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OXYGEN IN UNEVOLVED METAL-POOR STARS FROM KECK ULTRAVIOLET HIRES SPECTRA

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ABSTRACT

The determination of the abundance of oxygen (O) is important in our understanding of mass–spectrum of previous generations of stars, the evolution of the Galaxy, stellar evolution, and the age-metallicity relation. We have measured O in 24 *unevolved* stars with Keck HIRES observations of the OH lines in the ultraviolet spectral region at a spectral resolution of $\sim$45,000. The spectra have high signal-to-noise ratios, typically 60–110, and high dispersion, 0.022 Å per pixel. Very special care has been taken in determining the stellar parameters in a consistent way and we have done this for two different, plausible temperature scales. The O abundance from OH has been computed by spectrum synthesis techniques for all 24 stars plus the Sun for which we have a Keck spectrum of the daytime sky. In addition, we determined O abundances from the O I triplet with our stellar parameters and the published equivalent widths of the three O I lines from six sources. The comparison of data analyzed with the same, consistently determined, parameter sets show generally excellent agreement in the O abundances; differences in the origin of the models (not the parameters) may result in abundance differences of 0.07 to 0.11 dex. We show that the O abundances from OH and from O I are reliable and independent and average the two for the adopted O. This averaging has the great benefit of neutralizing uncertainties in the parameters since OH and O I strengths depend on effective temperature and gravity in opposite directions. For these cool, unevolved stars we find that O is enhanced relative to Fe with a completely linear relation between [O/H] and [Fe/H] over 3 orders of magnitude with very little scatter; taking the errors into account in determining the fits, we find [O/H] = +0.66 (±0.02) [Fe/H] + 0.05 (±0.04). The O abundances from 76 disk stars of Edvardsson et al. have a measured slope of 0.66 (identical to our halo dwarf stars) and fit this relationship smoothly. The relation between [O/Fe] and [Fe/H] is robustly linear and shows no sign of a break at metallicities between −1.0 and −2.0, as has been discussed by others. At low metallicities, [Fe/H] < −3.0, [O/Fe] > +1.0. The fit to this relationship (taking the errors into account) is [O/Fe] = −0.35 (±0.03) [Fe/H] + 0.03 (±0.05). The enrichment of O is probably still from massive stars and Type II supernovae; however, the absence of a break in [O/Fe] versus [Fe/H] runs counter to traditional galactic evolution models, and the interplay of Type II and Type Ia supernovae in the production of O and Fe should be reexamined. It appears that either Fe or O can be used as a chronometer in studies of galactic evolution.

Key words: Galaxy: evolution — Galaxy: halo — stars: abundances — stars: atmospheres — stars: Population II

1. INTRODUCTION

The elements carbon, nitrogen, and oxygen (CNO) are very important to our understanding of stellar and galactic evolution because they are the most abundant of the heavy elements. They help determine stellar energy production rates and interior stellar opacities. The amounts of these elements in stars of different ages or metallicities provide important clues needed to trace the mass spectrum of previous generations of stars. Tracing the production of O throughout the Galaxy also helps to document the extent of chemical mixing in the Galactic disk. Oxygen is the result of α-processing in the interiors of massive stars. The trends of [O/H] and [O/Fe] with [Fe/H] for field stars can reveal the chemical history of the Galaxy. These relations of O and of other alpha-elements with [Fe/H] have been displayed and discussed in the review by Wheeler, Sneden, & Truran (1989), and in papers by Edvardsson et al. (1993) and Tomkin et al. (1992), among others.

Conti et al. (1967) found evidence that suggested that O was enhanced compared to Fe in metal-deficient stars. Higher than solar [O/Fe] values were also found by Lambert, Sneden, & Ries (1974) and Sneden, Lambert, & Whitaker (1979) in low-metallicity stars. Clegg, Lambert, & Tomkin (1981) showed the trend of increasing [O/Fe] with decreasing metallicity in an important paper on abundances in unevolved disk stars. Whereas high-mass stars are the source of O production, stars of a variety of masses can produce Fe. Observations of the abundances of O and Fe in unevolved stars in both the Galactic disk and halo yield very

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interesting trends of [O/H] and [O/Fe] with [Fe/H]: over a wide metallicity range, $-0.5 \geq [Fe/H] \geq -3.0$, O is more abundant than Fe relative to the solar ratio (Sneden et al. 1979; Abia & Rebolo 1989; Bessell, Sutherland, & Ruan 1991, hereafter BSR; Tomkin et al. 1992; Edvardsson et al. 1993; Boesgaard & King 1993; Nissen et al. 1994, hereafter NGEG; Cavallo, Pilachowski, & Rebolo 1997; Isrealian, García-López, & Rebolo 1998). Most of these studies have used the high-excitation O I triplet at 7774 Å and concerns have been raised due to the probable presence of non-LTE effects and convective inhomogeneities in the formation of the triplet, at least for the hotter stars and those that are more metal-rich or have low gravities (see, e.g., Johnson, Milkey, & Ramsey 1974; García-López et al. 1993; Kiselman 1991, 1993; Kiselman & Nordlund 1995).

An important reason to determine O abundances is to determine the age-metallicity relation in the Galaxy. The most abundant metal in stars is O. Although metallicity is usually found from [Fe/H] because Fe has numerous spectral features, it does not show a secure age-metallicity relation (see Wheeler, Sneden, & Truran 1989 for a discussion of this point). There are both empirical and nucleosynthetic arguments against the use of [Fe/H] as a chronometer. Twarog's (1980) seminal data and work on the age-metallicity relation were revisited by Carlberg et al. (1985) and by Nissen, Edvardsson, & Gustafsson (1985). Over 12 Gyr the average [Fe/H] increases by perhaps a factor of 6 but there is a large spread at a given age. Nissen (1988) has used Strömgren photometry and Boesgaard (1989) and Boesgaard & Friel (1990) have used high-resolution spectroscopy of stars in open clusters to look at the metallicity in objects of known age. In fact, between 50 Myr and 2 Gyr ago there is no trend of [Fe/H] with age; differences that do exist may result from the place of origin of the clusters and variations in the local star formation rates. The nucleosynthesis of Fe occurs in two major ways: stellar core collapse in high-mass stars and thermonuclear reactions in low-mass stars. The synthesis of Fe by the *e*-process occurs in several different astrophysical environments (Wallerstein et al. 1997). Since O is synthesized in massive stars (one source), Wheeler, Sneden, & Truran argue that it would make a better chronometer.

The enhancement of O relative to Fe in unevolved, metal-poor halo stars is regarded as a signature of supernovae of massive, short-lived stars, Type II supernovae. As Type Ia supernovae (the explosive events caused by mass transfer onto white dwarfs in binary systems from long-lived, low-mass progenitors) begin to occur, more Fe will be synthesized. If the halo is formed over several Gyr, then the increase in Type Ia supernovae with the concomitant increase in Fe should result in a decrease in [O/Fe] with age. However, armed with field star ages determined from Strömgren photometry by Schuster & Nissen (1989b) and Marquez & Schuster (1994), Laird & Sneden (1996) examined a sample of halo stars near the main-sequence turn-off stars and did not find the expected correlation between [O/Fe] and age over an age range of 10–20 Gyr.

Oxygen abundances have been determined from the O I triplet at 7774 Å (see, e.g., Tomkin et al. 1992), from the forbidden lines of [O I] at 6300 and 6363 Å (see, e.g., Barbuy 1988; Kraft et al. 1992), and from the OH lines in the ultraviolet near 3100 Å (see, e.g., BSR; NGEG). Disagreements have been found in the trends of O versus Fe between the giants (determined from [O I]) and dwarfs (mostly determined from the triplet). King & Boesgaard (1995) observed 18 relatively metal-rich F and G dwarfs in both O I and [O I] and collected literature data for some 30 additional stars; they derived stellar parameters for all the stars and analyzed them consistently. They conclude that for $T_{\rm eff} \leq 6250$ there is no significant difference between the O I and [O I] abundances; for higher temperatures the O abundance from the permitted lines is significantly larger than that from the forbidden line. Part of the difference in the O trend with Fe between the dwarfs and giants may be due to the fact that the surface material in the giants may have been "processed," and reflects the changes in the core composition. In addition, there is evidence that that surface oxygen in halo giants may have been processed as follows. Lithium observations in halo subgiants (Pilachowski, Sneden, & Booth 1993) form a well-defined (Ryan & Deliyannis 1995) diluted Li plateau down to $T_{\rm eff} = 5000$ K, consistent with standard theory. However, below this $T_{\rm eff}$, the Li abundances of all halo giants, observed so far plummet. Furthermore, the $^{12}C/^{13}C$ ratio also plummets there, from its diluted value of 40–60 all the way down to the CN–cycle equilibrium ratio of 4 (Sneden, Pilachowski, & Vandenberg 1986). These abrupt abundance declines suggest the action of an additional (nonconvective) mixing mechanism that brings surface material in contact with the CNO nucleosynthesis regions. (For more details on this and also implications for ^{3}He destruction and the D + ^{3}He constraint in big bang nucleosynthesis, see Deliyannis 1995.) In addition, there is evidence from globular cluster data that surface O gets processed to N on the giant branch (Kraft 1994; Kraft et al. 1997).

Accurate and consistently determined O abundances are needed. We have done two things to improve the situation. (1) We have taken exceptional care in determining the physical parameters for our stars in a self-consistent way. (2) Our Keck/HIRES data set improves the data quality with high signal-to-noise spectra for 24 unevolved halo and disk dwarfs and expands the number of halo stars with O abundances determined from the UV OH lines. In addition, we determine O abundances from the O I triplet from published equivalent widths. We argue that the mean value for O/H from these two methods should be used and that it shows an exceptionally tight correlation with Fe/H over 3 orders of magnitude of [Fe/H]. Furthermore, we show that the trend of [O/Fe] versus [Fe/H] is starkly linear, with no break at moderately low metallicities (-1.0 to -1.5), and [O/Fe] reaches a value of $+1.2$ at [Fe/H] $= -3.0$.

2. OBSERVATIONS AND ANALYSIS

We have made Keck/HIRES observations of 23 unevolved metal-poor stars taken from five different observing runs with the Keck HIRES spectrometer (Vogt et al. 1994); this includes one star observed for us on a Keck engineering/service run. Although the spectra were obtained as part of our program to determine Be abundances, we are able to determine O abundances from the OH features longward of the Be II resonance lines. The details of the observations appear in that paper on Be (Boesgaard et al. 1999). In addition to the spectra of the metal-poor stars, we took exposures of the daytime sky as a solar spectrum and of HR 3775, another solar-like star. The spectral range in the order where the Be II and the OH lines occur is approximately 3102–3147 Å. The S/N ratios per pixel for our data in this order is 45–175, typically 60–110 with an average value of 95. (S/N ratios were determined empirically from the flux measurements.) This is considerably higher than previous studies of the UV OH lines: the S/N for BSR was 20, the S/N for NGEG was 30 per resolution element and the S/N for Israelian et al. (1998) was 30–50.

Table 1 gives information about the observational data: the star names, the V magnitude, $B-V$, the date(s) of the observation(s), the total exposure time, and the total S/N in the order where the OH lines occur.

The IRAF reductions used imported FIGARO routines; the procedures are described in Boesgaard et al. (1998, 1999). Nightly master flat and master bias frames were made from multiple flat field and bias exposures taken each night, and these were applied to the stellar frames. The Th-Ar nightly comparison spectra was used to determine the dispersion solutions from low-order Legendre polynomial fits to hundreds of lines. The effective resolution was ~45,000 as determined from the measured FWHM for the comparison lines and a measured dispersion of 0.022 Å per pixel. The spectra from different times of night or from different nights/runs were co-added after determining shifts via the cross-correlation techniques in IRAF. The continuum fitting was quite straightforward for the lowest metallicity stars since there are relatively few features with strong absorption and few blends. The metal-poor star spectra could then be used as a guide to locate progressively the continua in the stars of higher metallicity. The continua were adjusted to the final value during the spectrum synthesis fitting (see below).

Various temperatures scales for metal-poor stars have been used by researchers in this field. Inasmuch as we do not know which, if any, is correct, we have chosen to use two different scales and to investigate the sensitivity of our results to the different sets of parameters that devolve from the two temperature scales. We have selected a widely used scale (whether correct or not), essentially that of Carney (1983b), for one scale. For the other we have chosen one more consistent with the Hα and other Balmer-line temperatures and the photometric temperatures of Fuhrmann, Axer, & Gehren (1995) and Gratton, Carretta, & Castelli (1996), essentially that of King (1993). Fuhrmann et al. (1995) derive temperatures from one to four Balmer lines in more than 100 dwarfs and subgiants covering a range of metallicities and note that their temperatures are generally 100–200 K hotter than those used in many abundance analyses. For the five stars we have in common our King scale temperatures agree well, with a mean difference (King − Fuhrmann et al.) of $+11 \pm 41$, while the Carney scale temperatures show a mean difference of -121 ± 38.

TABLE 1

STARS OBSERVED FOR OH AT KECK

Star	V	$B-V$	Nights[a]	exp (m)	S/N
HD 19445	8.05	0.46	1	20	88
HD 64090	8.30	0.62	1	20	77
HD 74000	9.67	0.42	10	60	44
HD 76932	5.83	0.53	7	10	110
HD 84937	8.32	0.39	3	45	98
HD 94028	8.23	0.47	10	20	60
HD 103095	6.45	0.75	4	15	81
HD 134169	7.69	0.53	9	25	62
HD 140283	7.21	0.49	3	60	164
HD 184499	6.61	0.58	1	25	109
HD 194598	8.35	0.48	7	60	67
HD 201889	8.06	0.59	8	30	75
HD 219617	8.16	0.49	7	30	67
HD 221377	7.57	0.39	1,2	95	176
BD +37°1458	8.92	0.60	10	75	76
BD +26°3578	9.36	0.39	5	90	88
BD +23°3912	8.88	0.51	1,2	60	66
BD +20°3603	9.75	0.39	6,10	155	90
BD +17°4708	9.47	0.44	7	90	73
BD +03°740	9.81	0.36	2,3,7,8	480	166
BD +02°3375	9.92	0.44	5	90	63
BD −04°3208	10.0	0.39	5	87	56
BD −13°3442	10.3	0.40	3	665	129
HR 3775	3.17	0.46	3	3	95
Sun	...	...	2	20	138

[a] (1) 1993 October 6; (2) 1993 October 7; (3) 1994 March 1; (4) 1994 April 28 (service); (5) 1994 June 12; (6) 1994 July 5; (7) 1994 October 26; (8) 1994 October 27; (9) 1995 March 14; (10) 1995 March 15.

The parameters for our stars have been determined in a careful and consistent way by Deliyannis et al. (1998, hereafter DBKD), and more details can be found there. We have used three different color indices as temperature indicators: $(b-y)$ values from Schuster & Nissen (1988); $(V-K)$ from Carney (1983a, 1983b), Laird, Carney, & Latham (1988), and B. W. Carney (1993, private communication); $(R-I)$ from Eggen (1978), Carney & Aaronson (1979), Carney (1980, 1983a), Laird (1985), and Ryan (1989). The primary source used to estimate reddening was $E(b-y)$ from Schuster & Nissen (1988, 1989a, 1989b); we used the Johnson (1968) relations to find the reddening appropriate for the other indices: $E(V-K) = 3.75E(b-y)$ and $E(R-I) = 1.08E(b-y)$. The temperatures from the three different color indices were weighted 4:2:1 for $T(b-y)$, $T(V-K)$, $T(R-I)$, except for the coolest stars, where we used 3:3:1. The standard deviation of the weighted mean is typically 40 K.

The metallicities, [Fe/H], were taken from published values based on high spectral resolution data. These were all put on a scale with *the same solar value* of log N(Fe/H) + 12.0 = 7.51 (Anders & Grevesse 1989). They were also *corrected for any difference between the published temperature and our temperatures*. The mean error in [Fe/H] is 0.14 dex.

The first technique to find log g values was to utilize detailed analyses in the literature, which used ionization balance to find log g (see, e.g., Magain 1989; Gratton & Sneden 1988; Tomkin et al. 1992). We then revised the log g values as appropriate to our values of temperature and [Fe/H]. In the second method we found each star's evolutionary status (dwarf, turn-off, subgiant) from $(b-y)_0$ versus c_0 diagrams and used the log g versus $T_{\rm eff}$ plane of a 17 Gyr isochrone (Green, Demarque, & King 1987) for $Y = 0.24$ and interpolated for each's star's metallicity. Also, the star's location in the Strömgren diagram of c_0 versus $(b-y)_0$ is a good indicator of log g for F and early G stars; we estimated a log g value by comparing the Strömgren indices to R. L. Kurucz's (1993, private communication) atmosphere/color grids and applying an empirical correction factor described by DBKD. The three methods were weighted 2:2:1. The mean error in log g is 0.22.

For the microturbulence we have used the Magain (1987) value for Population II stars of $\xi = 1.5$ km s^{-1}. The value of the microturbulence parameter has virtually no effect on the abundances derived for ξ between 1 and 2 km s^{-1}. For the solar model we used 1.0 km s^{-1}.

Tables 2 and 3 give the derived stellar parameters for the two temperature scales along with the associated errors.

Painstaking attention was given to determining these parameters and doing it in a completely consistent way. Inasmuch as the abundances depend on the temperature and log g fairly sensitively, it was deemed important to have this consistent set of model parameters to elucidate abundance trends.

TABLE 2

STELLAR PARAMETERS ON THE KING (1993) SCALE

Star	T_{eff} (K)	σ	log g	σ	[Fe/H]	σ
HD 19445	5996	52	4.48	0.13	−2.01	0.08
HD 64090	5478	40	4.70	0.27	−1.67	0.15
HD 74000	6249	40	4.33	0.10	−1.99	0.12
HD 76932	5943	80	4.07	0.10	−0.87	0.09
HD 84937	6307	40	4.00	0.10	−2.14	0.14
HD 94028	6043	40	4.45	0.18	−1.46	0.08
HD 103095	5133	40	4.75	0.10	−1.26	0.20
HD 134169	5900	40	3.74	0.24	−0.85	0.08
HD 140283	5847	40	3.63	0.20	−2.46	0.14
HD 184499	5670	40	4.00	0.20	−0.51	0.14
HD 194598	6042	40	4.36	0.10	−1.16	0.19
HD 201889	5693	40	3.81	0.31	−0.84	0.26
HD 219617	6011	40	4.42	0.26	−1.49	0.21
HD 221377	6327	40	3.70	0.45	−0.86	0.14
BD +37°1458......	5554	48	3.62	0.12	−2.06	0.18
BD +26°3578......	6269	51	4.04	0.22	−2.24	0.11
BD +23°3912......	5854	40	3.84	0.10	−1.41	0.16
BD +20°3603......	6234	76	4.33	0.26	−2.15	0.16
BD +17°4708......	6091	57	3.81	0.19	−1.73	0.10
BD +03°740	6227	60	3.75	0.27	−2.81	0.09
BD +02°3375......	5949	40	4.17	0.30	−2.30	0.11
BD −04°3208......	6401	113	3.94	0.34	−2.31	0.21
BD −13°3442......	6273	53	3.60	0.55	−2.94	0.08
HR 3775	6300	40	4.10	0.20	−0.17	0.10
Sun	5770	...	4.44	...	0.00	0.04

TABLE 3

STELLAR PARAMETERS ON THE CARNEY (1983) SCALE

Star	T_{eff} (K)	σ	log g	σ	[Fe/H]	σ
HD 19445	5852	40	4.41	0.23	−2.10	0.12
HD 64090	5341	40	4.73	0.10	−1.77	0.18
HD 74000	6134	40	4.26	0.10	−2.05	0.12
HD 76932	5807	40	4.00	0.12	−0.95	0.11
HD 84937	6206	40	3.89	0.13	−2.20	0.14
HD 94028	5907	64	4.44	0.17	−1.54	0.09
HD 103095	5007	40	4.65	0.15	−1.37	0.18
HD 134169	5759	82	3.68	0.16	−0.94	0.05
HD 140283	5692	40	3.47	0.13	−2.56	0.12
HD 184499	5670	40	4.00	0.15	−0.51	0.14
HD 194598	5911	42	4.32	0.13	−1.25	0.16
HD 201889	5553	41	3.74	0.24	−0.95	0.26
HD 219617	5872	40	4.52	0.15	−1.58	0.16
HD 221377	6238	40	3.70	0.45	−0.93	0.14
BD +37°1458......	5408	40	3.41	0.26	−2.14	0.17
BD +26°3578......	6158	64	3.94	0.12	−2.32	0.15
BD +23°3912......	5691	40	3.68	0.10	−1.53	0.15
BD +20°3603......	6114	89	4.27	0.20	−2.22	0.16
BD +17°4708......	5956	62	3.65	0.26	−1.81	0.10
BD +03°740	6110	82	3.64	0.33	−2.89	0.09
BD +02°3375......	5800	40	4.07	0.41	−2.39	0.17
BD −04°6316......	6316	121	3.90	0.42	−2.35	0.20
BD −13°3442......	6159	40	3.50	0.44	−3.02	0.16
HR 3775	6300	40	4.10	0.20	−0.17	0.10
Sun	5770	...	4.44	...	0.00	0.04

3. ABUNDANCE DETERMINATIONS

3.1. *Oxygen from* OH

3.1.1. O *from Spectrum Synthesis of* OH

The OH lines used for the O abundance determination are from the (0, 0) and (1, 1) band of the A $^2\Sigma$-X $^2\Pi$ system. Our observed spectral region is 3139–3147 Å, although some of the longer wavelength lines were not available in a few of the spectra. This region contains some 26 OH features (not including the OH lines that are badly obscured by blending with the C $^2\Sigma^+$-X $^2\Pi$ (0, 0) Q band of CH at 3143–3145 Å). Typically 5–9 of these lines were useful abundance discriminators, although in the most metal-poor stars with the weakest OH lines only three features could be used. We followed Nissen et al. (1994) in deriving O abundances from these lines and have used their line list in which they corrected the *gf*-values of the lines in the (0, 0) band by −0.16 dex and in the (1, 1) band by −0.49 dex. They made this adjustment in order to achieve a solar abundance of log N(O)/N(H) + 12.00 = 8.93 (Anders & Grevesse 1989; NGEG; BSR; Lambert 1978). Hereafter we use log N(O) to mean log N(O)/N(H) + 12.00. The reference solar O abundance that has been used in this work is 8.93.

We have interpolated between the R. L. Kurucz (1993, private communication) grid point model atmospheres to make models for each star for the two sets of parameters. The synthetic spectra were computed with the use of the stellar line analysis package MOOG (Sneden 1973). The line lists of NGEG contain the needed information for atomic and molecular lines: wavelength, ionization state, excitation potential, oscillator strength, and dissociation potential for the molecules. The value for the FWHM of the Gaussian profile for our Keck spectra was found to be ∼0.08 Å, with the exception of the F6 IV dwarf, HR 3775, which has a v sin i value of 12 km s^{-1} and a Gaussian of 0.15 Å.

Minor adjustments in the continuum level, never larger than a few percent, were made to bring the observed and synthetic spectra into better agreement. The O abundance was varied to find a good match with the observed spectrum. A preliminary O abundance was found from the spectrum synthesis. Then the calculation was done for three O abundances: the preliminary O abundance and ones that were a factor of 2 above and below this. The best-fitting abundance from each OH line was then interpolated, and the mean from all the lines was then determined. The errors in the mean from the different lines were ±0.07 to ±0.20, typically ±0.15. Our Keck sky spectrum was well matched to an O abundance of 8.87 ± 0.09 with the revised OH *gf*-values, in good agreement with the aforementioned solar value of 8.93. (For the solar model the microturbulence used was 1.0 km s^{-1}.) Examples of the synthesis fits to the OH lines are shown in Figure 1. Tables 4 and 5 give the temperatures, [Fe/H], and O abundances from OH for our program stars on the two T_{eff} scales.

3.1.2. *Determination of the Errors*

The errors in the O abundances from the OH lines given in Tables 4 and 5 are from the random errors in the mean O/H from the 3–9 OH features, the temperature errors shown in Tables 2 and 3, and the log g errors shown in

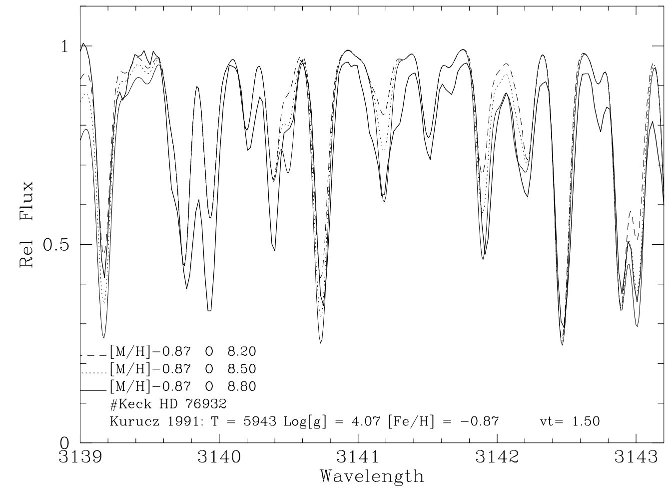

FIG. 1*a*

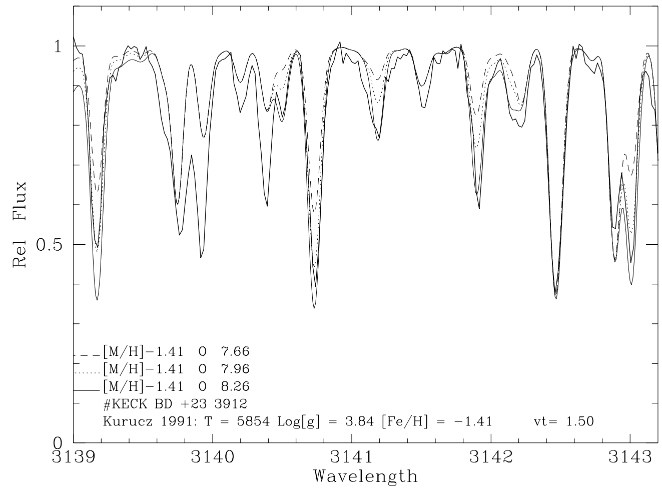

FIG. 1*b*

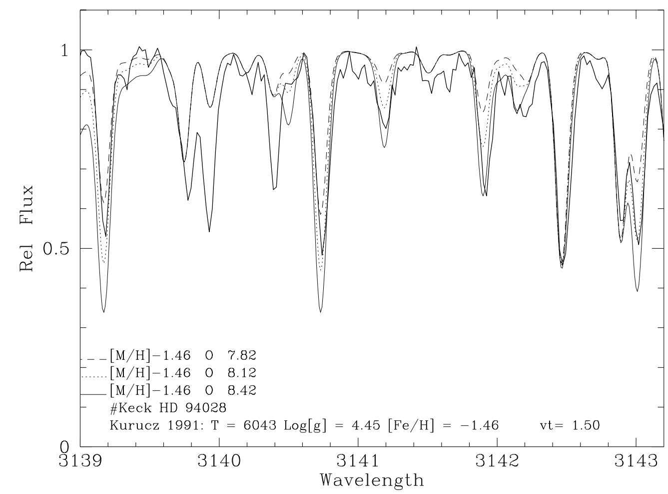

FIG. 1*c*

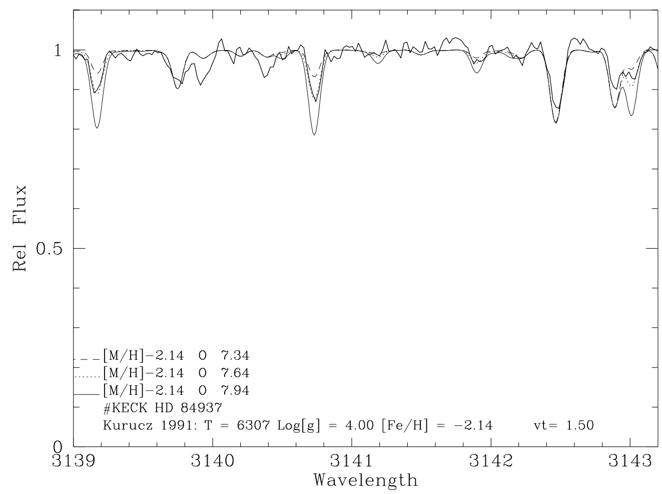

FIG. 1*d*

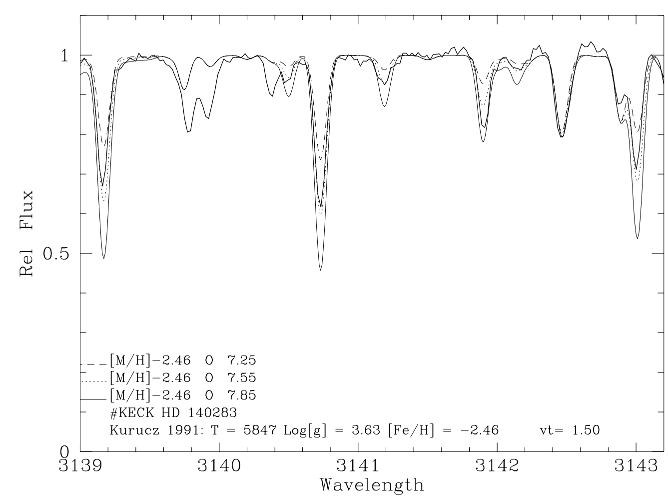

FIG. 1*e*

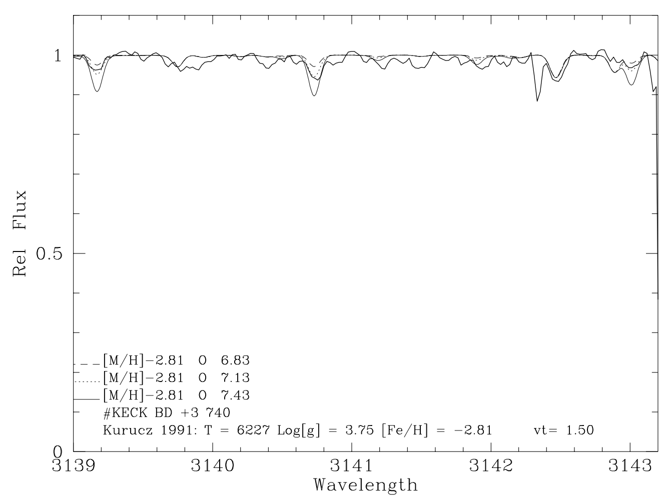

FIG. 1*f*

FIG. 1.—(*a–f*) Examples of the observed and three synthetic spectra to determine the O abundance from the OH lines; the heavy solid line is the observed spectrum, and the synthetic spectrum closest to the best fit is the dotted line. The stellar parameters for each model are shown on the bottom line of each panel. These are samples of the fits with the King scale parameters.

Tables 2 and 3. The errors are nearly independent, the three errors were added in quadrature. The effect of changing T by 100 K was determined empirically by changing that model parameter and refitting the observed data to a model 100 K hotter and 100 K cooler. A small dependence of the size of the error on temperature was noted. An increase in the temperature of $+50$ K corresponds to a change in [O/H] of $+0.06$ dex at 6300 K and of 0.11 dex at 5800 K.

TABLE 4

O ABUNDANCES FROM OH, KING (1993) SCALE

Star	T_{eff} (K)	[Fe/H]	log O/H + 12.0	σ
HD 19445	5996	−2.01	7.80	0.15
HD 64090	5478	−1.67	...	...
HD 74000	6249	−1.99	7.61	0.08
HD 76932	5943	−0.87	8.50	0.19
HD 84937	6307	−2.14	7.64	0.10
HD 94028	6043	−1.46	8.12	0.17
HD 103095	5133	−1.26	8.05	0.17
HD 134169	5900	−0.85	8.60	0.23
HD 140283	5847	−2.46	7.55	0.15
HD 184499	5670	−0.51	8.54	0.20
HD 194598	6042	−1.16	8.26	0.16
HD 201889	5693	−0.84	8.41	0.25
HD 219617	6011	−1.49	8.09	0.22
HD 221377	6327	−0.86	8.29	0.15
BD +37°1458......	5554	−2.06	7.74	0.15
BD +26°3578......	6269	−2.24	7.45	0.08
BD +23°3912......	5854	−1.41	8.20	0.17
BD +20°3603......	6234	−2.15	7.64	0.17
BD +17°4708......	6091	−1.73	7.73	0.13
BD +03°740	6227	−2.81	7.13	0.09
BD +02°3375......	5949	−2.30	7.43	0.20
BD −04°3208......	6401	−2.31	7.61	0.16
BD −13°3442......	6273	−2.94	7.37	0.16
HR 3775	6300	−0.17	8.92	0.19
Sun	5770	0.00	8.87	0.09

The effects of changing log g by 0.3 were also determined empirically: decreasing log g by 0.3 in the model and refitting the observed spectra. It was found that a change in log g of −0.3 corresponds to an increased O abundance of +0.08 dex. A change of +0.10 in [Fe/H] was found to be negligible, as is a change of 0.5 km s^{-1} in the microturbulent velocity. Other sources of error include the final continuum placement and the size of the Gaussian profile used to match the instrumental profile in the synthesis. Both of these are deemed to be small.

TABLE 5

O ABUNDANCES FROM OH ON THE CARNEY (1983) SCALE

Star	T_{eff} (K)	[Fe/H]	log O/H + 12.0	σ
HD 19445	5852	−2.10	7.57	0.16
HD 64090	5341	−1.77	7.65	0.18
HD 74000	6134	−2.05	7.50	0.12
HD 76932	5807	−0.95	8.29	0.17
HD 84937	6206	−2.20	7.45	0.06
HD 94028	5907	−1.54	7.88	0.21
HD 103095	5007	−1.37	7.79	0.19
HD 134169	5759	−0.94	8.34	0.30
HD 140283	5692	−2.56	7.34	0.14
HD 184499	5670	−0.51	8.54	0.18
HD 194598	5911	−1.25	8.03	0.19
HD 201889	5553	−0.95	8.12	0.22
HD 219617	5872	−1.58	7.81	0.22
HD 221377	6238	−0.93	8.14	0.16
BD +37°1458......	5408	−2.14	7.60	0.16
BD +26°3578......	6158	−2.32	7.30	0.11
BD +23°3912......	5691	−1.53	7.95	0.17
BD +20°3603......	6114	−2.22	7.33	0.17
BD +17°4708......	5956	−1.81	7.84	0.20
BD +03°740	6110	−2.89	6.90	0.16
BD +02°3375......	5800	−2.39	7.20	0.19
BD −04°3208......	6316	−2.35	7.47	0.16
BD −13°3442......	6159	−3.02	7.22	0.21
HR 3775	6300	−0.17	8.92	0.19
Sun	5770	0.00	8.87	0.09

3.1.3. *Comparison with Other Results from* OH

We have two stars in common with NGEG, whose line lists and method we have employed in this study: HD 84937 and HD 140283. We have done syntheses for these stars using their model parameters and Kurucz models (vs. the MARCS models they used; Gustafsson et al. 1975). For HD 84937 we find [O/H] = −1.79, where they find −1.87. For HD 140283 we find [O/H] = −1.99 compared to their −2.10. This agreement is good; if there is a systematic effect—that our results would typically be larger than theirs by 0.10 dex—it could be due to the differences in the models. The quality of the data may also be a factor as their S/N is 30 and ours is 98 and 164 for those two stars.

(A. Stephens (1998, private communication) has determined spectroscopic temperatures with equivalent widths from Nissen & Schuster (1997) and Kurucz models; he finds temperatures that are +45 K hotter than those from the MARCS-type atmospheres used by Schuster & Nissen. It is the MARCS-type models that are used in NGEG. This difference in the models can perhaps account for the difference in the O abundance that we find.)

We have Keck data on five stars that BSR studied: HD 19445, 76932, 140283 (two models), 219617, and BD +02 3375. We have used their parameters to make Kurucz models and then used MOOG to synthesize the OH spectra to determine O abundances from our Keck spectra. Our MOOG synthesis with Kurucz models yield [O/H] abundances that are systematically higher than those of BSR by 0.34 on average, ranging from 0.19 to 0.50. (BSR use 8.92 as the solar value of log N(O).) This difference may be partly attributed to the Kurucz atmospheres, perhaps 0.1 dex as seen above in the comparison with NGEG, and partly to the *gf*-values used. As noted earlier we followed NGEG in adjusting the OH band *gf*-values. A data quality effect may be involved here too as BSR have S/N ∼20, while for those five stars our S/N ratios are 88, 110, 164, 67, and 63 per pixel.

The new paper by Israelian et al. (1998) presents determinations of O abundances from OH using Kurucz atmospheres. They made individual adjustments in log *gf* values to match the solar atlas OH line strengths for log N(O) = 8.93. They did not use the shift for all the lines as did NGEG of −0.16, but the one line in common to both studies has the same log *gf* to within 0.05 dex. Isrealian et al. (1998) have 10 stars in common with our work, listed in Table 6. We have taken into account the differences in parameters by changing their O abundances by the appropriate amount for the temperature and log g differences as shown in columns (3), (4), (5), and (6) of Table 6. (These are the temperature and log g differences on our Carney scale, which is closer to the one they have adopted.) Columns (7) and (8) show our revised version of their [O/H] values and our [O/H] values on the Carney scale and the difference is given in the last column. The mean difference is 0.00 ± 0.06, excluding the one "misfit," HD 103095, the coolest star in our respective samples. This agreement is very impressive. It shows how important it is to take into account differences

TABLE 6

ABUNDANCE COMPARISON FROM OH LINES

Star (1)	[O/H] (IGR) (2)	ΔT (3)	Δ[O/H] (4)	$\Delta \log g$ (5)	Δ[O/H] (6)	[O/H] (IGRr) (7)	[O/H] (BKDV) (8)	Δ[O/H] (BKDV − IGRr) (9)
HD 19445	−1.36	+42	+0.07	+0.11	−0.03	−1.32	−1.36	−0.04
HD 64090	−1.04	−44	−0.15	+0.28	−0.07	−1.26	−1.28	−0.02
HD 76932	−0.62	+7	+0.01	+0.15	−0.04	−0.65	−0.73	−0.08
HD 84937	−1.45	−4	−0.01	−0.11	+0.03	−1.43	−1.48	−0.05
HD 94028	−0.91	−68	−0.11	+0.34	−0.09	−1.11	−1.05	+0.06
HD 103095	−0.68	−23	−0.04	+0.10	−0.03	−0.75	−1.14	(−0.39)
HD 134169	−0.61	−61	−0.10	−0.12	+0.03	−0.68	−0.59	+0.09
HD 140283	−1.85	+142	+0.23	+0.12	−0.03	−1.65	−1.59	+0.06
HD 201889	−0.71	−62	−0.10	+0.14	−0.04	−0.85	−0.81	+0.04
BD +37°1458......	−1.43	+148	+0.24	+0.41	−0.11	−1.30	−1.33	−0.03
Mean difference		$N = 9$						+0.003 ± 0.060

in the adopted parameters when comparing results from different authors. It also underscores the differences that can arise from the use of different model atmospheres; we and Israelian et al. (1998) have used Kurucz models as opposed to NGEG and BSR, who use the MARCS/OSMARCS generated models.

The difference in [O/H] found for HD 103095 deserves some discussion. The O abundance of this star is the subject of a paper by Balachandran & Carney (1996). They determine the O abundance from the near-infrared OH lines. Their parameters (5050/4.7/−1.22) are identical to ours within the quoted errors (5133/4.75/−1.26 [King scale] and 5007/4.65/−1.37 [Carney scale]). For the purpose of this comparison we look at the means from our two scales (5070/4.7/−1.31) since they are the same as those of Balachandran & Carney. Our O abundances are similar; they find [O/H] = −0.93, and we find −1.01. The value found by Isrealian et al. (1998) is −0.68 with parameters 5030/4.55/−1.30; the parameter adjustment only brings this down to −0.71. They do remark that this is one of two stars where the synthetic spectrum looks broader than the observed one. The OH lines are strong in this cool star, making the lines difficult to fit.

3.2. *Oxygen from* O I

3.2.1. *Abundance from the Equivalent Widths of the* O I *Triplet*

Several researchers have determined O abundances for metal-poor stars from the O I triplet at 7771, 7774, and 7775 Å and have published the equivalent widths of the three lines (Tomkin et al. 1992, hereafter TLLS; Abia & Rebolo 1989, hereafter AR; Boesgaard & King 1993, hereafter BK; Sneden et al. 1979, hereafter SLW; Cavallo et al. 1997, hereafter CPR; King 1994a, hereafter K). All of our stars turn out to have at least one set of published line strengths, and two-thirds have two or more sets. For the Sun we have used the published equivalent widths of Edvardsson et al. (1993) and our spectrum of the asteroid, Vesta, taken with the CFHT f/8 coudé at a dispersion of 0.072 Å pixel^{-1}. We have used oscillator strengths, $\log gf = 0.325$, 0.212, and −0.010, for the three lines following TLLS, which are from Bell & Hibbert (1990) and Butler & Zeippen (1991).

We have redetermined O abundances from all three lines from those equivalent widths and our stellar parameters, for both temperature scales. The average for each star from each paper's equivalent widths for each temperature scale was found. The individual means are shown in columns (2)–(7) of Tables 7 and 8. The adopted mean is given in column (8). For the Sun we used the measured equivalent widths of the three lines from Edvardsson et al. (1993) and from our Vesta spectrum with the Kurucz solar model, which gave $\log N(\mathrm{O}) = 8.91$ and 8.92 for a mean of 8.915, in excellent agreement with the value from OH (8.87) and previous solar determinations (8.93).

We have investigated the difference in [O/H] (and [O/Fe]) caused by the model atmospheres used by also determining O abundances from TLLS exactly as they did but with Kurucz atmospheres. For a sample of nine stars, we find that the mean difference in [O/H] to be +0.07 ± 0.03 dex between the Kurucz and the MARCS-generated atmospheres. The size of this difference is similar to that found in the OH comparisons above.

The O I triplet lines have high excitation potentials—9.15 eV—and are thus possibly subject to the effects of departures from local thermodynamic equilibrium (LTE). These non-LTE effects have been considered and discussed by several authors, e.g., TLLS, AR, CPR, and Kiselman (1991, 1993), García-López et al. (1993), Takeda (1994), and King & Boesgaard (1995). While an accounting of these various studies could be the topic of a separate paper, it seems that there are significant uncertainties in the theoretical NLTE calculations. For example, while TLLS's typical corrections for their metal-poor dwarfs are only a few hundredths of a dex, those inferred by Kiselman (1991) are much larger (e.g., 0.3 dex and 0.7 dex for 6000 K, $\log g = 4.0$ dwarfs with [O/Fe] = +0.5 having [Fe/H] = −1.0 and −2.75 respectively). Most all of these studies deduce a significant NLTE correction (0.2–0.4) dex for the Sun. However, the empirical correction deduced from analysis of the solar O I and [O I] features is ≤0.1 dex (see, e.g., King & Boesgaard 1995).

An important lingering uncertainty is the collisional rates/cross section for collisions with neutral hydrogen in the NLTE computations. Many studies employ Drawin (1967) rates, but these have been criticized on various grounds as being 2–3 orders of magnitude too large. Indeed, Kiselman (1993) notes that reduction of the rates by this amount leads to excellent agreement with the observed center-to-limb dependence of the solar O I equivalent widths, but only *if* the solar O abundance has been overestimated by 0.2–0.3 dex. Kiselman (1993) notes that enhancing the Drawin (1967) rates by a factor of 16 removes the [O I]- and O I-based abundance discrepancies in the study of metal-rich dwarfs by Nissen & Edvardsson (1992); however,

TABLE 7

O ABUNDANCES FROM THE O I TRIPLET ON THE KING (1993) SCALE

Star (1)	TLLS (2)	AR (3)	BK (4)	SLW (5)	CPR (6)	K (7)	Mean (8)	σ (9)
HD 19445	7.58	7.69	...	7.53	...	...	7.60	0.10
HD 64090	7.83	...	...	...	...	...	7.83	0.10
HD 74000	7.36	...	...	...	...	...	7.36	0.07
HD 76932	...	...	8.49	...	8.50	...	8.50	0.10
HD 84937	7.32	7.72	...	...	...	...	7.52	0.07
HD 94028	8.07	...	...	7.93	7.99	...	8.00	0.09
HD 103095	8.11	...	...	8.01	...	...	8.06	0.14
HD 134169	...	8.50	...	8.41	...	...	8.45	0.11
HD 140283	7.07	...	7.10	7.16	...	...	7.11	0.08
HD 184499	...	8.96	8.88	...	...	...	8.92	0.10
HD 194598	8.22	...	8.23	...	...	...	8.22	0.07
HD 201889	...	8.66	8.74	...	8.68	...	8.69	0.06
HD 219617	...	8.12	...	...	...	...	8.12	0.10
HD 221377	...	...	...	8.62	...	...	8.62	0.16
BD +37°1458......	7.63	...	...	...	7.70	...	7.66	0.09
BD +26°3578......	7.37	7.53	...	...	...	...	7.45	0.09
BD +23°3912......	8.23	...	...	...	...	...	8.23	0.07
BD +20°3603......	7.41	7.51	...	...	...	...	7.46	0.16
BD +17°4708......	...	8.15	...	...	7.91	...	8.03	0.08
BD +03°740	6.83	...	...	...	...	...	6.83	0.16
BD +02°3375......	7.54	7.85	...	...	...	...	7.70	0.11
BD −04°3208......	7.36	...	...	...	...	...	7.36	0.14
BD −13°3442......	...	...	...	...	...	6.98	6.98	0.18
HR 3775	...	...	...	...	...	...	9.14[a]	0.12
Sun	...	...	...	...	...	...	8.92[b]	0.04

[a] From Clegg et al. 1981 O I equivalent widths.

[b] Includes 8.91 from the O I equivalent widths of Edvardsson et al. 1993 and 8.92 from our measurements on our spectrum of Vesta from CFHT.

TABLE 8

O ABUNDANCES FROM THE O I TRIPLET ON THE CARNEY (1983) SCALE

Star (1)	TLLS (2)	AR (3)	BK (4)	SLW (5)	CPR (6)	K (7)	Mean (8)	σ (9)
HD 19445	7.69	7.80	...	7.63	...	...	7.71	0.12
HD 64090	7.98	...	...	...	...	...	7.98	0.07
HD 74000	7.43	...	...	...	...	...	7.43	0.07
HD 76932	...	...	8.57	...	8.60	...	8.58	0.09
HD 84937	7.37	7.76	...	...	...	...	7.50	0.08
HD 94028	8.19	...	...	8.04	8.10	...	8.11	0.11
HD 103095	8.21	...	...	8.11	...	...	8.16	0.14
HD 134169	...	8.59	...	8.50	...	...	8.54	0.11
HD 140283	7.13	–	7.16	7.22	...	...	7.17	0.07
HD 184499	...	8.96	8.88	...	...	...	8.92	0.09
HD 194598	8.32	...	8.32	...	...	...	8.32	0.07
HD 201889	...	8.77	8.84	...	8.79	...	8.80	0.09
HD 219617	...	8.27	...	...	...	...	8.27	0.08
HD 221377	...	...	...	8.67	...	...	8.67	0.16
BD +37°1458......	7.69	...	...	...	7.76	...	7.73	0.11
BD +26°3578......	7.42	7.58	...	...	...	...	7.50	0.08
BD +23°3912......	8.31	...	...	...	...	...	8.31	0.07
BD +20°3603......	7.49	7.59	...	...	...	...	7.54	0.16
BD +17°4708......	...	8.20	...	...	7.96	...	8.08	0.10
BD +03°740	6.88	...	...	...	...	...	6.88	0.17
BD +02°3375......	7.62	7.90	...	...	...	...	7.76	0.13
BD −13°3442......	...	...	...	...	...	7.02	7.02	0.15
BD −04°3208......	7.41	...	...	...	...	...	7.41	0.16
HR 3775	...	...	...	...	...	...	9.14[a]	0.12
Sun	...	...	...	9.05	...	...	8.92[b]	0.04

[a] From Clegg et al. 1981 O I equivalent widths.

[b] Includes 8.91 from the O I equivalent widths of Edvardsson et al. 1993 and 8.92 from our measurements on our spectrum of Vesta from CFHT.

King & Boesgaard (1995) suggest that there is no such discrepancy when only cool ($T < 6200$–6300 K) stars are considered. Recently, Takeda (1995) suggested that the Drawin rate unaltered seemed to adequately reproduce the solar O I profiles. TLLS also used solar constraints to advocate a mild enhancement of the Drawin rates in their calculations.

At present, our tentative assessment of the various evidence suggests that calculations employing near-Drawin collision rates probably yield the best current assessment of NLTE corrections. For stars with $T_{\rm eff}$, log g, and [Fe/H] typical our sample, we expect the NLTE corrections to be ≤ 0.15 dex. However, uncertainty in the exact magnitude of the NLTE effects and their detailed dependence with metallicity are acknowledged. Furthermore, the continued inability to simultaneously reproduce the solar O abundance, the O I solar line profiles, and their variation in strength from the Sun's center-to-limb when using any collisional rate strongly suggests that our understanding of O I formation remains incomplete. Thus, other effects such as convective inhomogeneities and/or depth-dependent microturbulence and/or chromospheric effects (Takeda 1994) may play an important role in some of the stars we consider.

In a more empirical approach we look at the NLTE corrections calculated by TLLS for the 15 stars we have in common. The average difference for these 15 stars, LTE $-$ NLTE, is $+0.027$ dex. Ten of the stars have differences ≤ 0.02 dex. The two that have differences of $+0.08$ dex, BD $+3$ 740 and BD -04 3208, are among our hottest and lowest log g stars. Takeda, Kawanomoto, & Sadakane (1998) find that for giants the NLTE corrections can be 0.1–0.2 dex. It is the low values of log g for giants and some hotter subgiants that make the LTE values from the O I lines poor; this applies to most of the stars in the work by CPR. We conclude that in our sample the stars are sufficiently cool with high enough log g values that the non-LTE effects can be safely ignored. Furthermore, the empirically low corrections for the TLLS sample confirm this. Our disk star, HR 3775, has very strong O I lines (133, 117, 92 mÅ) according to Clegg et al. 1981); they find that at such line strengths NLTE effects are strong. For this star we have derived but not used the O abundance from the O I triplet lines.

3.2.2. *Errors in the* O *Abundances from* O I

Again we have determined the effects of changes in the model parameters on the abundances empirically by recalculating O abundances from each of the three lines in the triplet with models that are (1) 100 K hotter and (2) -0.3 lower in log g. An increase in $T_{\rm eff}$ by 100 K corresponds to a decrease in log O/H by 0.07 dex, while a decrease in log g of 0.3 results in a decrease in log O/H of 0.09 dex. (The size of the error has very small temperature and gravity sensitivities: 0.02 dex over 500 K and 0.03 dex over 0.8 in log g.) The errors in $T_{\rm eff}$ and log g in Tables 2 and 3 were used to find the error in log O/H for each star. The third source of error is the random error in the determination of the individual O abundances. For the stars where three or more sets of equivalent widths were used from three or more sources, we used the agreement between the O abundances as the measure of the random errors. For those stars with one of two determinations we used the agreement between the three O I lines; when there were two sets of equivalent widths we found the standard deviation of the mean from each set and took the average. Once again we added the three errors (due to T, log g, and the internal O agreement) in quadrature.

3.2.3. *Comments on Other* O *Abundances from the* O I *Triplet*

In their study of O I-based O abundances in metal-poor dwarfs, TLLS noted a curious trend of their [O/Fe] values with $T_{\rm eff}$. They attributed this to the possible effects of convective inhomogeneities on their abundance determinations. In order to investigate this odd behavior, we selected 10 of their stars having a range in $T_{\rm eff}$ and [Fe/H] that are part of the present study and rederived O abundances based on their equivalent widths alone, their model parameters, and our model parameters. The results using our model parameters (on the C83 scale, which is closest to that used by TLLS), [Fe/H] values, and Kurucz atmospheres show no significant trend with $T_{\rm eff}$. We find that 58% of TLLS's slope is removed by simply employing our preferred [Fe/H] values; in this regard, we recall the discrepancies noted by Balachandran & Carney (1998) in reanalyzing TLLS's Fe data for HD 103095. The remaining 42% of TLLS's slope is removed by the influence of the Kurucz model atmospheres (having adopted parameters of TLLS) on the derived O abundances. We find that substituting our preferred values for log g and $T_{\rm eff}$ for those of TLLS makes no appreciable contribution in removing the slope of [O/Fe] with $T_{\rm eff}$ seen in their work. In any case, we find that there may be no need for recourse to convective inhomogeneities to explain the TLLS results.

We also investigated differences in the [O/Fe] versus [Fe/H] slopes using these 10 stars. Our C83-based results using the TLLS equivalent widths show a slope some 0.17 dex/dex more negative than results of TLLS. Approximately 35% of this slope difference can be explained by each of (1) our choice of [Fe/H] values and (2) the effects of our preferred parameters on the O I abundances. The remaining 30% of the slope difference is explained by differences in the model atmospheres utilized (as assessed by repeating the TLLS analysis using their preferred parameters).

The results of AR showed a monotonic decrease of [O/Fe] with increasing metallicity from [Fe/H] $= -3.0$ to 0.0. King (1993) found that the equivalent widths measured by AR for some of the stars are 25% too high compared to values from TLLS, SLW, and his own data. He found no dependence of the equivalent width differentials on [Fe/H] and the monotonic decrease remained. BSR did a reanalysis of the AR data and derived O abundances that were typically 0.1 dex smaller than those of AR. The slope of the relation between [O/Fe] and [Fe/H] for stars with [Fe/H] < -1.0 from their Figure 1 was still ~ -0.33.

3.3. *Adopted* O *Abundances*

We have searched for trends of O abundances found from each method with temperature and log g. Figure 2 shows the difference in the O abundances found from the two methods as a function of log g. Figure 3 shows the difference from the two methods as a function of $T_{\rm eff}$. *There are no systematic effects that would lead us to prefer one method over the other.*

Figure 4 shows the relationship between O from OH with Fe (on the King temperature scale) and Figure 5 shows that of O from O I with Fe (also on the King scale). The OH-based O abundances appear to be slightly larger than the O I-based abundances at the lowest metallicities; this effect

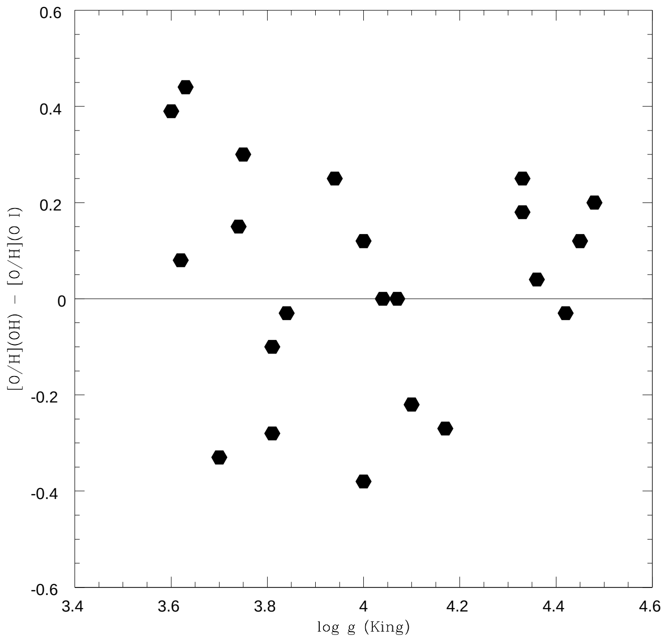

FIG. 2.—Differences in the [O/H] determined by the two methods ($[O/H]_{OH} - [O/H]_{OI}$) is plotted against the log g of the (King scale) model. No trend with log g is found.

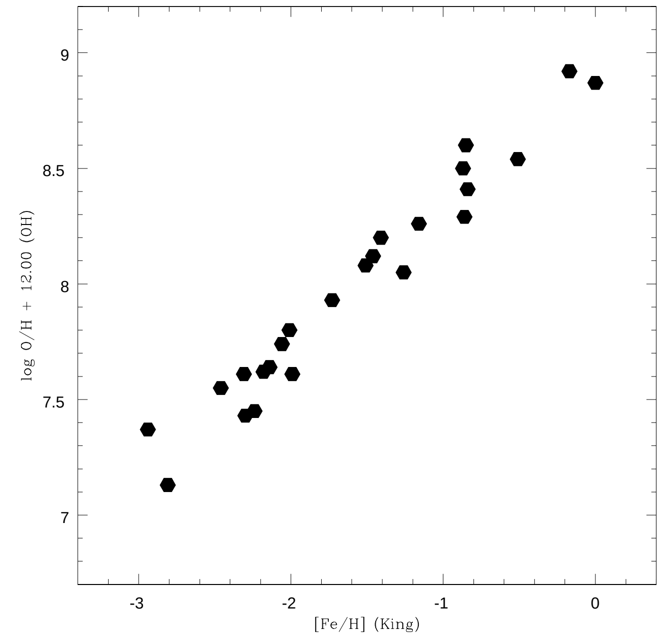

FIG. 4.—log O/H + 12.00 from OH vs. metallicity, [Fe/H] (King scale). The linear relationship can be seen. Compare with Fig. 5.

may be due to the weaker OH lines in the very metal-deficient stars and the greater difficulty in determining the best synthesis fits (see Figs. 1*d*–1*f*). With high-quality spectra the O I lines remain detectable in our most metal-poor stars. Our star with the lowest [Fe/H], BD −13°3442, at −3, has equivalent widths for the three O I lines of 13.1, 8.2, 4.8 (all ±0.5) mÅ (King 1994a); his spectrum has a S/N ratio of 140 with a spectral resolution of 0.16 Å. In comparison the strongest OH line in this star is 6 mÅ.

We conclude that these are two equally valid methods of determining O/H *values*. We therefore take the mean of the two as the adopted log N(O). The final error for the log O/H abundance is the reciprocal of the square root of the quadrature sum of $1/\sigma_{OH}^2 + 1/\sigma_{OI}^2$.

We note the interesting circumstance that the two ways of determining the O abundance have opposite sensitivities to temperature and log g. An increase of 100 K in tem-

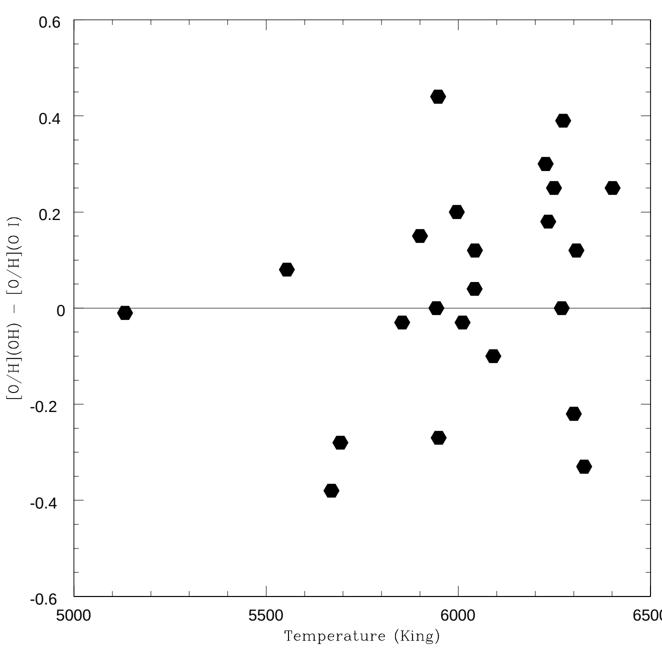

FIG. 3.—Difference in [O/H] determined by the two methods ($[O/H]_{OH} - [O/H]_{OI}$) is plotted against T_{eff} of the (King scale) model. No trend with T_{eff} is found.

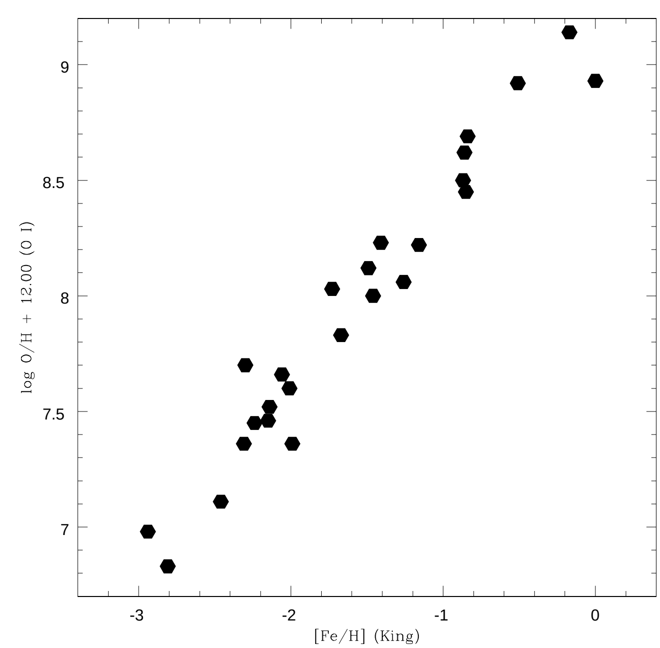

FIG. 5.—log O/H +12.00 from O I vs. metallicity, [Fe/H] (King scale). Again the relationship is linear. The comparison with Fig. 4 shows lower values for the O abundance for the metal–poorest stars.

TABLE 9

Adopted Fe and O Abundances on the King (1993) Scale

Star	[Fe/H]	log O	[O/H]	σ	[O/Fe]	σ
HD 19445	−2.01	7.70	−1.23	0.08	0.78	0.11
HD 64090	−1.67	7.83	−1.10	0.10	0.57	0.18
HD 74000	−1.99	7.485	−1.445	0.05	0.545	0.13
HD 76932	−0.87	8.50	−0.43	0.09	0.44	0.13
HD 84937	−2.14	7.58	−1.35	0.06	0.79	0.15
HD 94028	−1.46	8.06	−0.87	0.08	0.59	0.11
HD 103095	−1.26	8.055	−0.875	0.11	0.385	0.23
HD 134169	−0.85	8.525	−0.405	0.10	0.445	0.13
HD 140283	−2.46	7.33	−1.60	0.07	0.86	0.16
HD 184499	−0.51	8.73	−0.20	0.09	0.31	0.17
HD 194598	−1.16	8.22	−0.71	0.06	0.47	0.20
HD 201889	−0.84	8.55	−0.38	0.06	0.46	0.27
HD 219617	−1.49	8.105	−0.825	0.09	0.665	0.23
HD 221377	−0.86	8.455	−0.475	0.11	0.385	0.18
BD +37°1458......	−2.06	7.70	−1.23	0.08	0.83	0.20
BD +26°3578......	−2.24	7.45	−1.48	0.06	0.76	0.13
BD +23°3912......	−1.41	8.215	−0.715	0.06	0.695	0.17
BD +20°3603......	−2.15	7.55	−1.38	0.12	0.77	0.20
BD +17°4708......	−1.73	7.98	−0.95	0.07	0.78	0.12
BD +03°740	−2.81	7.385	−1.545	0.08	1.26	0.12
BD +02°3375......	−2.30	7.565	−1.365	0.10	0.935	0.15
BD −04°3208......	−2.31	7.485	−1.445	0.11	0.865	0.24
BD −13°3442......	−2.94	7.175	−1.755	0.12	1.185	0.14
HR 3775	−0.17	8.92	−0.01	0.10	0.16	0.14
Sun	0.00	8.89	−0.04	0.04	−0.04	0.06

perature increases the O from OH by +0.16 but decreases the O from O I by −0.07. A decrease in log g of −0.3 leads to an increase in O from OH by +0.08 and a decrease in O from O I by −0.09. Therefore, by taking the mean O abundance we reduce the overall sensitivity to the stellar parameters. In fact, due to this circumstance, our errors in the final O abundances may be overestimated.

Tables 9 and 10 summarize the final results with the star name, [Fe/H], log O/H + 12.00, [O/H], the error in [O/H], [O/Fe], and the error in [O/Fe]. The errors in [O/H] and [Fe/H] were combined in quadrature to find the error in [O/Fe]. In determining [O/H] and [O/Fe] for the stars we have used the solar O abundance of 8.93. Our O determinations from our solar spectra agree with that abun-

TABLE 10

Adopted Fe and O Abundances on the Carney (1983) Scale

Star	[Fe/H]	log O	[O/H]	σ	[O/Fe]	σ
HD 19445	−2.10	7.64	−1.29	0.10	0.81	0.16
HD 64090	−1.77	7.815	−1.115	0.07	0.655	0.19
HD 74000	−2.05	7.465	−1.465	0.06	0.585	0.13
HD 76932	−0.95	8.435	−0.495	0.08	0.455	0.14
HD 84937	−2.20	7.475	−1.455	0.05	0.745	0.15
HD 94028	−1.54	7.995	−0.935	0.10	0.605	0.13
HD 103095	−1.37	7.975	−0.955	0.11	0.415	0.21
HD 134169	−0.94	8.44	−0.49	0.10	0.45	0.11
HD 140283	−2.56	7.255	−1.675	0.06	0.885	0.13
HD 184499	−0.51	8.73	−0.20	0.08	0.31	0.16
HD 194598	−1.25	8.175	−0.755	0.07	0.495	0.17
HD 201889	−0.95	8.46	−0.47	0.08	0.48	0.27
HD 219617	−1.58	8.04	−0.89	0.08	0.69	0.18
HD 221377	−0.93	8.405	−0.525	0.11	0.405	0.18
BD +37°1458......	−2.14	7.665	−1.265	0.09	0.875	0.19
BD +26°3578......	−2.32	7.40	−1.53	0.06	0.79	0.16
BD +23°3912......	−1.53	8.13	−0.80	0.06	0.73	0.16
BD +20°3603......	−2.22	7.435	−1.495	0.12	0.725	0.20
BD +17°4708......	−1.81	7.96	−0.97	0.09	0.84	0.03
BD +03°740	−2.89	7.295	−1.635	0.12	1.255	0.15
BD +02°3375......	−2.39	7.48	−1.45	0.11	0.94	0.20
BD −04°3208......	−2.35	7.44	−1.49	0.11	0.86	0.11
BD −13°3442......	−3.02	7.12	−1.81	0.12	1.21	0.20
HR 3775	−0.17	8.92	−0.01	0.10	0.16	0.14
Sun	0.00	8.89	−0.04	0.04	−0.04	0.06

dance very well. The Sun is shown in the tables and figures with our values so it is essentially another point on the plots, although we do use $[Fe/H]_{\odot} = 0.0$.

4. RESULTS AND DISCUSSION

In Figures 6*a* and 6*b* we show the final O abundance (from the mean of the values from OH and O I) versus [Fe/H] with error bars in both parameters on both the King and the Carney temperature scales. It can be seen clearly that the scatter in Figure 6*a* is much reduced compared to Figures 4 and 5. The starkly linear relationship has a slope of 0.663 ± 0.023 (King) or 0.659 ± 0.023 (Carney); the slopes and intercepts were calculated taking the error bars into account. Not only is this relationship well fitted by a straight line over 3 orders of magnitude in [Fe/H], but also there is very little scatter around the line. The low scatter results from using two independent methods of finding the O abundance and the care that was taken in the determination of the [Fe/H] parameter. The excellent agreement of the slopes found for the two temperature scales is also a result of using the two different methods for the O abundance determination because the temperature and log *g* dependencies are opposite as discussed in § 3.3.

The equations for the best fits for the relation between O and Fe, taking into account the error bars in both parameters, are

$$\log N(\mathrm{O}) = 0.663\,(\pm 0.023)\,[\mathrm{Fe/H}] + 8.987\,(\pm 0.038)$$

(King scale, Fig. 6*a*)

$$\log N(\mathrm{O}) = 0.659\,(\pm 0.023)\,[\mathrm{Fe/H}] + 8.973\,(\pm 0.038)$$

(Carney scale, Fig. 6*b*).

Considering errors in both [O/H] and [Fe/H], χ^2 tests suggest that the scatter is well explained by the errors alone. This underscores the surprisingly tight relation between O and Fe. Of course, we cannot rule out the possibility of intrinsic scatter of the same order or smaller than the errors themselves.

In Figures 7*a* (King scale) and 7*b* (Carney scale) we show the traditional plot of [O/Fe] versus [Fe/H]. The trend is completely linear, with no sign of a break at metallicities between -1.0 and -2.0. The slopes of the linear fits of [O/Fe] with [Fe/H] taking into account the errors in both are -0.356 ± 0.030 (King) and -0.350 ± 0.030 (Carney), again in excellent agreement from the two temperature scales.

The solutions for our fits to the data in Figures 7*a* and 7*b* (taking into account the errors in both values) are

$$[\mathrm{O/Fe}] = -0.356\,(\pm 0.030)\,[\mathrm{Fe/H}] + 0.031\,(\pm 0.049)$$

(King scale, Fig. 7*a*)

$$[\mathrm{O/Fe}] = -0.350\,(\pm 0.030)\,[\mathrm{Fe/H}] + 0.033\,(\pm 0.50)$$

(Carney scale, Fig. 7*b*).

For $[\mathrm{Fe/H}] = -1.0, -2.0, -3.0$ the values for [O/Fe] are safely averaged to 0.385, 0.738, and 1.091.

We note with pleasure the agreement between the slopes we have found and those of Israelian et al. (1998). For O versus Fe they find 0.63 to our 0.66, and for O/Fe versus Fe they find -0.33 to our -0.35.

Earlier work on this subject has shown a possible break in the [O/Fe] versus [Fe/H] relationship with an apparent leveling off of [O/Fe] for low metallicities. Such a break has been discussed by Wheeler, Sneden, & Truran (1989), by BSR, and by King (1994b), among others. Although our results, as well as those of Abia & Rebolo (1989) and Isrealian et al. (1998), show no break, several factors have led to the confusion surrounding the data in the past. First, results for giants and dwarfs were not always clearly separated in plots of [O/Fe] versus [Fe/H]. Second, different methods of determining the O abundance were not separated in the data presentation; different symbols may have been used,

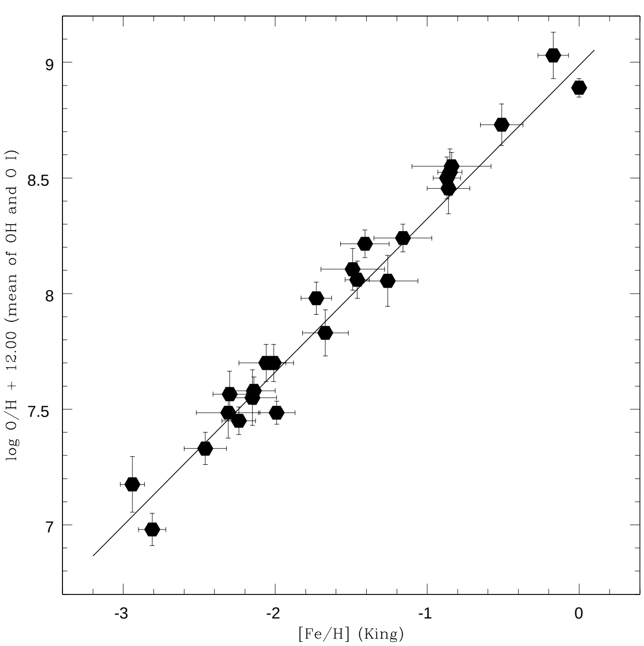

FIG. 6*a*

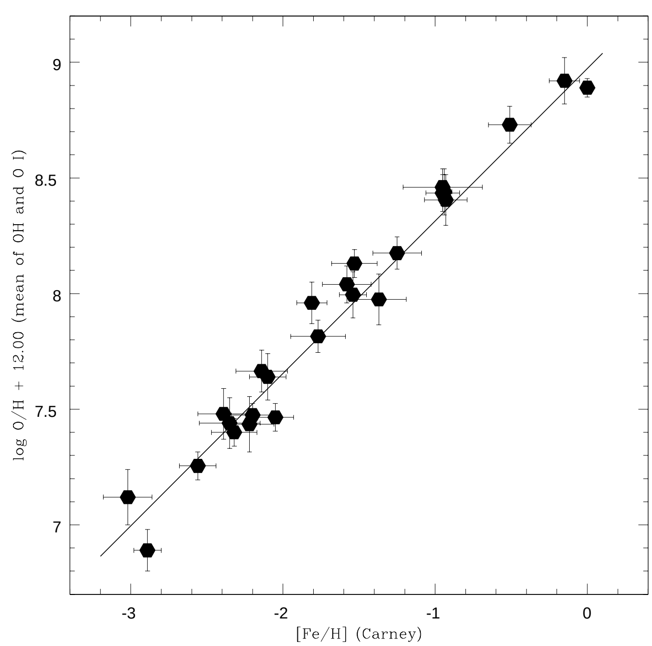

FIG. 6*b*

FIG. 6.—Log O/H + 12.00 as the mean of the OH and O I values plotted against [Fe/H]; the individual error bars for each quantity are shown. The line is the linear fit that takes in account the error bars in both coordinates. (*a*) King scale; (*b*) Carney scale.

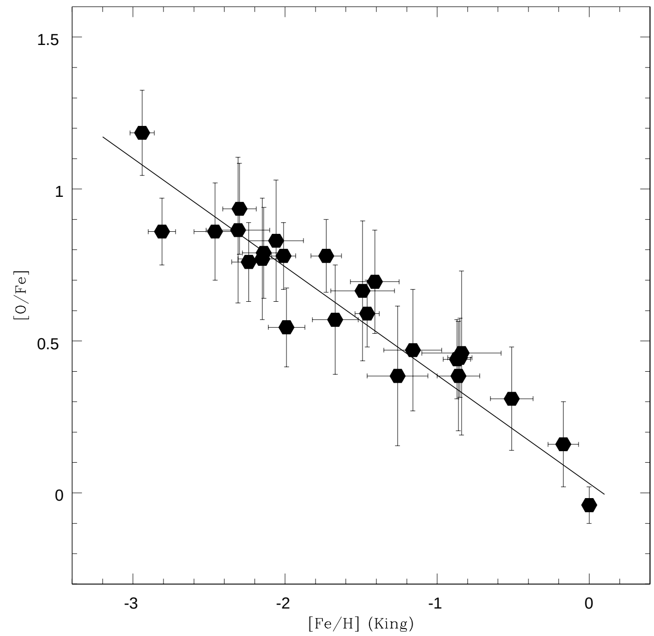

FIG. 7*a*

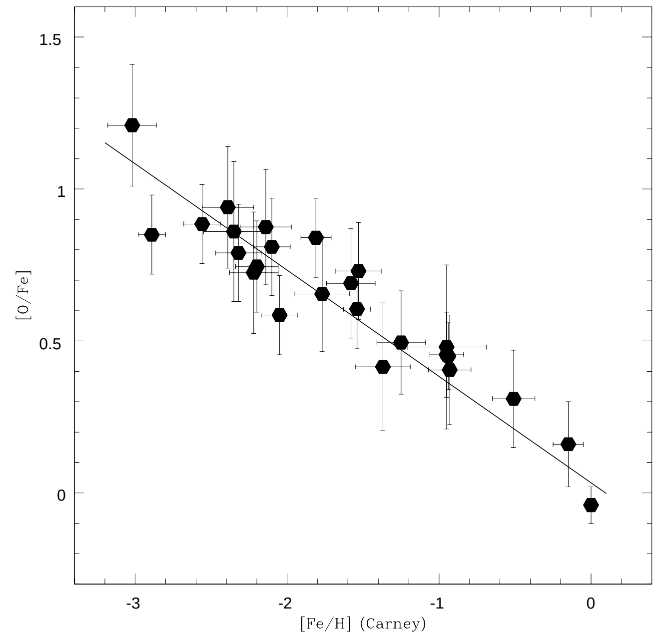

FIG. 7*b*

FIG. 7.—[O/Fe] (with O as the mean of the OH and O I determinations) plotted against [Fe/H] with the individual error bars. The line is the linear fit that takes in account the error bars in both coordinates. (*a*) King scale; (*b*) Carney scale.

but the resultant scatter hid the real trends. Third, results for many authors would be plotted together without regard for the differences in the stellar parameters that were used for individual stars and data sets. In this era when abundances can be determined to a precision of 0.1 dex and the errors in the parameters contribute to errors in the abundances of 0.1–0.5 dex or more, it is not acceptable to plot results from different authors without correcting them all to the same set of parameters. The example given in our Table 6 shows that the scatter is reduced by a factor of 2.5 when the data are put on the same parameter scale instead of simply adopting the published abundances. Fourth, the values that are plotted for the abscissa, [Fe/H], are often based on different solar values for Fe/H from different authors, with no corrections made. Fifth, various studies used different sets of model atmospheres and different normalizations to solar O/H, but this is not accounted for in many of the heterogeneous plots of [O/Fe] versus [Fe/H].

In Figures 8*a* and 8*b* we show our results as [O/H] to compare with 76 disk stars of Edvardsson et al. (1993), who found O abundances from the O I triplet and scaled them to the [O I] results of Nissen & Edvardsson (1992). We have

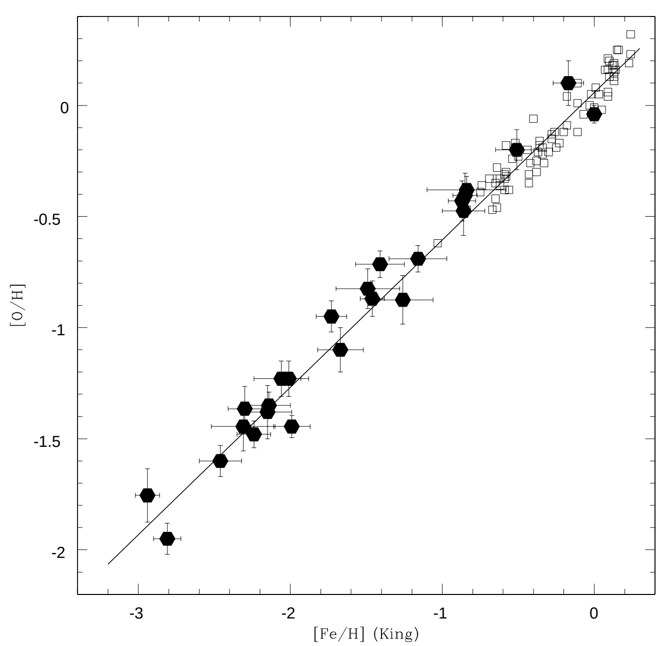

FIG. 8*a*

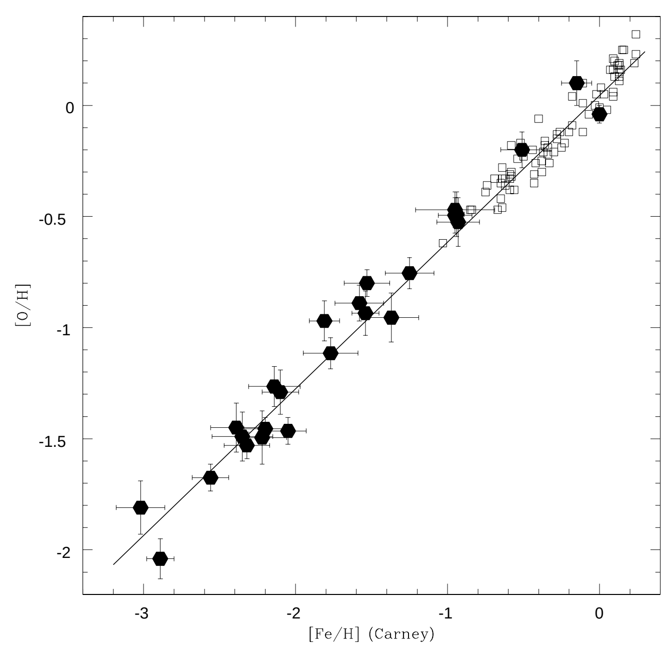

FIG. 8*b*

FIG. 8.—[O/H] vs. [Fe/H] including the disk star data of Edvardsson et al. (1993). The line is the fit to our data alone with our error bars, like Figs. 6*a* and 6*b*. The slope from our data and for the disk stars is exactly the same. (*a*) King scale; (*b*) Carney scale.

further scaled their abundances by +0.10 to match our OH + O I abundances and to account for the differences in the model atmospheres used. The line through the points is the line from our data alone and fits the disk stars remarkably well. These disk stars alone have a slope of 0.660 in perfect agreement with our values of 0.663 and 0.659. The position of the Sun on these plots shows it to be a normal, typical G dwarf. The excellent fit of the disk and halo stars shows a remarkable consistency in the production of Fe and O over the lifetime of the Galaxy and over large distances within the Galaxy. The robustly linear relationship between Fe and O shows that either element can be used equally well (or equally poorly) as a chronometer.

The slope of −0.35 that we find between [O/Fe] and [Fe/H] is in better agreement with models of O nucleosynthesis (see, e.g., Twarog & Wheeler 1982) than the previously often-assumed slope of −0.5. In future investigations of such issues as the "G-dwarf problem" and age-[O/H] this slope of −0.35 should be used, if, instead of directly determined O abundances, people use [O/H] found from [Fe/H].

Previous results have not shown such clear trends and such small scatter in their counterparts to our Figures 6 and 7. One major difference in our work is that we have been exceptionally careful in determining the best possible stellar parameters in as consistent a way as possible (see DBKD). We wish to emphasize the consistency issue. In addition, we have an excellent data set of high S/N spectra from Keck I +HIRES. And we have reanalyzed the O I lines with our consistent model parameters. The O abundances determined from the two methods have been combined; this not only reduces the observational errors, but also makes the final results less sensitive to the atmospheric parameters. This in turn reduces the scatter and the final errors.

In field halo giants O is usually found from [O I], and the results of [O/Fe] versus [Fe/H] do not show the pattern we have found for the halo field dwarfs. Rather, in the metallicity range of [Fe/H] of −1 to −3, there is a mean [O/Fe] of ∼ +0.3, but a large range of values from +0.1 to +0.6 (see McWilliam 1997 for a summary figure of data primarily from Barbuy 1988, Sneden et al. 1991, Kraft et al. 1992, and Shetrone 1996). The giants in the globular clusters, M92 and M15 (Sneden et al. 1991), M3 and M13 (Kraft et al. 1992), show both "high" [O/Fe] values (∼ +0.3) and "low" [O/Fe] values (<0.0). The low values could be the results of O–N nucleosynthesis and mixing (Sneden et al. 1991). Perhaps even those giants with the "high" [O/Fe] values have undergone dredge-up of O-depleted material.

King & Hiltgen (1996) have found that the [O I]-based O abundances for the Hyades giants are 0.23 dex lower than those for the Hyades dwarfs; they discuss discrepencies between dwarf and giant O abundances and suggest deficiencies in the giant model atmospheres. For the globular cluster, M92, the models for the giants result in [Fe/H] = −2.25 (Sneden et al. 1991), while the models for the turn-off stars give −2.52 (King et al. 1998); this raises questions about the models also. TLLS suggest that [O I] underestimates O in the presence of convective inhomogeneities. (This is done for the subdwarf, HD 103095, but such inhomogeneities would be more prevalent in giants.) Temperature scale calibrations for giants versus dwarfs may also account for some of the difference.

The remarkably linear relation between O and Fe and between O/Fe and Fe/H now stands in contrast to the other alpha-produced elements, like Mg, Si, Ca, and Ti. Edvardsson et al. (1993) showed that relative to Fe, these elements increase as [Fe/H] goes from 0 to −1, reaching values of [α/Fe] of 0.2 to 0.3 dex at [Fe/H] ∼ −1. Studies of halo stars (see, e.g., Fuhrmann, Axer, & Gehren 1995) indicate that [α/Fe] is roughly constant with [Fe/H] as it decreases to −2.5, albeit with large scatter and errors in the individual determinations. The different trends of O and the other α's with [Fe/H] challenges current chemical evolution models.

One possible application of our results may be in estimating globular cluster ages. Bergbusch & Vandenberg (1992) have suggested that oxygen enhancements can lead to reductions in the age estimates by 10%–20%. However, Salaris, Chieffi, & Straniero (1993) have argued that if one also takes into account the enhancements of the other α elements, the age reduction is minimal. In view of the possibility that O is more enhanced in halo stars than the other α's, new models should explore possible effects on derived ages by assuming different amounts of O overenhancement. For discussions of this and other recent issues involving globular cluster ages, see the reviews by Vandenberg, Bolte, & Stetson (1996), D'Antona, Caloi, & Mazzitelli (1997), and Sarajedini, Chaboyer, & Demarque (1997).

The star BD +23 3912 deserves special mention, for its potential importance to assessing the primordial lithium abundance and implications for testing models of big bang nucleosynthesis (King, Deliyannis, & Boesgaard 1996). This star's Li abundance lies about a factor of 2–3 above the Spite plateau of halo Li abundances. Either the big bang Li abundance was higher than the level of the halo Li plateau, in which case this star depleted its Li less (from such a higher abundance) than did the other plateau stars, or big bang Li was indeed close to the level of the Li-plateau, in which case Galactic production of Li enriched the surface of this star, before or after it formed. (Both depletion and production are also possible.) In the case of Galactic Li production, one expects to see signatures of the production mechanism(s). King et al. (1996) examined several elements in this star and found *all* of them to be perfectly normal, with the exception of Li. We can now add oxygen to the list of perfectly normal elemental abundances in this star. There is as yet no evidence of Li production signatures in this star.

5. SUMMARY AND CONCLUSIONS

We have obtained high S/N spectra of 24 unevolved stars plus the Sun in the UV spectral region with Keck I and HIRES. For our sample the values for [Fe/H] ranges from 0.0 to −3.0. These spectra have been used to determine the abundance of O by analyzing the OH bands in the UV near 3140 Å. Typically, our spectra have S/N of 60–110 in the echelle order we use for the OH features with a dispersion of 0.022 Å $pixel^{-1}$.

We have taken special care to determine stellar parameters consistently and accurately. We have used two different temperature scales along with the log g and [Fe/H] values that devolve from them.

The O abundance from OH was determined through spectral synthesis with Kurucz models that have been interpolated from his grid point models for both sets of parameters for each star. The internal agreement from the OH lines was typically ±0.15 dex. We also found abundances of O from the high-excitation O I triplet near 7774 Å. We reanalyzed the data published in six papers on the equivalent widths of the three O I lines with our stellar parameters. The internal agreement from the three lines was typically ± 0.10 dex. We have compared our O abundances from both methods with published results after adjusting each to the same parameter set. When thus adjusted to the same scale, the agreement is excellent in almost all cases. There seems to be a difference, however, that depends on what model atmospheres are used; the abundances from the Kurucz atmospheres relative to those from MARCS/OSMARCS are 0.07–0.11 dex higher.

We compared the abundances found from OH and from O I over our range in temperatures and log g values and found no systematic differences with those parameters. The slight metallicity dependence noticed is probably a result of the fact that the OH lines are weaker than the O I lines in the low-metallicity stars. The two methods are independent measures of the O abundance and, therefore, we took the average O abundance from OH and O I as the adopted abundance. The sensitivities of the two methods to gravity and temperature are opposite, so by combining the results, the influence of our selection of model parameters is reduced.

The relationship between log N(O) and [Fe/H] is completely linear over 3 orders of magnitude in [Fe/H]. The slope of this relationship is 0.66 (± 0.02). When the values of [O/H] and [Fe/H] for the 76 disk stars of Edvardsson et al. (1993) are added, the same linear relationship fits them also. (The slope for the disk stars alone is 0.660.) It is remarkable that the thin disk, the thick disk, and the halo can be represented by the same relationship.

Oxygen is enhanced relative to Fe over the 3 orders of magnitude in [Fe/H] in a robustly linear relation. The slope of this relationship is -0.35. There is no break in this relationship anywhere, and not between $[Fe/H] = -1.0$ and -2.0 as has been discussed by others. At metallicities 1000 times less than the Sun, O is enhanced relative to Fe and is only 81 times less than the solar O; at 100 times less than solar Fe, O is only 18 times less than solar. As [Fe/H] increases from -3 to -2, a factor of 10, O increases by a factor of 4.6. The final relationship, independent of the parameter scale, is $[O/H] = -0.35[Fe/H] + 0.03$.

Oxygen is produced easily in the early days of the evolution of the Galaxy through the production and rapid evolution of massive stars. As such stars become Type II supernovae, newly made O is released for the next generations of stars. The production of Fe occurs in core collapse of massive stars and in the lower mass stars with supernovae of Type Ia. The build-up of Fe occurs more slowly. Traditional chemical evolution models suggest that [O/Fe] versus [Fe/H] is flat when Fe production comes from Type II supernovae, and then there is a break near disk metallicities as the larger Fe production of Type Ia's kicks in. In contrast to this view, our data show a *constant* slope in [O/H] versus [Fe/H], which poses new challenges for understanding the chemical evolution of our Galaxy. Since the most massive Type II's produce proportionately more O relative to Fe; (Woosley & Weaver 1995), we speculate that our sloped [O/Fe] might be due to an evolving IMF, which changes continuously in time from one in which higher masses play a more important role early on to one in which lower masses play an increasingly important role. Perhaps an early enrichment in O occurs before [Fe/H] reaches -3.

There are some other implications of this work. (1) The apparent difference at low metallicities in O in the unevolved stars compared to the giants needs to be understood. (2) The apparent difference between O and other α elements in unevolved metal-poor stars requires more investigation. (3) The effect of enhanced O and other α elements on the ages of globular clusters should be revisited. (4) The normal oxygen abundance of BD +23 3912 further underscores the absence (so far) of any evidence supporting a Galactic Li production origin for this star's unusually high Li abundance, as opposed to an origin from a big bang Li abundance lying at least a factor of 2–3 above the halo-Li plateau.

Although one of the motivations of this work was to establish a more reliable age-metallicity relation by using the most abundant metal, O, the robust correlation between O and Fe shows that either element can be used as achronometer.

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ERRATUM: "OXYGEN IN UNEVOLVED METAL-POOR STARS FROM KECK ULTRAVIOLET HIRES SPECTRA" [ASTRON. J. 117, 492 (1999)]

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There is an error in Tables 9 and 10 for the abundances of O for BD $+3°740$. These are the O abundances from the mean of O derived from OH and from O I (on the two parameter scales). The correct values for this star for O from OH are in Tables 4 and 5, and the correct values for this star for O from O I are in Tables 7 and 8.

For Table 9, the correct values should be $\log O = 6.98$, $[O/H] = -1.95$, and $[O/Fe] = 0.86$.
For Table 10, the correct values should be $\log O = 6.89$, $[O/H] = -2.04$, and $[O/Fe] = 0.85$.

All of the figures have the correct values, as do Tables 4 and 5 and Tables 7 and 8.