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Key Points:

- Mars experienced a singular large impact in its first ~130 Myr
- This event is most likely the primary source of the highly siderophile element abundance in the Martian mantle
- Mars' crustal hemispherical dichotomy and satellites may be a visible remnant of this impact

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A colossal impact enriched Mars' mantle with noble metals

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Abstract Once the terrestrial planets had mostly completed their assembly, bombardment continued by planetesimals left over from accretion. Highly siderophile element (HSE) abundances in Mars' mantle imply that its late accretion supplement was 0.8 wt %; Earth and the Moon obtained an additional 0.7 wt % and 0.02 wt %, respectively. The disproportionately high Earth/Moon accretion ratio is explicable by stochastic addition of a few remaining Ceres-sized bodies that preferentially targeted Earth. Here we show that Mars' late accretion budget also requires a colossal impact, a plausible visible remnant of which is the emispheric dichotomy. The addition of sufficient HSEs to the Martian mantle entails an impactor of at least 1200 km in diameter to have struck Mars before ~4430 Ma, by which time crust formation was well underway. Thus, the dichotomy could be one of the oldest geophysical features of the Martian crust. Ejected debris could be the source material for its satellites.

1. Introduction

Terrestrial planet formation, which includes such details as the effects of late accretion on the final compositional makeup of the planets, remains a long-standing problem in planetary science. In traditional dynamical models the terrestrial planets grow from a coagulation of planetesimals into protoplanets [Kokubo and Ida, 1998]. These objects eventually become dynamically unstable and subsequently evolve into a phase wherein planetary mergers through large impacts (or sometimes "giant impacts" in the sense of Earth's Moon-forming event) were commonplace [Hansen, 2009]. Consequently, these protoplanetary collisions eventually led to the observed terrestrial planet inventory [e.g., Chambers and Wetherill, 1998]. One of the predicted outcomes of giant impact models is that the Moon, Earth, and other inner solar system planets ought to have experienced a long history of what is termed "late accretion." That is, after core formation and initial separation of the silicate reservoirs (crust/mantle), leftover planetesimals on planet-crossing orbits are consumed by the terrestrial bodies as substantial mass supplements [Wetherill, 1975]. These highly energetic late accretion events strongly modulated the preservation of silicate crusts on the terrestrial planets and as such also provide a robust temporal upper limit on the earliest sustainable appearance of a biosphere in the inner solar system.

Evidence for such late addition to the masses of the inner planets is inferred from the abundance of highly siderophile elements (HSEs; Re, Os, Ir, Ru, Pt, Rh, Pd, and Au) in the mantles of Earth, Moon, and Mars. The proportions are chondritic relative to each other but greatly exceed their expected abundance after metal-silicate partitioning [Kimura *et al.*, 1974]. This indicates that either HSEs were delivered after core formation and silicate differentiation [Chou, 1978] or were left behind by inefficient metal-silicate partitioning at higher pressures and temperatures [e.g., Murthy, 1991, Richter *et al.*, 2015]. Here we explore the implications of the former.

The relative abundance accreted by the planets should scale as the ratio of their gravitational cross sections, if it is assumed that all the planetesimals have the same size and are far more numerous than the planets. For the Earth and the Moon this ratio is approximately 20. Instead, HSE abundance in the terrestrial and lunar mantles suggest that Earth experienced ~2 orders of magnitude more late accretion than the Moon, contrary to that proposed by theory [Day *et al.*, 2007; Day and Walker, 2015].

The high ratio of the terrestrial and lunar HSE mantle budgets led Bottke *et al.* [2010] to conclude that the size-frequency distribution of the remaining planetesimals from planet formation had to have been shallow even at large diameters ($D \geq 500$ km), and the majority of the mass delivered to the Earth came from a few large objects comparable in size to the asteroid 1 Ceres (diameter ~ 950 km) that yet lurked within the inner solar

system. The low population number of these large objects leads to a stochastic impact regime that statistically favors collisions with Earth [Sleep *et al.*, 1989].

The late accretion model to explain Earth's HSE budget is a subject of ongoing debate [e.g., cf. Touboul *et al.*, 2012, 2014; Willbold *et al.*, 2011, 2015; Righter *et al.*, 2015]; this dispute is no less vigorous for purported late accretion to Mars. Early analyses of HSEs in Martian meteorites suggested a late addition of 0.1 to 1 wt % to Mars [Kong *et al.*, 1999; Warren *et al.*, 1999]. Walker [2009] reported that Mars experienced a mass supplement of ~0.7 wt %, which is comparable to the 0.3 to 0.8 wt % proposed for Earth [Day *et al.*, 2016]. Interpretations of osmium isotope values in Martian meteorites seem to back this assertion by indicating that Mars accreted at least 0.5 wt % of material of chondritic composition after core formation [Brandon *et al.*, 2012; Day and Walker, 2015], with the most likely contribution being approximately 0.8 wt % [Day *et al.*, 2016].

A recent analysis of metal-silicate partitioning for the platinum group elements (HSEs minus Au and Re) in Martian meteorites, combined with theoretical partitioning models used to construct inverse models of Mars' mantle composition, shows that the concentration of these rare metals in the Martian mantle cannot be solely established by metal-silicate equilibration early in the planet's history [Righter *et al.*, 2015] because the long-term time-integrated Os concentration would be subchondritic, in violation of the evidence from Martian meteorites. In short, the amount of late accretion on Mars is still questioned, but given its existence on the Moon and the Earth and what we understand about the nature of late accretion and the dynamics in the inner solar system, it makes sense that Mars experienced something similar.

Recently, Brasser *et al.* [2016] combined N-body and Monte Carlo simulations to establish the nature of late accretion onto the terrestrial planets and the likely total mass accreted by the Earth and Mars when calibrated to lunar values. That work could not reproduce the high ratio between the mass accreted by the Earth and the Moon at greater than 99% confidence if the diameter of the largest planetesimals did not exceed 2000 km. The implication is that Earth's late accretion came predominantly from a single impact with a lunar-sized (~3500 km diameter) object between ~4500 Ma and 4400 Ma which delivered most of the HSEs presently lodged in the terrestrial mantle. In an alternative view, Sleep [2016] suggested that the HSEs were delivered during the giant impact (GI) that formed the Moon, obviating the need for a late accretion component. This assertion is, however, in contradiction with dynamical models [e.g., Wetherill, 1975; Raymond *et al.*, 2013] and geochemical analyses. On the other hand, the analysis of Brasser *et al.* [2016] neglected to survey the possible nature of late accretion on Mars, and to assess the likelihood that a single impactor could explain the Martian HSE abundances. In this study, we investigate that scenario in more detail.

Here we combined N-body and Monte Carlo simulations from Brasser *et al.* [2016] with the results of new Monte Carlo simulations to explain Mars's HSE budget. In our discussion of implications of our models for a singular large impact, we explicitly set out predictions of our results in the context of Martian composition and dynamical regimes, including both the origin of the crustal dichotomy and the Martian moons, Phobos and Deimos.

2. Methods

The Monte Carlo impact simulations undertaken for this study consisted of the following: Planetesimals with diameters that range from 1 km to 2000 km were randomly generated. The size-frequency distribution of the planetesimals was defined to be identical to that of the main asteroid belt because the oldest (>4.4 Ga) surfaces on the Moon and Mars, and possibly Mercury, exhibit the same shape of their distributions [Strom *et al.*, 2005; Fassett *et al.*, 2012; Werner, 2014]. This is a top heavy distribution and the majority of the mass resides in the largest bodies. It was assumed that each planetesimal has a density of 3000 kg m^{-3} and its mass is added to the total mass in planetesimals.

The total mass added to the terrestrial planets and the Moon depends on the amount of mass in remnant planetesimals from terrestrial planet formation, and on the impact probability of the planetesimals with the planets. From N-body simulations of the inner solar system after the Moon-forming impact, Brasser *et al.* [2016] compute the average impact probability of a planetesimal as 12% with Earth, 1.9% with Mars, and 0.5% with the Moon, respectively. The lunar value is barely affected by tidal evolution owing to the fact that the Moon's gravitational focusing is negligible. If in the Monte Carlo simulation a planetesimal strikes one of these three target bodies, its mass is added to the total accreted mass because for simplicity we assume

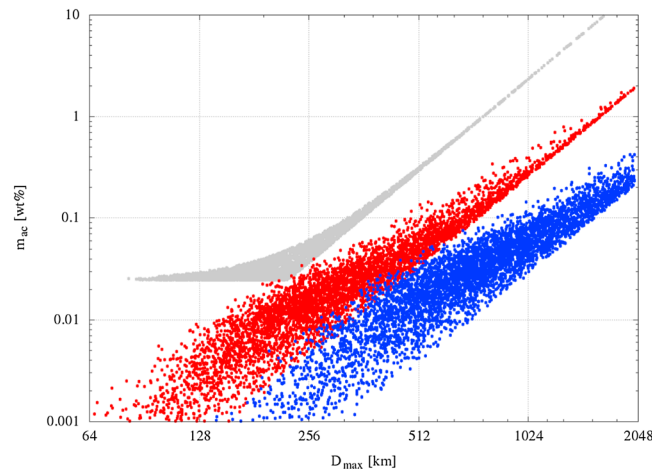


Figure 1. The total late accreted mass (in wt %) versus the diameter of the largest body to strike the Moon (gray), Mars (red), and the Earth (blue). The plateau seen for the Moon near 0.025 wt % is caused by the requirement that the Moon experienced at least this much late accretion. In this experiment the diameter of the largest body was set to 2000 km. For the Earth to accrete 1 wt % requires the impact of a lunar-sized body. If Mars experienced all its 0.7 wt % late accretion after Moon formation, it should have been struck by a body with a diameter of 1000 km or larger.

as part of this project. The simulations were terminated once Mars reached a threshold where at least 0.5 wt % was added to account for the calculated accretion component [Day and Walker, 2015].

3. Results

Before we proceed to investigate late accretion to Mars, we quickly review an important result from Brasser *et al.* [2016]. Figure 1 shows the diameter of the largest planetesimal to strike the Moon (gray), Mars (red), or the Earth (blue) versus the total accreted mass reported in weight % of the target's mass. Closer examination of the lunar data shows that the largest planetesimal accreted by the Moon in our previous model has a diameter of approximately 200 km, consistent with the size of the impactor required to account for the diameter of the South Pole-Aitken basin [Potter *et al.*, 2012]. Data show that even when Earth was struck with at least one "planetesimal" with a diameter of 2000 km, the total amount of mass accreted by Earth in the late veneer is at best 0.4 wt %. Extrapolation of the Earth data indicates that a planetesimal diameter of about 3000 km is required to have the Earth accrete another 0.7 wt % subsequent to the Moon-forming event. This extrapolation led Brasser *et al.* [2016] to conclude that the late veneer on the Earth was most likely the result of a single, large impact with a lunar-sized (~3000 km diameter) body.

For Mars, the outcome is somewhat more complicated compared to the Earth-Moon case. If we begin with the assumption that all of Mars's late accretion was delivered *after* the Earth's Moon had already formed, then Mars should have experienced a collision with a planetesimal with a diameter in excess of 1000 km.

The results of the new Monte Carlo simulations, where Mars had to have accreted a minimum of 0.5 wt %, are depicted in Figure 2. Here we show that the minimum diameter of the largest object to have struck Mars is about 500 km if it experienced only 0.5 wt % late accretion, whereas this object had to have been at least 1200 km in diameter to yield 0.8 wt % late accretion. A roughly Ceres-sized (or somewhat larger) object is expected have been mostly accreted by Mars, with only a small fraction of the mass escaping [Raymond *et al.*, 2013]. The impact of a planetesimal with a diameter of 1200 km delivers approximately 0.5 wt % of material to Mars. For the shallow size-frequency distribution that was employed in our work, approximately one-third of the total delivered mass is in the largest planetesimal [Tremaine and Dones, 1993]. The rest of the mass (in this case 0.3 wt %) is delivered by smaller bodies.

Even though crater scaling laws are usually not applicable to basins, we can still use the number of known Martian basins to implicitly constrain the size of the largest impactor. All that is required is the diameter of

perfect accretion. This assumption agrees with previous N-body simulations that included imperfect accretion [Raymond *et al.*, 2013]. Once this is accomplished, the next planetesimal is produced in our Monte Carlo simulation. In their time-independent simulations, Brasser *et al.* [2016] continued to generate planetesimals until the Moon had accreted at least 0.025 wt %, corresponding to estimates of its late accretion complement [Day *et al.*, 2007; Day and Walker, 2015].

Mars, however, is demonstrably older than the Moon [Dauphas and Pourmand, 2011; Tang and Dauphas, 2014] so that it correspondingly had more time to accrete its mantle HSE budget. For this reason, additional Monte Carlo simulations were performed

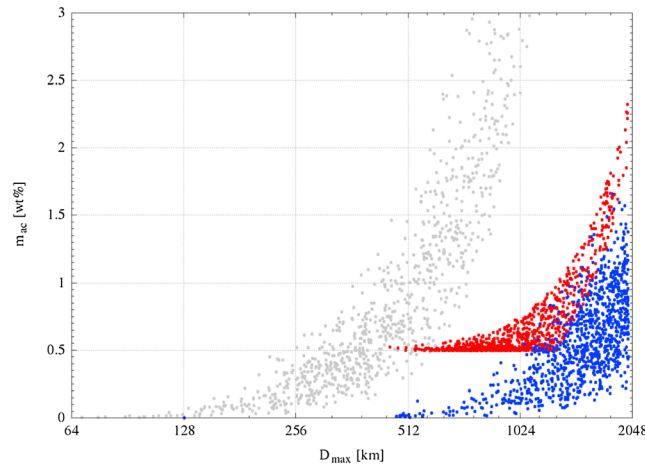


Figure 2. The total late accreted mass (in wt %) versus the diameter of the largest body to strike the Moon (gray), Mars (red), and the Earth (blue). The plateau seen for Mars at 0.5 wt % is caused by the requirement that it experienced at least this much late accretion. In this experiment the diameter of the largest body was set to 2000 km. The data indicate that Mars should have been struck by a body with a diameter of 1000 km or larger if it experienced 0.7 wt % late accretion.

of its mass by late accretion, then this must account for (at least) one large body with a diameter of a minimum 1200 km. Importantly, our model outcome coincides with the largest expected impactor described in *Marinova et al.* [2008] and *Bottke et al.* [2010]. Strangely enough, such an outcome cannot account for Mars’s approximately 25 h rotation period. The expected number of sidereal rotations of a planet per revolution around the Sun following an episode of stochastic accretion is $\eta = (R_H/R_M)^{3/2}(m/M_M)$ [Dones and Tremaine, 1993], where R_M is Mars’s radius, R_H is Mars’s Hill radius, m is the mass of the impactor, and M_M is Mars’s mass. Currently $R_H/R_M \sim 450$ and an impactor with $D = 1200$ km and Mars’s mean density has $m/M_M \sim 0.003$ so that $\eta \sim 30$. Thus, the impact that contaminated Mars’ mantle is expected to have only contributed about 5% of Mars’s spin angular momentum. This is a topic for future work.

4. Discussion

We now explore whether the amount of late accretion on Mars computed here is consistent with the expected mass in planetesimals from leftover terrestrial planet formation [cf. *Quintana et al.*, 2016].

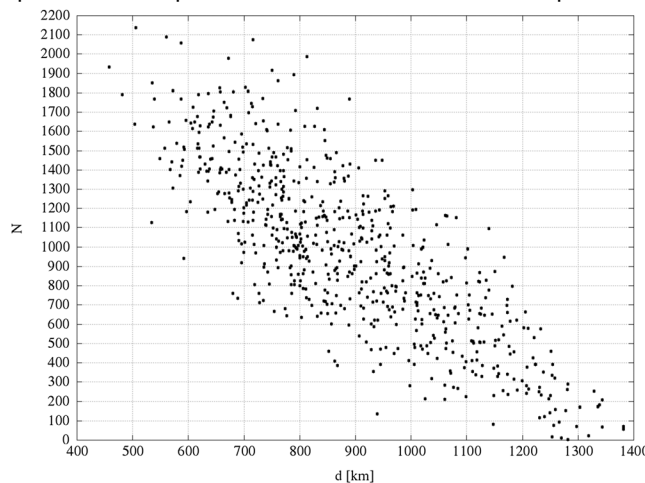


Figure 3. The number of expected Martian basins versus the diameter of the largest impactor. The current number of basins is only reproduced if the diameter of the largest impactor is 1300 km or higher.

the smallest planetesimal that will excavate a basin on Mars; any planetesimals that strike Mars larger than this size will automatically form additional basins. There are at least 30 large impact basins that can be confidently documented on Mars [e.g., *Werner*, 2014]. In Figure 3 we plot the number of expected basins on Mars versus the size of the largest impactor from our Monte Carlo numerical simulations. If we can only account for approximately 30 basins, Figure 3 and the simulation data show that the largest impactor in the field of possibilities in the late accretion Monte Carlo simulations and tied to the HSE abundance has a diameter of approximately 1300 km.

In summary, if Mars did experience an approximately 0.8 wt % increase

Data strongly suggest that Mars is a stranded planetary embryo which formed in less than 10 Myr [*Dauphas and Pourmand*, 2011; *Tang and Dauphas*, 2014]. Mars formed in a region with a relatively low density of planetesimals [*Brasser et al.*, 2017], whereas Earth and Venus were still busy accreting planetesimals and planetary embryos. *Brasser et al.* [2016] determined that at the time of Moon-formation, the mass in remnant planetesimals was of the order of a fifth of a lunar mass (or ~ 0.002 Earth masses). The Monte Carlo simulations performed here keep track of the total number and mass of planetesimals (see section 2). For Mars to

have accreted an additional 0.8 wt %, we compute that there was on average 0.04 Earth mass in planetesimals on Mars-crossing orbits in the inner solar system (otherwise the planetesimals cannot impact Mars) by using the typical impact probability of a planetesimal with Mars. In other words, the remaining planetesimal mass is computed as $m_p = m_{\text{imp}}/P_M$, where m_{imp} is the mass that impacted Mars (0.8 wt %) and P_M is the probability of impacting Mars (about 2%). Mars is thought to have had a magma ocean phase that lasted approximately 100 Myr [Debaïlle *et al.*, 2007; cf. Humayun *et al.*, 2013]; in our view it is easier, though not necessary, to incorporate the HSEs into the Martian mantle before crust formation was completed. We further suggest the low mass in planetesimals occurred by about 4.55 Ga, by which time Mars had nearly fully formed [Dauphas and Pourmand, 2011; Tang and Dauphas, 2014]. This mass value is consistent with a few times 10^{-3} Earth masses in planetesimals remaining at the time of the Moon-forming event when accounting for dynamical ejection and collisions with the terrestrial planets [Brasser *et al.*, 2016].

If Mars indeed experienced a large late veneer-scale impact early in its history, what evidence could possibly exist for such an event in its lithosphere? Unlike the Earth or Venus, Mars has undergone relatively little resurfacing; the southern half of its surface is characterized by an ancient (~4.3–4.4 Ga) cratered terrane [Werner *et al.*, 2014], while the northern hemisphere shows evidence of some form of later crustal processing and extensive volcanism and its corresponding surface age is only 3.7 Ga [Werner *et al.*, 2011]. These points lead us to conclude that Mars probably avoided the sort of planet-wide devastating impact that melted the crust and mantle down to great depth in conditions comparable in magnitude (equimass impactor:target) to that which created Earth's Moon.

Others have proposed that Mars's hemispheric dichotomy came about from a giant impact, the most obvious expression being the northern lowlands [Wilhelms and Squyres, 1984; Andrews-Hanna *et al.*, 2008; Nimmo *et al.*, 2008; Marinova *et al.*, 2008]. Based on geometric arguments, the impactor to account for this purported structure had a diameter of about 1000 km, if the collision occurred head-on [Wilhelms and Squyres, 1984], or 1600–2700 km in diameter for an oblique collision that comports relatively well with the dichotomy's geometry and ellipticity [Nimmo *et al.*, 2008; Marinova *et al.*, 2008]. Our results outlined in the previous section are in agreement with these various size estimates for a giant impact, and because it appears necessary for Mars to have experienced a large impact to be consistent with its mantle HSE budget, it is well within the realm of possibility that the Martian hemispherical dichotomy is the result of this giant impact.

The timing of this event, however, is uncertain. Wilhelms and Squyres [1984] suggest that the colossal impact that created the hemispherical dichotomy occurred before 4.4 Ga. Nimmo *et al.* [2008] preferred a similar timing because of the suggested longevity of the Martian magma ocean [Debaïlle *et al.*, 2007; cf. Humayun *et al.*, 2013]. On the other hand, Harper *et al.* [1995] were the first to report an excess of ^{142}Nd in Martian meteorites and used these data to conclude that differentiation of the silicate reservoirs—the last time that the crust and mantle of Mars were equilibrated from complete melting—occurred by 4.54 Ga. They suggest that Mars experienced no giant impacts afterward. Foley *et al.* [2005] reached the same conclusion from coupled ^{142}Nd and ^{182}W anomalies in Martian meteorites and Borg *et al.* [2016] use neodymium isotopes to derive an age of 4.5 Ga for the formation age of the Martian basaltic meteorites. It is difficult to imagine, however, that an impact this early in Mars's history would leave a lasting imprint on its crust. The oldest known Martian zircon is found in NWA 7533, a sibling of NWA 7034 [Agee *et al.*, 2013], with an age of 4.428 Ga [Humayun *et al.*, 2013]. This age coincides with the end of the purported long-lived Martian magma ocean, and if it is interpreted to be a minimum age of crust formation, we conclude that the impact that created the hemispherical dichotomy occurred before about 4.43 Ga.

Mars is a small, old, and cold world that ineffectively recycles its crust in a stagnant-lid regime over geologic timescales [Yin, 2012, and references therein]. A mass augmentation event of the magnitude we propose to the crust and mantle of primordial Mars from what we can safely conclude was a chemically and isotopically distinct source ought to impart a geochemical signal in the form of strong isotopic heterogeneities in different ancient Martian silicate reservoirs. Over billion-year timescales, we further expect that these implanted isotopic heterogeneities would become gradually subdued or homogenized with bulk Mars by slow crustal processing such as intracrustal partial melting and sluggish convection. Earlier, we insinuated that a very early (~4.5 Ga) impact would most likely result in a homogenization of the HSEs in the Martian mantle [Harper *et al.*, 1995; Foley *et al.*, 2005] when the internal heating regime was sufficient to cause effective mixing of the mantle. A late (~4.4 Ga) delivery, on the other hand, ought to result in an uneven (possibly patchy) distribution of

the HSEs and other isotopic signatures [Day *et al.*, 2016]. Relatively late addition to an already differentiated Mars might be expected to lead to tungsten isotopic anomalies for impact-affected materials. Such anomalies have been observed in lunar samples and infer the existence of late accretion to the Moon [Kruijer *et al.*, 2015; Touboul *et al.*, 2015]. Our testable prediction from this model is that different components of different ages of different origins (exogenous versus endogenous) in the oldest Martian meteorites, such as NWA 7034 mentioned above, may be expected to preserve strongly contrasting three-oxygen isotope values (expressed in the conventional $\Delta^{17}\text{O}$ notation) well outside the contemporary Martian range. It is worth noting that Agee *et al.* [2013] documented the existence of multiple Martian oxygen reservoirs based on its isotope heterogeneities in NWA 7034 [Nemchin *et al.*, 2014]. We predict that further studies with different isotopic systems (e.g., ^{182}W) in the oldest components of the Martian meteorites will yield a similar outcome. Such a result favors a relatively late, colossal, impact event.

An impact of this magnitude would also be expected to eject a substantial amount of material into orbit around Mars, which could then be the source material that eventually formed its satellites [Craddock, 2011; Citron *et al.*, 2015; Rosenblatt and Charnoz, 2012; Rosenblatt *et al.*, 2016]. Smooth-particle hydrodynamics (SPH) impact simulations onto Mars of a body with 2.6% of the mass of Mars yield a circum-Martian debris disc of 1–4% of the impactor's mass (i.e., 0.026 to 0.1 Martian wt %) [Citron *et al.*, 2015]. Such a disc is composed of a mixture of materials from both the impactor target, with 20–70% coming from Mars [Rosenblatt *et al.*, 2016; Canup and Salmon, 2016]. The circum-Martian disc is then thought to coagulate into a series of satellites, of which Phobos and Deimos are the last two that remain [Rosenblatt and Charnoz, 2012; Rosenblatt *et al.*, 2016]. A recent analysis of the cratering on Phobos indicates it could be older than ~ 4.3 Ga [Schmedemann *et al.*, 2014], lending tentative support to the very early impact-generated formation of Mars's satellites.

The composition, age, and origins of the Martian satellites remain controversial. Phobos's high porosity appears inconsistent with an origin from a differentiated body, and the satellite's density and spectrum supports an asteroidal origin [cf. Andert *et al.*, 2010; Rosenblatt *et al.*, 2016]. Non-Martian material in the disc can be reconciled with the giant collision scenario and the primitive composition of the Martian satellites suggested by remote sensing observations of their surfaces [Murchie *et al.*, 2015], although such measurements are only representative of the surface, not of the bulk composition of the bodies.

5. Conclusions

After their final assembly, all of the terrestrial planets experienced late accretion from planetesimals left over from planet formation. Some of this late accretion occurred at a time when core separation in the inner planets had been mostly completed. After crust formation was complete, some of the highly siderophile elements that were delivered in late accretion ended up suspended in the mantles of the terrestrial planets rather than in their cores. The amount of late accretion on Mars as traced by HSEs is still uncertain, but best estimates show it was approximately 0.8 wt %. Through a combination of N-body and Monte Carlo experiments, we show that if Mars indeed suffered this much late accretion, then it must have experienced an impact with a Ceres-sized planetesimal. This impact occurred early, before the onset of global crust formation near 4.43 Ga, and is possibly responsible for the hemispherical dichotomy as well as the origin of its satellites. A cryptic signal of this event may be preserved in the oldest components of the Martian meteorite clan in the form of isotope heterogeneities.

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