OXYGEN IN THE VERY EARLY GALAXY

GARIK ISRAELIAN, RAFAEL REBOLO,1 AND RAMÓN J. GARCÍA LÓPEZ3
Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain; gil@iac.es, rrl@iac.es, rgl@iac.es
PIERCARLO BONIFACIO AND PAOLO MOLARO
Osservatorio Astronomico di Trieste, via G. B. Tiepolo 11, I-34131 Trieste, Italy
GIBOR BASRI
Astronomy Department, University of California, Berkeley, Berkeley, CA 94720; basri@soei.berkeley.edu
AND
NATALIYA SHCHUKINA
Main Astronomical Observatory, National Academy of Sciences, 03680 Kyiv-127, Ukraine; and Instituto de Astrofísica de Canarias,
E-38200 La Laguna, Tenerife, Spain; shchukina@iac.es
Received 2000 August 3; accepted 2001 January 2

ABSTRACT

Oxygen abundances in a sample of ultra-metal-poor subdwarfs have been derived from measurements of the oxygen triplet at 7771−5 Å and OH lines in the near-UV performed in high-resolution and high signal-to-noise ratio spectra obtained with WHT/UES, Keck I/HIRES, and VLT/UVES. Our Fe abundances were derived in LTE and then corrected for non-LTE (NLTE) effects. The new oxygen abundances confirm previous findings for a progressive linear rise in the oxygen-to-iron ratio with a slope $-0.33 \pm 0.02$ from solar metallicity to $[\text{Fe/H}] \sim -3$. A slightly higher slope would be obtained if the Fe NLTE corrections were not considered. Below $[\text{Fe/H}] = -2.5$ our stars show $[\text{O}/\text{Fe}]$ ratios as high as $\sim 1.17$ (G64-12), which can be interpreted as evidence for oxygen overproduction in the very early epoch of the formation of the halo, possibly associated with supernova events with very massive progenitor stars. We show that the arguments against this linear trend given by Fulbright & Kraft in 1999, based on the LTE Fe analysis of two metal-poor stars, cannot be sustained when an NLTE analysis is performed. We discuss how the Fulbright & Kraft LTE ionization balance of Fe lines underestimates the gravity of the very metal-poor star BD +23°3130 ($[\text{Fe/H}] = -2.43$) and how this leads to an underestimation of the oxygen abundance derived from the forbidden line. Gravities from Hipparcos appear to be in good agreement with those determined in NLTE, giving higher values than previously assumed, which reduces the discrepancies between the oxygen abundances derived from OH, triplet, and forbidden lines. Using one-dimensional models, our analysis of three oxygen indicators available for BD +23°3130 gives an average $[\text{O}/\text{Fe}]$ ratio of $0.78 \pm 0.15$. The high oxygen abundances at very low metallicities do not pose a problem to theoretical modeling since there is a range of parameters in the calculations of nucleosynthesis yields from massive stars at low metallicities that can accommodate our results.

Subject headings: Galaxy: abundances — Galaxy: evolution — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: late-type — stars: Population II

1. INTRODUCTION

The halo dwarfs contain fossilized records of the early Galaxy's composition. The chemical composition of their atmospheres is not altered by any internal mixing and provides a unique opportunity to constrain models of the chemical evolution of the Galaxy. Oxygen is a key element in this scheme. It is produced in the interiors of massive stars by hydrostatic burning and returned to the interstellar medium (ISM) when the stars explode as Type II supernovae (SNe).

There have been numerous investigations of the oxygen abundances in halo stars. Despite considerable observational effort, the trend of the $[\text{O}/\text{Fe}]$ ratio with $[\text{Fe}/\text{H}]$ is still unclear. Analysis of the forbidden line [O I] 6300 in giants shows a plateau with $[\text{O}/\text{Fe}] = 0.4$–0.5 in the metallicity domain $-3 < [\text{Fe}/\text{H}] < 0$ (Barbuy 1988; Kraft et al. 1992). On the other hand, results based on the near-IR triplet at 7771−5 Å in unevolved subdwarfs (Abia & Rebolo 1989; Tomkin et al. 1992; King & Boesgaard 1995; Cavallo, Pilachowski, & Rebolo 1997) point toward increasing $[\text{O}/\text{Fe}]$ values with decreasing $[\text{Fe}/\text{H}]$, reaching a ratio $\sim 1$ for stars with $[\text{Fe}/\text{H}] \sim -3$ (but see Carretta, Gratton, & Sneden 2000) and suggesting a higher production of oxygen during the early life of the Galaxy. More recent non-LTE (NLTE) analyses of the triplet in metal-poor stars have been performed by Mishenina et al. (2000), Carretta et al. (2000), and Takeda et al. (2000) showing a range for the NLTE abundance corrections.

Studies based on OH lines in the near-UV (Bessell, Sutherland, & Ruan 1991; Nissen et al. 1994) concluded that $[\text{O}/\text{Fe}]$ is constant at $[\text{Fe}/\text{H}] < -1$, in agreement with results based on the forbidden lines in giants. Contrary to this, oxygen abundances derived from near-UV OH lines for 24 metal-poor stars by Israeliian, García López, & Rebolo (1998) show that the $[\text{O}/\text{Fe}]$ ratio increases from 0.6 to 1 between $[\text{Fe}/\text{H}] = -1.5$ and $-3$ with a slope of $-0.31 \pm 0.11$. These new abundances derived from low-
excitation OH lines agreed well with those derived from high-excitation lines of the O I triplet. The comparison with oxygen abundances derived using O I data from Tomkin et al. (1992) showed a mean difference of $0.00 \pm 0.11$ dex for the stars in common. Boesgaard et al. (1999b), using high-quality Keck spectra of many metal-poor stars in the near-UV, found a very good agreement with the results obtained by Israelian et al. (1998) and basically the same dependence of $[O/Fe]$ versus metallicity. The mean difference in oxygen abundance for 10 stars in common is $0.00 \pm 0.06$ dex when the differences in stellar parameters are taken into account.

The linear trend of the $[O/Fe]$ ratio found in the analysis of OH and triplet lines has been recently questioned by Fulbright & Kraft (1999, hereafter FK99), who obtained low values of $[O/Fe]$ for two metal-poor subgiants using the [O I] lines. In the present paper we discuss their claims in light of an NLTE analysis of Fe lines and report on new detections of the OH and O I triplet lines in several unevolved ultra-metal-poor stars with $[Fe/H] \leq -2.5$.

## 2. OBSERVATIONS

The spectroscopic observations of several metal-poor subdwarfs were carried out in different runs using the 4.2 m WHT/UES (La Palma), the 10 m Keck I/HIRES (Hawaii), and the 8.2 m VLT Kueyen/UVES (Paranal). See the observing log in Table 1. All observations with WHT/UES were obtained using the E31 grating. In the first run (1996) we observed BD $+03^\circ 740$, BD $+23^\circ 3130$, and G4-37 using a 1$'$.1 slit and a TEK CCD (1024 $\times$ 1024 pixel$^2$ giving a dispersion of 0.06 $\AA$ pixel$^{-1}$). The same configuration but a CCD SITE1 (2148 $\times$ 2148 pixel$^2$ detector giving a dispersion of 0.076 $\AA$ pixel$^{-1}$) was used to obtain a few images of G64-37 in 1997. This star, together with G268-32, was observed in 1999 with the same configuration and a slit width of 3$'$.0. All the WHT/UES images were reduced using standard IRAF routines. Normalized flats created for each observing night were used to correct the pixel-to-pixel variations, and a ThAr lamp was used to find a dispersion solution. Observations with the 2.5 m Nordic Optical Telescope (NOT) and the SOFIN high-resolution spectrograph were used only to study the Fe abundance of some of the targets. A resolving power of $\sim 30,000$ has been achieved with the short camera (350 mm focal length, third camera) with a slit width of $\sim 1'$.0. The CCD used in this run was a 1152 $\times$ 770 pixel$^2$ EEV.

The Keck observations were carried out with the HIRES spectrograph and the TEK 2048 $\times$ 2048 pixel$^2$ CCD, which has been its only detector to date. We did not bin the chip, so the resolution is about 60,000 with the 1$'$.1 slit. The slit length was 14$'$.0, allowing good sky subtraction. The seeing was slightly worse than 1$'$.0. Standard calibration exposures and procedures were used to reduce the data. A red wavelength setting was used to observe the oxygen triplet lines; this setting has incomplete coverage of the echelle format.

The UVES data for G271-162, G275-4, and LP 815-43 were obtained during the commissioning of the instrument, while the data for G64-12 were obtained during the science verification. UVES has two arms: blue and red. In the blue arm the detector is an EEV of 4096 $\times$ 2048 pixel$^2$ of size 15 $\mu$m. In the red arm the detector is a mosaic of two CCDs: an EEV identical to that of the blue arm and an MIT with the same number of pixels and pixel size as the EEV. The data for G271-162 consist of four spectra in the red arm centered at 7100 $\AA$ with a slit width of 0$'$.3, which results in a resolution of $\approx 110,000$. These spectra are the same ones used by Nissen et al. (2000) although they have been independently reduced by us. The O I triplet falls on the MIT CCD. The spectra of G271-162 were trailed along the slit for G275-4 the data consist of three spectra taken with dichroic I, the blue arm spectra are all centered at 3460 $\AA$, while the red arm spectra are centered at 5400, 5800, and 8600 $\AA$. The only red spectrum used in this paper is that centered at 8600 $\AA$, in which the triplet (not detected) falls on the EEV CCD. The slit width was 1$'$.0 both for the red and the blue arm. For LP 815-43 we also have three spectra, but taken in the blue arm only (no dichroic). Two spectra were taken with a slit width of 1$'$.1 and one with a slit width of 0$'$.8. In order to combine the spectra, the higher

### TABLE 1

**Observing Log**

| Configuration     | $\lambda/\Delta \lambda$ | Spectral Region (\AA) | Date       | Target | $V$ | Exposure Time (s) | S/N |
|-------------------|--------------------------|-----------------------|------------|--------|----|------------------|-----|
| WHT/UES .......... | 30000                    | 5280–10300            | 1999 Jul 26 | G64-37 | 11.13 | 6000             | 150 |
| WHT/UES .......... | 30000                    | 5280–10300            | 1999 Jul 27 | G268-32 | 12.11 | 7500             | 150 |
| WHT/UES .......... | 50000                    | 4120–8100             | 1997 Jun 15 | G64-37 | 11.13 | 3600             | 60  |
| WHT/UES .......... | 50000                    | 4930–7940             | 1996 Oct 25 | BD $+23^\circ 3130$ | 8.95 | 3600             | 250 |
| WHT/UES .......... | 50000                    | 4930–7940             | 1996 Oct 25 | G4-37  | 11.42 | 13600            | 180 |
| WHT/UES .......... | 50000                    | 4930–7940             | 1996 Oct 25 | BD $+03^\circ 740$ | 9.81 | 3600             | 220 |
| NOT/SOFIN ......... | 30000                    | 3800–10600            | 1999 May 31 | BD $+23^\circ 3130$ | 8.95 | 2400             | 50  |
| NOT/SOFIN ......... | 30000                    | 3800–10600            | 1998 Oct 06 | LP 831-70 | 11.62 | 6600             | 80  |
| NOT/SOFIN ......... | 30000                    | 3800–10600            | 1998 Oct 07 | G268-32 | 12.11 | 4800             | 60  |
| Keck I/HIRES ...... | 60000                    | 6430–8750             | 1999 Dec 4  | G275-4 | 12.12 | 3600             | 170 |
| Keck I/HIRES ...... | 60000                    | 6430–8750             | 1999 Dec 4  | LP 831-70 | 11.62 | 2400             | 160 |
| Keck I/HIRES ...... | 60000                    | 6430–8750             | 1999 Dec 4  | G268-32 | 12.11 | 3600             | 170 |
| Keck I/HIRES ...... | 60000                    | 6430–8750             | 1998 Jun 24 | G275-4 | 12.12 | 1200             | 100 |
| VLT/UVES .......... | 110000                   | 6052–8205             | 1999 Oct 11,12,13 | G271-162 | 10.35 | 10800            | 300 |
| VLT/UVES .......... | 40000                    | 3025–3918             | 1999 Oct 8,16 | LP 815-43 | 10.91 | 10800            | 100 |
| VLT/UVES .......... | 40000                    | 3025–3918             | 1999 Oct 9   | G275-4 | 12.12 | 9000             | 80  |
| VLT/UVES .......... | 55000                    | 6652–10433            | 2000 Feb 15  | G64-12  | 11.47 | 9600             | 100 |
| VLT/UVES .......... | 55000                    | 3025–3918             | 2000 Feb 13,15 | G64-12  | 11.47 | 20400            | 120 |

**Note.** S/N is provided at 7760 and 3130 $\AA$ in the red and blue spectra, respectively.
resolution spectrum has been degraded to lower resolution by convolving with a Gaussian of appropriate FWHM. For G64-12 the data consist of four blue and four red spectra observed with dichroic 1. All blue arm spectra are centered at 3460 Å. Two of the red arm spectra are centered at 5800 Å and two at 8600 Å. The triplet falls on the EEV CCD of these latter frames. The slit width was always 0.8' for both arms. The UVES spectra have been background-subtracted, filtered for cosmic rays, flat-fielded, extracted, and wavelength-calibrated using the echelle context of the European Southern Observatory Munich Image Data Analysis (MIDAS).

Our detections of the oxygen triplet are presented in Figure 1. We have detected for the first time the oxygen triplet in G268-32, G4-37, and G271-162. We also report on a possible detection of the bluest line of the triplet with an

![Graph showing the OI triplet and FeI features with metallicities and wavelengths]

Fig. 1.—Oxygen triplet observed in the metal-poor subdwarfs. The metallicities quoted have been estimated in LTE.
Fig. 2.—OH lines in the UVES spectra of three ultra-metal-poor sub-
dwarfs. The metallicities quoted have been estimated in LTE.

equivalent width of 6 mÅ in G64-12. Unfortunately, the line is
located at the edge of the order (which in addition suffers
strong fringing), and therefore we cannot give much weight
to this detection. The presence of the triplet is confirmed in
BD +03°740 (the strongest line was already measured by
Tomkin et al. 1992) and in BD +23°3130. In the latter case
we have detected all three lines of the triplet and measured
equivalent widths of 7 ± 2, 5 ± 2, and 3 ± 2 mÅ, in good
agreement with the observations of Mishenina et al. (2000).

We have achieved the detection of OH lines in the
near-UV spectra of three ultra-metal-poor subdwarfs
observed during VLT/UVES commissioning and science ver-
ification. Most of the unblended OH lines carefully select-
ted and studied by Israeli et al. (1998) have been unam-
biguously detected in the spectra of G64-12, G275-4 (CD
−24°17504), and LP 815-43. Some of these lines are shown
in Figure 2. The signal-to-noise ratio (S/N) in the contin-
uum is given in Table 1. The quality of these spectra allows
us to perform spectral synthesis and to determine the abun-
dance of oxygen.

3. SPECTRAL SYNTHESIS, STELLAR PARAMETERS,
AND ABUNDANCES

The LTE spectrum synthesis program WITA (Pavlenko
1991) and ATLAS9 model atmospheres (R. L. Kurucz 1992,
private communication) were employed in the present
study. However, in this paper we have also performed com-
putations with the MOOG code (Sneden 1973) in order to
be sure that there are no systematic differences connected
with the use of different spectrum synthesis packages.
We found that in all cases considered the agreement between
WITA and MOOG was very good. The solar oxygen abun-
dance used for the differential analysis of OH lines was
\[ \log e(O) = 8.93 \] [on the customary scale in which \[ \log e(H) = 12 \] according to Anders & Grevesse (1989). For
the triplet and [O i] we used the solar abundances
\[ \log e(O) = 8.98 \] and \[ \log e(O) = 8.90 \], respectively, derived by Israeli et al. (1998). The oscillator strengths of the O i
triplet and iron lines were taken from Tomkin et al. (1992)
and O’Brian et al. (1991), respectively. Effective tem-
peratures \( T_{\text{eff}} \) for our stars were estimated using the
Alonso, Arribas, & Martínez-Roger (1996) and Carney
(1983) calibrations versus \( V-K \) colors and cover a wide
range of spectral types and metal content. The K-band
photometry was kindly provided by A. Alonso prior
the publication of the data (A. Alonso 2000, private
communication). Our final \( T_{\text{eff}} \) is an average value obtained
from these two calibrations. Since there are no accurate
Hipparcos parallaxes available for our targets (except for
BD +23°3130), we estimated surface gravities by compar-
ing Strömgren \( b-y \) and \( c_1 \) indices with synthetic ones
generated using the corresponding filter transmissions and a
grid of ATLAS9 blanketed model atmosphere fluxes. For
BD +23°3130 we obtained \( \log g = 3.05 \pm 0.25 \) from the
Hipparcos parallax (Perryman et al. 1997) following the
recipe given in Allende Prieto et al. (1999) and assuming an
infrared flux method (IRFM) based \( T_{\text{eff}} = 5130 \pm 150 \, \text{K} \)
from Israeli et al. (1998). The final stellar parameters of
our targets (except BD +23°3130, which will be treated
separately in § 5), along with a representative selection of
parameters reported by different authors in the literature
(by no means exhaustive), are listed in Table 2. It can be
seen that our parameters are not very different from those
reported in different sources.

For the present analysis we used the same model atmos-
pheres as Israeli et al. (1998), provided by R. L. Kurucz
(1992, private communication) and built with the approx-
imate overshooting option switched on (note that a typo-

| Star          | \( T_{\text{eff}} \) | \( \log g \) | \([\text{Fe/H}]\) | Reference |
|---------------|-----------------|------------|----------------|-----------|
| G4-37         | 6050            | ...        | −2.7           | 1         |
|               | 6124            | ...        | −2.78          | 2         |
|               | 5837            | 4.23       | −2.89          | 3         |
| G64-12        | 6380            | 4.39       | −3.12          | 4         |
|               | 6220            | ...        | −3.24          | 1         |
|               | 6197            | ...        | −3.52          | 2         |
|               | 6318            | 4.2        | −3.37          | 3         |
| G64-37        | 6240            | ...        | −3.15          | 1         |
|               | 6376            | ...        | −2.70          | 2         |
|               | 6310            | 4.2        | −3.22          | 3         |
| G268-32       | 5841            | ...        | −3.5           | 2         |
|               | 6000            | 3.8        | −2.7           | 5         |
|               | 6090            | 3.86       | −2.81          | 3         |
| G271-162      | 5860            | 3.71       | −2.05          | 4         |
|               | 6135            | ...        | −2.69          | 2         |
|               | 6050            | 4.0        | −2.46          | 3         |
|               | 6000            | 4.39       | −3.12          | 4         |
| G275-4        | 6070            | ...        | −3.24          | 1         |
|               | 6168            | ...        | −3.70          | 2         |
|               | 6212            | 4.13       | −3.32          | 3         |
| LP 815-43     | 6380            | 4.39       | −2.64          | 4         |
|               | 6340            | ...        | −3.00          | 1         |
|               | 6423            | ...        | −3.20          | 2         |
|               | 6265            | 4.54       | −3.05          | 3         |
| LP 831-70     | 6000            | 4.40       | −2.85          | 4         |
|               | 6050            | ...        | −3.32          | 1         |
|               | 6119            | ...        | −3.40          | 2         |
|               | 6205            | 4.3        | −2.97          | 3         |
| BD +03°740    | 6146            | 3.98       | −2.5           | 4         |
|               | 6240            | ...        | −2.7           | 1         |
|               | 6401            | ...        | −2.77          | 2         |
|               | 6135            | 4.0        | −2.93          | 3         |

REFERENCES.—(1) Ryan, Norris, & Beers 1999. (2) Thorburn
1994. (3) This paper. (4) Thévenin & Idiart 1999. (5) Norris, Ryan,
& Beers 1997.
have been made using the work of Thévenin & Idiart (1999). In their Figure 9 we can see NLTE corrections for Fe abundances in metal-poor stars as a function of [Fe/H]_LTE. In a first approximation we can see that these corrections mostly depend on metallicity and there is no clear dependence on the effective temperatures and gravities. Hence, we have fitted a third-order polynomial to the data provided in their Table 1, suitably reproducing the trend seen in their figure. The resulting polynomial fit is:

\[
[\text{Fe/H}]_{\text{NLTE}} - [\text{Fe/H}]_{\text{LTE}} = -0.001 - 0.204 \left( [\text{Fe/H}]_{\text{LTE}} \right)^2 - 0.006 \left( [\text{Fe/H}]_{\text{LTE}} \right)^3
\]

We have used this function to estimate the [Fe/H]_NLTE for our stars and listed the resulting values in Table 7. All our targets except two (BD +03°740 and BD +23°3130) are relatively distant, and their colors could be affected by interstellar reddening. Unfortunately, the

\[\text{TABLE 3} \]

ABUNDANCES DERIVED FROM THE OXYGEN TRIPLET AND IRON LINES

| Ion       | \(\lambda\) (Å) | \(\log gf\) | \(\chi\) | G4-37 | G64-37 | G268-32 | G271-162 | LP 831-70 | BD +23°3130 | BD +03°740 |
|-----------|-----------------|-------------|--------|------|-------|--------|---------|----------|------------|------------|
| O I       | 7771.95         | 0.358       | 9.14   | 7.41 | <6.97 | 7.35   | 7.27    | <7.08    | 7.50       | 7.07       |
| O I       | 7774.18         | 0.212       | 9.14   | 7.43 | ...   | 7.21   | 7.31    | ...      | 7.48       | 7.01       |
| O I       | 7775.40         | -0.01       | 9.14   | 7.57 | ...   | 7.23   | 7.28    | ...      | 7.45       | ...        |
| Fe I      | 4271.774        | -0.173      | 1.49   | ...  | 4.24  | 4.61   | 5.24    | 4.55      | 5.26       | ...        |
| Fe I      | 4325.775        | 0.006       | 1.61   | ...  | 4.21  | 4.73   | ...     | ...       | 4.45       | 5.23       |
| Fe I      | 4383.557        | 0.208       | 1.48   | ...  | 4.23  | 4.79   | ...     | ...       | 4.45       | 5.27       |
| Fe I      | 4415.135        | -0.621      | 1.61   | ...  | 4.38  | 4.69   | 5.18    | 4.56      | 4.87       | ...        |
| Fe I      | 5227.192        | -1.227      | 1.56   | 4.61 | 4.26  | 4.73   | ...     | 4.49      | ...        | 5.10       |
| Fe I      | 5232.952        | -0.057      | 2.94   | 4.63 | 4.31  | 4.59   | 4.98    | ...       | 4.83       | 4.44       |
| Fe I      | 5269.550        | -1.333      | 0.86   | 4.62 | 4.31  | 4.67   | ...     | 4.66      | 4.98       | 4.62       |
| Fe I      | 5397.141        | -1.982      | 0.91   | 4.58 | 4.31  | 4.76   | 5.07    | 4.62      | 5.08       | 4.59       |
| Fe I      | 5405.785        | -1.852      | 0.99   | 4.61 | 4.35  | 4.77   | 5.01    | 4.62      | 5.06       | 4.58       |
| Fe I      | 5429.706        | -1.881      | 0.96   | 4.65 | 4.39  | 4.66   | ...     | ...       | 5.08       | 4.61       |
| Fe I      | 5434.534        | -2.126      | 1.01   | 4.61 | 4.35  | 4.80   | 5.02    | ...       | 5.09       | 4.57       |
| Fe I      | 5569.630        | -1.881      | 3.42   | 4.77 | ...   | ...    | 4.90    | ...       | ...        | 4.68       |
| O(mean)   | ...             | ...         | ...    | 4.74±0.09 | ... | 7.26±0.07 | 7.29±0.03 | ...       | 7.48±0.03 | 7.04±0.04 |
| Fe(mean)  | ...             | ...         | ...    | 4.63±0.06 | 4.30±0.06 | 4.71±0.07 | 5.06±0.12 | 4.55±0.08 | 5.07±0.14 | 4.59±0.07 |

\[\text{TABLE 4} \]

ABUNDANCES DERIVED FROM THE OH AND Fe I LINES

| Ion       | \(\lambda\) (Å) | \(\log gf_{\alpha}\) | \(\log gf_{\alpha}\) | \(\chi\) | G275-4 | G64-12 | LP 815-43 |
|-----------|-----------------|----------------------|----------------------|--------|--------|--------|-----------|
| OH        | 3085.199        | -1.971               | -2.060               | 0.843  | 6.70   | 7.15   | 6.90      |
| OH        | 3123.948        | -2.003               | -2.086               | 0.204  | 6.90   | 7.05   | 6.80      |
| OH        | 3127.687        | -1.588               | -1.590               | 0.612  | 6.85   | 6.95   | 6.70      |
| OH        | 3128.266        | -2.074               | -2.070               | 0.209  | 6.90   | 7.10   | 6.85      |
| OH        | 3139.169        | -1.563               | -1.762               | 0.760  | ...    | 6.95   | ...       |
| OH        | 3140.730\(^a\) | -1.994               | -2.090               | 0.300  | ...    | 6.95   | 6.90      |
| OH        | 3167.169        | -1.544               | -1.694               | 1.108  | ...    | 7.05   | 6.85      |
| OH        | 3186.084        | -1.859               | -2.097               | 0.685  | 6.90   | 7.10   | 6.80      |
| Fe I      | 3786.682        | -2.185               | ...                  | 1.01   | 4.26   | 4.23   | 4.43      |
| Fe I      | 3787.891        | -0.838               | ...                  | 1.01   | 4.08   | 4.09   | 4.49      |
| Fe I      | 3790.098        | -1.739               | ...                  | 0.99   | 4.23   | 4.21   | 4.53      |
| Fe I      | 3820.436        | 0.157                | ...                  | 0.86   | 4.15   | 4.07   | 4.46      |
| Fe I      | 3821.187        | 0.198                | ...                  | 3.27   | ...    | 4.20   | 4.52      |
| Fe I      | 3825.891        | -0.024               | ...                  | 0.91   | 4.29   | 4.10   | 4.46      |
| O(mean)   | ...             | ...                  | ...                  | 6.85±0.09 | 7.05±0.08 | 6.82±0.09 | ...       |
| Fe(mean)  | ...             | ...                  | ...                  | 4.20±0.08 | 4.15±0.07 | 4.48±0.04 | ...       |

\(^a\) The log \(gf_{\alpha}\) values for the OH and Fe I lines are from Gillis et al. 2001 and O'Brien et al. 1991, respectively. The log \(gf_{\alpha}\) values come from Israeli et al. 1998.

\(^b\) The line \(\lambda 3140.73\) has been added from the list of Nissen et al. 1994 and was also used by Boesgaard et al. 1999b.
reddening values of our targets are very uncertain, and we have decided not to consider them. The reddening correction will increase the $T_{\text{eff}}$ values of our stars that will increase the oxygen abundances derived from the OH and [O I] lines and diminish the abundance derived from the triplet.

In Table 3 we present oxygen LTE abundances from the parameters given in Table 2. It is well known that the oxygen abundance in metal-poor subdwarfs derived from the O I is slightly sensitive to NLTE effects (Kiselman 1993; Takeda 1995). Tomkin et al. (1992) estimate NLTE corrections of less than 0.1 dex for hot subdwarfs with $T_{\text{eff}}$ around 6200 K. Our stars have these temperatures, and corrections will be of this order or smaller because of the weakness of our triplet lines. However, larger NLTE corrections could be necessary if the hydrogen collision rates employed by Tomkin et al. (1992) were overestimated, as suggested by Fleck et al. (1991) and Belyaev et al. (1999).

Oxygen abundances in G275-4, G64-12, and LP 815-43 were derived by fitting the OH lines (see Fig. 3) in the

![Graph of normalized flux vs. wavelength for G64-12 OH](image1)

![Graph of normalized flux vs. wavelength for G64-12 OH](image2)

![Graph of normalized flux vs. wavelength for G64-12 OH](image3)

**Fig. 3.**—Synthetic spectral fits to the OH lines in the UVES spectrum of G64-12. The synthetic spectra are computed for $\log \epsilon(\text{O}) = 6.95, 7.05, \text{and} 7.15$. 
near-UV with oscillator strengths adjusted to reproduce the solar spectrum (log $g_{f, \text{obs}}$ used by Israeliian et al. 1998). The adjustments were most probably due to imprecise $g_f$-values of other weak lines blended with OH. It is well known that the line lists available in the literature are not complete and/or perfect, and Israeliian et al. (1998) tried to minimize empirically the effect they could have by adjusting the $g_f$-values of the OH. It is possible that some of these blended lines will disappear in metal-poor stars (especially if they belong to one of the Fe group elements), causing a systematic difference in oxygen abundance. However, this will not affect our [O/H] ratios by more than 0.1 dex.

The results for each star and each line are listed in Table 4. In this table we also provide theoretical log $g_{f, \text{th}}$ values derived from new transition probabilities recently computed by Gillis et al. (2001). When computing new theoretical $g_f$-values from the transition probabilities provided by Gillis et al. (2001), we found two mistakes in Table 2 of Israeliian et al. (1998). The values of log $g_{f, \text{th}}$ for the 3167.169 and 3186.084 Å lines were not correct. The correct values of log $g_{f, \text{th}}$ must be $-1.540$ and $-1.830$ for the 3167.169 and 3186.084 Å lines, respectively. It can be seen from our Table 4 and Table 2 of Israeliian et al. (1998) that these new $g_f$-values of Gillis et al. (2001) are almost identical to those of Goldman & Gillis (1981) and that the maximum difference between the log $g_f$ values adjusted to reproduce the solar OH lines and the new theoretical ones is $-0.24$ dex, while the mean difference correction is $-0.11$ dex. We note that the most accurate measurement is achieved in G64-12 where the error in oxygen abundance due to the continuum placement for individual OH lines is as small as 0.2 dex (see Fig. 3). However, in the case of G275-4 these errors may reach 0.35 dex. We regard the clear detection of OH lines in G64-12 as an important confirmation of the linear trend of [O/Fe] versus [Fe/H]. Indeed, even if we suppose that the near-UV continuum is not well determined and that the $g_f$-values of the OH lines are underestimated, the [O/Fe] ratio in G64-12 will decrease because of this effect by 0.1 at most. In addition, assuming for this star the smallest effective temperature reported in the literature ($T_{\text{eff}} = 6197$ K; Table 2) would bring the [O/H] ratio down by another 0.2 dex. In any case we would obtain a value of [O/Fe] > 0.9.

4. HOW RELIABLE ARE THE ABUNDANCES DERIVED FROM THE O I TRIPLET, OH, AND [O I]?  

Recently, Mishenina et al. (2000) performed an NLTE analysis of the O I triplet to rederive oxygen abundances for a sample of 38 metal-poor stars from the literature. They confirmed earlier results (Abia & Rebolo 1989; Tomkin et al. 1992; Kiselman 1993) indicating that the mean value of the NLTE correction in unevolved metal-poor stars is typically 0.1 dex and never exceeds 0.2 dex. Mishenina et al. (2000) found the same linear trend as Israeliian et al. (1998) and Boesgaard et al. (1999b) from the OH lines and confirmed that oxygen abundances do not show any trend with $T_{\text{eff}}$ or log $g$ (Boesgaard et al. 1999b). Furthermore, Asplund et al. (1999) showed that the O I triplet is not affected by three-dimensional effects, convection, or small-scale inhomogeneities in the stellar atmosphere. In addition, oxygen abundances derived from this triplet are not significantly affected by chromospheric activity either, showing that the O I triplet provides reliable oxygen abundances in metal-poor dwarfs. Preliminary calculations by Asplund et al. (1999) and Asplund (2000) show that three-dimensional models give stronger OH lines than those computed with one-dimensional models, which would decrease the oxygen abundances found in the present paper. However, (1) the precise value of three-dimensional corrections will consistently require a revision of the stellar parameters according to the same models, and (2) Fe abundances including NLTE effects should be obtained with these models in order to estimate the [O/Fe] ratio properly.

Carretta et al. (2000) performed an independent analysis of 32 metal-poor stars hotter than 4600 K using the triplet and provide LTE and NLTE oxygen abundances that are significantly lower than those found in previous works. A preliminary attempt to understand the reasons for this discrepancy can be made by looking in detail into their most metal-poor star (BD +03°740, [Fe/H] = -2.66), where a surprisingly low oxygen abundance ([O/Fe] = 0.38) is claimed. A recent study of stellar parameters based on the NLTE analysis of iron lines (Thévenin & Idiart 1999) gives a lower effective temperature by 140 K (actually very similar to the temperature we have derived in this paper) and a higher gravity by 0.3 dex (also very similar to ours) than the values adopted by Carretta et al. (2000) for this star. Using the Thévenin & Idiart (1999) parameters, we obtain an LTE oxygen abundance 0.4 dex higher than that found by Carretta et al. (2000; i.e., [O/Fe]$_{\text{LTE}}$ = 1.05), and for a star with these parameters the NLTE correction to the oxygen abundance is of the order of 0.05 dex (Mishenina et al. 2000; Tomkin et al. 1992), much lower than the 0.25 dex value used by Carretta et al. (2000). We therefore arrive at a value [O/Fe]$_{\text{NLTE}}$ ~ 1.0, in good agreement with the OH determination by Boesgaard et al. (1999b). The oxygen abundances derived by Carretta et al. (2000) are computed using the gravities from Gratton, Carretta, & Castelli (1996), whose values come from an LTE Fe ionization balance. As a matter of fact, Gratton et al. (1996) remark that their gravities are considerably lower (see their Fig. 2) than those derived from the color-magnitude diagram. They also suggest that this discrepancy may be due to an NLTE effect. The OH lines may be affected by the UV “missing opacity,” as discussed by Balachandran & Bell (1998). Allende Prieto & Lambert (2000) found a good agreement between effective temperatures obtained from the IRFM and from the near-UV continuum for stars with 4000 < $T_{\text{eff}}$ ≤ 6000 K when accurate Hipparcos gravities are used. This also agrees with our good reproduction of the near-UV spectral region and indicates that the model atmospheres used provide an adequate description of the near-UV continuum-forming region. In any case, even if a poorly understood opacity problem existed as described by Balachandran & Bell (1998), it would have a minor effect on the OH results since most of the stars in the samples of Israeliian et al. (1998) and Boesgaard et al. (1999b) are hotter than the Sun and very metal poor. It must be mentioned that the OH lines employed by Israeliian et al. (1998) and Boesgaard et al. (1999b) to study the most metal-poor stars in their samples are from the (0, 0) band, where the corrections to theoretical $g_f$-values are not large. Considering the list used by Israeliian et al. (1998), we note that only for three lines out of 12 these corrections exceed 0.15 dex. The same is true for the list employed by Boesgaard et al. (1999b), who used $g_f$-values from Nissen et al. (1994). The corrections applied to their $g_f$-values are only 0.15 dex. Thus, corrections to oxygen abundances due to opacity problems should not exceed 0.15 dex for the stars used in the present.
study. This will not change the [O/Fe]-versus-[Fe/H] trend significantly.

The forbidden line of oxygen is sensitive to the stellar gravity. Israelian et al. (1998) synthesized this line for four dwarfs adopting the same set of stellar parameters as in the OH analysis, the gf-value given by Lambert (1978), and the equivalent widths provided in the literature for the 6300 Å line. The estimated abundances are in good agreement with those derived from OH when gravities from Hipparcos are used. This strongly suggests that a reliable gravity scale may indeed be the key to explaining the discrepancies in oxygen abundances from forbidden and permitted lines in unevolved metal-poor stars. This conclusion is supported by Mishenina et al. (2000), who also found good agreement between [O l] and the triplet for three unevolved halo stars in their sample. Nevertheless, all stars with measured [O l] in Mishenina et al. (2000) and Israelian et al. (1998) have [Fe/H] > −1.4 and leave open the possibility that differences between oxygen indicators may appear at much lower metallicities. Indeed, FK99 claimed that there were inconsistent results for the two metal-poor stars BD +23°3130 and BD +37°1458 using stellar parameters derived from an LTE analysis of iron lines. These objects were also considered by Israelian et al. (1998) and Boesgaard et al. (1999b) (only BD +37°1458 in the latter case). While the conclusions of FK99 for BD +37°1458 do not challenge the linear trend in [O/Fe], their results for BD +23°3130 are claimed to be inconsistent with those from OH lines. However, we argue in the next section that this discrepancy cannot be sustained when a critical analysis of the uncertainties involved in the determination from the forbidden line is performed.

It is often claimed in the literature that the abundances derived from the forbidden lines are more reliable than those from the triplet and OH. The authors of this statement refer mainly to the fact that the forbidden lines at 6300 and 6363 Å are not affected by NLTE effects and are less sensitive to the uncertainties in $T_{\text{eff}}$. However, results based on the forbidden lines should be interpreted with caution. Figure 4 demonstrates that very small errors in the equivalent widths of the forbidden line at 6300 Å may have a dramatic effect on the derived oxygen abundances. Very high S/N is required in order to minimize this uncertainty, a condition that is normally not satisfied in most of the studies based on the forbidden line. For example, Barbuy (1988) used data with an S/N of 90 and $R \sim 40,000$ in order to derive the oxygen abundance from the forbidden line (EW = 4 mÅ) in the most metal-poor giant in her sample, BD -18°5550 ([Fe/H] = −3). Note that an S/N of ~90 optimistically implies about $± 2$ mÅ of uncertainty (at 1 σ level) in the equivalent width according to Cayrel’s formulae (Cayrel 1988), which introduces an uncertainty in the derived abundance of oxygen larger than 0.18 and −0.3 dex (Fig. 4). To this error (which comes from measuring only one weak line) we must add the systematic errors due to the uncertainties in gravity (note that Barbuy 1988 used only three lines each of Sc I and Sc II to estimate the gravity) and effective temperature. This makes the total error from the [O l] line large.

Another problem is that the gravities of metal-poor giants derived from the LTE Fe analysis are most probably underestimated because of the neglect of NLTE effects. This effect is already proven to exist in metal-poor dwarfs (Thévenin & Idiart 1999) and also in a subgiant (BD +23°1330; this paper). It has been argued (Thévenin & Idiart 1999; Gratton et al. 1996) that this effect also operates in metal-poor giants. Work is in progress to study NLTE effects on Fe in several metal-poor giants, and our preliminary results indicate that corrections to gravities derived from the LTE analysis of Fe can indeed be as large as 0.5 dex. We also note that recently Takeda et al. (2000) proposed that the [O l] lines in metal-poor giants may suffer some filling in emission that leads to the weakening of the absorption lines. This possibility has been noticed by Langer (1991), who proposed that the emission from the surrounding nebulosity, formed from the mass ejected in the post-RGB phase, may account for the observed weakness of the forbidden lines. The fact that some giants such as HD 115444 show [O/Fe] about 0.3 dex larger (Westin et al. 2000) than “expected” from the plateau ([O/Fe] ~ 0.4) supports this idea. This is also consistent with the fact that there is no discrepancy between [O l], O I, and OH in several unevolved dwarfs.

5. THE PARTICULAR CASE OF BD +23°3130

The analysis carried out by FK99 is based on gravities derived from LTE Fe ionization balance of these subgiants where the NLTE effects are strong. In general, NLTE effects play a dominant role in very metal-poor stars as a result of a decrease in electron density. Collisions with free electrons no longer dominate the kinetic equilibrium as they do in the stars of solar composition, and this leads to significant deviations from LTE. Another consequence of the metal deficiency is an appreciable weakening in UV blanketing. Both effects lead to a large depletion of the Fe I atoms affecting the equivalent widths and central depths of spectral lines (Shchukina & Trujillo Bueno 2001). In a recent paper, Allende Prieto et al. (1999) have shown that gravities derived using LTE analyses of iron in metal-poor stars do not agree with the gravities inferred from accurate Hipparcos parallaxes, which casts a shadow over oxygen abundance analyses of very metal-poor stars based on gravities derived from the LTE Fe ionization balance. They find that gravities are systematically underestimated when derived from ionization balances and that upward corrections of 0.5
The abundances derived from OH will be affected as well but in the opposite direction. Thévenin & Idiart (1999) derived gravity corrections of up to 0.5 dex with respect to LTE values, for the case of stars with [Fe/H] — 3.0. They have shown that NLTE effects are important in determining stellar parameters from ionization balance.

It has been established (see Rutten 1988 and references therein) that a strong overionization of neutral iron in metal-poor stars leads to the systematic difference in abundances determined from the Fe I and Fe II lines. This difference increases with decreasing metallicity. For the Fe II lines NLTE effects are found to be unimportant. The NLTE modeling predicts a dependence of the NLTE abundance corrections of Fe I lines on the lower excitation potential (χ). The corrections are particularly large for the low-excitation Fe I lines. Empirical determinations by Ruland et al. (1980), Magain (1988), and Magain & Zhao (1996) support this conclusion. The NLTE abundance corrections in the Sun are in the range 0.02–0.1 dex, while in the main-sequence stars later than type A they can reach 0.3–0.4 dex. Taking the above into account, we evaluate the extent to which NLTE effects could influence the determination of the stellar parameters of BD +23°3130.

5.1. NLTE Analysis

5.1.1. The Models and the NLTE Solution

Our study is based on horizontally homogeneous models of LTE atmospheres in hydrostatic equilibrium. The grid of interpolated ATLAS9 models is used to perform NLTE computations spanning the following range of atmospheric parameters: 4800 ≤ Teff ≤ 5130 K, 2 ≤ log g ≤ 3, and −3 ≤ [Fe/H] ≤ −2.5. Our NLTE stellar parameter analysis is based on the usual assumptions that (1) iron abundances used to fit equivalent widths of Fe I and Fe II lines to observed ones have to be independent of excitation potential of the lower level χ; (2) the iron abundances have to be independent on the line strengths, namely, the stronger Fe I lines have to give on average the same abundance as the weaker ones; and (3) the average abundances obtained from Fe I and Fe II lines have to be equal.

The theoretical equivalent widths of the Fe I and Fe II lines were computed using the formal solution of the radiative transfer equation. NLTE departure coefficients were found from the self-consistent solution of the kinetic and radiative transfer equations using a new NLTE code, NATAJA (for details see Shchukina & Trujillo Bueno 1998, 2001). Here it is enough to mention that we employed novel and effective iterative multilevel transfer methods and formal solvers that are capable of handling hundreds of transitions efficiently and make feasible two- and three-dimensional multilevel modeling (Auer, Fabiani Bendicho, & Trujillo Bueno 1994; Trujillo Bueno & Fabiani Bendicho 1995). Our Fe I + Fe II atomic model takes into account a multiplet structure and includes over 250 levels and 500 UV, optical, and IR transitions including the regime near Fe I continuum. The Fe I term diagram is, in fact, complete up to χ ≈ 5.7 eV. At higher energies it contains about 50% of the terms identified by Nave et al. (1994). The Fe II diagram is very similar to the atomic model of Gigas (1986). It contains only the lowest terms with χ < 5.9 eV and 25 strong transitions (see Shchukina & Trujillo Bueno 1998, 2001).

5.1.2. Spectral Lines Selected for the Analysis

Notwithstanding such a comprehensive atomic model, it contains only 21 lines from the list of Fe I lines observed and measured in the spectrum of BD +23°3130 by FK99. All of them except one line cluster into a narrow χ range between 2 and 3 eV. We marked them in Figures 5 and 6 by large open circles. The only line that is outside the range (7511.02 Å) has χ = 4.16 eV.

This selection effect prevents us from using the Fe I abundance–versus–χ trend as a criterion of correctness of the stellar parameters. To avoid this shortcoming, we tried to extend our line list to larger χ samples. According to FK99, LTE synthesis of the 58 Fe I lines for the atmospheric model with parameters derived by these authors (Teff = 4850, log g = 2, and log ε = 4.69) produces very good agreement with observations (the standard deviation, σ, is only 0.04 dex). If we assume that these stellar parameters reproduce both the equivalent widths from FK99 and that such modeling of Fe I lines is correct not only for their observed list of Fe I lines but also for other Fe I lines located in the same wavelength region (4000–8000 Å), then we can consider synthetic LTE equivalent widths of the latter lines as “observed” ones. Following this idea, we have selected from our atomic model 98 Fe I lines and calculated their LTE equivalent widths using the model atmosphere with stellar parameters obtained by FK99. Furthermore, these equivalent widths, ranging from 1.5 to 80 mA, are considered as “quasi-observations.” The wavelengths of these Fe I lines, their χ values, and oscillator strengths are listed in Table 5. Note that these lines are distributed rather uniformly with χ. In addition to the line cluster between 2 and 3 eV, the new set contains 13 Fe I lines with χ < 2 eV, 27 lines in the range 3–3.8 eV, and 17 lines with χ > 3.8 eV. Using our list of Fe I lines we obtain with the stellar parameters of FK99 the same LTE Fe abundance claimed in their paper. It is interesting to note that everywhere in our figures abundances for the aforementioned high-excitation Fe I line λ7511.02 deviate considerably in comparison with those for other high-excitation lines. For Fe II lines we used the real observations obtained by FK99, which include seven lines.

5.2. NLTE Abundance Correction

Our NLTE simulation reveals that Fe II lines in all the atmospheric models considered do not in fact suffer from NLTE effects. However, this is not the case for the Fe I lines. The LTE abundances derived from the Fe I lines are lower compared with NLTE values. Our computations clearly demonstrate that for the fixed value of metallicity the NLTE corrections are very sensitive to the changes in Teff and log g. The NLTE correction increases with Teff as a result of the ultraviolet overionization effects. For the same Teff a larger gravity results in larger NLTE abundance corrections. The mean δ log ε are in the range 0.2–0.35 dex.

The NLTE abundance corrections for individual Fe I lines and for the stellar parameters of BD +23°3130 suggested by FK99 are plotted in Figure 5. The abundance corrections are largely independent of the excitation potential up to χ ≈ 2 eV. However, δ log ε decreases when the lines with χ > 2 eV are considered. The mean value of the NLTE abundance correction δ log ε for the Fe I lines is 0.22 dex, while for the Fe II lines there are no corrections for...
Fig. 5.—Results of NLTE abundance determinations for Fe i lines and model atmosphere with parameters $T_{\text{eff}} = 4850$ K, $\log g = 2$, $V_t = 1.35$, and $\log \epsilon = 4.69$. The lines with $\chi < 0.8$ eV are marked as squares, the lines with $0.8 < \chi < 1.8$ eV as small open circles, the lines with $1.8 < \chi < 2.2$ eV as plus signs, $2.2 < \chi < 3.0$ eV as triangles, $3 < \chi < 3.8$ eV as stars, and $3.8 < \chi < 4.8$ eV as crosses. The lines of Fe II are marked as filled circles. Top: NLTE abundances as a function of the lower excitation potential $\chi$. Middle: NLTE abundance corrections vs. $\chi$. Bottom: NLTE abundances as a function of reduced equivalent widths $\log \left( EW/\lambda \right)$. The results for Fe i lines of different $\chi$ classes are denoted by different symbols. Fe i lines from the line list by Fulbright & Kraft (1999) are marked by large open circles.

departures from LTE. Although the standard deviation of the abundance derived from Fe i lines is not very large (0.07 dex), there is a trend with $\chi$ and a clear gap of 0.11 dex between the abundances derived from the “low-” ($\chi < 3.8$ eV) and “high-excitation” ($\chi > 3.8$ eV) lines. In general, the gap is smaller in the case of LTE. It is also interesting to point out that dependence on the line strength is less pronounced.

Our computations confirm the results by Thévenin & Idiart (1999) that the LTE Fe analysis in very metal-poor stars strongly underestimates gravities and metallicities. If we take into account the NLTE abundance corrections, the stellar parameters suggested by FK99 do not meet the condition requiring equal abundances derived from the Fe i and Fe II lines. The abundance difference due to neglect of the NLTE effects in the ionization equilibrium balance
amounts to 0.2 dex. We found that the parameters used by Israeli et al. (1998) do not meet the conditions listed in § 5.1.1 either. Figure 6 shows that a model similar to the one used by FK99, but with a gravity that is higher by 0.5 dex, is able to improve the situation considerably. With such a model the difference in abundances derived from Fe I and Fe II lines becomes only 0.026 dex, while the standard deviation from the mean abundance derived from the Fe I lines is 0.06. The gap between “low-” (χ < 3.8 eV) and “high-excitation” (χ > 3.8 eV) lines has also decreased to 0.07 dex.

5.3. Uncertainties in the NLTE Analysis

Classical abundance determination depends on a large number of parameters. We evaluated the sensitivity of the abundances, log ε, derived from the Fe I and Fe II lines to the uncertainties of the most important parameters.

Several tests showed that a change in the enhancement factor, E, of the van der Waals damping constant, εv, from 1.5 to 2.0 produces changes of less than 0.04 dex in the Fe I abundance and can be neglected. The strongest low-
Excitation lines display the largest errors. The lines with equivalent widths $EW < 80$ mÅ are insensitive to the uncertainties in $E$ factors. Fortunately, all Fe I and Fe II lines from Table 5 have equivalent widths smaller than this value.

The values of microturbulent velocity ($V_t$) used by Israeliian et al. (1998) and FK99 for BD $+$23$^\circ$3130 differ by 0.35 km s$^{-1}$. Our tests show that Fe I lines with $EW \approx 80$ mÅ and $\chi < 3$ eV are most sensitive to $V_t$. However, even in that case the influence of the microturbulence uncertainties could be reduced or even eliminated by using lines with $EW < 30$ mÅ. It turned out that the change in log $e$ corresponding to $0.35$ km s$^{-1}$ for the Fe I lines listed in Table 6 is $\sim 0.04$ dex. Thus, the influence of uncertainties in the microturbulent velocity on the abundance derived from Fe I lines is negligibly small.

The accuracy of the oscillator strengths has a strong influence on the dispersion and the mean value of the iron abundance derived from Fe I lines. In our study we used for low-excitation lines ($\chi < 3$ eV) mainly the Oxford $gf$-values (Blackwell et al. 1979a, 1980, 1982a, 1982b; Blackwell, Petford, & Shallis 1979b; Blackwell, Booth, & Petford 1984; Bard et al. 1991; Holweger et al. 1991, 1995. (5) Lambert et al. 1996. (6) Gurvenco & Kiss 1989. (7) Bridges & Kornblith 1974.

### Table 5

Fe I Line List for BD $+$23$^\circ$3130

| Wavelength | $\chi$ | log $gf$ | Reference | Mult. Number |
|------------|--------|-----------|-----------|--------------|
| 4011.710... | 2.450  | $-2.693$  | 1         | 135          |
| 4055.030... | 2.559  | $-0.815$  | 1         | 218          |
| 4076.630... | 3.211  | $-0.356$  | 1         | 555          |
| 4084.498... | 3.332  | $-0.597$  | 1         | 698          |
| 4085.300... | 3.241  | $-0.708$  | 1         | 559          |
| 4100.740... | 0.859  | $-3.179$  | 1         | 18           |
| 4112.960... | 4.178  | $-0.325$  | 1         | 1103         |
| 4126.180... | 3.332  | $-0.959$  | 1         | 695          |
| 4181.750... | 2.832  | $-0.187$  | 1         | 354          |
| 4199.090... | 3.047  | $-0.250$  | 1         | 522          |
| 4216.026... | 0.000  | $-3.356$  | 1         | 3            |
| 4219.360... | 3.573  | $0.120$   | 1         | 800          |
| 4224.170... | 3.368  | $-0.400$  | 1         | 689          |
| 4276.680... | 3.882  | $-1.207$  | 1         | 976          |
| 4282.400... | 2.176  | $-0.810$  | 1         | 71           |
| 4285.440... | 3.237  | $-1.190$  | 1         | 597          |
| 4326.750... | 2.949  | $-1.920$  | 1         | 413          |
| 4388.410... | 3.603  | $-0.580$  | 1         | 830          |
| 4439.880... | 2.279  | $-3.002$  | 1         | 116          |
| 4445.470... | 0.087  | $-5.440$  | 2         | 2            |
| 4484.227... | 3.603  | $-0.724$  | 1         | 828          |
| 4528.610... | 2.176  | $-0.822$  | 1         | 68           |
| 4581.510... | 3.241  | $-1.833$  | 1         | 555          |
| 4602.944... | 1.485  | $-2.155$  | 1         | 39           |
| 4647.430... | 2.949  | $-1.350$  | 2         | 3            |
| 4733.996... | 1.490  | $-2.987$  | 2         | 38           |
| 4736.790... | 3.211  | $-0.752$  | 3         | 554          |
| 4957.603... | 2.808  | $-0.043$  | 3         | 318          |
| 4966.096... | 3.332  | $-0.879$  | 3         | 687          |
| 4973.100... | 3.960  | $-0.955$  | 1         | 984          |
| 4976.600... | 3.984  | $-0.940$  | 1         | 966          |
| 5001.860... | 3.882  | $-0.004$  | 1         | 965          |
| 5012.071... | 0.860  | $-2.642$  | 2         | 16           |
| 5044.210... | 2.850  | $-2.017$  | 3         | 318          |
| 5049.825... | 2.280  | $-1.355$  | 3         | 114          |
| 5162.270... | 4.178  | $0.019$   | 3         | 1089         |
| 5166.286... | 0.000  | $-4.195$  | 2         | 1            |
| 5171.600... | 1.485  | $-1.790$  | 1         | 36           |
| 5198.710... | 2.220  | $-2.135$  | 2         | 66           |
| 5202.339... | 2.180  | $-1.839$  | 2         | 66           |
| 5217.389... | 3.210  | $-1.162$  | 3         | 553          |
| 5232.946... | 2.940  | $-0.057$  | 3         | 383          |
| 5242.495... | 3.630  | $-0.967$  | 3         | 843          |
| 5247.052... | 0.087  | $-4.950$  | 2         | 1            |
| 5250.212... | 0.120  | $-0.940$  | 2         | 1            |
| 5253.460... | 3.280  | $-1.570$  | 4         | 553          |
| 5322.040... | 2.280  | $-3.022$  | 1         | 112          |
| 5324.185... | 3.210  | $-0.100$  | 4         | 553          |
| 5393.174... | 3.340  | $-0.720$  | 4         | 553          |

References—(1) Fuhr et al. 1988. (2) Blackwell et al. 1979a, 1979b, 1980, 1982a, 1982b, 1982c, 1984, 1986. (3) O'Brian et al. 1991. (4) Bard et al. 1991; Holweger et al. 1991, 1995. (5) Lambert et al. 1996. (6) Gurvenco & Kiss 1989. (7) Bridges & Kornblith 1974.
not contain any lines with $\chi > 3$ eV. Our sample of the high-excitation lines is dominated by $gf$-values measured by O’Brien et al. (1991) and the Kiel-Hannover group (Bard, Kock, & Kock 1991; Holweger et al. 1991; Holweger, Kock, & Bard 1995). There is also a large set of the Fe I lines whose measured oscillator strengths are taken from the old sources (compilation by Fuhr, Martin, & Wiese 1988).

Several authors (Grevesse & Noels 1993; Lambert et al. 1996; Grevesse & Sauval 1998) suggest that $gf$-values of the higher excitation Fe I lines that come from laboratory measurements provide likely less accurate results than those from the $gf$-values of low-excitation lines. The use of the oscillator strengths mentioned above opened a new “iron problem” (Grevesse & Noels 1993), namely, “the behavior of the abundance derived from Fe I lines versus the excitation energy for a very large range of $\chi$, from 0 to 7.5 eV, observed in the solar spectrum.” The solar photospheric abundances found from the low-excitation lines using $gf$-values of the Oxford group turn out to be systematically larger than those from high-excitation lines obtained with $gf$ measured by the Kiel-Hannover group and by O’Brien et al. (1991). Since $gf$-values and abundance values enter the line extinction coefficient as a product, such behavior might be attributed to a $gf$ systematic trend of about 0.06 dex (Bard et al. 1991; Holweger et al. 1995; Lambert et al. 1996). Another point of view is to attribute the trend to differences in the atmospheric properties of low- and high-excitation lines (Blackwell et al. 1995) or both effects together (Kostik, Shchukina, & Rutten 1996; Grevesse & Sauval 1998).

The most accurate Fe II oscillator strengths are not yet as accurate as for the Fe I lines. Following FK99, we used $gf$-values obtained by Biémont et al. (1991) and Kroll & Kock (1987). A discussion of these and other sources of the oscillator strengths has been given recently by Grevesse & Sauval (1999) and Lambert et al. (1996). The mean uncertainty in the $gf$-values for Fe II lines is found to be in the range $\pm 0.05$–$0.07$ dex, which corresponds to an abundance dispersion of $\sim 0.1$ dex. Uncertainties of the NLTE abundance corrections $\delta \log \epsilon$ are discussed in detail by Shchukina & Trujillo Bueno (2001). The $\delta \log \epsilon$ values are not very sensitive to uncertainties in collisional rates, photoionization cross sections, continuum opacity, etc. The errors introduced by uncertainties in these parameters may lead to errors in the mean NLTE abundance, $\delta \log \epsilon$, of about $\pm 0.03$ dex.

5.4. Errors of the Stellar Parameter Determinations

Summing up the analyses completed above, we conclude that the largest errors in the iron abundance determination using Fe I lines are expected to be caused by neglecting the NLTE effects. The largest errors in the abundance derived from Fe II lines are caused by the uncertainties in the oscillator strengths (if we exclude the errors in equivalent width measurements). To what extent can these errors influence the stellar parameter determination for the star BD +23°3130?

Our computations show that the variations in $T_{\text{eff}}$ primarily affect the abundance derived from Fe I lines but make little difference to the abundance from Fe II lines. Abundance changes for Fe I lines that result from a 270 K change in effective temperature are in the range $\sim 0.26$ for the LTE case and $\sim 0.36$ dex for NLTE. In the case of Fe II lines they are an order of magnitude smaller. On the contrary, for Fe II lines the gravity dependence is much more pronounced, while for Fe I lines it is negligibly small. As a result, small errors in the Fe I abundances can only be compensated for by large changes in the assumed gravity, or small errors in Fe II abundances can only be fixed by large changes in the assumed effective temperature. Our computations show that for the NLTE $\delta \log \epsilon$ range 0.2–0.35 dex obtained using Fe I lines the correction in $\log g$ may reach $\sim 0.5$ dex in the cooler model ($T_{\text{eff}} = 4850$ K) or even more in the hotter one ($T_{\text{eff}} = 5130$ K). An abundance dispersion of 0.1 dex for Fe II lines causes dispersion of $T_{\text{eff}}$ of 100 K. To reduce the latter effect, it would be extremely desirable to enlarge the set of Fe II lines. It is obvious that the small seven-line sample can be a source of serious troubles in stellar parameter determinations.

5.5. The “Best-Choice” Parameters of BD +23°3130 and Its Oxygen Abundance

Our computations are aimed at finding the NLTE solution that gives the minimum standard deviation, $\sigma$, of the mean abundance and satisfies the criteria discussed in § 5.1.1. If we neglect the offset in abundances derived from the high-excitation ($\chi > 3.8$ eV) and low-excitation ($\chi < 3.8$ eV) lines, then the best model is the one displayed in Figure 6. The “best-choice” stellar parameters for this NLTE case turn out to be $T_{\text{eff}} = 4825$ K, $\log g = 2.5$, and [Fe/H] = −2.66. The top panel shows the NLTE equivalent widths for the atmospheric model represented by these parameters against LTE values computed for the model with parameters by FK99. Agreement between “quasi-observed” equivalent widths and those obtained in NLTE is quite satisfactory. However, if the Fe I line sample is divided into “low” ($\chi < 3.8$) eV and “high” ($\chi > 3.8$) eV samples, the mean NLTE abundances are $4.86 \pm 0.05$ and $4.79 \pm 0.06$ for the “low” and “high” samples, respectively. This means that even this solution cannot be considered as final given the abundance offset found for the two samples of Fe lines.

We could not find a model that did not show an abundance gap between low- and high-excitation lines. This failure can be attributed to our poor knowledge of the atmospheric model structures and is possible as a result of some three-dimensional and/or hydrodynamical effects.

This shortcoming can possibly be avoided if we concentrate our study only on the high-excitation lines with
we must add the systematic one due to uncertainties in
gravity and effective temperature, which makes the total
error in the oxygen abundance from the [O I] line very
large. In conclusion, the failure to detect the forbidden line
cannot be used to question the validity of the abundances
derived from the OH lines and triplet. The new really high
S/N measurement of the forbidden line in this star per-
formed by Cayrel et al. (2000), using UVES at VLT, of
EW = 1.5 ± 0.3 mÅ is perfectly consistent with our deter-
minations of OH and triplet lines, definitely solving the
controversy. We show in what follows that there is consist-
tency between the abundances inferred from the three
oxygen indicators.

Assuming our stellar parameters, the equivalent width measurement by Cayrel et al. (2000) for the forbidden line,
and our new triplet observations and the OH measurements
by Israelian et al. (1998), we find [O/H] = −1.61 ± 0.15,
−1.5 ± 0.14, and −1.83 ± 0.33, respectively. There is a
clear agreement between these three indicators given the
error bars from each measurement. We conclude that in this
cool subgiant it is possible to find a consistent determi-
nation of oxygen abundances using one-dimensional
models and stellar effective temperature from IRFM-based
 calibration and gravity from Hipparcos parallax and/or Fe
NLTE analysis. The plot in Figure 7 shows the difference in
oxygen abundances derived for OH and [O I] in a number of
stars whose parameters have been estimated in this way.
These stars cover the metallicity range from −1 to −2.5
and strongly support the reliability of the linear trend in
oxygen abundances as metallicity decreases. Four of these
stars are listed in Table 4 of Israelian et al. (1998), and
two others were studied by FK99. The [O I] abundance
([O/H] = −1.52) for the star BD +37°1458 ([Fe/H] =
−2.1) has been estimated from the equivalent width of the
[O I] line using a Hipparcos-based gravity (log g =
3.35 ± 0.21) and effective IRFM temperature T_{eff} = 5260
± 100 K from Israelian et al. (1998). Using the same stellar
parameters, we find excellent agreement with the oxygen
abundance [O/H] = −1.50 derived from the OH lines
observed by Israelian et al. (1998).

Using a different calibration, Carretta et al. (2000) have
claimed that their oxygen NLTE analysis yields the same O
abundances from both permitted and forbidden lines for
stars with T_{eff} > 4600 K. If this had been the case, there
would have been no problems with oxygen abundance
derived from the triplet and the forbidden line in BD
+23°3130. Assuming the parameters of FK99 for this star,
one can find from the triplet an LTE abundance
[O/H] = −1.39. In this parameter range the NLTE abun-
dance correction for the triplet is about −0.1 according
to Carretta et al. (2000) and Mishenina et al. (2000). Thus, the
[O/H] = −1.39 ratio obtained from the triplet is in odds
with the [O/H] = −2.49 limit claimed from the undetected
[O I] line by FK99.

6. DISCUSSION

6.1. A Plateau versus Linear Trend

Our results support a linear increase of [O/Fe] with
decreasing metallicity (Table 7 and Figs. 8, 9, 10, and 11).
This is in agreement with some previous analyses (Abia &
Rebolo 1989; Tomkin et al. 1992; King & Boesgaard 1995;
Cavallaro et al. 1997; Israelian et al. 1998; Boesgaard et al.
1999b; Mishenina et al. 2000; Takeda et al. 2000) but at
FIG. 8.—New oxygen abundances derived in this work together with those measured by Israelian et al. (1998), Boesgaard et al. (1999b), and Edvardsson et al. (1993). The results for OH lines are denoted by filled circles, triplet by filled squares, and upper limits from triplet by filled triangles. The asterisks indicate the oxygen abundances derived from OH, triplet, and [O I] for BD +23°3130. Data from Israelian et al. (1998), Boesgaard et al. (1999b), and Edvardsson et al. (1993) are marked by open circles, open diamonds, and crosses, respectively.

odds with others (Barbuy 1988; Kraft et al. 1992; Carretta et al. 2000); there appears to be a clear dichotomy among authors who support a plateau in [O/Fe] for stars with [Fe/H] < -1 and those who do not. The situation is made even more confusing by the fact that there is an overlap both of objects and of O indicators used by authors arriving at different conclusions. The comparison we made with the results of FK99 and Carretta et al. (2000) suggests that the discrepancies are rooted in the atmospheric parameters adopted by different authors. Differences in the observational data, in the one-dimensional models, and in the NLTE treatment of the O I triplet lines are second-order effects. The set of atmospheric parameters chosen is always debatable; however, we wish to point out that our choice provides gravities that are in agreement with Hipparcos parallaxes and achieve consistency among different O indicators, when available. We independently derived metallicities from our spectra and only in one case from equivalent widths taken from the literature (for G271-162). We discard any significant change in the slope of the [O/Fe]-versus-[Fe/H] relation in the whole metallicity range from 0 to -3.1. The corresponding increase in Figure 11 can be fitted using a straight line with a slope $-0.33 \pm 0.02$ (taking the error bars into account).

The existence of a plateau with [O/Fe] $\sim$ 0.4 at [Fe/H] $\sim$ -1 in metal-poor giants could be questioned. The results of Takeda et al. (2000) show that metal-poor giants may have [O/Fe] > 0.6 in the metallicity range [Fe/H] $\sim$ -2. To some extent different conclusions on the existence of a plateau may be derived from the same data set. Tomkin et al. (1992) point out that “a linear least-squares fit to the 10 field giants ($-3 \leq [Fe/H] \leq -1.7$) in Figure 8 of Sneden et al. (1991) provides a slope of $-0.33 \pm 0.10$ for [O/Fe] versus [Fe/H]. . .” It is interesting that this slope derived from the data of Sneden et al. (1991) is in excellent agreement with our value and the slopes found by Israelian et al. (1998) and Boesgaard et al.
| Star               | V - K | $T_{eff}$ | log $g$ | [Fe/H] LTE | [Fe/H] NLTE | [O/H]_{Trip} | [O/H]_{OH} | [O/Fe]_{Trip} LTE | [O/Fe]_{Trip} NLTE | [O/Fe]_{OH} LTE | [O/Fe]_{OH} NLTE |
|-------------------|------|---------|--------|----------|-----------|--------------|------------|----------------|----------------|----------------|----------------|
| G4-37             | 1.450| 5837±80 | 4.23±0.3| -2.89±0.1| -2.59      | -1.51±0.16   | ...        | 1.38           | 1.08           | ...            | ...            |
| G64-12            | 1.196| 6318±150| 4.20±0.3| -3.37±0.16| -3.05     | -2.14        | -1.88±0.31 | 1.23           | 0.91           | 1.49           | 1.17           |
| G64-37            | 1.191| 6310±110| 4.20±0.3| -3.22±0.12| -2.90     | < -2.01      | ...        | <1.21          | <0.89          | ...            | ...            |
| G268-32           | 1.306| 6090±100| 3.86±0.4| -2.81±0.12| -2.51     | -1.72±0.18   | ...        | 1.09           | 0.79           | ...            | ...            |
| G271-162          | 1.320| 6050±70 | 4.03±0.3| -2.46±0.14| -2.18     | -1.69±0.16   | ...        | 0.77           | 0.5            | ...            | ...            |
| G275-4            | 1.254| 6212±150| 4.13±0.3| -3.32±0.17| -2.99     | < -1.96      | -2.08±0.32 | <1.36          | <1.03          | 1.24           | 0.91           |
| LP 815-43         | 1.218| 6265±125| 4.54±0.3| -3.05±0.13| -2.74     | ...          | -2.11±0.27 | ...            | ...            | 0.94           | 0.63           |
| LP 831-70         | 1.251| 6205±120| 4.30±0.3| -2.97±0.14| -2.66     | < -1.90      | ...        | <1.07          | <0.76          | ...            | ...            |
| BD +23°3130       | 1.97 | 5130±150| 3.05±0.25| ...       | -2.43     | -1.50±0.14   | -1.83±0.33 | ...            | ...            | 0.93           | ...            |
| BD +03°740        | 1.284| 6135±100| 4.00±1  | -2.93±0.12| -2.63     | -1.94±0.13   | ...        | 0.99           | 0.69           | ...            | ...            |

* Refers to the [Fe/H] ratio estimated after Thévenin & Idiart 1999. See § 3 for details. The NLTE Fe abundance of BD + 23°3130 is estimated in this paper.
(1999b), who provide $-0.31 \pm 0.11$ and $-0.35 \pm 0.03$, respectively. In spite of this, the results of Sneden et al. (1991) are usually quoted as evidence against the plateau probably because they obtained $[O/Fe]$ ratios lower than 0.6.

So what is the $[O/Fe]$-versus-$[Fe/H]$ relation for giants? We can think of two possibilities. There is a real scatter in the range $0.3 < [O/Fe] < 1$ at $[Fe/H] < -1$, which could be explained by a weakening of the forbidden lines in some of the evolved giants as a result of the presence of circumstellar matter. Indeed, differences in the published equivalent widths of the forbidden line for some giants may support this hypothesis (work in preparation). If this is the case, then one cannot display both giants and unevolved subdwarfs on the same $[O/Fe]$-versus-$[Fe/H]$ graph (e.g., Carretta et al. 2000). It is also possible that giants follow the linear trend just as unevolved subdwarfs, but previous investigators have failed to discover this for two main reasons: (1) they did not use sufficiently high $S/N$ (e.g., $S/N > 400$) to investigate uncertainties involved in the determination of oxygen abundance from the forbidden line at 6300 Å in the most metal-poor targets of their samples, and (2) the stellar parameters of the most metal-poor giants were not correct because NLTE effects were not taken into account. However, we cannot exclude the possibility that the plateau derived from the [O i] giants is correct. Work is in progress to study the stellar parameters of several giants with $[Fe/H] < -2$ by performing an NLTE analysis of Fe lines and investigating its impact on the oxygen abundances derived from OH, forbidden, and triplet lines.

6.2. Oxygen Nucleosynthesis in the Early Galaxy

The new data in ultra-metal-poor unevolved stars confirm the previous findings for a progressive rise in oxygen overabundances as we go to $[Fe/H] < -2.5$. In particular, the high $[O/Fe]$ ratio in G64-12 provides evidence for enhanced oxygen production in the first nucleosynthesis events in our Galaxy. Can these high $[O/Fe]$ ratios in ultra-metal-poor stars be understood in terms of massive star nucleosynthesis models?

The first attempts to explain the linear trend were made by Abia, Canal, & Isern (1991), and more recently Goswami & Prantzos (2000) have suggested three possible scenarios to explain the observed linear trend of $[O/Fe]$. The first possibility, which has already been explored in the literature, considers the early evolution of Type Ia SNe, which started to contribute Fe to the ISM already in the epoch when $[Fe/H] \sim -3.0$. Goswami & Prantzos (2000) remark that this model cannot be accepted, as it also predicts similar linear trends for other $\alpha$-elements that are not observed. However, we would like to recall that the “traditional” trend of $\alpha$-elements (i.e., a unique plateau at $[Fe/H] < -1$) has been challenged recently by Idiart & Thielemann (2000) on the basis of NLTE computations of $\alpha$-elements. In addition, the observations indicate (Francois 1987, 1988) that the $[S/Fe]$ ratio increases from approximately 0 to 0.7 in the metallicity range $-1.5 < [Fe/H] < 0$. There is no plateau observed at $[Fe/H] < -1$, and the models fail to account for the observed $[S/Fe]$ ratios (Goswami & Prantzos 2000). This is confirmed by recent observations of Takeda et al. (2000), who report $[S/Fe] = 1.11$ in the metal-poor $([Fe/H] = -2.72)$ giant HD 88609. As a second possibility, Goswami & Prantzos (2000) mention the metallicity-dependent oxygen yields proposed by Maeder (1992). Given that the stellar mass loss at very low metallicity is poorly understood, one can propose a model in which $[O/Fe]$ increases below $[Fe/H] \sim -1$ while $[\alpha/Fe]$ is constant. However, Goswami & Prantzos (2000) argue that even this model is not acceptable, as it predicts $[C/Fe]$ and $[N/Fe]$ ratios increasing with $[Fe/H]$ (which are not observed). The third model proposed by Goswami & Prantzos (2000) considers the possibility of having metallicity-dependent Fe and $\alpha$-element yields at $[Fe/H] < -1$. This is possible if, when the supernova layers inside the carbon-exhausted core are well mixed during the explosion (to have $[\alpha/Fe] \sim$ constant, in the ejecta for any $[Fe/H]$). This last model requires that the oxygen, carbon, and helium layers will escape with the same yields, independent on the metallicity, as they are loosely bound. Note that these models did not take into account stellar rotation, which plays a very important role in low-metallicity massive stars (Maeder & Maynet 2000). Strong observational support for matter mixing, which occurs in SN ejecta during or prior to explosion, comes from the analysis of the low-mass X-ray binary system Nova Sco 1994 (Israelian et al. 1999). If the mass of the black hole in Nova Sco 1994 is more than $4 M_\odot$ (which is just a lower limit given by observations), then it must have “eaten” all Fe group elements plus the $\alpha$-elements Ti, Ca, and S. Some amount of Mg and Si, together with almost all the O, may escape the collapse and therefore appear in the supernova ejecta captured by the secondary. However, observations show that all $\alpha$-elements are uniformly enhanced in the atmosphere of the secondary star and that therefore there must have been some mixing in the supernova ejecta. Most probably, this system is a relic of a hypernova that left a massive black hole and ejected similar amounts of $\alpha$-elements (Israelian et al. 1999; Brown et al. 2000).

The yields from standard Type II supernovae have been investigated by a number of authors (e.g., Woosley & Weaver 1995; Thielemann, Nomoto, & Hashimoto 1996). It is well known that stellar yields are influenced by metallicity. Low mass-loss rates in very metal-poor massive stars lead to more massive He cores, and therefore more He is converted into oxygen (Maeder 1992). In contrast, the most massive solar metallicity stars ($M_{ZAMS} > 40 M_\odot$) go through a Wolf-Rayet phase where the mass loss is very efficient and end up with low-mass ($4-6 M_\odot$) He cores (Maeder & Meynet 1987). It is well known (Woosley 1996; Fryer, Woosley & Heger 2000) that during the contraction phase of helium cores with $M \geq 40 M_\odot$, the temperature in the center of the star gets very high ($\geq 3 \times 10^9$ K) while the density remains low. This favors the electron-positron pair instability, which leads to explosive oxygen or even silicon burning. It is interesting that the pair creation supernovae produced by stars with $M_{ZAMS} > 150-200 M_\odot$ and $Z = 0.0004$ lead to the formation of CO cores with $M_{CO} = 60-100 M_\odot$. A complete thermonuclear disruption of these objects produces very large amounts of oxygen and carbon (see Fig. 2 in Portinari 2000). As a matter of fact, the maximum amount of oxygen at $Z = 0.0004$ is produced not by 20–25 $M_\odot$ progenitors but by $M_{ZAMS} = 150–200 M_\odot$ stars (Portinari 2000). Thus, it is possible that the early ISM of our Galaxy has been polluted by very massive CO cores of the first pair creation supernovae. This idea is supported by Qian & Wasserburg (2001), who, on the basis of a three-component mixing model for the evolution of O relative to Fe, suggest a linear rise of $[O/Fe]$ if the contribution of the
first very massive stars is taken into account. The stability of ultra-metal-poor very massive stars was investigated recently by Baraffe, Heger, & Woosley (2001), who concluded that such stars could take an active role in the nucleosynthesis of the early Galaxy.

Our observations suggest that the Fe production sites were active already in the early halo. Recently, Nomoto et al. (1999) have presented a model of an exploding CO core with a mass of $12 - 15 \, M_\odot$ and an explosion energy of $2 - 5 \times 10^{52}$ ergs in order to explain the observations of the hypernova SN1998bw. The progenitor of the CO core initially had $M_{\rm ZAMS} = 40 \, M_\odot$ and large angular momentum. Placing a mass cutoff at $2.9 \, M_\odot$, Nomoto et al. (1999) have computed that $0.7 \, M_\odot$ of $^{56}\text{Ni}$ is ejected, the amount required to explain observations of SN1998bw. It is possible that the linear trend can be explained by an increasing role of hypernovae in the early epochs of the formation of the Galaxy (i.e., $[\text{Fe}/\text{H}] < -1$). The estimated Galactic rate of Type Ic hypernovae is $10^{-3}$ yr$^{-1}$ (Hansen 1999), but it could have been much higher in the early Galaxy. Small mass-loss rates due to the low metallicity in the first generations of massive halo stars could have led to large helium cores and the conservation of the primordial angular momentum. Since hypernovae are favored by stars with a large helium core mass and rapid rotation, we anticipate significant sulfur (e.g., Takeda et al. 2000) and iron production in the early Galaxy following the yields computed by Nomoto et al. (1999). Whether the objects that started to produce large amounts of Fe in the very early halo were metal-poor progenitors of the first hypernovae, very massive stars, or other types of supernovae remains to be solved by future investigations.

Accelerated protons and $\alpha$-particles in cosmic rays interact with ambient CNO in the ISM and create beryllium and boron. According to the standard Galactic cosmic-ray (GCR) theory, these interactions in the general ISM should have given a quadratic relation between these elements and O that is not observed. Alternatively, spallation of cosmic-ray CNO nuclei accelerated out of freshly processed material could account for the primary character of the observed early Galactic evolution of Be and B. Another production site is the collective acceleration by SN shocks of ejecta-enriched matter in the interiors of superbubbles. In these two cases, the evolution of Be should reflect the production of CNO from massive stars.

The dependence of $\log (\text{Be/H})$ on $[\text{Fe/H}]$ and on $[\text{O/H}]$ is essentially linear but with different slopes: $\sim 1.1$ and $\sim 1.5$, respectively, and similar behavior is found for boron (Molaro et al. 1997; García López et al. 1998; García López 1999; Boesgaard et al. 1999a). Three types of GCR models exist at present that try to explain their observed evolution. These are (1) a pure primary GCR from superbubbles (Ramaty et al. 2000); (2) a hybrid model based on GCR and superbubble accelerated particles (Vangioni-Flam & Cassé 2000), which could be accomplished by a pure superbubble model (Parizot & Drury 2000); and (3) standard GCR (Olive 2000; Fields & Olive 1999). The models presented by Ramaty et al. (2000) and Olive (2000) show more consistency when a steady increase in $[\text{O}/\text{Fe}]$ with decreasing metallicity is adopted. In addition, Ramaty et al. (2000) have proposed that a delay between the effective deposition times into the ISM of Fe and O (only a fraction of which condensed in oxide grains) can explain a linear trend in $[\text{O}/\text{Fe}]$. Their model also predicts a linear rise in $[\text{S}/\text{Fe}]$.

7. CONCLUSIONS

Oxygen abundances in several unevolved ultra-metal-poor stars have been derived using UV OH and O I IR triplet lines. It is found that the new abundances from both indicators confirm the linear trend of $[\text{O}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ first reported by Abia & Rebolo (1989) and more recently by Israelian et al. (1998) and Boesgaard et al. (1999b). In G64-12, the most metal-poor star in our sample, we find the highest $[\text{O}/\text{Fe}]$ ratio at 1.17. Our best estimate of the slope in the trend $[\text{O}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ is $-0.33 \pm 0.02$.

A detailed NLTE analysis of Fe I lines has been carried out for the subgiant star BD +23°3130, providing more reliable stellar parameters, in particular a surface gravity in good agreement with the value derived from its accurate Hipparcos parallax. Using these parameters and taking into account the uncertainties involved in deriving oxygen abundances from the weak forbidden line, we argue that the discrepancy noticed by FK99 can no longer be sustained. New measurements of the forbidden line by Cayrel et al. (2000) confirm our conclusions. There is no significant discrepancy between OH, triplet, and forbidden lines in BD +23°3130 when one-dimensional ATLAS9 models are employed. Similar good agreement between the OH lines and the forbidden lines is found for several other metal-poor unevolved stars.

Examination of several scenarios for nucleosynthesis in low-metallicity Type II supernovae and/or hypernovae provides a variety of possible explanations for the increase of oxygen overabundance with decreasing metallicity in the early Galaxy.

The data presented here were obtained with the William Herschel Telescope, operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias; the public data released from the UVES commissioning and Science Verification at the VLT Kueyen telescope, European Southern Observatory, Paranal, Chile; as well as with the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck foundation. We are grateful to Ya. V. Pavlenko for providing the code WITA3 and for helpful discussions. N. S. would like to thank R. Kostik for several useful discussions. We thank Carlos Allende Prieto for providing us with the gravity values for BD +23°3130 and BD +37°1458. Iliia Ilyin is thanked for helping with the reduction of NOT/SOFIN spectra. This research was partially supported by the Spanish DGES under projects PB95-1132-C02-01 and PB98-0531-C02-02 and also by NATO grant 950875.
