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On the origin and composition of Theia: Constraints from new models of the Giant Impact

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ABSTRACT

Knowing the isotopic composition of Theia, the proto-planet which collided with the Earth in the Giant Impact that formed the Moon, could provide interesting insights on the state of homogenization of the inner Solar System at the late stages of terrestrial planet formation. We use the known isotopic and modeled chemical compositions of the bulk silicate mantles of Earth and Moon and combine them with different Giant Impact models, to calculate the possible ranges of isotopic composition of Theia in O, Si, Ti, Cr, Zr and W in each model. We compare these ranges to the isotopic composition of carbonaceous chondrites, Mars, and other Solar System materials. In the absence of post-impact isotopic re-equilibration, the recently proposed high angular momentum models of the Giant Impact ("impact-fission", Cúk, M., Stewart, S.T. [2012]. Science 338, 1047; and "merger", Canup, R.M. [2012]. Science 338, 1052) allow – by a narrow margin – for a Theia similar to CI-chondrites, and Mars. The "hit-and-run" model (Reufer, A., Meier, M.M.M., Benz, W., Wieler, R. [2012]. Icarus 221, 296–299) allows for a Theia similar to enstatite-chondrites and other Earth-like materials. If the Earth and Moon inherited their different mantle FeO contents from the bulk mantles of the proto-Earth and Theia, the high angular momentum models cannot explain the observed difference. However, both the hit-and-run as well as the classical or "canonical" Giant Impact model naturally explain this difference as the consequence of a simple mixture of two mantles with different FeO. Therefore, the simplest way to reconcile the isotopic similarity, and FeO dissimilarity, of Earth and Moon is a Theia with an Earth-like isotopic composition and a higher (~20%) mantle FeO content.

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1. Introduction

1.1. The Giant Impact and the isotopic conundrum

The favored model for the formation of the Moon is the "Giant Impact": during the last stage of terrestrial planet formation, planetary embryos of Moon- to Mars-size (approximately 0.01–0.1 Earth masses, M_E) collide in a sequence of massive mutual collisions – called Giant Impacts – until all or most of them have been accreted into a few, large rocky planets (e.g., Weidenschilling, 2000). In the Solar System, two "fully grown" rocky planets – Venus and Earth – formed, while two likely planetary embryos – Mercury and Mars – remained on stranded orbits (e.g., Hansen, 2009). A planetary embryo having between one fourth to two Mars masses (depending on the Giant Impact model; see below), called "Theia" after the mythological mother of the Greek Moon-goddess Selene, then collides with the almost fully formed, differentiated proto-Earth, a few 10 Ma after the formation of the Solar System. Such a Giant Impact can explain the observed physical properties of the Earth–Moon system: the high angular momentum, the iron-deficiency of the bulk Moon and the high mass ratio between the Moon and Earth (Hartmann and Davis, 1975; Cameron and Ward, 1976).

In the classical (or "canonical") Giant Impact simulations, most of the mass of the Moon is derived from Theia (e.g., Benz et al., 1986, 1989; Canup and Asphaug, 2001). Therefore, the Moon should chemically and isotopically reflect Theia. Recently, Hosono et al. (2013) and Karato (2014) have pointed out possible problems with the smoothed particle hydrodynamics (SPH) method that is used for most Giant Impact simulations, and have suggested that taking into account these problems might increase the fraction of proto-Earth-derived material in the Moon. In the absence of detailed simulations that quantify the extent of this

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effect, we will have to work with Giant Impact simulations as published in the recent literature.

While there are some chemical differences between the Earth and the Moon (e.g., the Moon has higher FeO relative to the terrestrial mantle, and is depleted in both volatile and siderophile elements relative to Earth; Jones and Palme, 2000), the Earth and Moon are isotopically identical in all elements which show substantial mass-independent stable isotope variations in meteorites, i.e. O, Ti, Cr and Zr (Wiechert et al., 2001; Zhang et al., 2012; Qin et al., 2010a,b; Akram, 2013). A small deviation (∼12 ppm) in the $\Delta^{17}O$ (see SOM for a definition of that notation) of Earth and Moon has recently been reported, which might either be a signature of Theia, or perhaps of a carbonaceous chondritic late veneer (Herwartz et al., 2014). The Earth and Moon also have an identical Si isotopic composition, which is however (mass-dependently) fractionated toward heavier isotopes, relative to all other Solar System materials (e.g., Georg et al., 2007; Fitoussi et al., 2009; Zambardi et al., 2013). Earth and Moon also have an identical Hf/W ratio, though within relatively large uncertainties (König et al., 2011), and a $\varepsilon^{182}W$ value that is indistinguishable (within uncertainties) from the terrestrial value, at least after correction for the contribution of the late veneer (Touboul et al., 2007, 2009, 2014; Willbold et al., 2011; Kleine et al., 2014). Hence, we are confronted with the "isotopic conundrum" that Theia must have been isotopically more Earth-like than any known (non-lunar) Solar System material. Can, or should we expect Theia to be isotopically similar to the Earth? Pahlevan and Stevenson (2007) suggested that the Earth–Moon isotopic similarity is the result of isotopic re-equilibration between the terrestrial magma ocean and the circum-terrestrial disk formed in the Giant Impact, via a common silicate vapor atmosphere. Unfortunately, this elegant solution to the isotopic conundrum seems to be problematic for several reasons (e.g., Melosh, 2009; Salmon and Canup, 2012; Pahlevan et al., 2011; Nakajima and Stevenson, 2014). We will therefore neglect the effects of such re-equilibration for the purpose of this article.

In the last few years, another possible solution to the isotopic conundrum has been put forward. New variants, or models, of the Giant Impact have been proposed, which predict a significantly lower fraction of Theia-derived material in the Moon than what was thought possible before. Reufer et al. (2012) presented the *hit-and-run model*, where a more massive ($0.2M_E$) Theia is partially disrupted by the collision, such that about half of its mass escapes to a heliocentric orbit after the Giant Impact. The resulting Moon-forming disk is not as enriched in Theia-derived material as in the canonical model. The angular momentum of the Earth–Moon system in the hit-and-run model was intentionally kept on the order of no more than 10–50% larger than its present value, and is thus relatively low compared to the high-angular momentum Giant Impact models discussed next. Canup (2012) extended the hit-and-run parameter space to somewhat higher masses and the correspondingly higher angular momentum, but much of the parameter space remains unexplored. Reufer et al. (2012) also introduced the parameter δf_T, to compare the relative abundances of the proto-Earth-derived (silicate) fractions in the Moon and the Earth's mantle. The parameter f_T is the fraction of "target" (proto-Earth) silicate material in the Earth (f_{TE}) and the Moon (f_{TM}), and $\delta f_T = (f_{TM}/f_{TE} - 1) \times 100\%$. Thus, a δf_T value of -100% indicates that the Moon is derived exclusively from Theia, while a δf_T value of 0% indicates that the Moon has exactly the same proto-Earth-derived (or Theia-derived) fraction as the Earth. We use this parameter here because it allows us to compare different Giant Impact models in a single graph, irrespective of absolute Theia-derived fractions in Earth and Moon. These fractions vary strongly between different Giant Impact models, but for the isotopic composition of Earth and Moon only the *deviation* of the two fractions from one-another is important, and it is this deviation which is expressed by δf_T. In the hit-and-run model, the typical δf_T value is about -35%, a significant improvement over the canonical model ($\delta f_T = -70\%$ to -90%). Negative values for δf_T dominate for most Giant Impact model runs, although in a few cases positive values have been observed, almost exclusively within the model from Canup (2012; see below). For simplicity, and as in Canup (2012), we will always discuss the absolute δf_T values ($=|\delta f_T|$), so that *low* $|\delta f_T|$ values indicate very *similar* Theia-derived fractions of Earth and Moon, while *high*

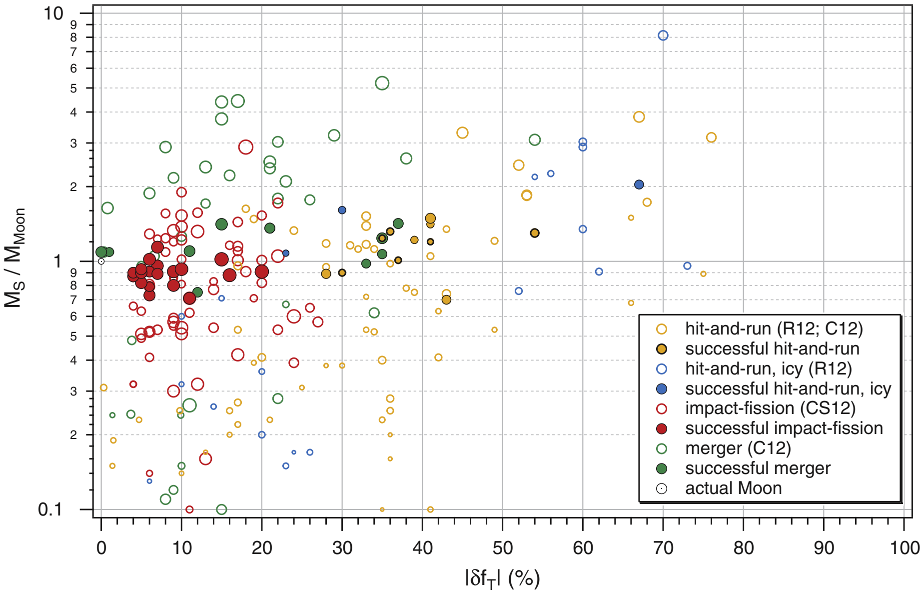

Fig. 1. Giant Impact simulation runs from the literature, from all three new models, plotting the resulting mass of the satellite vs. $|\delta f_T|$. Solid symbols represent simulation runs that were "successful", i.e., that resulted in a satellite with parameters comparable to those of the actual Moon (see main text), while open symbols represent all other ("unsuccessful") simulation runs. Symbol size corresponds to the final angular momentum of the Earth–Moon system after the Giant Impact. While the hit-and-run and impact fission models lead to relatively tight clusters at $|\delta f_T| = 35\%$ and 8%, respectively, the merger simulations show considerable scatter, from $|\delta f_T| = 0\%$ to 40%. Abbreviations in the legend: R12 = Reufer et al. (2012); C12 = Canup (2012); CS12 = Cúk and Stewart (2012). The symbol corresponding to the actual Moon is arbitrarily plotted at $|\delta f_T| = 0\%$ for comparison.

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