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Uranium-Thorium evolution of extrasolar silicate worlds

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As the suite of known exoplanets expands with the discovery of thousands of worlds around other stars, the need arises to further constrain the range of possible compositions of these objects. This is of particular importance for geophysical modeling of terrestrial exoplanets that may be capable of supporting life. A poorly constrained parameter in these models is radiogenic heating from the long-lived, heat-producing isotopes that are key to keeping planetary interiors warm. In Earth's mantle, the decay of ^{40}K, ^{232}Th, ^{235}U, and ^{238}U provides the majority of the heat output that helps sustain plate tectonics. Given that plate tectonics plays an integral role in keeping Earth's surface habitable, radiogenic heat production is an important factor to consider in modeling terrestrial exoplanets. In published models, radiogenic heat production is scaled from Earth's or chondritic values. Given that Earth's own heat production has decreased at least fivefold over solar system history, it is unreasonable to assume that exoplanets with different ages and geochemical histories should have comparable values. Age is an important factor for heating in that not only will old stars form with a lower metallicity than young stars, but their isotopes will have had a longer period of time to decay. Here we present a model in which we make predictions for the heat generated by ^{232}Th, ^{235}U, and ^{238}U in a solar system within the (galactic) solar cylinder as a function of age. The primary constraints in our model are (i) the ages of our solar system and galaxy, (ii) production ratios of the isotopes, (iii) concentrations of ^{232}Th, ^{235}U, and ^{238}U at the time our solar system formed, and (iv) half-lives. We assumed a hybrid model of the production of these nuclides in our galaxy by taking into account both the burst of nuclides created by massive stars at galaxy formation and those generated in supernovae over galactic history. We numerically solved for the relative contributions of nuclides generated by each process and then used the resulting proportions to constrain the heat they generate in a solar system given its age. Sensitivity tests indicate that of the constraints, the ^{235}U/^{238}U and ^{232}Th/^{238}U production ratios have the most significant effect on the results. By comparison, our predictions are relatively insensitive to the age of the galaxy. The ^{235}U/^{238}U production ratio is particularly fickle due to the relatively short half-life of ^{235}U compared to ^{238}U. For a galaxy age of 12.5 Gyr, the ^{235}U/^{238}U production ratio can only provide a minimum production ratio, found to be 1.42, whereas the allowable spectrum of the ^{232}Th/^{238}U production ratio is found to be 1.02 to 1.64, the higher values of which are consistent with published ratios. To ground-truth our model, we compared predicted Th/U ratios to published observations of ancient, metal-poor halo stars. Despite the wide error bars for the calculated ages of these stars due to observational limitations, our model predicts Th/U ratios consistent with observations. As such, in addition to making predictions for heat production in extrasolar systems, our model may also be used to constrain stellar ages.