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# STELLAR OXYGEN ABUNDANCES. III. THE OXYGEN ABUNDANCE OF THE VERY METAL POOR HALO STAR BD −13°3442

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## ABSTRACT

A spectrum of the very metal poor ([Fe/H] ∼ −3) halo star BD −13°3442 is presented and used to determine this star's oxygen abundance. Our determination makes BD −13°3442 the most metal poor dwarf (though a somewhat evolved one) with an O abundance determination. The O abundance (determined from the 7774 Å O I triplet) and [O/Fe] ratio is compared to that of two other metal-poor stars. The [O/Fe] ratio of BD −13°3442 is found to be ∼0.35 dex larger than that of the other two halo stars. Possible implications of this result are discussed.

*Subject headings:* stars: abundances — stars: individual (BD −13°3442) — stars: Population II

## 1. INTRODUCTION

The O abundance and [O/Fe] ratio of metal-poor stars provide extremely important constraints on Galactic formation scenarios (e.g., Matteucci & François 1992). The O abundances of the most metal-poor stars might also provide clues about the nature of Population III stars (e.g., Boyd & Fuller 1991 and references therein). Additionally, halo star O abundances and abundance ratios are data fundamental to understanding the chemical evolution of the early Galaxy. Indeed, a long-standing puzzle is that the abundance ratios of very heavy elements (e.g., Ba or Eu) show significant (and considerable) scatter at a given [Fe/H] in metal-poor stars (e.g., Wheeler, Sneden, & Truran 1989 and references therein) while O ratios do not. Since the heavy element ratios are often cited as evidence of chemical inhomogeneity in the halo, one might also expect to see similar scatter in the O ratios. It would seem profitable to further investigate this issue by examining O abundances in the most metal poor stars. However, the O abundances of stars with [Fe/H] $\lesssim -2.5$ are very poorly known—this unfortunate situation being due to the weakness of the few accessible O I features at low metallicity. In this contribution, we describe our O abundance determination for the very metal poor dwarf BD −13°3442, which we find to have anomalously strong O I near-IR triplet lines.

## 2. OBSERVATIONS AND REDUCTIONS

Observations of the 7774 Å O I triplet were performed at the 3.6 m Canada-France-Hawaii Telescope during one night in 1993 March. The f/8 Coudé spectrograph was used with the red mirror train, the 830 lines mm$^{-1}$ grating, and the Lick No. 2 2048 × 2048 CCD. This configuration yielded a measured dispersion of 0.072 Å pixel$^{-1}$, and the measured resolution was 0.16 Å. Six individual 1800 s exposures were obtained of BD −13°3442.

Our IRAF reductions followed standard procedures including bias-overscan removal, trimming, flat-fielding, and extraction of the spectra to one dimension. Wavelength solutions were determined by fitting the positions of 33 lines from a Th-Ar lamp exposure with a fourth-order Chebyshev polynomial; this fit had rms residuals of 0.004 Å. The BD −13°3442 spectra were co-added, and the measured S/N in our final spectrum is ∼140. Figure 1 shows the spectrum with the O I lines marked.

## 3. OXYGEN ABUNDANCE DERIVATION

The 7774 Å O I triplet was easily identifiable since the lines are among the stronger features in the spectrum. We also computed the radial velocity of the star by comparing the spectrum to that of BD +42°2667 (acquired with the same instrumentation during the same run). Using the radial velocity for BD +42°2667 given in the SIMBAD database, a heliocentric velocity of +113 km s$^{-1}$ for BD −13°3442 was estimated. This value is in good agreement with the measurement of Ryan & Norris (1991), who list a value of +117 km s$^{-1}$ in their Table 3.

Equivalent widths for the lines were estimated using routines in the IRAF and SPECTRE (Fitzpatrick & Sneden 1987) packages. We find values of 13.1 ± 0.5, 8.2 ± 0.6, and 4.8 ± 0.5 mÅ for the 7772, 7774, and 7775 Å O I lines. The uncertainties are the standard deviations of the various measurements for each line. These uncertainties are only internal ones—more realistic uncertainties are closer to 1.5 mÅ (due to uncertainties in the continuum placement, etc.) as estimated from the formulations given in Cayrel (1988).

The effective temperature for BD −13°3442 was estimated from the $(b-y)$ index given by Ryan, Norris, & Bessell (1991) using the relation in King (1993a). For $(b-y) = 0.311$, the resulting value is $T_{\rm eff} = 6261$ K. Ryan et al. (1991) list a reddening of $E(B-V) = 0.01$ (or a reddening of ∼0.007 in $b-y$); taking this into account gives $T_{\rm eff} = 6307$ K. Since this reddening is not significant within the uncertainties, we adopt a compromise value of $T_{\rm eff} = 6285$ K as our final number; this is in good agreement with the value (6250 K) adopted by Ryan et al. (1991). The gravity of BD −13°3442 was estimated in two ways. First, we determined log $g \sim 3.85$ using the $T_{\rm eff}$ and a 17 Gyr Revised Yale Isochrone (Green, Demarque, & King 1987). We also solved for the gravity by locating the position of the star on a log $g$ locus in the $c_1$ versus $(b-y)$ plane using the [M/H] = −3.0 colors from the new Kurucz (1992) models. This value was then adjusted using a calibration of the Kurucz

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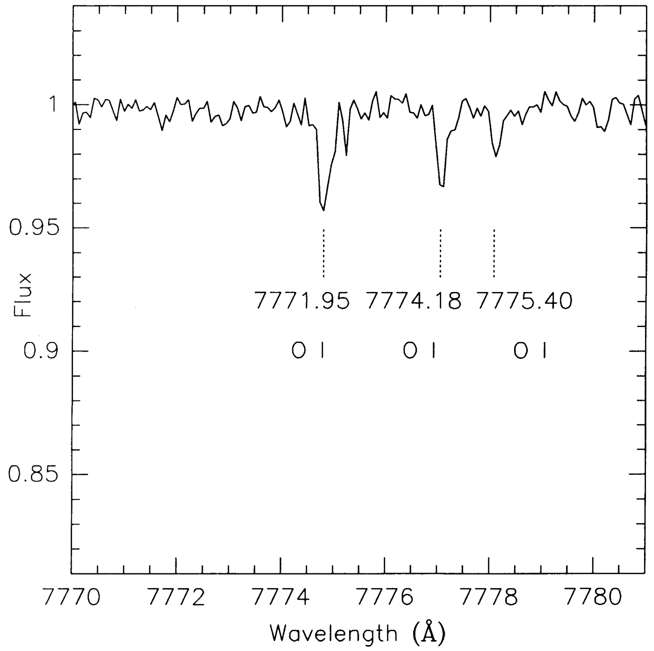

FIG. 1.—CFHT spectrum of BD −13°3442. The O I triplet lines are marked with their rest wavelengths. The spectrum has not been shifted to rest wavelength in this figure in order that the reader may verify that the inferred radial velocity is in close agreement with published values (see text).

model log $g$ values versus the ionization balance log $g$ values for stars taken from Tomkin et al. (1992); this procedure is similar to that used by King (1993b) for metal-rich stars. This gives the result log $g = 3.11$, which is probably unrealistically low, but consistent with the surprisingly large value of $c_1$ given in Ryan et al. (1991). We arbitrarily give the isochrone value 3 times the weight of the Strömgren value and determine a final gravity of log $g = 3.67$, which is reasonably consistent with that (log $g = 3.8$) adopted by Ryan et al. (1991). The iron abundance was taken from the estimate of Ryan et al. (1991) after adjusting for their solar iron abundance (−4.35 vs. newer values near −4.49 which we favor here) and different adopted $T_{\rm eff}$. The final adopted value is [Fe/H] = −2.97.

We also require parameters for BD +03°740 and HD 140283—two other metal-poor stars that we will compare to BD −13°3442. Both of these stars show the same ambiguity in their reddening estimates and the same discrepant behavior in their log $g$ values. While these uncertainties are unfortunate, we do not believe they create uncertainties in the relative abundances since the final parameters are derived self-consistently. The final parameters assumed for these two stars are given in Table 1 (along with those for BD −13°3442); some of the details (i.e., the photometry and the references for the Fe abundances) have been presented in King (1993a, 1994b). We reiterate that the parameters have been derived in the same manner as for BD −13°3442 (e.g., $T_{\rm eff}$ comes from the same relation as used for BD −13°3442; scale and $T_{\rm eff}$ adjustments have been applied to the literature [Fe/H] estimates; and the same weighting of the isochrone- and photometry-based gravities has been utilized). The usual microturbulence of 1.5 km s$^{-1}$ is assumed for all three stars; this is not a critical choice as the O I lines are weak.

O abundances were determined from measured equivalent widths by constructing curves of growth using the LTE analysis program RAI10 (courtesy of M. Spite). Equivalent widths for HD 140283 and BD +03°740 were taken from Tomkin et al. (1992) for consistency; we note that their total equivalent width for the 7774 Å triplet (15.9 mÅ) agrees closely with that of Boesgaard & King (1993; 17.2 mÅ). Oscillator strengths of log $gf = +0.333$, $+0.186$, and $-0.035$ were taken from Wiese, Smith, & Glennon (1966) for the 7772, 7774, and 7775 Å O I features. The model atmospheres used in the analysis came from the new grids of Kurucz (1992). The O I abundance from the 7774 Å triplet is quite insensitive to the metal abundance of the atmospheres; models with [M/H] = −2.5 were used for HD 140283 and BD +03°740 while models with [M/H] = −3.0 were used for BD −13°3442. We determined a solar abundance of log $\epsilon$(O) = 8.91 by constructing a curve of growth using the Kurucz (1992) solar model atmosphere and using the equivalent widths of high-dispersion solar spectra discussed in King (1993b); this value is in excellent agreement with the usual accepted value of the photospheric O abundance (8.93; e.g., Grevesse & Anders 1989).

Table 1 lists the stellar abundances (relative to the Sun) for each line (when available). The value in column (8) was determined by considering the lines together (except for BD +03°740, whose value is just a mean of the 7772 and 7774 Å abundances). The agreement between the abundances from different lines is quite respectable as found by Boesgaard & King (1993). The value in column (8) is combined with the iron abundance in column (4) to give the [O/Fe] ratio in column (9). Our estimate of the errors (not systematic effects) in the *absolute* abundance ratios, based on our estimates of errors in the temperatures, gravities, equivalent widths, and iron abundances are given in column (10). As a guideline, raising the effective temperature by 100 K results in a decrease in the O abundance by 0.07 to 0.08 dex. Raising the log $g$ value by 0.2 dex results in an increase in the O abundance by 0.07–0.08 dex. Our error estimate for the equivalent widths leads to an uncertainty of 0.04 dex in O abundance (per line).

## 4. DISCUSSION

The results in Table 1 indicate that the [O/Fe] ratio for BD −13°3442 is apparently much larger than that for either HD 140283 or BD +03°740, which are slightly more metal rich

TABLE 1

PARAMETERS AND ABUNDANCES

| STAR (1) | $T_{\rm eff}$ (K) (2) | log $g$ (3) | [Fe/H] (4) | [O/H] $\lambda$7772 (5) | [O/H] $\lambda$7774 (6) | [O/H] $\lambda$7775 (7) | [O/H] All (8) | [O/Fe] (9) | $\sigma$([O/Fe]) (dex) (10) |
|---|---|---|---|---|---|---|---|---|---|
| BD −13°3442 ......... | 6285 | 3.67 | −2.97 | −1.86 | −1.96 | −2.00 | −1.93 | +1.04 | ±0.18 |
| BD +03°740 .......... | 6255 | 3.83 | −2.76 | −2.17 | −2.02 | ... | (−2.09) | +0.67 | ±0.23 |
| HD 140283 ............ | 5813 | 3.62 | −2.57 | −1.84 | −1.82 | −1.84 | −1.83 | +0.74 | ±0.17 |

halo stars. We first ask if this difference is significant. Recall that the uncertainties in Table 1 are those for the absolute [O/Fe] ratios. We estimate that the *relative* errors are smaller—less than 0.15 dex. For example, (1) the relative $T_{\rm eff}$ uncertainties hinge on the reddening ambiguities which are only at the ±50 K level, and (2) the relative [Fe/H] values seem to be accurate to well within ±0.1 dex. As an illustration, note that the relative abundances of BD −13°3442 and HD 140283 in Table 1 are in excellent agreement with the relative abundances of Ryan et al. (1991).

Since BD −13°3442 is not a well-studied object, we investigated its Fe abundance further by examining the 7780 Å Fe I feature—the strongest iron line in the 7774 Å region. The equivalent width was measured for HD 140283 using the spectrum described in Boesgaard & King (1993); unfortunately, the feature is not detected in our spectrum of BD −13°3442. However, we place a 2 $\sigma$ upper limit on its equivalent width of 3.2 mÅ. Using atmospheric parameters in Table 1, we find that the [Fe/H] of BD −13°3442 is at least 0.31 dex lower than that of HD 140283. This is perfectly consistent with the relative abundances of Ryan et al. (1991) and confirms the very metal poor nature of BD −13°3442. Based on the relative error estimate of ±0.15 dex in [O/Fe], we find the chance that the [O/Fe] of BD −13°3442 and the [O/Fe] ratios of BD +03°740 *and* HD 140283 differ to the extent they do because of random errors is ~0.2%; i.e., our result is significant at the ~2.9 $\sigma$ level for the usual Gaussian confidence intervals.

NLTE effects on the 7774 Å triplet's line formation might be suspected of causing spurious [O/Fe] ratios (Tomkin et al. 1992; King 1993a). However, the NLTE corrections calculated by Tomkin et al. (1992) and Takeda (1994) are small. Since BD +03°740 and BD −13°3442 are so similar, the differential NLTE effects should be quite small. Inspection of Table 4 from Tomkin et al. (1992) indicates that the differential NLTE correction between BD +03°740 (or BD −13°3442) and HD 140283 is (at most) ≤0.06 dex—not enough to explain the observed difference. It has also been proposed that atmospheric inhomogeneities might affect O abundances derived from the 7774 Å triplet (e.g., Nissen & Edvardsson 1992). Indeed, asymmetries in the solar 7774 Å line profiles (e.g., Altrock 1968) indicate the presence of such inhomogeneities. The existence and effect of such inhomogeneities in halo stars is uncertain since, e.g., the hydrodynamical calculations of Nordlund & Dravins (1990) have not been extended to the metal-poor regime. The empirical evidence suggests that the effects of inhomogeneities are small—the halo dwarf 7774 Å based [O/Fe] ratios of King (1993a) are in very good agreement with the values determined from the 6300 Å [O I] line in metal-poor dwarfs (e.g., Spite & Spite 1991) and giants (Bessell, Sutherland, & Ruan 1991). In any case, we expect the effect of any inhomogeneities on the *relative* O abundances of BD −13°3442 and BD +03°740 to be small.

We therefore regard the [O/Fe] difference between BD −13°3442 and the other two stars as real. Indeed, we believe our result to be a conservative one since the gravities of HD 140283 and BD +03°740 derived from ionization balance arguments (e.g., Tomkin et al. 1992) are considerably lower than those we have adopted here. If we had included these ionization-based estimates, our values of log $g$ would be lowered for HD 140283 and BD +03°740. This would lower the O abundance derived for these two stars (by at least 0.05–0.10 dex) and hence further *increase* the O abundance difference between them and BD −13°3442.

The implications of a high [O/Fe] ratio for BD −13°3442 are necessarily speculative since it is only a single datum and needs confirmation. We can say that the high [O/Fe] ratio found here is qualitatively consistent with the results of recent Galactic chemical evolution models (Matteucci & François 1989, 1992; Prantzos, Cassé, & Vangioni-Flam 1993) which indicate that [O/Fe] ratio begins to rise from a roughly constant value beginning at [Fe/H] ~ −3. Such behavior in the models seems to be due to the assumptions of increasing O yield with increasing stellar mass and a *constant* Fe yield with stellar mass for the higher mass stars. However, the models predict only a ≤0.1 dex difference in [O/Fe] between [Fe/H] = −2.5 and −3.0. The observed difference we find, ~0.4 dex, could suggest that a more realistic assumption is that the Fe yield decreases with increasing mass (or decreasing metallicity if metallicity is any sort of chronometer in the early halo) for the massive stars that first formed in the Galaxy. However, even given the small relative errors, we feel that one can still not definitively exclude the possibility that the genuine difference between the [O/Fe] ratios of BD −13°3442 and HD 140283 or BD +03°740 is, in fact ~0.1 dex.

The [O/Fe] ratios of halo dwarfs appear to show little star-to-star scatter (i.e., the ratios are consistent within the measurement uncertainties; King 1993a, b). This behavior is in stark contrast to the ratios of heavy elements (e.g., [Ba/Fe] or [Eu/Fe]), which show a very large scatter beginning at [Fe/H] ~ −2.2 (Wheeler et al. 1989 and references therein). Our estimate of [O/Fe] for BD −13°3442 may be the first indication from O of inhomogeneity in the early halo—behavior similar to that seen for Ba and Eu. It remains puzzling why scatter in the [O/Fe] ratio does not show up until [Fe/H] ~ −3. This latter point is an important one since the lack of scatter in the [O/Fe] ratio can be used to constrain variations in the SFR in the early Galaxy (Gilmore, Wyse, & Kuijken 1989) and is also used (in conjunction with the alleged break in the [O/Fe] versus [Fe/H] curve near [Fe/H] ~ −1; King 1994a) to date the formation time of the Galactic halo (e.g., Gilmore et al. 1989 and Smecker-Hane & Wyse 1992) via comparison with stellar evolutionary models.

Finally, we note that Boyd & Fuller (1991) have suggested that the presence of massive negatively charged particles ($X^-$ particles) in primordial ultramassive stars could significantly enhance the synthesis of O in the early halo. Such enhancement seems to be qualitatively consistent with the enhanced O abundance of BD −13°3442 over and above that predicted by recent chemical evolution models. There are a number of even more speculative topics and questions one might address:

1. Could the different behavior of O and heavy element ratios in the halo be explained by a combination of rapid decay of $X^-$ particles, causing a drop in the [O/Fe] ratio from possibly inhomogeneous but large values (but not affecting heavy element ratios), and a somehow variable (from star to star) process of hot hydrogen burning (e.g., Wallace & Woosley 1981), which might lead to scatter in heavy element ratios (but not affect O)?
2. The possible existence of two (or more) breaks in the [O/Fe] versus [Fe/H] relation for the halo.
3. Whether or not two such breaks might be a signature of two-stream production of Fe in the halo or a signature of two-phase collapse of the Galactic halo (perhaps consistent with the two broad classes of globular clusters—the younger outer halo members which apparently show an age spread of a

few Gyr and the primarily older, inner halo clusters which seem to show no discernible age spread).

Clearly, addressing these intriguing questions will have to await more O abundances in very metal poor stars. Nevertheless, such questions indicate that the [O/Fe] ratio of extreme halo stars is an important quantity. Certainly, confirmation of our results and detection of O in additional very metal poor stars is needed to draw any firm conclusions.

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