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CARBON AND NITROGEN ABUNDANCES IN METAL-POOR STARS

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ABSTRACT

Carbon and nitrogen abundances have been derived for 10 metal-poor stars. For each star, a combination of coarse and fine analyses have been used to determine a model atmosphere. Then, using the model and atomic- and molecular-line parameters in a spectrum-synthesis program, artificial CH, CN, and NH spectra have been computed. Finally, by comparing the synthetic and observed spectra, carbon and nitrogen abundances have been obtained. The principal results of the analysis are: (1) in metal-poor dwarfs [C/Fe] $\simeq +0.0$; (2) all but one dwarf also show [N/Fe] $\simeq +0.0$; (3) metal-poor giants with $\log g \lesssim 2.4$ appear to possess [C/N] $\lesssim -1.0$, while those with higher gravities show [C/N] $\gtrsim +0.0$. The anomalously low [C/N] values are interpreted here as effects of internal evolutions of the giant metal-poor stars. Finally, the consequences for galactic nucleosynthesis theories using the present results are discussed.

Subject headings: abundances, stellar — late-type stars — nucleosynthesis — weak-line stars

I. INTRODUCTION

Metal-poor stars have provided important information regarding the chemical evolution of our Galaxy. Results of abundance analyses of these stars can be used as constraints on theoretical models of galactic nucleosynthesis. In particular, knowledge of carbon, nitrogen, and oxygen contents in metal-poor stellar atmospheres may possibly shed some light on probable sites of nucleosynthesis. This paper reports the determination of carbon and nitrogen abundances in 10 metal-deficient stars.

Recent theoretical treatments of nucleosynthesis have dealt with two possible sites: ordinary stars and so-called supermassive objects (SMO). The work on ordinary star models has concentrated on the later stages of stellar evolution. Heavy-element generation has been considered in calculations of explosive carbon burning (Arnett 1969), oxygen burning (Truran and Arnett 1970) and silicon burning (Arnett, Truran, and Woosley 1971). Generally these calculations have been able to match the observed solar-system abundances with remarkable precision. However, some solar-system abundances, notably those of ^{14}N and ^{18}F, are not matched through the various explosive nucleosynthesis processes. In Arnett's models, nitrogen is labeled as a secondary burning product; that is, it is not produced directly in an explosion but rather is generated in the outer shells of a star via the slower CNO-cycle hydrogen burning. In a stellar explosion, then, nitrogen merely tries to survive. Arnett (1971) reasoned that in early generations of stars very little carbon and oxygen exists, and thus nitrogen cannot be produced in large quantities in the CNO cycle. In metal-poor stars, then, one ought to see an underabundance of nitrogen relative to the rest of the metals.

The theory of supermassive objects has been developed by Wagoner (1968). These hypothetical objects have masses of 50 to 100 solar masses and central temperatures in excess of 10^{10} ° K. Wagoner calculated the amounts of elements produced in an explosion of a SMO limiting his detailed results to atomic species with $A \leq 28$. Two of his more promising models give some agreement with abundances of Population II stars, but not with solar-system abundances. The SMO calculations have been criticized on theoretical grounds, but we attempt here to test the models through observation. Nitrogen production in a SMO is a direct process, and abundances of the CNO group generated in it are predicted to have roughly their solar-system ratios.

Since the nitrogen abundance predictions for stellar and SMO nucleosynthesis appear to be very different, abundance studies of the CNO-element group ought to help us choose between these two models. Metal-poor stellar atmospheres are particularly useful for such work, because they contain material which probably has been processed very few times by earlier generation stars or SMOs. Therefore abundances in metal-poor stars ought to show best the results of individual nucleosynthesis events.

One must be careful, however, to discuss abundance results for carbon and nitrogen in dwarfs and giants separately. Testing the nucleosynthesis theories discussed above requires abundances from atmospheres which are free from effects of internal stellar evolution. Iben (1964) has predicted that during the evolution of a star toward the giant branch, nitrogen which has been generated from carbon in the CNO cycle will be mixed by convection to the surface. Therefore the C/N should be lower in giants than dwarfs. Nitrogen may also be enhanced after the onset of helium burning in giants. Sackmann, Smith, and Despain (1973) have performed calculations which indicate that if helium flashing occurs, deep mixing from the core to surface

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TABLE 1

ABUNDANCE RESULTS FOR METAL-POOR STARS

Star	[Fe/H]	[C/Fe]	[N/Fe]	[C/N]	log (g)	Source
HD 122563	-2.75	-0.4			1.2	Wolffram (1972)
	-2.55	-0.9	~+0.7	≤-1.6	1.2	Ball and Pagel (1967)
ν Indi	-1.17	+0.00	-0.74	+0.74		Harmer and Pagel (1970)
	-1.1	+0.0	-1.9	+1.9	2.7[1]	Bell (1970)
HD 25329	-1.32	~+0.0	~+0.5	~-0.5	4.2[2]	Harmer and Pagel (1970)
HD 2665	-1.68	~-0.4	~-0.4	~+0.0	1.8	Koelbloed (1967)
HD 6755	-1.05	~-0.4	~-0.4	~+0.0	2.6	Koelbloed (1967)
HD 140283	-2.0	~+0.0			3.7	Cohen and Strom (1968)
HD 19445	-2.5	~+0.0			4.0	Cohen and Strom (1968)
μ Cas	-0.6	~+0.5			4.2	Cohen (1968a)
HD 103095	-1.0	-0.34	-0.85	~+0.5	4.3[2]	Tomkin (1972)
	-1.2	~+0.0			4.3	Cohen (1968b)
	-1.3	~-0.15	~-0.7	~+0.65	4.4-4.6	Tomkin and Bell (1973)

Notes:

1): a mean of two models.

2): These gravities were computed with the results of the named references and the formulas of Pagel (1962).

can enhance the surface abundance of nitrogen. This, however, is but one of the possible changes in composition which arise in their complicated theory. All this indicates, therefore, that one must treat the abundances in atmospheres of giants with some care.

Before discussing in detail the present study, let us review previous determinations of carbon and nitrogen in metal-poor stars. Most metal-poor stars are too faint for very-high-dispersion spectroscopy. Also, in the G- and K-type stars most commonly studied, one must rely on the CH and CN molecular bands for carbon and nitrogen abundances. It is difficult, however, to find any unblended CH or CN lines in the crowded violet spectral regions. In addition, it is extremely difficult to determine the oxygen abundance in these stars. Since oxygen affects the carbon equilibrium through formation of CO molecules, an unknown oxygen abundance leads to an increased uncertainty in the carbon abundance. For these reasons investigators have been understandably reluctant to attempt determinations of C/N in metal-poor stars.

Results of previously completed relevant studies are summarized in table 1. No attempt has been made here to consider the early-type metal-poor stars because it appears that some, if not all, are evolved objects. In table 1 the carbon abundances were derived from lines of the CH bands at 4300 Å. All nitrogen determinations are based on the violet CN bands. The abundances for HD 2665 and HD 6755 were based on only a single, possibly blended line of the 4215 Å band. The other nitrogen abundances come from lines of the $\Delta v = 0$ bands starting at 3883 Å. These bands have an advantage over the $\Delta v = -1$ bands at 4200 Å in that they have oscillator strengths about a factor of 10 larger. The $\Delta v = 0$ bands will therefore remain visible in metal-poor stars in which the $\Delta v = -1$ bands have disappeared.

In the present study, carbon and nitrogen abundances of 11 metal-poor stars have been derived, using the CH bands at 4300 Å, the CN bands at 3883 Å, and, when possible, the NH bands at 3360 Å. Use of the NH bands is desirable because the NH density is linearly dependent on the metal abundance, while the CN density depends on the square of the metal abundance. In addition, since the nitrogen equilibrium depends chiefly on the free nitrogen and the N_2 molecule, the derived nitrogen abundance is free of oxygen abundance uncertainties if the NH bands are employed. However, since these stars are generally faint at 3360 Å, only four of them have had nitrogen determinations based on the NH bands.

A spectrum-synthesis technique has been employed in the reduction of the spectroscopic plate data. This permitted the use of many blended molecular lines in the analysis. Model atmospheres have been derived for the program stars with the exception of HD 122563, for which a model already exists (Wolffram 1972). The analysis of HD 122563, which served as the prototype in this study, has been previously published (Sneden 1973). The remaining sections give more detail about the analysis of the rest of the program stars.

II. THE OBSERVATIONS AND PLATE REDUCTIONS

The list of newly discovered weak-lined stars of Bond (1970) was searched for stars which met the following criteria: (1) the metal deficiency must be

TABLE 2

BASIC DATA FOR THE PROGRAM STARS

Star	R.A.	Decl.	Epoch	V*	Sp.†	Sp.‡
HD 2665.........	00ʰ25ᵐ.2	+56°32′	1900	7.73	G5 III	G6 III–IV
HD 2796.........	00 26.3	−17 21	1900	8.3§	G0§	...
HD 6755.........	01 03.2	+61 01	1900	7.73	...	F9 V
HD 88609........	10 08.0	+54 04	1900	8.61	G5 III	K0 II
+52°1601........	11 52.5	+52 35	1855	8.80	G5 III	G7 III
HD 105546.......	12 04.1	+59 35	1900	8.61	G2 III	G2 III
HD 105755.......	12 05.3	+55 02	1900	8.59	G0 V	G1 V
HD 122563.......	13 57.6	+10 11	1900	6.21	...	K2 III
HD 134169.......	15 03.3	+04 18	1900	7.70	G1 V	G1 V
HD 188510.......	19 50.4	+10 28	1900	8.82	G5 V	G2 V
HD 195633.......	20 27.4	+06 11	1900	8.56	G0 V	G1 IV

* From Bond 1970. † Based on Bond's 1970 classification dispersion spectroscopy.
‡ Based on Bond's 1970 four-color photometry. § From the Henry Draper catalog.

apparent ([M/H] $\leqslant -1.0$) because the nucleosynthesis effects discussed above are not expected to be obvious in stars of nearly solar metallicity; (2) the spectral type must be no earlier than roughly G0, for the CH, CN, and NH molecules will dissociate fairly completely in much hotter stars; (3) $m_v \leqslant 8.5$, to permit reasonable exposure times with coudé spectrographs. Three of the stars chosen for analysis, HD 122563, HD 2665, and HD 6755, have been examined by other workers (see table 1). Basic data for the program stars are given in table 2.

The McDonald Observatory 2-m Struve reflector and coudé spectrograph were used to obtain at least three plates for most stars in the violet-blue spectral region, at a dispersion of 18 Å mm^{-1}. Where possible, plates at 9 Å mm^{-1} were also taken. Table 3 lists the plate data. It was realized during the course of the investigation that the coudé spectrograph of the Struve reflector was too slow to get NH data for most stars. Therefore the Kitt Peak National Observatory 2-m telescope and coudé spectrograph were used to obtain additional NH band spectroscopic plates. In all, four out of 11 program stars had NH band data for the analysis.

All spectra were taken with baked IIa-O emulsions. The spectrograph slit widths projected on the plates were 20 μ, and the lengths varied from 0.3 to 0.5 mm. The lengths were smaller than is usually desired for abundance work but the faintness of the stars dictated these sizes. Calibration plates were simultaneously exposed in tube sensitometers for all spectra.

The plates were traced on the microdensitometer of the Astronomy Department. The digital output of this instrument permitted different plates for each star to be added together, after conversions from density to intensity and from plate position to wavelength had been made.

Equivalent widths of relatively unblended atomic lines were then measured from the tracings. Since these stars are at least a factor of 10 poorer in metals than the Sun, the continuum could be set with some confidence. It was drawn by eye through the highest points in the spectrum. Using the triangle approximation, equivalent widths of the narrowest lines were then measured. A least-squares fit was made of these equivalent widths as a function of line central residual intensities. This relation was used to compute equivalent widths of the rest of the atomic lines for each star. Sneden (1973) showed that equivalent widths of HD 122563 measured from McDonald 9 Å mm^{-1} plates compared well with the equivalent widths of Wallerstein *et al.* (1963). For the program star HD 134169, plates of 18 and 9 Å mm^{-1} dispersions were taken. Figure 1 shows a comparison of the two sets of equivalent widths. With large scatter, the two dispersions give the same values.

III. DETERMINATION OF THE STELLAR MODELS

In this section we describe the determination of model atmospheres for our stars and the derivation of the metal abundances. Infrared color indices and spectral scans were not available for the program stars. Preliminary model-atmosphere parameters were therefore derived from a coarse analysis, using the neutral and ionized iron, chromium, and titanium equivalent widths. Spectral classifications of Bond (1970) could have given starting models, but it was felt that while temperatures could be accurately estimated in this manner, gravities could not. For instance, the designation "giant" could cover stars with gravities ranging over two orders of magnitude.

The theory of a coarse analysis is well known. Our analysis followed closely the method devised by Pagel (1964), and will not be discussed in detail here. Using neutral and ionized lines of iron, chromium, and titanium, the following quantities were derived for each star: $\Delta\theta_{\rm exc}$, $[P_e]$, $[W/\lambda]$, [Fe/H], [Cr/H], and [Ti/H], where we have the standard notation

$$[X] \equiv \log(X)_{\rm star} - \log(X)_{\odot}\,,$$

X being any atmosphere quantity. Here, θ is the reciprocal temperature $5040/T$, and $[W/\lambda]$ is the vertical curve-of-growth shift, from which the microturbulent velocity ξ_t may be derived. All three elements were used in the determination of the electron pressure

TABLE 3

PLATE DATA FOR THE PROGRAM STARS

Star	Plate	Date	Disp.	Cam.-Gr.	Approx. λ range	Dur.	Seeing
HD 2665	7574	7/29/71	18	C-II	3800-4700	1^h41^m	1-3"
	7901	8/30/72	18	C-II	3800-4700	1 30	1-2
HD 2796	7895	8/29/72	18	C-II	3800-4700	2 05	1-2
	7900	8/30/72	18	C-II	3800-4700	2 40	1-2
	7904	8/31/72	18	C-II	3800-4700	2 43	2
HD 6755	7696	1/02/72	18	C-II	3800-4700	1 35	2-4
	7700	1/05/72	18	C-II	3800-4700	2 00	4-7
HD 88609	7726	3/24/72	18	C-II	3800-4700	4 15	2-3
	7733	3/26/72	18	C-II	3800-4700	5 25	2-6
	7750	4/01/72	18	C-II	3800-4700	2 50	1-3
+52°1601	7394	5/14/71	18	C-II	3800-4700	2 10	2
	7761	4/06/72	18	C-II	3800-4700	3 15	1-2
HD 105546	7743	3/30/72	18	C-II	3800-4700	5 00	3-7
	7758	4/03/72	18	C-II	3800-4700	2 20	2-3
	7771	4/28/72	18	C-II	3800-4700	4 45	2-6
	D-3687	5/13/73	17	2-B	3300-3700	7 50	1-3
HD 105755	7395	5/14/71	18	C-II	3800-4700	1 45	2-3
	7747	3/31/72	18	C-II	3800-4700	2 00	2-4
	7751	4/01/72	18	C-II	3800-4700	2 00	1-3
	7754	4/02/72	18	C-II	3800-4700	3 47	1-2
	D-3683	5/11/73	17	2-B	3300-3700	5 15	2
HD 122563	7216	2/16/71	9	B-II	3800-4700	1 18	2-3
	7444	6/16/71	9	B-II	3800-4700	1 20	2-5
	7762	4/06/72	9	B-II	3300-3700	4 00	1-2
	7770	4/27/72	9	B-II	3300-3700	6 30	1-10
	7773	4/29/72	9	B-II	3300-3700	5 15	1-4
HD 134169	7402	5/16/71	18	C-II	3300-3700	2 00	1-2
	7442	6/15/71	18	C-II	3300-3700	3 00	1-3
	7445	6/16/71	9	B-II	3800-4700	3 30	2-4
	7744	3/30/72	18	C-II	3800-4700	2 00	6-7
	7769	4/26/72	9	B-II	3800-4700	3 30	3-5
HD 188510	7396	5/14/71	18	C-II	3800-4700	2 10	2-3
	7443	6/15/71	18	C-II	3800-4700	3 05	1-2
	7573	7/29/71	18	C-II	3800-4700	2 55	1-2
HD 195633	7893	8/29/72	18	C-II	3800-4700	2 20	1-3
	7898	8/30/72	18	C-II	3800-4700	2 20	1-2
	7905	9/01/72	18	C-II	3800-4700	2 34	1-2

Note: Plate numbers beginning with "D-" were obtained at Kitt Peak

$[P_e]$, and $\Delta\theta_{\text{exc}}$ was derived separately for the neutral and the ionized lines.

Since most of the plate data were obtained with a dispersion of 18 Å mm^{-1}, all of the clearly resolved lines on the spectrum tracings were moderately strong. This is illustrated by figure 2, which shows the Fe I curve of growth for HD 105755. No lines used in this analysis were weak enough to fall on the linear part of the curve of growth. This means that it was difficult to determine atomic abundances unambiguously. Since one can make both horizontal and vertical curve-of-growth shifts, an apparent horizontal (abundance) shift could also be interpreted, within limits, as a vertical (microturbulence) shift. This uncertainty should not severely harm our values of $\Delta\theta_{\text{exc}}$, however, because the temperatures were determined through comparing lines of differing excitation potential, but similar equivalent width. Also it must be stressed that the coarse analysis was used merely to get (hopefully good) trial model-atmosphere parameters for each star.

With these derived quantities, and the crude assumption

$$\Delta\theta_{\text{exc}} \simeq \Delta\theta_{\text{ion}} \simeq \Delta\theta_{\text{eff}}\,,$$

parameters for model atmosphere computations were specified as follows. We assume $\theta_{\text{eff}}(\odot) = 0.87$ (Allen 1955), and $\log P_e(\odot) \simeq +1.0$ (Koelbloed 1967), and

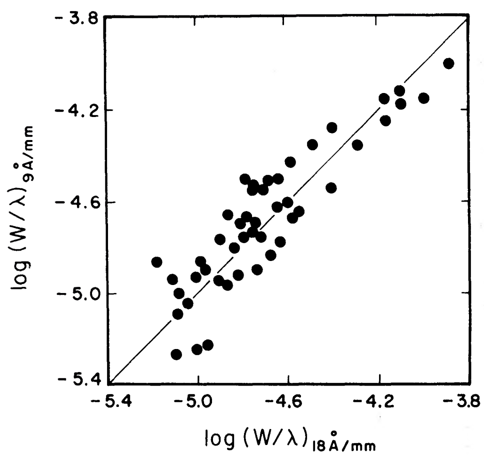

FIG. 1.—A comparison of equivalent widths of HD 134169. Ordinates are values from 9 Å mm^{-1} McDonald 82-inch (2-m) plates, abscissas are values from 18 Å mm^{-1} McDonald plates.

thereby compute $T_{\rm eff}$(star) and log P_e(star). The surface gravity may be approximated as

$$P_g \simeq g\tau_0/\kappa_\lambda ,$$

where P_g is the gas pressure, g is the gravity, κ_λ is the mass absorption coefficient, and τ_0 is the optical depth of the effective level of line formation, here taken to be 0.4 (Aller 1960). Tables of $P_g(P_e, T)$ and $\kappa_\lambda(P_e, T)$ have been computed in accordance with the discussion of Aller (1960). With interpolated values from these tables, we may calculate a trial value for g, the surface gravity.

In this manner preliminary model-atmosphere parameters were chosen for each star. These quantities ($T_{\rm eff}$, log g, [M/H]) were used with the model-atmosphere program ATLAS (Kurucz 1970) to generate a flux-constant model atmosphere. The model was calculated under the assumption of local thermodynamic equilibrium and either radiative or convective equilibrium, as appropriate. Strom, Cohen, and Strom (1967) indicated that line blanketing would not be a significant opacity source in our domain of $T_{\rm eff}$ and [M/H]. More recently, Böhm-Vitense (1972) showed that $T(\tau)$ is virtually the same for Population I and Population II stars of the same effective temperature. Therefore line blanketing was ignored in our model calculations. All models were computed for 35 layers beginning at $\tau = 1.0 \times 10^{-5}$ and separated by $\Delta \log \tau = 0.2$. Model iterations continued until flux errors were less than 1 percent for all layers down to $\tau = 6.3$.

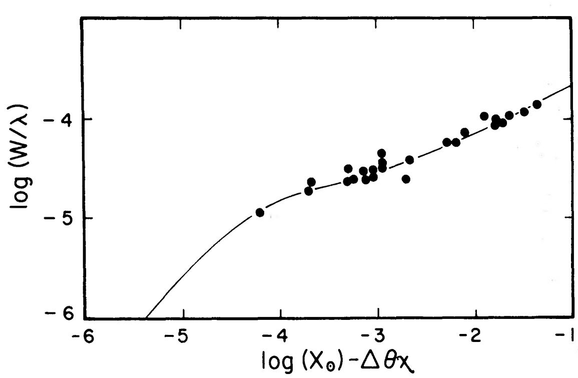

FIG. 2.—The Fe I curve of growth for HD 105755. The curve represents the best average fit to the data points.

The models were tested by using them with a line-analysis program to predict equivalent widths of the atomic lines used in the coarse analysis. This computer program, developed during the course of the present research, was given the model atmosphere in question, line parameters for the Fe, Cr, and Ti neutral and ionized lines, and the line equivalent widths. By varying the element abundances, the measured equivalent widths and those predicted by the line analysis program could be matched. If a proper model for a program star had been chosen, the computed abundances would be the same for lines of differing ionization state, excitation potential, and equivalent width. A trend of abundance with excitation potential would indicate a need to change the model effective temperature. Different predictions for neutral and ionized lines necessitated a change in the surface gravity. Finally, a trend of predicted abundance with equivalent width showed a need to alter the assumed microturbulent velocity.

Of the line parameters needed by the line-analysis program, all are accurately known except the oscillator strengths. Since it is difficult to find well-determined oscillator strengths for astrophysically interesting lines, the values for our lines were determined in the following manner. Van der Waals damping was presumed to be the dominant line-damping mechanism, with the constant C_6 increased by a factor of 6.3 (Holweger 1971). Using the Wolffram (1972) model of the metal-deficient star HD 122563, equivalent widths for this star as given by Wallerstein *et al.* (1963), and the line-analysis program, oscillator strengths were computed which forced the predicted and given equivalent widths to match.

As a test of the oscillator strengths, they were used to predict solar abundances, using the Harvard-Smithsonian Reference Solar Atmosphere of Gingerich *et al.* (1971). Figure 3 shows the results for lines used in this analysis. The strong lines of Fe I multiplets 41, 42, and 43 were not used in the model analysis, because these lines, which are located well up on the damping part of the curve of growth, could not have satisfactory oscillator strengths assigned. These lines were not expected to be sensitive to abundance changes. Also, predicted solar abundances were somewhat lower than the best determinations of these abundances in the solar atmosphere (Warner 1968; account here has been taken of the recent changes in the Fe I f-value scale). The solar equivalent widths of many of the lines used in this analysis are very sensitive to the choice of a damping parameter. Our choice of the van der Waals C_6 is probably too large. The error should not be large, however, in using these gf-values to derive atomic abundances in other weak-lined stars. It should be

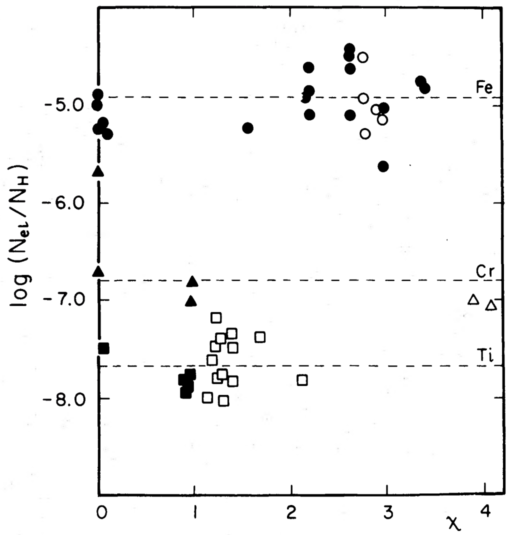

FIG. 3.—Solar abundances, log (N_{el}/N_H), predicted with the derived line quantities, are plotted as functions of the excitation potentials. The symbols are: *circles*, Fe; *squares*, Ti; *triangles*, Cr. The filled symbols represent neutral lines of each element.

noted here, anticipating a later result, that the most important derived quantity for this study, the ratio [C/N], is fairly independent of the atmosphere uncertainties.

With these quantities, the trial models for each star were tested for the three criteria mentioned previously. Normally, the effective temperatures derived from the coarse analysis proved to be fairly good. Additional models usually had to be computed to determine an acceptable value of log g. Adjustment was usually also needed of the initial microturbulent velocity ξ_t. Figures 4 and 5 demonstrate the effect of changing the micro-

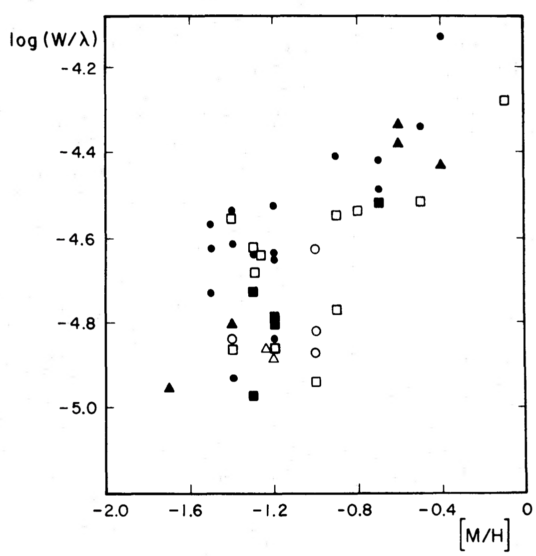

FIG. 4.—Predicted abundances [M/H] plotted as functions of equivalent widths, for the final HD 105755 model and ξ_t = 2.5 km s^{-1}. The symbols are as in fig. 3.

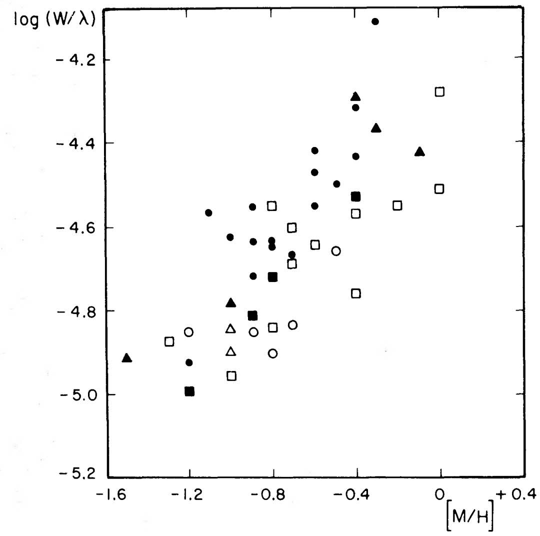

FIG. 5.—Predicted abundances [M/H] plotted as functions of equivalent widths, for the final HD 105755 model and ξ_t = 1.4 km s^{-1}. The symbols are as in fig. 3.

turbulence by about 1 km s^{-1} in the model for the program star HD 105755. With ξ_t = 2.5 km s^{-1}, no trend with equivalent width is seen for the weaker lines. Lines with log (W/λ) $\gtrsim -4.5$ were found to lie on the damping part of the curve of growth and, hence, were insensitive to the choice of ξ_t.

Table 4 summarizes the results of the atmosphere analysis for our stars. Included in this table are the values derived by other workers for three of the stars. Comments on individual stars are reserved for a later section.

IV. CARBON AND NITROGEN ANALYSIS

Carbon and nitrogen abundances were determined for the program stars by means of a comparison of observed and synthetic spectra. For most of the stars, the observations included the CH ($A\,^2\Delta$–$X\,^2\Pi$) bands at 4300 Å and the CN ($B\,^2\Sigma^+$–$X\,^2\Sigma^+$) $\Delta v = 0$ bands at 3800 Å. Four stars had spectra of the NH ($A\,^3\Pi_1$–$X\,^3\Sigma^-$) 0–0 and 1–1 bands at 3360 Å. The line parameters for these molecular bands and parameters for the atomic lines which contaminate the band spectra are discussed by Sneden (1973) and will not be repeated here. We merely call to the reader's attention the problem of the dissociation energy of CN. While recent experiments have indicated that D_0(CN) is around 7.85 eV, the observed solar CN $\Delta v = 0$ spectrum (Minnaert, Mulders, and Houtgast 1940) is matched much better with the use of D_0(CN) = 7.55. Some experiments have yielded this value, and the analysis of HD 122563 (Sneden 1973) also indicated D_0(CN) = 7.55 eV. We therefore adopt this lower value for the work on the remainder of the program stars. A further discussion of the CN dissociation energy problem can be found in Arnold and Nicholls (1972) or in Lambert and Mallia (1973).

A spectrum-synthesis program was written to com-

TABLE 4

Basic Atmosphere Parameters

Star	T_{eff} (° K)	log g	ξ_t (km s^{-1})	[M/H]	Remarks
HD 2665.........	4775	1.8	0.6	−1.6	Koelbloed 1967
	4950 ± 400	2.6 ± 0.4	2.5 ± 1.0	−2.3 ± 0.6	...
HD 2796.........	5000 ± 400	1.8 ± 0.4	2.5 ± 1.0	−2.4 ± 0.6	...
HD 6755.........	5200	2.8	0.7	−1.1	Koelbloed 1967
	5200 ± 400	2.8 ± 0.4	1.4 ± 1.0	−1.7 ± 0.6	...
HD 88609........	4200 ± 500	1.3 ± 0.6	2.0:	−2.5 ± 0.8	...
+52°1601........	4600 ± 400	2.1 ± 0.5	2.0 ± 1.0	−1.8 ± 0.7	...
HD 105546.......	5300 ± 400	2.4 ± 0.5	3.0 ± 1.0	−1.6 ± 0.7	...
HD 105755.......	5550 ± 400	3.7 ± 0.4	2.5 ± 1.0	−1.2 ± 0.6	...
HD 122563.......	4600 ± 150	1.2 ± 0.4	2.6 ± 0.4	−2.75 ± 0.3	Wolffram 1972
HD 134169.......	5800 ± 400	3.8 ± 0.4	3.0 ± 1.0	−1.6 ± 0.6	...
HD 188510.......	5300 ± 400	3.8 ± 0.4	2.0 ± 1.0	−1.8 ± 0.6	...
HD 195633.......	6150 ± 400	3.7 ± 0.5	2.0 ± 1.0	−1.1 ± 0.7	...

pute spectrum depths of atomic lines and diatomic molecular lines. The program requires as input a model atmosphere, line quantities of all relevant lines in a given spectral region, and element abundances. Synthetic spectra were computed for our stars with the assumption of a general metal abundance [M/H] for all metals, and with various values of carbon and nitrogen abundances. For want of the observations, the oxygen abundances were prescribed as [O/H] = [M/H].

The artificial line depths had to be convolved with a representation of the spectrograph instrumental profile before being compared to the observed spectra. Most of the plate data were obtained with the C camera of the Struve reflector coudé spectrograph. Spectra of a laser line have been obtained with this camera by Drs. Frank N. Edmonds and Edwin H. Barker, who kindly loaned their plates for our use. Since the natural laser line half-width is very much smaller than the slit itself, the profile of the line on the plate is a good representation of the slit profile. The intensity tracing of this line could be well approximated by a simple Gaussian function. This function was therefore used to smooth the synthetic spectra for comparison with the C camera spectra tracings. The slit profile of the B camera has not been measured, so since its dispersion is twice that of the C camera, the profile was represented by a Gaussian of half-width one-half that of the C camera function. No data appear to exist for the No. 2 camera of the Kitt Peak 2-m telescope coudé spectrograph. The dispersion of this camera is 16.7 Å mm^{-1} in the violet spectral region, while that of the Struve reflector C camera is 18 Å mm^{-1}. Therefore the crude approximation was made that the two profiles should be roughly the same.

An example of the synthetic spectrum-fitting technique can be seen in figures 6–9 which show the band spectra for HD 105755. Figure 6 shows part of the CH spectrum (the CH spectrum was actually generated from 4290 Å to 4315 Å). Three synthetic spectra are shown, generated for [C/H] = −0.7, −1.0, and −1.3, as well as the observed spectrum. The continuum was set in this region by a relatively line-free area just past 4315 Å. In deriving a carbon abundance, we obviously must concentrate on those regions of the spectrum which are most sensitive to the carbon abundance. Inspection of this figure indicates that [C/H] = −1.2 ± 0.2, where the error is an error of fit only.

Figure 7 shows a similar plot of the NH 0–0 band, and figure 8 gives the NH 1–1 band. Several remarks should be made here. Most observed band spectra are an average of data from three plates, but here only one plate of the NH was obtained. The plate density is thin in the region of the bands, but even the deepest part of the 0–0 band is above the plate fog level. In figures 7 and 8 the synthetic spectra are calculated for [N/H] = −1.2 and −1.5. Note that this spectral region is heavily contaminated with atomic lines, so that even with the nitrogen abundance changed by a factor of 2, spectrum depths are altered appreciably in only two small areas ($\lambda \simeq 3360$ Å and $\lambda \simeq 3371$ Å). Finally, it appears from these bands that [N/H] = −1.2 ± 0.3.

Do the CN bands agree with the above carbon and nitrogen determinations? Figure 9 gives the observed CN spectrum and two synthetic spectra ([C/H] = −1.2 and [N/H] = −0.9, and −1.2). The continuum is difficult to place in this region. There are several strong atomic transitions and a strong Balmer line at 3889.05 Å. By noting the position of the highest points of the spectrum surrounding this wavelength region, a continuum was defined. Some of the strongest atomic lines are not well matched in this spectrum, but matching these lines would force the CN features to have unrealistic profiles. Since little trouble was found in matching atomic lines in the CH and NH spectral regions, the problem here may be one of inaccurate oscillator strengths. Note also that the spectra of the CN bands in other program stars were generally matched better by the synthetic spectra than is indicated by figure 9. The best guess here for a nitrogen abundance from the CN bands is [N/H] = −1.0 ± 0.3, which differs little from the answer from the NH bands.

Table 4 gives [M/H] = −1.2 ± 0.5 for HD 105755. The analysis of the CH, NH, and CN bands in this star has yielded [C/H] ≃ −1.2 and [N/H] ≃ −1.2 (from the NH bands). It therefore appears that carbon and nitrogen have roughly their solar abundance ratio in HD 105755.

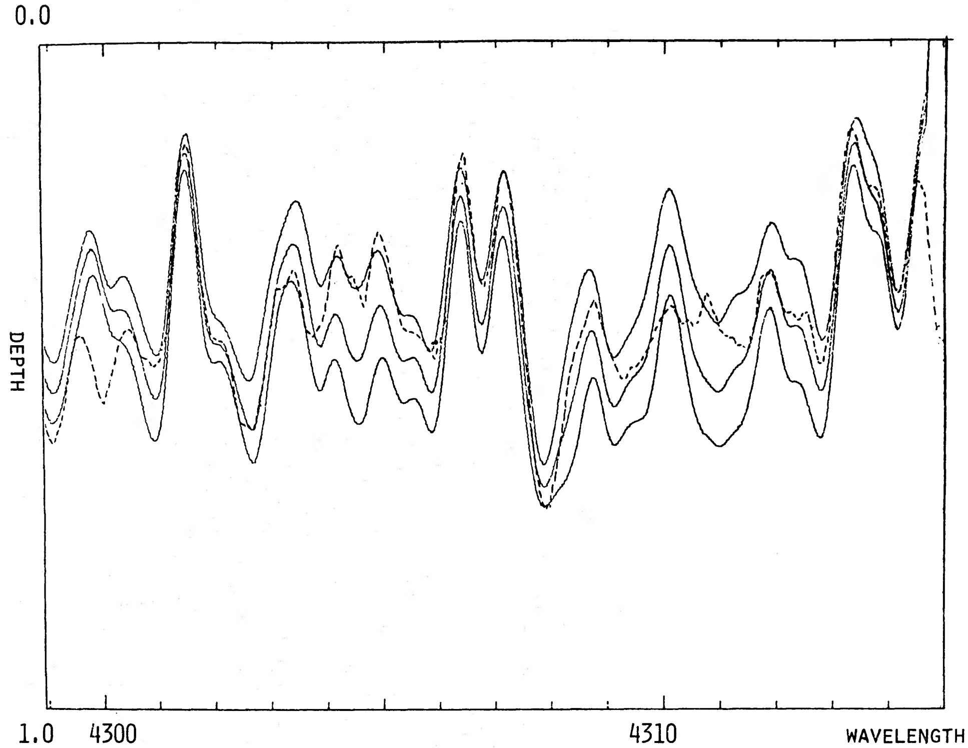

FIG. 6.—Part of the HD 105755 CH spectrum: the dashed line is the observed spectrum, and the solid lines are the synthetic spectra for [C/H] = −0.7, −1.0, and −1.3.

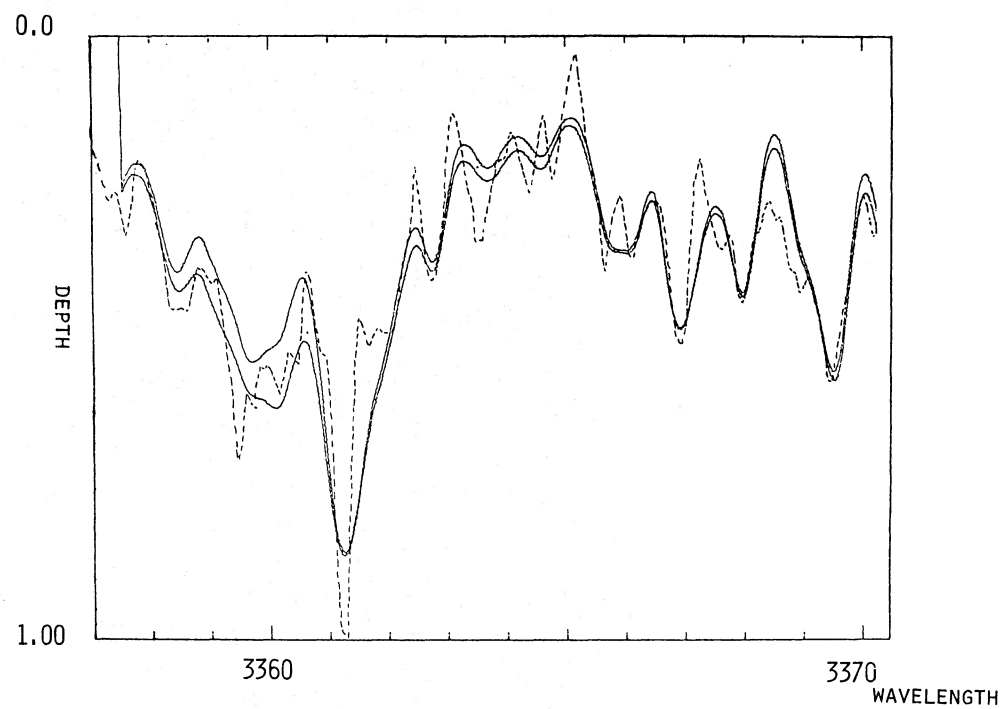

FIG. 7.—The HD 105755 NH 0–0 band: the dashed line is the observed spectrum, and the solid lines are the synthetic spectra for [N/H] = −1.2 and −1.5.

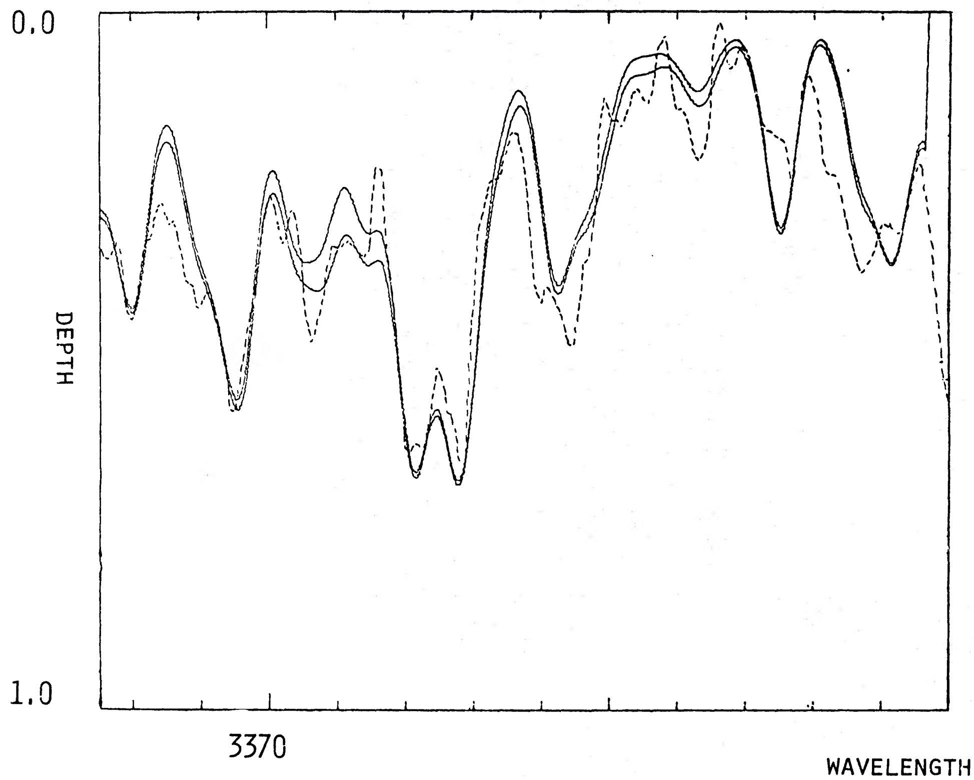

FIG. 8.—The HD 105755 NH 1–1 band: the synthetic spectra abundances are as in fig. 7

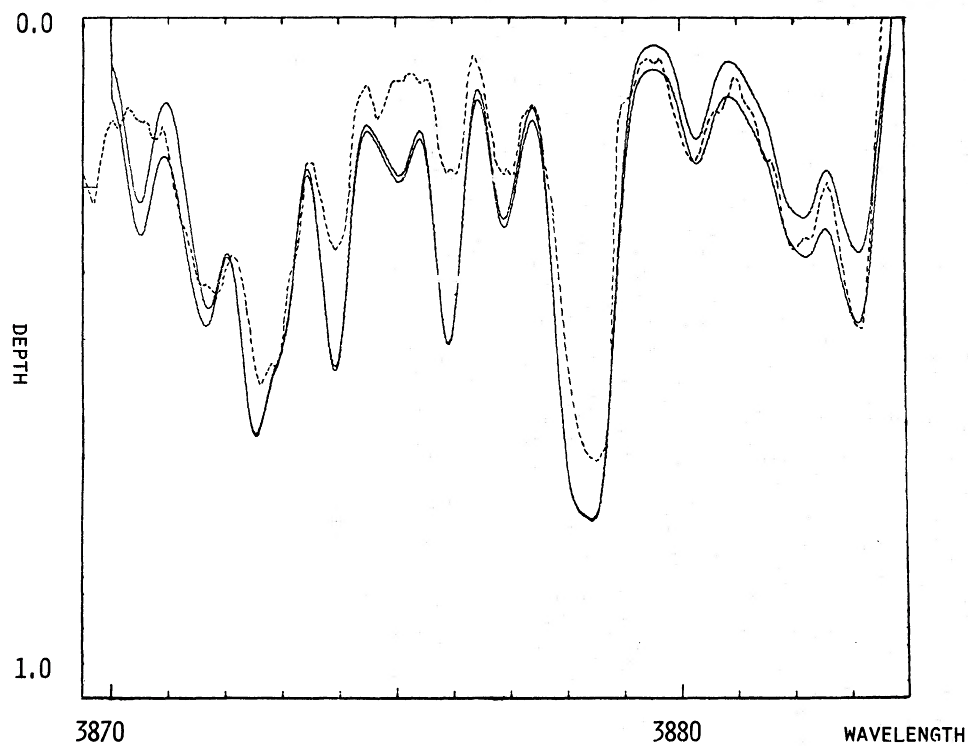

FIG. 9.—The HD 105755 CN spectrum: the dashed line is the observed spectrum, and the solid lines are of [C/H] = −1.2, [N/H] = −0.9 and −1.2.

TABLE 5

Carbon and Nitrogen Abundances

Star	[C/H]	[N/H]	[C/M]	[N/M]	[C/N]	Δ log C for Δ log O = 0.5	Remarks
HD 2665.....	−2.5 ± 0.7	−2.4 ± 0.8	−0.9 ± 0.6	−0.8 ± 0.7	−0.1 ± 0.5	±0.15	using model of Koelbloed 1967
	−2.5 ± 0.7	−2.5 ± 0.8	−0.2 ± 0.6	−0.2 ± 0.7	+0.0 ± 0.5	±0.10	...
HD 2796.....	−3.2 ± 0.8	−1.5 ± 0.9	−0.8 ± 0.7	+0.9 ± 0.8	−1.7 ± 0.6	±0.05	...
HD 6755.....	−1.7 ± 0.7	−2.0 ± 0.7	−0.6 ± 0.6	−0.9 ± 0.6	+0.3 ± 0.4	±0.05	using model of Koelbloed 1967
	−1.7 ± 0.7	−2.0 ± 0.7	+0.0 ± 0.6	−0.3 ± 0.6	+0.3 ± 0.4	±0.05	...
HD 88609....	−3.7 ± 0.7	−2.5:	−1.2 ± 0.6	+0.0:	−1.2:	±0.30	...
+52°1601....	−2.6 ± 0.7	−1.2 ± 0.7	−0.8 ± 0.6	+0.6 ± 0.6	−1.4 ± 0.4	±0.30	...
HD 105546...	−2.1 ± 0.7	−1.1 ± 0.7	−0.5 ± 0.6	+0.5 ± 0.6	−1.0 ± 0.4	±0.05	...
HD 105755...	−1.2 ± 0.7	−1.2 ± 0.7	+0.0 ± 0.6	+0.0 ± 0.6	+0.0 ± 0.4	±0.10	...
HD 122563...	−3.15 ± 0.4	−1.55 ± 0.4	−0.4 ± 0.4	+1.2 ± 0.4	−1.6 ± 0.2	±0.10	using model of Wolffram 1972
HD 134169...	−1.3 ± 0.6	−1.3 ± 0.6	+0.3 ± 0.5	+0.3 ± 0.5	+0.0 ± 0.3	±0.05	...
HD 188510...	−1.8 ± 0.7	−2.3 ± 0.7	+0.0 ± 0.6	−0.5 ± 0.6	+0.5 ± 0.5	±0.15	...
HD 195633...	−0.8 ± 0.7	−0.8 ± 0.7	+0.3 ± 0.6	+0.3 ± 0.6	+0.0 ± 0.5	±0.01	...

Table 5 summarizes the results of the molecular band analysis for all program stars. Columns (2)–(6) in this table give the abundance ratios involving carbon and nitrogen. Column (7) represents an estimate of the uncertainty involved in deriving carbon and nitrogen abundances without knowledge of the oxygen abundance. In § VI we discuss the results of this analysis in more detail.

V. ERROR ANALYSIS

A thorough discussion of the errors involved is necessary in any abundance analysis. A detailed study of the atmosphere parameter uncertainties has been made for the program star HD 105755. The errors encountered for this star were typical of all the program stars except HD 122563, for which better observational data was available. By inspection of the internal scatter of abundance predictions for the atomic lines, the following probable uncertainties can be assigned to our model atmosphere for HD 105755: $T_e = 5550 \pm 400°$ K; $\log g = 3.7 \pm 0.4$; $\xi_t = 2.5 \pm 1.0$ km s^{-1}; [M/H] = −1.2 ± 0.6. Let us now consider the effect on our abundances when different model parameters are used.

How will a temperature change affect the calculations? Two extreme models were constructed, both with $\log g = 3.7$ and $\xi_t = 2.5$ km s^{-1}, but one had $T_{\rm eff} = 6250°$ K and the other had $T_{\rm eff} = 4850°$ K. These two models were 700° K different from our best model, or nearly double the range of the probable errors in $T_{\rm eff}$. The hot model produced the following logarithmic abundance changes in weak lines. For Fe I, a $\chi = 0$ eV line decreased by 0.3 relative to a $\chi = 3$ eV line. Fe I was weakened relative to Fe II by 0.5. An error in $T_{\rm eff}$ should therefore be easily seen in the predicted atomic abundances. The logarithmic abundances predicted for a CH ($\chi = 0$) and NH ($\chi = 0$) line both dropped by about 1.0, and the abundance for a CN ($\chi = 0$) line dropped by 1.4. These effects are understandable. The CH ($D_0 = 3.45$ eV) and NH ($D_0 = 3.21$ eV) lines should vary by the same amount with temperature variations. Since CN has a larger dissociation energy, $D_0 = 7.55$ eV, it should exhibit a greater sensitivity to temperature changes. Similar effects of opposite sign were shown with the cool model. We can therefore state these changes as uncertainties in our abundance ratios, given that the actual temperature uncertainty is ±400° K. The ratio [M/H] is good to ±0.3, [(C or N)/M] to about ±0.3 and [(C or N)/H] to ±0.6, but [C/N] can be in error by at most ±0.2 if the CH and CN bands are used, and by at most ±0.1 if the CH and NH bands are employed.

How will a surface-gravity change affect the abundances? Again two models were computed, both with $T_e = 5550°$ K and $\xi_t = 2.5$ km s^{-1}, but one model had $\log g = 3.0$ and the other had $\log g = 4.4$. Each of the models produced roughly the following abundance effects. Both the $\chi = 0$ and $\chi = 3$ eV lines of Fe I gave the same very small change in abundances. The ratio [Fe I/Fe II] varied by about 0.3. The abundance changes using CH, CN, and NH lines were all roughly 0.4. Since the gas pressure enters into the equilibrium in much the same manner for each molecule, this should be no surprise. Therefore, under consideration of our probable errors in the surface gravity, we can attach the following abundance uncertainties: [M/H], about ±0.2; [(C or N)/M], about ±0.3; [(C or N)/H], about ±0.3; and [C/N] much less than ±0.1.

An estimation of the effect on the metal abundances caused by uncertainties in the microturbulence can be seen in figures 4 and 5. An increase in the microturbulence by 1 km s^{-1} changes the average derived abundance by about 0.4 in the log. This is because the metal lines used in this analysis are located, almost without exception, on the flat portion of the curve of growth. The molecular features, however, with the possible exception of the 0–0 band lines of NH, are composed of weak lines. Errors, then, in ξ_t have negligible effects on CH, CN, and NH 1–1 band strengths, and thus the ratios [M/H] and [(C or N)/M] are sensitive to the microturbulence, but not [(C or N)/H] and [C/N].

We cannot normally determine the oxygen abundance. What error does this cause in the carbon and nitrogen abundances? In general, the carbon equilibrium is controlled by the CO molecule. If the CO formation is not large, we can determine carbon abundances from the CH bands fairly unambiguously. A look at column (7) of table 5 shows the change in the derived carbon abundance (using CH bands) with a change in the oxygen abundance by ± 0.5 in the log. With the exception of two of the cooler stars, the changes are small, the uncertainty in HD 105755 amounting to ± 0.1. Also, note that the changes in CH and CN line strengths are similar. Therefore the influence of the unknown oxygen abundance on the ratio [C/N] is even smaller when the CH and CN bands are used. The oxygen uncertainty has no effect, however, on the nitrogen abundance derived from the NH bands, because the nitrogen equilibrium is controlled by the N_2 molecule.

Computing an rms average of all of the above mentioned sources of error, we can assign the following probable errors to the abundance determinations of HD 105755: for [M/H], ± 0.6; for [(C or N)/M], to ± 0.6; for [(C or N)/H], ± 0.7; and finally for [C/N], ± 0.4. This last abundance ratio can therefore be used with more confidence than the others.

A check was also made to be sure that the errors seen for HD 105755 were not peculiar to the program dwarfs. Models for the giant star HD 2796 were calculated with the temperature changed by $\pm 500°$ K and log g varied by ± 0.5. Very similar results to those of HD 105755 were seen. Therefore, we can use these errors as representative of the uncertainties encountered in the analysis of the rest of the program stars.

VI. COMMENTS ON THE ANALYSIS OF INDIVIDUAL STARS

HD 2665.—Our derived atmosphere differs noticeably from that of Koelbloed (1967) in that it is hotter and the surface gravity is larger. Our microturbulence is higher, and thus our atomic abundances are smaller. Koelbloed had better plate data available so his answers are probably to be preferred. Higher T_e and log g values have opposite effects on the molecular equilibrium, and thus cancel each other to a large extent. This is borne out in the [C/H] and [N/H] values with the two different atmospheres. Remember also that the value of ξ_t has little effect on the CH and CN bands. The [C/N] of Koelbloed is confirmed, but our [C/M] and [N/M] values are lower than his, especially with the use of his model atmosphere.

HD 6755.—Our model atmosphere agrees with that of Koelbloed (1967) except that again we derive a larger microturbulence. Our carbon analysis is in substantial agreement with his, but our derived nitrogen is about 0.3 less in the log. This is not surprising, because it seems that his nitrogen analysis was based on a single, blended, CN line.

HD 88609.—This very metal-poor star unfortunately yielded our most uncertain results. First, the internal errors in the atmosphere analysis render our atmosphere parameters uncertain. Sturch and Helfer (1972) determined a temperature of about 5000° K for HD 88609, using *UBVRI* photometry. Their temperature is higher than our determination, and also is higher than expected from the classification of Bond (1970). He listed G5 III ($T_{\rm eff} \simeq 4700°$ K) based on classification dispersion spectroscopy, and K0 II ($T_{\rm eff} \simeq 4000°$ K), based on Strömgren photometry. For this reason, and for the reason that 5000° K simply does not fit our data, the determination of Sturch and Helfer (1972) has been rejected in this study. The nitrogen abundance contains an additional uncertainty because the CN bands are very weak. Finally, the unknown oxygen abundance is a large source of error in the carbon abundance derivation. Clearly this star needs to be reanalyzed with higher dispersion data.

HD 105546.—The NH and CN bands give consistent nitrogen abundance determinations. Our final abundance is based on the answer from the NH bands.

HD 134169.—As mentioned previously, plate data at both 9 and 18 Å $\rm mm^{-1}$ exists for this star. No large differences were found between the atmosphere parameters derived from each set of plate data. Excellent agreement was also found between carbon and nitrogen abundances derived from tracings of each set of data. Note finally that the availability of NH data strengthens our answer for nitrogen in HD 134169.

VII. DISCUSSION OF THE ABUNDANCE RESULTS

In this section we discuss the general trends in abundances found in the present study. The reader is cautioned again that large uncertainties are encountered in considering the results from individual stars.

a) The Correlation between [M/H] *and log g*

Figure 10 shows the general metal abundance [M/H] plotted versus log g for the program stars. We have added to this and succeeding figures the results of stars which are listed in table 1 and which have not been reexamined in the present study. There is an obvious trend of greater metal deficiencies with smaller

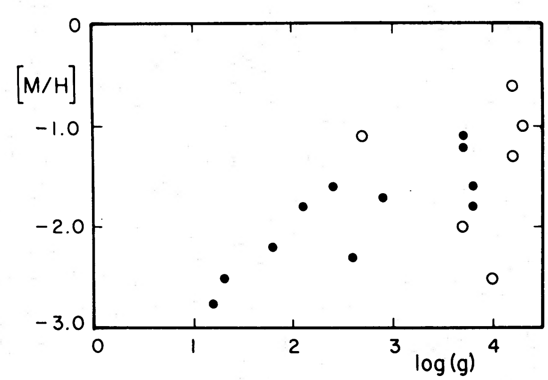

FIG. 10.—Metal abundances as functions of the surface gravities. The filled circles are the result of the present study, the open circles results of other investigations.

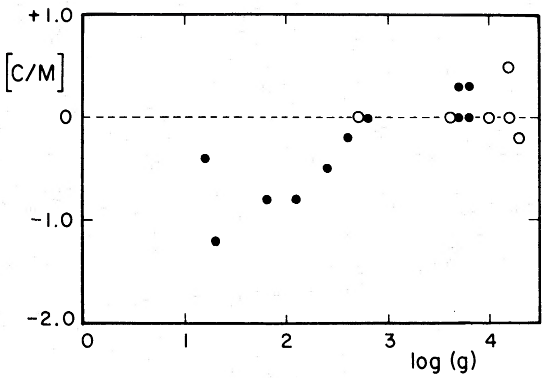

FIG. 11.—Carbon abundances relative to the metals, as functions of the gravities. Filled circles are from this work, open circles from other studies. The dashed line represents a solar [C/M] value.

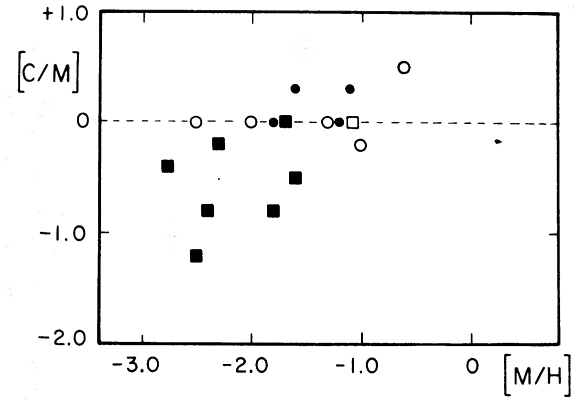

FIG. 12.—Relative carbon abundances as functions of the general metal abundances. Filled and open symbols represent results from this and other studies, respectively. Circles denote dwarfs, and squares denote giants.

surface gravities for the program stars. This can be understood in terms of two selection effects. The list of Bond (1970), from which our program stars come, is based solely on apparent line weakening in the spectra of the stars. Our list of stars was composed of the more weak-lined G-type stars of Bond (1970). Giants, however, show stronger atomic-line spectra than dwarfs, due to their smaller continuous opacities. For the same apparent line strength a giant will have lower metal content than a dwarf. Therefore a list of program stars based on apparent line weakening will tend to have lower abundances of metals in giants.

There should, however, exist dwarfs with as low metallicity as giants, like HD 140283 or HD 19445. These do not appear here due to the fact that objective-prism surveys like that of Bond (1970) tend to compare stars of the same range of apparent magnitudes. Giant stars, having higher luminosities than dwarfs, can be detected from a larger volume of space. Therefore we can search farther out into the galactic halo for weak-lined giants. The most metal-poor stars ought to reside in the halo, so here again lower average abundances are to be expected for our giant stars.

b) *The Carbon Abundances*

Figure 11 shows the relative carbon abundances [C/M] plotted versus $\log g$. The first obvious point to be seen is that our four dwarfs ($\log g \geqslant 3.7$) appear to have normal abundances, within the error bars, with respect to the metals. With the results of other studies, we now have nine metal-poor dwarfs whose carbon abundances do not deviate markedly from [C/M] $\simeq$ 0.0. The nucleosynthesis calculations for ordinary stars and SMOs both predict [C/M] $\simeq$ 0.0, so that neither idea is ruled out based on a carbon analysis.

Four of the program giants ($\log g \leqslant 2.8$) have pronounced relative deficiencies of carbon, and the deficiency in HD 122563, while only 0.4, seems well established. In figure 12 we show [C/M] as a function of the general metal abundance [M/H] for each star. We see that, regardless of the metal deficiency, [C/M] $\simeq$ 0.0 in dwarfs (note that to establish this we must combine our data with that of other workers). Only in giants are low [C/M] values found. In § I we referred to possible depletion of carbon in giants due to mixing between atmosphere and interior, where the CNO-cycle hydrogen burning has transformed carbon into, eventually, nitrogen. This effect may be at work here based just on the carbon analysis. We discuss this further after reviewing the nitrogen results.

c) *The Nitrogen Abundances and the Ratio* [C/N]

Relative nitrogen abundances [N/M] are plotted versus $\log g$ in figure 13. The dwarf stars, with one exception, do not show any underabundance of nitrogen. Unfortunately no nitrogen determinations exist for the interesting stars HD 140283 and HD 19445. This is in conflict with some of the early models of Arnett (1971) and is more in line with the thinking of Wagoner (1968) on SMOs. One star, however, has an apparent nitrogen overdeficiency, HD 188510.

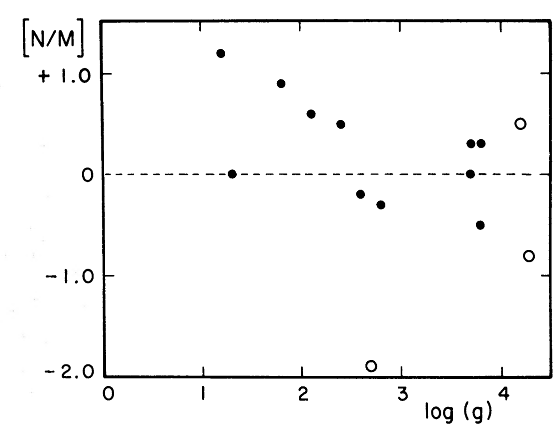

FIG. 13.—Nitrogen abundances relative to the metals as functions of the gravities. Filled circles are for results from this study, and open circles are for results from other studies. The dashed line represents a solar [*N*/M] value.

Kinematically, HD 188510 (Bond 1970) resembles HD 103095 (Gmb 1830), both of which have extremely large space velocities and eccentricities. Since HD 103095 also has evidence of a nitrogen underabundance (Tomkin 1972; Tomkin and Bell 1973) one might be tempted to lump these stars together as the most extreme examples of halo population stars, and claim that the nitrogen underabundance predictions of Arnett (1971) have been confirmed. We must remember, however, the large uncertainties in our analysis and that two stars do not make a correlation. Note finally that HD 25329, which has a rather large space motion itself, apparently has an overabundance of nitrogen relative to the metals (Harmer and Pagel 1970).

We see that at present there is no real justification for assuming [N/M] $\neq$ 0 for most metal-poor dwarfs. This seems to be in conflict with the ideas of Arnett (1971). A possible mechanism for nitrogen enhancement during stellar evolution has been pointed out by Truran and Cameron (1971). Citing work of other investigators, they claim that helium flashing in giants may lead to a mixing of products of the helium burning (^{12}C and ^{16}O) up to the hydrogen-burning shell. This will provide "fuel" for the CNO cycle hydrogen shell burning even in stars which had little initial carbon and oxygen content. Through this mechanism, then, we may see nitrogen built up in quantities comparable to carbon and oxygen even at very early stages of galactic star formation. Succeeding generation of stars should reflect this equality of the CNO group.

Four of the program giants show apparent overabundances of nitrogen. A better look at this trend can be had in figure 14, where [C/N] is plotted versus $\log g$. This demonstrates that five of the giants have anomalously low [C/N] values. We have seen (fig. 12) that [C/M] $\simeq$ 0.0 for all [M/H] values in metal-poor dwarfs. It appears, therefore, that we may interpret a low [C/M] value or a low [C/N] value as an indicator of internal stellar evolution rather than a consequence

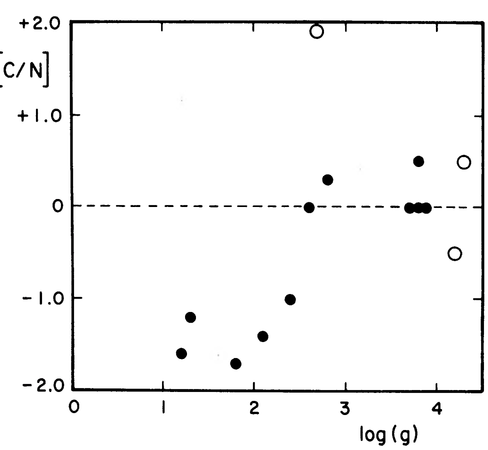

FIG. 14.—The carbon-to-nitrogen ratios as functions of the surface gravities. The dashed line represents the solar abundance ratio. As before, filled circles are results from this study.

of initial metal content. The giants with the highest surface gravities (HD 2665, HD 6755, ν Indi) however, do not fit into this pattern. The star ν Indi, in fact, seems to have a very high [C/N] (Bell 1970). We may ask, then, at what point mixing is expected to alter the content of an atmosphere. According to Iben (1964) mixing will cause surface abundances to change when a star begins its ascent up to the red-giant tip. The calculations of Ulrich and Scalo (1972) and Sackmann *et al.* (1973) indicate that noticeable abundance changes will again occur starting at the onset of helium flashing, i.e., at the top of the red-giant branch. Wagner (1972) has calculated evolutionary tracks for metal-poor stars ($Z = 10^{-4}$) up to the onset of helium burning, and we can use his results to derive a rough value of the surface gravity for the probable start of mixing. For a star of a given mass, at the main-sequence (MS) and evolved (E) stages of its history,

$$\left(\frac{g_{\rm E}}{g_{\rm MS}}\right) = \left(\frac{R_{\rm MS}}{R_{\rm E}}\right)^2 = \left(\frac{L_{\rm MS}}{L_{\rm E}}\right)\left(\frac{T_{\rm E}}{T_{\rm MS}}\right)^4 .$$

This equation, combined with Wagner's (1972) work, showed that we should expect to see mixing effects in stars with gravities no greater than $\log g \simeq 2.4$. At, or below, this value, the mixing predicted by Iben (1964) should be apparent. This is approximately what we do have, taking our results at face value. Our data, however, could not distinguish between the two types of possible mixing mechanisms.

The above discussion on mixing in giants has assumed two facts of crucial importance. First, the Galaxy may not possess a homogeneous chemical composition. This study cannot shed further light on this question. Second, for want of data on the ages of stars, we have assumed that dwarfs and giants with the same metal content were formed at the same epoch. Differences in [C/N] between the two groups of stars can then be attributed to internal evolution of the giants. This assumption may not be valid. If we assume that the giants are older than the dwarfs, then we cannot assume that the giants necessarily began their lives with an essentially solar C/N. It is believed here, however, that the stars HD 2665 and HD 6755 strengthen the mixing proposition. The gravities of these two stars indicate that they ought to have essentially unevolved atmospheres. Their extremely large space motions (Koelbloed 1967) suggest that they are among the oldest stars of the present survey. These two facts, coupled with their solar C/N, show that [C/N] $\simeq$ 0 throughout the history of the Galaxy may not be an unreasonable assumption.

Finally, three special comments should be made here. First, Koelbloed (1967) derived $\log g \simeq 1.8$ for HD 2665, which is somewhat lower than our value of 2.6. If his gravity is accepted, then depending on the assumed mass of the star, HD 2665 may have an evolved atmosphere. In this case it may not fit into the scheme proposed here. Second, Pagel (1972) has also studied nitrogen abundances in some metal-poor halo stars. His results indicated that [N/Fe] $\simeq$ [Fe/H], with a few stars showing [N/Fe] $\simeq$ 0 for all metal abundances. Pagel put more emphasis on the stars which showed [N/Fe] $\simeq$ [Fe/H]. This trend is not confirmed in general by the present study. Finally, are our [C/N] values in giants plausible? Iben's (1964) calculations, starting with solar-composition stars showed that after mixing, the surface abundances would be changed such that [C/N] $\simeq$ -0.5. Our results indicate [C/N] $\simeq$ -1.0 to -1.5 in our giants, which is somewhat different. If, however, there is another mechanism for nitrogen enhancement available such as Truran and Cameron (1971) suggest, it may be possible to get closer agreement with our abundance results. The final nitrogen abundance under these conditions need not be a function of the initial CNO content.

VIII. POSSIBLE NON-LTE EFFECTS

We have assumed throughout that the LTE expressions describe adequately the radiative transfer in our atmospheres. Sneden (1973) discussed the effect of including scattering in the source functions for HD 122563. Line strengths were found to be altered, but not enough to change the basic conclusions about the derived carbon and nitrogen abundances. HD 122563 has the smallest surface gravity of any of the program stars, and thus the effect should be smaller in the other stars.

Another non-LTE effect may be seen in the predissociation of CH. Predissociation is probably an important process for CH (Elander and Smith 1973) but not for NH or CN. This is illustrated by the fact that NH and especially CN are subject to large dissociation energy uncertainties. What this means for us is that there is a possibility, particularly for the giants (where low densities mean that collisions between particles are less frequent than in dwarfs), that a substantial fraction of the CH has been radiatively dissociated; in the outer atmospheres the mean continuum intensity is greater than the Planck function at the wavelength responsible for predissociation. This gives rise to spuriously low values of [C/H]. If this occurs, then, we should raise our [C/N] by some fraction to compensate for this effect. It should be noted, however, that the results from CH, CN, and NH are in substantial agreement for the two dwarfs and two giants for which NH data exist. Therefore it appears that predissociation of the CH molecule is not a large source of error.

IX. FUTURE WORK

This study is considered hopefully as a first step toward a better understanding of light-element abundances in metal-poor stars. The work can be furthered by the following steps. (1) Photometry (*UBVRI*) and continuum spectral scans should be obtained for these (and other) metal-poor stars to improve temperature determinations. (2) When more efficient coudé spectrum scanners are available, one should attempt to determine oxygen abundances using the 6300 Å [O I] line or the permitted O I lines at 7774 Å. (3) An attempt should be made to determine $^{12}C/^{13}C$ in metal-poor stars. This ratio is also an indicator of mixing, and is not plagued with many of the atmosphere uncertainties which render the present abundances uncertain. (4) Finally, there is an obvious need to extend this work to any other metal-poor stars of sufficient apparent brightness. In particular, the southern sky should provide, as Bond (1970) has demonstrated, many more metal-poor stars.

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