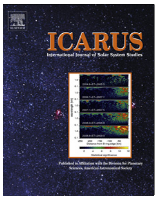
Icarus 226 (2013) 671–681

Contents lists available at SciVerse ScienceDirect

Icarus

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



Dynamical and collisional constraints on a stochastic late veneer on the terrestrial planets

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ARTICLE INFO

Article history:
Received 6 March 2013
Revised 18 June 2013
Accepted 18 June 2013
Available online 27 June 2013

Keywords:
Planetary formation
Planetary dynamics
Origin, Solar System
Accretion
Terrestrial planets

ABSTRACT

Given their tendency to be incorporated into the core during differentiation, the highly-siderophile elements (HSEs) in Earth's mantle are thought to have been accreted as a "late veneer" after the end of the giant impact phase. Bottke et al. (Bottke, W.F., Walker, R.J., Day, J.M.D., Nesvorny, D., Elkins-Tanton, L. [2010]. Science 330, 1527) proposed that the large Earth-to-Moon HSE abundance ratio can be explained if the late veneer was characterized by large ($D = 1000$–4000 km) impactors. Here we simulate the evolution of the terrestrial planets during a stochastic late veneer phase from the end of accretion until the start of the late heavy bombardment ~500 Myr later. We show that a late veneer population of $0.05M_{\oplus}$ dominated by large ($D > 1000$ km) bodies naturally delivers a $\sim 0.01M_{\oplus}$ veneer to Earth, consistent with geochemical constraints. The eccentricities and inclinations of the terrestrial planets are excited by close encounters with the largest late veneer bodies. We find the best agreement with their post-veneer orbits if either (a) the terrestrial planets' pre-veneer angular momentum deficit AMD_0 was less than about half of the current one AMD_{now}, or (b) $AMD_0 \leqslant AMD_{now}$ and the veneer was limited to smaller ($D_{max} \leqslant 2000$ km) bodies. Veneer impacts on Venus, Earth and Mars were mostly accretionary but on Mercury and the Moon they were mostly erosive. In ~20% of simulations an energetic impact occurred that could have removed $\geqslant 25\%$ of Mercury's mass, thereby increasing its iron mass fraction. We show that, due to the erosive nature of larger impacts, the Moon cannot accrete any material from objects larger than 500–1000 km. The large Earth-to-Moon HSE abundance ratio is naturally explained if the late veneer included large impactors ($D \gtrsim 500$–1000 km) regardless of their size distribution, as long as most of Earth's veneer came from large bodies. The spin angular moment imparted by stochastic late veneer impacts was far in excess of the current ones for Mercury and Venus, meaning that their post-veneer spin rates were much faster. The late veneer, if it included large impactors, was an accretionary phase for Venus, Earth and Mars but an erosive phase for Mercury and the Moon.

1. Introduction

The so-called "late veneer" phase in Earth's accretion is sandwiched between two far more dynamic epochs. The late veneer comes at the end of the giant impact phase of terrestrial accretion, which lasted 30–100 Myr (Kleine et al., 2009) and during which the growing Earth underwent numerous impacts with Moon- to Mars-sized planetary embryos (Wetherill, 1985; Chambers and Wetherill, 1998; Agnor et al., 1999; Chambers, 2001; Raymond et al., 2006, 2009). Thus, the late veneer probably represents accretion during the final clearing-out of planetesimals leftover from terrestrial accretion, starting after the Moon-forming impact and dwindling in time for ~500 Myr. After the end of the late veneer came the late heavy bombardment, a spike in the impact flux that lasted a few hundred million years (Tera et al., 1974; Wetherill, 1975).

Evidence for the late veneer comes from the existence of highly-siderophile elements (HSEs) in the mantles of Earth, Mars and the Moon. Simply put, HSEs are "iron-loving" elements that tend to partition into metal and should thus be removed from a planet's mantle during core formation. The abundance of HSEs on Earth imply that it accreted at least an additional 0.3–0.7% of an Earth mass of material with chondritic composition after the last core-forming event (Kimura et al., 1974; Day et al., 2007; Walker, 2009), presumed to be the Moon-forming impact (Benz et al., 1986; Canup and Asphaug, 2001). The concentration of HSEs in the lunar mantle is 20–40 times lower than the concentration in Earth's mantle (Day et al., 2007). As the Earth's mantle is about 70 times more massive than the Moon's, this naively implies that the Earth accreted ~1400–2800 times more mass in HSEs during the late veneer than the Moon. However, by taking into account the lunar crust as an

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0019-1035/$ - see front matter © 2013 Published by Elsevier Inc.
http://dx.doi.org/10.1016/j.icarus.2013.06.019

additional, possibly dominant, repository for HSEs (Walker et al., 2004), Schlichting et al. (2012) calculated a significantly higher total concentration of HSEs on the Moon. Schlichting et al. (2012) found a Earth-to-Moon HSE abundance ratio – meaning the ratio in the total masses, not concentrations, of HSEs in their mantles – of 150–700 (see also the discussion in Bottke et al. (2010), who favor a range from 200 to 1200). The large Earth/Moon HSE abundance ratio is problematic because the ratio of the physical cross sections of the Earth and the Moon is only 13.5. The measured concentration of HSEs in the martian mantle is similar to the Earth's (Walker, 2009; Brandon et al., 2012). Taking into account the relative sizes of their mantles, this implies that Earth accreted roughly 9 times more mass in its late veneer than Mars.

To date, two potential solutions to this problem have been proposed that make vastly different assumptions about the characteristic size of late veneer impactors. Bottke et al. (2010) showed that the large Earth/Moon HSE abundance ratio can be reproduced by a veneer population skewed toward large objects such that almost all of the HSEs are delivered by a few big impacts with $D > 2000$ km. The combination of the small number of impactors and the Earth's larger collisional cross section allow the Earth to accrete far more veneer mass than the Moon. This model is consistent with the observed patchiness in Tungsten isotopes in Earth's mantle (Willbold et al., 2011). In contrast, the model of Schlichting et al. (2012) requires a veneer made of very small ($D \sim 10$ m) planetesimals, which collisionally damp to very low eccentricities and thus increase the gravitational focusing factor of the Earth sufficiently to explain the Earth/Moon HSE abundance ratio. These small planetesimal could at the same time provide the required damping of the eccentricities and inclinations after giant impacts. Bottke et al.'s model is consistent with planetesimals being born big (Johansen et al., 2007; Morbidelli et al., 2009b) whereas Schlichting et al.'s model is consistent with collisional models that start from small planetesimals (Weidenschilling, 2011). Of course, all planetesimals must have undergone some collisional evolution by this point so it is unclear how the veneer size distribution relates to the initial one.

In this paper we explore the consequences of the "stochastic late veneer" (Bottke et al., 2010) model for the dynamics and collisional history of the terrestrial planets. We address the orbital excitation of the terrestrial planets, the collisional regime of veneer impacts on each planet, and the effect of the late veneer on planetary spins.

The orbital excitation of the terrestrial planets can be quantified using the normalized angular momentum deficit *AMD* (Laskar, 1997), which measures the difference in angular momentum of a set of orbits from coplanar, circular orbits with the same semimajor axes:

$$AMD = \frac{\sum_j m_j \sqrt{a_j}\left(1 - cos(i_j)\sqrt{1 - e_j^2}\right)}{\sum_j m_j \sqrt{a_j}}, \tag{1}$$

where a_j, e_j, i_j, and m_j refer to planet *j*'s semimajor axis, eccentricity, inclination with respect to a fiducial plane, and mass. The current *AMD* of the Solar System's terrestrial planets is 0.0018; we refer to this value throughout the paper as AMD_{now}.

Simulations of terrestrial planet formation have historically produced planetary systems that were overly dynamically excited, i.e., with $AMD > AMD_{now}$ (e.g. Chambers and Wetherill, 1998; Agnor et al., 1999; Chambers, 2001; Raymond et al., 2004). This problem was a result of numerical limitations. Including a large population of planetesimals mediated this discrepancy and produced planetary systems with $AMD \sim AMD_{now}$ (Raymond et al., 2006, 2009; O'Brien et al., 2006) because dynamical friction from the small bodies acts to damp random velocities in the larger ones. However, some high-resolution simulations show large increases in the orbital excitation of the entire system at late times by objects that represent less than 1% of the total system mass. For example, in the simulation illustrated in Figs. 2–12 of Raymond et al. (2006), a series of close encounters with a roughly lunar-mass embryo more than doubled the eccentricity of the system's Earth analog, and roughly doubled the mass-weighted eccentricity of the entire terrestrial planet system (see in particular Figs. 8, 9 and 11 in Raymond et al. (2006)).

The terrestrial planets' orbital eccentricities during the late veneer epoch are poorly constrained. A large-scale re-arrangement of the giant planets' orbits is thought to have occurred during the late heavy bombardment (the so-called "Nice model"; Tsiganis et al., 2005; Morbidelli et al., 2010). During this instability, secular resonances with the giant planets may have crossed the terrestrial planet region. If the orbits of Jupiter and Saturn evolved slowly the terrestrial planets' eccentricities and inclinations would have been excited to larger than the current values (Brasser et al., 2009; Agnor and Lin, 2012). However, scenarios that invoke rapid evolution of the giant planets' orbits adequately reproduce the architecture of both the giant and terrestrial planets (Brasser et al., 2009; Morbidelli et al., 2009a). Brasser et al. (2013) showed that if the terrestrial planets' *AMD* at early times was larger than about $0.7AMD_{now}$, then their eccentricities would have been over-excited by the giant planet instability. Given that chaotic diffusion tends to increase rather than decrease orbital excitation in time (Laskar et al., 1993), the only reasonable constraint that we can place is that the excitation of the terrestrial planets after the late veneer phase could not have been larger than this.

2. Simulations

Our simulations start immediately after the end of the giant impact phase of terrestrial accretion. At this stage there remained a substantial population of planetesimals too small to cause another core-forming impact on Earth. Bottke et al. (2010) argued that objects for which the diameter of the iron core was larger than the depth of the Earth's presumed magma ocean would trigger a differentiation event (Rubie et al., 2003) and thus constrained the maximum size of the veneer to have diameters $D < 2000$–4000 km.

We model this late veneer population by assuming that it follows a power law in size:

$$\frac{dN}{dD} \propto D^{-q}, \tag{2}$$

where d*N* is the differential number of objects in a bin of width d*D* and *q* is the size-distribution exponent. Bottke et al. (2010) found that the Earth/Moon HSE abundance ratio was best reproduced for $q = 1$–2 and maximum impactor size $D_{max} = 3000$–4000 km. We adopt the same parameter range with $q = 1$, 1.5 and 2 and $D_{max} = 2000$, 3000 and 4000 km, for a total mass in the veneer population of 0.05–$0.1 M_{\oplus}$.

To generate a population of late veneer impactors, we determined the size of each object by drawing from a size–frequency distribution with a fixed *q* value and *D* between 1000–4000 km. We neglected objects smaller than 1000 km because (1) they are too numerous to include a reasonable number of objects with an N-body approach, and (2) for $q \leqslant 2$ the total veneer mass is dominated by the largest objects such that the $D < 1000$ km population represents only about 1/4 of the total veneer mass. Although their dynamical influence is probably small, these small bodies may be very important in determining the Earth-to-Moon HSE abundance ratio, as we discuss in detail in Sections 7 and 8.

We assigned an orbit to each veneer particle, consistent with recent simulations of terrestrial planet formation, in particular Raymond et al. (2006) and Walsh et al. (2011). The semimajor axis