HD 196390: A tight correlation of differential abundances with condensation temperature

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ABSTRACT

Bedell et al. (2018) give precision differential abundances for 79 mostly G-dwarf stars. We correct these abundances for Galactic chemical evolution in a manner similar to that used by these authors but with parameters derived from linear fits to plots of [El/H] vs. age in lieu of [El/Fe]. We examine the resulting abundances for correlations with the 50% condensation temperature using values from both Lodders (2003) and Wood et al. (2019), and compare with the results of Bedell et al. HD 196390 is distinct in having the most significant correlation of the 79-star sample. We report statistics for a subset of stars with lower significance, but of some interest.

Keywords: stars: abundances — sun: abundances

1. INTRODUCTION

One of the most exciting developments in the field of analytical stellar spectroscopy is the possible inference of extrasolar planetary properties from precision differential abundances in solar twins (Meléndez, et al. 2009). Of special significance has been the discovery that small abundance differences in the sun and some of its twins are correlated with the 50% condensation temperature, \(T_c\), defined in Lodders (2003). Such correlations have been suggested by numerous workers to be caused by processes related to star-planet formation (see Nissen & Gustafsson 2018; Ramírez, et al. 2019, and references cited therein). The sun itself is believed to be slightly depleted in refractory elements, leading to the suggestion that those elements have been sequestered in the terrestrial planets.

2. CORRECTIONS FOR GALACTIC CHEMICAL EVOLUTION

The solar twin HD 196390 (HIP 101905) is one of 79 stars with precision differential abundances (PDAs) in the study of Bedell, et al. (2018, henceforth, BD18). We find its PDA distribution, after corrections for Galactic chemical evolution (GCE) effects (see below), to exhibit the tightest correlation with condensation temperature of any of the stars in this sample.

BD18 derived GCE parameters \(m(Z)\) and \(b(Z)\), where \(Z\) is the atomic number of element \(El\), using data for 68 of their 79 stars after removing stars older than 8 Gyr or displaying anomalous abundances for neutron-addition species. Numerical values for these quantities were derived from fits for \([El/Fe] = m(Z)t + b(Z)\), with \(t\) the stellar age in Gyr; the results are given in their Tab. 3. Acuna (2020) has derived similar GCE parameters for 19 elements based on independent PDA measures in 17 sun-like stars; for most elements in common with BD18, her values for the fitted slopes agree to within the quoted uncertainties with those of BD18.

We find empirically that, on average, the function \(GCE(t) = m(Z)t + b(Z)\) is an excellent approximation to plots of \([El/H]\) for typical old and young stars in the BD18 sample (see Cowley, Yüce & Bord 2020, Panel 4, Slides 1 and 2). Thus, for any star in the sample, we consider

\[
\Delta[El/H] = [El/H] - GCE = [El/H] - (m(Z) \cdot t + b(Z))
\]

(1)

to represent the elemental abundance difference between star and sun that is not due to GCE.

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Figure 1. Differential abundances for HD 196390 vs. condensation temperature, \( T_c \), after GCE corrections based on the BD18 parameters. Values for \( T_c \) are taken from Wood, et al. (2019). Black circles designate elements C-Zn; gray (red online) circles denote the neutron-addition elements Sr-Dy. Linear least-squares fits to the data for C-Zn are shown: The solid line gives the best fit with all points weighted equally (or essentially unweighted); the dashed line displays the best fit with each point weighted by its (variance)\(^{-1}\) computed using composite uncertainties derived by propagating the reported uncertainties in the BD18 PDAs and GCE correction parameters, as well as in the star’s age in the usual manner assuming the errors to be uncorrelated. For illustration, the mean error for the fitted elements is shown; errors for the volatile elements (C, O, S, Na, Cu, and Zn) are somewhat larger than that shown, while those for the remaining elements in the set are smaller. The statistical significance of either fit is very high with \( p \approx 10^{-6} \) or less.

We have determined GCE parameters, \( m(Z) \) and \( b(Z) \), based on \([El/H]\) rather than \([El/Fe]\) as in BD18. The absolute value of the differences between observed and predicted abundances of the 68-star sample was slightly smaller when the BD18 coefficients were used instead of those based on \([El/H]\). This could be because correlations of \([El/Fe]\) vs. age are generally tighter than those based on \([El/H]\).

3. HD 196390 AND CONDENSATION TEMPERATURE

The quantity \( \Delta[El/H] \) defined in Eq. 1 is plotted for 30 elements in HD 196390 in Fig. 1 for an assumed age of 1.2 Gyr (Spina, et al. 2018). The quantitative values of the ‘significance’ of the linear fits displayed in Fig. 1, as measured, for example, by \( p \), the probability that the fit arises by chance, depend on the specific choice of elements, as well as on the method of assigning uncertainties and weights for the points included in the fits and the source of the values of \( T_c \). In Fig. 1, we fit only the elements carbon through zinc. Our rationale is that the neutron-addition elements, Sr-Dy, owe at least some of their abundance anomalies to processes unrelated to condensation (see Meléndez, et al. 2014). We accept this viewpoint with the caveat that it deserves deeper consideration. The adopted uncertainties reflect contributions from the uncertainties in the tabulated PDAs for this star, as well as those associated with the parameters \( m(Z) \), \( b(Z) \), and \( t \). Several different weighting schemes based on the uncertainties were applied; for all plausible choices, we find the significance of the fit for HD 196390 stands well out from its congeners in the BD18 sample. Tests of the degree to which the fits are sensitive to the sources, either Lodders (2003) or Wood, et al. (2019), reveal only small differences which do not alter the overall conclusions presented here (see Appendix).

We have made additional \( T_c \) fits for all of the other BD18 stars. These have been also been made using the newly derived GCE parameters based on correlations of \([El/H]\) vs. age, as well as the BD18 parameters based on \([El/Fe]\). We have again compared results from using both the Lodders (2003) and Wood, et al. (2019) values of \( T_c \). The results
for three data sets are presented in the Appendix. While they differ in small details, they all point to the prominence of HD 196390. In addition, they agree on the stars with the next most significant fits, though the ranking by probabilities varies somewhat. These stars show formal significances with probabilities in the range $10^{-3}$ to $10^{-5}$. The top (five) stars are: HD 42618 (HIP 29432), ψ Ser (HD 140538; HIP 77052), HD 45346 (HIP 30502), HD 12264 (HIP 9349), and HD 158210 (HIP 85402). Of these, only HD 42618 (5.2 Gyr) has a known planet. Interestingly, for this star, the slope of the plot $\Delta [El/H]$ vs. $T_c$ is negative.

Meléndez, et al. (2014) found a very tight correlation of $[El/H]$ with $T_c$ for the solar twin 18 Sco (HD 146233, HIP 79672), also included in the BD18 sample. Their correlation was also developed for the elements carbon through zinc using $T_c$ values from Lodders (2003), but for PDAs uncorrected for GCE effects. We find that this correlation weakens significantly once GCE corrections are applied, regardless of the source of the correction parameters used in Eq. 1. This was also found by Acuna (2020), who gives a slope after correction of $(0.96 \pm 1.61) \cdot 10^{-5} K^{-1}$.

While we have made our fits for elements C-Zn, other workers, e.g. BD18, sometimes neglect the elements with $T_c < 900 K$ while including the n-addition elements, or use a broken-line fit to accommodate the volatiles. The complexities associated with star/planet formation likely admit the legitimate application of all these approaches.

**APPENDIX**

Tab. 1 presents the statistics for the most significant of the $\Delta [El/H]$ vs. $T_c$ for three sets of input data. Set A comes from the use of BD18 GCE parameters according to Eq. 1, and $T_c$ of Lodders (2003). Set B used GCE parameters based on fits to $[El/H]$ vs age, and $T_c$ from Lodders (2003). Set C used BD18 GCE parameters and the more recent $T_c$ from Wood, et al. (2019). For each star, we give (1) the probability the fit is due to chance, and (2) the slope of the $\Delta [El/H]$ vs. $T_c$ plots. The probabilities are all smaller than $10^{-4}$. Note that the order of the stars is nearly the same in all three sets of results.

The set of four stars below the horizontal line are again common to all three sets. They have probabilities between $10^{-4}$ and $10^{-3}$, and are of marginal interest.

| star       | Set A | Set B | Set C |
|------------|-------|-------|-------|
|            | prob  | slope | prob  | slope | prob  | slope |
| HD 196390  | 1.96E-09 | 5.38E-05 | 1.19E-07 | 4.90E-05 | 1.96E-09 | 5.38E-05 |
| HD 42618   | 1.32E-05 | -2.68E-05 | 3.14E-06 | -2.48E-05 | 1.31E-05 | -2.68E-05 |
| HD 140538  | 2.76E-05 | 5.29E-05 | 6.03E-06 | -2.62E-05 | 2.76E-05 | 5.29E-05 |
| HD 45346   | 3.76E-05 | 3.74E-05 | 1.73E-05 | 4.04E-05 | 3.76E-05 | 3.74E-05 |
| HD 12264   | 5.06E-05 | -1.93E-05 | 2.41E-05 | 3.35E-05 | 5.06E-05 | -1.93E-05 |
| HD 158210  | 5.94E-05 | 2.94E-05 | 2.68E-05 | 5.29E-05 | 5.94E-05 | 2.94E-05 |
| HD 96423   | 1.05E-04 | 3.51E-05 | 5.97E-05 | 3.75E-05 | 1.05E-04 | 3.51E-05 |
| HD 44665   | 1.61E-04 | -1.68E-05 | 1.10E-04 | -3.53E-05 | 1.61E-04 | -1.68E-05 |
| HD 134664  | 2.50E-04 | 2.51E-05 | 6.8168   | 2.91E-04 | 2.50E-04 | 2.51E-05 |
| HD 68168   | 2.59E-04 | 4.15E-05 | 134664   | 3.73E-04 | 2.37E-05 | 4.15E-05 |

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**REFERENCES**

Acuna, L. 2020, Master’s Thesis, Lund University, Sweden

Bedell, M., Bean, J. L., Meléndez, J., et al. 2018, ApJ, 865, 68
Cowley, C. R., Yüce, K. & Bord, D. J. 2020, aas235-aas.ipostersessions.com/
default.aspx?s=58-BE-9F-2E-6D-57-C6-85-88-1E-B6-1D-29-37-EC-8E&guestview=true
Lodders, K. 2003, ApJ, 591, 1220
Meléndez, J., Asplund, M., Gustafsson, B. & Yong, D. 2009, ApJ, 704, L66
Meléndez, J., Ramírez, I., Karakas, A., et al. 2014, ApJ, 791, 14
Nissen, P. E. & Gustafsson, B. 2018, A&AR, 26, 6
Ramírez, I., Khanal, S., Lichon, S. J., et al. 2019, MNRAS, 490, 2448
Spina, L., Meléndez, J., Karakas, A. I., et al. 2018, MNRAS, 474, 2580
Wenger, M., Ochsenbein, F., Egret, D., et al. 2000, A&AS, 143, 9
Wood, B. J., Smythe, D. J. & Harrison, T. 2019, AmMin, 104, 844