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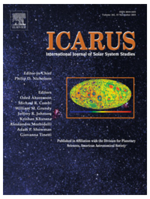

The elemental abundances (with uncertainties) of the most Earth-like planet

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ABSTRACT

To first order, the Earth as well as other rocky planets in the Solar System and rocky exoplanets orbiting other stars, are refractory pieces of the stellar nebula out of which they formed. To estimate the chemical composition of rocky exoplanets based on their stellar hosts' elemental abundances, we need a better understanding of the devolatilization that produced the Earth. To quantify the chemical relationships between the Earth, the Sun and other bodies in the Solar System, the elemental abundances of the bulk Earth are required. The key to comparing Earth's composition with those of other objects is to have a determination of the bulk composition with an appropriate estimate of uncertainties. Here we present concordance estimates (*with uncertainties*) of the elemental abundances of the bulk Earth, which can be used in such studies. First we compile, combine and renormalize a large set of heterogeneous literature values of the primitive mantle (PM) and of the core. We then integrate standard radial density profiles of the Earth and renormalize them to the current best estimate for the mass of the Earth. Using estimates of the uncertainties in i) the density profiles, ii) the core-mantle boundary and iii) the inner core boundary, we employ standard error propagation to obtain a core mass fraction of 32.5 ± 0.3 wt%. Our bulk Earth abundances are the weighted sum of our concordance core abundances and concordance PM abundances. Unlike previous efforts, the uncertainty on the core mass fraction is propagated to the uncertainties on the bulk Earth elemental abundances. Our concordance estimates for the abundances of Mg, Sn, Br, B, Cd and Be are significantly lower than previous estimates of the bulk Earth. Our concordance estimates for the abundances of Na, K, Cl, Zn, Sr, F, Ga, Rb, Nb, Gd, Ta, He, Ar, and Kr are significantly higher. The uncertainties on our elemental abundances usefully calibrate the unresolved discrepancies between standard Earth models under various geochemical and geophysical assumptions.

1. Introduction

The number of known rocky exoplanets is rapidly increasing. Transit photometry and radial velocity measurements, when combined, yield rough estimates of the densities and therefore mineralogies of these exoplanets. Independent and potentially more precise estimates of the chemical composition of these rocky planets can be made based on the known elemental abundances of their host stars combined with estimates of the devolatilization process that produced the rocky planets from their stellar nebulae. To proceed with this strategy, we need to quantify the devolatilization that produced the Earth from the solar nebula. Knowledge of the bulk elemental abundances of the Earth with uncertainties is an important part of this research. The elemental abundances of bulk Earth (including both the bulk silicate Earth and the core) can tell us a more complete story of the potentially universal accretion and fractionation processes that produce rocky planets from nebular gas during star formation. Uncertainties associated with the bulk Earth composition are needed to compare and quantify compositional differences between the Earth, Sun, and other solar system bodies. Such comparisons can lead to a more detailed understanding of devolatilization and the chemical relationship between a terrestrial planet and its host star. The bulk Earth elemental abundances will help determine what mixture of meteorites, comets and other material produced the Earth (Drake and Righter, 2002; Burbine and O'Brien, 2004) and can also help determine the width of the feeding zone of the Earth in the protoplanetary disk (Chambers, 2001; Kaib and Cowan, 2015).

There are many stages of compositional fractionation between the collapse of a stellar nebula, the evolution of a protoplanetary

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disk and a final rocky planet. Composition- and position-dependent differences in the duration and strength of the various fractionating processes can lead to a variety of outcomes. The different (but somewhat similar) compositions of Earth, Mars and Vesta are a measure of these variations within our own Solar System.

A major challenge to estimating the bulk chemical composition of the Earth is that we can only sample the upper part of the possibly heterogeneous mantle, and we have no direct access to its deep interior, and even less to the core (Allègre et al., 2001). Early studies on primitive mantle (PM) elemental abundances include O'Neill (1991), Kargel and Lewis (1993), McDonough and Sun (1995), and O'Neill and Palme (1998). Bulk elemental abundances with uncertainties (Allègre et al., 2001) were reported 16 years ago but much work on PM abundances and on core abundances (usually separately) has been done since then (e.g., Lyubetskaya and Korenaga, 2007; Palme and O'Neill, 2014; Rubie et al., 2011; Wood et al., 2013; Hirose et al., 2013). The determination of uncertainties is central to the quantification of elemental abundances but has been a missing priority in previous work. The most recent, highly cited estimates of the elemental abundances of the bulk Earth do not include uncertainties (McDonough, 2003; McDonough and Arevalo, 2008).

Elemental abundance discrepancies are in large part model-dependent (McDonough, 2016), but over the past 15 years progress has been made in making more plausible models. Our knowledge of the core (and therefore of the bulk Earth) has increased significantly: high pressure experiments yield improved partition coefficients of siderophiles (Siebert et al., 2013) and improved affinities of light elements for iron (Ricolleau et al., 2011; Mookherjee et al., 2011). Seismic velocities through the core provide increasingly precise constraints on densities and on mineral physics models (Vočadlo, 2007; Li and Fei, 2014; Badro et al., 2014). Better subduction models (Poitrasson and Zambardi, 2015) and estimates of the degree of homogeneity of the mantle (Javoy et al., 2010; Nakajima and Stevenson, 2015; McDonough, 2016) provide new constraints that are being included in the upper and lower mantle abundance estimates. Better observations of geo-neutrinos (Bellini et al., 2010; Gando et al., 2011; Bellini et al., 2013; Gando et al., 2013) provide new thermal constraints for the abundances of heat-producing elements in the Earth (e.g. Sramek et al., 2013; Huang et al., 2013). The large majority of the literature on elemental abundances of the Earth, involving either the analysis of the PM or of the core, is increasingly important and when combined, yields improved elemental abundances of the bulk Earth composition and more realistic uncertainties.

Our main research goal is to analyze the compositional differences between the Earth, Sun and other solar system bodies and from this comparison quantify the devolatilization of stellar material that leads to rocky planets. This requires estimates of the bulk Earth abundances *with uncertainties*. These bulk abundances and their uncertainties are poorly constrained and often ignored in the literature. Motivated by this, we make a concordance estimate of the bulk Earth elemental abundances and their uncertainties. The words "concordance estimate" specifically mean a compositional estimate that is representative of, and concordant with previous estimates. The aim of this work therefore is not to resolve the discrepancies between competing models and assumptions but to construct a concordance model (*with uncertainties*) that represents current knowledge of bulk Earth composition and calibrates unresolved discrepancies. We envisage that if the discrepancies can be resolved, a better formulation for estimating uncertainties might be forthcoming. However, at this stage, some of the arguments concerning the derivation of models, or values resulting from these models, appear intractable. Nevertheless, there is an essential need for uncertainties in the estimates if we are to make progress in comparing planetary objects.

We organize this paper as follows. In Section 2 we present the concordance estimate for the composition of PM. In Section 3 we present the concordance estimate of the core; in Section 4 we make a new estimate (with uncertainty) of the core mass fraction of the Earth, using it as the weighting factor to combine the PM with the core to yield our concordance estimates for the bulk Earth. In Section 5 we discuss details of how our work differs from previous work and some unresolved issues that might affect our results.

2. Composition of the primitive mantle

2.1. Data sources

Earth's primitive mantle (PM) or bulk silicate Earth (BSE) is the mantle existing after core segregation but before the extraction of continental and oceanic crust and the degassing of volatiles (Sun, 1982; Kargel and Lewis, 1993; Saal et al., 2002; McDonough, 2003; Lyubetskaya and Korenaga, 2007; Palme and O'Neill, 2014). There are two major, and partially-overlapping modeling strategies for estimating the PM composition.

The peridotite model is based on the analysis of chemical data from basalts and peridotite massifs. Peridotite-basalt melting trends yield an estimate of the PM composition (e.g., Ringwood, 1979; Sun, 1982; McDonough and Sun, 1995; McDonough, 2003; Lyubetskaya and Korenaga, 2007). The peridotite model has a number of intrinsic problems, including the non-uniqueness of melting trends, large scatter in the data from mid-ocean ridge basalts (MORB) and from ocean island basalts (OIB), and the difficulty of imposing multiple cosmochemical constraints on refractory lithophile element (RLE) abundances, often resulting in model-dependent, poorly quantified uncertainties (Lyubetskaya and Korenaga, 2007).

The cosmochemical model is based on the identification of Earth with a particular class of chondritic or achondritic meteorites or their mixtures (e.g., Morgan and Anders, 1980; Javoy et al., 2010; Fitoussi et al., 2016), along with a number of assumptions on accretion and fractionation processes (Allègre et al., 2001). The cosmochemical model uses chondritic ratios of RLEs and volatility trends (e.g., Wanke and Dreibus, 1988; Palme and O'Neill, 2003; 2014). Palme and O'Neill (2003, 2014) present a core-mantle mass balance approach for calculating the primitive mantle composition. This approach requires an accurate determination of magnesium number (Mg # = molar Mg/(Mg+Fe)). A reasonable range for Mg# can be inferred from fertile mantle periodites.

Our aim is not to resolve the differences between these strategies and models but to construct a concordance model whose mean values and uncertainties adequately represent current knowledge and disagreement.

2.2. Concordance PM estimate

We construct our concordance PM abundances from three major papers reporting PM abundances (Lyubetskaya and Korenaga, 2007; McDonough and Arevalo, 2008; Palme and O'Neill, 2014), supplemented with noble gas abundances from Marty (2012) and Halliday (2013). McDonough and Arevalo (2008) is an updated version of their pioneering peridotite model (McDonough and Sun, 1995; McDonough, 2003). Updates of some abundances, for example W, K and Pb, can be found in Arevalo and McDonough (2008) and Arevalo et al. (2009). Lyubetskaya and Korenaga (2007) performed a principal component analysis of the same peridodite database but with different model parameters. Palme and O'Neill (2014) is largely based on a cosmochemical model using mass balance and is an updated version of their pioneering earlier work (Palme and O'Neill, 2003).