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ON THE CARBON-TO-OXYGEN RATIO MEASUREMENT IN NEARBY SUN-LIKE STARS: IMPLICATIONS FOR PLANET FORMATION AND THE DETERMINATION OF STELLAR ABUNDANCES

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ABSTRACT

Recent high-resolution spectroscopic analysis of nearby FGK stars suggests that a high C/O ratio of greater than 0.8, or even 1.0, is relatively common. Two published catalogs find C/O > 0.8 in 25%–30% of systems, and C/O > 1.0 in ∼6%–10%. It has been suggested that in protoplanetary disks with C/O > 0.8 that the condensation pathways to refractory solids will differ from what occurred in our solar system, where C/O = 0.55. The carbon-rich disks are calculated to make carbon-dominated rocky planets, rather than oxygen-dominated ones. Here we suggest that the derived stellar C/O ratios are overestimated. One constraint on the frequency of high C/O is the relative paucity of carbon dwarf stars (10^{-3}–10^{-5}) found in large samples of low-mass stars. We suggest reasons for this overestimation, including a high C/O ratio for the solar atmosphere model used for differential abundance analysis, the treatment of a Ni blend that affects the O abundance, and limitations of one-dimensional LTE stellar atmosphere models. Furthermore, from the estimated errors on the measured stellar C/O ratios, we find that the significance of the high C/O tail is weakened, with a true measured fraction of C/O > 0.8 in 10%–15% of stars, and C/O > 1.0 in 1%–5%, although these are still likely overestimates. We suggest that infrared T-dwarf spectra could show how common high C/O is in the stellar neighborhood, as the chemistry and spectra of such objects would differ compared to those with solar-like abundances. While possible at C/O > 0.8, we expect that carbon-dominated rocky planets are rarer than others have suggested.

Key words: brown dwarfs – planets and satellites: composition – stars: abundances – stars: carbon

Online-only material: color figures

1. INTRODUCTION

1.1. *The Composition of Stars and Planets*

The determination of the abundances of atoms in the atmospheres of stars is an essential element of modern astronomy. Recently, tremendous work has occurred on understanding the relationship between planets and the abundances of planet-hosting and non-planet-hosting stars. Since the pioneering work of Gonzalez (1997), many investigators have worked to understand connections between stellar abundances and the observed frequency (Santos et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) and composition (Guillot et al. 2006; Burrows et al. 2007; Miller & Fortney 2011) of planets.

Our solar system is one realization of the complex planet formation process. The raw materials that made up the Sun and solar nebula, through a process of condensation, grain growth, and accumulation, gave rise to four rocky planets in our inner solar system that are predominantly composed of Mg–Si–O-bearing rocks and Fe–Ni metals. In other solar systems, with parent star disks with other abundances, a different selection of refractory materials, or in different relative abundances, surely occur. For instance, if a nebula's carbon-to-oxygen (C/O) ratio is $\gtrsim$0.8, condensation pathways can change dramatically, leading to carbon-dominated rocky planets, as recently discussed in detail by Bond et al. (2010).

There had been prior intermittent interested in carbon-dominated planets in the past decade, from Gaidos (2000), Lodders (2004), and Kuchner & Seager (2005), to name three examples. In particular, Gaidos (2000) discussed different formation scenarios for giant planet cores and rocky planets in disks with varied C/O ratios, as well as how the chemical evolution of the galaxy generally can lead to enhanced C/O through time. Lodders (2004) suggested that the planetesimals that make up Jupiter's heavy element enrichment were carbon-rich, and that Jupiter initially formed at the "tar line" rather than at the "ice line." This is one possible explanation for the low water abundance measured by the *Galileo Entry Probe* (Wong et al. 2004). Kuchner & Seager (2005), similar to Gaidos (2000), were interested in giant planets and terrestrial planets that could form in environments where the local (or entire disk's) C/O > 1, leading to carbon-dominated (rather than oxygen-dominated) silicates.

More recently, Bond et al. (2010) coupled protoplanetary disk abundances derived from stellar spectra to a model of disk chemistry, which yields the condensation sequence of solids. Their work further coupled the formation of solids to an *N*-body model of planet formation (O'Brien et al. 2006). For particular planetary systems, with measured C/O and Mg/Si ratios of the host star, they calculated the equilibrium disk chemistry and solid composition for the initial planetesimal distribution. Bond et al. (2010) furthermore kept track of the contribution of particular planetesimals as they add their mass to growing protoplanets, and in the end find the relative contributions of C, O, Mg, Si, etc., to the masses of formed planets.

Within the context of giant planets, Madhusudhan et al. (2011a) suggested that dayside photometry of the transiting planet WASP-12b indicates an atmosphere with C/O > 1.0. More recently, Madhusudhan et al. (2011b) and Öberg et al. (2011) have investigated the accumulation of gas and icy planetesimals in disks with a range of C/O ratios to understand possible pathways to forming "carbon-rich" gas giants.

1.2. *C/O Ratio in Stars*

Composition-dependent planet formation models depend on the stellar abundances of C and O for the initial conditions of

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disk chemistry. The stellar C/O ratios in Bond et al. (2010) were taken from determinations of C from Ecuvillon et al. (2004) and of O from Ecuvillon et al. (2006). Motivated by Bond et al. (2010), larger tabulations of C and O abundances were recently made by Delgado Mena et al. (2010), for 370 FGK stars from the HARPS planet-search sample, and Petigura & Marcy (2011), for 457 F and G stars from the California Planet Survey sample. These two studies are relatively similar, as they cover large samples that include planet-hosting stars and those not found to host planets.

The two studies do have some differences in the lines of C and O chosen. For the carbon abundance, the Delgado Mena et al. (2010) work used C I lines at 5380.3 and 5052.2 Å, with only 5380.3 Å used for stars with $T_{\rm eff} < 5100$ K. For oxygen, the forbidden line of [O I] at 6300 Å was used. The derivation of the abundances was done with a combination of the code MOOG, for the generation of synthetic spectra (Sneden 1973 as updated in 2002), the Kurucz ATLAS9 atmosphere grid with overshooting (Kurucz 1993), and the equivalent widths were measured using the ARES program (Sousa et al. 2007). The Petigura & Marcy (2011) study used a C I line for carbon at 6587 Å, and the [O I] line for oxygen at 6300 Å. The derivation of the abundances was performed with the Spectroscopy Made Easy (SME) code (Valenti & Piskunov 1996) with Kurucz stellar atmospheres.

Tabulations from Bond et al. (2010, who quote Ecuvillon et al. values), Delgado Mena et al. (2010), and Petigura & Marcy (2011) are shown in Figure 1. Both these large studies found a somewhat similar shape. They found a maximum at C/O ratios modestly higher than that of the Sun (0.55; from Asplund et al. 2009), with a noticeably enhanced peak in the distribution found by Delgado Mena et al. (2010), shown most clearly in Figure 1(bottom). Of particular interest to all of these authors, and our *Letter*, is the tail off to higher C/O ratios > 0.8 (dotted line) and even further onto > 1.0 (short dashed line). Delgado Mena et al. (2010) find C/O > 0.8 for 24% of their stars, and C/O > 1.0 for 6%. For the Petigura & Marcy (2011) sample, they find C/O > 0.8 for 29% of their stars, and C/O > 1.0 for 10%. The numbers quoted are for the mixed sample of planet-hosting and non-planet-hosting stars. Taken at face value, and the condensation chemistry in Bond et al. (2010), this potentially implies carbon planets (formed when C/O > 0.8) in ∼25% of planetary systems.

However, one must take care when estimating the fraction of stars with high C/O ratios, given observational error bars. Of interest is the positive tail at high C/O, and a tail such as this is expected since the error is approximately constant in the logarithmic abundance ratio, [C/O]. This leads to an error distribution that is log-normal in the C/O ratio, and is seen in, for instance, Table 6 in Petigura & Marcy (2011). Their average error at C/O = 1 is 0.23, which is 1.61σ above the solar C/O ratio they use, of 0.63. From this 1.61σ, 5.4% of the stellar sample is thus expected to be found with C/O > 1, just due to observational errors. This would yield a "true" fraction of stars with C/O > 1 of ∼5%, rather than 10%. Delgado Mena et al. (2010) do not provide individual errors on their C/O determinations, but assuming similar errors, their entire sample of C/O > 1 stars (6%) can be explained by errors. At C/O = 0.8, in the Petigura & Marcy (2011) sample, the average error is 0.16, a difference of 0.17 above their solar value, or 1.06σ. This yields an expected fraction of 14.5%, which would move the 29% with C/O > 0.8 down to 15%. For Delgado Mena et al. (2010), this expected fraction moves their 24% at

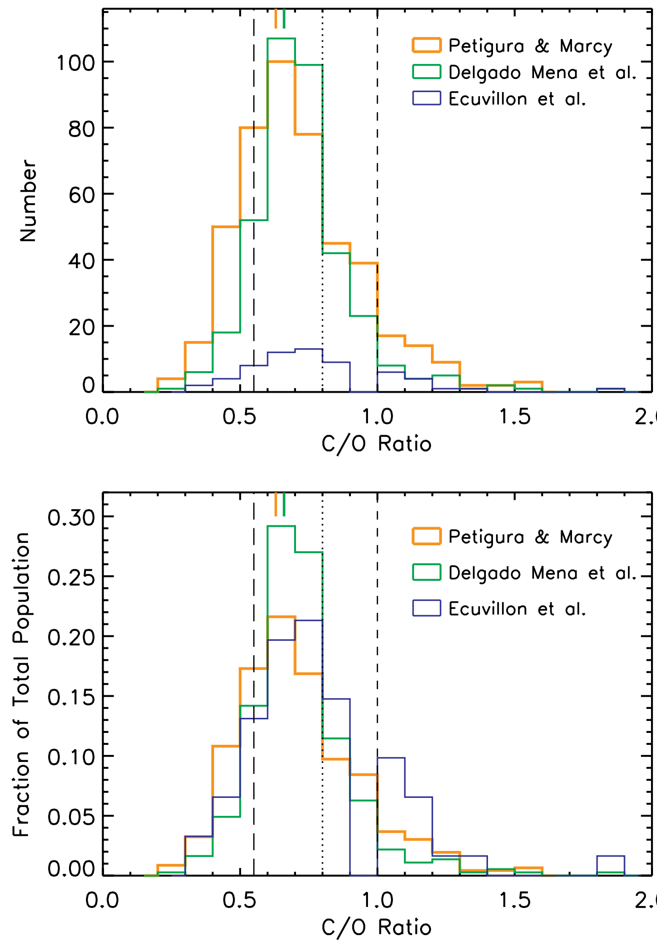

Figure 1. Top: histogram of the C/O ratios from the papers of Ecuvillon et al. (2004, 2006; as tabulated in Bond et al. 2010), Delgado Mena et al. (2010), and Petigura & Marcy (2011), in blue, green, and orange, respectively. C/O ratios of 0.55 (the solar value from Asplund et al. 2009), 0.8, and 1.0 are shown as long dashed, dotted, and short dashed lines, respectively. The adopted solar C/O ratios from Delgado Mena et al. (2010) and Petigura & Marcy (2011) are shown as thick green and orange ticks at the top. Bottom: the data sets are normalized, yielding fractions of each sample, instead of number. The large samples of Delgado Mena et al. (2010) and Petigura & Marcy (2011) find 24%–29% of FGK stars have C/O > 0.8, and 6%–10% have C/O > 1.

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

C/O > 0.8 down to 10%. The upshot is a much reduced tail of stars with high C/O ratios.

2. MOTIVATION

Deriving the abundances of C and O in stellar atmospheres is a demanding task. Even for the Sun, this has been especially difficult over the past decade (e.g., Allende Prieto et al. 2001, 2002; Asplund et al. 2009). The most recent state-of-the-art work includes intense efforts to find unblended lines, calculated NLTE corrections where applicable, and solar atmosphere pressure–temperature profiles that come directly from three-dimensional (3D) simulations (Asplund et al. 2009; Caffau et al. 2011).

While deriving the abundances of atoms and molecules in low-mass M and K dwarf stellar atmospheres is more difficult that than of Sun-like stars, they do have one natural asset. Cooler dwarf atmospheres have a natural "flip" in the chemistry at C/O = 1. At C/O < 1, most O goes into the CO molecule, but additional O is left over and partitions into H_2O and, for M stars, TiO/VO gases. TiO/VO absorption bands dominate the optical spectra of M stars. However, at C/O > 1, the CO molecules use up nearly all O in cool stars, leaving excess C, which goes into molecules such as C_2 and CN. In such a cool star, the optical region is dominated by C_2 and CN. We suggest that if C/O > 1 in FGK stars is a relatively common phenomenon then cool carbon dwarfs showing C_2 and CN bands should be relatively common in the solar neighborhood. This is something that can be investigated, and was even briefly noted by Petigura & Marcy (2011).

3. TRUE FRACTION OF CARBON DWARFS?

Carbon dwarfs, which appear to have C/O > 1 in their atmosphere, are rare stars. The best current understanding of their formation is that they are *not* made of primordial C/O > 1 gas, but instead have high C abundances due to accretion of asymptotic giant branch dredge-up material from a companion (e.g., de Kool & Green 1995; Steinhardt & Sasselov 2005). Carbon dwarfs have been found by many authors, with most being found by large surveys, such as the Sloan Digital Sky Survey (SDSS; Margon et al. 2002; Downes et al. 2004). Their numbers are predominantly spread among what would otherwise be G, K, and M spectral types.

For our purposes here, instead of forming these carbon-rich stars by accretion, we can take the extremely optimistic view that these are in fact primordial C/O > 1 systems. Then the fraction of dwarfs that are carbon dwarfs would be the upper limit on the fraction of stars with primordial C/O > 1. de Kool & Green (1995) have previously estimated the frequency of carbon dwarfs, based on detections before SDSS. They estimate a space density in the disk of $\sim 1 \times 10^{-6}$ pc^{-3}, but noted this may be an overestimate. This can be compared to the space density of stars with mass $< 0.7\ M_\odot$, 6.5×10^{-2} pc^{-3}, from Bochanski et al. (2010). This is a 4–5 orders of magnitude difference.

There are other ways to estimate the carbon dwarf frequency. In particular, Covey et al. (2008) have analyzed SDSS spectra and Two Micron All Sky Survey (2MASS) photometry of 25,000 sources, in an effort to take a census of low-mass stars out to $J = 16.2$, over a mass range from 0.1 to 0.7 $M_\odot$. For these cool stars, if C/O > 1 did occur, it should be clear, given the abundance of carbon-rich molecules (C_2, CN) that would occur in such cool atmospheres. Of their sample of 9649 low-mass stars, they note 24 "exotic contaminants" including 4 carbon stars. This implies a C/O > 1 in only 0.04% of cases, although based on color cuts ∼1/2 of the carbon dwarfs may have been missed (K. Covey 2012, private communication). This work, and the fact that Downes et al. (2004) found only ∼100 carbon dwarfs from a large SDSS search at $15.6 < r < 20.8$ to specifically find such stars, certainly strengthens the point of de Kool & Green (1995) that carbon dwarfs are quite rare. The relative frequency is likely 10^{-3}–10^{-5}.

We can think of no reason that Sun-like stars in the solar neighborhood would be uniformly more enriched in carbon (or oxygen deficient) than the KM stars. One potential way out could be if the later-type stars are systematically older than the earlier-type stars, so that some amount of galactic chemical evolution could have taken place. In this case the younger (FG) stars could have higher C/O (e.g., Gaidos 2000). However, the HARPS/California samples are not young stars, so constructing a credible explanation through this path seems unlikely.

4. DIAGNOSING HIGH C/O FROM BROWN DWARFS?

The K and M dwarfs from the SDSS give us leverage into the fraction of dwarfs with C/O > 1. Are there any stellar populations that could be used to understand the fraction of stars with 0.8 < C/O < 1? One possibility is the L and T dwarfs. L-type dwarfs, from $T_{\rm eff}$ of ∼2400–1400 K, have atmospheres whose infrared opacity is dominated by molecular bands of H_2O, CO, and cloud layers made up of refractory condensates like corundum (Al_2O_3), enstatite ($MgSiO_3$), forsterite (Mg_2SiO_4), and iron (Fe; Ackerman & Marley 2001). Corundum, enstatite, and forsterite need abundant oxygen to form. If C/O > 0.8, or C/O > 1, are common in L dwarfs, then perhaps we could see a different kind of cloudy L dwarf, with condensates dominated by SiC instead of the Mg–Si–O forms. Certainly the spectra of such objects would be highly abnormal at C/O > 1, as they would strongly favor CO at the expense of H_2O, but perhaps even at C/O ratios closer to 0.8, the cloud condensation pathway would be different from normal L dwarfs.

In the cooler objects, the T dwarfs, the silicate clouds appear to reside below most of the visible atmosphere. Quite importantly, these refractory clouds remove 21% of oxygen from the atmosphere (e.g., Visscher et al. 2010 and references therein). This removal of oxygen from the gas raises the C/O ratio in the visible atmosphere. Lodders (2010) has investigated chemistry as a function of C/O ratio at 1100 K and 0.01 bar, which is after silicate condensation. Lodders finds a dramatic change in chemistry even at C/O = 0.8. At C/O > 0.8, methane becomes more abundant than water (by two orders of magnitude at C/O = 0.9) and HCN becomes nearly as abundant as water. Since CO, CH_4, H_2O (and HCN) all have prominent opacity in the infrared, C/O > 0.8 brown dwarfs could appear distinctly different from those with a C/O ratio closer to that of the Sun.

Since most brown dwarfs are found from color–color diagrams in surveys such as SDSS and 2MASS, it is quite possible that high C/O brown dwarfs, should they exist, could have previously eluded detection. The cuts from SDSS use $i - z$ color, which could in principle be less sensitive to the C/O chemistry since the optical spectra of brown dwarfs are shaped by pressure-broadened lines of Na and K (Burrows et al. 2000). But 2MASS uses JHK_s cuts, which could lead to high C/O dwarfs being missed, since in some cases H_2O would not be the dominant opacity source, leading to different near-infrared colors. As far as we are aware, there are no compelling outliers for high C/O brown dwarfs, but a search for them could be valuable.

A full exploration of C/O ratio in brown dwarfs, and its effects on clouds, is beyond the scope of this work. However, there is an additional point that we can motivate. In T dwarfs, essentially all infrared opacity is due to water, methane, and carbon dioxide, which tie up nearly all C and O. The relatively cloud-free spectra of T dwarfs may allow for accurate determinations of C/O in the solar neighborhood. In Figure 2 we show model spectra of two 900 K dwarfs, one with C/O = 0.55 (the solar value) and another at C/O = 0.7. These models were computed using the atmosphere code of M. Marley and J. Fortney and collaborators, described elsewhere (Marley et al. 2002; Fortney & Marley 2007). The opacity and chemistry databases are taken from a previous tabulation (Fortney et al. 2005). The differences between the two spectra can be prominent, in particular as a ratio. One can see differences of 10% in the *JHK* peaks, and 20%–30% in the water bands. With future improvements in the accuracy of opacities, in particular a high-temperature database for CH_4, we suggest it may be possible to derive relative C

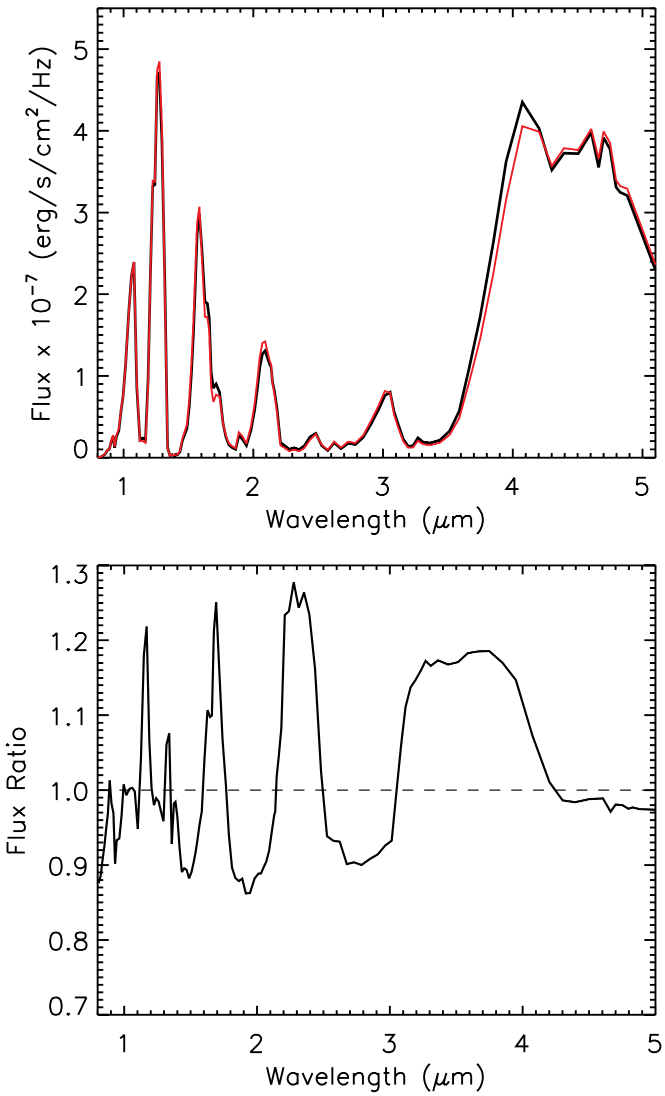

Figure 2. Top: emitted spectra from two models of a brown dwarf with $T_{\rm eff}$ = 900 K and log g = 5.0. The thick black curve is for solar abundances, at C/O = 0.55. The thin red curve is for a model with C/O = 0.7, with the carbon abundance enhanced. Bottom: the ratio of the flux between these two models.

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

and O abundances, from H_2O, CH_4, and CO, from infrared T-dwarf spectra. High spectral resolution observations of brown dwarfs are now being achieved as well (Rice et al. 2010), which could allow further progress in abundance analysis. The utility of such efforts would be a better understanding of the C/O ratio of stars in the solar neighborhood. Recently, work by Tsuji et al. (2011) on a small number of brown dwarfs with AKARI observations has moved in this direction.

5. DISCUSSION

We suggest that recent high-resolution spectroscopic analyses have overestimated the fraction of FGK stars with C/O > 1.0, and, by extension, perhaps with C/O > 0.8 as well. Gaidos (2000) and Bond et al. (2010) suggested that the pathway to form "rocky" planets in C/O > 0.8 systems will differ in these carbon-rich system, making carbon-rich planets. While this logic seems secure, we find it is less likely than some have anticipated. This is because the true fraction of carbon-rich parent stars is quite low, 10^{-3}–10^{-5}. However, our work should not be interpreted as claiming that carbon-rich terrestrial or giant planets cannot form. The C/O ratio surely varies in the interstellar medium and the region of phase space between 0.8 < C/O < 1 is less constrained by our work. However, given the overestimation at C/O > 1 it appears probable that this region is less populated than has been recently suggested (Bond et al. 2010; Delgado Mena et al. 2010; Petigura & Marcy 2011), although not empty. Furthermore, we showed in Section 1.2 that the quoted observational error bars from these groups imply smaller measured fractions of high C/O stars, which eliminated 15% from C/O > 0.8 and 5% from C/O > 1.0.

These authors of course put in great effort to understand the sources of their errors, and to correct for them. The choice of lines used could be re-examined. The choice of low-excitation forbidden [O I] lines along with high-excitation permitted C I lines could introduce systemic errors. A revised (although difficult) study could examine [C I]/[O I] or C I/O I, since these lines would behave similarly at a given stellar temperature and in deviations from LTE (M. Asplund 2011, private communication).

An additional point is that both the large Delgado Mena et al. (2010) and Petigura & Marcy (2011) works tuned their abundance retrieval methods to match the Sun's C/O ratio as a standard. Asplund et al. (2009), in a recent review, find C/O = 0.55. However, in Delgado Mena et al. (2010) the particular abundances used for the Sun lead to C/O = 0.66, while in Petigura & Marcy (2011), it is 0.63. (See the thick tick marks at the top of Figure 1.) So, there clearly could be an offset of ~0.1, toward higher C/O, in these works.

An issue with the Ni blend of the [O I] line used by Petigura & Marcy (2011) may potentially skew their results toward higher C/O ratios. These authors adopt the abundances of O and Ni from 3D abundance analyses, and then use them in their one-dimensional analysis. To obtain a good fit to the solar spectrum, they adopted $\log(gf) = -1.98$ for the Ni I line, which is 35% higher than the laboratory measurement of -2.11 measured by Johansson et al. (2003). Consequently, Petigura & Marcy (2011) in their Figure 3 show a Ni I line that is 40% stronger than found in, for example, Allende Prieto et al. (2001). This could explain the upward trend in C/O with increasing [Fe/H] in their Figure 16, as follows: a known trend is that [Ni/Fe] increases slightly (e.g., Robinson et al. 2006) and [O/Fe] decreases as metallicity ([Fe/H]) increases (e.g., Delgado Mena et al. 2010). A Ni blend that is too strong in the solar fit will increase in importance as [Fe/H] increases, leading to an overestimation of the Ni blend, an underestimation of the O abundance, and a C/O ratio that is too high. In the Petigura & Marcy (2011) sample, this could explain why most of the C/O > 1 stars occur when [Fe/H] > 0.2.

We note that Delgado Mena et al. (2010) and Petigura & Marcy (2011) both relied on the stellar atmosphere models of Kurucz. As a comparison, one could alternatively use the PHOENIX (Hauschildt et al. 1999) or MARCS (Gustafsson et al. 2008) stellar atmospheres. Gustafsson et al. (2008) have compared their MARCS models to published models from Kurucz and PHOENIX, and the agreement does indeed vary with $T_{\rm eff}$ and with plane parallel versus spherical symmetry.

There are still other pathways toward understanding extrasolar abundances. As FG stars evolve onto the red giant branch and cool to $T_{\rm eff}$ values of ~ 4000 K, it may be easier to constrain their C/O ratios in the same qualitative manner we suggest for M dwarfs. The composition of extrasolar planetesimals can be determined by studying externally polluted white dwarf atmospheres, and some early evidence has been found for carbon-poor planetesimals (Jura 2006).

While we have focused exclusively on stellar abundances, it is important to recall that condensation of solids within a disk itself can potentially lead to non-stellar C/O ratios in nebula gas. For instance, condensation of water in a protoplanetary disk can leave the surrounding nebula gas relatively carbon-rich (through large abundance of gaseous CO), which can change the relative ratios compared to those of the parent star (Stevenson & Lunine 1988; Lodders 2010; Öberg et al. 2011). This may be a pathway to forming giant planets with relatively high C/O ratios in their envelopes. A giant planet atmosphere with $C/O > 1$ was recently suggested for planet WASP-12b, based on fits to seven photometric points of dayside planet emission (Madhusudhan et al. 2011a). Their finding could be made more robust with the inclusion into their model of the absorption bands of molecules that are expected in the high C/O regime, such as HCN and C_2H_2 (Lodders 2010; Kopparapu et al. 2012), which were not considered in the Madhusudhan et al. (2011a) study.

Carbon-dominated rocky planets would be extremely interesting objects. Their prevalence around stars of Sun-like abundances, and those stars with enhanced C/O ratios, would certainly tell us much about nebular condensation chemistry and the planet formation process. While these planets may be inherently rare, we look forward to additional advances in the future.

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