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The building blocks of Earth and Mars: A close genetic link

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ABSTRACT

The Earth formed in a swarm of Moon- to Mars-sized objects that collided together to build our planet. A large body of work has been dedicated to understanding the Earth's composition as being made of single groups or mixtures of chondrites, however, these models cannot account for the isotopic and elemental characteristics of the Earth. Here, we test mixtures of meteorites, including achondrites, analyzed for seven isotope systems (O, Cr, Ni, Ti, Mo, Ca and Sr), to reproduce the isotope compositions of the Earth and Mars. Our Monte Carlo inversion (a numerical method based on generation of random numbers used to invert multiparameter models) yields a new compositional model where Earth and Mars come almost entirely from the same source material. This finding is in striking agreement with recent planetary formation models in which Earth and Mars formed in a common narrow zone of the protoplanetary disk with Mars being ejected to its current position which prevented further accretion. An important outcome of the model is that a significant mass fraction of the Earth could have been made of volatile depleted and refractory enriched planetary bodies such as angrites (among the oldest known achondrites). This conclusion is also in agreement with new Si isotope data in angrites which suggest that a component of angrites would help explain the difference in δ^{30}Si between the bulk silicate Earth and its building blocks. Our model matches all isotope compositions for both planets, reproduces the volatile element budget of Mars, and accounts for the enrichment in refractory elements of the Earth and Mars compared to chondrites.

1. Introduction

CI chondrites, which have the closest elemental composition to the solar photosphere, were often chosen as the reference composition for Bulk Earth for relative abundances of refractory elements (e.g. McDonough and Sun, 1995). However, from the viewpoint of isotope compositions (e.g. Cr isotopes), it is not plausible for the Bulk Earth to have a CI chondrite composition. Another type of model, based on isotopic similarities between Earth and enstatite chondrites, proposed that these meteorites best represented the Bulk Earth (Javoy et al., 2010). However, it was recently shown that enstatite chondrites cannot represent more than 15% of the Earth's mass, based on silicon isotopes (Fitoussi and Bourdon, 2012). Conflicting reports on stable Ca isotopes have shown that the Earth was not identical to enstatite chondrites (Simon and DePaolo, 2010) while a more recent study indicated the reverse (Valdes et al., 2014). In addition, high-precision measurements of Mo (Burkhardt et al., 2011), Ti (Zhang et al., 2012), and O (Herwartz et al., 2014) isotope compositions have now revealed small but resolvable differences between Earth and enstatite chondrites. Furthermore, strong chemical dissimilarities between Earth and enstatite chondrites, in particular in terms of Mg/Si ratio and refractory lithophile element budget, make it unlikely that this single type of meteorite represents the bulk Earth composition (Fitoussi and Bourdon, 2012; Palme and O'Neill, 2013).

Overall, models based on chondrites generally fail to account for the Earth's composition (Drake and Righter, 2002; Palme and O'Neill, 2013). More specifically, Allègre et al. (2001) showed that ordinary chondrites are a poor match for the trace element composition of the Earth and used intermediate compositions in the carbonaceous chondrite group to determine an Earth composition. In contrast, recent studies of Nd isotopes and nucleosynthetic anomalies in refractory elements have shown that carbonaceous chondrites cannot represent a major portion of the Earth's material (Carlson et al., 2007; Warren, 2011). In summary, there is currently no satisfactory model for the building blocks of the bulk Earth using chondrites.

Reports of nucleosynthetic anomalies and mass-independent isotope effects have shown that there was a heterogeneous distribution of isotope compositions in the solar nebula, and these

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systems (e.g. O, Cr isotopes) have even become a reliable tool for classifying various meteorite groups (Clayton, 2003; Trinquier et al., 2007), indicating that these meteorite parent bodies must have formed from discrete compositional reservoirs within the solar nebula. These signatures have the advantage of being robust as they are immune to parent body processes inducing mass-dependent fractionation such as metal–silicate equilibrium or evaporation. We have used these constraints to test whether mixtures of known and isotopically characterized meteorites from our collections could reproduce the Bulk Earth and Bulk Mars compositions.

2. Rationale of the approach

We used Monte Carlo simulations to search for mixtures of meteorites that could represent the Bulk Earth composition using meteorites that have been analyzed for Δ^{17}O and nucleosynthetic anomalies reported in Cr, Ni, Ti, Mo, Ca and Sr isotopes. Similar approaches have been used in previous studies (Burbine and O'Brien, 2004; Dauphas et al., 2014; Lodders, 2000; Warren, 2011) using only chondrites as possible building blocks. For example, Lodders (2000) obtained a model for the Earth including 70% enstatite chondrites, 21% H chondrites, 5% CV chondrites and 4% CI chondrites. Similarly, Dauphas et al. (2014) calculated that the Earth would consist of 91% enstatite chondrites, 7% ordinary chondrites and 2% carbonaceous chondrites.

In contrast to cosmochemical models based on undifferentiated planetary materials, dynamical models for the accretion of terrestrial planets conclude that their formation was dominated by collisions of differentiated objects with a size ranging between planetesimals and “planetary embryos” (Moon- to Mars-sized bodies) (Morbidelli et al., 2012). Although differentiated objects were originally thought to have formed later than chondrites, they were recently shown to have accreted among the earliest objects in the nebula (Markowski et al., 2006; Qin et al., 2008; Kruijer et al., 2014). Therefore, differentiated bodies represent a range of compositions that was already present in the early history of the protoplanetary disk. Although widely unexplored in existing models for the Earth composition (Allègre et al., 2001; Warren, 2011; Lodders, 2000; Dauphas et al., 2014), they could represent precursor materials for planetesimals or embryos, even though an exact connection between achondrites and embryos or planetesimals cannot be established. Taking achondrites as possible building blocks of terrestrial planets is thus based on recent advances in early solar system chronology, which suggests that achondrites could represent components that were present in the terrestrial planet region. This novel approach has the advantage of testing new models for the composition of terrestrial planets with objects having isotope and elemental compositions that are distinct from chondrites. This approach is further justified by the failure of models based only on chondritic compositions, as shown in Palme and O'Neill (2013) or Drake and Righter (2002), which suggests that additional components have to be considered. An additional feature is that differentiated bodies are depleted in volatile elements, which is also a characteristic of planets that is never so pronounced in chondrites. One obvious disadvantage of using achondrites is that we do not have a direct access to the bulk compositions of their parent bodies. However, their bulk silicate composition can be inferred from experimental studies (Jurewicz et al., 2004; Longhi, 1999; Stolper, 1977) or estimated from chemical trends in the corresponding meteorite groups (Dreibus et al., 1977). This represents a limitation of our study and more work on determining better the chemical composition of the corresponding parent bodies would be warranted. In any case, for the sake of our modeling, the results are only weakly sensitive to actual concentrations (for example, if the concentrations of the elements are changed by 20%, the mixing proportions of the endmembers would only change by 2%). Thus, an important novelty of our modeling attempt was to include in the possible mixtures differentiated meteorites (SNC (Shergottites, Nakhlites and Chassigny) from Mars, HED (Howardites, Eucrites and Diogenites) presumably from Vesta, and angrites) whose isotope compositions have been determined. Altogether, we considered CI, CM, CO, CV, H, L, LL, EH, EL chondrites, angrites, HED, and SNC meteorites and used an extensive database for Ni, Cr, Ti, O, Mo, Ca, and Sr isotopic anomalies (see Section 3.1). A limitation of our study is that there are meteorite groups that have not yet been characterized isotopically and that our meteorite collection may not contain all materials present in the early solar system. The variability in isotope signatures found in meteorites reflects the known compositional heterogeneity that was present in the protoplanetary disk. A calculated mixture was deemed valid for the Earth if it had isotope compositions identical to that of the Earth, within uncertainty, for all the isotope systems.

3. Monte Carlo simulation

3.1. Input data

In order to determine the proportions of components in the bulk Earth, a database of Ni, Cr, Ti, O, Mo, Ca, and Sr concentrations and isotopic anomalies was compiled. The isotope data and their corresponding analytical uncertainties are reported in Table A1 (see supplementary material). The description of data handling is also given in the supplementary material.

3.2. Method

The Monte Carlo simulation used in this study was based on random sampling of an isotope space including eight variables (ε^{62}Ni, ε^{54}Cr, ε^{50}Ti, O (δ^{17}O and δ^{18}O), ε^{92}Mo, ε^{48}Ca, and ε^{84}Sr). A uniform distribution using a pseudo-random number generator was used to sample each interval corresponding to the acceptable range defined for each parameter. For all isotope compositions other than oxygen, this was defined as the interval $[\varepsilon - 2\sigma, \varepsilon + 2\sigma]$, where ε is the mean value, and 2σ is the associated error (see supplementary material). The values used for ε and 2σ are given in Table A1. At each trial in the Monte Carlo simulation, the components were first randomly selected. For example, three components were selected out of twelve meteorite groups. In a second step, a subset of eight random numbers r_j (one for each nucleosynthetic anomaly and two for oxygen isotopes) was generated ($r_j \in [0, 1]$) and these numbers were used to set the initial model parameters used for the mixing calculations:

$$\varepsilon^i_j = \varepsilon^i_{\min} + r_j\left(\varepsilon^i_{\max} - \varepsilon^i_{\min}\right)$$

In a third step, the mass fraction of each component X_i was randomly generated and the following closure condition was also assumed:

$$\sum_i X_i = 1$$

The isotope composition of two, three and four component mixtures, using CI, CM, CO, CV, H, L, LL, EH, EL, angrites, HED, and SNC meteorite data, was then calculated with the following equation:

$$\varepsilon^j_{mix} = \frac{\sum_i X_i C_{ij} \varepsilon_{ij}}{\sum_i X_i C_{ij}}$$

with X_i, C_{ij} and ε_{ij} representing the mass fraction of component i, the concentration of element j in component i, and the isotope composition of element j in component i, respectively.