Earth and Planetary Science Letters 468 (2017) 85–93

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The cool and distant formation of Mars

R. Brasser[a,∗,1], S.J. Mojzsis[b,c,∗,1], S. Matsumura[d,2], S. Ida[a]

[a] *Earth Life Science Institute, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8550, Japan*
[b] *Department of Geological Sciences, University of Colorado, UCB 399, 2200 Colorado Avenue, Boulder, CO 80309-0399, USA*
[c] *Institute for Geological and Geochemical Research, Research Center for Astronomy and Earth Sciences, Hungarian Academy of Sciences, 45 Budaörsi Street, H-1112 Budapest, Hungary*
[d] *School of Science and Engineering, Division of Physics, Fulton Building, University of Dundee, Dundee DD1 4HN, UK*

ARTICLE INFO

Article history:
Received 19 December 2016
Received in revised form 29 March 2017
Accepted 1 April 2017
Available online xxxx
Editor: F. Moynier

Keywords:
Mars
formation
Grand Tack
composition
isotopes

ABSTRACT

With approximately one ninth of Earth's mass, Mars is widely considered to be a stranded planetary embryo that never became a fully-grown planet. A currently popular planet formation theory predicts that Mars formed near Earth and Venus and was subsequently scattered outwards to its present location. In such a scenario, the compositions of the three planets are expected to be similar to each other. However, bulk elemental and isotopic data for martian meteorites demonstrate that key aspects of Mars' composition are markedly different from that of Earth. This suggests that Mars formed outside of the terrestrial feeding zone during primary accretion. It is therefore probable that Mars always remained significantly farther from the Sun than Earth; its growth was stunted early and its mass remained relatively low. Here we identify a potential dynamical pathway that forms Mars in the asteroid belt and keeps it outside of Earth's accretion zone while at the same time accounting for strict age and compositional constraints, as well as mass differences. Our uncommon pathway (approximately 2% probability) is based on the Grand Tack scenario of terrestrial planet formation, in which the radial migration by Jupiter gravitationally sculpts the planetesimal disc at Mars' current location. We conclude that Mars' formation requires a specific dynamical pathway, while this is less valid for Earth and Venus. We further predict that Mars' volatile budget is most likely different from Earth's and that Venus formed close enough to our planet that it is expected to have a nearly identical composition from common building blocks.

1. Introduction

The formation of the terrestrial planets is a long-standing problem that is gradually being resolved. The past decade has witnessed important progress towards a unified model of terrestrial planet formation. From analysis of samples of the oldest-known rocks collected on Earth and the Moon, from lunar, martian and asteroidal meteorites, as well as remote sensing studies, we now have information on the nature and timing of formation of several worlds in our solar system through combined geochemical models, elemental and isotopic abundances, and geochronology. Analysis of martian meteorites show that it formed within ∼10 Myr of the start of the solar system (Dauphas and Pourmand, 2011). The chemical and mechanical closure of Earth's metallic core, as derived from the Hf–W chronometer, took place at least 20 Myr later than this (e.g. Kleine et al., 2009 and references therein). Adding these observations together leaves us with a general timeline for the formation of the terrestrial planets, and thus a foundation for computational models to explain their history.

In traditional dynamical models the terrestrial planets grow from a coagulation of planetesimals into protoplanets and subsequently evolve into a giant impact phase, during which the protoplanets collide with one other to give rise to the terrestrial worlds. Several variations of this scenario exist. The most recent of these, dubbed 'pebble accretion' (e.g. Levison et al., 2015 and references therein), postulates that the terrestrial planets grow directly from the accretion of a swarm of centimetre-sized planetesimals termed pebbles; the outcomes of the pebble accretion model are presently an area of much active research. For this work, however, we shall make use of the popular and more established *Grand Tack* model (Walsh et al., 2011).

Grand Tack relies on early gas-driven migration of Jupiter and Saturn to gravitationally sculpt the inner solid circum-solar disc

---

∗ Corresponding authors.
E-mail addresses: brasser_astro@yahoo.com (R. Brasser), mojzsis@colorado.edu (S.J. Mojzsis).
[1] Collaborative for Research in Origins (CRiO).
[2] Dundee Fellow.

http://dx.doi.org/10.1016/j.epsl.2017.04.005
0012-821X/

down to ∼1 AU after which terrestrial planet formation proceeds from solids in an annulus ranging from roughly 0.7 AU to 1 AU. Grand Tack has booked some successes, such as its ability to reproduce the mass-orbit distribution of the terrestrial planets, the compositional gradient, and total mass of the asteroid belt (Walsh et al., 2011). Its predictions for the composition of the terrestrial planets, however, have not been widely explored. Through a combination of geochemical and N-body simulations we here report what the Grand Tack models predicts for the variation in the bulk compositions of the terrestrial planets, with particular focus on Mars. The aim of this study is to constrain Mars' building blocks and whether these are identical to those of Earth's.

2. Isotopic heterogeneities

Geochemical data from martian meteorites suggests that the overall composition of Mars is unlike that of the Earth (and Moon). Early investigations into Mars' bulk composition concluded that its primary constituents are a highly reduced component devoid of most volatiles, and more oxidised material that follows CI abundances (Wänke and Dreibus, 1988); these are present in an approximately 2:1 ratio (Wänke and Dreibus, 1994). These same studies concluded that Mars accreted homogeneously, while Earth did not – cf. Dauphas et al. (2004). Based on the analysis of the isotopic variations in O, Cr, Ti and Ni in various meteorites, terrestrial and martian rocks, this composition ratio was recently revised: Mars is a mixture of carbonaceous and non-carbonaceous material, with the former contributing only 9%; for Earth the fraction is 24% (Warren, 2011). The link between isotopic anomalies and bulk composition is debated, but good cases for such a link have been made in the past (Warren, 2011; Dauphas et al., 2014, 2015). Therefore, in this study, we will follow these works and assume that isotopic anomalies are correlated to differences in bulk compositions.

The three oxygen isotope system (expressed in the conventional $\Delta^{17}\mathrm{O} = \delta^{17}\mathrm{O}_{\mathrm{VSMOW}} - 0.52\delta^{18}\mathrm{O}_{\mathrm{VSMOW}}$ notation; the δ-notation denotes deviations in parts-per-thousand where isotopic ratios of the same element are normalised to a standard) permits discrimination between primordial nebular heterogeneities inherited during planet formation and mass-dependent planetary processes (Clayton and Mayeda, 1983). Mars is defined by oxygen that is significantly enhanced in the minor isotope (^{17}O) with respect to terrestrial and lunar values (Franchi et al., 1999; Rubin et al., 2000; Mittlefehldt et al., 2008; Agee et al., 2013; Wittmann et al., 2015), suggesting that the mixture of source components was different for Earth and Mars (Wänke and Dreibus, 1988, 1994; Lodders, 2000; Warren, 2011), which implies different source locations from within different compositional reservoirs of the solar nebula – cf. Fitoussi et al. (2016).

This conclusion is lent weight by several recent isotope studies in meteorites and in terrestrial and martian samples. The terrestrial isotopic composition of ^{17}O, ^{48}Ca, ^{50}Ti, ^{62}Ni and ^{92}Mo is best reproduced by a mixture of 90% enstatite chondrite, 7% ordinary chondrite and 2% carbonaceous chondrites (Dauphas et al., 2014). In contrast, for Mars a mixture of 45% enstatite chondrite and 55% ordinary chondrite can match its ^{17}O, ^{50}Ti, ^{54}Cr, ^{62}Ni and ^{92}Mo values (Sanloup et al., 1999; Tang and Dauphas, 2014), which is different from Earth's and thus hints at a formation region well away from that of Earth.

Here we build upon these previous studies and highlight isotopic differences between Earth (cf. Javoy et al., 2010) and Mars and major meteorite groups. In Fig. 1 we present comparative Si vs. Δ^{17}O (top-left panel), V vs. Δ^{17}O (top-right panel), multiple-Cr (bottom-left panel), and Ti vs. Cr (bottom-right panel) isotope data for Mars vs. Earth, and when compared to various meteorite groups for which data are available and correlative to the same sample. Correlated silicon and oxygen isotopes for Mars generally match the ordinary chondrites (Georg et al., 2007; Pringle et al., 2013a), indicating there is little to no silicon in Mars' core, but Earth and Moon do not. The non-chondritic Si isotope composition of the Earth's mantle points to Si incorporation into the core (Georg et al., 2007). There is some debate in the literature regarding the source of Si fractionation. One argument revolves around nebular fractionation of SiO in fosterite at high temperature (Dauphas et al., 2015), while another suggests Si is fractionated during impact-induced evaporation rather than core formation (Pringle et al., 2014). Therefore, it is possible that the lower δ^{30}Si of Mars compared to Earth implies a more distant formation from the Sun, where temperatures were cooler. If the latter mechanism dominates then Mars' lower escape velocity compared to Earth could be the source of its lighter Si isotopic composition.

The correlated vanadium isotopic composition, expressed as δ^{51}V, vs. Δ^{17}O for Mars is 5σ from terrestrial standards, which cannot be explained by metal-silicate partitioning (Nielsen et al., 2014). Both ε^{50}Ti and ε^{54}Cr, as well as ε^{62}Ni (the ε-notation denotes deviations in parts-per-ten thousand normalised to another standardised isotopic ratio of the same element), reflect the presence of planetary-scale nucleosynthetic anomalies (Warren, 2011; Tang and Dauphas, 2014), while the origin of δ^{51}V variations is unknown.

The neutron-rich isotopes are suggested to have been implanted into the proto-solar disc by nearby supernovae (Qin et al., 2010), which is more effective at larger distances from the Sun, and could thus explain the ε^{54}Cr vs ε^{62} Ni trend observed across various meteorite groups (Warren, 2011). Studies have shown that, like in the O, Si and V systems cited above, major meteorite groups also possess ^{54}Cr/^{52}Cr vs. ^{53}Cr/^{52}Cr values that show clear differences from Earth (Trinquier et al., 2007, 2008; Qin et al., 2010). Of the Cr isotopes ε^{53}Cr is a tracer for volatility, and thus formation distance from the Sun, so that Mars' depletion in ε^{53} Cr relative to Earth hints at a cooler formation environment. Finally, the neutron-rich system, ^{50}Ti/^{47}Ti (expressed as ε^{50}Ti with respect to the terrestrial standard), contains anomalies comparable to the ε^{54}Cr values for the same meteorites and components (Trinquier et al., 2009). Hence, multiple lines of evidence show that different bulk elemental and isotopic makeups of Earth and Mars point to different accretionary histories and therefore source regions for the two planets.

In an alternative view presented by Fitoussi et al. (2016), Monte Carlo mixing models for a subset of isotopic systems can be devised that yield a singular mixture of various achondrite and chondritic components – some of which were likely comprised of compositionally-unconstrained differentiated planetesimals – that provide an Earth and Mars bulk composition. Such Monte Carlo mixing models ultimately formulate a compositional fit for both Earth and Mars out of 10^{10} trials from 18 variables. Fitoussi et al. (2016) report that Earth and Mars are built from up to 93% of the same material. It is important to note, however, that the Monte Carlo mixing method neglects to take the dynamics of planetary formation into account. The authors state that a scenario where Mars forms beyond 2 AU is inconsistent with the outcome of their experiments and instead prefer a formation model where Mars and Earth share the same feeding zone i.e. one in which they both accrete from very similar (well-mixed) materials.

Our approach is instead to track compositions of the forming planets with dynamical simulations that yield Mars while simultaneously accounting for observational constraints. In the next section we argue for Mars' building blocks to predominantly consist of a specific mixture of meteorite parent bodies, just like most of the other terrestrial planets (Warren, 2011). We further argue from the isotope data and our dynamical simulations that bulk Mars is composed of different material than bulk Earth. Therefore Mars most