THE ASTROPHYSICAL JOURNAL, 493:195–205, 1998 January 20

CHEMICAL EVOLUTION OF THE ORION ASSOCIATION. IV. THE OXYGEN AND IRON ABUNDANCES OF F AND G STARS

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Received 1997 April 30; accepted 1997 August 28

ABSTRACT

Oxygen and iron abundances are derived for a sample of pre–main-sequence F and G stars of the Orion association. Results for association members are compared with results published previously for main-sequence B stars in the association. The abundances reveal that the F and G stars exhibit the pattern of abundances shown by the main-sequence B stars: the stars have a single iron abundance, but there is a star-to-star variation of oxygen abundance. Oxygen-rich and oxygen-poor stars are roughly segregated on the sky.
Subject headings: open clusters and associations: individual (Orion association) — stars: abundances — stars: pre–main-sequence

1. INTRODUCTION

The Orion association is a nearby active star-forming region consisting of four subgroups (Ia, Ib, Ic, and Id) of different locations, sizes, and ages. The age difference between the youngest (Id) and oldest (Ia) subgroup is about 12 Myr: Blaauw (1991) lists the ages (in Myr) as 12, 7, 3, and 0 for subgroups Ia–Id, respectively, but Brown, de Geus, & de Zeeuw (1994), who find a similar spread between the Ia and Id subgroups, find Ib at an age of 1.7 ± 1.1 Myr to be younger than Ic. The association is often cited as an example of supernova-induced sequential star formation. Our spectroscopic studies of stars in the association are prompted by the speculation (Reeves 1972, 1978) that the association may be self-enriched, i.e., the gas from which the Id stars have formed may be contaminated by ejecta from mass-losing stars, probably supernovae, belonging to earlier generations of stars.

Elemental abundances of C, N, O, Si, and Fe have been derived for a sample of 18 main-sequence B stars from the association's different subgroups (Cunha & Lambert 1992, 1994). The results suggest that, unlike the carbon, nitrogen, and iron abundances, the oxygen abundance is not homogeneous but depends on spatial location of the stars within the association. Silicon probably behaves similarly to oxygen. Since the most massive stars disperse considerable amounts of oxygen and silicon but smaller amounts of carbon, nitrogen, and iron, the variation of oxygen and silicon abundances across the association was interpreted as evidence of the proposed process of self-enrichment by supernovae. In this paper we search for additional evidence of chemical inhomogeneities in the Orion association.

Our search involves the F and G stars in the Orion association. Such cooler stars provide independent objects with which to test the results derived from the hotter (B-type) stars. In particular, the line selection is necessarily different for the two groups of stars. Sources of systematic error are likely to be different too. In our earlier pursuit of lithium in the F and G stars (Cunha, Smith, & Lambert 1995, hereafter Paper I), we segregated Orion members from nonmembers by means of criteria based on proper motions, radial velocities, X-ray detections, projected rotational velocities, and lithium abundances. The bona fide members are used here to further studies of the chemical evolution of the Orion association. In this paper, we present results for oxygen and iron abundances in nine F and G Orion stars sampling the Ib, Ic, and Id subgroups. Thirteen nonmembers, also F and G stars, are analyzed as well. The results for the members of the association are used to constrain speculations about the chemical evolution of the Orion association.

2. OBSERVATIONS

Spectra of F and G stars in the direction of the Orion association were obtained at McDonald Observatory with the 2.1 m telescope plus a Cassegrain cross-dispersed echelle spectrometer (McCarthy et al. 1993). Analysis in Paper I concentrated on the spectral region around the Li I feature at 6707 Å and the Fe abundances in the more slowly rotating stars. Details concerning the spectra and data reduction can be found in Paper I. In addition, Figures 1, 2, and 11 of Paper I show sample spectra with resolution $R = \lambda/\delta\lambda \simeq 60{,}000$ and signal-to-noise ratios ranging from 100 to 300 (see Table 1 of Paper I).

In this paper we concentrate on oxygen abundances using permitted and forbidden O I lines. A useful spectral line is [O I] λ6300, which is weak but falls in a region where telluric O_2 lines reside. In order to remove telluric lines, the stellar spectra were divided by the spectrum of a rapidly rotating hot star observed at roughly the same air mass as the program star. In the region of the O I triplet (the other oxygen abundance indicator), additional concerns are fringing in the CCD plus scattered light (due to the closeness of the orders in the red). For this spectrometer, however, division by an internal quartz flat-field lamp is able to remove the fringes effectively to the point of being undetectable within the signal-to-noise ratio of the spectra. Scattered-light corrections were made by fitting two-dimensional smooth functions to the interorder light. The effectiveness of this procedure was investigated by observing the atmospheric O_2 band head near 7593 Å, where the strongest lines go to zero intensity at our resolution of $R = 60{,}000$ (again within the limits of the signal-to-noise ratio).

3. DERIVED ABUNDANCES

The model atmospheres used in this abundance analysis are from the grid of models calculated previously for our target stars: line-blanketed LTE model atmospheres generated with the ATLAS9 (R. L. Kurucz 1992, private communication) program for solar metallicity, an assumed depth-independent turbulence of 2 km s^{-1}, and a mixing-length parameter $\alpha = 1.25$.

We adopt the stellar parameters (Table 6 of Paper I) estimated previously for these stars: spectroscopic temperatures derived from the Fe I equivalent widths (for the slow rotators), and photometric temperatures derived from the reddening-free Strömgren β-index (for the remaining stars in the sample). Our photometric temperature scale was tied to the spectroscopic values of $T_{\rm eff}$ using an internal calibration consisting of β versus effective temperature (where the $T_{\rm eff}$ was derived from the Fe I analysis) for eight program stars. The calibration was excellent, with an internal error of ± 70 K (see Paper I for more details). Examination of the Hβ index versus $(b-y)$ for all of the stars in the Warren & Hesser (1977, 1978) catalogs shows that, for the Orion members included here, there is no evidence that Hβ is affected by detectable chromospheric activity relative to the field stars; thus the β-index is an adequate temperature indicator. The surface gravities for the stars were derived by forcing agreement between Fe I and Fe II abundances. The microturbulences, determined demanding no trend of abundance with equivalent width, are also from Paper I. We revised the effective temperature for the nonmember HD 294269 to a value that is in better agreement with its spectral type G0 (Warren & Hesser 1978): new $T_{\rm eff} = 5700$ K and $\log g = 4.70$. This star has a β-index that is also more compatible with the new $T_{\rm eff}$. The revised upper-limit Li abundance for this nonmember is now $\log \epsilon$ (Li) ≤ 1.4.

Two of the Orion members from the list in Paper I (P1374, P1626) are not considered in this study because of large uncertainties in their derived stellar parameters: their effective temperatures were estimated from extrapolations in our calibration (to lower $T_{\rm eff}$ for P1626 and higher $T_{\rm eff}$ for P1374) of the photometric β-index versus spectroscopic $T_{\rm eff}$ (which was defined for β-indices spanning the range 2.543–2.634). In addition, one of these stars, P1374, shows strong Hα emission (Fig. 2 of Paper I). If emission is also present in the Hβ line, the β-index would be affected. P1626 also shows nebular emission in Hα, and its measured β is quoted as uncertain by Warren & Hesser (1977). We excluded the probable Ib member HD 294298 because it has vanishingly weak lines. In this study we investigate whether there are abundance spreads in O and Fe and thus want a sample of Orion members with well-defined stellar parameters.

3.1. *Oxygen*

Here we discuss oxygen abundances obtained from the permitted triplet O I lines, at 7774 Å, and the forbidden [O I] line at 6300.3 Å. We also investigate the O I lines at 6158 Å for the Orion members.

The forbidden line is a useful oxygen abundance indicator, as it is both weak and formed in conditions close to LTE. However, this line is so weak in F and G dwarf stars that it is detectable only in stars with rather low rotational velocities (less than about 8 km s^{-1}). The permitted O I triplet lines, on the other hand, are much stronger (typically 100 mÅ for each component) but are affected by departures from LTE. Thus, the permitted and forbidden lines have complementary advantages and disadvantages. When analyzed at the same time, these lines can provide us with a more secure determination of the oxygen abundances in the stars.

We have analyzed the [O I] line at 6300.3 Å using the technique of spectrum synthesis and also directly from the measured total equivalent width. Equivalent widths for the [O I] lines are shown in Table 1, where we list first the Orion members followed by the nonmembers in our sample. We were able to measure the [O I] line in only one Orion member: P2374. The remaining members rotate too rapidly for the weak [O I] line to be measured reliably. Most of the O abundances determined from [O I] are for nonmembers. However, as we will show, these [O I] results provide valuable tests of the predicted non-LTE (NLTE) corrections for the O I triplet, which is the primary source of oxygen abundances for Orion member stars.

For the abundance analysis, we use a recent version of the program MOOG (Sneden 1973). The line list for the [O I] region was obtained from B. Barbuy (1990, private communication) and modified to include CN molecular lines, although the CN lines are very minor contributors. (The line list is available from the authors upon request.) The *gf*-value for the [O I] line comes from Lambert (1978) and is known rather accurately. Comparisons of both theoretical calculations and laboratory measurements yield agreements that are better than about 25%, or 0.1 dex. The

TABLE 1

MEASURED EQUIVALENT WIDTHS

Star	λ6300	λ7771	λ7774	λ7775
Orion Members				
P1179	...		[406 ± 25][a]	
P1455	...	114	90	84
P1657	...	111	108	89
P1789	...		[429 ± 20]	
P1953	...		[308 ± 15]	
P1955	...		[332 ± 15]	
P2339	...	98	95	68
P2374	5.0	98	86	75
HD 294297......	...	107	88	81
Nonmembers				
P1037	3.0	...	57	44
P1158	4.5	69	54	41
P1199	...	67	61	46
P1467	6.6	124	105	85
P1474	10.0	127	117	87
P1590	1.7	73	59	52
P1662	...	83	...	63
P2125	8.8	96	86	80
P2267	...	96	86	75
P2909	...	90	72	63
HD 36235	4.1	101	87	77
HD 294269......	...	70	66	53
HD 294302......	6.0	136	117	110

[a] See text for explanation of bracketed entries.

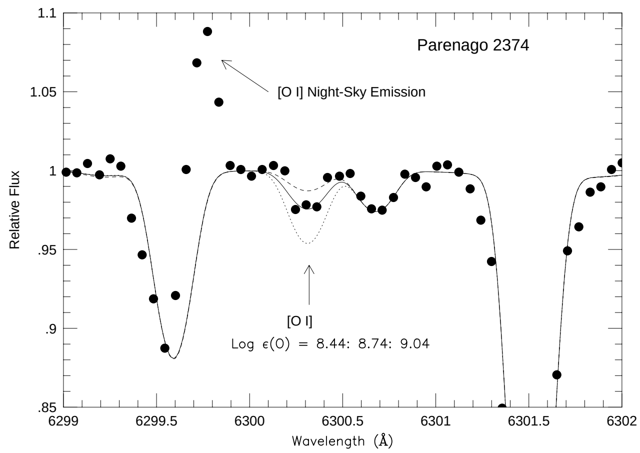

FIG. 1.—Sample synthesis for the [O I] line at 6300 Å for the star P2374. The three curves represent three different oxygen abundances specified in the figure, while the filled circles represent the observed spectrum. This is the star with the lowest $v \sin i$ in our sample of Orion members and the only member for which we could detect [O I] well enough to determine a reliable oxygen abundance.

synthetic spectra were broadened to account for the instrumental profile and also stellar rotation for the $v \sin i$ values estimated from the best fit between the observed and theoretical spectra in Paper I. A sample synthesis for this spectral region is presented in Figure 1 for the Orion member P2374. The derived [O I] abundances are in Table 2 and consist of an average value obtained from both synthesis and measured equivalent width. Differences between these two values were small: the average difference was smaller than 0.1 dex. As discussed above, it was not possible to derive reliable oxygen abundances for the more rapidly rotating stars in our sample.

The high-excitation O I lines at 6156.78 and 6158.19 Å represent another possibility for studying oxygen abundances in our stars. These features are as weak as the [O I] line in our spectra, and therefore no reliable abundance determinations based on these lines are feasible for most of the Orion members in our sample (which are fast rotators). We have investigated the oxygen abundance from the two lines at 6158 Å in P2374 (the only slow rotator in our sample of Orion members) by synthesizing the spectral region around these features. The line list for the calculation of the synthetic spectra was obtained from the list of Kurucz (1992, private communication). The LTE abundance results obtained from the analysis of both 6156.78 and 6158.19 Å lines are very consistent with the oxygen abundance obtained from the [O I] line: $\log \epsilon(\mathrm{O}) = 8.73 \pm 0.1$ dex, in excellent agreement with the [O I] result of 8.74. NLTE effects for these transitions are predicted to be very small (Kiselman 1991; Takeda 1994).

The analysis of the permitted O I triplet 7774 Å lines used either equivalent width measurements (for the slow rotators) or spectrum synthesis (for the four most rapid rotators in our sample, with $v \sin i \geq 40$ km s^{-1}). Measured equivalent widths for each triplet component are listed in Table 1. For the rapid rotators, where the triplet lines are blended, we list the total integrated equivalent width plus the estimated uncertainty in the measurements. Estimated uncertainties in the individual components are not listed because we derive uncertainties in the oxygen abundance from these measurements based upon the scatter of the derived individual line abundances. The line list for the calculation of the synthetic profiles was obtained from Kurucz (1992, private communication). The *gf*-values adopted for

TABLE 2

OXYGEN AND IRON ABUNDANCES

Star	T_{eff}	log g	O $\mathrm{I_{LTE}}$	σ	O $\mathrm{I_{NLTE}}$	[O $\mathrm{I]_{LTE}}$	Fe	σ
			Orion Members					
P1179 (Ic)	6050	4.0	8.94	0.10	8.71	...	...	...
P1455 (Id)	5950	4.0	9.08	0.09	8.86	...	7.59	0.15
P1657 (Ic)	6100	3.8	8.98	0.05	8.72	...	7.20	0.14
P1789 (Ic)	6120	4.0	9.54	0.12	9.29	...	7.31	0.04
P1953 (Ic)	5850	4.0	9.31	0.10	9.11	...	7.34	0.15
P1955 (Ic)	5890	4.0	9.33	0.08	9.13	...	7.53	0.07
P2339 (Ic)	5950	4.0	8.96	0.10	8.74	...	7.33	0.10
P2374 (Ic)	5900	3.9	8.98[a]	0.02	8.78	8.74	7.41	0.09
HD 294297 (Ib)......	6150	4.0	8.87	0.07	8.61	...	7.32	0.14
			Nonmembers					
P1037	5410	4.6	9.21	0.02	*	8.80	7.27	0.11
P1158	5700	3.7	8.57	0.10	8.41	8.52	6.70	0.09
P1199	5800	4.9	8.90	0.02	*	...	7.40	0.13
P1467	6000	3.8	9.15	0.10	8.89	8.80	7.50	0.09
P1474	5950	4.0	9.26	0.10	9.05	9.03	7.63	0.11
P1590	6050	4.5	8.58	0.06	*	8.52	7.10	0.12
P1662	5850	4.0	8.88	0.02	8.69	...	7.12	0.13
P2125	5800	3.9	9.14	0.07	8.96	8.95	7.30	0.11
P2267	5900	4.1	9.06	0.03	8.88	...	7.48	0.12
P2909	5750	4.9	9.20	0.05	*	...	7.64	0.08
HD 36235	6000	3.5	8.80	0.04	8.48	8.42	6.99	0.10
HD 294269	5700	4.7	8.99	0.05	*	...	7.45	0.09
HD 294302	6100	3.7	9.19	0.07	8.88	8.70	7.48	0.16

[a] Analysis of the O I 6158 Å line gives the LTE abundance 8.73. NLTE corrections are predicted to be small.

the triplet lines were taken from Bell & Hibbert (1989) and Butler & Zeippen (1991) and differ by only 5% ($\sim$0.02 dex from the earlier values of Wiese et al. 1966). We used similar techniques in the analysis of both slow and fast rotators in order to avoid any systematic effects appearing in a comparison of stars with differing $v \sin i$. For the slowly rotating stars, where all three triplet components are clearly discernible, individual equivalent widths were measured, as shown in Table 1, and each component equivalent width was compared to a synthetic one. In the cases where the components were blended by rotation, the total equivalent width was measured off the observed spectrum and matched with a total equivalent width computed from rotationally broadened synthetic spectra. As a test of whether rotational broadening might introduce systematic errors, the observed stellar spectra in the O I spectral region were all broadened to $v \sin i = 110$ km s^{-1} (the value for the most rapidly rotating star observed, P1179). The blended equivalent widths in this now uniformly rotating set of stellar spectra were compared to the sum of individual component or blended equivalent widths, in the original data. No significant trends were found, and a comparison between measured total absorption was excellent. This indicates that O abundances derived in the slow rotators can be compared directly to those derived in the rapid rotators. In Figure 2 we show the O I triplet in the rapidly rotating member P1955 as well as the synthetic fit. The mean oxygen abundances derived from the O I triplet lines for the target stars are presented in Table 2. For all stars we also quote an estimate of the abundance uncertainties: for the slow rotators (for which we have individual measurements for the triplet lines) this is the standard deviation of the mean, and for the rapid rotators it is estimated from the uncertainties in the measured integrated equivalent widths listed in Table 1.

Inspection of the LTE oxygen abundances in Table 2 shows that the [O I] abundances are systematically lower than the triplet O I abundances. This same result has been found by several other studies in the literature: e.g., Clegg, Lambert, & Tomkin (1981) and Nissen & Edvardsson (1992). The O I − [O I] discrepancy is discussed in § 4.1.

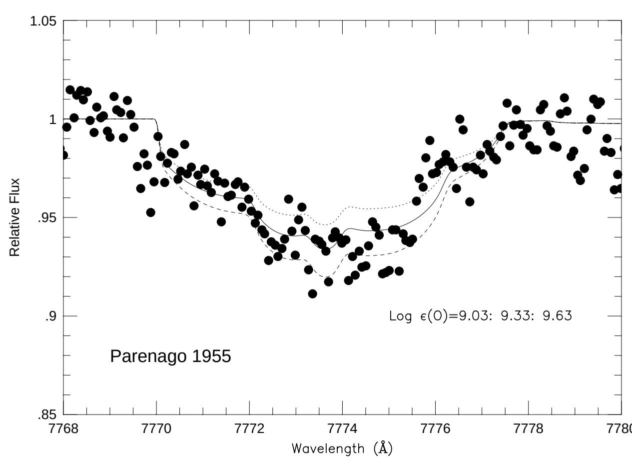

FIG. 2.—Sample synthesis for the O I triplet region for the star P1955, a member with $v \sin i = 80$ km s^{-1}, one of the largest rotational velocities in our sample. The three curves represent three oxygen abundances as indicated in the figure, while the filled circles represent the observed spectrum. A synthetic spectrum defined by $\log \epsilon(\mathrm{O}) = 9.33$ is the best fit to the integrated equivalent width. Note that even though the O I feature is weak, it contains many data points, and thus the total integrated equivalent width of the O I feature is sensitive to the oxygen abundance.

3.2. *Iron*

Fe abundances are presented in Table 2 for stars in our sample. Most of these Fe abundances (and standard deviations) are from Paper I; exceptions are three rapidly rotating Orion members (P1789, P1953, and P1955), which will be discussed here. The line selection and *gf*-values for Fe can be found in Paper I, in particular § 4.1 and Table 2. Briefly, the Fe I and Fe II lines were selected by inspection of spectra of the asteroid Ceres, used as a solar proxy, taken with the same instrument as that used for the program stars. These lines are unblended, or nearly unblended, at $R = 60{,}000$ in slowly rotating FG dwarfs. Solar *gf*-values were derived from equivalent widths measured from Ceres spectra using a solar model atmosphere generated with ATLAS9 code (the same as used to generate the program stellar atmospheres) and adopting a solar Fe abundance of $\log \epsilon(\mathrm{Fe}) = 7.51$. A comparison of accurate laboratory *gf*-values, as discussed in Lambert et al. (1996), with the solar *gf*-values here for 30 Fe I lines shows them to be nearly on the same scale, with a mean difference and standard deviation of mean (solar − laboratory) $= +0.01 \pm 0.05$ dex. Using laboratory *gf*-values for these 30 Fe I lines in the comparison, with the ATLAS9 solar model generated here, would thus yield a solar iron abundance of $\log \epsilon(\mathrm{Fe}) = 7.52$.

In the present paper we extract Fe abundances for the three Orion members that are rotating faster than roughly 40 km s^{-1} by spectrum synthesis of features dominated by Fe I. We selected four spectral regions where strong Fe I lines, which were used also for the slow rotators, could be found. These regions were near 6170, 6190, 6205, and 6330 Å. We show in Figure 3 a sample synthesis and observed spectrum for the star P1789 ($v \sin i = 75$ km s^{-1}) in the region of 6200 Å. The line list and *gf*-values for the calculation of the synthetic spectra, in each region, were compiled from Kurucz's (1992, private communication) line list, although for the Fe I lines we used the *gf*-values as derived by us in Paper I. Thus, both the slow and rapid rotators are on the same Fe abundance scale. We note that for one star in our sample (P1179) we were unable to derive a reliable Fe

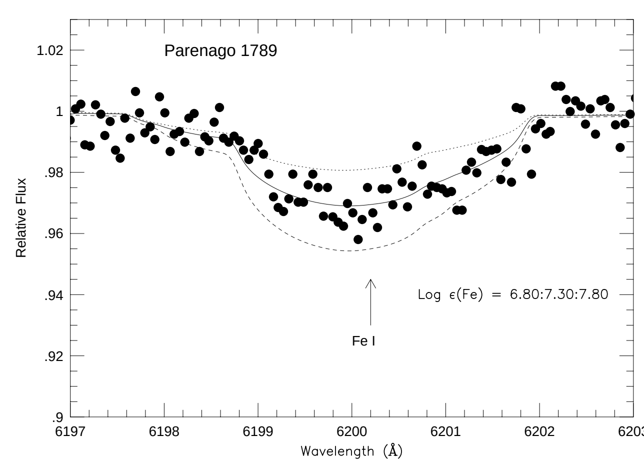

FIG. 3.—Sample synthesis for the Orion member P1789 in the region of 6200 Å, where an Fe I feature selected for analysis is displayed. The filled circles in the figure represent the observed spectrum in this region, while the three curves represent three different Fe abundances as shown in the figure.

abundance because its projected rotational velocity of 110 km s^{-1} is too fast for even the strong Fe I lines to be well defined.

In order to match observed and synthetic features, we compare the total equivalent width of a Fe I feature in real and synthetic spectra. In the case of the syntheses, we sampled the spectra at the same wavelength intervals as the observed spectra and used the same IRAF routines in order to manipulate and measure the synthetic and observed spectra in identical manners. Iron abundances were then derived for four features in the rapid rotators, and the errors listed in Table 2 are the standard deviations of the mean abundances of these four Fe I features.

4. ABUNDANCE UNCERTAINTIES

Before turning to the discussion of the iron and oxygen abundances in Orion, we need to consider the errors in the derived abundances and also the uncertainties due to the assumption of the validity of LTE for the temperature range spanned by the studied stars.

In short, abundance uncertainties can arise from errors in the measured equivalent widths, derived effective temperatures, surface gravities, and microturbulent velocities. If we assume that the typical errors in the measured equivalent widths, effective temperatures, gravities, and microturbulences are 5 mÅ, 100 K, 0.3 dex, and 0.5 km s^{-1} (see Paper I), respectively, we obtain a combined error in the Fe abundance of roughly ± 0.14 dex. The uncertainty in the equivalent widths is a combination of two estimates: one from the formula by Cayrel (1988), as well as the fact that many of the Fe I lines (and the O I lines) are somewhat strong and have pressure-broadened wings. The presence of non-Gaussian wings is not accounted for in the Cayrel formula, and we simply add an extra uncertainty of a few milliangstroms to these stronger lines. The sensitivity of the derived O I abundances to the same errors in the equivalent width measurements is 0.08 dex, and is 0.09, 0.12, and 0.08 dex for the same estimated errors in temperature, gravity, and microturbulence, respectively. The combined error in this case is ± 0.19 dex (on the assumption that these errors are statistically independent).

The abundances derived from the forbidden [O I] line at 6300 Å are not nearly as sensitive to temperature variations as the triplet lines. They are, on the other hand, sensitive to the choice of the surface gravity: a change of 0.3 dex in log g changes the [O I] abundance by about 0.13 dex, while changes in $T_{\rm eff}$ of 100 K will only change the [O I] abundance by 0.02 dex. The derived oxygen abundances are almost insensitive to the choice of microturbulence, as is expected for a weak line. An additional error is the equivalent width uncertainty, which can be substantial for a weak line. In the case of our spectra, given a typical signal-to-noise ratio of 200 and the formula by Cayrel (1988), we estimate that random errors of 1–1.5 mÅ are expected in our [O I] equivalent widths. For a typical equivalent width of 4 mÅ we would then estimate an abundance uncertainty of 0.1–0.14 dex. The combined error in our derived [O I] abundances would be typically of the order of ± 0.18 dex (again on the assumption that the errors are statistically independent).

4.1. *NLTE Corrections*

Inspection of Table 2 shows that the oxygen abundances derived from the O I 7774 Å triplet lines are generally higher than that given by [O I] λ6300. Since oxygen abundances for the F and G members rely almost exclusively on the triplet lines, it is clearly important to understand the origin of the systematic difference between the permitted and forbidden lines. A similar difference was noted by Clegg et al. (1981) and Nissen & Edvardsson (1992) for field F dwarfs and attributed by them to NLTE effects. This attribution may now be tested using recent calculations of NLTE effects in the excitation of neutral oxygen atoms.

NLTE calculations require a model atom and assumptions about the processes controlling the excitation (and de-excitation) and ionization (and recombination) of the oxygen atom. Ionization is relatively unimportant for oxygen atoms in atmospheres of the temperatures of F and G stars. Excitation is affected by photons and particles. Rates for bound-bound and bound-free radiative processes are now well known. Excitation (and ionization) by free electrons are included, for which rates are reasonably well determined from theoretical calculations. A major uncertainty is the contribution to the excitation from collisions of oxygen atoms with neutral hydrogen atoms; rates for O-H collisional excitation are quite uncertain and presently based on a "modified classical Thomson formula" (Steenbock & Holweger 1984).

Of the several calculations of NLTE effects in O I reported recently, those by Takeda (1992, 1994) are the most extensive and most easily applied to our stars. In addition to excitation by electron collisions, he includes excitation by hydrogen atoms. Indeed, Takeda notes that collisions with hydrogen are generally more important than collisions with electrons for O I line formation in F and G dwarfs. His predictions of the NLTE corrections for the O I 7774.2 Å line for a small grid of atmospheres are based on the rate constant for hydrogen collisions originally proposed by Steenbock & Holweger (1984). Takeda (1995), in a more extensive study of O I in solar models, finds no need to change this rate constant for the formation of the O I triplet lines. In addition, by inclusion of a solar chromosphere, he then obtains better agreement with the observed center-to-limb variation of the strength of O I over the solar disk. However, his NLTE corrections for the disk-integrated O I lines remain the same as his earlier (Takeda 1994) results.

Interpolation in Table 7 of Takeda (1994) provides NLTE abundance corrections corresponding to the O I 7774.2 Å line. These NLTE abundances, corresponding LTE abundances, and the LTE abundances from the [O I] 6300 Å line are tabulated in Table 2. An asterisk in the NLTE column indicates that the stellar parameters for the star fall outside the range of Takeda's grid of atmospheres. We note that Takeda's calculations are based on essentially the same grid used by us for the LTE analyses. His adopted microturbulence (2 km s^{-1}) is slightly larger than the values derived by us from Fe I (see Table 6 of Paper I). The [O I] line is effectively immune to NLTE effects.

The NLTE corrections taken from Table 7 of Takeda (1994) were calculated for an assumed input oxygen abundance of log ϵ(O) = 8.86; however, the departures from LTE depend somewhat on the oxygen abundances themselves. To investigate the size of this effect, we also derived NLTE corrections from Takeda's table by taking varying O abundances into account. Takeda's small grid does not provide a range of input O abundances for solar-metallicity atmospheres, but a comparison of his metal-poor models with solar-metallicity models reveals that his calculations can be extended safely to a range of oxygen abundances for solar-Z models. For example, Takeda does provide results for $0.1Z/Z_{\odot}$ models with $[\mathrm{O/Fe}] = +1.0$, or $\log \epsilon(\mathrm{O}) = 8.86$ and these values can be compared with the same oxygen abundance for solar-Z models: the differences in the NLTE corrections for all temperatures and gravities in the table are less than 0.04 dex. The same comparison can be made for $0.01Z/Z_{\odot}$ and $0.1Z/Z_{\odot}$ models for oxygen abundances of 7.86, and again the differences between the models are small (≤ 0.01 dex). This means that NLTE corrections for input oxygen abundances of 6.86, 7.86, and 8.86 can be derived. For the most O-rich Orion stars, where $\log \epsilon(\mathrm{O}) \geq 9.0$, we must extrapolate. To do this, a second-degree polynomial was fitted to the NLTE corrections for the oxygen abundances of 6.86, 7.86, and 8.86: there is very little curvature to these corrections, and continuing these curves provides NLTE corrections for the larger O abundances. The results listed in Table 2 are changed almost not at all by this procedure. For example, the most O-rich star P1789 (for which this effect should be the largest), has its NLTE O abundance reduced from 9.28 to 9.22, while the average and standard deviation of the O abundances of the Orion members change very little—from 8.88 ± 0.23 to 8.86 ± 0.21.

A comparison of the estimated NLTE abundances from the O I 7774.2 Å line and the LTE [O I] 6300 Å line clearly shows that the calculations correctly predict the magnitude of the NLTE effects: the mean abundance difference between the NLTE O I and the LTE [O I] abundances is 0.04 ± 0.08 dex; this comparison is illustrated in Figure 4. This difference is insignificant and bolsters our confidence that both the NLTE corrections are presumably approximately correct, as well as the T_{eff} scale, as [O I] arises from the ground state while O I λ7774.2 has an excitation potential of 9.15 eV. As noted previously, nonmembers contribute all but one of the data points entering into the calculation of the mean abundance difference: the members are generally too broad-lined for the weak [O I] 6300 Å line to be measured. Then the importance of the comparison is that it shows that oxygen abundances for member stars based on the O I lines may be reliably corrected for NLTE effects. The NLTE calculations also predict that LTE is a good assumption for the O I 6158 Å lines, as found here for the member P2374; see also Clegg et al. (1981). Another prediction is that the O I 9260 Å lines are less affected by NLTE effects than the O I 7774 Å triplet. This is also consistent with the LTE abundances given by Clegg et al. (1981) for F and G stars.

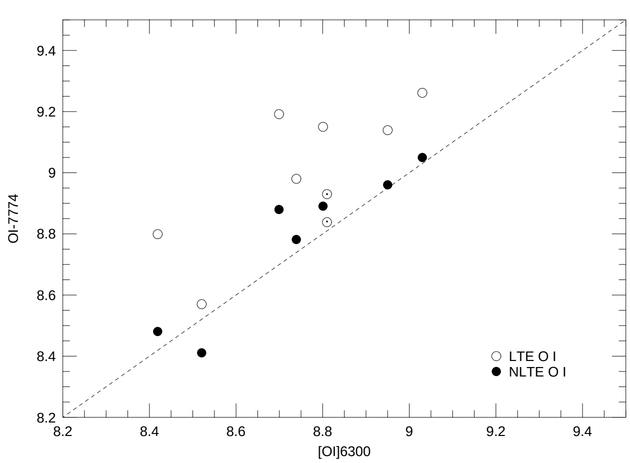

FIG. 4.—Comparison of the LTE and NLTE triplet oxygen abundances (at 7774 Å) with the LTE oxygen abundance derived from the [O I] line at 6300 Å. The dashed line indicates perfect agreement between the triplet O I and forbidden line abundances. The LTE triplet abundances are represented by open circles, the NLTE triplet abundances by filled circles, and the solar symbols are indicated (the larger solar O I λ7774 abundance is the LTE one). Note that the NLTE O I abundances are in better agreement with the LTE [O I] abundances, for which the NLTE effects are expected to be insignificant.

We have also tested the analysis of the O I and [O I] lines by performing a solar analysis. Meylan et al. (1993) list accurate Voigt profile–fitted equivalent widths for the O I lines, and we use our measurement of the [O I] λ6300 equivalent width from the solar atlas of Kurucz et al. (1984). These equivalent widths are 74, 66, and 52 mÅ for the O I triplet lines, respectively, and 4.6 mÅ for the [O I] line. We use a solar model generated with the same ATLAS9 code used for the program stars (for $T_{\mathrm{eff}} = 5777$ K and $\log g = 4.43$) to remove any systematic effects in the models. Using this solar model, with a microturbulence of 1.3 km s^{-1} (Smith, Edvardsson, & Frisk 1986; J. J. Drake 1994, private communication) the solar oxygen abundances are 8.93 from the O I triplet (8.93, 8.93, 8.91) and 8.81 from the [O I] line. As a test of our use of Takeda's small grid of NLTE corrections, we extrapolate his corrections to larger gravities for the Sun. Assuming a linear extrapolation from $\log g = 3.5$–4.0 and then on to 4.43, we estimate a NLTE correction to the solar O I abundance of -0.09 dex. This leads to an oxygen abundance of 8.84 from the O I triplet—in excellent agreement with the [O I] abundance of 8.81. Furthermore, this abundance is also in very good agreement with the adopted solar abundance of 8.87 ± 0.07 from Grevesse, Noels, & Sauval (1996). We note that Takeda also provides a NLTE correction to the O I lines for his solar model, which is -0.06 dex: again this is in fine agreement with our extrapolated estimate using his small grid. The solar O I versus [O I] NLTE and LTE points are also plotted in Figure 4.

It should, perhaps, be noted that we deem the correction for NLTE effects on the 7774.2 Å line to be an empirical one. The principal reason for this is the approximate nature of the recipe for the hydrogen atom collisions. Takeda adopted Steenbock & Holweger's (1984) original formula for the rate constants. Analyses of solar and stellar lines of various species have suggested that the formula overestimates the rate constant by a large factor (say 80%); see Watanabe & Steenbock (1986), Solanki & Steenbock (1988), and Stürenburg & Holweger (1990). Lambert (1993), in a review of the limited theoretical and experimental data on the rate constants, noted that the original formula grossly overestimated rates for the strong resonance transitions of Li I and Na I. Takeda justifies his use of the original formula on the grounds that the corresponding NLTE calculations reproduce well the solar O I 7774 Å triplet lines and their center-to-limb variation.

There is a second reason for denoting the correction as empirical: the present atmospheres ignore the likely presence of stellar granulation. Takeda argues that the failure of his NLTE calculations to reproduce the full center-to-limb variation of the 7774 Å lines may well be due to the failure to model the solar granulation. Since the NLTE calculations appear to fit the stellar lines very well, we surmise that, if granulation has a sizable effect on the predicted equivalent widths of the oxygen lines, this effect is well simulated by the NLTE calculations with hydrogen rate constants set at the level proposed in 1984.

5. DISCUSSION

Our analyses of the Orion B stars (Cunha & Lambert 1992, 1994) suggested that the stars were of the same iron abundance but of different oxygen abundances. Stars of the highest oxygen abundance appear concentrated in the youngest subgroups of the association. The present study was undertaken in order to see whether oxygen and iron abundances derived from F and G stars provide confirmation of the intriguing results from the B stars. We discuss first the iron abundances that confirm that stars of the Orion association all have the same abundance.

The distributions of iron abundance across the sample of member and nonmember F and G stars is shown in Figure 5. It is clear that the members show very little spread in iron abundance. By contrast, the nonmembers show a sizable spread, as expected for samples of unrelated field stars. For the eight members (one from subgroup Ib, six from Ic, and one from Id) the mean Fe abundance is log ϵ(Fe) = 7.38 $\pm$ 0.13. If the Ib member (HD 294297) and the Ic member (P1455) are omitted, the mean from six Ic members is log ϵ(Fe) = 7.35 $\pm$ 0.11 or [Fe/H] = -0.16 (see § 3.2). The standard deviations are consistent with the estimated errors of measurement discussed in § 4, suggesting that the members can be characterized by a single Fe abundance. In particular, the Fe abundance is independent of $T_{\rm eff}$ and projected rotational velocity. Additional stars will have to be observed before we can test the result from the B stars suggesting that all subgroups have the same Fe abundance.

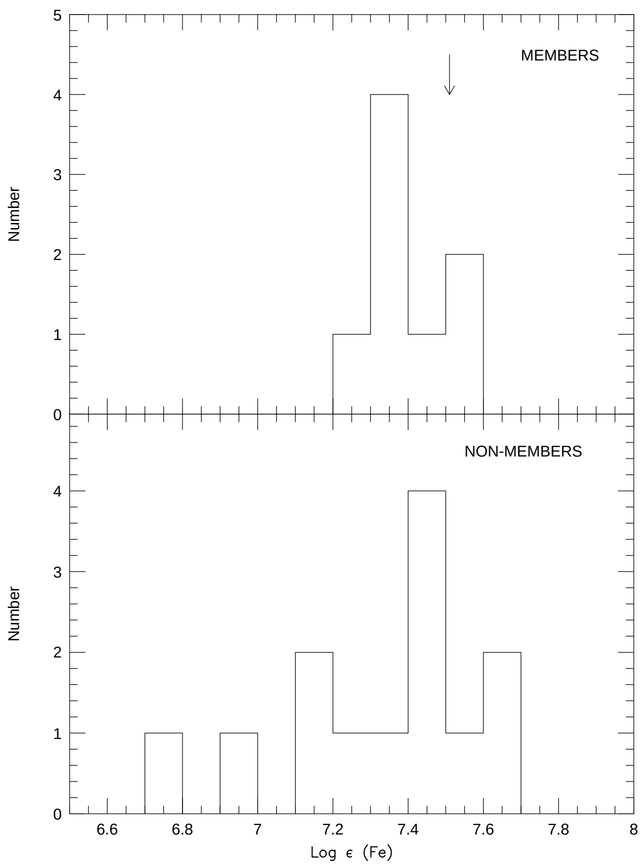

FIG. 5.—Distribution of the Fe abundances of our sample of Orion members (*top panel*) and nonmembers (*bottom panel*). The distribution of the Orion members peaks out at an abundance roughly 0.1 dex below the solar value (which is indicated by an arrow) and can be represented within the errors by a single Fe abundance of log ϵ(Fe) = 7.38. The distribution of the nonmembers shows much larger scatter and includes lower metallicity field stars observed in the direction of the association.

The Fe abundance for the Ic FG members overlaps the mean Fe abundance derived for the Ic B stars of 7.47 $\pm$ 0.10 by Cunha & Lambert (1994) from their LTE analysis of Fe III lines. This is pleasing agreement, as stars of quite different temperatures and lines of different stages of ionization are used for the two analyses. We consider that the FG stars are likely to provide the more reliable result. Several reasons may be suggested. First, the derivation of the Fe abundance in the B stars is influenced by errors in the Fe III *gf*-values, which are likely more uncertain than the solar Fe I and Fe II *gf*-values used here; recall that these solar *gf*-values compare very well with accurate laboratory values (§ 3.2). Second, NLTE effects may be significant for Fe III lines in B stars, but departures from LTE in the Fe I and Fe II lines used for the FG stars have been shown to be small. Third, the model atmospheres of the FG stars are perhaps truer representations of real atmospheres than is the case for the B stars. This assertion is based on the rather favorable comparison of model and empirical solar atmospheres.

The iron abundance indicated by the FG stars (and also the B stars) points to a slight underabundance with respect to the Sun. The magnitude of this underabundance is in line with those reported for lighter elements (C, N, and O) from stellar and nebular analyses (see Cunha & Lambert 1994; Gies & Lambert 1992). Although the less than solar Fe abundance is unexpected by simple theories of galactic chemical evolution, observations of several different kinds of stars show that there is at any time a spread in the iron abundance of stars located in the solar neighborhood; for example, Fry & Carney (1997) from analyses of Cepheids show that these young stars near the Sun have [Fe/H] from about $+0.1$ to -0.2 dex (see also Edvardsson et al. 1993). The Orion metallicity of [Fe/H] = -0.16 fits in this range (just).

In contrast to iron, the oxygen abundances of the FG members appear to vary from star to star. Oxygen abundances derived from the B stars suggested a similar spread. The comparison of oxygen abundances for FG and B stars is illustrated in Figure 6 and shows that five out of the eight Ic/Id FG members have O abundances that fall in the middle of the B star distribution, but three of the FG members have significantly larger O abundances (log ϵ(O) $\geq$ 9.1). The mean O abundance from FG stars is slightly higher than that from B stars of the same subgroup: log ϵ(O) = 8.92 and 8.76 from the FG and B stars of Ic/Id, respectively. It is possible that such a difference represents nothing more than the difference in systematic errors of the analyses of the two different groups of stars using different sets of oxygen lines. The fact that the spread in O abundance across the two samples is large and similar is presumably indicative of a real spread and not simply a reflection of a spread in systematic errors across a sample of quite similar stars.

In the case of the B stars (Cunha & Lambert 1994), a Monte Carlo simulation of the spread arising from the measurement errors showed that the O abundances, but not the C, N, or Fe abundances, were likely reflecting an intrinsic spread. Briefly, it was found that the C, N, and Fe abundances could be represented by a single abundance value with the observed distribution well represented by a Gauss-

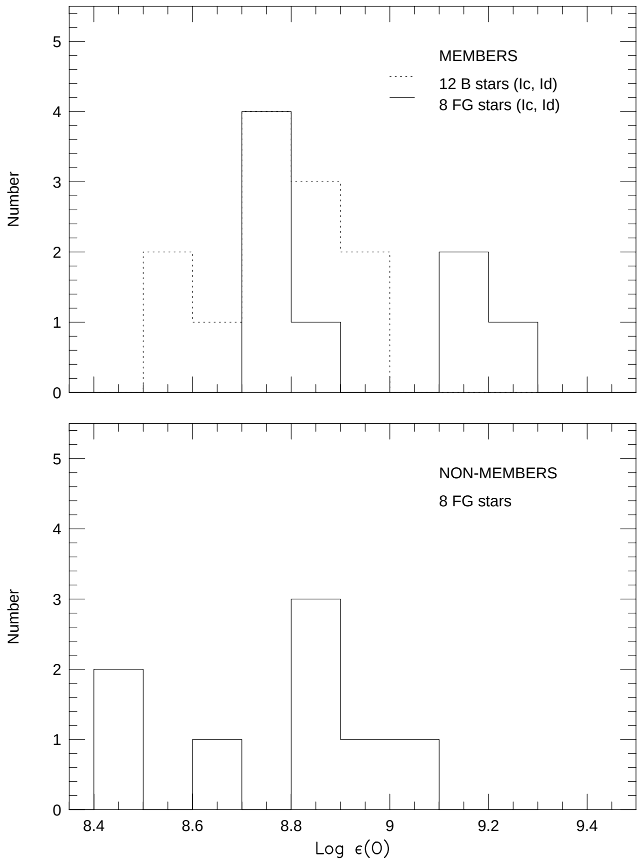

FIG. 6.—Distribution of the oxygen abundances for our sample of FG stellar members of the subgroups Ic and Id in the Orion association (*top panel*). As a comparison, we also show the distribution of the oxygen abundances of the B stars which are members of the same subgroups. The histogram with the nonmembers in our sample is displayed in the bottom panel.

ian distribution dictated by the estimated respective analysis errors for each element. Oxygen, on the other hand, could not be well represented by a single abundance. Although the total spread in the oxygen abundances was not much larger than the estimated analysis errors, the observed abundance distribution was very poorly fitted by a Gaussian distribution as defined by the estimated errors. A very similar situation is found here for Fe and O in the FG stars. The observed Fe abundances in the top panel of Figure 5 are fitted very well by a single Fe abundance equal to log ϵ(Fe) = 7.38 (the mean from Table 2), with a Gaussian-distributed uncertainty of ± 0.14 dex (with the error estimate coming from § 4). A reduced χ^2 comparison of a model Gaussian distribution with the observed Fe distribution yields a value of $\chi^2 = 1.0$ for 3 degrees of freedom. This satisfies the criterion of a fit in the sense that a single-abundance model cannot be rejected. We thus conclude that the Fe abundance in the Orion members is likely represented by a single value, within our uncertainties of about 0.14 dex. A comparison of the observed O abundances with a model Gaussian distribution [with a mean log ϵ(O) = 8.88 from Table 2 and an estimated error of 0.19 dex from § 4] yields a value of the reduced $\chi^2 = 9.2$ for 4 degrees of freedom. This is a much worse fit than for Fe and indicates that oxygen cannot be represented by a single abundance value unless we have grossly underestimated the errors in the O analysis (this is the same conclusion reached by Cunha & Lambert 1994 for the B stars). Even increasing the standard deviation of a model Gaussian to 0.23 dex (which is the measured dispersion) results in a reduced χ^2 of 4.6: such a model can be rejected at a highly significant level (in contrast to Fe). It is not so much the total spread of the oxygen abundance but the distribution of the values that is crucial. This is the same result as found for the B stars. Clearly, analyzing more stars in the future is desirable.

An interesting insight into the reality of the intrinsic spread in O abundances is offered by examination of the members P1657 and P1789. Inspection of the NLTE oxygen abundances (Table 2) for the members shows a spread from log ϵ(O) = 8.61 to log ϵ(O) = 9.29. Is this spread real, or is it an artifact of the abundance analysis? This question can be answered by appealing to a straightforward comparison: consider P1657 and P1789, for which we derive $T_{\rm eff} = 6100$ K, log $g = 3.8$, $\xi = 1.6$ km s^{-1} and $T_{\rm eff} = 6120$ K, log $g = 4.0$, and $\xi = 1.2$ km s^{-1}, respectively. These are very similar stellar parameters, yet the O I lines are of very different strength in the two stars. This is illustrated in Figure 7, where we compare the O I 7774 Å triplet and the Ca I 6162 Å line. In order to compare spectra readily, we rotationally broaden the spectrum of P1657 ($v \sin i = 16$ km s^{-1}) to $v \sin i = 75$ km s^{-1} in order to match that of P1789, and we show this in the top left panel of Figure 7. Clearly, the blended O I feature is considerably stronger in P1789. In the top right panel of Figure 7, we illustrate a spectral comparison for the strong Ca I 6162 Å line: here the match between P1657 and P1789 is perfect. Also the blended feature at 6170 Å, dominated by Fe I, is a perfect match. Stronger O I lines in P1789, relative to P1657, could be caused by a substantial temperature error; a difference of roughly 600 K would be required if the oxygen abundances were to be the same. However, the stars have similar Strömgren β-indices: β(P1657) = 2.611 and β(P1789) = 2.615. A 600 K temperature difference would manifest itself as a difference in β of 0.14; this is not likely. As an illustration of what a 600 K difference in $T_{\rm eff}$ would look like, we plot synthetic spectra in the bottom panel of Figure 7. These synthetic spectra were generated with two models separated by 600 K in order to mimic approximately the observed differences in the O I line strengths in P1657 and P1789; models with $T_{\rm eff} = 6000$ K, log $g = 4.0$, $\xi = 1.5$ km s^{-1} and $T_{\rm eff} = 6600$ K, log $g = 4.0$, $\xi = 1.5$ km s^{-1} were used. The synthetic spectra were sampled at about the same wavelength increments as the real spectra ($\delta\lambda = 0.06$ Å at 6160 Å and 0.07 Å at 7774 Å), and noise was added such that the synthetic S/N ~ 200–300, which corresponds roughly to that observed. As is apparent, differences in the O I feature exist; however, large differences in the Ca I and Fe I features also exist, which are not observed in the real spectra. In fact, a close comparison of other spectral regions in both P1657 and P1789 reveals almost perfect matches except for O I. The two stars almost certainly have very similar parameters, yet the O I 7774 Å feature in P1789 is much stronger.

Some other phenomenon, such as perhaps spots or differing chromospheric structures, might play a role in explaining the differences in the O I absorption, although spots would also influence other lines (spots are really just temperature differences). Or are we witnessing a simple difference in the oxygen abundances themselves? This rather direct comparison of two definite members suggests that real oxygen abundance inhomogeneities exist in the Orion association, more specifically within subgroup Ic.

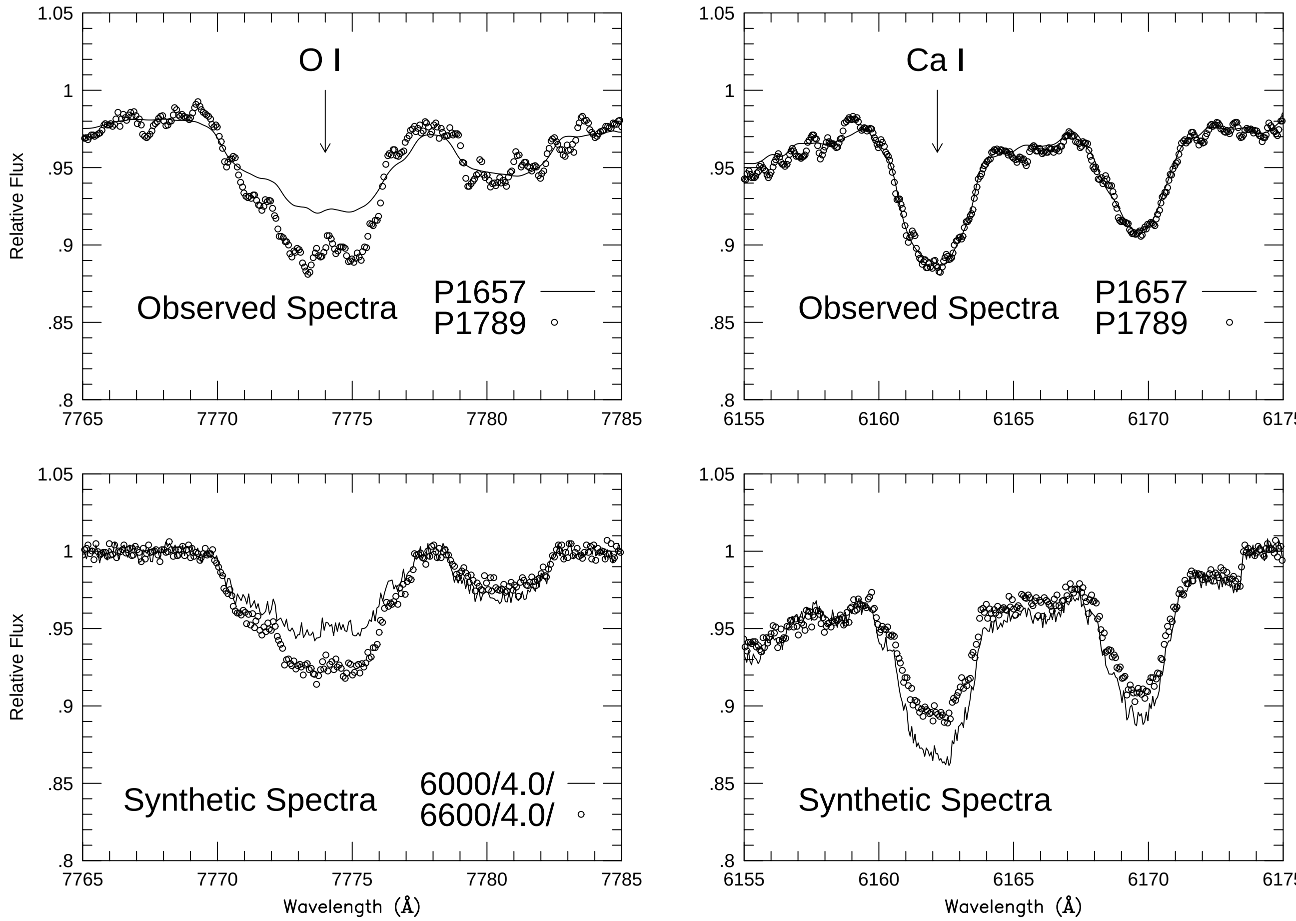

FIG. 7.—Comparison between the observed spectra of two Orion members (P1657 and P1789) with similar stellar parameters, in the region of the triplet O I lines (*top left panel*) and in the region of the Ca I feature at 6162 Å (*top right panel*). Note that the O I line is significantly stronger in the spectrum of P1789 when compared to P1657, while there is a perfect overlap of the features displayed in the region of the Ca I line shown in the top right panel. An artificial increase in $T_{\rm eff}$ of roughly 600 K in the star P1789 would force an agreement of the synthetic oxygen features (*bottom left panel*) but at the same time would produce a difference in the strength of the Ca feature (*bottom right panel*), which is not observed.

The alternative explanation for O I line-strength variations might be that they are due to differences in the chromospheres of the stars. Takeda (1995) points out that the formation of the line cores of the O I triplet can be sensitive to the presence of chromospheres. Based on our spectra, however, we find no compelling evidence of large chromospheric differences between P1657 and P1789. In particular, these two stars have identical Fe I 6678 Å profiles (when the spectrum of P1657 is rotationally broadened to 75 km s^{-1} in order to match that of P1789) with no contribution from He I λ6678, which lies only 0.16 Å to the red of the Fe I and which would be formed in a chromosphere. We thus see no evidence of any He I component in P1789 when compared to P1657. This is an indication that there is not a substantial chromospheric contribution in the spectrum of P1789 relative to P1657. Such a conclusion is supported as well by the similarity of their respective Hα profiles, although P1789 shows a very small emission feature. Concerning any connections between rapid rotation and chromospheric enhancement of the O I lines, it is worth noting that the most rapidly rotating member studied here, P1179, has a rather low oxygen abundance. Therefore, this argues that there is not a strong correlation between rapid rotation and the presence of strong O I absorption.

In Figure 8 we show the distribution on the sky of the FG and B star members and indicate which have above average O abundance and which have below average: filled symbols indicate above average O abundance, while open symbols indicate below average. By classifying the stars with respect to the average abundances, we allow for the small offset in mean abundances for FG and B stars. We can see from this figure that the FG stars and the B stars which have above average O abundances are concentrated in the same regions of the sky. Stars in the northern part of the association ($\delta > -5°$) are all of below average O abundance. The southern part of the association includes all stars of above average O abundance. The below average O abundance stars are scattered equally throughout the association. Note that the single low-mass Ib member, HD 294297 in the northern part, has a low O abundance (8.65) that matches that of the Ib B stars. The three FG Ic/Id stars with high oxygen abundances (9.1–9.3) are all located within less than 1° of each other, near the Trapezium region. Qualitatively this kind of behavior is similar to that found for the B stars, i.e., spatial oxygen variations with stars having higher abundances being more centrally located. However, there are low-abundance stars colocated on the sky with the high-abundance stars. In the case of the B stars, there is evidence that at least some of the low-abundance stars, although in the same direction as high-abundance stars, are at greater distances along the line of sight. Unfortunately, accurate distances are not available for the FG stars.

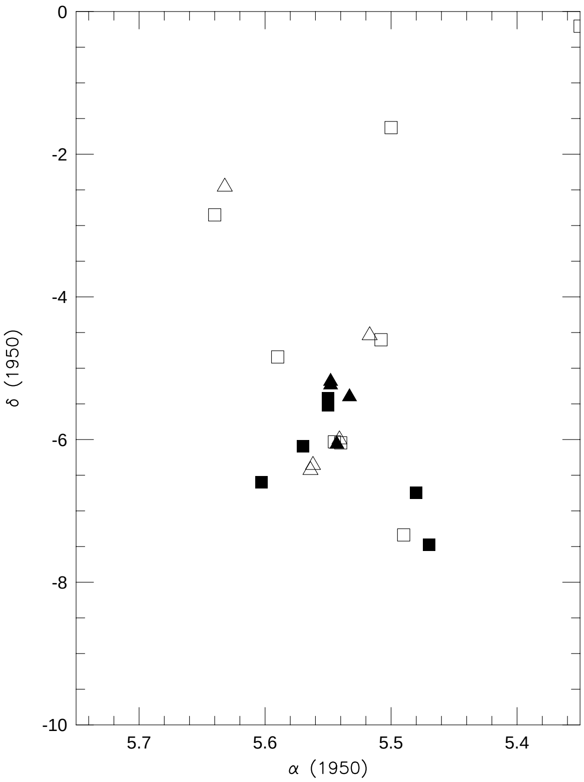

FIG. 8.—Positions of the observed stars on the sky, where the triangles are the FG stars and the squares are the B stars. The stars are divided according to their oxygen abundances, with those stars having below average abundances represented by open symbols and those with higher than average oxygen abundances shown by filled symbols. Note that the stars with the higher abundances tend to be concentrated in one area toward the southern part of the region.

A useful comparison to field stars is the quantity [O/Fe], which encompasses values from -0.1 to $+0.6$ for the Orion members, while for the field stars studied here it ranges from 0.0 to $+0.4$ (based on the NLTE O I triplet results). The large study by Edvardsson et al. (1993) finds values of [O/Fe] as large as $+0.2$ at roughly the metallicity of Orion ([Fe/H] $= -0.1$). Although the oxygen-rich Orion members have [O/Fe] that are quite large, it must be noted that the Edvardsson et al. study does not contain many stars at the metallicity of Orion; in addition, it is not known what fraction of field F and G stars are formed in associations similar to Orion, i.e., associations that may show evidence of self-enrichment. Values of [O/Fe] $= +0.6$ are perfectly plausible in terms of the predicted yields from models of Type II supernovae. For example, the 20 $M_\odot$ model by Hashimoto, Nomoto, & Shigeyama (1989) for SN 1987A predicts [O/Fe] $= +0.5$. Thus, the oxygen-rich star P1789 could easily result from contamination by the products of massive supernovae.

As a final comparison, we investigate the behavior of Li and O for the Orion members. In Paper I we found very small dispersion in the Li abundance for the more rapidly rotating members: $\log \epsilon(\mathrm{Li}) = 3.3 \pm 0.1$ for $v \sin i \geq 20$ km s^{-1}. For the stars with $v \sin i \leq 20$ km s^{-1} the Li abundance was lower [$\log \epsilon$ (Li) from 2.3 to 2.8], and it was suggested that Li was destroyed by mixing induced by rotational braking of these stars. In Figure 9 we plot the Li abundances versus the O abundances for the nine members under discussion here. There is an apparent correlation: the four stars with lithium less than $\log \epsilon(\mathrm{Li}) = 3.0$ have among the lowest O abundances of the members. The meaning of this correlation is not clear: there may be no causal connection between Li and O abundances. But perhaps the stars with the highest oxygen abundances are the youngest and thus most rapidly rotating. Then the oldest stars, the least O-enriched, have been rotationally braked and have destroyed lithium. On the other hand, one might wish to argue that this correlation is an indication that Li and O are produced together, as Timmes, Woosley, & Weaver (1996) predict for Type II supernovae with lithium production occurring by neutrino-induced spallation ("the ν-process"). This possibility is not supported by the study of boron in Orion B stars by Cunha et al. (1997): boron, which is predicted to be produced with lithium in the ν-process, was not overabundant in O-rich B stars relative to its abundance in O-poor B stars.

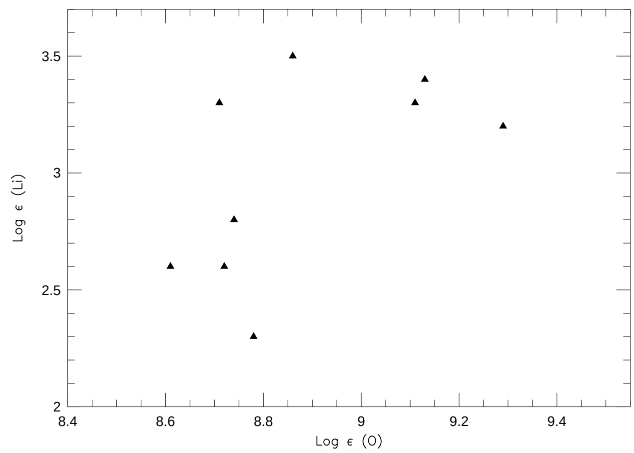

FIG. 9.—Display of the NLTE oxygen abundances derived for the Orion members vs. their Li abundances derived in Paper I. It can be seen that all of the members with lower Li abundances also have lower O abundances.

6. CONCLUDING REMARKS

This analysis of F and G members of the Orion association, primarily stars from subgroup Ic, supports our earlier suggestion that there is an intrinsic star-to-star spread of the oxygen abundances but not the iron abundances. The O-rich stars are colocated on the sky and, according to the line-of-sight distance derivable for the B stars, at a common distance. The Trapezium region is the approximate center of oxygen enrichment. This chemical signature may be the result of self-enrichment of the association by ejecta of Type II supernovae from the most massive stars.

A subsidiary conclusion of this study is that analyses of F and G stars and of B stars yield similar abundances. This shows that systematic errors in standard modern methods of spectrum analysis including corrections for NLTE effects are certainly similar for the two groups of stars of quite different temperatures. Possibly, the similarity of abundances also shows that the systematic errors are small (less than ~ 0.2 dex; see Fig. 6) for both groups.

This research is supported by the National Science Foundation (AST 93-15124 to D. L. L. and AST 96-18459 to V. V. S.) and the Robert A. Welch Foundation of Houston, Texas. K. C. acknowledges travel support for observing trips from CNPq-Brazil. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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