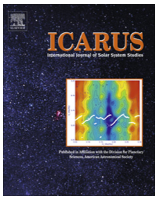
Icarus 243 (2014) 274–286

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



A radiogenic heating evolution model for cosmochemically Earth-like exoplanets

Elizabeth A. Frank [a,*], Bradley S. Meyer [b], Stephen J. Mojzsis [a,c,d,*]

[a] Department of Geological Sciences, NASA Lunar Science Institute, Center for Lunar Origin and Evolution (CLOE), University of Colorado, 2200 Colorado Avenue, UCB 399, Boulder, CO 80309-0399, USA
[b] Department of Physics and Astronomy, Clemson University, Clemson, SC, 29634-0978, USA
[c] Laboratoire de Géologie de Lyon, École Normale Supérieure de Lyon, Université Claude Bernard Lyon 1, CNRS UMR 5276, 2 rue Raphaël Dubois, 69622 Villeurbanne, France
[d] Hungarian Academy of Sciences, Institute for Geological and Geochemical Research, 45 Budaörsi ut, H-1112 Budapest, Hungary

ARTICLE INFO

Article history:
Received 11 August 2013
Revised 12 August 2014
Accepted 19 August 2014
Available online 27 August 2014

Keywords:
Extra-solar planets
Terrestrial planets
Thermal histories
Abundance, interiors
Cosmochemistry

ABSTRACT

Discoveries of rocky worlds around other stars have inspired diverse geophysical models of their plausible structures and tectonic regimes. Severe limitations of observable properties require many inexact assumptions about key geophysical characteristics of these planets. We present the output of an analytical galactic chemical evolution (GCE) model that quantitatively constrains one of those key properties: radiogenic heating. Earth's radiogenic heat generation has evolved since its formation, and the same will apply to exoplanets. We have fit simulations of the chemical evolution of the interstellar medium in the solar annulus to the chemistry of our Solar System at the time of its formation and then applied the carbonaceous chondrite/Earth's mantle ratio to determine the chemical composition of what we term "cosmochemically Earth-like" exoplanets. Through this approach, predictions of exoplanet radiogenic heat productions as a function of age have been derived. The results show that the later a planet forms in galactic history, the less radiogenic heat it begins with; however, due to radioactive decay, today, old planets have lower heat outputs per unit mass than newly formed worlds. The long half-life of ^{232}Th allows it to continue providing a small amount of heat in even the most ancient planets, while ^{40}K dominates heating in young worlds. Through constraining the age-dependent heat production in exoplanets, we can infer that younger, hotter rocky planets are more likely to be geologically active and therefore able to sustain the crustal recycling (e.g. plate tectonics) that may be a requirement for long-term biosphere habitability. In the search for Earth-like planets, the focus should be made on stars within a billion years or so of the Sun's age.

1. Introduction

Since the first extrasolar planet orbiting a main-sequence star was verified in 1995 (Mayor and Queloz, 1995), scores more have been discovered, with >1500 confirmed, >3800 considered candidates, and more being added to the roster every day (http://planetquest.jpl.nasa.gov). The *CoRoT* (*COnvection, ROtation, and planetary Transits*) and *Kepler* telescopes have spearheaded the current era of exoplanet discovery. The primary goal of *CoRoT* is to discover exoplanets with short orbital periods, whereas that of *Kepler* was to find rocky Earth-mass worlds in their star's habitable zone; thus far, the suite of finds runs the gamut from super-Jupiters (e.g. Johnson et al., 2009) to sub-Mercuries (Barclay et al., 2013). Given that *CoRoT* and *Kepler* can directly measure little more than mass and orbital distance, inferring the atmospheric and geophysical regimes of exoplanets requires modeling, which itself necessitates extrapolations and inferences based on knowledge of our own Solar System. Rocky (composed of silicate and metal, also called "terrestrial") exoplanets in particular have received attention for their potential to be geologically active and thus potentially habitable to alien biomes. In the past several years, there has been a flurry of reports attempting to model the interiors of rocky exoplanets, their thermal histories, and the plausibility of present geological activity (e.g. Foley et al., 2012; Fortney et al., 2007; O'Neill, 2012; Papuc and Davies, 2008; Seager et al., 2007; Valencia and O'Connell, 2009; Valencia et al., 2006, 2007). A focus of these modeling efforts has been to determine the tectonic

---

* Corresponding authors. Address: Department of Geological Sciences, NASA Lunar Science Institute, Center for Lunar Origin and Evolution (CLOE), University of Colorado, 2200 Colorado Avenue, UCB 399, Boulder, CO 80309-0399, USA (S.J. Mojzsis). Fax: +1 303 492 2606.

E-mail addresses: elizabeth.frank@colorado.edu (E.A. Frank), mojzsis@colorado.edu (S.J. Mojzsis).

http://dx.doi.org/10.1016/j.icarus.2014.08.031
0019-1035/© 2014 Elsevier Inc. All rights reserved.

regimes of the so-called "super-Earths" (1–10 $M_{\oplus}$; Valencia et al., 2006), and in particular, whether these worlds are capable of sustaining plate tectonics.

The geophysical state of a super-Earth or any rocky planet is dictated in part by processes that occur long before its Solar System coalesced. The thermal regime of a planetary mantle, which on Earth manifests itself via plume activity and plate tectonics, is set largely by the long-lived, heat-producing radionuclides that were created during nucleosynthesis and injected into the interstellar medium from which all stars and their planetary systems form. The most important of these isotopes, ^{40}K, ^{232}Th, ^{235}U, and ^{238}U, contribute significantly to Earth's modern heat budget, complemented by lingering heat from accretion and differentiation (e.g. Richter, 1988).[1] Estimates of the Urey ratio, or the fraction of Earth's surface heat loss derived from radiogenic heating, range between 0.21 and 0.74 (Lenardic et al., 2011 and references therein). Despite their slow decay (^{40}K, $\tau_{1/2}$ = 1.25 Gyr; ^{232}Th, $\tau_{1/2}$ = 14.0 Gyr; ^{235}U, $\tau_{1/2}$ = 0.704 Gyr; and ^{238}U, $\tau_{1/2}$ = 4.47 Gyr), the concentrations of the long-lived isotopes in Earth's mantle have declined significantly over geologic time. For example, although ^{235}U was 88 times more abundant at the time of Solar System formation (t_{ss} = 4.568 Ga; Amelin et al., 2002; Bouvier and Wadhwa, 2010) than it is now, it became effectively extinct in Earth's mantle after less than about 3 Gyr. This has left the other three isotopes to produce the radiogenic heat that helps sustain Earth's present geological activity. With a half-life comparable to the age of the Universe, ^{232}Th has lost a mere 20% of its original abundance since t_{ss}, while ^{40}K has lost ~90%. When Earth reaches an age of ca. 10 Gyr, its radiogenic heat production will be ~15% of what it was at t_{ss}. At that time, ^{40}K will no longer be a heat contributor and ^{232}Th will continue to dominate heat production as it does today. In as soon as 900 Myr from now, there may no longer be enough heat in the mantle to sustain mobile-lid convection, and plate tectonics will shut down (Sleep, 2007).

Despite how significantly Earth's own heat production has changed with time, exoplanet modelers assume modern Earth, primordial Earth, or chondritic values for the concentrations of the important heat-producing nuclides. This is due to the challenge of having no direct data on the chemistry of rocky exoplanets, and thus, one is forced to make assumptions based on our Solar System with the understanding that it may not be representative of the hundreds of billions of others in the Galaxy. Furthermore, most exoplanet models inaccurately assume a heat production rate at steady-state rather than one that declines over time. This is especially important to recognize because while the age of a planet plays a pivotal role in the relative heat contributions of the relevant isotopes, it is equally important to consider their initial concentrations (cf. Gonzalez et al., 2001; Kite et al., 2009) since the ability of a planet to sustain plate tectonics changes with its initial and evolving thermal profile, which in turn affects its resulting surface convective regime (Noack and Breuer, in press). To constrain the initial radiogenic heat production of a planet, it is necessary to turn to galactic chemical evolution (GCE) models that predict the chemical composition of the gas in the galactic disk—and therefore the solar systems and planets that form from it—over the Galaxy's history. By coupling the chemical evolution of the Galaxy with that of solar systems and their planets, we have made first-order predictions of the ^{40}K, ^{232}Th, ^{235}U, and ^{238}U concentrations in rocky exoplanets within the solar annulus (an annular region centered on the Sun's orbit in the Galaxy), and in doing so, have generated radiogenic heating estimates for these exoplanets as a function of their age.

2. Galactic chemical evolution

Astrophysicists have long been faced with the challenge of trying to encapsulate the chemical evolution of the Galaxy into a single cohesive narrative (Burbidge et al., 1957). To tackle this problem, GCE models were formulated to address how the bulk chemistry of the Galaxy changes in both time and space as old stars perish and new generations arise (Matteucci, 2003). They quantitatively describe how the Galaxy evolves chemically as gas collapses into stars, stars generate "metals" (in the context of astrophysics, elements heavier than H and He) via nucleosynthesis, and the new elements are released back into the gas at the end of a star's lifetime. All GCE models share four common components: (i) boundary conditions, such as the Galaxy's initial composition and whether it is an open or closed system; (ii) stellar yields of heavy nuclides produced by nucleosynthesis; (iii) a star formation rate (SFR) and the initial mass function (IMF), which describes the distribution of initial masses for a stellar population; and (iv) gas inflows and outflows to the galactic system (Pagel, 1997). Quantitative constraints on GCE models include solar and meteorite compositions derived from observation and direct measurements of solar wind, the solar photosphere, the abundance ratios of the isotopes in primitive meteorites, the metallicity of G-dwarf stars, and galactic abundance gradients (Nittler and Dauphas, 2006). The resulting output is strongly model-dependent given the uncertainties inherent in each component. Operating as they do over colossal length scales for billions of years, nucleosynthetic processes enrich the interstellar medium (ISM) with heavy elements that accumulate and mix into the mass of material that supplies star-forming regions (Cowan and Sneden, 2006).

The effectively instantaneous appearance of heavy elements was due to production in the first generation of massive stars that lived on the order of 10^6 years after the Galaxy formed (Bromm and Larson, 2004), a period of time that was brief compared to the lifetime of the Galaxy. Indeed, a recent discovery of a galaxy that formed 700 Myr after the Big Bang and has a SFR > 100 times our Galaxy's provides evidence for the rapid heavy element enrichment of galaxies following their formation (Finkelstein et al., 2013). Due to their intrinsic instability as radioactive isotopes, the long-lived, heat-producing nuclides enter the decay process as soon as they are generated. Although it is unclear how the rate of supernova explosions has changed over time, early Solar System abundances of the actinides are approximately that expected for near-uniform production since the Galaxy formed (Reeves, 1991; Wasserburg et al., 1996).

The predictions set forth in GCE models have important implications for bulk chemical properties of planets, and so the models must account for the different processes by which elements are generated. The actinides U and Th are produced in the rapid-process ("r-process") nucleosynthesis, in which seed nuclei at the Fe peak experience a series of neutron captures that occur rapidly relative to the rate of β-decay if the nucleus is unstable (e.g. Cowan et al., 1991). Because of the neutron densities required for the r-process to occur, it was originally suggested that this happens in the neutron-dense areas around neutron stars produced in supernovae (Burbidge et al., 1957). Other sites have been proposed such as binary neutron star or black hole mergers, quick low-mass supernova explosions, accretion-induced collapse models, and bubbles or jets produced during supernova explosions (Sneden et al., 2008). In contrast, ^{40}K is created both during oxygen burning when lighter elements fuse in the cores of massive stars and s-process (slow-process) nucleosynthesis, and it has a different galactic accumulation history than the r-process nuclides (Clayton, 2003; Zhang et al., 2006). These different histories must be taken into account in GCE models.

---

[1] The important heat-producing short-lived nuclides ^{26}Al ($\tau_{1/2}$ = 7.17 × 10^5 y) and ^{60}Fe ($\tau_{1/2}$ = 2.6 × 10^6 y) become effectively extinct about 3 Myr after they form and thereafter cease to contribute to heat production.