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Geo-neutrinos and Earth Models

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Abstract

We present the current status of geo-neutrino measurements and their implications for radiogenic heating in the mantle. Earth models predict different levels of radiogenic heating and, therefore, different geo-neutrino fluxes from the mantle. Seismic tomography reveals features in the deep mantle possibly correlated with radiogenic heating and causing spatial variations in the mantle geo-neutrino flux at the Earth surface. An ocean-based observatory offers the greatest sensitivity to the mantle flux and potential for resolving Earth models and mantle features. Refinements to estimates of the geo-neutrino flux from continental crust reduce uncertainty in measurements of the mantle flux, especially measurements from land-based observatories. These refinements enable the resolution of Earth models using the combined measurements from multiple continental observatories.

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1. Introduction

Geo-neutrinos stream to space from the decay of radioactive isotopes within the Earth. Their flux at the surface is predicted to vary spatially, primarily due to variations in continental crust - in which radioactive isotopes are concentrated - with secondary effects due to possible compositional heterogeneities in the mantle. Geo-neutrino flux measurements, which account for the predicted variation, estimate radiogenic heating in the mantle. This heating helps power plate tectonics, earthquakes, volcanism, and mantle convection. Estimates of radiogenic heating in the mantle constrain Earth models, providing important information on the origin and thermal history of the planet.

Ongoing measurements of the surface flux of geo-neutrinos, which are initiated by the decays of ^{238}U and ^{232}Th, provide an encouraging outlook for resolving mantle heating. At Japan the flux measurement is $(3.4 \pm 0.8) \times 10^6$ cm^{-2} s^{-1} [1], while at Italy the flux measurement is $(4.3 \pm 1.3) \times 10^6$ cm^{-2} s^{-1} [2]. Subtracting the predicted flux from the crust [3, 4, 5] and assuming negligible flux from the core estimates the flux from the mantle. It is customary to express geo-neutrino flux as a rate of recorded interactions in a perfect detector with a given exposure. The usual unit is the terrestrial neutrino unit (TNU) [6].

Combining the surface geo-neutrino flux measurements at Japan and Italy estimates a mantle geo-neutrino detection rate of 7.7 ± 6.2 TNU [7]. The main sources of uncertainty in the estimate are the experimental errors in the flux measurements and limited knowledge of the subtracted crust fluxes [3, 4, 5]. Translating the detection rate into radiogenic heating introduces additional uncertainty due to ambiguity in the amounts and distributions of uranium and thorium in the mantle [8, 9]. Standard assumptions for the ratios of thorium to uranium and of potassium to uranium [10] suggest 2 − 21 TW of radiogenic heating in the mantle (Figure 1).

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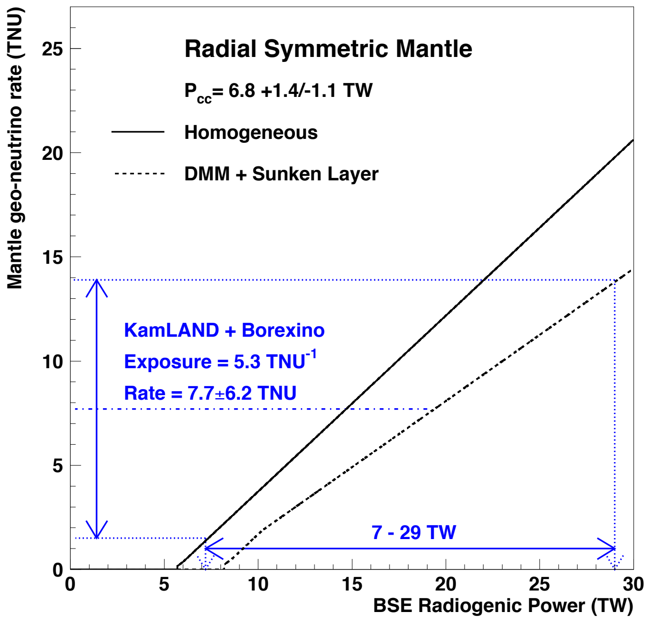

Figure 1. Radiogenic power of bulk silicate Earth (BSE) is constrained between 7 and 29 TW by the combined measurement of geo-neutrinos from the mantle [7]. The lower bound on BSE radiogenic heating obtains with a homogeneous mantle and the lower limit of radiogenic heating in continental crust. The upper bound on BSE radiogenic heating obtains with a 150-km thick sunken layer enriched in heat-producing elements at the base of depleted MORB-source mantle and the upper limit of radiogenic heating in continental crust.

Radiogenic heating in the mantle is an important component of the energy budget of the Earth. The other main components are the flow of heat across the core-mantle boundary [11] and the rate at which the mantle sheds primordial heat. Together with the heat generated in the crust, these sum to the surface heat flux of 47 ± 3 TW [12]. Improving the estimate of mantle radiogenic heating better constrains models of the origin and thermal evolution of the Earth. Although the required precision is currently under investigation, there is clearly much room for improvement in this estimate. Additional exposure to the flux of geo-neutrinos reduces experimental errors and detailed investigations of the crust better defines the subtracted crust fluxes [5]. These improve precision but do not eliminate uncertainty in the radiogenic heating. Ambiguity in the amounts and distributions of uranium and thorium in the mantle remain. For example, a perfect measurement of the mantle signal rate at the central value of the estimated 7.7 TNU suggests 8 – 11 TW of radiogenic heating in the mantle, assuming radial symmetry. Assigning increased uranium and thorium concentrations to deep mantle seismic structures suggests a similar spread in values and motivates observational strategies [13].

We describe various Earth models classified by low, medium, and high levels of radiogenic heating. These models all accommodate the estimated 7 TW of radiogenic heating in the crust [5]. Depending on the model the residual excess in the mantle is as low as 3 TW [14] and as much as 18 TW. In addition to minimum levels of mantle radiogenic heating defined by studies of the source of mid-ocean ridge basalt (MORB) [15, 16, 17], we consider heterogeneity of radioactive isotopes associated with seismically resolved mantle structures, including large low seismic velocity provinces (LLSVPs) and ultra-low velocity zones (ULVZs). Variation in the values of the radioactive isotope content of MORB-source mantle and potential heterogeneity of radioactive isotopes associated with seismic structures contribute uncertainty to the estimate of mantle radiogenic heating. We then describe observational strategies for reducing these uncertainties and resolving mantle models.