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Uncertainties in the composition of Earth, its core and silicate sphere

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Abstract. A self consistent model for the Earth has the heat producing elements, K, Th and U concentrated in the silicate Earth, with negligible quantities stored in the core. With uncertainties reported at the 2 sigma level, the silicate Earth has 80 ± 25 ng/g Th and 20 ± 8 ng/g U, with a Th/U of 3.9 ± 0.4; it also has a K/U of $1.38 \pm 0.26 * 10^4$ and a K content of 280 ± 120 μg/g. Thus, the radiogenic contribution to the Earth's thermal power is 21 ± 4 TW relative to a total output of 46 ± 6 TW.

1. Introduction

As geoneutrino data are accumulated, the particle physics community looks to the geological community for insight and guidance into the composition of the bulk Earth and its major reservoirs: the crust, mantle and core. A fundamental question is - how well do we know the composition of the Earth, including its core and mantle, as these regions not directly accessible? Establishing uncertainties on geochemical estimates depends critically on what are the known knowns, known unknowns, and worse yet, the unknown unknowns, to quote Don Rumsfeld. This paper examines the absolute uncertainties in our Earth models and provides a reference frame for future geoneutrino tests.

Compositional models of the Earth must be consistent with geophysical and cosmochemical data. First order geophysical constraints on the Earth come from seismology and geodesy, whereas constraints from cosmology come from compositional comparisons between the solar photosphere and meteorites, gross features of planet in the solar system and astronomical observations on mineral phases in the interstellar medium and accretion disks of other systems.

The Earth's shape is a function of its spin, mass distribution, and rotational flattening, which gives a coefficient of the moment of inertia for the Earth of 0.330 Ma^2 [1], which is consistent with it having a metallic liquid core that is surrounded by a stiffer, less deformable, lower density mantle. The seismological profile of the Earth is a description of seismic wave speed velocities through the planet, which is a function of the distribution of density and the bulk and shear moduli. These data can be used to describe a radial density profile for the Earth that is perturbed to be consistent with the Earth's free oscillation frequencies. By combining this information with mineral physics data (e.g., equation of state, or EOS, data for Earth materials at appropriate conditions), we can identify the mineralogical

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and chemical constituents of the core and mantle and compare these phases with candidate materials found in meteorites and terrestrial rocks.

As the building blocks of planets, chondritic meteorites are undifferentiated materials (possessing a mixture of metal and silicate components) upon which our planetary models are constructed. Of fundamental importance is the observation that the solar photosphere and carbonaceous chondrites have a 1:1 match in composition for >5 orders of magnitude for most elements except the gases, when referenced to 10^6 atoms of Si. This stunning compositional match coupled with the fact that the Sun represents the mass of the solar system, empowers geochemists to use chondrites for modelling the composition of the planet. There is, however, a broad compositional spectrum of chondritic meteorites with different proportions of refractory inclusions, chondrules and matrix, the dominant components that make up chondrites. Also, chondrites formed under a broad range of oxidation-reduction conditions with some types (carbonaceous) being completely oxidized (i.e., all Fe as Fe-oxides) and other types (enstatite) very reduced (i.e., all Fe as metal or sulfide and other elements such as Si as both oxide and metal; figure 1). Nonetheless, as a first order cut, there is only a factor of 2 spread in their absolute U and Th contents, as is the case for other refractory elements across the different groups of chondrites. This observation translates to an upper bound of uncertainty for the Earth's U and Th content. Moreover, chondritic meteorites have a narrow range in Th/U ratios of 3.5 to 4.2, which is also confirmed by their limited range of $^{208}Pb/^{206}Pb$ isotopic compositions. In contrast, the only other significant heat producing element in terms of a planetary thermal budget, K, varies by more than a factor of 2 between different groups of chondritic meteorites, and there are reasons to believe that the Earth has an even lower K/U bulk value than that found in chondritic meteorites. Thus, estimating the abundance of K, and other non-refractory (volatile) elements requires further constraints to describe the Earth.

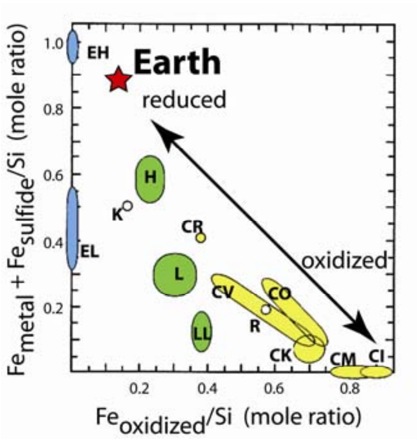

Figure 1. Urey-Craig diagram showing the fields for different groups of chondritic meteorites with respect to their oxidation state of iron relative to silicon. Oxidized iron is incorporated into silicate minerals, whereas reduced iron is in metals and sulfides. Blue fields are for the enstatite chondrites (EH, EL), green the ordinary chondrites (H, L, LL), yellow the carbonaceous chondrites (CI, CM, CO, CV, CR), and unfilled are other. High iron content chondrites (EH and H) contrast with low iron ones (EL, L and LL). The K chondrites (Kakangari) and R chondrites (Rumuruiites) are the least populated groups. The Earth (star) has the vast majority of its iron (87% by mass) in the core.

Astronomical observations find that gas-dust clouds in the interstellar medium and accretion disks contain a small fraction of minerals and that these minerals are dominated by olivine ($(Mg,Fe)_2SiO_4$), pyroxene ($(Mg,Fe)_2Si_2O_6$) and Fe-metal. These are also the common minerals in chondrites and non-chondritic meteorites, and thus are the dominant phases that contribute to planet building.

2. Earth Model

A simple model for the Earth that describes 95% of its mass consists of a core, which is mostly an Fe-Ni alloy with a chondritic Fe/Ni ratio (17.5 ± 1.0, 2σ; [2]), and a silicate shell (with ~6.5% of oxidized Fe, based on mantle samples) made up of a mixture of olivine and pyroxene. Compositional models for the Earth consider a range from a pyroxene- to olivine-rich mantle, or Mg/Si atomic proportions of >1.0 to <1.3, respectively, for the silicate Earth. A model composition [2, 3] for the Earth, including its core and silicate shell, is presented in Table 1. This compositional model has a homogenous major element composition for the silicate portion of the Earth with an Mg/Si atomic proportion of 1.25.

Table 1. Composition of the Earth, core and silicate Earth ***(adapted from [2, 3, 10])***

Element	silicate Earth	Core	Earth	Element	silicate Earth	Core	Earth
H (μg/g)	100	600	300	Rh (μg/g)	0.001	0.7	0.2
Li	1.6	0	1.1	Pd	0.004	3	1.0
Be	0.068	0	0.046	Ag	0.008	0.2	0.1
B	0.3	0	0.2	Cd	0.04	0.2	0.1
C	120	2000	730	In	0.01	0	0.007
N	2	170	57	Sn	0.13	0.5	0.3
O	440,000	0	297,000	Sb	0.0055	0.1	0.05
F	15	0	10	Te	0.012	0.9	0.29
Na	2,670	0	1,800	I	0.01	0.1	0.05
Mg	228,000	0	153,900	Cs	0.021	0.07	0.04
Al	23,530	0	15,880	Ba	6.6	0	4.5
Si	210,000	64,000	163,000	La	0.65	0	0.44
P	90	3,200	1,100	Ce	1.7	0	1.1
S	250	19,000	6,300	Pr	0.25	0	0.17
Cl	17	200	76	Nd	1.2	0	0.84
K	280	0	190	Sm	0.41	0	0.27
Ca	25,300	0	17,080	Eu	0.15	0	0.10
Sc	16.2	0	11	Gd	0.54	0	0.37
Ti	1205	0	815	Tb	0.10	0	0.067
V	82	120	94	Dy	0.67	0	0.47
Cr	2,625	9,000	4,700	Ho	0.15	0	0.10
Mn	1,045	50	720	Er	0.44	0	0.30
Fe	62,600	850,000	319,000	Tm	0.07	0	0.046
Co	105	2,500	885	Yb	0.44	0	0.30
Ni	1,960	52,000	18,200	Lu	0.068	0	0.046
Cu	30	125	60	Hf	0.28	0	0.19
Zn	55	0	35	Ta	0.037	0	0.025
Ga	4.0	0	2.7	W	0.013	0.5	0.17
Ge	1.1	20	7.2	Re	0.00028	0.23	0.075
As	0.05	5	2	Os	0.003	2.8	0.9
Se	0.075	8	2.7	Ir	0.003	2.6	0.8
Br	0.05	0.7	0.3	Pt	0.007	5.7	1.9
Rb	0.6	0	0.4	Au	0.001	0.5	0.2
Sr	19.9	0	13.4	Hg	0.01	0.05	0.02
Y	4.30	0	2.90	Tl	0.0035	0.03	0.01
Zr	10.5	0	7.07	Pb	0.15	1.2	3.3
Nb	0.66	0	0.44	Bi	0.0025	0.03	0.01
Mo	0.05	5	2	Th	0.080	0	0.054
Ru	0.005	4	1	U	0.020	0	0.014

There is good evidence that the mantle has been sufficiently overturned throughout Earth's history such that surface processes randomly and representatively sample the bulk of the mantle, and that there is a negligible bulk compositional gradient in the mantle. Support for this perspective comes from tomographic images of subducted plates of oceanic lithosphere penetrating the 660 km seismic discontinuity. Not all subducted plates directly penetrate this boundary layer in the mantle; some have been imaged translating laterally through the mantle transition zone (between the 410 km and 660 km seismic discontinuities) and appear to sink later, perhaps due to thermal densification effects.

Alternatively, there are geophysical models of the mantle based on EOS and seismological constraints that do not correspond with a compositionally homogeneous system, but rather require a chemically distinct upper and lower mantle. These models generally appeal to a lower mantle that is either SiO_2 or FeO enriched [5, 6]. These models are dependent on the quality of the input EOS data and the form of the equation used, as well as requiring that there are isolated mantle domains not sampled today. The tomographic seismic images and chondritic ratios plots for mantle samples are observations that are at odds with such alternative compositional models.

Based on the above observations, we can now use key element ratios in chondrites to further constrain models for the U, Th and K content of the silicate Earth. Importantly, the 5 most abundant elements in the Earth (O, Fe, Si, Mg, Ni), which make up 95% of the planet's composition (both atomic and by weight), can be determined by key ratios (e.g., atomic Mg/Fe and Fe/Ni) in both chondrites and mantle samples. Aside from Mg and Th, however, other elements have been suggested to have been sequestered into the Earth's core. Therefore, constraints on the Th and U content of the silicate Earth come from the range (<30%) of Mg/Th 3.3 ± 0.9 (2σ) in average chondrite types [7].

Compositional models for the silicate Earth estimate the abundances of the refractory lithophile elements at 2.2 to 2.8 times that in C1 carbonaceous chondrites, which translates into a 25% spread in the concentration of Th and U in the silicate Earth (63-83 ng/g Th and 17-22 ng/g U, respectively). Cosmochemical constraints, both isotopic and chemical, and melting models add to this uncertainty, resulting in a silicate Earth with 80 ± 25 ng/g Th and 20 ± 8 ng/g U, with a Th/U of ~3.9 (with only 10% uncertainty; [3]). The combination of Sr, Pb and U isotope systematics shows that the silicate Earth has a chondritic Th/U ratio within uncertainties, although these data do not preclude a negligible amount of U in the core. However, combined evidence from geochemical, cosmochemical and petrological studies demonstrate that there is negligible U and/or K in the core [8, 9]. Therefore, based on the above and the silicate Earth's K/U value ($1.38 \pm 0.26 * 10^4$; [10]), we estimate that the heat-producing elements (i.e., U, Th and K) contribute 21 ± 4 (2σ) TW of power to the Earth.

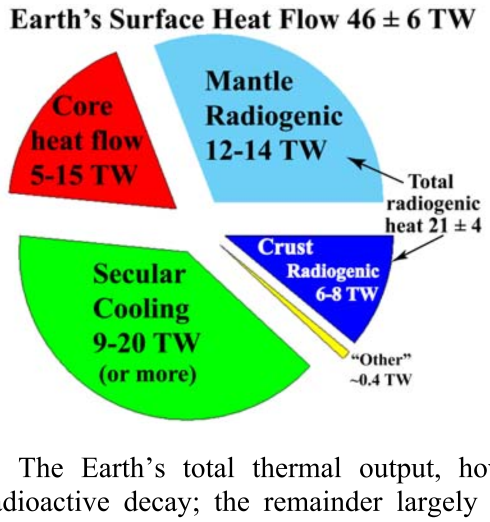

Figure 2. Earth's thermal budget and its contributors, based on a model of 46 ± 6 TW (2σ) of total output power from Jaupart et al. [11] with modifications from Arevalo et al. [10]. The radiogenic contribution is ~40% of the Earth total surface heat flow. The continental crust constitutes ~0.55% of the mass of the silicate Earth, with the remainder made up by the mantle. The continental crust is on average 40 km thick (base of the mantle is 2890 km) and has a factor of 10^2 more heat producing elements than the mantle.

The Earth's total thermal output, however, is not entirely derived from heat generated by radioactive decay; the remainder largely comes from secular cooling of the planet (see [11] and references therein). Figure 2 presents a simplified model for the relative contributions of the thermal emission from inside the planet. The "other" component in this figure includes contributions from differentiation, tidal forces, thermal contraction, etc. Also note, Davies [12] has estimated up to 28 TW for the mantle radiogenic component (as cited in [11]). Estimates of the planet's Urey ratio, defined as the ratio of total heat production to total heat loss (i.e., surface heat flux), range from 0.4 to 1.0, depending on the assumed abundances for heat producing elements within the Earth and the total thermal output of the planet. An estimate for the mantle Urey ratio (i.e., mantle heat production to total heat loss minus the continental contribution) vary from as low as 0.2 to as high as 0.7 ([11, 13, 14] and references therein), reflecting that continents contain a significant portion (~33%) of the heat producing elements in the planet. A current value for the radiogenic heat contribution is 21 TW (14 TW from the mantle and 7 TW from the continents), which, in turn, would imply a mantle Urey ratio of 0.3. This mantle Urey ratio is low and outside the range of most geophysical models that attempt to parameterize convection in the mantle (e.g., [15-18]).

Geophysical and geochemical interpretations of the systematics of mantle convection (including the distribution of radioactive elements and the mode of convective cycling) are currently incongruous. Geophysical models that describe the kinetics and dynamics of mantle convection are designed to be self-consistent and comprehensive, such that they integrate the entire history of convection in the Earth. In general, these models place numerical limits on the secular evolution in the heat flux out of the Earth. One form of a scaling law that can be used to describe the thermal evolution of the mantle is $Q \propto Ra^{\beta}$, which relates heat flux (Q) for a fluid (e.g., convective mantle) to the Rayleigh number (Ra) of the fluid [19-21]. Constraints on the exponent β, an amplifier for the force balance between viscosity and heat dissipation, in this analysis are crucial and not presently available; for an isoviscous fluid it is recognized that the exponent β has a value of ≈1/3, a self-regulated state, which expresses a balance of forces between heat generation and dissipation. Such high values for β suggest slower cooling rates due to enhanced viscosity (as a result of lower internal heating) and thus the evolution of the system depends more on the initial conditions. A considerable effort has been invested in understanding the relative balance of forces and thus what might be appropriate values of β (see summary in [17]). For a mantle Urey ratio of ~0.3, appropriate β values are low; Grigné et al. [17] and Labrosse and Jaupart [13] however believe that the size and distribution of plates and subduction zones and aspect ratios of convective cells may play a greater role in thermal dissipation than previously thought. Alternatively, Loyd et al. [22] and Korenaga [14] conclude that changes in the oceanic heat flux and past sea-level variations have been limited, based on plate reconstruction and sea-level changes. However, all models depend on the core heat flux, as well as any potential heat generation in a D" reservoir that sits on the core-mantle boundary, which may play a significant role in heat production. Recent estimates of the heat flux across this region (from the core and D"), based on the post-perovskite phase transition [23, 24], imply fluxes in this region of 10 TW or more.

Further collaborations between physics and geology in the field of geoneutrino research should generate observations requiring inputs from both disciplines to interpret more precisely the terrestrial antineutrino spectral data. Our ultimate goal is to map out the Earth's internal distribution of radioactive elements in order to better define the nuclear engine that powers this planet.

Acknowledgments

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