A RADIOGENIC HEATING MODEL FOR COSMOCHEMICALLY EARTH-LIKE EXOPLANETS. E.A. Frank,[1] B.S. Meyer[2], and S. J. Mojzsis[1,3], [1]Dept. Geological Sciences & CLOE, UCB 399, 2200 Colorado Ave, Boulder, CO 80309, USA, elizabeth.frank@colorado.edu, [2]Dept. Physics & Astronomy, 118 Kinard Laboratory, Clemson University, Clemson, SC 29634, USA, [3]Hungarian Academy of Sciences, RCAES, Institute for Geological and Geochemical Research, 45 Budaörsi ut, H-1112 Budapest, Hungary.

Introduction: The success of the *Kepler* mission has inspired a wave of studies addressing the geophysical regimes of terrestrial exoplanets, e.g., [1 and references therein]. Given the limited knowledge regarding exoplanet geochemistry—and in particular, the suite of long-lived, heat-producing radioactive isotopes that heat silicate mantles—assumptions must be made for those model parameters. Here we present the results of a study that integrates galactic chemical evolution (GCE) models with knowledge of our own solar system in order to constrain radiogenic heating in chemically Earth-like exoplanets as a function of their age.

Radiogenic heating: The radionuclides ^{40}K, ^{232}Th, ^{235}U, and ^{238}U provide heat to silicate mantles over billion-year timescales. As a planet ages, however, that heat contribution declines as the nuclides decay towards extinction. Earth itself has ~25% of the radiogenic heat output that it had at its formation (ca. 4568 Ma). Constraining this parameter is important for geophysical models due to its role in modulating a planet's tectonic regime [2]. Of particular relevance is the suite of geochemical and geophysical parameters that permit plate tectonics. Radiogenic heating is one such parameter that has been addressed before [3], but here we provide new, more rigorous constraints.

Galactic chemical evolution: To address the problem of how the Galaxy has chemically evolved with time, GCE models have been formulated to describe changes in its bulk chemistry in both time and space as old star perish and new generations arise, enriching the interstellar medium (ISM) with heavy elements [4]. A GCE model must take into account both primary and secondary species: primary species are produced via nucleosynthesis in stars of pure H, while secondary species are produced from pre-existing seed nuclei created in previous generations of stars.

Model: Although there are a number of detailed numerical GCE models [4], an analytical model by [5] parameterizes galactic infall in a computationally convenient but realistic way that reproduces the Galactic age-metallicity relation as observed in G dwarf stars. The Clayton model allows for straightforward computation of species mass fractions as a function of Galactic age using the following simplifying assumptions: 1) the instantaneous recycling approximation (IRA: stars that die and return gas to the interstellar medium do so instantaneously) and 2) instantaneous mixing approximation (IMA: stellar ejecta mix instantaneously with the bulk interstellar medium). Because there is a radial chemical gradient in the Galaxy, we limit our results to solar systems within the solar annulus. The model is fit to the elemental and isotopic abundances of the solar system at time of formation [6], and the Galactic disk age is taken to be 12.5 Ga [7].

Analysis: We ran the Clayton model for the isotopes of interest as well as important major planet-forming elements: C, O, Na, Mg, Al, Si, S, K, Ca, Ti, Cr, Fe, and Ni. Output is given in terms of gas mass fractions of a species. Clouds of such gas collapse to form solar systems, and from the IMA it follows that the gas is well-mixed and thus solar systems should match the chemistry of the gas from which they form. However, translating the bulk chemistry of a solar system to that of its planets is far more challenging, even just for our own solar system, e.g., [8]. As such, we consider here mantles that are Earth-like in their chemistry, i.e. that the ratio of a species' abundance in bulk solar system material (ignoring volatiles such as H, He, Li, and the noble gases) to the mantle of an Earth-like exoplanet is identical to the carbonaceous chondrite [6] to bulk silicate Earth [9] ratio. Concentrations of ^{40}K, ^{232}Th, ^{235}U, and ^{238}U were calculated by dividing their modeled mass fractions into the sum of those for O, Na, Mg, Al, Si, S, K, Ca, Ti, Cr, and Fe.

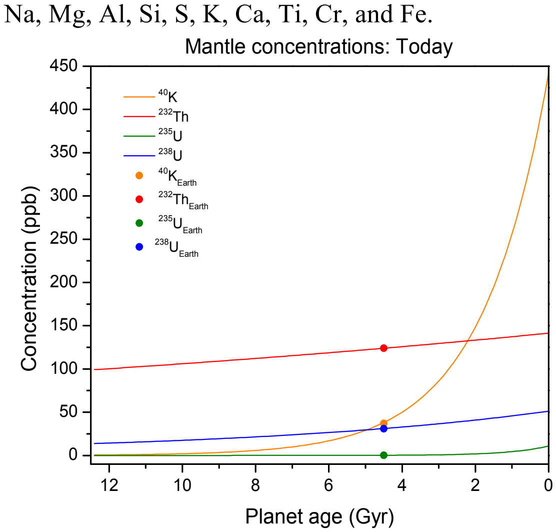

Figure 1. Current mantle concentrations of ^{40}K, ^{232}Th, ^{235}U, and ^{238}U in exoplanets with rocky mantles of similar compositions to Earth's. The dots show Earth's present-day concentrations of each isotope.

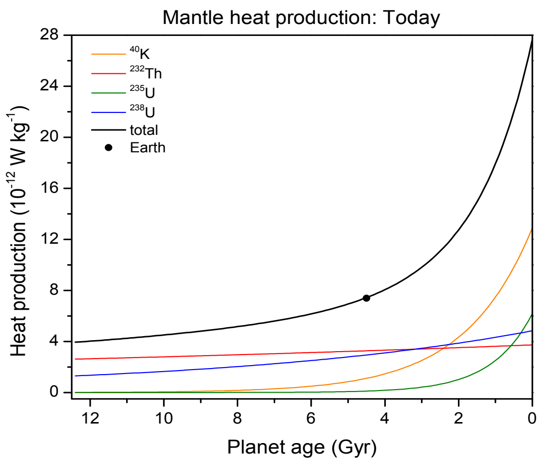

Figure 2. Heat production from ^{40}K, ^{232}Th, ^{235}U, and ^{238}U in exoplanets with rocky mantles of similar compositions to Earth's. The black dot shows Earth's present-day heat production, confirming the model fit.

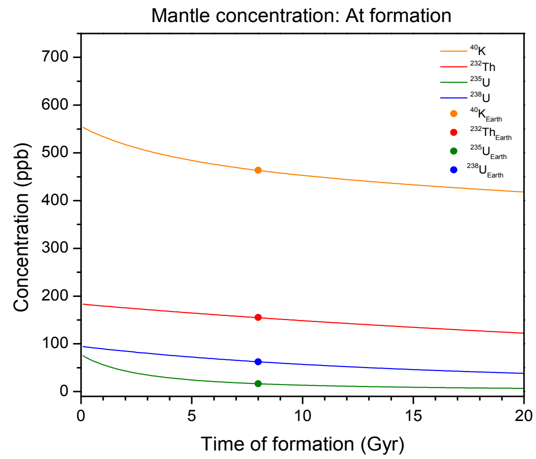

Figure 3. Mantle concentrations of ^{40}K, ^{232}Th, ^{235}U, and ^{238}U in exoplanets at the time of their formation in Galactic history. The dots show Earth's concentrations 4568 Ma.

Finally, heat production was calculated by multiplying the modeled concentrations by the known heat output of the individual radioactive isotopes.

Results: Figures 1 and 2 show the calculated concentrations and heat production rates, respectively, for ^{40}K, ^{232}Th, ^{235}U, and ^{238}U in an Earth-like mantle as a function of a planet's age today. Uranium-235 is effectively extinct in planets by 3 Gyr after their formation, and ^{232}Th continues to provide heat to planets 12.5 Gyr at ~50% of Earth's current production. Planets forming today have heat production rates three times higher than Earth's despite having lower concentrations of the isotopes at the time of formation relative to concentrations in Earth's 4.56 Ga (Figure 3). Figure 4 shows the evolution of the Si/Fe ratio over the course of galactic history. Iron is a primary species, so while, like Si, it is initially produced solely in massive stars, it will receive a boost in production once the Type Ia supernovae, which are thermonuclear explosions of white dwarf stars, kick in several billion years after Galaxy formation. This trend suggests that planets that formed in the early Galaxy might have had small cores due to low Fe availability.

Conclusion: While the concentrations of ^{40}K, ^{232}Th, ^{235}U, and ^{238}U are declining in the mantles of new planets as the Galaxy becomes increasingly enriched in stable mantle-forming species, age is a more important factor in determining the heat production from those isotopes. Potassium-40 is currently the dominant heat-producing species in planets younger than ~2 Ga, but ^{232}Th still provides heat in the oldest exoplanets at ~50% of Earth's current heat production. Due to the initially low Si/Fe ratio in the Galaxy, the first planets that formed likely had small cores.

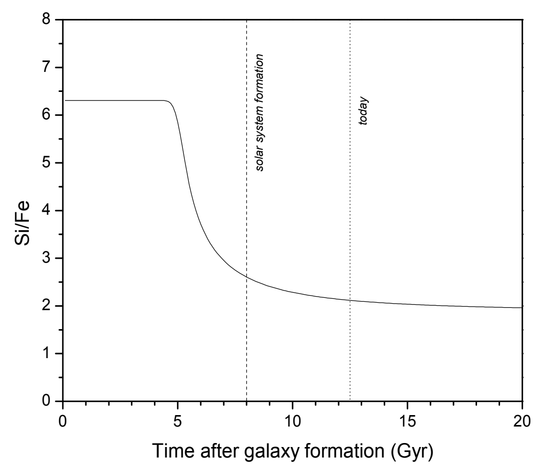

Figure 4. The Si/Fe ratio in the Galaxy as a function of Galactic age (the solar system formed at 8 Gyr). The sharp drop at ~5 Gyr results from the added contribution of Fe from Type Ia supernovae. Type Ia supernovae are thermonuclear explosions of white dwarf stars. The delay in their onset arises from the fact that time is required for the evolution of low-mass stars into white dwarfs.

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