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GALACTIC [O/Fe] AND [C/Fe] RATIOS: THE INFLUENCE OF NEW STELLAR PARAMETERS

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ABSTRACT

We consider the effects of recent NLTE gravities and Fe abundances on stellar [O/Fe] and [C/Fe] ratios. The NLTE parameters greatly reduce or eliminate the well-known discrepancy between CH- and C I–based C abundances in metal-poor stars and previously seen trends of atomic-based [C/Fe] and [O/Fe] with $T_{\rm eff}$. With the NLTE parameters, the metal-poor molecular-based [C/Fe] ratio maintains its increase with declining [Fe/H]; this may also be demonstrated by the revised atomic-based ratios. [O/Fe] values derived from OH and O I features are considerably reduced and typically show improved agreement but are 0.1–0.2 dex larger than those exhibited by the Lick-Texas syndicate's recent [O I]–based giant determinations. The revised [O/Fe] ratios still show an increase down to at least [Fe/H] ~ -2; we suggest that recent field giant data show an increase with similar slope. Even adopting uniform NLTE parameters, study-to-study abundance differences can be significant; moreover, different NLTE studies yield differing gravities and Fe abundances even after taking $T_{\rm eff}$ differences into account. Comparison of metal-poor giant gravities and cluster abundances with isochrones, trigonometric gravities, and near-turnoff cluster abundances yields conflicting indications about whether the evolved gravities might be underestimated as suggested for metal-poor dwarfs. Regardless, we argue that even extreme gravity revisions do not affect the [O/Fe]-[Fe/H] relation derived from the extant results. Combining what we believe the most reliable giant and dwarf data considered here, we find [O/Fe] $= -0.184(\pm 0.022) \times$ [Fe/H] $+ 0.019$ with an rms scatter of only 0.13 dex; there is no indication of a break or slope change at intermediate [Fe/H]. The gentle slope is in very reasonable agreement with some chemical evolution models employing yields with small mass and metallicity dependences. Finally, two notes are made concerning Na abundance-spatial position and element-to-element correlations in M13 giants.

Key words: Galaxy: abundances — Galaxy: halo — stars: abundances — stars: atmospheres — stars: distances — stars: fundamental parameters — stars: late-type — stars: Population II

1. INTRODUCTION

The Galactic history of stellar oxygen abundances has implications for a range of issues such as stellar ages, halo formation, chemical evolution, the production of Li/Be/B, and in situ stellar processing. Despite recent efforts, uncertainty lingers in stellar [O/Fe] ratios and their variation with [Fe/H]. Much of the history and results of stellar O abundances have been recounted in the work of, e.g., Israelian et al. (1998), Balachandran & Carney (1996), Cavallo, Pilachowski, & Rebolo (1997), King (1993), and Tomkin et al. (1992). Recently, Fullbright & Kraft (1999; hereafter FK99) have derived the [O/Fe] ratio in two metal-poor evolved subgiants using the λ6300 [O I] feature. This work highlights the important issues of (1) the morphology of [O/Fe] with [Fe/H], (2) differences in [O/Fe] derived from giants and dwarfs, and (3) the similarity of [O/Fe] ratios and their morphology with that of other α elements.

Figure 2 of King (1994a) shows [O/Fe] versus [Fe/H] from several giant analyses employing the λ6300 [O I] feature, which maintains measurable strength in metal-poor giants and is believed immune from various systematic errors. The data show a clear rise from [O/Fe] ~ -0.1 at [Fe/H] ~ 0 to values near $+0.4$–0.5 near [Fe/H] ~ -1.2, below which [O/Fe] is constant. This is similar to the behavior of other α elements (e.g., Fig. 3 of Wheeler, Sneden, & Truran 1989). The exact metal-poor plateau ratios, location of break points near [Fe/H] ~ -1, location of the initial rise of the ratios near [Fe/H] ~ 0, and possible α element-to-element variation remain unclear perhaps owing to study-to-study and element-to-element differences (e.g., Fuhrmann, Aver, & Gehren 1995; King 1994a; Wheeler et al. 1989).

Because the λ6300/λ6363 [O I] features are very weak even in metal-rich dwarfs and lie in a region of considerable telluric contamination, analyses of O in dwarfs[1] have relied upon the high-excitation λ7774 O I triplet with its significant strength and clean spectral region. The O I results show a rise in [O/Fe] from [Fe/H] ~ 0 to ~ -1 similar to the giant results. At lower [Fe/H], though, studies differ. The average metal-poor [O/Fe] ratios of Tomkin et al. (1992; hereafter TLLS) are $\sim +0.8$ and show no significant trend with [Fe/H]; the ratios from Abia & Rebolo (1989) continue to increase from $\sim +0.7$ at [Fe/H] ~ -1 to $\sim +1.2$ at [Fe/H] ~ -2.5. This is different from the trend exhibited by other α-element ratios, and the [O/Fe] ratios from both studies are 0.3–0.7 dex above the giant [O I]–based values.

The dwarf-giant discrepancy persists in recent studies. Israelian et al. (1998) use near-UV OH lines to determine [O/Fe] ratios in 23 dwarfs, finding a smooth increase in [O/Fe] from $+0.0$ at [Fe/H] ~ -0.3 to $+1.0$ at [Fe/H] ~ -3.0. Boesgaard et al. (1999; hereafter BKDV99) combine near-UV OH and O I data to derive [O/Fe] in 24 dwarfs. They find a smooth increase too: from $+0.0$ at [Fe/H] $\sim +0.0$ to $+1.1$ at [Fe/H] ~ -3.0. In contrast, FK99 determine [O/Fe] $= +0.50$ and $+0.35$ in two evolved metal-poor subgiants ([Fe/H] $= -2.84$ and -2.31)

[1] Subgiants slightly evolved past the turn-off are included in this category here.

from the λ6300 [O I] line. The lower subgiant [O/Fe] values relative to the OH/O I dwarf results follow the pattern noted above. Modern and homogeneous [O I]–based [O/Fe] data from field giants come from the Lick-Texas (L-T) syndicate (e.g., Sneden et al. 1991; Kraft et al. 1992; Shetrone 1996).

The current picture is seen in Figures 1*a* and 1*b*, which shows [O/Fe] versus [Fe/H] from the ([O I]–based) giant and (OH/O I–based) dwarf results. A disparity of several tenths of a dex in the metal-poor [O/Fe] ratios is seen. Notably, the recent giant results also suggest the metal-poor [O/Fe] ratio is not constant with [Fe/H]; the data with $[Fe/H] \leq -1.2$ exhibit a correlation significant at the 98.5% confidence level, though the slope (-0.13 dex dex^{-1}) is small.

2. STELLAR PARAMETERS AND RECENT NLTE STUDIES

Several recent studies have examined the adequacy of fundamental parameters ($T_{\rm eff}$, log *g*, and Fe abundance) of late-type stars in light of (semi-) physical determinations and possible NLTE effects. Following up on the work of Nissen, Hog, & Schuster (1997), Allende Prieto et al. (1999; hereafter AP99) present evidence of systematic errors in late-type stellar spectroscopic gravities, derived from ionization balance of Fe I and Fe II lines, which evince departures from accurate values determined with *Hipparcos* parallaxes. Figure 4*b* of AP99 plots the difference between various studies' spectroscopically inferred log *g* values and AP99's parallax-based estimates versus [Fe/H].

Two notable things are evident in this figure. First, each data set presents gravity differences that seem to be functions of [Fe/H]. Second, there are striking study-to-study differences in the gravity differences. The most numerous data (with spectroscopic gravities from Gratton, Caretta, & Castelli 1996) demonstrate spectroscopic gravities larger (on average) than trigonometric values at solar metallicity; agreement is reached as metallicity declines to the lowest values ($[Fe/H] \sim -2.5$). The fewer remaining data from other studies, however, show trigonometric and spectroscopic gravities in agreement at solar and intermediate metallicities, but spectroscopic gravities 0.5 dex lower than trigonometric values at $[Fe/H] \sim -2.5$.

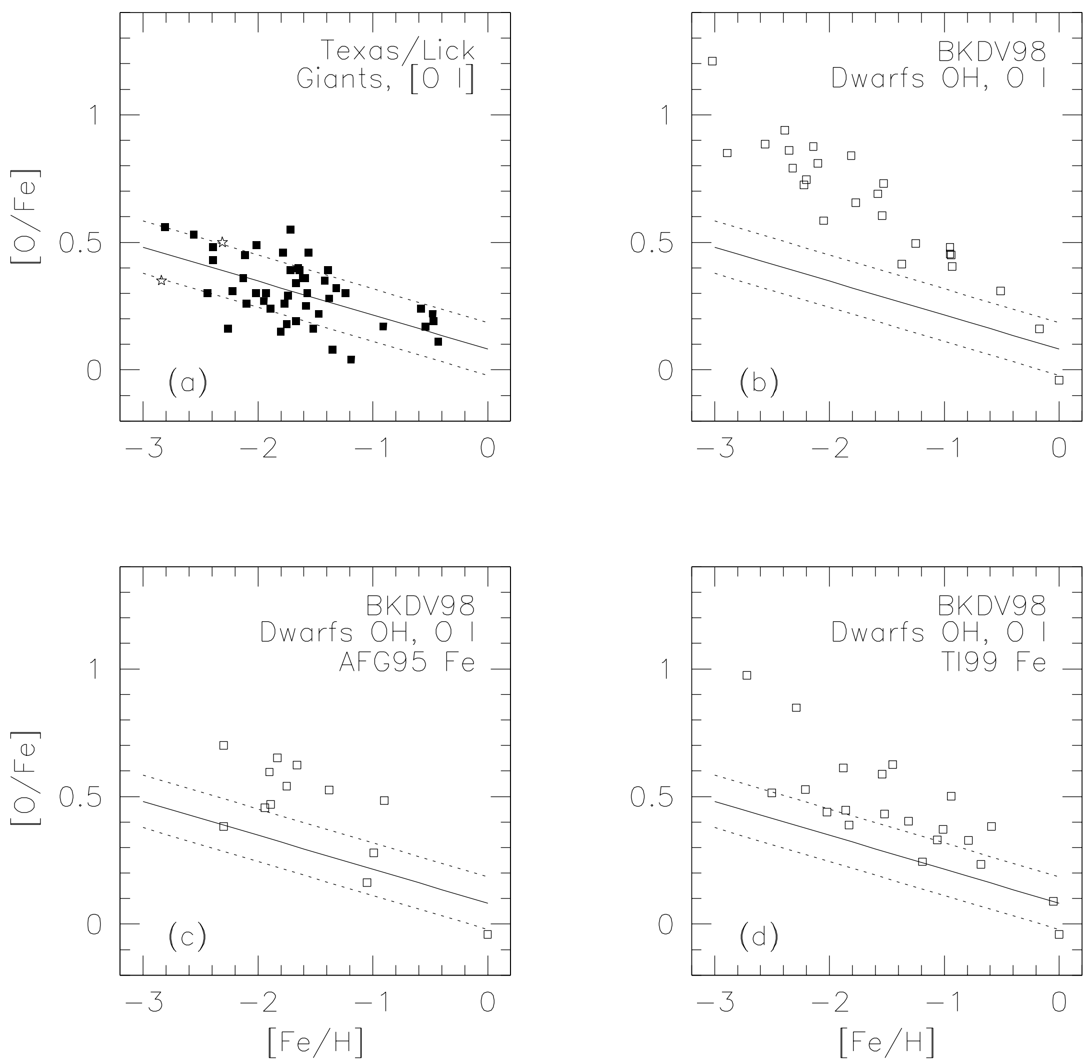

FIG. 1.—(*a*) The [O/Fe]-[Fe/H] relation from field giants in the recent homogeneous studies of the Lick-Texas group; the least-squares fit to the giant data and rms scatter are shown by the lines. (*b*) The relation from the OH- and O I–based results of Boesgaard et al. (1999; *open squares*) with the giant relation (*lines*). (*c*) The same as (*b*) except adjusting the O abundances for the parameters of Axer et al. (1995) and employing their Fe abundances for the (fewer) stars in common. (*d*) The same as (*b*) except adjusting the O abundances for the parameters of Thévenin & Idiart (1999) and employing their Fe abundances for the (fewer) stars in common.

This dichotomy is reflected in AP99's Figure 10, which indicates that the gravity differences of the few data points from other studies can be explained very well by NLTE effects (mostly due to Fe I overionization) calculated by Thévenin & Idiart (1999; hereafter TI99). However, the gravity differences evinced by the stars from the study of Gratton et al. (1996) cannot be accounted for by such NLTE corrections. There are thus significant study-to-study differences that make even a single general description of spectroscopic-trigonometric gravity differences nearly impossible, let alone a precise elucidation of their cause(s). This is an important issue since accurate gravities are important for accurate [O/Fe] determinations given the sensitivity of the OH, O I, and [O I] features to this parameter; of course, accurate Fe abundances themselves are necessary since this is half of the [O/Fe] ratio.

Numerous factors influence the determination of spectroscopic gravities and putative NLTE effects. These include neutral and ionized line oscillator strengths, other atomic data (model atoms, photoionization cross sections, etc.), model atmospheres and a related host of assumptions/simplifications, treatment of damping (Ryan 1998), and the adequacy of the assumed/adopted/derived stellar $T_{\rm eff}$ values. The latter may be particularly important since the Gratton et al. (1996) $T_{\rm eff}$ scale is substantially different from those utilized in the other studies considered by AP99 and from the TI99 study. It must be emphasized, then, that attempts to ascribe such gravity differences (or other possible discrepancies such as, e.g., departures from excitation balance) to NLTE effects requires that we be assured that all the other variables entering abundance and NLTE analyses be well known. Unfortunately, one can probably only be assured that this is not the case. At the very least, as noted by AP99, NLTE effects are not the sole mechanism(s) producing the gravity differences in their Figures 4 and 10.

Uncertainties in the extent of NLTE effects on Fe abundances and derived gravities of metal-poor stars are illustrated in comparing the results of Gehren, Reile, & Steenbock (1991; hereafter GRS91) and Axer, Fuhrmann, & Gehren (1995; hereafter AFG95) with those of TI99. After applying a perceived $T_{\rm eff}$ shift in metal-poor stellar evolutionary models (ascribed to changes in mixing length parameter and nonsolar [O/Fe] ratios), AFG95 conclude that comparison of model luminosities and surface gravities with their spectroscopic values suggest small NLTE ionization equilibrium deviations that afflict the spectroscopic values. Based on theoretical calculations in GRS91 and comparison of model and derived luminosities, they suggest corrections in Fe abundance and log g of typically $\sim +0.05$ dex and $\sim +0.15$ dex, respectively, for metal-poor subdwarfs and subgiants. Given the above discussion, one should note that this cannot be a rigorous conclusion of NLTE effects since such a conclusion depends on manifold other assumptions. In particular, one might note that AFG95's own set of model atmospheres and $T_{\rm eff}$ values (derived from Balmer line profile fitting) are distinct from those utilized in other studies of metal-poor stars.

TI99 have carried out detailed statistical equilibrium calculations for Fe I and Fe II in late-type stellar models of various metallicity. Their work uses sophisticated atomic models, numerous transitions, and new Iron Project photoionization cross sections. They find that metal-poor stars like those in the study of AFG95 are affected significantly by Fe I overionization from UV radiation. NLTE adjustments suggested by TI99 for metal-poor stars are markedly larger than those inferred by AFG95; typical corrections in Fe abundance and log g are $+0.25$ dex and $+0.4$ dex. TI99 note that their NLTE parameters are able to explain the discrepancy between *their* LTE spectroscopic and *Hipparcos*-based trigonometric gravities. Figures 4 and 10 of AP99, however, remind us that the same can not be said for the LTE spectroscopic gravities derived in some other studies.

While TI99 cite the correspondence between their NLTE spectroscopic surface gravities and the *Hipparcos*-based trigonometric values as "proof of the validity" of their results, the NLTE study-to-study differences in Figures 4 and 10 of AP99 again remind us that it is possible (at least in principle) to achieve such consistency without any recourse to NLTE effects. On the other hand, TI99's results are not inferred from a comparison between observation and theory but are a direct result of their calculations. While a clear quantitative exposition of uncertainty in their NLTE corrections is lacking, it seems that reasonable changes in various extant parameters (model atmospheres, collisional damping, adopted $T_{\rm eff}$ values) would not substantially decrease the corrections for metal-poor stars derived within their specific framework. Whether differing frameworks involving novel features or differing assumptions lead to significantly different results (e.g., convective inhomogeneities, chromospheres, inclusion of additional transitions, etc.) remains a topic for future investigation.

While the issues of the reality and magnitude of NLTE-based adjustments to Fe abundances and gravities of late-type stars remain unsettled, they are potentially quite important for a host of issues. Here, we reconsider recent stellar O studies in light of these NLTE parameters.

3. [O/Fe] IN DWARFS: THE BOESGAARD ET AL. (1999) DATA

We first consider the dwarf study of BKDV99 since their O abundances come from both near-UV OH lines and the O I triplet. The sensitivity of the OH and O I lines to the assumed parameters (e.g., $T_{\rm eff}$ and log g) is opposite in sign but similar in magnitude. While the influence of the parameters on the resulting average O abundance is thus minimal, alterations to [O/Fe] arise from the NLTE Fe abundances. BKDV99 adopt homogenized Fe abundances from the literature. We explore here the effects of the NLTE parameter/Fe values from TI99 and AFG95 on the BKDV99 results.

We compared original parameters and [O/Fe] ratios of BKDV99[2] with the NLTE parameters/Fe from TI99 and AFG95 and estimated the revised [O/Fe] values that would result in adopting the NLTE values. These estimates are made by adjusting BKDV99's mean O abundances using typical sensitivities of ± 0.045, 0.005, and 0.025 dex changes in O for ± 100 K, 0.3 dex, and 0.3 dex changes in $T_{\rm eff}$, log g, and [M/H]. The typical change in O abundance is ~ 0.02 (TI99) and ~ 0.07 (AFG95) dex; most of the change in [O/Fe] is due to the different [Fe/H] values.

Several stars exhibit particularly large gravity differences. Differences for HD 76932, HD 84937, HD 134169, HD 201889, BD +23 3912, BD +17 4708, BD +2 3375, and

[2] Our [O/Fe] value for BD +03 740 replaces an errant value that appears in Tables 9 and 10 of BKDV99; the correct value appears in their other tables and figures (A. M. Boesgaard 1999, private communication).

BD -13 3442 (BKDV99 vs. TI99) represent changes from (slightly evolved) subgiant to dwarf classification and vice versa. The same holds for HD 201889, HD 219617, BD $+26$ 3578, and BD $+17$ 4708 for BKDV99 versus AFG95. Secure gravities for these famous metal-poor stars have importance for derived kinematics (AFG95), globular cluster ages from main-sequence fitting (e.g., Reid 1997), interpretation of isotopic Li ratios in metal-poor stars (Crifo, Spite, & Spite 1998), and chemical evolution anomalies in the halo (e.g., the case of BD $+03$ 740 noted by King 1997).

The revised [O/Fe] ratios are shown in Figures 1*c* and 1*d* for AFG95 and TI99 parameters/Fe. These revised ratios are reduced by a typical 0.3 dex from the BKDV99 values when adopting TI99's parameters but remain $\gtrsim 0.2$ dex larger than the field giant values. The revised ratios' implications for the [O/Fe] versus [Fe/H] morphology are unclear. The TI99 results could suggest a rise in [O/Fe] from near zero values at $[Fe/H] = 0$ to values $\sim +0.5$ near $[Fe/H] = -1.3$, below which there is a constant plateau with a few stars (BD -13 3442 and BD $+02$ 3375) showing anomalously larger ratios; this has been discussed previously by King (1994b). A second possibility is a linear relation with large scatter for $[Fe/H] \lesssim -2$, where scatter also appears in heavy element ratios (e.g., McWilliam 1997). The AFG95 results are also too limited to make definitive claims about the morphology. If a linear relation, though, BD $+03$ 740 may evince an unexpected low value—perhaps seen in the original BKDV98 data; possibly anomalously low [α/Fe] ratios in this star have been noted previously by King (1997). The observational challenge of an increased metal-poor sample is needed to address these issues.

4. CARBON AND OXYGEN IN METAL-POOR DWARFS

4.1. *Raw TLLS Results*

In addition to O I–based O abundances, TLLS provide C abundances from both CH and high-excitation C I lines in their metal-poor dwarfs. They concluded that (1) molecular-based (CH) abundances are more reliable than their atomic-based abundances, which seem errantly large and evince a trend with $T_{\rm eff}$, but (2) the [C/O] *ratios* inferred from the atomic features are reliable since they show no trend and agree well those determined from CH and OH. As noted by McWilliam (1997), this provides an indirect means to determine a presumably reliable [O/Fe] from O I data even if the latter are unreliable. Combining the CH-based [C/Fe] and atomic-based [C/O] ratios yields presumably more reliable "expected" [O/Fe] ratios. To repeat, we define a presumably reliable "expected" [O/Fe] ratio from TLLS's (1) presumably reliable [C/O] ratio formed from potentially unreliable individual atomic (C I– and O I–based) [C/H] and [O/H] values, (2) presumably reliable molecular (CH-based) [C/H] values, and (3) their presumably reliable Fe abundances. The expected TLLS [O/Fe] ratios are plotted in the bottom left-hand panel of Figure 2; the actual (suspect) atomic-based ratios are plotted in the top left-hand panel.

The clear difference between the TLLS expected and actual [O/Fe] ratios is simply another way to infer that these O I abundances are suspect. The expected ratios are in better agreement with the giant results but show a larger slope with [Fe/H] similar to the raw BKDV99 results, though their [O/Fe] values are typically 0.3 dex higher. Figure 3 shows that TLLS's trend of increasing actual [O/Fe] ratios with declining $T_{\rm eff}$ disappears with the expected ratios.

Concern may persist even with the expected [O/Fe] ratios. Extrapolation of a least-squares fit to these indicates for $[Fe/H] = 0$ that $[O/Fe] \lesssim -0.3$, lower than values from disk star studies (e.g., Fig. 15*a* of Edvardsson et al. 1993). Additionally, the correlation between the actual [O/Fe] values and $T_{\rm eff}$ may be replaced with one of opposite sign in the expected ratios; the $\lesssim 90\%$ confidence level of the correlation is not significant but is uncomfortably large. Finally, the increase of the expected [O/Fe] ratios with decreasing [Fe/H] is dictated by the similar rise in the CH-based [C/Fe] ratios. The rise in [C/Fe] at low [Fe/H] persists when combining results from other dwarf studies (Fig. 1 of Wheeler et al. 1989) but is not well understood in terms of Galactic chemical evolution (e.g., Fig. 13 of Timmes, Woosley, & Weaver 1995). In principle, the TLLS CH-based [C/Fe] ratios depend upon the assumed [O/Fe] value utilized in their molecular equilibrium calculations to account for the effects of CO formation. However, most of their objects are warm, high-gravity, metal-poor stars, and trial calculations indicate that utilizing the "expected" [O/Fe] ratios instead of their assumed value of $[O/Fe] = +0.4$ typically alters the derived CH-based [C/Fe] ratios by much less than 0.1 dex. Moreover, the sense of these small changes would be only to *strengthen* the rise in CH-based [C/Fe] with declining [Fe/H].

4.2. *NLTE Parameter*/Fe *Results*

We considered the effects of the TI99 and AFG95 parameter/Fe values on TLLS's O and C results using the typical abundance sensitivities in their Table 5. The revised ratios are shown in the middle and right-hand columns of Figures 2 and 3. The top, middle, and bottom rows show the actual O I–based [O/Fe] ratios; the C I–based (*squares*) and CH-based (*stars*) [C/Fe] ratios; and the "expected" [O/Fe] ratios. The actual [O/Fe] ratios employing the TI99 and AFG95 results move much closer to the field giant results—declining by 0.36 and 0.54 dex (on average) from the TLLS values. However, the TI99- and AFG95-based results show no significant slope in the [O/Fe]-[Fe/H] plane; this is in contrast to the field giants and both the raw and revised O I– and OH-based results of BKDV98. Figure 3 indicates that the trend of TLLS's [O/Fe] with $T_{\rm eff}$ is mitigated using the TI99 parameters but persists with the AFG95 parameters.

The middle rows of Figures 2 and 3 display the CH-based (*stars*) and C I–based (*squares*) [C/Fe] ratios. The raw TLLS results (*left-hand panels*) evince the long-known discrepancy between the atomic and molecular abundances (Wheeler et al. 1989). Like the O I results, the middle and right-hand panels indicate the typical 0.4 dex difference is greatly reduced or essentially eliminated by adopting the TI99 and AFG95 parameters/Fe. A rise in the C I–based [C/Fe] ratios with declining [Fe/H] is not statistically established—in contrast to the raw and revised CH-based [C/Fe] ratios. Like O I, Figure 3 shows TLLS's trend in atomic [C/Fe] ratios with $T_{\rm eff}$ disappears using the TI99 parameters/Fe but persists with the AFG95 values. The star near $[Fe/H] \sim -1$ with low molecular-based [C/Fe] (irrespective of parameter choice) and expected [O/Fe] ratio is HD 193901.

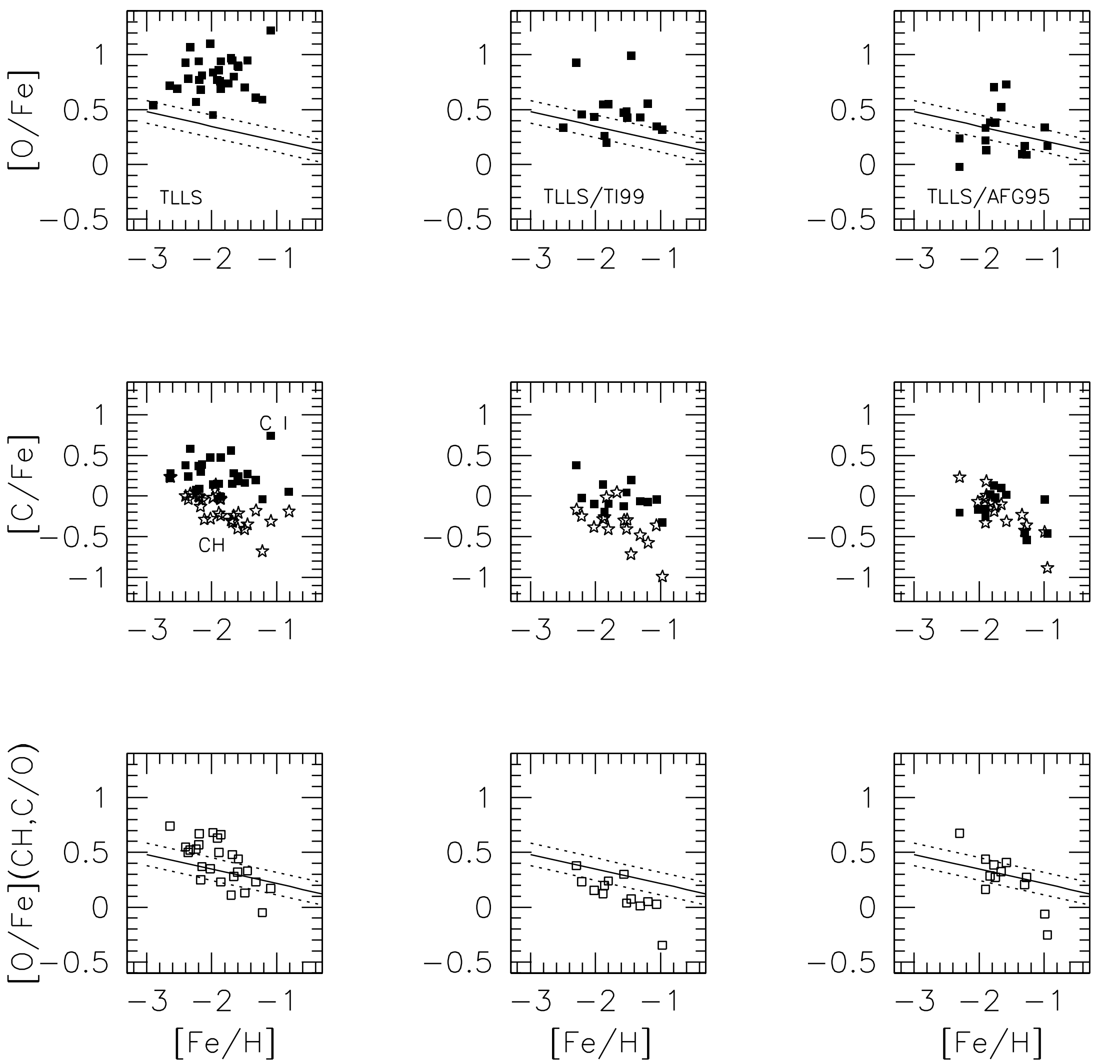

FIG. 2.—The top, middle, and bottom rows plot O I–based [O/Fe] ratios, CH- (*stars*) and C I–based (*squares*) [C/Fe] ratios, and "expected" [O/Fe] ratios (from the CH abundances and atomic-based [C/O] ratios) vs. [Fe/H] for objects in the study of TLLS. The left, middle, and right columns contain the raw TLLS results, TLLS results adjusted for TI99 parameters/Fe, and TLLS results adjusted for AFG95 parameters/Fe. The lines in the [O/Fe] vs. [Fe/H] plane are the least-squares fit and rms scatter of the field giant data in Fig. 1*a*.

Employing the TI99 or AFG95 parameters changes TLLS's atomic-based mean [C/O] ratio by only a couple hundredths of a dex. The correlation between increasing [C/O] and declining [Fe/H] in the TLLS results is significant. The slope actually increases using TI99 and AFG95 parameters/Fe (from -0.04 dex in [C/O] per dex in [Fe/H] to -0.05 and -0.11); however, the revised correlation is not significant given the reduced sample size. The lack of a correlation between [C/O] and $T_{\rm eff}$ is maintained using the revised parameters.

The bottom row of Figure 2 shows the rise in TLLS's expected [O/Fe] ratios with declining [Fe/H] persists when incorporating the TI99 and AFG95 parameters/Fe. The slope of the TI99-based results (-0.23 dex dex^{-1}) is considerably shallower than the TLLS and AFG95-based results (-0.36 and -0.40 dex dex^{-1}), and in fine agreement with the field giant slope (-0.13 dex dex^{-1})—though the TI99 ratios are offset by $\sim$0.2 dex from those of the giants. There is no significant trend between expected [O/Fe] and $T_{\rm eff}$ for any parameter set. The intercept of the least-squares fit to even the TI99-based results (-0.23) seems uncomfortably low. An intriguing interpretation might be flat [O/Fe] for [Fe/H] $\gtrsim -1$—perhaps consistent with suggested "edges" in [Mg/Fe] (Fuhrmann et al. 1995; Wheeler et al. 1989).

5. OH VERSUS O I

Because BKDV99's use of OH and high-excitation O I features is analogous to the CH and C I features in TLLS, we consider the former's O features separately in Figure 4. The raw BKDV99 data (*top left*) suggest the atomic-based [O/Fe] ratios are equal to or slightly less than the OH-based ratios at low [Fe/H] but become larger at higher [Fe/H]. The intercept of a linear fit to the atomic-based ratios is a large $+0.35$ dex. Kiselman's (1991) downward O I NLTE corrections have a minimum at intermediate [Fe/H] and increase for both higher and lower [Fe/H]. Simple qualitative reasoning suggests, then, that these NLTE corrections can not fully explain the observed O I–OH offset, which is similar to the C I–CH offset seen in Figure 2.

Like the C I– and CH-based results, most of the atomic-based O ratios fall closer to the OH-based values when adopting the TI99 and AFG95 parameters/Fe. The TI99/atomic-based results are interesting, however, in that a few

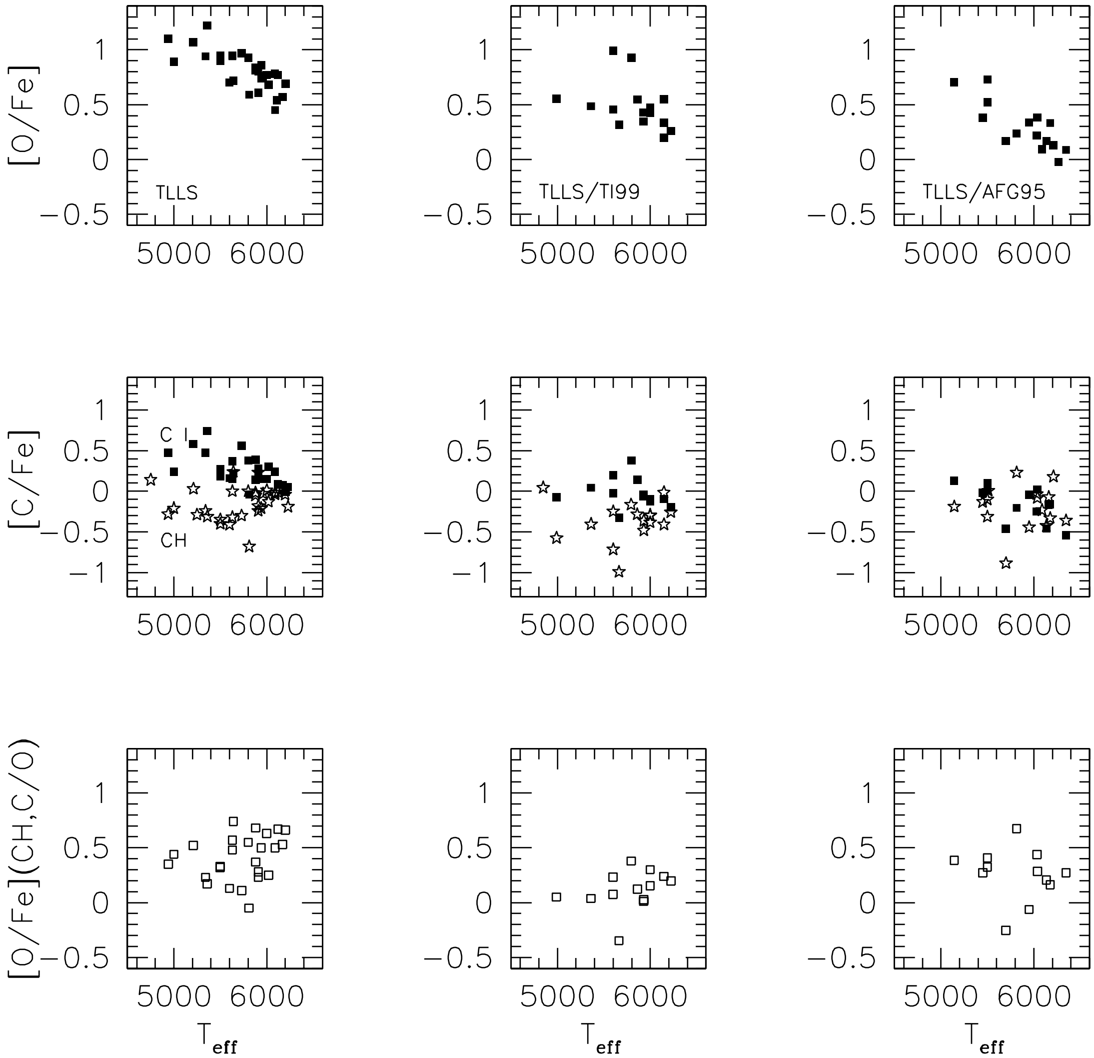

FIG. 3.—Same as Fig. 2, except the C and O ratios are plotted vs. effective temperature

discrepantly large ratios are derived, leading to an increase in the scatter. Objects showing these anomalous ratios are HD 184499, HD 221377, HD 201889, BD +23 3912, BD +2 3375, and BD +17 4708; BD +23 3912 and BD +2 3375 have anomalously large TI99/atomic-based ratios in the TLLS study, too (Fig. 2). These are discussed below.

BKDV99's sloping O I–based [O/Fe]-[Fe/H] morphology (Fig. 4) is very different from the near-flat relation of TLLS (Fig. 2). BKDV99 note the difference is equally attributable to differences in the Fe abundances, stellar parameters, and model atmospheres. The top middle panels of Figures 2 and 4 show that uniform parameters/Fe do not necessarily explain study-to-study O I differences. One can explore the consistency of the TLLS and BKDV99 molecular analyses by comparing the TLLS CH-based "expected" [O/Fe] ratios with BKDV99's OH-based values. Figure 4 indicates the slopes of the expected and OH-based [O/Fe]-[Fe/H] relations agree well regardless of parameter/Fe assumptions, but the molecular ratios are ~ 0.2 dex larger. This offset persists when consistently assuming TI99 or AFG95 parameters/Fe and points to inconsistency in the molecular abundances of BKDV99 and TLLS—likely causes are model atmosphere differences, solar normalization, or errors in *gf*-values. Regardless, to the extent that TLLS's atomic [C/O] ratios are reliable, the OH-based [O/Fe] versus [Fe/H] morphology suggests that [C/Fe] increases with declining [Fe/H] in the metal-poor regime; the zero point, though, remains uncertain.

Figure 4 indicates that the TI99 parameters/Fe lead to considerably lower OH-based [O/Fe] ratios and a flatter [O/Fe] versus [Fe/H] morphology than the raw BKDV99 results; we shall see later that the ratios are in good accord with the field giant data. Additionally, the linear fit to the TI99 results yields a reasonable intercept of -0.08. The AFG95 parameter/Fe values, though, lead to ratios and slopes not significantly different from the raw BKDV99 results. Regardless, Figure 4 supports increasing OH-based [O/Fe] with declining [Fe/H] despite different parameter/Fe choices considered here—at least in the metal-poor regime. The metal-rich OH data points are too few to exclude a near-constant [O/Fe] ratio for $-1 \lesssim$ [Fe/H] $\lesssim +0.0$.

We noted that HD 184499, HD 221377, HD 201889, BD +17 4708, BD +23 3912, and BD +2 3375 show anomalously high BKDV99/TI99 atomic-based [O/Fe] ratios. The latter two show similarly anomalous ratios in the TLLS/TI99 results, while HD 201889 and BD +17 4708 exhibit the largest ratios for the BKDV99/AFG95 results.

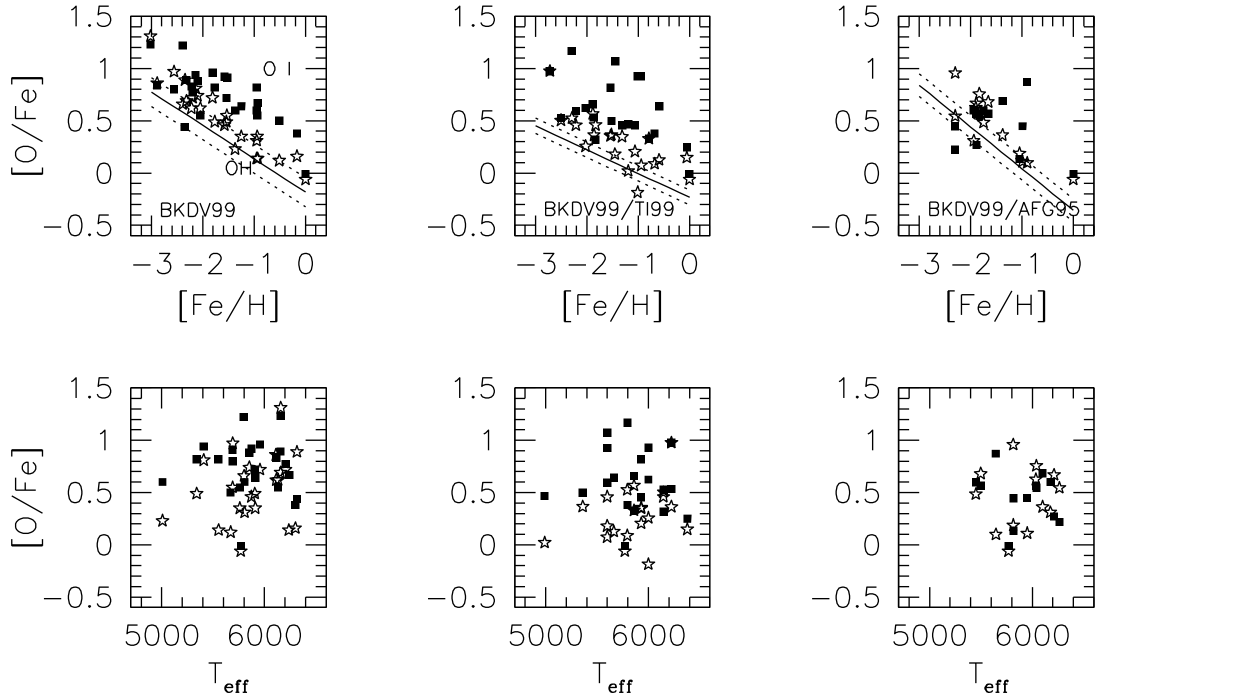

FIG. 4.—The top row shows the O I– (*squares*) and OH-based [O/Fe] ratios from BKDV99 vs. [Fe/H]. The bottom row plots these ratios vs. effective temperature. The left, middle, and right columns contain the raw BKDV99 ratios, ratios adjusted for TI99's parameters/Fe, and ratios adjusted for AFG95's parameters/Fe. The lines show the least-squares fit and rms scatter of the TLLS/CH-based "expected" [O/Fe] ratios in Fig. 2.

Four of the six objects were mentioned before because their NLTE gravities differ significantly from the BKDV99 values. However, *Hipparcos* parallaxes generally confirm TI99's higher gravities for HD 201889, BD +17 4708, BD +23 3912, and BD +2 3375; curiously, their c_1 indices favor the lower subgiant-like gravities of BKDV99. Another trait of the six stars is that the TI99 − BKDV99 [Fe/H] difference of $+0.05 \pm 0.06$ (mean error) is considerably less than the $+0.25 \pm 0.02$ difference exhibited by the other stars. This might suggest the role of lingering [Fe/H] errors. Even the NLTE results conflict in several cases—e.g., the TI99 and AFG95 [Fe/H] values for BD +02 3375 differ by 0.39 dex, and the gravities for BD +17 4708 differ by 0.49 dex. Since the six stars are 30% of the BKDV99/TI99 sample, understanding the source of these anomalous ratios remains an important step in deriving reliable O I–based abundances.

6. RED GIANT [O/Fe] RATIOS

Systematic effects on parameter/Fe values of metal-poor giants are a potential concern since the [O I]–based abundances are sensitive to log g and input metallicity. However, the case for NLTE effects is even more uncertain than for metal-poor dwarfs. Ruland et al. (1980) inferred NLTE departures in low-excitation neutral lines in the metal-rich ([M/H] ~ -0.2) giant Pollux; the implications for considerably more metal-poor giants like those considered in this paper are unclear, however. Their analysis of Pollux and the more metal-poor Arcturus (an L-T sample member) might also suggest a relation to photospheric granulation or chromospheric inhomogeneities, and they note indirect evidence of these in metal-poor globular cluster giants. More observational and theoretical work is warranted to clarify the magnitude of these putative effects in metal-poor giants like those in the L-T field sample.

The NLTE corrections to [Fe I/H] of TI99's three stars having log $g \lesssim 2.75$ are modest ($\sim$0.05 dex). However, these stars have [Fe/H] $\gtrsim -0.40$, and small corrections are more attributable to the high metallicity than to low log g (TI99's Fig. 9); still, such a metallicity dependence could alter the [O/Fe] versus [Fe/H] morphology. Gratton & Sneden (1991) suggest Fe I lines with reduced equivalent widths $\lesssim -4.9$ may yield LTE abundances too large by 0.2 dex in metal-poor giants; however, inclusion of collisions in apparently the same manner as TI99 lowers the NLTE corrections to 0.06 dex. Gratton et al. (1996) perform exploratory NLTE calculations for the cool metal-poor cool giant HD 187111 and find LTE Fe I abundances too low by 0.08 dex, and ionization balance-based gravities too low by 0.25 dex.

Gratton & Sneden (1991) and Gratton et al. (1996) note that metal-poor giant gravities derived via ionization balance are significantly lower than values from semiempirical and theoretical color-magnitude diagrams. Such disagreement, though, may also be influenced by the neutral and ionized *gf*-values, the assumed $T_{\rm eff}$, and the adopted model atmospheres. AFG95 derive NLTE gravities for the evolved subgiants BD +37 1458 and BD +23 3130 that are 0.77 and 1.10 dex larger than the ionization balance–based values of FK99. However, even the former's LTE gravities are 0.64 and 0.92 dex larger than the FK99 values; a substantial portion of these differences are related to the $T_{\rm eff}$ values—AFG95's being 350 and 340 K larger than FK99's.

6.1. *Metal-poor Giant Gravities from Parallaxes*

To explore the effects of parameter/Fe deviations on resulting [O/Fe] ratios, we searched for metal-poor giants and evolved subgiants in the L-T O studies having *Hipparcos* parallaxes of quality $\pi/\sigma_\pi \gtrsim 3.0$. These are listed in the top part of Table 1. Below these, we list other giants in

TABLE 1

Field Giant Data

Star (1)	T_{eff} Ref (2)	log g Ref (3)	[Fe/H] Ref (4)	[O/Fe] Ref (5)	References (6)	π (mas) (7)	σ_π (mas) (8)	log g' Trig (9)	σ Trig (10)	[Fe II/H] Trig (11)	[O/Fe II] Trig (12)	log g'' Trig, ΔLK (13)
HD 8724	4800	1.90	−1.52	+0.16	1	3.04	0.95	2.31	0.29	−1.24	+0.14	1.76
HD 21581	4875	2.00	−1.74	+0.29	2	4.27	1.20	2.80	0.26	−0.98	+0.26	2.39
HD 37828	4350	1.20	−1.42	+0.35	1	3.83	0.81	1.67	0.20	−1.01	+0.19	1.47
HD 44007	4890	2.20	−1.61	+0.36	2	5.17	1.02	2.71	0.18	−1.26	+0.36	2.54
HD 85773	4450	1.00	−2.22	+0.31	3	4.07	1.30	2.80	0.30	−0.92	+0.21	2.21
HD 122563	4650	1.20	−2.56	+0.53	3	3.76	0.72	1.55	0.18	−2.39	+0.45	1.39
HD 122956	4620	1.60	−1.77	+0.26	3	3.30	0.88	1.84	0.25	−1.47	+0.22	1.48
BD +23 3130	4850	2.00	−2.84	+0.35	4	4.29	1.17	2.88	0.25	−2.51	+0.33	2.50
BD +37 1458	5100	2.90	−2.31	+0.50	4	5.78	1.31	3.26	0.21	−2.14	+0.48	3.03
HD 4306	4900	2.00	−2.54	…	5	4.81	1.40	3.03	0.27	…	…	2.58
	4950	1.85	−2.87		6							
	5000	1.50	−2.65		7							
HD 6755	5150	2.70	−1.57	…	5	7.74	0.91	3.05	0.11	…	…	3.00
	5280	1.70	−1.4		8							
HD 25532	5300	1.90	−1.46	…	5	4.39	1.25	2.84	0.38	…	…	2.41
	5330	2.20	−1.1		8							
HD 93529	4650	1.70	−1.67	…	5	3.70	1.21	2.78	0.31	…	…	2.15
HD 108317	5300	2.90	−2.28	…	5	4.53	1.06	2.78	0.22	…	…	2.53
	5000	2.30	−2.29		7							
HD 115444	4750	1.70	−2.77	…	5	3.55	1.12	2.65	0.30	…	…	2.08
	4850	1.60	−2.4		8							
HD 126238	4979	2.50	−1.67	…	9	3.81	0.95	2.33	0.24	…	…	2.03
	4979	2.16	−1.73		10							
HD 128279	5480	3.10	−2.08	…	6	5.96	1.32	3.09	0.21	…	…	2.87
	5165	3.12	−1.92		12			2.95	0.21			
	5165	3.00	−2.30		15							
	5125	2.20	−2.50		16							
HD 175305	5100	2.50	−1.40	…	5	6.18	0.56	2.63	0.10	…	…	2.60
	5160	3.00	−1.53		11							
HD 184266	5600	1.70	−1.73	…	5	3.28	0.95	2.45	0.27	…	…	2.00
HD 200654	5160	2.55	−2.82	…	6	3.20	1.25	2.84	0.37	…	…	1.79
	5524	3.56	−2.38		12							
	5090	2.70	−3.02		13							
CD −24 1782	5360	3.00	−2.35	…	14	4.42	1.75	3.54	0.38	…	…	2.44
	5250	2.60	−2.31		7							
BD +03 2782	4600	1.50	−2.01	+0.49	3	3.90	1.39	2.96	0.34	…	…	2.16

References.—(1) Shetrone 1996; (2) Kraft et al. 1992; (3) Sneden et al. 1991; (4) Fullbright & Kraft 1999; (5) Pilachowski et al. 1996a; (6) McWilliam et al. 1995; (7) Luck & Bond 1985; (8) Gratton & Ortolani 1984; (9) Gratton & Sneden 1991; (10) Gratton & Sneden 1994; (11) Gratton & Sneden 1987; (12) Axer et al. 1995; (13) Nissen et al. 1994; (14) Gratton & Sneden 1988; (15) Cavallo et al. 1997; (16) Peterson, Kurucz, & Carney 1990.

recent abundance studies[3]—some with slightly lower quality parallaxes. Columns (2)–(4) list T_{eff}, log g, and [Fe/H] adopted/determined in these studies, which are identified in column (6); the L-T [O I]–based [O/Fe] ratio is given in column (5). Parameters from other studies are also listed, but this is not intended to be a complete listing.

References 4, 6, 7, 9, 10, and 16 in Table 1 rely on ionization balance to derive log g. The other studies employ some combination of (1) ionization balance, (2) T_{eff} (or color) and isochrones (or globular cluster fiducials), (3) T_{eff} and assumed distances and masses, (4) Strömgren color indices, (5) empirical T_{eff} versus log g relations, and (6) profile fitting of strong lines. Sometimes, ionization balance results are averaged with other techniques. Other times, ionization balance–based values are used to "adjust" (in which cases and by how much is usually not apparent) other determinations. In other cases, indirect techniques are used to adjust initial ionization balance–based determinations.

Trigonometric gravities (assuming log $g_\odot = 4.44$) for the Table 1 stars were derived from the parallaxes, T_{eff} values, V magnitudes, and bolometric corrections and masses from the 13 Gyr Yale96 isochrones and their semiempirical color transformation[4] (Demarque et al. 1996). The latter quantities are insensitive to plausible metallicity and age errors, so errors in the parallaxes dominate. The parallaxes, derived gravities, and their uncertainties are listed in columns (7)–(10).

Our trigonometric gravities are certainly too large owing to well-known bias—given small intrinsic giant parallaxes (a few mas), stars with errantly large parallaxes are preferentially included in our sample. We treat this below. For

[3] That of Pilachowski, Sneden, & Kraft (1996a) is very similar to the L-T analyses.

[4] http://shemesh.gsfc.nasa.gov/iso.html.

now, the typical log g difference (0.55 dex) between biased trigonometric gravities and literature values provides an "extreme" case of parameter errors to consider. We thus rederived [O I], Fe I, and Fe II abundances using the L-T equivalent widths, atomic data, assumed solar abundances, original parameters, and extreme trigonometric log g values using an updated version of the LTE analysis package MOOG (Sneden 1973) and employing R. L. Kurucz (1992, private communication) model atmospheres with metallicities enhanced by 0.3 dex over the L-T mean Fe abundance to mimic α-element enhancement. When there were very large increases in the derived Fe II abundances, the assumed model atmosphere metallicity was similarly increased. [C/Fe] = [N/Fe] = 0 was assumed in molecular equilibrium calculations. Insignificant trends of the L-T abundances with χ or line strength were found in our reanalysis except for HD 21581 and possibly HD 44007, where adjustments are warranted in the stellar parameters—but we have not done so for consistency. Repeating the L-T analysis with their own parameters, we found the Fe I–Fe II differences depend on metallicity—negligible at low [Fe/H], but rising to $\sim$0.13 dex near [Fe/H] ~ -1.4. This indicates reasonable analysis-to-analysis differences can result in ionization balance–based log g differences of $\gtrsim$0.20 dex.

Changing log g itself leads to no significant revision in the inferred $T_{\rm eff}$ and ξ values. The revised Fe II–based [Fe/H] and [O I]–based ratios are given in columns (11) and (12) of Table 1. The original and revised [O/Fe] ratios are plotted in Figure 5. Even the "extreme" log g revisions lead to [O/Fe] ratios and morphology that are little changed; the slopes with [Fe/H] (-0.135) and intercepts ($+0.08$) of least-squares fits to the two data sets are the same. Utilizing revised Fe I ratios yields a flat relation with [O/Fe] $\sim +0.6$. However, we suspect the Fe II–based values to be more reliable partners with the [O I] results since (1) if overionization is important, then Fe I is unreliable; (2) excitation departures also favor the Fe II values; and (3) the Fe II and [O I] abundances have similar gravity and metallicity sensitivities.

6.2. *Globular Cluster Giants*

Lutz & Kelker (1973)–type bias corrections were made to our trigonometric gravities following Hanson (1979) assuming the proper motion distribution of the *Hipparcos* catalog. These log g values are listed in the final column of Table 1. Figure 6 plots the giant data from the studies in Table 1 (*filled squares*), our results (*open stars*), and the [Z/H] = -2.0, $Y = 0.23$, 13 Gyr Yale96 isochrone (*short-dashed line*) in the log g versus $T_{\rm eff}$ plane. Most of the literature data lie below the theoretical giant branch (typically by 0.2 dex in log g); the discrepancy may be an increasing function of decreasing $T_{\rm eff}$.

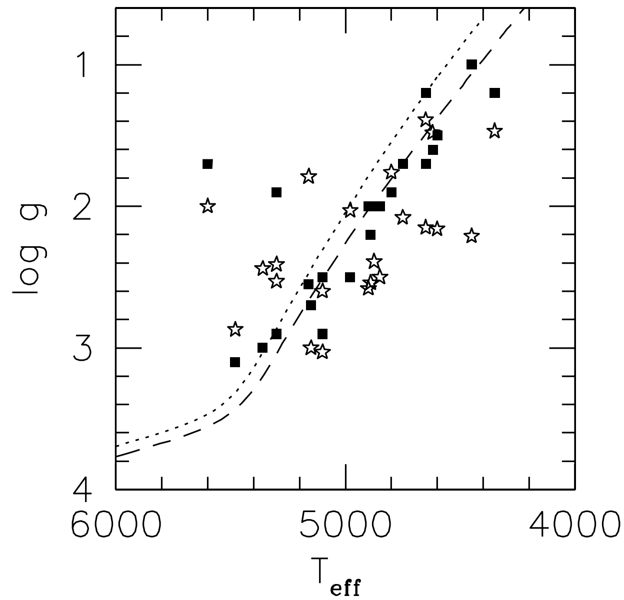

FIG. 6.—The literature results (*squares*) in Table 1 are plotted in the log g vs. $T_{\rm eff}$ plane with our corrected trigonometric gravities (*stars*), the [Z/H] = -2.0, $Y = 0.23$ 13 Gyr Yale96 isochrone (*short-dashed line*), and [Z/H] = -1.7 isochrone (*long-dashed line*).

The majority of the Table 1 data have gravity estimates from the absolute magnitude implied by a color-based assignment along the M92 fiducial (Sneden et al. 1991). These gravities are thus dependent on adopted reddenings and the M92 distance, which they took as $(m - M)_0 = 14.49$. While future space missions will allow direct parallax measurements of globular cluster stars, field subdwarf *Hipparcos* data have been used to infer cluster distances via main sequence fitting. Reid (1997) finds an M92 distance modulus 0.45 mag larger, which would result in the L-T gravities being *over*estimated by $\sim$0.18 dex. This explains much of the average offset between the data and isochrone in Figure 6; some of the offset may also arise from uncertainty in the color transformations/bolometric corrections

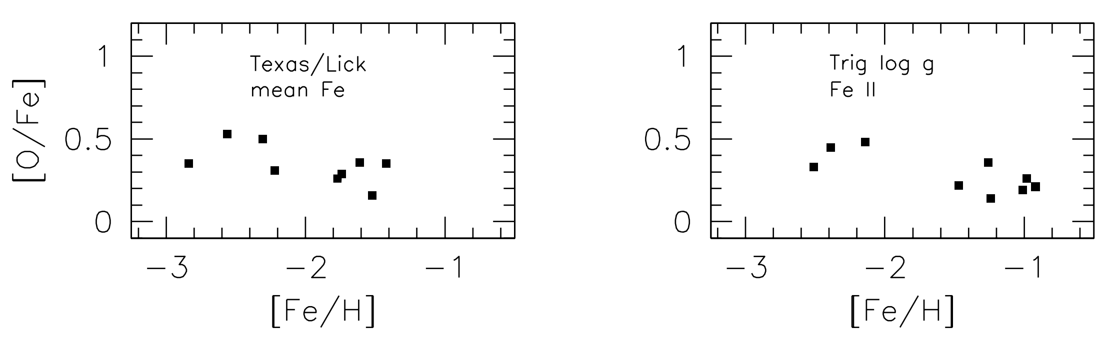

FIG. 5.—The left-hand panel plots the [O/Fe] vs. [Fe/H] relation defined by the raw L-T data listed in the top of Table 1. The right-hand panel plots the relation using the [O I] and Fe II results assuming our "extreme" trigonometric gravities.

and the evolutionary calculations themselves. Figure 6 suggests that, in contrast to extant metal-poor dwarf gravities, the L-T giant gravity *scale* is likely to be overestimated, not underestimated.

On the other hand, the mean difference between the corrected trigonometric gravities and the literature values (LK − lit) is $+0.159 \pm 0.096$ (m.e.) dex. This difference is marginal and may be due in part to metallicity effects. For L-T values alone, the difference is $+0.32 \pm 0.09$ dex. Sneden et al. (1991) assumed negligible metallicity effects in estimating gravities from the M92 fiducial, but this may not be the case since the $[Z/H] = -1.7$ isochrone (long dashed line) lies ~ 0.2 dex in log g below the $[Z/H] = -2.0$ model. Indeed, We find the L-T values to be in better agreement with the isochrones after accounting for metallicity effects. Exceptions are three of the four stars with $\pi/\sigma_\pi \geq 5$. The difference between the trigonometric and ionization-based gravities also appears to be insignificant, $+0.15 \pm 0.18$ dex, and the latter also are closer to the isochrone values. At present, these limited comparisons suggest that systematic errors in the L-T gravities (and probably the other studies) seem limited to $\lesssim 0.2$ dex star-to-star uncertainties may be larger, however.

6.2.1. *Cluster Subgiant versus Giant Abundances*

Overionization effects on metal-poor giants can be empirically gauged by comparing Fe I giant abundances in M92 from Sneden et al. (1991) with those for mildly evolved M92 subgiants by King et al. (1998). The latter are similar in metallicity and evolutionary status to HD 140283, BD +26 3578, BD −10 388, and NLTT R740 in Table 1 of TI99, which suggests overionization effects of 0.3 dex on the Fe I abundances. Indeed, the King et al. abundances are almost exactly 0.3 dex larger than the giant values. The inference that metal-poor giants suffer negligible overionization effects relative to dwarfs may be illusory, however, since King et al. note that the difference with the giant results can be nearly exactly accounted for by differences in model atmospheres, atomic data, and instrumental effects. This would then suggest that overionization effects in the bright cluster giants must be similar to those in slightly evolved subgiants. While remaining uncertainties in this comparison noted by King et al. still need to be clarified, at present it appears that overionization effects in metal-poor giants are no larger than those for dwarfs. An appendix presents two peripheral notes on M13 giant abundances.

7. REMAINING UNCERTAINTIES AND FUTURE WORK

Remaining uncertainties that may affect stellar [O/Fe] ratios need clarification. First are NLTE effects on O abundances. Kiselman's (1991) calculations suggest substantial NLTE effects on the λ7774 O I abundances—with metal-poor corrections for a 6000 K star with log $g = 4.0$ and $[O/Fe](LTE) = +0.5$ ranging from -0.2 to -0.7 dex. The estimates of Abia & Rebolo (1989) and Tomkin et al. (1992) suggest corrections of $\lesssim 0.1$ dex. An important point is the absence of collisional cross sections with hydrogen. If one employs collisional *rates* along the lines of Drawin (1968), this drives O I formation into near-LTE. This approach has found both criticism (Severino, Caccin, & Gomez 1993) and support (Takeda 1995).

A second source of uncertainty is the homogeneity and self-consistency of analyses. Ideally, both the O and Fe abundances would be derived from homogeneous data and analyses that employ a self-consistently derived solar abundance with which to normalize the stellar abundances. But this is not strictly the case for our reanalysis and the individual analyses used here. For example, our revised [O/Fe]-[Fe/H] relation uses (1) (adjusted) BKDV99 O abundances, but TI99 Fe values; and (2) (adjusted) NE92 O abundances, but TI99 Fe values. This means that the abundance ratios are dependent upon the adequacy of the *gf*-values and other assumptions (model atmospheres, damping, etc.). We have noted how such effects might alter the scale of the [O/Fe] ratios by a couple tenths of a dex. Gratton et al. (2000) have recently derived both O and Fe abundances in a large number of metal-poor stars. The comparisons in their § 6.3 illustrate the potential for at least 0.2 dex [O/Fe] offsets arising from use of inhomogeneous sources of O and Fe. Their results (their Fig. 9) may illustrate the value in using self-consistently determined O and Fe abundances.

Given complete homogeneity and self-consistency, a third uncertainty remains the adequacy of model atmospheres—particularly for giants versus dwarfs. For example, effects of chromospheres on O and Fe abundances is not well known. Takeda (1995) suggests the temperature rise may be important for solar O I line formation. McWilliam et al. (1995) have discussed possible 0.1 dex differences in (LTE) metal-poor giant Fe abundances due to both model atmosphere differences and inclusion of chromospheric T-τ structure. While Kiselman & Nordlund (1995) have considered the line formation of OH and O I features in the Sun using three-dimensional hydrodynamic models, similar studies of convective inhomogeneities in metal-poor stars are not available. Interestingly, the simple two-stream calculations for the cool metal-poor dwarf Gmb 1830 by Tomkin et al. (1992) indicate inhomogeneities may raise [O I]–based abundances and lower the O I values; this is in the sense needed to account for the [O I]–O I discrepancy.

Finally, there is the issue of excitation. While overionization may be an effective means, supported by recent calculations, to bring spectroscopic and trigonometric gravities of metal-poor dwarfs into agreement, it is not the only means. In particular, an increase in metal-poor $T_{\rm eff}$ values, advocated by Gratton et al. (1996), AFG95, and King (1993), would increase the derived Fe I abundances, and hence the gravities needed to produce larger matching Fe II abundances. Metal-poor dwarf $T_{\rm eff}$ values suggested by the above authors are typically some 100–150 K larger than the values used in the TI99 analysis.

We noted above that AFG95 parameter/Fe values yield trends in TLLS's O I–based [O/Fe] and C I–based [C/Fe] ratios with $T_{\rm eff}$. Inspection of Figures 1 and 4 indicates that AFG95's parameters/Fe also lead to distinctly different slopes in BKDV99's O I– and OH-based [O/Fe]-[Fe/H] plane (not seen with the TI99 or BKDV99 parameters/Fe), and both are very different from the [O I]–based giant relation. Are these indictments against the adoption of both higher $T_{\rm eff}$ and overionization corrections (at least as formulated in AFG95)? Perhaps, but not a conclusive one, since the ratios depend on the consistency of the TLLS and AFG95 model atmospheres and analysis. Additionally, in Figure 7 we plot the $T_{\rm eff}$ and log g differences for metal-poor stars ($[Fe/H] \leq -1.5$) in common to TI99 and AFG95. Several things are to be noted. First, is the clear offset in $T_{\rm eff}$. Including more metal-rich stars, though, gives a near-zero mean offset. Thus, not only are $T_{\rm eff}$ *scales* at

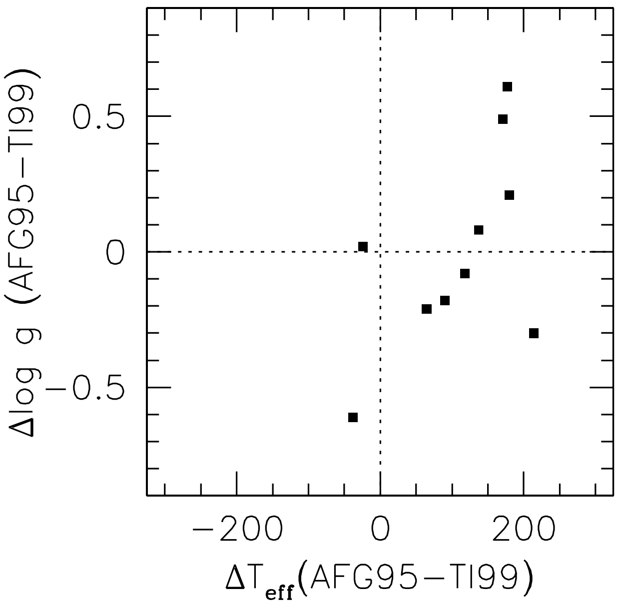

FIG. 7.—Differences in NLTE gravity from AFG95 and TI99 are plotted against $T_{\rm eff}$ differences for metal-poor ([Fe/H] ≤ -1.5) stars in common.

issue, but their variation with [Fe/H]. Second, a significant fraction of the stars have positive $T_{\rm eff}$ differences, but negative log g differences, which is unexpected. Third, there is large scatter that persists when including more metal-rich stars. The four stars with positive $\Delta T_{\rm eff}$ of 160–225 K show a Δ log g spread of 0.9 dex; the star with $\Delta T_{\rm eff}$ of only ~ -50 K shows a large log difference of -0.6 dex. The point is that the study-to-study log g and Fe differences do not depend just on $T_{\rm eff}$ differences. Rather, there must be lingering significant uncertainties (in one or both analyses) and/or other analysis differences (e.g., atmospheric structure). Until these are sorted out, definitive stellar parameters and abundances await.

A few additional puzzles persist. First, evolved M13 stars display an [O I]–O I discrepancy in the opposite sense of field stars. Pilachowski & Armandroff (1996; hereafter PA96) combined medium-resolution spectra of the λ7774 O I triplet in 40 evolved M13 subgiants to derive an upper limit on the average [O/Fe] ratio, presumably little affected by deep mixing in these stars, of $\lesssim -0.1$. In their study of mostly evolved metal-poor stars similar to the M13 stars, Cavallo et al. (1997) conclude that the O I triplet yields abundances ~ 0.5 dex too large—most likely due to NLTE effects. If so, the PA96 upper limit must be reduced to [O/Fe] $\lesssim -0.6$. The PA96 stars are characterized by $T_{\rm eff} = 5300$ and log $g = 3.0$. However, the O I–based [O/Fe] upper limit is nearly a full dex *below* the [O I]–based values of low-Na M13 giants with $T_{\rm eff} \gtrsim 4300$ (Kraft et al. 1997). Second, [O I]–based [O/H] values for Hyades giants appear to be 0.2–0.3 dex lower than those estimated for Hyades dwarfs from the same [O I] feature (King & Hiltgen 1996) and the λ8664 O I lines (Takeda et al. 1998); comparison with dwarf λ7774 O I results (e.g., García Lopez et al. 1993) is unsettled (King & Hiltgen 1996).

8. A REVISED [O/Fe]-[Fe/H] RELATION

Despite remaining uncertainties, we attempt to derive a reliable estimate of the [O/Fe]-[Fe/H] relation from extant data. Of course, this depends on educated guesses and the underlying assumptions made. Additionally, it does not deny the existence of multiple relations or structure within a relation defined by, e.g., kinematically or spatially distinct subpopulations. We begin by including the L-T field giant data from Figure 1 owing to the perceived (rightly or not) reliability of the [O I]–based determinations and the lack of convincing evidence for overionization effects in their parameters. Moreover, we showed that even large log g deviations yield [O/Fe II]–[Fe II/H] relations determined with R. L. Kurucz (1992, private communication) model atmospheres, used for the rest of our sample, that are indistinguishable from the L-T results (Fig. 5).

We omit high-excitation O I data owing to the large scatter at a given [Fe/H] seen in Figures 2 and 4, and the possibility of remaining trends with $T_{\rm eff}$. Table 2 contains O abundances of five little-evolved stars from the λ6300 [O I] line (see below), near-UV OH features (BKDV99), and the O I triplet (BKDV99)—all adjusted for the TI99 parameters. The mean difference between the molecular and forbidden values (former minus the latter) is $+0.022 \pm 0.116$ (m.e.) dex; that for the permitted and forbidden results, though, is $+0.242 \pm 0.049$ dex. Until the cause of the scatter, possible trends, and offset is understood, we prefer the OH values over the O I ones. To the extent that the TI99 results are in more satisfactory agreement with *Hipparcos* gravities, we have adopted their parameter/Fe values in making adjustments to the BKDV99 OH results; whether these values differ from previous ones because of overionization effects or errant $T_{\rm eff}$ values is unimportant for the gravity and Fe values; uncertainty in $T_{\rm eff}$ still affects [O/Fe], though. $T_{\rm eff}$-induced errors in O and Fe are correlated, so that 100 K deviations alter the [O/Fe] ratios by ~ 0.09 dex. At present, one simply accepts a resulting ~ 0.15 dex uncertainty in the metal-poor OH-based metal-poor ratios; [Fe/H]-dependent $T_{\rm eff}$ scale differences may give [O/Fe] offsets across the full [Fe/H] range as large as 0.3 dex.

TABLE 2

O ABUNDANCE COMPARISON

Star	$T_{\rm eff}$ TI99	log g NLTE	[Fe/H] NLTE	[[O I]/H] Tab. 4	[OH/H] BKDV99/TI99	[O I/H] BKDV99/TI99
HD 76932	5861	3.75	−0.79	−0.64	−0.40	−0.45
HD 82328	6380	4.23	−0.05	−0.05	+0.16	+0.21
HD 103095......	4990	4.77	−1.19	−0.81	−1.11	−0.71
HD 134169......	5794	4.06	−0.68	−0.62	−0.53	−0.29
HD 184499......	5663	4.18	−0.59	−0.27	−0.40	+0.06

Finally, we sought to include metal-rich stars to provide information on [O/Fe] at high [Fe/H]. The work of Edvardsson et al. (1993) provides O and Fe abundances for numerous F- and G-type disk dwarfs. However, these are based on the high-excitation λ6158 and λ7774 O I features. They thus corrected their [O/Fe] ratios according to [O/Fe] itself in order to match ratios derived from the λ6300 [O I] feature for 20 stars in common. The sensitivity of the O I abundances to atmosphere differences, and thus the accuracy of [O/Fe]-based NLTE corrections, has been discussed by King & Boesgaard (1995). Since the Edvardsson et al. (1993) [O/Fe]-[Fe/H] relation is essentially forced to the [O I] results of Nissen & Edvardsson (1992; hereafter NE92), we have simply reanalyzed NE92 stars in common with TI99 using the latter's parameter/Fe values. Calculations were carried out in MOOG using the Kurucz atmospheres. The results are given in Table 3; we note that solar normalization has been achieved using log $N(O)_{\odot} = 8.93$ derived from NE92's mean solar equivalent width.

The final sample is shown in Figure 8. Because (1) no clear break is apparent in the [O/Fe]-[Fe/H] relation, (2) the field giant and OH/dwarf data both suggest rising [O/Fe] with declining [Fe/H] in the metal-poor regime, and (3) statistical tests following King (1994a) show that fits with break points around [Fe/H] ∼ −1 are slightly worse (though not significantly so) than a single linear fit to all the data, we have simply fitted a linear relation to all the data. Analytic and bootstrap and jackknife resampling ordinary least-squares fits all give [O/Fe] = −0.184(±0.022) × [Fe/H] + 0.019(±0.029). Least-squares bisector fits yield [O/Fe] = −0.272(±0.025) × [Fe/H] − 0.102(±0.038). The rms scatter about the ordinary least-squares fit is a satisfying 0.128 dex.

Westin et al. (2000) have recently determined λ6300.3 [O I]–based [O/Fe] values in the very metal-poor giants HD 122563 ([Fe/H] = −2.74) and HD 115444 ([Fe/H] = −2.99) from high-resolution, very high S/N spectra. The ratios, +0.61 and +0.66 respectively, are in very good agreement with our derived relation and seem to confirm the modest rise in [O/Fe] from [Fe/H] ∼ −1.5 to ∼ −3. The rising [O/Fe] with declining [Fe/H] is similar to the average (though more complex) morphology of the Galactic chemical evolution models of Timmes et al. (1995; their Fig. 11), whose nonconstant [O/Fe] ratio at low [Fe/H] is due to small metallicity and mass dependences of the employed yields. The fitted [O/Fe] ratios in Figure 8 are ∼0.10 dex larger than the Timmes et al. model; these small differences seem easily accommodated by uncertainty in the Fe yields, or lingering systematic effects in the data.

Gratton et al. (2000) have recently derived self consistent Fe and O I– and [O I]–based O abundances in a large sample of metal-poor stars with $-2 \lesssim$ [Fe/H] $\lesssim -1$ and spanning a range of evolutionary states from the main sequence to the upper RGB and HB. After applying small NLTE corrections (<0.2 dex) to the O I–based abundances, they find good agreement between these and the forbidden line–based values (the former are only +0.08 dex larger on average). Over the above limited metallicity range, their [O/Fe]-[Fe/H] relation (see their Fig. 9) is nearly indistinguishable from that in Figure 8, with their [O/Fe] values perhaps typically 0.1 dex larger at the metal-rich end. As the

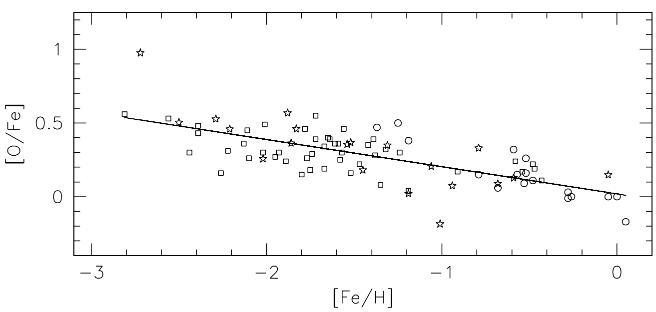

FIG. 8.—[O/Fe] vs. [Fe/H] for our final sample, which comprises the [O I]–based L-T field giants (*squares*) in Fig. 1, the OH-based BKDV99/TI99 results shown in Fig. 4 (*stars*), and the reanalyzed NE92 [O I] data using TI99 parameter/Fe values (*circles*; includes the Sun at [Fe/H] = [O/Fe] = 0). The solid line is the ordinary least-squares fit.

TABLE 3

[O I] DATA AND REANALYSIS

Star	T_{eff} TI99	log g NLTE	[Fe/H] NLTE	ξ (km s^{-1})	W([O I]) (mÅ)	References	[O/Fe]
HD 48938	6073	4.28	−0.26	1.0	3.7	1	+0.00
HD 59984	6000	4.44	−0.52	1.0	3.9	1	+0.26
HD 61421	6632	4.00	+0.05	1.7	3.7	1	−0.17
HD 63077	5728	4.36	−0.53	1.0	3.3	1	+0.09
HD 76932	5861	3.75	−0.79	1.0	3.8	1	+0.15
HD 82328	6380	4.23	−0.05	1.2	4.7	2	+0.00
HD 89707	6000	4.49	−0.28	1.0	3.3	1	+0.03
HD 98553	5930	4.50	−0.28	1.0	3.1	1	−0.01
HD 103095......	4990	4.77	−1.19	1.2	2.0	3	+0.38
HD 130551......	6222	4.32	−0.48	1.0	2.8	1	+0.11
HD 132475......	5479	3.88	−1.37	0.8	3.3	3	+0.47
HD 134169......	5794	4.06	−0.68	1.0	3.0	3	+0.06
HD 160693......	5728	4.21	−0.52	1.0	4.5	3	+0.16
HD 184499......	5663	4.18	−0.59	1.0	6.0	3	+0.32
HD 203608......	6073	4.54	−0.57	0.9	3.	4	+0.15
HD 211998......	5196	3.74	−1.25	1.2	6.1	4, 5	+0.50

REFERENCES.—(1) Nissen & Edvardsson 1992; (2) Clegg, Lambert, & Tomkin 1981; (3) Spite & Spite 1991; (4) Barbuy & Erdelyi-Mendes 1989; (5) Gratton & Ortolani 1986.

referee notes, their similar results are achieved in a different manner—not via considering overionization effects on Fe in metal-poor giants or discarding O I data owing to perceived large systematic errors, but rather through a specific choice of model atmosphere parameters ($T_{\rm eff}$ in particular) and self-consistent determination of O and Fe abundances. This emphasizes the previous remarks concerning the potential degeneracy of $T_{\rm eff}$ scales and inference of NLTE effects, and the possible dangers of combining inhomogeneously derived abundances of different elements to form abundance ratios.

9. SUMMARY AND CONCLUSIONS

We have considered the effects of TI99's and AFG95's NLTE gravities and Fe abundances on [O/Fe] and [C/Fe] ratios determined in the studies of BKDV99 and TLLS. Comparison of (1) BKDV99's and TLLS's O I–based [O/Fe] ratios and (2) BKDV99's OH-based and TLLS's CH-based "expected" [O/Fe] ratios uncovers study-to-study differences that persist in the revised ratios estimated using the same NLTE parameter/Fe values. Better understanding of such differences (presumably reflecting other assumptions—atmospheres, atomic data, solar normalization, etc.—in the analyses) is needed to derive confident abundances—even with perfect knowledge of fundamental stellar parameters.

Within the TLLS study, the NLTE parameter/Fe values reduced or eliminated the well-known discrepancy between CH-based and C I–based [C/Fe] ratios. The TI99 values eliminate the trend in TLLS's atomic-based [C/Fe] and [O/Fe] ratios with $T_{\rm eff}$. The NLTE parameter/Fe values still result in a rise in CH-based [C/Fe] with declining [Fe/H], probably shown by the revised atomic results, too. The NLTE parameter/Fe values maintain TLLS's flat atomic-based [O/Fe]-[Fe/H] morphology, but with substantially lower values of [O/Fe] $\sim$ 0.3–0.5. This represents greatly improved agreement with [O I]–based field giant results, which show a significant slope, however.

Within the BKDV99 study, the NLTE parameter/Fe values significantly reduce the discrepancy between the mean OH- and O I–based [O/Fe] ratios and those of the L-T field giants, though the former remain 0.1–0.2 dex higher. The data are too limited to elucidate clearly the revised [O/Fe]-[Fe/H] morphology, though a rise between [Fe/H] $= -1$ and -2 seems indicated—perhaps with increased scatter. Like TLLS's C I and CH results, most of BKDV99's O I and OH abundances move into improved agreement using the NLTE parameter/Fe values. A large minority ($\sim$30%) of points, though, show no improvement or a larger discrepancy; the revised O I data show large scatter relative to the OH results. The cause is unclear.

As gauged from TLLS's atomic-based [C/O] ratios, the raw and revised BKDV99 and TLLS OH and CH results are consistent in that both show an increase with declining [Fe/H] of similar slope. The NLTE parameter/Fe values do not change this. However, we infer a 0.2 dex offset between the TLLS and BKDV99 results, which persists using the same NLTE parameters; this is likely due to other differences in the two analyses.

We considered systematic errors in the gravities of metal-poor red giants from *Hipparcos*-based trigonometric log g values. The trigonometric results and comparison of M92 giant and near-turnoff Fe I abundances may suggest that the L-T gravities are modestly underestimated. However, comparison with theoretical isochrones suggest they may be modestly (0.2 dex) overestimated; this is also supported by the M92 distance inferred from field subdwarf parallaxes. Regardless, the [O I]–/Fe II–based [O/Fe] ratios rederived from the L-T data assuming extreme log g adjustments leave the [O/Fe]-[Fe/H] relation manifested by the raw L-T data unaltered.

Uncertainties remain in the reliable determination of stellar parameters and O and Fe abundances. Particularly important are clarification of NLTE effects and adequacy of model photospheres on the O abundances. The issue of stellar $T_{\rm eff}$ scales and their variation with [Fe/H] is also important, but at present still clouded. Finally, inconsistencies between (1) the BKDV99 and TLLS molecular O and C abundances, and (2) even after accounting for $T_{\rm eff}$ differences, comparison of the TI99 and AFG95 gravities indicates that assumptions in different analyses easily lead to abundance differences of several tenths of a dex even when adopting identical underlying parameters.

We suggest that the L-T field giant [O I]–based, BKDV99/TI99 dwarf OH-based, and NE92/TI99 dwarf [O I]–based data are the most reliable of the studies considered here with which to establish the [O/Fe]-[Fe/H] relation. Combining these data reveals a linear relation with no evidence of a slope change at intermediate [Fe/H]. Least-squares fits yield [O/Fe] $= -0.184(\pm 0.022) \times$ [Fe/H] $+ 0.019(\pm 0.029)$ with a modest rms scatter of 0.128 dex; systematic errors surely dominate the formal uncertainties. This gentle slope is similar to the chemical evolution models of Timmes et al. (1995), though our metal-poor [O/Fe] ratios are typically 0.10 dex larger than suggested there. Whether other α-element ratios agree with the O results when utilizing similar NLTE parameter/Fe values remains to be explored.

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APPENDIX

TWO PERIPHERAL NOTES ON M13 GIANT ABUNDANCES

We make two notes with peripheral relation to the above issues but of potential interest to others. The first concerns correlation of abundances in M13 giants. Figure 9 plots the Kraft et al. (1997) cluster giant Fe abundances versus those of other elements. Marked correlations between Fe and Na, Ca, and Sc are seen, as are anticorrelations between Fe and O and Mg. A frequent exception is the most Fe-rich star, L337. Excluding this case, notable correlations are also apparent between Fe and Al and Si. The correlations with Ca, Si, and Sc might be caused by correlated measurement errors but would not explain the anticorrelations with O and Mg. The abundance sensitivities indicate that parameter errors are unable to explain

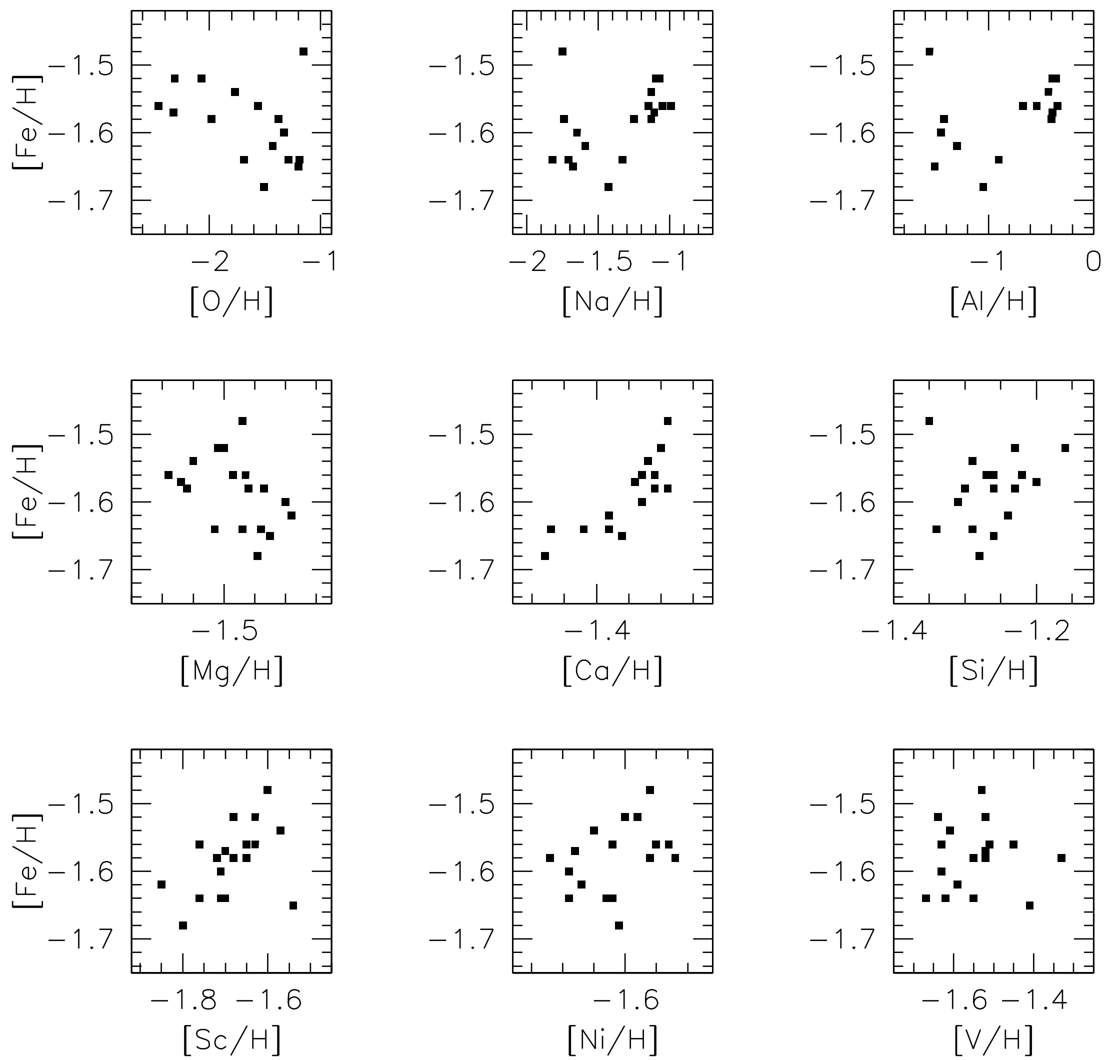

FIG. 9.—The M13 Fe abundances from Kraft et al. (1997) vs. their abundances of other light elements

opposing trends with, e.g., Na or Al and Mg. Intrinsic variations (in the nascent gas or due to self-enrichment) are unattractive given the correlations with Ca and Si, but anticorrelations with the other α elements Mg and O. An intriguing possibility is that in situ deep mixing alters the photospheric structure, and thus the derived abundances. If so, then field giants are likely little affected since their O, Na, Mg, Al abundance patterns are distinct from cluster giants (Kraft 1994).

The second note concerns the M13 giants' spatial distribution and Na abundances. If cluster angular momentum were coupled to its individual stars, this might provide a basis for understanding in situ mixing in the latter. The relation between CN indices and cluster flattenings (presumably reflecting cluster rotation) found by Norris (1987) may implicate such a coupling. However, Kraft (1994) notes a coupling's existence and specific mechanism remain unclear.

We considered giants in the M13 Na study of Pilachowski et al. (1996b; hereafter PSKL) with radial velocities from Lupton, Gunn, & Griffin (1987), excluding objects noted as "AGB" and "AGB?" by PSKL as well as the few stars at the RGB tip ($\log g < 1.5$) to avoid possible errors from pulsation. The data were divided into "high" and "low" [Na/Fe] samples of similar number using two cuts. The first defined 23 high- and 22 low-Na stars by [Na/Fe] $\geq +0.14$ and $\leq +0.11$. A more restrictive cut used [Na/Fe] $\geq +0.31$ (14 stars) and ≤ -0.01 (13 stars). The [Na/Fe] values represent variations in [Na/H] alone since PSKL adopted a single Fe abundance for all stars.

Using a K-S test, we compared the cumulative distributions of radial velocity (Figs. 10*a* and 10*b*). The significance of the distributions' differences is large (86% and 81% confidence levels), though marginally significant at best. Comparison of the Na samples' *Y* (north-south) distance (Figs. 10*c* and 10*d*) is more interesting. These differences are significant at the 98.7% and 97.1% confidence levels, but no significant differences are seen in east-west distance from cluster center. The marginal radial velocity and significant north-south position differences might be related via cluster rotation if the position angle of the isophotal semimajor axis is aligned to the north-south axis. This is unclear. At our typical cluster center distances, Figure 4 of Kadla et al. (1976) indicates an angle near $\sim 115°$; however, Lupton et al. (1987) suggest a higher value of 130°.

The differences in the cumulative distributions do not seem to reflect central concentration differences, but (projected) spatial position along one axis. Given typical cluster crossing times of $\sim 10^5$ yr (e.g., Binney & Tremaine 1987), one might

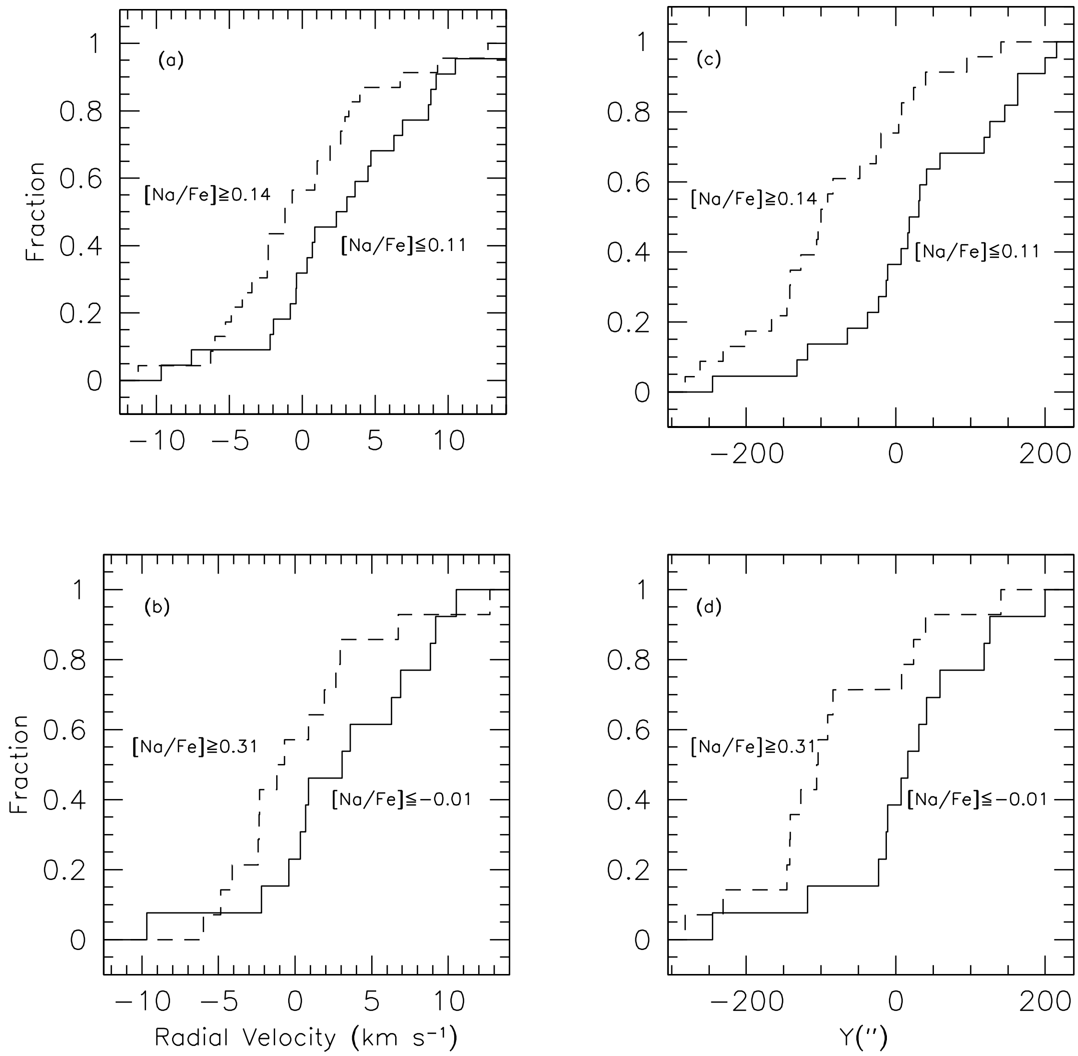

FIG. 10.—Cumulative distributions in radial velocity (*a* and *b*) and north-south cluster location (*c* and *d*) for two differently defined high- and low-Na abundance samples of M13 giants from PSKL.

expect that stellar orbits and encounters have spatially mixed the presumably identical mass M13 Na-poor and -rich giants. It is unclear why the two samples show a spatial difference.

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