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STELLAR ELEMENTAL ABUNDANCE PATTERNS: IMPLICATIONS FOR PLANET FORMATION

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ABSTRACT

The solar photosphere is depleted in refractory elements compared to most solar twins, with the degree of depletion increasing with an element's condensation temperature. Here, I show that adding 4 Earth masses of Earth-like and carbonaceous-chondrite-like material to the solar convection zone brings the Sun's composition into line with the mean value for the solar twins. The observed solar composition could have arisen if the Sun's convection zone accreted material from the solar nebula that was depleted in refractory elements due to the formation of the terrestrial planets and ejection of rocky protoplanets from the asteroid belt. Most solar analogs are missing 0–10 Earth masses of rocky material compared to the most refractory-rich stars, providing an upper limit to the mass of rocky terrestrial planets that they possess. The missing mass is correlated with stellar metallicity. This suggests that the efficiency of planetesimal formation increases with stellar metallicity. Stars with and without known giant planets show a similar distribution of abundance trends. If refractory depletion is a signature of the presence of terrestrial planets, this suggests that there is not a strong correlation between the presence of terrestrial and giant planets in the same system.

Key words: planets and satellites: formation – protoplanetary disks – stars: abundances – Sun: abundances

1. INTRODUCTION

Recently, high-precision elemental abundances have become available for a number of "solar twins" (stars with surface temperature, gravity, and metallicity almost identical to the Sun) and "solar analogs" (G dwarfs similar to the Sun). Meléndez et al. (2009) obtained abundances for 11 solar twins, while Ramírez et al. (2009) obtained abundances for 22 solar twins and 42 solar analogs. The new abundances for the solar twins have errors of 0.01–0.03 dex (2%–7%).

Most of the solar twins have different abundances than the Sun, with the maximum difference amounting to 0.1 dex (25%). The Sun is depleted in highly refractory elements such as Al with respect to most of the solar twins when normalized to Fe and enriched in volatile elements such as C and N (see Figure 1). Equivalently, the Sun is depleted in all astrophysical metals (elements heavier than He) when normalized to C, the most volatile element considered. The solar depletions are strongly correlated with an element's condensation temperature T_c (Lodders 2003), with refractory elements more depleted than volatile elements.

Meléndez et al. (2009) attribute the Sun's elemental depletion pattern to the existence of the terrestrial planets. These authors argue that the terrestrial planets contain refractory elements that would otherwise be present in the Sun, and that the equivalent material is present in most of the solar twins. If this interpretation is correct, most solar twins may not possess terrestrial planets.

Ramírez et al. (2009) confirmed the fractionation–volatility trend for solar twins. These authors note that the solar depletion pattern roughly mirrors that seen in most chondritic meteorites, which are progressively enriched in refractory elements with increasing T_c (Wasson & Kallemeyn 1988). Ramírez et al. (2009) found that almost all solar twins and solar analogs with subsolar metallicity ([Fe/H]) are progressively enriched in refractory elements compared to the Sun. For twins and analogs with supersolar metallicity, the picture is more complicated: some stars show the same pattern as those with subsolar metallicity, while others are depleted in refractories compared to the Sun.

Meléndez et al. (2009) also obtained abundances for 10 metal-rich solar analogs that are part of a Doppler radial velocity survey for extrasolar planets. Of these stars, four have known giant planets while six do not. Both groups on average show a progressive enrichment in refractory elements compared to the Sun with increasing T_c. The solar analogs with known planetary companions show a stronger correlation on average between elemental abundance and condensation temperature than stars without planets. At first sight, these results seem to contradict the hypothesis that the Sun is depleted in refractory elements because it has planets.

In this paper, I examine the possible link between stellar abundance patterns and planet formation in the solar system and elsewhere. Section 2 considers the mass and composition of refractory material that is missing from the Sun in relation to the terrestrial planets. Section 3 describes a way to estimate the mass of refractory material that is missing in other stars observed by Meléndez et al. (2009) and Ramírez et al. (2009). Section 4 examines a correlation between abundance trends and stellar metallicity and what this might mean for planet formation. Section 5 looks at the effect of known planetary companions on abundance trends. Finally, Section 6 contains a summary.

2. SOLAR ABUNDANCES AND THE PRESENCE OF PLANETS

Meléndez et al. (2009) proposed that the Sun accreted material from the solar nebula that was depleted in rock-forming elements due to mass contained in the precursors of the terrestrial planets. This material was not depleted in ice-forming elements such as C and N because these elements did not condense in the region where the terrestrial planets formed.

An important caveat is that the depleted material must have remained in the surface layers of the Sun in order to have a noticeable effect on the solar abundance pattern. Conventionally, it is thought that solar-mass protostars undergo a fully convective phase (Hayashi 1961) lasting longer than the lifetime of a protoplanetary disk. Such a phase will mix material deposited at the surface throughout the star.

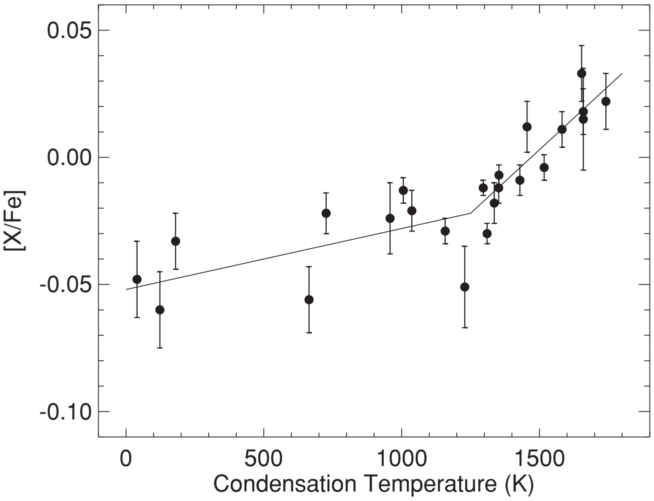

Figure 1. Mean elemental abundances ("X") for 11 solar twins, normalized to Fe, relative to the Sun, as a function of condensation temperature T_c. The line segments show rms fits for elements with $T_c < 1250$ and >1250 K, respectively. Note the increase in abundances relative to the Sun with increasing T_c. Data from Meléndez et al. (2009).

However, one-dimensional models for the formation of protostars from molecular cloud cores suggest that solar-mass protostars are never fully convective, and their structure is similar to the Sun today, with a thin convective zone (CZ) restricted to the outer layers (Wuchterl & Tscharnuter 2003). Models for episodic accretion onto solar-mass protostars also predict a large radiative core and a small convective envelope (Baraffe et al. 2009; Baraffe & Chabrier 2010). If solar-mass protostars generally behave this way, deposition of refractory-depleted material at the solar surface during planet formation could yield the elemental abundance pattern seen in the solar photosphere.

This hypothesis is supported by another line of evidence. Models for the solar interior based on helioseismology suggest that the Sun has a metal mass fraction $Z = 0.017$ (Antia & Basu 2006), significantly higher than the value $Z = 0.013$ based on spectroscopy of the solar photosphere (Asplund et al. 2009). Fits to the helioseismological data using the spectroscopically determined metallicity are poorest for the regions below the CZ (Serenelli et al. 2009), suggesting that the surface is depleted in metals compared to the interior. If this difference arose due to planet formation, it suggests that the current thin CZ was already in place when the planets were forming.

Planetary material could have been added to the Sun after the solar nebula dispersed, when the CZ was firmly established according to the standard model. This would make sense if the solar CZ was metal-rich compared to the interior. However, it is hard to imagine a source of planetary material that would have reduced the metallicity of the CZ unless this material came from the solar nebula.

Meléndez et al. (2009) find that the solar photosphere is depleted in the major rock-forming elements (Fe, Mg, Si, Ni) by roughly 0.04 dex (10%) relative to the ice-forming elements (C, N, O) compared to the mean value for the solar twins. If this depletion is restricted to the Sun's CZ, comprising 2.5% of the Sun's mass, the depletion amounts to 2.5 $M_\oplus$ of refractory elements using the solar abundances of Asplund et al. (2009). Adding O, roughly 4 $M_\oplus$ of rock is missing from the solar CZ compared to most solar twins.

The terrestrial planets contain 2 $M_\oplus$ of rock. The primordial asteroid belt probably contained a comparable mass of rocky protoplanets (Weidenschilling 1977). Much of this mass was ejected from the solar system once Jupiter formed (Chambers & Wetherill 2001; Petit et al. 2001) and will be missing from the Sun. Thus, the existence of the terrestrial planets and the asteroid belt can explain the degree of elemental fractionation seen in the Sun, provided that the fractionation is limited to the CZ.

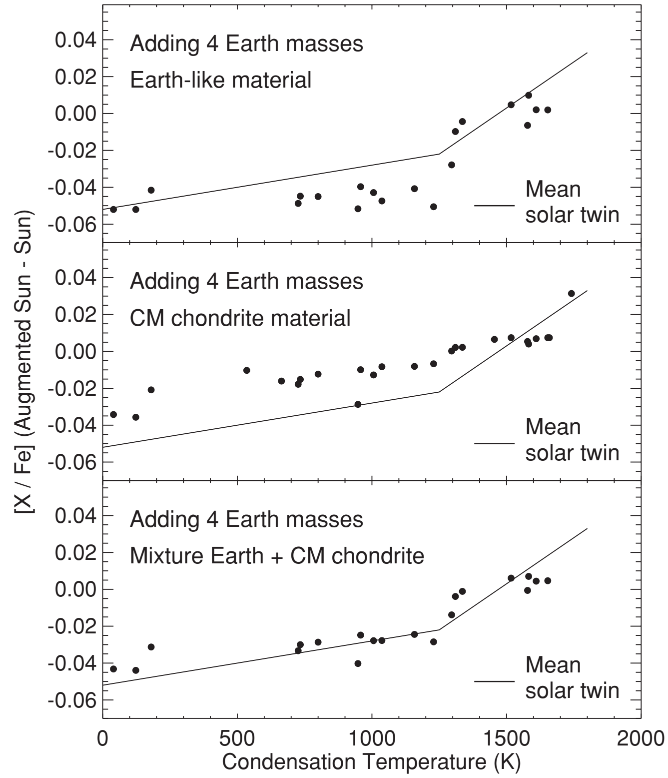

Figure 2. Composition of the solar photosphere when 4 $M_\oplus$ of refractory-rich material is added to the solar convection zone, compared to the unmodified Sun. Abundances are normalized with respect to Fe. The line segments show rms fits to the mean abundance pattern for 11 solar twins found by Meléndez et al. (2009).

The top panel of Figure 2 shows the effect of adding 4 $M_\oplus$ to the solar CZ with the same composition as Earth (Wanke & Dreibus 1988), taken to be representative of the terrestrial planets (see also Table 1). The line segments show the mean elemental abundance pattern for the solar twins (Meléndez et al. 2009). Adding Earth-like material brings the Sun closer to the solar twins but differences remain. Volatile and refractory abundances match reasonably well, but moderately volatile elements ($700 < T_c < 1300$ K) are underabundant in the augmented Sun compared to the solar twins.

The middle panel of Figure 2 shows the solar abundances after adding 4 $M_\oplus$ of material with the composition of CM chondrites (Wasson & Kallemeyn 1988), believed to be representative of the bulk composition of the asteroid belt (Meibom & Clark 1999). In this case, all elements with condensation temperatures $<$1500 K are overabundant in the augmented Sun compared to the solar twins. Reducing the mass of material improves the fit for the moderately volatile and volatile elements but worsens the fit for the refractory elements.

The bottom panel in Figure 2 shows the solar composition after adding 4 $M_\oplus$ that is an equal mixture of Earth-like and CM-chondrite-like material. The augmented solar abundance pattern is a close match to the mean solar twins for volatile, moderately volatile, and refractory elements. This suggests the

Table 1
Solar Convection Zone Abundances After Adding 4 Earth Masses of Rocky Material, Either as Earth-like Material (denoted as "Earth"), CM Chondrite-like Material (denoted as "CM"), or an Equal Mixture of the Two (denoted as "CM+Earth")

Element	T_c (K)	[X/Fe] (Earth)	[X/Fe] (CM)	[X/Fe] (CM+Earth)
C	40	−0.0520	−0.0342	−0.0432
N	123	−0.0520	−0.0357	−0.0439
O	180	−0.0416	−0.0209	−0.0313
F	734	−0.0448	−0.0152	−0.0300
Na	958	−0.0397	−0.0099	−0.0248
Mg	1336	−0.0044	0.0022	−0.0011
Al	1653	−0.0020	0.0074	0.0046
Si	1310	−0.0098	0.0022	−0.0039
P	1229	−0.0506	−0.0067	−0.0285
S	664		−0.0161	
Cl	9448	−0.0517	−0.0287	−0.0403
K	1006	−0.0429	−0.0128	−0.0278
Ca	1517	0.0047	0.0074	0.0061
Sc	1659		0.0074	
Ti	1582	0.0099	0.0040	0.0070
Cr	1296	−0.0278	0.0002	−0.0138
Mn	1158	−0.0408	−0.0081	−0.0245
Cu	1037	−0.0474	−0.0083	−0.0278
Zn	726	−0.0488	−0.0178	−0.0333
Rb	800	−0.0450	−0.0123	−0.0287
Zr	1741		0.0314	
I	535	−0.0515	−0.0103	−0.0308
Ba	1455		0.0065	
La	1578	−0.0064	0.0054	−0.0006
U	1610	0.0020	0.0069	0.0044

Sun accreted refractory-poor material from both the terrestrial-planet region and the asteroid belt.

The giant planets are enriched in metals compared to the Sun, but they do not appear to be enriched in rock-forming elements compared to ices (Owen et al. 1999). Thus, they may not have contributed to the Sun's refractory depletion signature. The giant planets contain 50–100 $M_\oplus$ of metals (Guillot 2005), somewhat more than the amount needed to explain the difference in metallicity between the solar interior and CZ. However, gas in the solar nebula was subject to photoevaporation (Gorti et al. 2009) that would have increased the metallicity of the nebula (Guillot & Hueso 2006) while planet formation was reducing it. Thus, it is hard to determine how much giant-planet formation reduced the metallicity of the solar CZ.

3. STELLAR ABUNDANCES AND PLANET FORMATION

Ramírez et al. (2009) quantify the degree of refractory enrichment of a star compared to the Sun using a slope parameter S, which is the rms slope of [X/Fe] versus T_c for elements with $T_c > 900$ K. Here, $[X/Fe] = \log_{10}(n_X/n_{Fe}) - \log_{10}(n_X/n_{Fe})_\odot$, where n is number density. Stars with elemental abundances similar to the Sun have $S = 0$. Stars that are enriched in refractory elements compared to the Sun, including most solar twins, have $S > 0$, while stars depleted in refractories have $S < 0$.

We can use S and stellar metallicity [Fe/H] to estimate the mass of rock missing from a star's CZ. We note that the major rock-forming elements (Mg, Si, Fe, Ni) all have $T_c \sim 1300$ K. If a star has accreted fractionated material with a mass of $M_{\rm frac}$, and this material was mixed with material in the stellar CZ with

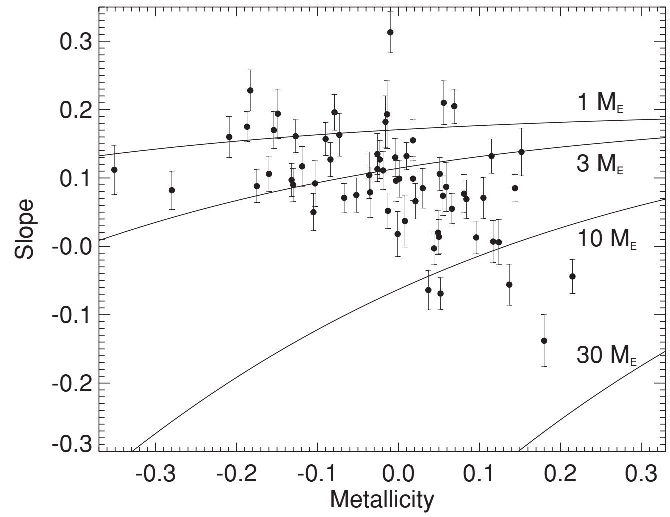

Figure 3. Slope parameter and metallicity for 64 solar analogs measured by Ramírez et al. (2009). The curves show the approximate mass of rocky material missing from each star's convection zone, assuming that the relative abundances of refractory elements were the same in each star's protoplanetary disk.

mass $M_{\rm cz}$, the slope parameter for the star will be

$$S = S_{\max} - \frac{\log_{10}[(M_{\rm cz} + M_{\rm frac})/M_{\rm cz}]}{(1300 - 900)K}, \qquad (1)$$

where $S_{\max}$ is the slope parameter for a star that has accreted no fractionated material. The most refractory-rich solar analogs examined by Ramírez et al. (2009) have $S \simeq 0.2$. We assume that these stars acquired no fractionated material so that $S_{\max} = 0.2$. We also assume that all the solar analogs had protoplanetary disks with identical relative abundances for different metals.

The mass of missing rock is

$$M_{\rm rock} = 0.0044 M_{\rm frac} 10^{[{\rm Fe/H}]}, \qquad (2)$$

where 0.0044 is the mass fraction of rock for the solar photosphere using abundances from Asplund et al. (2009).

Figure 3 shows S and [Fe/H] for the stars observed by Ramírez et al. (2009). The curves show contours of $M_{\rm rock}$. Here, we have neglected variation of the convection zone mass with stellar spectral type and also assume that $M_{\rm cz}$ remains constant over time for each star. The Sun lies at the origin, with $M_{\rm rock} = 7\,M_\oplus$. This is almost twice the missing mass found in the previous section since we are measuring abundances with respect to the most refractory-rich solar analogs rather than the mean refractory abundance for the solar twins.

Most stars in Figure 3 have lower $M_{\rm rock}$ than the Sun, but the values are not zero in many cases. These stars could possess terrestrial planets, although they may be less massive than those in the solar system. Roughly one-fifth of the stars have $M_{\rm rock} < 1\,M_\oplus$, and these stars may have no terrestrial planets. Several stars with high metallicities are missing $>10\,M_\oplus$ of rock, and these may have large terrestrial planets. Note that $M_{\rm rock}$ provides only an upper limit to the mass of terrestrial planets orbiting a star. Missing rock may have been ejected from the system or exist in an asteroid belt rather than planets.

4. PLANETESIMAL FORMATION

Many solar twins may lack large terrestrial planets. However, this does not entirely explain why these stars have no refractory depletion signature. Rocky material can also end up in massive

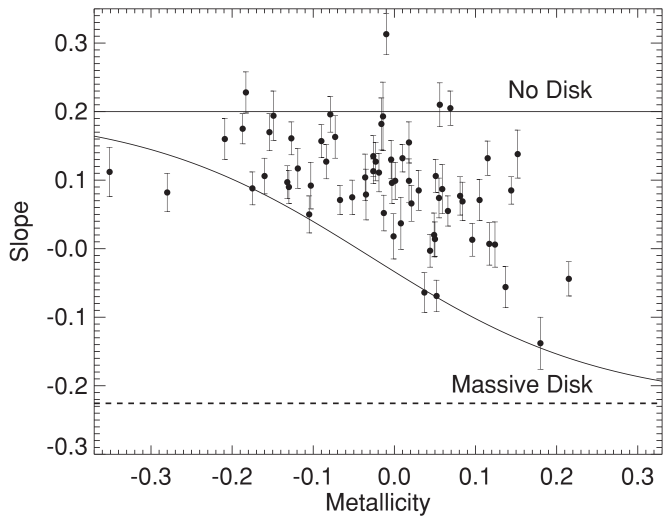

Figure 4. Slope parameter S and metallicity [Fe/H] for 64 solar analogs measured by Ramírez et al. (2009). The upper solid curve and dashed line show the expected range of S if planetesimal formation is independent of [Fe/H] and the maximum protoplanetary disk mass is $0.12\,M_{\odot}$. The solid curves show the expected range of S if the planetesimal formation efficiency increases with [Fe/H] following a logistic function.

analogs of the asteroid belt or become ejected from the system. In either case, the star will show a depletion signature like the Sun.

A substantial number of stars in Figure 3 show little or no refractory depletion, implying that the great majority of rocky material in their protoplanetary disks accreted onto the star. Solid material can be transported onto a star via planetary migration (see Section 5). Alternatively, refractory material can accrete onto the star as dust grains that are tightly coupled to the gas. Losing large amounts of dust in this way implies that the formation of planetesimals from dust was inefficient in these systems.

Recent models suggest that planetesimal formation in a turbulent disk is ineffective when the dust-to-gas ratio is low, but becomes increasingly efficient at higher dust-to-gas ratios (Cuzzi et al. 2008; Johansen et al. 2009). Inefficient planetesimal formation would explain why small dust grains are abundant in protoplanetary disks with ages of several million years (Haisch et al. 2001) and why many meteorite parent bodies took up to 4 million years to form in the solar nebula (Krot et al. 2009).

If metal-rich disks convert more of their dust into planetesimals than metal-poor disks, it would explain the correlation between stellar metallicity and the detection of giant planets in Doppler radial velocity surveys (Fischer & Valenti 2005). Theoretical models find that metal-poor disks inhibit giant-planet formation because a high surface density of condensible material is required to form giant-planet cores massive enough to accrete gaseous envelopes within the lifetime of a disk (Pollack et al. 1996; Ida & Lin 2004). If the formation of planetesimals depends sensitively on the dust-to-gas ratio, terrestrial-planet formation will also be hindered in metal-poor disks.

A correlation between planetesimal formation and metallicity should be apparent in the stellar abundance data. We test this using an idealized model in which a star accretes a mass $M_{\rm frac}$ of refractory-depleted material as a result of terrestrial-planet formation:

$$M_{\rm frac} = M_{\rm disk}\eta f, \qquad (3)$$

where $M_{\rm disk}$ is the protoplanetary disk mass, η is the fraction of dust converted into planetesimals, and f is the mass fraction of the disk inside the snow line while planetesimals are forming.

We consider disk masses $0 \leqslant M_{\rm disk} \leqslant M_{\rm max}$, where $M_{\rm max}$ is a parameter. We assume $f = 0.1$, independent of metallicity, which is broadly consistent with the value for the solar system allowing for planetesimals ejected from the asteroid belt and the outer solar system. We examine two possible models for η. In Model 1, all dust is converted into planetesimals so that $\eta = 1$, independent of [Fe/H]. In Model 2, the efficiency of planetesimal formation increases with [Fe/H] following a logistical function, with $\eta = 0.5$ for solar metallicity:

$$\eta = \frac{1}{1 + \exp(-k[{\rm Fe/H}])}, \qquad (4)$$

where k is a parameter.

Figure 4 shows the expected range of S as a function of [Fe/H] for the two models with $M_{\rm max} = 0.12\,M_{\odot}$. Stars with no disk produce no planetesimals in either model and have $S = S_{\rm max} = 0.2$ shown by the upper solid line in the figure. The dashed line shows S for stars with $M_{\rm disk} = M_{\rm max}$ for Model 1. If the planetesimal formation efficiency is independent of metallicity, the entire region between the upper solid line and lower dashed line should be populated, but this is not the case.

The lower solid curve in Figure 4 shows S for massive disks in Model 2 with $k = 7$. The two solid curves bracket the observed stars quite well. This model reproduces the absence of low-metallicity stars with large negative slopes and the wide range of slopes observed in high-metallicity stars. This suggests that the efficiency of planetesimal formation increases with metallicity.

5. EXTRASOLAR PLANETS

Meléndez et al. (2009) and Ramírez et al. (2009) measured elemental abundances for several stars with known planetary companions. These are listed in Table 2. Most of these planets have minimum masses >50 Earth masses and are presumably gas giants similar to Jupiter and Saturn.

Meléndez et al. (2009) measured elemental abundances for 10 metal-rich solar analogs that are part of a Doppler radial velocity search for planetary companions. Four of these stars have known planetary companions. Meléndez et al. (2009) found that, on average, the 10 stars are progressively enriched in elements

Table 2
Stars with Known Planets in the Samples Observed by Meléndez et al. (2009), Denoted as "M" and Ramírez et al. (2009), Denoted as "R," Together with the Stellar Abundance Slope S and Metallicity [Fe/H]

Star	Sample	S	[Fe/H]	a (AU)	e	M (Jupiter)
HD 1461	R	−0.138	0.180	0.0634	0.14	0.0239
16 Cygni B	R	−0.069	0.052	1.68	0.689	1.68
51 Pegasi	R	−0.044	0.215	0.052	0	0.468
HD 9446	R	0.071	0.105	0.189	0.2	0.7
				0.654	0.06	1.82
HD 141937	M	0.077	0.126	1.52	0.41	9.7
HD 107148	M	−0.050	0.315	0.269	0.05	0.21
HD 160691	M	−0.057	0.306	0.0909	0.172	0.0332
				0.921	0.0666	0.522
				1.5	0.128	1.68
				5.24	0.0985	1.81
HD 102117	M	0.034	0.320	0.153	0.106	0.172

Note. Also shown are the planetary orbital semi-major axis a, eccentricity e, and minimum mass M, taken from the Extrasolar Planets Encyclopedia (http://exoplanet.eu).

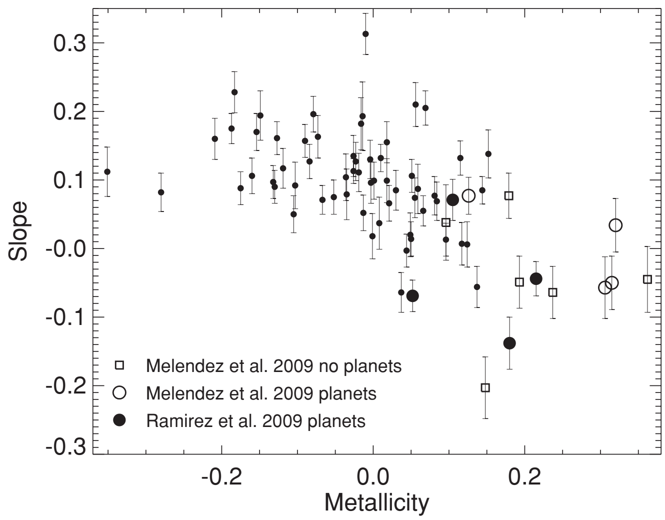

Figure 5. Slope parameter and metallicity for 64 solar analogs measured by Ramírez et al. (2009) (solid symbols). The large solid symbols show stars with known giant planets. Also shown are 10 solar analogs from a Doppler radial velocity survey with detected planets (open circles) and without detected planets (open squares), measured by Meléndez et al. (2009).

with increasing condensation temperature T_c compared to the Sun. The stars with planets show a stronger trend with T_c than stars without detected planets.

We can examine these trends in more detail and look for differences between the solar analogs with and without planets, using the slope parameter S used by Ramírez et al. (2009). The S values for these stars in a system similar to that employed by Ramírez et al. (2009) (J. Melendez 2010, private communication) are shown in Figure 5. Also, shown are the four solar analogs from the sample of Ramírez et al. (2009) that have planetary companions.

The distribution of S values is similar for stars with and without known planetary companions. The S values are also similar for stars with planets in the samples of Meléndez et al. (2009) and Ramírez et al. (2009). Five of the eight stars with planets have negative slopes compared to the Sun and are therefore even more depleted in refractory elements than the Sun, but this is also true of four of the six metal-rich solar analogs without detected planets. If negative values of S are a signature of the presence of terrestrial planets, this suggests that there is no clear correlation between the existence of giant planets and terrestrial planets in the same system.

Two stars, HD 1461 and HD 160691, have low-mass companions with minimum masses of about 7 and 11 Earth masses, respectively. It is unclear whether these objects represent ice-rich bodies analogous to Uranus and Neptune or rocky "super Earths." In the latter case, we would expect to see a large refractory depletion trend in the host star. Using Equations (1) and (2) and the procedure described in Section 3, the values of S and [Fe/H] for these stars suggest that they are each missing about 20 Earth masses of rocky material. Thus, the stellar data are consistent with a rocky composition for these objects.

Two of the solar analogs with giant planets, HD 141937 and HD 9446, have $S \simeq 0.07$, suggesting they may have small terrestrial planets or none at all. HD 141937 has a very massive planetary companion (minimum mass $\sim$10 Jupiter masses) on an eccentric orbit with a semi-major axis, $a = 1.5$ AU. Such an object will render a wide range of terrestrial-planet orbits unstable. HD 9446 has two smaller giants with $a = 0.19$ and 0.65 AU. While small planets in the outer portion of the terrestrial-planet region may be stable in this case, it is likely that the giant planets in this system migrated through the terrestrial-planet region. Numerical simulations have found that a migrating giant removes much of the rocky material interior to its orbit as it is captured at interior mean-motion resonances (Fogg & Nelson 2005). Terrestrial planets can form subsequently, but these will be composed mainly of volatile-rich material from the outer disk (Raymond et al. 2006), so these planets will not lead to a refractory depletion signature in the star. Thus, the absence of a strong refractory depletion signature for these two stars is not unexpected.

However, this cannot be the story in every case because 51 Pegasi has $S < 0$ and possesses a giant planet with $a = 0.05$ AU. This planet has presumably migrated through the terrestrial-planet region. This suggests that the timing of giant-planet migration relative to planetesimal formation in the terrestrial-planet region may play an important role in determining the refractory depletion signature seen in a star. Similarly, 16 Cygni B has a planet on a highly eccentric orbit with $a = 1.7$ AU and $e = 0.7$. This planet is likely to have destabilized small objects in much of the terrestrial-planet region and yet the star has $S < 0$, suggesting perhaps that refractory-rich material was ejected from this system rather than accreting onto the star.

Stars like HD 118475 provide an important test of the hypothesis that terrestrial planets lead to a refractory depletion signature in the host star. No giant planets have been detected orbiting HD 118475, although it is part of a Doppler radial velocity survey. HD 118475 has $S = -0.203$ (J. Melendez 2010, private communication), the most negative slope for any of the stars considered here. This implies that the star is missing a large amount of refractory material. If this mass is present in massive terrestrial planets, it seems likely that giant planets would also have formed in the system. The missing refractory material could have been ejected from the system, but this also requires one or more giant planets to be present. It is conceivable that large rocky planets formed but giant planets did not form due to very rapid dispersal of the gaseous component of the star's protoplanetary disk. Otherwise, we would predict that giant planets are present in this system but have yet to be detected.

6. SUMMARY

The difference between the Sun's elemental abundances and the mean abundances for the solar twins observed by Meléndez et al. (2009) can be removed by adding 4 Earth masses of rocky material to the solar convection zone that is an equal mixture of Earth-like and CM-chondrite-like material. This is consistent with the hypothesis that the Sun's abundance pattern was affected by the formation of rocky bodies in the inner solar nebula.

Ramírez et al. (2009) defined a parameter S that measures the slope of a star's elemental abundance pattern as a function of condensation temperature. Using S and the stellar metallicity [Fe/H], it is possible to estimate how much rocky material is missing from a star's convection zone compared to the most refractory-rich stars. Most solar analogs are missing 0–10 Earth masses of rock, while a few analogs show larger depletions. These masses provide an upper limit to the mass of rocky terrestrial planets in the system.

The range of S values is correlated with [Fe/H] for the solar analogs observed by Ramírez et al. (2009). Metal-poor analogs typically show little or no refractory depletion. Metal-rich stars show a wide range of S values. This result can be explained if the efficiency of planetesimal formation in a protoplanetary disk increases with the disk's metallicity. This is consistent with recent theoretical models for planetesimal formation by Cuzzi et al. (2008) and Johansen et al. (2009).

Meléndez et al. (2009) observed 10 metal-rich solar analogs that are part of a Doppler radial velocity survey for planets. Stars with and without detected planets show a similar range of S values. If values of $S \lesssim 0$ are a signature of terrestrial-planet formation, this suggests that there is no strong correlation between the presence of terrestrial and giant planets in the same system. However, the number of stars with known planetary companions is still small (only eight in the samples observed by Meléndez et al. 2009 and Ramírez et al. 2009) and all of these planetary systems have very different architectures than the solar system. A better picture will have to await precise abundance measurements for additional stars with known planetary companions, especially stars with giant planets similar to those in the solar system.

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