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^{26}Al IN THE EARLY SOLAR SYSTEM: NOT SO UNUSUAL AFTER ALL

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ABSTRACT

Recently acquired evidence shows that extrasolar asteroids exhibit over a factor of 100 variation in the iron to aluminum abundance ratio. This large range likely is a consequence of igneous differentiation that resulted from heating produced by radioactive decay of ^{26}Al with an abundance comparable to that in the solar system's protoplanetary disk at birth. If so, the conventional view that our solar system began with an unusually high amount of ^{26}Al should be discarded.

Key words: planetary systems – white dwarfs

Online-only material: color figure

1. INTRODUCTION

Concentrations of excess ^{26}Mg, the decay product of the short-lived radionuclide ^{26}Al (mean life = 1.03 Myr; Castillo-Rogez et al. 2009), show that the solar system formed with $n(^{26}\text{Al})/n(^{27}\text{Al}) = 5.2 \times 10^{-5}$ (Jacobsen et al. 2008). Although there is evidence that there may have been deviations from this "canonical" ratio across the solar protoplanetary disk by as much as a factor of two (Larsen et al. 2011; Liu et al. 2012), the overall concentration of ^{26}Al in the solar disk was more than a factor of 10 greater than the current average value in the interstellar medium of 3.0×10^{-6} (Tang & Dauphas 2012). While some ^{26}Al may have been produced within the early solar system, most of it was not (Duprat & Tatischeff 2007; Desch et al. 2010); there must have been a significant external source of this short-lived nuclide. Commonly, the natal ^{26}Al is taken as a signature of a nearby supernova that may have triggered the collapse of the molecular cloud from which the Sun formed (Meyer & Clayton 2000; Gritschneder et al. 2012). Alternatively, winds from massive stars may have supplied the bulk of the ^{26}Al (Prantzos 2004; Gaidos et al. 2009; Gounelle & Meynet 2012).

A major consequence of large amounts of ^{26}Al in the early solar system was substantial internal heating of young planetesimals which therefore melted and subsequently experienced igneous differentiation. Iron meteorites are thought to be modern fragments of iron-rich cores formed during this era (McSween & Huss 2010). If other planetary systems formed with considerably less ^{26}Al, then their asteroids may not be differentiated. We can test this scenario by examining the elemental compositions of extrasolar minor planets.

Evidence is now compelling that some white dwarfs have accreted some of their own asteroids (Debes & Sigurdsson 2002; Jura 2003; Jura & Young 2014). In some instances, we have detected excess infrared emission from circumstellar disks composed of dust (Farihi et al. 2009; Xu & Jura 2012) where gas also is sometimes evident (Gaensicke et al. 2006). These disks lie within the tidal radius of the white dwarf and are understood to be the consequence of an asteroid having been shredded after its orbit was perturbed so it passed very close to the star (Debes & Sigurdsson 2002; Bonsor et al. 2011; Debes et al. 2012). Accretion from these disks supplies the orbited white dwarf's atmosphere with elements heavier than helium where they are normally not found because the gravitationally settling times are very short compared to the cooling age of the star. Estimates of the amount of accreted mass argue that we are witnessing the long-lived evolution of ancient asteroid belts (Zuckerman et al. 2010; Jura & Young 2014). In the most extreme case, the accreted parent body may have been as massive as Ceres (Dufour et al. 2012) which has a radius near 500 km. However, the required mass more typically implies parent bodies with radii near 200 km (Xu et al. 2013). Externally polluted white dwarfs provide a means for placing the solar concentration of ^{26}Al in context.

As a first approximation, extrasolar asteroids resemble bulk Earth being largely composed of oxygen, magnesium, silicon, and iron, and deficient in volatiles such as carbon and water (Klein et al. 2010; Jura 2006; Jura & Xu 2012) as expected in simple models for planet formation from a nebular disk. When eight or more polluting elements are detected, it is possible to tightly constrain the history and evolution of the parent body (Zuckerman et al. 2007; Xu et al. 2013). Recent studies of such richly polluted stars have shown abundance patterns that can be best explained if the accreted planetesimal evolved beyond simple condensation from the nebula where it formed. For example, NLTT 43806 is aluminum-rich as would be expected if the accreted planetesimal largely was composed of a crust (Zuckerman et al. 2011) while PG 0843+516 is iron rich which can be explained by the accretion of a core (Gaensicke et al. 2012). Xu et al. (2013) found that the abundance pattern of the object accreted onto GD 362 resembles that of a mesosiderite—a rare kind of meteorite that is best understood as a blend of core and crustal material (Scott et al. 2001).

Here, we first revisit the current sample of extrasolar planetesimals with well-measured abundances and reconfirm that igneous differentiation is widespread (Jura & Young 2014). We then present a model to explain this result. Finally, we consider our solar system from the perspective of extrasolar environments.

2. EVIDENCE FOR WIDESPREAD DIFFERENTIATION

The evidence for igneous differentiation among extrasolar planetesimals can be presented in a variety of ways (Jura & Young 2014). Here, we display in Figure 1 the abundance ratios by number, $n(\text{Fe})/n(\text{Al})$ versus $n(\text{Si})/n(\text{Al})$, for all seven

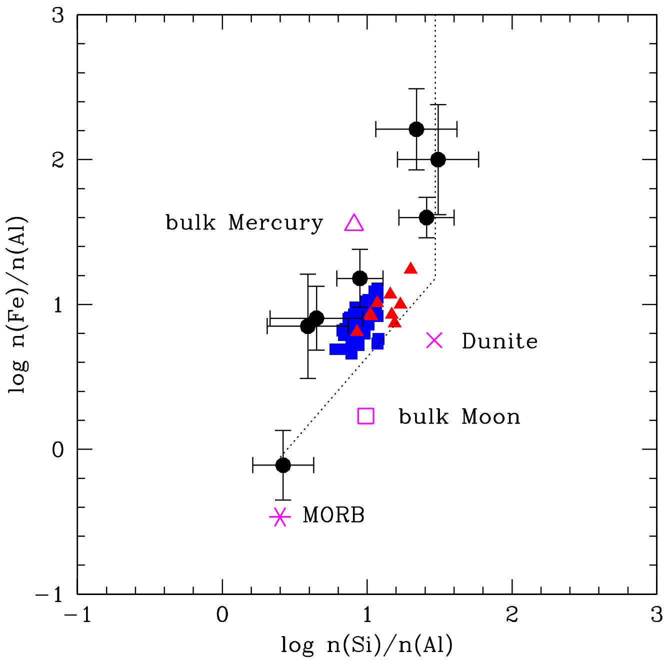

Figure 1. Abundance ratios by number of $n(\mathrm{Fe})/n(\mathrm{Al})$ vs. $n(\mathrm{Si})/n(\mathrm{Al})$ are denoted by black circles for those seven systems where all three elements have been detected. We assume a steady state approximation where the element's mass in the star's mixing zone is governed by a balance between the rate at which atoms are accreted and the rate at which they settle gravitationally into the interior (Jura & Young 2014) and employ the most recent settling times (Xu et al. 2013; http://www1.astrophysik.uni-kiel.de/~koester/astrophysics/). For comparison, we also display abundances among solar system chondrites as red triangles (Wasson & Kallemeyn 1988) and planet-hosting stars as blue squares (Gilli et al. 2006). Solar system materials are displayed by magenta symbols. The vertical dotted line represents model planetesimals composed of a blend of core and mantle rocks. The sloped dotted line represents model planetesimals composed of a blend of mantle and crustal rocks plus a core with 10% of the total mass. The observed ratios in externally polluted white dwarfs can be reproduced with different combinations of solar system objects.

(A color version of this figure is available in the online journal.)

externally polluted white dwarf atmospheres where these three elements have been reported.[3] We see that $n(\mathrm{Fe})/n(\mathrm{Al})$ varies by more than a factor of 100, a much greater range than shown among main-sequence planet-hosting stars, solar system chondrites, and even $n(\mathrm{Si})/n(\mathrm{Al})$ among these same polluted stars.

The large range in $n(\mathrm{Fe})/n(\mathrm{Al})$ among extrasolar planetesimals must be the result of some powerful cosmochemical process. One possibility is that unlike in the solar system, some extrasolar planetesimals were formed largely of refractory elements (Bond et al. 2010) resulting in low values of $n(\mathrm{Fe})/n(\mathrm{Al})$ because Al is highly refractory. However, this scenario is not supported by available observations (Jura & Xu 2013), and cannot explain why some systems have relatively high values of $n(\mathrm{Fe})/n(\mathrm{Al})$. Because there is no viable nebular model to explain the observed range in $n(\mathrm{Fe})/n(\mathrm{Al})$, the abundance variations must have been produced within the planetesimals themselves.

Abundance patterns in extrasolar planetesimals reproduce those in familiar rocks. The lowest value of $n(\mathrm{Fe})/n(\mathrm{Al})$ is comparable to the ratio in MORB (Mid Ocean Ridge Basalt), a characteristic crustal rock (Presnall & Hoover 1987). The highest value of $n(\mathrm{Fe})/n(\mathrm{Al})$ exceeds that of dunite, a mantle rock, implying sampling of iron-rich core material (Hanghoj et al. 2010). Figure 1 shows that the range of $n(\mathrm{Fe})/n(\mathrm{Al})$ among extrasolar asteroids is even greater than the difference found between bulk Moon (Warren 2005) and bulk Mercury (Brown & Elkins-Tanton 2009), two solar system objects which are understood as having a small and large iron core, respectively.

We understand the variety of elemental compositions among extrasolar planetesimals as the consequence of a familiar three-step process. First, planetesimals form within the disk; in this environment, volatiles such as water may be excluded. Second, differentiation results in iron being concentrated in the core and aluminum being concentrated in the crust. Third, collisions lead to stripping and blending of cores and crusts with a consequent dramatic variation in $n(\mathrm{Fe})/n(\mathrm{Al})$ in the end-product planetesimals, blends of different portions of core, mantle, and crustal material.

3. MODEL

As with solar system asteroids, the heat source for igneous differentiation of extrasolar planetesimals most likely was from radioactive decay of ^{26}Al (Ghosh & McSween 1998). Other possibilities do not seem viable. The gravitational potential energy released by forming a body of radius, R_0, and mass, M, can raise the temperature an amount, ΔT, given by

$$CM\Delta T = \frac{3}{5}\frac{GM^2}{R_0}, \quad (1)$$

where C is the specific heat (J kg^{-1} K^{-1}) and G is the gravitational constant. For a typical object with $R_0 \approx 200$ km and $M \approx 1.0\times 10^{20}$ kg (Jura & Young 2014) and with $C \approx 1000$ J kg^{-1} s^{-1} (Turcotte & Schubert 2002), then $\Delta T \approx 20$ K, much too small to be of importance. Although mutual collisions can produce local heating, it seems unlikely that most of the material is melted during the period of planetesimal growth by collisions (Davison et al. 2010). Within the average interstellar medium, $^{60}\mathrm{Fe}/^{56}\mathrm{Fe} = 2.8 \times 10^{-7}$ (Tang & Dauphas 2012), and if this ratio prevails within star-forming regions, then heating from the radioactive decay of ^{60}Fe cannot be an important heating source within extrasolar planetesimals. It is possible that some stars form near supernovae that produce large amounts of ^{60}Fe (Vasileiadis et al. 2013), and in these environments newly formed planetesimals could be significantly heated by radioactive decay of this radionuclide. However, because by number there is more ^{26}Al than ^{60}Fe within the entire Galaxy (Tang & Dauphas 2012) and because ^{26}Al is readily produced within massive stars and then injected into the local molecular interstellar medium where new stars form (Gounelle & Meynet 2012), it is probable that the majority of young stellar disks are similar to our own solar system where radioactive decay of ^{26}Al was the dominant source of planetesimal heating.

The usual expression (Turcotte & Schubert 2002) governing the time (t) variation of internal temperature, T, as a function of radius, r, of a spherical rocky body is

$$\frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa\frac{\partial T}{\partial r}\right) + \frac{\dot{Q}(t)}{C(T)}, \quad (2)$$

where κ (m^2 s^{-1}) is the thermal diffusivity and $\dot{Q}(t)$ (J kg^{-1} s^{-1}) is the heating energy per unit mass per unit time. The typical timescale for the loss of internal heat is $R_0^2\kappa^{-1}$. For a 200 km radius object with a thermal diffusivity of 10^{-6} m^2 s^{-1} (Turcotte

[3] The stars are GD 362 (Xu et al. 2013), GD 40 (Jura et al. 2012b), NLTT 43806 (Zuckerman et al. 2011), PG 0843+516, WD 1226+110, and WD 1929+012 (Gaensicke et al. 2012), and WD J0738+1835 (Dufour et al. 2012). All but NLTT 43806 harbor a dust disk while circumstellar gas has been detected orbiting WD J0738+1835, PG 0843+516 and WD 1226+110.

& Schubert 2002), the outward diffusion of heat represented by the first term on the right-hand side of Equation (2) typically requires more than 1 Gyr and has a negligible effect on the body's central temperature during the era of heating from ^{26}Al. To compute the maximum internal temperature, $T_{\rm Max}$, we integrate over a timescale much longer than the average decay time, t_R, and consider the total released energy, Q_0, defined as

$$Q_0 = \int_0^\infty \dot{Q}(t)\, dt \qquad (3)$$

from the decay of ^{26}Al. Consequently, if the planetesimal originates at temperature, T_0 (K), then

$$\int_{T_0}^{T_{\rm max}} C(T)\, dT \approx f_{26}\, Q_0, \qquad (4)$$

where f_{26} is the initial fraction of the mass of the planetesimal that is ^{26}Al.

We assume that igneous differentiation is only possible if the internal temperature exceeds the solidus temperature, $T_{\rm solidus}$, (Turcotte & Schubert 2002) and then derive the minimum aluminum isotope ratio by number, $n(^{26}{\rm Al})/n(^{27}{\rm Al})$, required to achieve this temperature. We assume that the extrasolar planetesimal will have formed at some time, $t_{\rm form}$, after inheritance of ^{26}Al from the molecular cloud. Subsequently, no fresh ^{26}Al enters the star-forming cloud; instead, there is only radioactive decay with mean life, t_R. Validated by our detailed calculations not shown here, we take C to be constant and independent of temperature. If $f_{\rm Al}$ is the fraction of mass of the planetesimal which is aluminum, and if $T_0 \ll T_{\rm solidus}$, then

$$\left(\frac{n(^{26}{\rm Al})}{n(^{27}{\rm Al})}\right) \geqslant \left(\frac{27}{26}\right)\left(\frac{T_{\rm solidus}\, C}{Q_0\, f_{\rm Al}}\right) e^{t_{\rm form}/t_R}. \qquad (5)$$

Using CV chondrites with their relatively high Al abundance, thus providing a minimum for Equation (5), we take $f_{\rm Al} = 0.0175$ (Wasson & Kallemeyn 1988). We adopt $T_{\rm solidus} = 1500$ K (Turcotte & Schubert 2002), and, for ^{26}Al, we take $Q_0 = 1.2 \times 10^{12}$ J kg^{-1} (Castillo-Rogez et al. 2009). We assume two contributions to $t_{\rm form}$. First, there is free-fall gravitational collapse of a cloud core with an initial radius of 0.1 pc that requires $\approx$0.5 Myr (Hartmann 2009). Second, planetesimals must assemble within the disk which, by analogy with the solar system, probably takes $\sim$1 Myr (Zhou et al. 2013). Adding both terms, $t_{\rm form} = 1.5$ Myr. Consequently, we compute from Equation (5) that in extrasolar environments where planetesimals internally melted, $n(^{26}{\rm Al})/n(^{27}{\rm Al}) \geqslant 3 \times 10^{-5}$, approximately its value in the early solar system. This result is inexact. If, for example, we take $f_{\rm Al} = 0.0086$ as found in CI chondrites (Wasson & Kallemeyn 1988), then the minimum values of $n(^{26}{\rm Al})/n(^{27}{\rm Al})$ should be doubled.

4. DISCUSSION AND PERSPECTIVE

As has been previously suggested qualitatively, a general enrichment of ^{26}Al in protoplanetary disks might occur if this radionuclide is not distributed evenly throughout the Milky Way but, instead, is confined to regions of star formation (Draine 2011). A plausible model to explain why ^{26}Al would be so concentrated is that this species is largely injected into the interstellar medium from rotating massive stars (Gaidos et al. 2009; Gounelle & Meynet 2012). These massive stars are so short-lived that they all reside near their birth sites within molecular clouds. Such a model can also explain why the solar system has a relatively high concentration of ^{26}Al and a relatively low concentration of ^{60}Fe (Tang & Dauphas 2012). However, winds from Wolf–Rayet stars might shred cloud cores and prevent the formation of planets (Boss & Keiser 2013). While some recent models for supernova ejecta into molecular clouds also predict that solar mass stars commonly form with elevated amounts of ^{26}Al (Pan et al. 2012; Vasileiadis et al. 2013), they do not naturally explain the solar system's simultaneously depressed value of $^{60}{\rm Fe}/^{56}{\rm Fe}$.

In the entire Milky Way, the mass of hydrogen in H_2 is $8.4 \times 10^8\ M_\odot$ (Draine 2011). The amount of interstellar ^{26}Al is measured from the intensity of the γ-ray line at 1.8 MeV that results from its radioactive decay. Including foreground emission, there is somewhere between 1.5 and 2.2 $M_\odot$ of ^{26}Al within the Galaxy (Martin et al. 2009). If we assume the solar aluminum abundance of $n(^{27}{\rm Al})/n({\rm H}) = 3.5 \times 10^{-6}$ (Lodders 2003), and if all measured interstellar ^{26}Al is confined only to molecular clouds, then in these locations $n(^{26}{\rm Al})/n(^{27}{\rm Al}) \approx$ 2.0–3.0 $\times 10^{-5}$, nearly the same as the minimum ratio we infer for the birth environment of extrasolar planetesimals. Consider not only the entire Milky Way but also observations of the Orion region, the nearest molecular cloud where large numbers of high-mass stars currently are being formed. Orion's γ-ray line emission is explained with $5.8 \times 10^{-4}\ M_\odot$ of ^{26}Al (Voss et al. 2010) from a region where the total mass of H_2 is approximately $2 \times 10^5\ M_\odot$ (Genzel & Stutzki 1989). The implied value of $n(^{26}{\rm Al})/n(^{27}{\rm Al})$ in the Orion star-forming region is therefore 3×10^{-5}, again substantially elevated over the average interstellar value. Remarkably, the apparent fraction of ^{26}Al within star-forming molecular clouds agrees with the value required to explain the widespread occurrence of differentiated extrasolar planetesimals. It follows that the solar system's initial complement of ^{26}Al was essentially normal.

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