggests that during this period a large protoplanet impacted Earth, resulting in the formation of the Moon out of debris from the collision (Hartmann and Davis, 1974, 1975; Cameron and Ward, 1976; Thompson and Stevenson, 1983; Canup, 2004, 2008, 2012; Stevenson and Halliday, 2014).

The isotopic composition of samples from Earth, the Moon, and enstatite chondrites from the innermost edge of the asteroid belt is all remarkably similar to each other and all dramatically different from isotopic compositions of ordinary chondrites, ureilites, and carbonaceous material from farther out in the solar system. Most numerical models have established that a moon formed by a giant impact would likely have a different proportion of impactor material than Earth (e.g. Canup, 2004, 2008; Stewart et al., 2013), and should thus have different isotope ratios than Earth if the impactor were formed from material originating even slightly farther out in the solar system. However, the measured terrestrial and lunar isotope ratios are essentially equal (within error bars) for potassium (Humayun and Clayton, 1995); chromium (Lugmair and Shukolyukov, 1998); titanium (Zhang et al., 2012); and oxygen (Young et al., 2016; also see Herwartz et al., 2014). Late accretion of material after formation of the Moon has been invoked to explain recently measured differences in lunar and terrestrial tungsten

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http://dx.doi.org/10.1016/j.icarus.2016.04.007

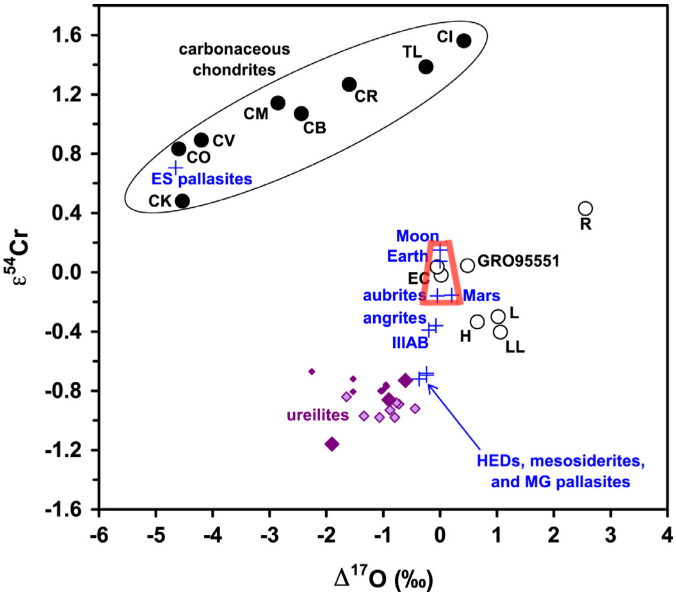

Fig. 1. Chromium and oxygen isotope systematics of sampled solar system objects. The red trapezoid highlights the small region containing all known rocks from the inner solar system and innermost edge of the asteroid belt, i.e. Earth, Moon, Mars, enstatite chondrites, and aubrites (often described as enstatite achondrites). The isotope crisis exists for all Moon-forming impactors not originating in the upper portion of the red trapezoid. The crisis worsens dramatically if source regions of the impactor include areas in the bottom or outside of the trapezoid, such as the main belt and outer solar system (ordinary chondrites, ureilites, carbonaceous objects, etc.). Other isotopic systems show similar patterns. [Figure is adapted from Warren (2011).]

isotope ratios (Touboul et al., 2015), which may have been more similar when the Moon formed.

Fig. 1 illustrates the data for chromium and oxygen isotopes. From this figure it is clear that the conflict between the dynamics and the geochemistry becomes more exacerbated if the Moon-forming impactor includes material from the main asteroid belt (e.g., ordinary chondrites, ureilites) or, far worse, carbonaceous chondrite-type material from the outer solar system. Melosh (2009, 2014), lamenting the apparent need for an isotopically identical impactor, declared this problem an “isotope crisis” that shed doubt on the giant impact model. Hartmann (1986, 2014) noted, however, that the original Hartmann-Davis (1974, 1975) model of a giant impact argued for a locally-grown impactor and noted that the solar system indeed still contains “local” objects (enstatite chondrites) with virtually Earth-like compositions. Hartmann (2014) thus argued that the answer to the isotope crisis is simply to accept empirically that any Moon-forming impactor was a very local object, which would solve most (but not all) of the isotope crisis. Indeed, a slight offset in lunar oxygen isotopes, relative to Earth has been reported (Herwartz et al., 2014; see their Fig. 1) in the direction of enstatite chondrite. Mastrobuono-Battisti et al. (2015) recently lent support to this when they showed that 10–20% of terrestrial planet giant impacts the impacting object is a local body compositionally similar to the planet being impacted. However, Kaib and Cowan (2015a, 2015b) showed that isotopic differences within the measured Earth–Moon range are to be expected in only 5% of potential Moon-forming impactors. Nakajima and Stevenson (2015) discuss circumstances related to the Grand Tack scenario (Walsh et al., 2011) that could increase the probability that the Moon-forming impactor had a similar oxygen isotopic ratio as Earth.

The other component of the isotope crisis has to do with the timing of the Moon-forming impact. If the impactor did originate very close to Earth (to ensure a more plausible likelihood of similar isotopic composition) then a mechanism may be needed to delay the impact. Age estimates for differentiation of Earth’s core (Halliday, 2008) and modeling of a late veneer chronology utilizing highly siderophile elements in Earth’s mantle (Jacobson et al., 2014) each generally agree that the Moon-forming impact must have occurred between roughly 70 and 130 Myr after condensation of Calcium Aluminum Inclusions (CAIs), the first solids in the solar system. Bottke et al. (2015) independently supported this Moon-formation time scale by combining dynamical simulations, geochemistry, and proposed asteroid impact age distributions. Thus, resolving the isotope crisis may not only require a very local impactor, but a mechanism to sequester this impactor very close to 1 AU for up to 130 Myr after CAIs. New research into the process of planet formation, described below, may suggest that both of these conditions could be natural consequences of the process of terrestrial planet formation and early evolution.

Discoveries of extrasolar planetary systems with numerous Earth-size planets (see catalogs by Burke et al., 2014; Rowe et al., 2015; Mullay et al., 2015) have brought renewed interest to the process of terrestrial planet formation and early evolution, and interactions of local planet-size bodies that may no longer exist in our solar system. Several independent groups have utilized modern techniques to examine these processes and found interesting results unseen in modeling from a generation ago (e.g., Safronov, 1972; Wetherill and Stewart, 1989, 1993). For example, Beaugé et al. (2007) modeled terrestrial planet formation in theoretical extrasolar systems and reported the formation of co-orbital planets, with a terrestrial planet forming in a 1-to-1 orbital resonance with a pre-existing giant planet. Collins and Sari (2009) found that relatively narrow terrestrial planet accretion zones within a protoplanetary disk can produce not just a single dominant protoplanet but numerous large protoplanets forming in mutual co-orbital resonance with each other. Cresswell and Nelson (2008, 2009) studied formation of somewhat larger planets (sub Neptune-mass) and found as many as 30% of their simulated planetary systems emerging with long-lived co-orbital planets. While co-orbital planets have not yet been confirmed (also see Goździewski and Konacki, 2006), these new theoretical models provide a type of qualitative motivation for the investigation described in this paper.

With an eye on the isotopic similarities between Earth and the Moon, Belbruno and Gott (2005, 2008) suggested that the Moon-forming impactor may have originated in co-orbital resonance with Earth until eventually escaping the resonance and impacting Earth. In this scenario the co-orbital resonance could provide the necessary dynamical safe haven to delay the timing of the last giant impact with Earth. We acknowledge that some isotopic properties may depend on the objects’ mass (e.g., Si; Armytage et al., 2012) and time-scale of accretion and differentiation (e.g., W; Kleine et al., 2004). Likewise, a co-orbital origin does not necessarily imply that Earth and a companion would have similar chemical properties. Chambers (2001, 2013) demonstrated that the late stage of planet formation is likely a stochastic process. Two objects growing in the vicinity of each other may not necessarily incorporate material from different regions in the same proportions. We point out that all models of Moon formation that invoke a Mars-mass impactor, regardless of where it originates, suffer from these same issues. In light of the recent work on co-orbital planet formation described above, we argue that of all the possible locations where a protoplanet isotopically similar to the proto-Earth could have formed the most plausible and/or least objectionable location may be within Earth’s co-orbital region.

With these caveats acknowledged, we ask, “If an isotopically similar protoplanet could form in co-orbital resonance with Earth would this provide a dynamical basis for delaying the moon-forming impact?”