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Earth's Uranium and Thorium content and geoneutrinos fluxes based on enstatite chondrites

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ABSTRACT

The Earth's thermal evolution is controlled by the amount of heat released by the radioactive decay of ^{40}K, ^{238}U, ^{235}U and ^{232}Th. Their crust and upper mantle content is inferred from direct sampling, whereas estimating the lower mantle concentrations requires indirect constraints, such as those brought by primitive chondrites, or by geoneutrinos. Here we follow the framework of "E-Earth" models, based on the isotopic and chemical composition of E-chondrites (EC), to calculate U and Th concentrations in the Earth's present day mantle, and the corresponding geoneutrinos flux. The model uses a compilation of data of U and Th contents of EC and account for the Earth differentiation and crust extraction. We obtain that the Bulk Silicate Earth (BSE) contains 15.4 ± 1.8 ppb of Uranium and 51.3 ± 4.4 ppb of Thorium, and has an average Th/U mass ratio of 3.4 ± 0.4, with a peak value around 3.15. The prediction of geoneutrinos events originating from the mantle (i.e., without taking into account the local contribution of the crust) is 5.1 ± 1.0 TNU, with 4.3 ± 0.9 TNU coming from Uranium, and 0.8 ± 0.2 TNU from Thorium. These numbers are in good agreement with the most recent KamLAND detector estimate, and compatible with the (higher) Borexino flux. On the other hand, the KamLAND constraints are not consistent with the high content of heat producing elements in the mantle predicted by the simple application of parameterized convection model to the thermal evolution of the Earth's mantle. Since the measurement error in the mantle neutrino flux is currently dominated by the crustal contribution, geoneutrinos cannot for now discriminate between CI-based and EH-base models of the Earth's composition. Further progress is expected if an ocean based geoneutrino detector is deployed.

1. Introduction

Thermal evolution of the Earth depends on the (im)balance between surface heat loss and internal heat production (e.g., Labrosse and Jaupart, 2007). Present-day heat losses at the surface of the Earth are known through direct measurements of heat flux, and a 43–49 TW range is widely accepted (e.g., Pollack et al., 1993; Jaupart et al., 2007; Davies and Davies, 2010). Heat lost in the past history of the planet is more difficult to assess, as it depends both on the evolution of the mode of thermal convection in the Earth's mantle (e.g., presence and efficiency of plate tectonics) and on the evolution of the rate of heat production within the Earth's mantle and core (e.g., Korenaga, 2008).

Heat production in the core depends on the release rate of latent heat by iron crystallization, and can be constrained using the age of the inner core and estimates of heat flux transported by mantle plumes originating from the core–mantle boundary (Labrosse, 2002). Heat production in the mantle depends on the concentration of radioactive elements (^{40}K, ^{238}U, ^{235}U and ^{232}Th), that, until recently, could be only obtained through direct (terrestrial) and indirect (cosmic) sampling (e.g., McDonough and Sun, 1995; Allegre et al., 1995; Javoy, 1999; Palme and O'Neill, 2003; Lyubetskaya and Korenaga, 2007). The resulting estimates depend strongly on the method and on the (terrestrial or meteoritic) sample used, and no consensus has been reached yet on the content of heat producing elements in the so-called "Bulk Silicate Earth", or BSE = crust + mantle. A lower bound is $U = 12 \pm 2$ ppb and $Th = 43 \pm 4$ ppb (Sramek et al., 2013), and an upper bound is $U = 21.8 \pm 3.3$ ppb and $Th = 83.4 \pm 12.5$ ppb (Palme and O'Neill, 2003). Hence the different models of Earth composition yield almost a factor 3 variation in the estimates of heat production, which range between 9 and 24 TW (Dye, 2012; Sramek et al., 2013). Much higher numbers are provided by the so-called "geodynamical" estimate of heat production (Turcotte and Schubert, 2002), which is not based on a model of Earth's composition but on the application of scaling laws characterizing the thermal evolution of convective systems. Following this approach,

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Table 1
Compilation of literature data on U and Th contents of E-chondrites.

Chondrites	U (ppb)	Th (ppb)	Th/U (mass ratio)	References
CI	7.4	29	3.92	McDonough and Sun (1995)
Average EH	9	30	3.33	Wasson and Kallemeyn (1988)
Average EL	10	35	3.50	Wasson and Kallemeyn (1988)
Sahara 97072 (EH3)	6.5	25.7	3.95	Gannoun et al. (2011)
ALHA 77295 (EH3)	7.1	28	3.94	Gannoun et al. (2011)
Sahara 97072 (EH3)	8.92	28.40	3.18	Dauphas and Pourmand (2011)
Qingzhen (EH3)	7.61	25.84	3.39	Dauphas and Pourmand (2011)
Indarch (EH4)	9.44	27.37	2.90	Dauphas and Pourmand (2011)
Adhi Kot (EH4)	7.86	26.76	3.40	Dauphas and Pourmand (2011)
St. Mark's (EH5)	8.39	27.60	3.29	Dauphas and Pourmand (2011)
Saint-Sauveur (EH5)	7.62	24.40	3.20	Dauphas and Pourmand (2011)
Abee (EH4)	9.0	30.0	3.33	Morgan and Lovering (1968)
Indarch (EH4)	10.8	28.7	2.66	Morgan and Lovering (1968)
St. Mark's (EH5)	7.2	29.8	4.14	Morgan and Lovering (1968)
St. Mark's (EH5)	8.7	31.0	3.56	Morgan and Lovering (1968)
Abee (EH4)	7.34	–	–	Manhès (1982)
Indarch (EH4)	8.33	–	–	Manhès (1982)
Saint Mark's (EH5)	8.13	–	–	Manhès (1982)
Saint Sauveur (EH5)	8.01	–	–	Manhès (1982)
ALHA 77295 (EH3)	7.2	27.6	3.83	Barrat et al. (2013)
GRO 95517 (EH3)	7.1	26.3	3.70	Barrat et al. (2013)
Kota Kota (EH3)	–	31	–	Barrat et al. (2013)
MIL 07028 (EH3)	6.9	25.7	3.72	Barrat et al. (2013)
Sahara 97096 (EH3)	7.6	26.3	3.46	Barrat et al. (2013)
Sahara 97123 (EH3)	12	37	3.08	Barrat et al. (2013)
Sahara 97158, A (EH3)	7	31	4.43	Barrat et al. (2013)
Sahara 97158, B (EH3)	8	32	4	Barrat et al. (2013)
Galim (b) (EH3/IMB)	6.85	24.4	3.56	Barrat et al. (2013)
Indarch (EH4)	7.42	28.5	3.84	Barrat et al. (2013)
Abee (EH4/IMB)	8	29	3.62	Barrat et al. (2013)
St. Mark's (EH5)	8.9	29.2	3.28	Barrat et al. (2013)
St. Sauveur (EH5/IMB)	10.7	29.8	2.78	Barrat et al. (2013)
MAC 88136 (EL3)	8.35	34.65	4.15	Barrat et al. (2013)
MAC 02837 (EL3)	8.8	34.4	3.91	Barrat et al. (2013)
PCA 91020 (EL3)	7.7	33.6	4.36	Barrat et al. (2013)

the production of heat can be estimated to 33 ± 3 TW, and the U and Th content of the BSE to 35 ± 4 ppb and 140 ± 14 ppb, respectively (Sramek et al., 2013).

Since 2005, measurements of geoneutrinos have become accurate enough to be consider as a potential original and independent constraint on the amount of radioactive U and Th in the Earth (Araki et al., 2005; Bellini et al., 2010) hence on internal heat production and thermal history of the planet. However, recent estimates of the flux of geoneutrinos produced by the disintegration of U and Th in the Earth's mantle still show significant variations between Japanese KamLAND and Italian Borexino detectors, although the total geoneutrinos fluxes agree with uncertainties (Bellini et al., 2013; Gando et al., 2013). A minimum value of radiogenic heating in the mantle, $14^{+14}/_{-13}$ TW, was estimated from KamLAND measurements, whereas the maximum value, $62^{+44}/_{-46}$ TW, was obtained from Borexino measurements by Dye (2012), using additional geological constraints based on the K/U of the mantle to assess the amount of heat produced by ^{40}K which for now cannot be constrained by geoneutrinos. The flux of ^{40}K geoneutrinos is however estimated to exceed that of U + Th combined, and that with advanced detection methods sensitivity to ^{40}K geoneutrinos should be possible.

The combined use of geoneutrino signals with both terrestrial and chondritic constraints is likely to improve the estimates of U and Th contents of the Earth. A specific "cosmic" constraint brought by the "E-Earth" model of the composition of the Earth (Javoy, 1995; Javoy et al., 2010) is the isotopic proximity between Earth and Enstatite chondrites (E-chondrites) and the associated chemical parenthood between the two materials. Combining the composition of E-chondrites with geophysical constraints on the thermal and chemical state of the Earth's lower mantle makes possible the assessment of the BSE composition allowing for a chemically heterogeneous mantle (Javoy et al., 2010). The aim of this paper is to use the formalism of the E-Earth model, previously developed to assess the composition of the Earth in terms of major elements, to provide new estimates of the U and Th content of the Earth's mantle.

2. From U and Th contents in E-chondrites to U and Th contents in the Earth's building blocks

2.1. U and Th contents in E-chondrites

The isotopic and chemical composition of E-chondrites is the corner stone of the E-Earth model (Javoy, 1995). Hence the determination of the U and Th content of E-chondrites is a first step required for the assessment of U and Th content of the Earth. For that goal, we have performed a detailed review of the literature on the composition of EH and EL3 chondrites (EL3 being the only EL chondrites possibly relevant to Earth composition modeling, Kaminski and Javoy, 2013). The resulting synthesis in presented in Table 1, together with a reference CI chondrite U and Th concentrations (McDonough and Sun, 1995), and the average U and Th contents in EH and EL chondrites (Wasson and Kallemeyn, 1988).

The U concentrations in E-chondrites vary between 6.5 and 12 ppb, and the Th concentrations between 24.4 and 37 ppb. The average values are 8.2 ppb for U and 29 for Th, which is about 1 ppb smaller than the average given for EH chondrites (Wasson and Kallemeyn, 1988), but identical to the average proposed for CI chondrites. The Th/U mass ratio varies between 2.7 and 4.4, with an average value of 3.6. The range of Th/U variations thus includes the ratio obtained for CI (Th/U = 3.9; McDonough and Sun, 1995)