THE ASTROPHYSICAL JOURNAL, 234:964–972, 1979 December 15

THE OXYGEN ABUNDANCE IN METAL-POOR STARS

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Received 1979 May 4; accepted 1979 June 28

ABSTRACT

Oxygen abundances in the atmospheres of a dozen unevolved stars of various metallicities ($-2.3 \leq$ [Fe/H] $\leq +0.3$) have been derived. In nearly all cases, the metal-poor stars exhibit an enhanced oxygen triplet at 7700 Å. Substantial overabundances of oxygen are indicated for the program stars. This result is discussed in the light of current galactic nucleosynthesis theories.
Subject headings: nucleosynthesis — stars: abundances — stars: weak-line

I. OXYGEN AND GALACTIC NUCLEOSYNTHESIS

The element trio CNO dominates the heavy-element content of stars. However, most efforts have gone into abundance determinations of spectroscopically common iron-peak elements, rather than CNO, in metal-poor stars. The abundance information of these relatively rare heavy elements is translated into information on the chemical evolution of the Galaxy via stellar nucleosynthesis. However, the observational information on the abundant CNO group is far from satisfactory. The CNO element which has been treated most extensively is carbon. Recently, Peterson and Sneden (1978) determined carbon abundances for metal-poor stars through a spectrum synthesis technique applied to the CH $A^2\Delta$–$X^2\Pi$ bands near 4300 Å. Over their sample which extended down to a metal deficiency [Fe/H] = -2.30, the C and Fe abundances decreased in unison; i.e., [C/Fe] = 0.0 to within an uncertainty of about ± 0.3 dex. Earlier work on the carbon abundance (see Peterson and Sneden 1978 for references), which generally supports these conclusions, was limited to the less metal-poor stars. The result [C/Fe] = 0.0 is a strong constraint on theories of galactic nucleosynthesis (see, for example, Tinsley 1979).

The remarkable paucity of O abundance determinations in metal-poor stars is a direct consequence of the acute scarcity of accessible spectroscopic signatures of neutral oxygen atoms and O-containing molecules (e.g., OH and CO). The molecule OH has its absorption features principally below 3100 Å and those for CO lie beyond 1 μm; both molecules are therefore nearly useless for high-resolution observations for faint metal-poor stars. Two opportunities for O abundance determinations in extremely metal-poor stars currently exist: (a) the forbidden O I lines at 6300 and 6363 Å may be observed in the spectra of giant stars, and (b) the O I permitted triplet near 7770 Å may be observed in the spectra of dwarf stars. Use of these transitions presents problems: the forbidden lines are extremely weak in very metal-poor giants, while the triplet has a high-excitation potential (9.15 eV) and may not be formed in local thermodynamic equilibrium (LTE).

The literature is peppered with tantalizing hints that oxygen deficiencies are not as marked as the iron-peak deficiencies in metal-poor stars; i.e., [O/Fe] > 0. The first indication that oxygen might not follow the general trend of iron-peak abundances came in the classic study of oxygen in late-type stars by Conti *et al.* (1967). Those authors measured equivalent widths of the 6300/6363 Å [O I] lines in 29 G–M normal and peculiar giants and gave eye estimates for a larger sample. By using crude model atmospheres, they found that most low-velocity stars with normal CH and CN band strengths also had normal oxygen. For the weak CN, high-velocity stars (notably α Boo and γ Leo A and B), the [O I] lines were approximately a factor of 2 too strong. They argued that the O/H ratio in these stars, which ranged between factors of 2 and 4 deficient in metals, must be approximately solar.

A couple of the metal-poor stars in the list of Conti *et al.* (1967) have been more extensively studied. Alpha Boo has been analyzed several times (see the discussion by Lambert and Ries 1977). The metallicity of α Boo is [Fe/H] = -0.5 ± 0.17. Lambert and Ries derived [O/H] = -0.27 ± 0.17. [In that paper and in the present study, the recent revision by Lambert (1978) of the solar oxygen abundance, $\log \epsilon(\mathrm{O}) = 8.92$, is adopted.]

A relative overabundance of O in α Boo was also found by Kjaergaard and Gustafsson (1978) in a study of the [O I] 6300 Å line in a sample of 26 K giants spanning the range $-0.5 \lesssim$ [Fe/H] $\lesssim 0.5$. The authors remark that their results provide a hint that [O/Fe] $\neq 0$;

metal-poor stars appear to be relatively O rich (i.e., [O/Fe] > 0) and metal-rich stars appear to be relatively O poor (i.e., [O/Fe] < 0).

Conti *et al.* (1967) attempted to detect the forbidden oxygen feature in the well-studied, very metal-poor giant HD 122563. They derived [O/H] $\lesssim -2$ from an estimation of an upper limit of 12 mÅ for the 6300 Å line. Lambert, Sneden, and Ries (1974) used the coudé scanner of the McDonald Observatory 2.7 m reflector to detect this line and obtained [O/H] $= -2.1 \pm 0.3$. When combined with the well-determined metallicity of this star ([Fe/H] $= -2.75 \pm 0.3$; Wolffram 1972), this result lent more weight to the idea that oxygen may be enhanced in metal-poor stars.

The flow of evidence suggesting O enhancements in metal-poor stars received an input from Mould's (1978) analysis of infrared spectra of M dwarfs. OH and CO line intensities were measured in two metal-poor dwarfs ([Fe/H] ≈ -0.35). The CO intensities—a measure of the C abundance—are consistent with [C/Fe] = 0, but the OH lines indicate O is not as underabundant as the metals: [O/Fe] ≈ 0.15.

Recent work by several investigators has shown that the oxygen abundance of giants may have a considerable range at a single stellar metallicity. This scatter appears to exist in field giants (Pagel 1978) and in globular cluster giants (Wallerstein, Pilachowski, and Leep 1978; Cohen 1978) and is of the order of ± 0.4 in [O/Fe].

Almost all of these previous studies have been limited to giant stars, where effects of the internal evolution of the stars themselves may mask the primordial abundance variations. Note also Peimbert's (1972) analysis of the planetary nebula in M15 which showed that [O/H] ≈ -1.0 in this nebula, while the cluster as a whole has [Fe/H] $= -2.2$ (Cohen 1979). On theoretical grounds, it is improbable that most of the red giants will have altered their surface oxygen contents through (a) depletion of oxygen in extreme CNO-cycle conditions, or (b) enhancement of oxygen from the late stages of the triple-α helium burning. However, some stars appear to be somewhat pathological; e.g., HD 122563 exhibits [C/Fe] $= -0.4$ and [N/Fe] $= +1.2$ (Sneden 1973) and $^{12}C/^{13}C = 5$ (Lambert and Sneden 1977). A possible scenario for the enhancement of oxygen and explanation for the other species in this star was discussed by Lambert and Sneden (1977).

We have sought in the present study to eliminate the influence of internal stellar evolution on oxygen in metal-poor stars by deriving oxygen abundances in main-sequence (and essentially unevolved subgiant) stars only. Clearly this choice excludes the use of the forbidden oxygen lines (as well as the CO and OH bands). Our analysis has concentrated on the oxygen triplet at 7770 Å. We present the observations and reductions in § II, the analysis in § III, and a discussion of the results in § IV.

II. OBSERVATIONS AND REDUCTIONS

Observations of the oxygen triplet in metal-poor dwarfs were begun at Lick Observatory in 1974. The coudé spectrograph of the 3 m reflector was employed with a Varo single-stage image tube to gather photographic plate data for the program stars. The spectrograph camera gave a reciprocal dispersion of 10.7 Å mm^{-1}, the resolution was about 0.25 Å, and the spectra were recorded on IIIa-J and 103a-D emulsions. Reductions of the plate data were carried out with the Lick Observatory microdensitometer. We created the final spectrum tracings by digital addition of available plate data for each star.

While obtaining photographic spectra, it became apparent that the oxygen triplet in some of the more metal-poor stars could never be detected in this manner. We therefore commenced to reobserve many of the most interesting stars with the McDonald Observatory 2.7 m reflector coudé spectrograph and Reticon silicon diode array (Vogt, Tull, and Kelton 1978). These observations were obtained at a resolution of 0.4 Å. A single exposure covered about 100 Å. A principal advantage of high-resolution spectrophotometry over conventional plate spectroscopy lies in the enhanced signal-to-noise capabilities of the former. We were therefore able to include other features of interest for the present study, at least in the brighter stars. The extremely weak [O I] feature at 6300 Å was detected in one star (η Cas), and several C I lines were detected in a few stars. The importance of the carbon features is that they all originate from high (around 8 eV) lower states, and the carbon abundance in these stars has been previously determined from the CH band. They therefore serve as important checks on the oxygen analysis of the 9.15 eV triplet.

In Figure 1, we show typical spectra from the Lick image-tube plates and the McDonald Reticon spectra.

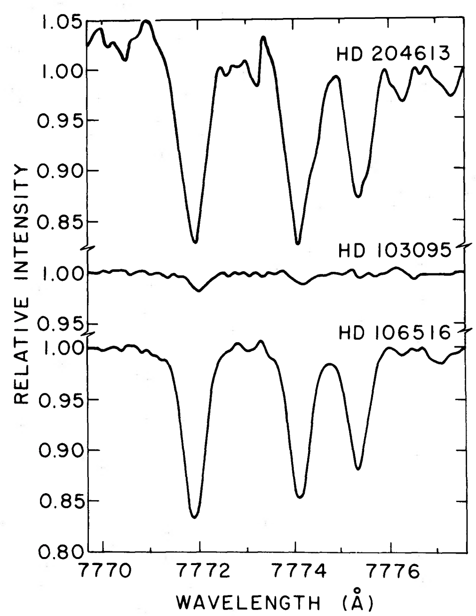

FIG. 1.—Typical spectra of 7770 Å neutral oxygen triplet. The spectrum of HD 204613 was obtained with the Lick coudé–image-tube system; the spectra of HD 103095 and HD 106516 are from the McDonald coudé-Reticon system.

The signal-to-noise ratio of the latter spectra averaged about 100. An intercomparison of the equivalent widths showed that the equivalent widths of the plate spectra (of the program stars and a couple of stars not included in this work) averaged +0.07 ± 0.02 higher (in log W/λ) than the Reticon equivalent widths. The difference exhibited no variation with equivalent width over the range of 25–140 mÅ. The Reticon equivalent widths are assumed to have no systematic errors, and we therefore subtracted 0.07 from all Lick values of log W/λ. The resulting set of equivalent widths for program stars from both instruments is given in Table 1. Normally the Reticon measures were assigned higher weight in the derivation of abundances; however, in a couple of cases the Reticon spectra had noise spikes at the positions of one of the O I lines. In these cases the Lick spectra took precedence.

III. DERIVATION OF THE ABUNDANCES

All abundances were derived with standard "fine analyses" of the transitions of interest. Model atmospheres for all the program stars were from the grid of Peytremann (1974). C. A. Pilachowski kindly made available to us her programs (1975) for interpolation in stellar atmosphere grids. We used these to produce interpolated Peytremann models at the $T_{\rm eff}$, log g, and [M/H] appropriate for each star.

TABLE 1

EQUIVALENT WIDTH DATA

Star	O I Wavelength	Equivalent Width (mÅ) McDonald/Lick	C I Wavelength	Equivalent Width (mÅ) McDonald
HD 4614 (η Cas)	7771.94	69/71	7113.18	15.1
	7774.17	59/73	7115.19	15.1
	7775.39	50/45	7116.99	16.4
	6300.31	4.6/...	8727.13	5.5
HD 6582 (μ Cas)	7771.94	30/30	8335.15	26
	7774.17	22/26		
	7775.39	17/22		
HD 19445	7771.94	11/...		
	7774.17	12/...		
	7775.39	6/...		
HD 34411 λ Aur)	7771.94	90/80	6587.61	12.4:
	7774.17	76/76	7111.48	24.0
	7775.39	62/63	7113.18	27.8
			7115.19	25.4
			7116.99	22.2
HD 94028	7771.94	29/...		
	7774.17	23/...		
	7775.39	14/...		
HD 103095 (Gmb 1830)	7771.94	8.1/...	8335.15	5:
	7774.17	5.6/...		
	7775.39	2.1/...		
HD 106516	7771.94	87/...	8335.15	89
	7774.17	80/...		
	7775.39	59/...		
HD 134169	7771.94	64/65		
	7774.17	47/46		
	7775.39	30:/39		
HD 134678	7771.94	84/...		
	7774.17	65/...		
	7775.39	52/...		
HD 140283	7771.94	9/...		
	7774.17	6/...		
	7775.39	4/...		
HD 204613	7771.94	.../81		
	7774.17	.../71		
	7775.39	.../60		
HD 221377	7771.94	.../98		
	7774.17	.../87		
	7775.39	.../65		
HD 224930 (85 Peg)	7771.94	36/43	8335.15	24
	7774.17	33/30		
	7775.39	22/28		
Sun	7771.94	80	6587.61	18.4
	7774.17	70	7111.48	13.2
	7775.39	52	7113.18	24.6
	6300.31	4.6	7115.19	26.1
			7116.99	19.8
			8335.15	108

NOTE.—Solar equivalent widths are from the Liège Solar Atlas and measured by Lambert (1978) or Tomkin and Lambert (1978).

Model atmosphere parameters for most of the candidate stars were taken from the literature (Clegg 1977; Peterson 1978; Tomkin and Bell 1973; Sneden and Bond 1976). For HD 134169, HD 134678, and HD 221377, new parameters have been derived. We determined effective temperatures principally from the $(b - y)$ colors of Bond (1974). A check of these temperatures was made through a comparison of neutral iron features measured from tracings of 9 Å mm^{-1} McDonald 2.1 m coudé spectrograms (the equivalent-width data are available on request) and theoretical iron curves-of-growth computed with a line analysis program (Sneden 1973) and trial model atmospheres. The temperatures from colors and line strengths proved to be consistent in all cases. We adopted a microturbulence of 1.5 km s^{-1} for all atmospheres. This choice is consistent with published results for metal-poor dwarf stars. Gravities were set from the requirement that neutral and ionized lines from the same element (Fe, Cr, Ti, and V) give consistent abundances.

Table 2 lists the model parameters for our stars and the sources of each. Typical uncertainties assigned to each quantity are: ± 200 K for $T_{\rm eff}$; ± 0.5 for $\log g$; ± 0.5 for ξ_t; and ± 0.2 for [Fe/H].

The models for each star were then used to derive theoretical LTE curves-of-growth for all atomic features of carbon and oxygen, at their appropriate excitation potentials. We adopted the oscillator strengths of Wiese, Glennon, and Smith (1966) for the 7770 Å triplet ($\log gf = +0.33, +0.19, -0.04$), and $\log gf = -9.68$ for the well-determined 6300 Å forbidden transition (see the discussion by Lambert 1978).

The neutral carbon lines present a less straightforward situation. Lambert (1978) has discussed the current unsatisfactory state of the oscillator strengths of permitted C I lines. The forbidden carbon feature at 8727 Å appears to be one of the few reliable indicators of the absolute abundance of this element in the Sun. Accordingly, we have adopted a mean $\log gf$ (8727 Å) = -8.21 and used "solar" oscillator strengths (taken mainly from Tomkin and Lambert 1978) for the rest of the C I transitions. Most of our carbon abundances are therefore differential abundances with the Sun as standard.

The C I 8335 Å line has been used extensively in our carbon analyses. We have matched this line to its observed width in the Sun for the several solar models mentioned above. The internal agreement among models is good (see below), and carbon is predicted to have an abundance of 8.57 from this feature. We have therefore adjusted the oscillator strength of the line by -0.10 for the program stars. The reader is again cautioned that the carbon abundances derived from this line are differential. However, the fairly decent agreement of the solar equivalent width and that calculated from the laboratory gf-value of this transition is encouraging; the solar carbon abundance must be fairly accurate.

We employed a variety of solar atmosphere models to predict the strengths of oxygen features in the Sun. Among the empirical models were those of Gingerich *et al.* (1971), Holweger and Müller (1974), and Vernazza, Avrett, and Loeser (1976); also we used the radiative equilibrium models of Bell *et al.* (1976) and Peytremann (1974). Calculated abundances for the high-excitation lines from the various solar models agree to within 10%. Variations larger than this are found for other transitions. However, these high-excitation lines tend to be formed rather deep, near the continuum level. The deep layers are those where all solar models converge; deviations among them typically increase toward the shallower layers. It is therefore not surprising that internal agreements are so good.

The results of the LTE abundance calculations for the carbon and oxygen features in the program stars are given in Table 3 and Figures 2 and 3. Note first that carbon abundances derived from the high-excitation neutral features are normal ([C/Fe] ~ 0), in agreement with the earlier CH band analyses. The consistency of the present carbon results and those of other workers indicates that the use of high-excitation features for the oxygen abundances probably presents no large analysis problems.

TABLE 2

STELLAR MODEL ATMOSPHERE PARAMETERS

Star	$T_{\rm eff}$	$\log g$	ξ_t	[Fe/H]	Source
HD 4614........	5710 K	4.4	1.4 km s^{-1}	−0.20	1
HD 6582........	5220	4.5	0.85	−0.55	1
HD 19445.......	5830	4.0	1.5	−1.82	2
HD 34411.......	5850	4.1	1.3	+0.30	1
HD 94028.......	5900	3.75	1.5	−1.25	2
HD 103095......	5000	4.5	0.5	−1.30	3
HD 106516......	6250	4.5	1.5	−0.65	2
HD 134169......	5800	3.8	1.5	−1.00	4
HD 134678......	6000	4.5	1.5	−0.50	4
HD 140283......	5600	3.25[2], 4.5[6]	1.5	−2.30	2
HD 204613......	5750	4.0	2.5	−0.30	5
HD 221377......	6000	3.5	1.5	−0.90	4
HD 224930......	5190	4.5	1.4	−0.70	1

SOURCES.—(1) Clegg 1978; (2) Peterson 1978; (3) Tomkin and Bell 1973; (4) this work; (5) Sneden and Bond 1976; (6) Ianna and McAlister 1974.

TABLE 3

ABUNDANCES FOR THE PROGRAM STARS

Star	[Fe/H]	[C/H] (literature)	[C/H] (this work)	[O/H]	[O/C]
HD 4614........	−0.20	−0.50	−0.14	−0.10	+0.22
HD 6582........	−0.55	−0.65	−0.47	−0.09	+0.47
HD 19445.......	−1.82	−1.97	...	−1.49	+0.48
HD 34411.......	+0.30	+0.30	+0.10	+0.23	+0.03
HD 94028.......	−1.25	−1.30	...	−1.17	+0.13
HD 103095......	−1.30	−1.50	−1.16	−0.75	+0.58
HD 106516......	−0.65	−0.70	−0.60	−0.12	+0.43
HD 134169......	−1.00	−1.30	...	−0.44	+0.86
HD 134678......	−0.50	...	...	−0.16	...
HD 140283......	−2.30	−2.20	...	−1.73, −1.43	+0.47, +0.77
HD 204613......	−0.30	+0.05	...	+0.00	−0.05
HD 221377......	−0.90	...	...	−0.17	...
HD 224930......	−0.70	−0.90	−0.54	+0.10	+0.82

NOTE.—The [O/C] values employ a straight mean of the carbon abundances derived in this work and literature values.

Figure 3 shows immediately that oxygen is overabundant with respect to the metals (iron) as well as to carbon in nearly all metal-poor stars. This result agrees with and extends the trends of positive [O/Fe] values suspected in earlier work. Moreover, the [O/Fe] ratios derived here could possibly be increased in at least four of the program stars. Peterson (1979) has reanalyzed her data for HD 19445, HD 94028, HD 103095, and HD 140283 and finds metal abundances about a factor of 2 lower than those given in Table 2. These new [Fe/H] values would lead to nearly the same numeric increases in [O/Fe] ratios for these stars.

Table 2 lists gravity values of 3.25 (Peterson 1978) and 4.50 for HD 140283. The higher value of the gravity comes from the parallax data of Ianna and McAlister (1974). The new parallax of HD 140283 appears to place the star on the subdwarf main sequence, and so a gravity similar to the Sun may be indicated. Both values of the gravity lead to substantial overabundances of oxygen (Table 3) for this star.

A careful analysis of errors is essential in any abundance analysis, but especially so for abundances derived from very high excitation lines. A single slab approximation to a stellar atmosphere would suggest that the oxygen triplet is extremely sensitive to temperature error. Typical errors in $T_{\rm eff}$ reported in the various sources are ± 150–200 K, corresponding to ± 0.03 in $\theta_{\rm eff}$; then the resulting uncertainty in the [O/H] values is $\pm 0.03 \times 9.15$ eV ≈ 0.3. Actual tests with our model atmospheres indicate that the actual temperature

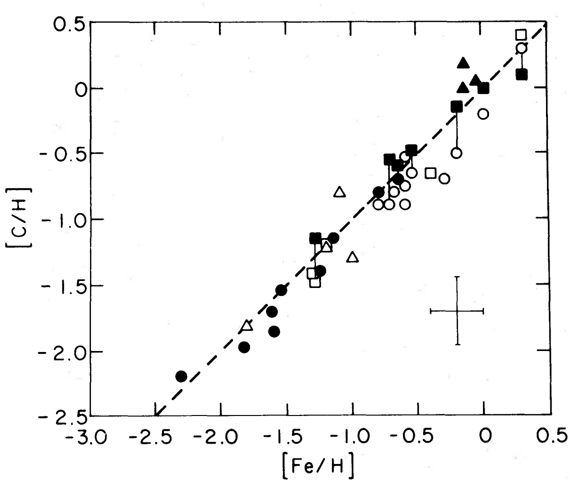

FIG. 2.—Carbon abundances of unevolved stars plotted against the iron abundances. The dashed line represents the relation [C/Fe] = 0. Data in this figure are taken from Clegg [1977; *open circles*, references in Clegg (1977); *open squares*], Tomkin and Lambert (1978; *filled triangles*), Sneden (1973; *open triangles*), Peterson and Sneden (1978; *filled circles*), and the present work (*filled squares*).

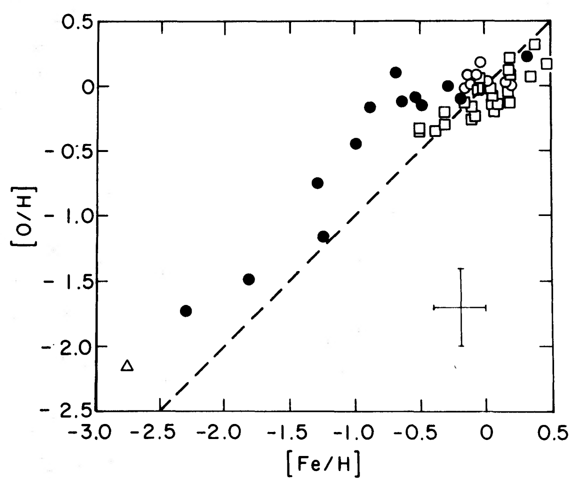

FIG. 3.—Oxygen abundances plotted against iron abundances. The dashed line represents the relation [O/Fe] = 0. Data in this figure are taken from Kjaergaard and Gustafsson (1978; *open squares*), Tomkin and Lambert (1978; *open circles*), Lambert and Ries (1977; *open circles*), Lambert, Sneden, and Ries (1974; *open triangle*), and the present work (*filled circles*).

dependence of the triplet strength is much less than that. We computed the abundance of oxygen necessary to produce a given equivalent width of a weak line for a variety of models with different effective temperatures. It turned out that the change in [O/H] with effective temperature change is about 0.1 per 100 K. This is due to the high temperature necessary to populate 9 eV atomic levels: as the effective temperature of a star decreases, the triplet is formed (for the same equivalent width) at increasingly deeper atmosphere levels. For example, consider models with parameters (6000, 4.5, −1.0) and (5200, 4.5, −1.0). The mean level of line formation computed at the reference wavelength of 5000 Å, $\langle \log \tau_R \rangle$, is −0.18 for the 6000 K model and −0.02 for the 5200 K model. The model temperatures at these levels are 6125 K and 5625 K, respectively. The 800 K effective temperature difference therefore has been reduced to a 500 K difference in excitation temperature. This shrinking of the temperature gradient reduces the abundance uncertainty to ±0.17 for a ±175 K effective temperature uncertainty.

The dependency of [O/H] on other parameters is more apparent. The influence of uncertainties in gravity may be seen by noting that for a weak oxygen line, $W_\lambda \propto K_l/K_c \propto N(\mathrm{O})/n_e$, since $N(\mathrm{O\,I}) \approx N(\mathrm{O})$ and the continuous opacity, largely H^-, depends directly on the number of electrons. As the gravity is decreased, the gas and electron pressures decrease while oxygen remains completely neutral in this temperature range. Therefore the line strengths of neutral oxygen increase with decreasing gravity. Model computations show that a change of 0.5 in $\log g$ alters [O/H] by an average of 0.18.

The oxygen abundance is very insensitive to the overall metallicity [M/H] assumed in the construction of the model atmosphere. Two effects contribute here: (a) the $T(\tau)$ relation changes very little with changes in metallicity in this T_{eff}–$\log g$ domain; (b) as shown in the discussion of possible departure from LTE, the oxygen triplet is formed near $\tau \approx 1$, where n_e is rather insensitive to metallicity changes. The line and continuum opacities are therefore largely unaffected by uncertainties in [M/H]. The predicted abundances from weak lines change by about 0.05 with a change of 0.5 in [M/H]. Adopting ±0.25 as a conservative error estimate for [M/H], the metallicity errors can contribute ±0.03 to [O/H] error.

The influence of CO formation on our results has been fully accounted for in molecular equilibrium calculations. In all but the very coolest of the program stars the ratio of CO to free oxygen atoms is less than 0.01 at the level of the O I triplet formation. In HD 6582 and HD 224930 the CO concentration does rise to ~5% or so, but even at this level the uncertainties in carbon abundances have negligible effects on the oxygen results.

Finally, the microturbulent broadening parameter has little effect on derived oxygen abundances. Changing the microturbulence by 1 km s^{-1} leaves the abundances determined from extremely weak lines unaltered and changes abundances from "strong" lines (~80 mÅ) by about 0.05. We adopt ±0.03 as a reasonable estimate for the influence of microturbulence uncertainties on [O/H].

An rms average of the errors in [O/H] from the temperature, gravity, metallicity, and microturbulence probable errors is ±0.3. This of course involves the assumption that each source of uncertainty is an independent variable. In practice, the temperature and gravity may be somewhat connected. Most atmosphere analyses rely on the ionization equilibrium of the iron-peak elements to determine gravities. Since an increase in temperature increases the ratio $n_{\mathrm{ion}}/n_{\mathrm{neutral}}$ and an increase in gravity decreases this ratio, any temperature adjustments will necessitate changes of the same sense in gravity. However, a temperature increase strengthens a line of the O I triplet, while a gravity increase weakens the same line. Therefore, the uncertainties in [O/H] caused by T_{eff} and $\log g$ errors will tend to cancel each other.

A possible departure from LTE in the population of the $3s\,^5S$ lower state could account for large equivalent widths of the triplet lines. The original discussion of Altrock (1968) indicated possible deviations in the source functions for these lines. Several arguments however suggest that non–LTE effects are negligible in our stars. Johnson, Milkey, and Ramsey (1974) investigated the formation of the oxygen triplet in stars of 6000–6500 K and gravities ranging from $\log g = 4.0$ to 1.0. They showed that departures from LTE could account very well for the increase in strength of this transition with increased luminosity, at least for F-type stars such as Canopus (F0 Ib). However, they found that LTE was a good approximation for oxygen level populations in the Sun and in main-sequence stars of this temperature range. A somewhat different result for the Sun was obtained by Sedlmayr (1974), who employed a more detailed model for the oxygen atom. He found that an LTE calculation for the triplet required a solar oxygen abundance of about $\log \epsilon(0) = 8.9$, while the non–LTE computation's intrinsically deeper absorptions forced the abundance to about 8.65. One difference between Johnson *et al.* and Sedlmayr (1974) appears to lie in the former study's somewhat higher *assumed* solar oxygen content for the LTE analysis: $\log \epsilon(0) = 8.8$. More importantly, the new study by Lambert (1978) of the CNO group abundances in the Sun recommends a value of 8.92 for oxygen (based primarily on the 6300 Å and to a lesser extent the 6363 Å forbidden lines). This new solar oxygen determination would make Sedlmayr's triplet equivalent widths too strong to be reconciled with the best solar data.

Does LTE hold equally well for this transition in metal-poor solar-type stars? Results from the recent work of Eriksson and Toft (1979) indicate that no very large non–LTE effects are probable. These authors made extensive computations for oxygen in cool giant stars ($4000 \leq T_{\mathrm{eff}} \leq 5000$; $1.5 \leq \log g \leq 3.0$; $-0.5 \leq [\mathrm{M/H}] \leq +0.5$). They showed that departures from LTE increase as the model temperatures are raised, as the gravities are lowered, and as the metallicities are increased. These trends make sense: for instance, dropping the stellar gravity leads to decreased electron number densities which of course makes collisions less efficient at populating atomic levels. Increased temperatures bring about stronger lines of this high-excitation triplet. The lines will therefore be formed at shallower atmosphere levels which will show more marked differences between the mean intensity J_ν and the Planck function B_ν. Finally, an increase in the oxygen abundance again forces formation of the triplet to shallower levels and larger departures from LTE. Our stars (see Tables 1–2) have higher temperatures (5000–6000 K) and higher gravities (mostly $\log g = 4.0$–4.5) than those considered by Eriksson and Toft (1979). Also the line strengths in our stars are fairly weak; typical equivalent widths are less than 50 mÅ. A look at Table 3 and Figure 6 of Eriksson and Toft suggests that the temperature, gravity, and oxygen line-strength domains of our stars limit the departure from LTE in oxygen to less than 10%.

Another estimate of the relative dominance of collision and radiation processes may be found in the line computations themselves. We derived the model reference optical depth at which the line plus continuum (at the line wavelength) optical depths exceed 1; we also calculated the mean level of line formation $\langle \log \tau_R \rangle$ [see, for example, Edmonds (1969) for a formal definition]. These both indicate that in almost every star, the lines are optically thin and formed near or at the level of continuum formation. An intercomparison of the Peytremann (1974) models at constant temperature and gravity but different metallicities ([M/H] = 0.0, −1.0, and −∞) reveals that in the outer layers of these models, the electron densities differ markedly. This is of course due to the different model metal abundances. Below about $\tau = 0.5$, and especially at around $\tau = 1$, no large differences in electron densities are seen. This is principally caused by the changeover in the hotter, deeper layers to hydrogen itself being the dominant electron donor and opacity source. The agreement of electron densities are better for the hotter effective temperature models. What this indicates for the formation of the oxygen triplet is that the lines will show at least no more departure from LTE (and probably less) than they do in the Sun.

Finally, we have tested the assumption of LTE by computing the oxygen line strengths in a full non-LTE calculation. We have employed the complete linearization line formation code of Auer, Heasley, and Milkey (1972) and the model oxygen atom of Johnson, Milkey, and Ramsey (1974) and the radiative equilibrium stellar atmospheres of Peytremann (1974) in this analysis. These computations show that in both solar abundance and metal-poor stellar atmospheres of solar temperature dwarf stars, the non-LTE line strengths essentially match those predicted in LTE calculations for the 7770 Å triplet.

IV. WHY IS OXYGEN OVERABUNDANT?

a) *Nucleosynthesis by Massive Stars*

A standard scenario for the origin of the light elements assigns C and O as well as the Fe-peak metals to nucleosynthesis in massive stars ($M \gtrsim 10\ M_\odot$). Our discussion will be based upon the bulk yields provided by Arnett (1978). The reader is referred to Arnett's paper for the derivation of these yields and a discussion of the major uncertainties. In Figure 4, we show the relative yields $Q_C' \equiv Q(\mathrm{Si + Fe})/Q(\mathrm{C})$ and $Q_O' \equiv Q(\mathrm{Si + Fe})/Q(\mathrm{O})$ as a function of stellar mass. We note that Q_C' is approximately constant, but Q_O' decreases appreciably in the higher mass stars. With Q_C' almost independent of stellar mass (MQ_j is the mass of nucleus j ejected from a star), the C/(Fe + Si) abundance ratio should not vary appreciably as the heavy-element abundances are progressively increased in the Galaxy through the operation of nucleosynthesis in massive stars. Furthermore, Arnett points out that (i) the yields of C and Fe do reproduce the observed ratio of C to (Si + Fe) in the Sun, and (ii) the rate of nucleosynthesis is sufficient to produce the observed abundances of C and O [see also Wheeler, Miller, and Scalo (1978) who adopt a new interstellar mass function (IMF) by Miller and Scalo (1980)]. Present observations yield the C/Fe ratio in metal-poor stars. If we suppose that [Si/Fe] = 0, the observed result that [C/Fe] = 0 is consistent with Arnett's predicted bulk yields—Q(C) and Q(Si + Fe)—for any plausible IMF.

For [Fe/H] $\lesssim -0.5$, the [O/Fe] ratio is approximately constant or [O/Fe] ~ 0.5. At higher metallicities [O/Fe] tends to lower values; the trend may be continuous reaching [O/Fe] ~ -0.2 at [Fe/H] $\sim +0.3$ (Kjaergaard and Gustafsson 1978). If Arnett's bulk yields are accepted at face value, the [O/Fe] results imply an approximately constant IMF (of the extremely short-lived progenitors of the Population II stars) up to about 2.5×10^9 yr ago (the rather uncertain conversion of [Fe/H] to age is taken from Perrin *et al.* 1977). A crude estimate of the IMF needed to produce the enhanced oxygen may be seen in Arnett's data and formulae: altering the IMF exponent

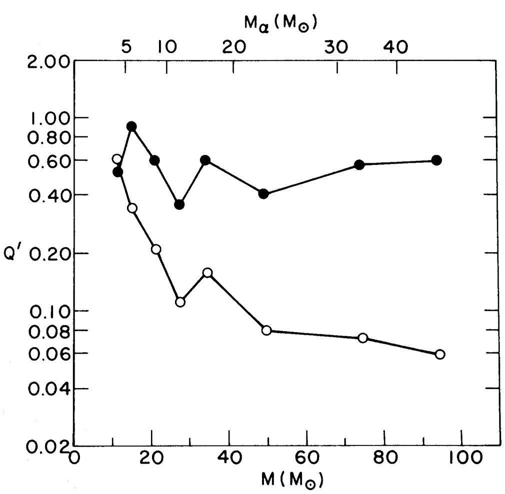

FIG. 4.—Relative bulk yields Q_C' and Q_O' for carbon and oxygen as functions of the core mass M_α and total mass M of a star undergoing explosive nucleosynthesis.

α from 4/3 to 2/3 increases the ratio of 95 $M_\odot$ to 10 $M_\odot$ stars by about a factor of 5 and increases the resulting O/C ratio from a generation of stars by about a factor of 2. Since then the IMF has provided fewer higher mass stars, and oxygen production relative to C, Si, and Fe has slowed down. This evolution of the IMF is consistent with suggestions that the upper mass limit for star formation may be higher in metal-poor gas clouds (Larson and Starrfield 1971; Kahn 1974). However, the reason for a relatively abrupt modification of the IMF at [Fe/H] ~ -0.5 is unknown.

b) *Nucleosynthesis and Type I Supernovae*

The massive stars considered by Arnett probably terminate as Type II supernovae. In the explosion, the products of nucleosynthesis occurring before and during the explosion are dispersed into the interstellar medium. The bulk yields refer to these ejecta.

The Type I supernovae may also be an important contributor to the progressive chemical evolution of the Galaxy. Tinsley (1979) has argued that these supernovae are the major source of synthesized heavy elements (e.g., iron). She also considers some C to be contributed by low-mass carbon stars and planetary nebulae. In her model, the massive stars contribute oxygen and carbon and only part of the heavier elements.

Tinsley calculates the evolution of the abundances of C, O, and Z (a heavy metal such as iron) as well as abundances of some secondary elements (^{14}N and *s*-process elements) for several model galaxies. The reader is referred to her paper for a detailed description of the bulk yields, the IMF, and the model galaxy (i.e., How is infall of gas modeled?). Our discussion will be restricted to a couple of key points.

The major producer of C (and, of course, O) in her model remains the massive stars ($M > 10\ M_\odot$). Her models predict approximately equal overabundances of C and O in metal-poor stars, i.e., [C/Fe] $\sim$ [O/Fe] > 0. As noted by Tinsley, the observations (Peterson and Sneden 1978) show [C/Fe] $= 0$. We confirm this result for the few stars for which we have obtained C I line observations. Moreover, the O/C ratio extracted from O I and C I lines is not very sensitive to model atmosphere uncertainties and probably also to small departures from LTE. The conclusion to be drawn from the result that [C/Fe] $= 0$ seems clear: C and Fe are probably produced by the same stars. Anticipating this conclusion, Tinsley suggested that intermediate mass ($3\ M_\odot \lesssim M \lesssim 8\ M_\odot$) stars be considered as a major source of C and that the massive stars ($M > 10\ M_\odot$) produce C with a yield far below that predicted by Arnett (1978); the C and Fe in this modified scheme are produced by similar stars. Since the progenitors of the Type I supernovae are assigned by Tinsley to range $4 < M < 6.5\ M_\odot$, C is produced by thermal pulses and dispersed into the interstellar medium through either a steady stellar wind or the supernova explosion.

Again, the change in the O/Fe ratio with increasing metallicity could be achieved with a change in the IMF. Alternatively, an increase in the C and Fe yields might result as the bulk yields from Type I supernovae increased with increasing metallicity of the progenitor.

c) *Galactic Nucleosynthesis*

Detailed interpretation of the C, O, and Fe abundances using models for the chemical evolution of the Galaxy is unwarranted for at least two reasons. First, it is uncertain whether [O/Fe] contains significant scatter; the possibly normal [O/Fe] ratio in HD 94028 may indicate this, but the data are too few. Also, significant questions remain to be resolved in the calculations of the bulk yields from nucleosynthesis calculations (see the discussions of Arnett and Tinsley).

Additional abundance information will be required before an understanding of the chemical evolution of the Galaxy is reasonably complete. Nitrogen is one obvious element for which few abundance determinations in unevolved stars are available. It is commonly assumed that N is a secondary element, but Pagel (1978) suggests that there is a significant contribution to the N abundance from a primary source. Thermal pulsing in intermediate mass stars could produce C which could be further processed to N in the CN cycle. Then, if these stars are an important C source, N could also be a primary element.

Remarkably little information is available on several other important elements (e.g., sulfur). We note that the recent opening of the near-infrared to high-resolution, low-noise stellar spectroscopy should permit strong lines of several critical neutral atoms to be observed in metal-poor stars. When these additional data are in hand and some major uncertainties in the theoretical calculations are reduced, a new look should be taken at the chemical evolution of the Galaxy.

We wish to thank C. A. Pilachowski, G. Wallerstein, J. Tomkin, and R. Canterna for helpful discussions. We especially thank J. L. Greenstein for encouragement in this project and for allowing us to have some spectral scans of a few of the program stars. This research has been supported by NSF grants AST 77-23213 to D.L.L. and AST 78-20405 to G. Wallerstein and a grant from the Robert A. Welch Foundation to D.L.L. Finally, we thank J. Tomkin for telescope assistance.

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