1978ApJ...223..937T

THE ASTROPHYSICAL JOURNAL, 223:937–948, 1978 August 1
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CARBON, NITROGEN, AND OXYGEN ABUNDANCES IN MAIN-SEQUENCE STARS. I. PROCYON AND THE HYADES CLUSTER STARS 45 TAURI AND HD 27561

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Received 1977 November 7; accepted 1978 February 7

ABSTRACT

High signal-to-noise observations of C I, N I, and O I lines in the near-infrared spectra of Procyon and the Hyades cluster main-sequence stars 45 Tau and HD 27561 have been analyzed to determine their carbon, nitrogen, and oxygen abundances. The carbon, nitrogen, and oxygen abundances of all three stars are solar. The estimated uncertainty of the abundances is ± 0.2 dex. Analysis of observations of the forbidden carbon and oxygen lines, CH blue system (0, 0) and (1, 1) band lines, and CN violet system (0, 0) band lines in Procyon provides a check of the results obtained from the permitted atomic lines.

The solar C/N ratio of the Hyades cluster dwarfs allows the less-than-solar C/N ratio of the Hyades giants recently determined by Lambert and Ries to be unambiguously interpreted as the effect of CNO cycle processing during the giants' main-sequence lifetime.

The iron abundances of Procyon, 45 Tau, and HD 27561 derived from the equivalent widths of Fe I and Fe II lines are found to be solar. This result is consistent with previous spectroscopic determinations of the iron abundance of Hyades cluster stars. The discrepancy between the spectroscopic determinations of a solar metal content of the Hyades and the metal richness inferred from photometry is discussed.

Subject headings: clusters: open — stars: abundances — stars: individual

I. INTRODUCTION

Carbon, nitrogen, and oxygen are key elements in the chain of nucleosynthesis of the elements in stellar interiors. Carbon is created primarily by the triple-α process in evolved stars of intermediate and high mass. Oxygen is formed from carbon by the addition of an α-particle. Nitrogen is a secondary product created from carbon and oxygen by the CNO cycle operating during the main-sequence lifetimes of later generations of stars.

A second mechanism of nitrogen production, which is first-generation and might be significant, can occur during the thermal pulse double-shell-source stage of evolution of intermediate-mass stars. Iben (1975, 1976) finds that ^{12}C formed during the helium-burning thermal pulses is mixed to the surface during the interpulse phases and that simultaneously it is partially or wholly burned to ^{14}N.

The incentive for studying the CNO abundances of main-sequence stars is to answer questions about the history of CNO production in the Galaxy. If nitrogen is indeed largely a secondary product, its deficiency in old metal-deficient main-sequence stars will be more marked than that of carbon and oxygen.

Knowledge of CNO abundances in main-sequence stars is also helpful for the interpretation of CNO abundances in red giants. The abundances of carbon, nitrogen, and oxygen and their isotopes in the atmospheres of red giants show distinctive changes resulting from evolution. Knowledge of the CNO abundances of main-sequence stars is essential in order to untangle the contributions of the initial abundances and evolutionary changes to the observed abundances of the giants.

In spite of the importance of CNO abundances in main-sequence stars, not much observational work has been done in this area. Clegg (1977) has analyzed 11 late F- and G-type dwarfs and subgiants. Kegel (1962) found a carbon deficiency of 0.3 dex and a solar oxygen abundance in γ Ser (F6 IV–V), while Baschek *et al.* (1967) found an overabundance of carbon of $+0.15$ dex relative to the Sun in the mildly metal-rich ($+0.3$ dex relative to the Sun) star β Vir (F8 V). Kohl (1964) and Hunger (1960) have determined metal abundances, including C, N, and O, in Sirius (A1 V) and in Vega (A0 V), respectively. Hearnshaw (1974) has obtained carbon abundances for 20 F- and G-type dwarfs and subgiants from analysis of their CH lines. Tomkin and Bell (1973) found that, in the subdwarf Gmb 1830, nitrogen is much more deficient than carbon. Abundance analyses of the subdwarfs HD 19445 (sdF7) and HD 140283 (sdF5) have been made by Chamberlain and Aller (1951), Aller and Greenstein (1960), and Cohen and Strom (1968); HD 140283 has also been analyzed by Baschek (1962). In both stars, carbon and iron-peak elements are deficient by approximately 2 dex. No results for nitrogen or oxygen are available. Harmer and Pagel (1973) have used violet CN band strengths to investigate nitrogen abundances in a sample of late-type stars that includes 10 F, G, and K dwarfs. A tendency for nitrogen to be overdeficient in metal-deficient stars is indicated.

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In this paper we report the results of an investigation of the CNO abundances of Procyon (HD 61421; F5 IV, $V = 0.37$) and of the Hyades cluster main-sequence stars 45 Tau (HD 26462, VB 14; dF4, $V = 5.73$) and HD 27561 (VB 37; F4 V, $V = 6.61$). Procyon was chosen because it is a bright, sharp-lined star and its spectral type is similar to that of 45 Tau and HD 27561. From a differential curve-of-growth analysis of Procyon with respect to the Sun, Griffin (1971) found that the abundances of the iron-peak elements are solar. In the same analysis, differential abundances of carbon, nitrogen, and oxygen, that are not significantly different from the solar abundances were obtained from permitted lines. HD 27561 and 45 Tau were chosen because they lie near the upper end of the Hyades main sequence and are sufficiently sharp-lined to allow measurement of weak lines.

Observations of permitted near-infrared lines of C I, N I, and O I are used in the analysis. Observations of the [C I] 8727 Å and [O I] 6300 Å lines, CH blue system lines, and CN violet system (0, 0) band lines in Procyon provide a check of the results from the permitted atomic lines. Lines of Fe I and Fe II in Procyon, 45 Tau, and HD 27561 are also analyzed to determine their iron abundances.

II. OBSERVATIONS

The McDonald Observatory 2.7 m telescope and a reticon self-scanned silicon photodiode array (Vogt, Tull, and Kelton 1978) mounted on the coudé spectrometer were used to observe selected wavelength intervals containing the C I, N I, and O I lines listed in Table 1. Each observation covered 100 Å of spectrum,

TABLE 1

CARBON, NITROGEN, AND OXYGEN LINES

			EQUIVALENT WIDTH (mÅ)			
λ (Å)*	χ (eV)	log *gf* †	Sun	Procyon	45 Tauri	HD 27561
		C I				
6587.61	8.54	−1.22	18.4	52	58	...
6655.51	8.54	−1.99	4.0	14	19	...
7087.83	8.65	−1.55	8.2	22	...	...
7111.48	8.64	−1.32	13.2	31	...	...
7113.18	8.65	−0.93	24.6	47	70	67
7115.19	8.64	−0.90	26.1	47	70	71
7116.99	8.65	−1.08	19.8	49	60	68
7119.67	8.64	−1.31	13.3	32	57	57
7483.44	8.77	−1.56	6.6	17	22	24
8727.13	1.26	−8.21	...	9	...	...
		N I				
7442.293	10.33	−0.33	...	12	19	...
7468.307	10.34	−0.16	...	15	26	16
8216.345	10.34	+0.13	...	26	46	...
8683.401	10.33	+0.11	...	28	45	33
8703.248	10.33	−0.29	...	17	...	...
8718.826	10.34	−0.26	...	19	...	...
9392.789	10.69	+0.31	...	38	...	...
		O I				
6158.184	10.74	−0.29	...	24	...	...
6300.311	0.00	−9.75	...	4.2	...	...
9260.806	10.74	... }				
9260.845	10.74	... }	...	44	67	...
9260.935	10.74	... }				
9262.584	10.74	... }				
9262.671	10.74	... }	...	67	93	77
9262.774	10.74	... }				
9265.827	10.74	−0.92 }				
9265.938	10.74	−0.08 }	...	82	120	86
9266.006	10.74	+0.51 }				

* The O I lines at 9260 and 9262 Å, which do not have reliable *gf*-values, were not used in the analysis.

† The *gf*-values of the permitted C I lines are solar *gf*-values, calculated using the listed center-of-disk solar equivalent widths, a carbon abundance log $N(C) = 8.67$ (Lambert 1978), and the Holweger and Müller 1974 solar model atmosphere. In the Sun some C I lines are blended with very weak CN lines; corrected equivalent widths are listed.

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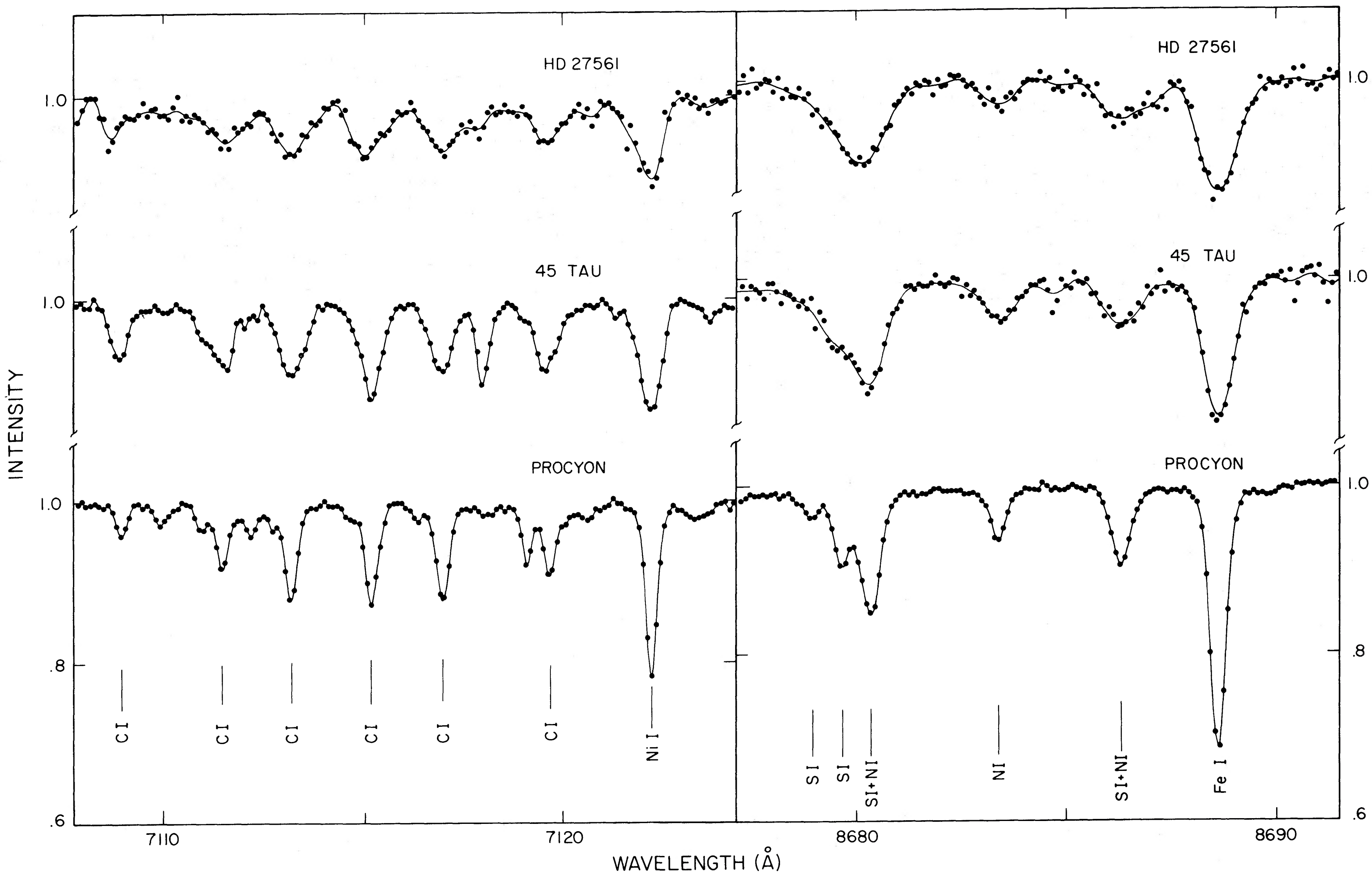

FIG. 1.—C I lines between 7110 and 7120 Å and the N I line at 8683.4 Å in Procyon, 45 Tau, and HD 27561 plotted with an expanded intensity scale

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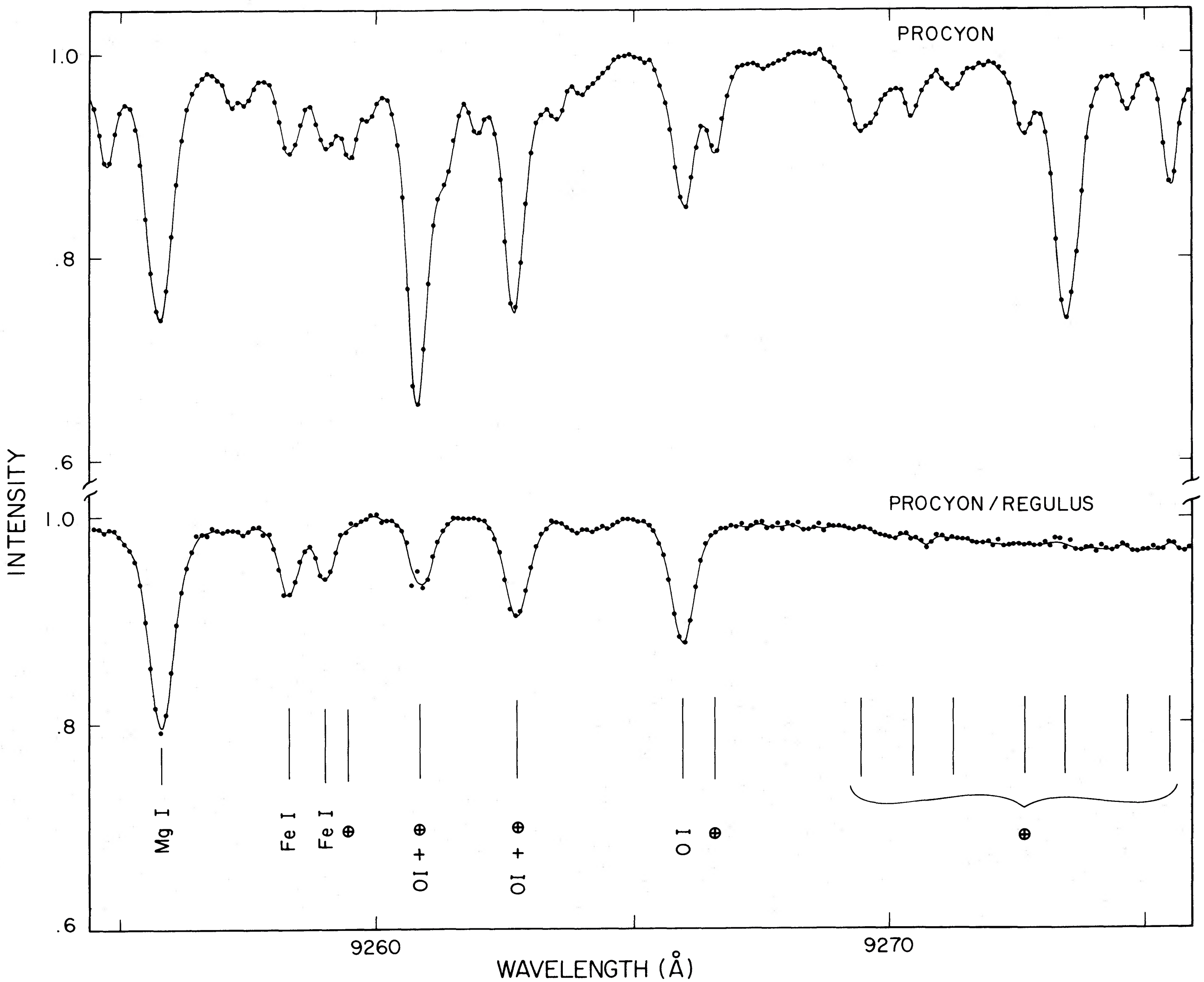

FIG. 2.—The O I lines at 9260.8, 9262.7, and 9266.0 Å in Procyon plotted with an expanded intensity scale. The upper plot shows the serious interference by telluric lines. In the lower plot the telluric lines have been removed by dividing the Procyon data by the Regulus data. The O I lines of Regulus (B7 V) are smeared out by its rapid rotation and therefore do not distort the Procyon O I lines.

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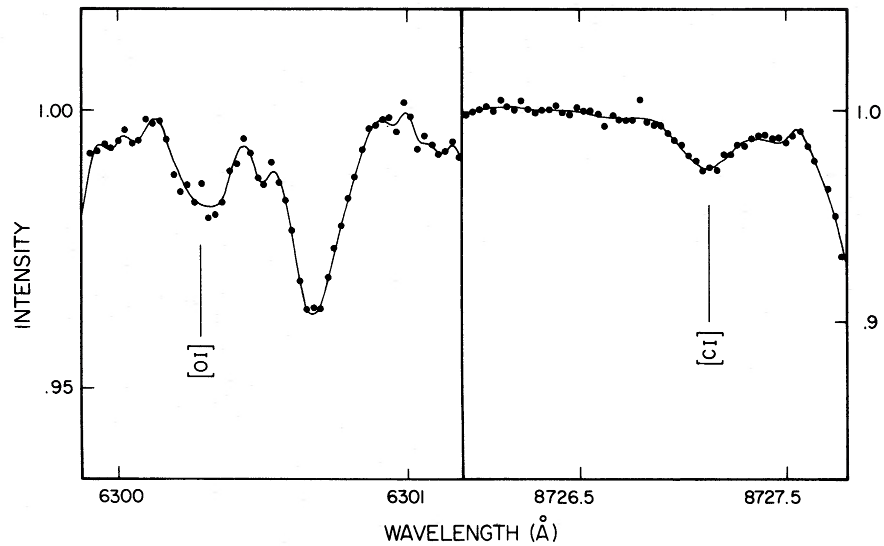

FIG. 3.—The [O I] and [C I] lines at 6300 and 8727 Å in Procyon plotted on expanded intensity scales

with a resolution of 0.2 Å (for Procyon and 45 Tau) and of 0.4 Å (for HD 27561) and with a signal-to-noise ratio that typically was 500 to 1 for Procyon and 200 to 1 for 45 Tau and HD 27561. Examples of the data—the C I lines of multiplets 25.02 and 26 between 7110 and 7120 Å and the N I line at 8683 Å in Procyon, 45 Tau, and HD 27561—are shown in Figure 1.

These observations were supplemented by low-noise photoelectric scans of the same lines in the Sun (center of disk) made with the McMath solar telescope. Associated limb scans, in which the lines, being of high excitation, are much weaker than in the center of the disk scans, were used to check that the C I, N I, and O I lines are unblended in the Sun.

Interference by telluric lines was minimized by making the observations at times when the telluric lines were shifted away from the C I, N I, or O I lines. In the case of the O I triplet at 9260, 9262, and 9266 Å, which is seriously affected by telluric lines, each program star observation was followed by an observation of the same lines in a bright, rapidly rotating B or A star at the same air mass. The telluric lines, being of the same strength and at the same location in the program star and early-type star data, are completely removed by dividing the program star data by the early-type star data. Figure 2, showing the O I lines in Procyon before and after division by the associated Regulus observation, illustrates how effectively the telluric lines are eliminated.

TABLE 2

CH LINES MEASURED IN PROCYON

λ (Å)	Identity	Equivalent Width (mÅ)
4223.093....	(1, 1)$R_{1dc,2dc}$16	11.7
4223.482....	(0, 0)R_{2cd} 14	22.3
4223.573....	(0, 0)R_{1cd} 14	
4355.713....	(0, 0)P_{2cd} 9	6.9
4356.376....	(0, 0)P_{2dc} 9	9.1
4356.617....	(0, 0)P_{1dc} 9	8.7
4360.300....	(0, 0)P_{2dc} 10	10.8
4377.253....	(0, 0)$P_{1dc,2dc}$15	20.4
4377.253....	(1, 1)P_{2cd} 15	
4377.253....	(2, 2)P_{1dc} 11	
4378.244....	(0, 0)P_{2cd} 16	18.8
4378.300....	(0, 0)P_{1cd} 16	
4378.921....	(1, 1)$P_{1dc,2dc}$15	9.4
4380.082....	(0, 0)$P_{1dc,2dc}$16	18.0
4380.727....	(0, 0)$P_{1cd,2cd}$17	30.9
4380.727....	(1, 1)P_{2cd} 16	
4380.838....	(1, 1)P_{1cd} 16	
4380.838....	(2, 2)P_{2cd} 12	
4386.095....	(1, 1)$P_{1dc,2dc}$17	7.0
4388.895....	(0, 0)$P_{1cd,2cd}$21	10.5

In Procyon, additional high signal-to-noise–ratio observations of weak forbidden lines and molecular lines were made as follows: the [C I] 8727 Å and [O I] 6300 Å lines, selected CH $A\,^2\Delta$–$X\,^2\Pi$ system (0, 0) and (1, 1) band lines between 4200 and 4400 Å, and the CN violet system (0, 0) band head at 3883 Å. The resolution used ranged from 0.06 Å at the shortest wavelength to 0.12 Å at the longest wavelengths. The equivalent widths of the forbidden lines are given in Table 1; identifications and measurements of the CH lines are given in Table 2. The forbidden O I and C I lines, plotted on expanded intensity scales, are shown in Figure 3.

The near-infrared observations of the C I, N I, and O I lines, each covering 100 Å of spectrum, included many neutral and ionized lines of other elements. Inspection revealed 17 Fe I and 4 Fe II lines that were unblended and weak or only moderately saturated. Their equivalent widths are given in Table 3.

III. ANALYSIS

a) Model Atmosphere Parameters

The abundances were derived by a straightforward analysis using flux-constant line-blanketed model

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TABLE 3

IRON LINES IN PROCYON, 45 TAURI, AND HD 27561

Wavelength (Å)	Line	χ (eV)	log gf	Equivalent Width (mÅ)			
				Sun	Procyon	45 Tauri	HD 27561
6113.329.......	Fe II	3.22	−3.90	17	25	27	...
6149.249.......	Fe II	3.89	−2.81	35	60	66	...
6165.363.......	Fe I	4.14	−1.67	33	23	19	...
6173.341.......	Fe I	2.22	−3.16	50	36	31	...
6180.209.......	Fe I	2.73	−2.86	40	27	18	...
6187.995.......	Fe I	3.94	−1.79	36	26	21	...
6200.321.......	Fe I	2.61	−2.68	55	43	33	...
6593.884.......	Fe I	2.43	−2.19	89	54	51	...
6609.118.......	Fe I	2.56	−2.36	76	30	26	...
7449.338.......	Fe II	3.89	−3.14	24	33	40	...
7479.701.......	Fe II	3.89	−3.59	11	13	17	15
7491.652.......	Fe I	4.30	−0.89	71	39	38	48
7507.273.......	Fe I	4.41	−0.86	67	33	27	47
7746.605.......	Fe I	5.06	−1.25	18	10	...	...
7751.116.......	Fe I	4.99	−0.71	46	26	21	...
7780.568.......	Fe I	4.47	−0.25	102	86	78	99
7802.51.........	Fe I	5.08	−1.45	12	8	...	...
7807.916.......	Fe I	4.99	−0.40	64	38	37	51
8207.749.......	Fe I	4.44	−0.92	64	34	33	...
8674.756.......	Fe I	2.83	−1.66	113	82	66	80
8699.461.......	Fe I	4.95	−0.39	73	45	43	51

atmospheres (Kurucz 1978). The two initial steps were (1) to determine the parameters (effective temperature, gravity, and microturbulence) for the model atmosphere of each star and (2) to choose the best set of oscillator strengths for the C I, N I, and O I lines.

The temperature- and gravity-sensitive indices $b-y$ and c_1 (Crawford and Perry 1966; Crawford and Barnes 1970), calibrated by the theoretical $b-y$ and c_1 indices of Relyea and Kurucz (1977), were used as the primary indicators of effective temperature and gravity. The theoretical $b-y$ and c_1 indices are based on the same grid of model atmospheres (Kurucz 1978) as was used in this analysis. The effective temperatures (in K) and gravities (log g), which were derived from the theoretical $b-y$ and c_1 indices computed with solar abundance model atmospheres, are as follows: 6600, 3.8 (Procyon); 7000, 4.0 (45 Tau); and 6700, 4.0 (HD 27561). A second temperature indicator for F-type stars is the strength of Hβ. The Hβ indices of Procyon (Crawford *et al.* 1966), 45 Tau, and HD 27561 (Crawford and Perry 1966) with the Hβ, T_e calibration of Powell (1968) give temperatures for all three stars that are in excellent agreement with the temperatures based on $b-y$.

Further temperature and gravity information is available for Procyon. An effective temperature of 6510 K is determined by Code *et al.* (1976) from the energy distribution of Procyon. Procyon has a white dwarf companion with a 40 year period and an accurate parallax ($\pi = 0\farcs283$ [Jenkins 1952, 1963]), so its mass and surface gravity can be determined directly; Gray (1967) calculates $M = 1.85\, M_\odot$ and $\log g = 4.0$. This value of the gravity is adopted.

A representative value of 2 km s^{-1} was used for the microturbulence. That the analysis of the Fe lines showed no dependence of derived Fe abundance on line strength indicates the choice of 2 km s^{-1} to be good. Dependence of the CNO abundances on the microturbulence is very slight, because for these light elements the thermal velocity is the major source of Doppler broadening. Adopted effective temperatures, gravities, and microturbulences are given in Table 4. Line-blanketed flux-constant models (Kurucz 1978) calculated with solar metal abundances were used in the analysis. The metal richness of the Hyades stars will be discussed below; for the moment we note that, whether they are mildly metal rich (as suggested by photometry) or of solar composition (as suggested by spectroscopy), the use of solar abundance models is valid.

b) *Adopted Oscillator Strengths*

Reliable experimental measurements of oscillator strengths are not available for the majority of C I, N I,

TABLE 4

STELLAR PARAMETERS

Star	Spectral Type	m_v	T_e (K)	log g	Microturbulence (km s^{-1})
Procyon...........	F5 IV	0.37	6600	4.0	2
45 Tau............	dF4	5.73	7000	4.0	2
HD 27561.........	F4 V	6.61	6700	4.0	2

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and O I lines used in this analysis. For C I lines the theoretical oscillator strengths are also unreliable because of severe cancellation in the radial integrals (Lambert 1968); so solar oscillator strengths have been used. A program, LINES, for calculating equivalent widths written by Sneden (1973) and modified by Luck (1977) was used to compute the solar oscillator strengths of the C I lines given in Table 1. Input data were the following: the center-of-disk equivalent widths measured off the Kitt Peak scans; the Holweger and Müller (1974) solar model atmosphere; a depth-independent microturbulence of 1 km s^{-1}; and abundances (Lambert 1978) log N(C) = 8.67, log N(N) = 7.99, and log N(O) = 8.92 [on a scale where log N(H) = 12.0].

The Holweger and Müller solar model atmosphere was chosen over other recently published solar models because it gives the best agreement between calculated and observed center-of-disk intensities as a function of wavelength and between calculated and observed center-to-limb intensity dependence (Lambert 1978). It might be argued that, because the Kurucz flux-constant models are used to analyze the program stars, then, to make the analysis self-consistent, the Kurucz solar model, not the Holweger-Müller solar model, must also be used in the calculation of the C I line solar oscillator strengths. This would appear to make the derived abundances with respect to the Sun more truly differential and therefore more reliable. In fact, we do not think that this is necessarily so. The agreement between the computed and observed solar center-of-disk continuum intensity as a function of wavelength is significantly better for the Holweger-Müller model than it is for the Kurucz model. Therefore, the temperature of the Holweger-Müller model in the continuum-forming layer, which is also where the high-excitation C I, N I, and O I lines are formed, is more consistent with observation. The effective temperatures of the program stars were chosen so that the observed $b - y$ colors and the theoretical $b - y$ colors, computed with Kurucz models, matched. In other words, there is a match of computed and observed continuum flux for the program stars and a match of computed and observed continuum intensity for the Sun; therefore, we have ensured that, in this important respect, the analysis is differential.

The discrepancy between the observed solar continuum intensity and that predicted with the Kurucz solar model is not seen as a serious weakness of the Kurucz grid of models. Relyea and Kurucz (1977) point out that, since their models do not include molecular opacities, they are not expected to provide an exact match of observations for effective temperatures of 6000 K or less. Most of the models in the grid, which covers a temperature range 5500–50,000 K, are hotter than this.

The C I line solar oscillator strengths derived from the Holweger-Müller model are 0.04 dex smaller than those from the Kurucz model. For the case of the iron lines, which will be discussed in § III*g*, the Fe II line solar oscillator strengths are insensitive to the choice of model, while for the Fe I lines they are 0.14 dex larger in the mean for the Holweger-Müller model than for the Kurucz model.

Theoretical oscillator strengths calculated by the Coulomb approximation and assuming *LS* coupling (Lambert 1968, 1978) were used for the N I and O I lines, with the exception of the 9260 Å O I multiplet. The solar N and O abundances obtained from the solar N I and O I lines with these oscillator strengths are in good agreement with the solar N and O abundances from other reliable indicators (Lambert 1978). Theoretical oscillator strengths were not used for the three lines (9260, 9262, and 9266 Å) of the 9260 Å multiplet, because the Landé interval rule is not obeyed by the lower term of the multiplet, which indicates that *LS* coupling does not hold—a conclusion confirmed by the relative strengths of the three lines in Procyon. The 9266 Å line, which is not seriously affected by telluric lines in the Delbouille atlas (Delbouille and Roland 1963), has a center-of-disk equivalent width of 31 mÅ. This and the solar model atmosphere of Holweger and Müller (1974) were used to calculate a solar oscillator strength that was used in the analysis. Solar oscillator strengths could not be derived for the 9260 and 9262 Å O I lines,

TABLE 5

C, N, AND O ABUNDANCES OF PROCYON

	ABUNDANCE						
	Model						Interpolated Results
FEATURE	6000, 4	6000, 4.5	6500, 4	6500, 4.5	7000, 4	7000, 4.5	6600, 4
C I	9.03	9.21	8.72	8.89	8.51	8.66	8.67
[C I]	8.52	8.75	8.57	8.77	8.71	8.88	8.59
CH	7.72	7.67	8.27	8.15	8.95	8.77	8.40
N I	8.58	8.77	8.15	8.34	7.80	7.98	8.07
CN	< 6.9	< 6.8	< 7.7	< 7.6	< 8.6	< 8.4	< 7.9
O I	9.56	9.74	9.08	9.26	8.71	8.89	9.00
[O I]	8.61	8.84	8.76	8.95	8.96	9.13	8.80

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TABLE 6

C, N, AND O ABUNDANCES

log N	Sun*	Procyon	45 Tauri	HD 27561
C...........	8.67	8.67	8.73	8.85
N...........	7.99	8.07	8.08	8.01
O...........	8.92	9.00	9.10	8.94

* Solar abundances from Lambert 1978.

which are seriously blended with telluric lines. (Note that each of these three O I lines has three close components, a complication allowed for by using a spectrum synthesis program, MOOG [Sneden 1973; Luck 1977]. Relative strengths of the components of a line were assigned assuming *LS* coupling.) Oscillator strengths for N I and O I lines are given in Table 1.

c) CNO *Abundances from Permitted Lines*

An abundance was calculated from the equivalent width of each C I, N I, and O I line using model atmospheres of effective temperature 6000, 6500, and 7000 K and gravity $\log g = 4$. To check for gravity dependence the calculations were also done for models of $\log g = 4.5$. The O I triplet lines at 7771, 7774, and 7775 Å were excluded, being too saturated to yield trustworthy abundances; as discussed earlier, the O I lines at 9260 and 9262 Å were not used. Scatter of the abundances obtained from individual lines about the mean abundance was small. For C I lines in Procyon, the standard deviation of the abundances was 0.10 dex. Mean abundances appropriate to the actual effective temperature of each star were calculated from the mean abundance for each model by three-point Lagrangian temperature interpolation. For Procyon, the results for each model and the interpolated results are given in Table 5. The C I, N I, and O I lines are of high excitation, so the derived abundances show some temperature dependence; at a higher temperature, a lower abundance is required to match the observed equivalent width of a line. With respect to ratios of abundances, such as the C/N ratio, the temperature dependence disappears. Abundances for all three stars, calculated using the parameters of Table 4, are given in Table 6.

d) *The* [C I] *8727 Å and* [O I] *6300 Å Lines in Procyon*

The method of analysis of the equivalent widths of the [C I] 8727 Å and [O I] 6300 Å lines was the same as for the permitted lines. Accurate theoretical *gf*-values are available. For the [C I] line, $\log gf = -8.21$ (a mean of the Nicolaides and Sinanoğlu 1973 and the Nussbaumer 1971 results) was used; for the [O I] line, $\log gf = -9.75$ (Garstang 1976) was used. These are the same values as those used by Lambert (1978) to analyze the solar forbidden lines. Inspection of Figure 4 shows the temperature dependence of the forbidden line abundances to be small and in the opposite sense to that of the permitted lines. In other words, forbidden line abundances provide a good check.

e) *The* CH *Lines in Procyon*

The 13 (0, 0) and (1, 1) band lines of the CH $A\,^2\Delta - X\,^2\Pi$ system that were analyzed are listed in Table 2.

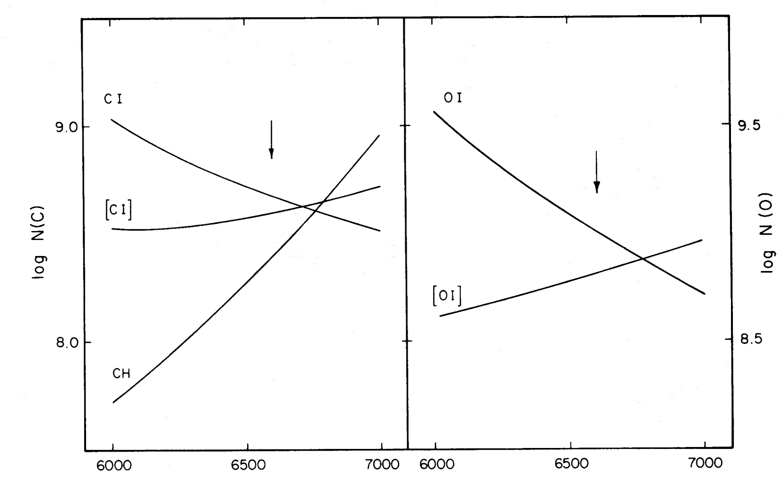

FIG. 4.—The carbon abundances derived from C I, [C I], and CH and the oxygen abundances derived from O I and [O I] for Procyon as a function of the effective temperature of the model atmosphere (with $\log g = 4.0$). The arrows show the adopted effective temperature which was obtained from the $b - y$ color of Procyon.

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The dissociation energy of CH ($D_0{}^0 = 3.464$ eV) and band oscillator strengths ($f_{0,0} = 0.00493$ and $f_{1,1} = 0.00488$) are accurately determined; these values are the same as those used by Lambert (1978) in an analysis of the solar CH lines. Excitation energies were from Botterud, Lofthus, and Veseth (1973).

Many of the CH lines have two or more components. They are sufficiently unsaturated, however, that no significant error was made by analyzing each line as if it had one component with a strength equal to the sum of the strengths of the individual components. The spectrum synthesis program was used to make an exact analysis of the lines at 4377 and 4380.7 Å, which have components of different excitation.

The consistency of carbon abundances obtained from individual lines was excellent; the standard deviation from the mean was 0.07 dex. Mean carbon abundances from the CH lines are given in Table 5; note the strong temperature dependence.

f) The CN *Lines in Procyon*

The reticon spectrum of the (0, 0) band head of the CN violet system was analyzed by matching it to synthetic spectra computed for a series of nitrogen abundances. A dissociation energy $D_0{}^0 = 7.66$ eV (Engleman and Rouse 1975) and band oscillator strength $f_{0,0} = 0.0342$ (Jackson 1974) were used in the calculations. These values are the same as were used by Lambert (1978) to analyze CN in the Sun. The band oscillator strength is accurately determined; the uncertainty of the dissociation energy is of order ± 0.2. The use of these parameters for CN and of the Holweger-Müller solar model atmosphere to analyze violet CN in the Sun leads to a solar nitrogen abundance that is 0.14 dex less than the actual solar nitrogen abundance (Table 5 of Lambert 1978). The discrepancy can be attributed to the uncertainty of $D_0{}^0$. To keep the analysis differential, the nitrogen abundance of Procyon derived from the violet CN has therefore been increased by 0.14 dex.

Violet CN is so weak in Procyon that no positive identification was possible. For each model an upper limit on the nitrogen abundance was set by comparing synthetic spectra (3880.5–3883.8 Å) of the (0, 0) band head—computed with a solar carbon abundance [log N(C) = 8.67] and a range of nitrogen abundances—with the observed spectrum. These upper limits are listed under CN in Table 5.

g) Iron Abundances of Procyon, 45 Tauri, and HD 27561

The equivalent widths of the neutral and ionized iron lines of Procyon, 45 Tau, and HD 27561 were analyzed to determine their iron abundances. The method was the same as for the C I, N I, and O I lines. The majority of lines do not have reliable experimental oscillator strengths; so solar oscillator strengths (listed in Table 3), calculated using the Holweger and Müller solar model atmosphere, a microturbulence of 1 km s^{-1}, and a solar iron abundance log N(Fe) = 7.50 (Ross and Aller 1976), were adopted for all Fe I and Fe II lines.

The iron abundance of Procyon is log N(Fe) = 7.35 (7.36 from 17 Fe I lines and 7.34 from four Fe II lines), that of 45 Tau is log N(Fe) = 7.45 (7.46 from 15 Fe I lines and 7.44 from four Fe II lines), and that of HD 27561 is log N(Fe) = 7.37 (7.43 from six Fe I lines and 7.31 from one Fe II line).

IV. RESULTS

The carbon, nitrogen, and oxygen abundances of Procyon, 45 Tau, HD 27561, and the Sun are given in Table 6. For consistency with the results for 45 Tau and HD 27561, which are based on permitted lines, the carbon and oxygen abundances of Procyon from permitted lines are listed. In Procyon all three elements have solar abundances. On the whole, the same is true of 45 Tau and HD 27561, although the oxygen abundance of 45 Tau [log N(O) = 9.10] and the carbon abundance of HD 27561 [log N(C) = 8.85] may indicate slight overabundances.

Figure 4 shows the carbon abundances derived from C I, [C I], and CH and the oxygen abundances derived from O I and [O I] for Procyon as a function of the effective temperature of the model atmosphere. At the adopted effective temperature of 6600 K the carbon abundances from the permitted lines and forbidden line agree to 0.1 dex. For oxygen the abundance derived from the [O I] line is 0.2 dex less than the abundance derived from the permitted lines. The less satisfactory agreement in the case of oxygen may, in part, be the result of uncertainty in the equivalent width of the very weak [O I] line. This comparison of the abundances derived from different abundance indicators shows that, in Procyon, the CNO abundances are accurate to about ± 0.2 dex. We estimate that, for the two Hyades dwarfs, they are also accurate to about ± 0.2 dex.

Although the CH and CN observations provide consistent results for the C and N abundances, a critical point deserves emphasis. The calculations (Fig. 3 and Table 5) show the sensitivity of the derived abundance to changes in effective temperature; e.g., a range of ± 500 K provides ± 0.6 dex spread in the C abundance from CH lines and a larger spread from the CN lines. This sensitivity arises because the molecular lines in these warm stars are formed in the upper photosphere and because the equivalent width of a weak line is approximately proportional to the function $P_g{}^2 \exp(-D/kT)$, where P_g is the gas pressure and D is the dissociation energy. The abundance analysis is also affected in an unknown way by the uncertainties in modeling the upper photosphere. Such uncertainties could be a serious factor for the upper photosphere, because line blanketing assumes a dominant role and because the deposition of mechanical energy near the chromosphere-photosphere boundary cannot yet be represented in model atmosphere calculations. This deficiency is apparent in comparisons of the theoretical and empirical solar atmosphere. On the other hand, the permitted and

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forbidden atomic lines are formed in layers showing a considerable overlap with the continuum-producing layers, which should be modeled satisfactorily by the theoretical atmospheres selected according to colors and hydrogen line profiles. The high sensitivity of molecular lines can be mitigated by combining observations of similar molecules. In F stars, the pair CH and NH should provide a C/N ratio which is insensitive to the atmospheric uncertainties. Clegg's (1977) initial exploitation of this combination should be extended.

Since this analysis is a local thermodynamic equilibrium (LTE) analysis, we must consider the possibility that non–LTE effects influence the abundances obtained from the high-excitation permitted lines. The forbidden C I and O I lines are not subject to non–LTE effects (Pagel 1971). Baschek, Scholz, and Sedlmayr (1977) have computed non–LTE effects for O I lines in A-type stars. In the extreme case of a strong line (O I 7771 Å) and a low gravity ($T = 10{,}000$ K, $\log g = 1.0$ model), they find that the equivalent width calculated for non–LTE is 3 times greater than for LTE. Effects are much less extreme for weaker lines and main-sequence gravities. For the case of a $T = 7500$ K, $\log g = 4.0$ model, the difference between the non–LTE and LTE equivalent widths is 0.18 dex for the 9266 Å O I line and only 0.04 dex for the 6158 Å O I line. In the case of the main-sequence F-type stars studied in this paper, smaller effects are expected because the lines are weaker than in A-type stars. The agreement between the permitted and forbidden line carbon and oxygen abundances for Procyon indicates that non–LTE effects do not amount to more than 0.1 dex.

When derived from lines of the same type (i.e., permitted or forbidden lines), the abundance ratios C/O and C/N for a star are insensitive to most of the factors that contribute to the uncertainty of the absolute abundances. The Procyon results substantiate this claim. The difference $\log N(\mathrm{O}) - \log N(\mathrm{C})$ is $+0.33$ from the permitted lines and $+0.21$ from the forbidden lines.

The iron abundances of 45 Tau [$\log N(\mathrm{Fe}) = 7.45$] and HD 27561 [$\log N(\mathrm{Fe}) = 7.37$] indicate that the Hyades cluster is *not* metal rich with respect to the Sun [$\log N(\mathrm{Fe}) = 7.50$]. What are the estimated errors? The main uncertainties in the 45 Tau and HD 27561 iron abundances come from the solar oscillator strengths and from the dependence on the assumed effective temperatures and gravities. The oscillator strength contribution is estimated to be ± 0.1 dex. The abundance from the Fe I lines varies by ± 0.06 dex as the effective temperature is changed ± 100 K; it is independent of gravity. The abundance from the Fe II lines is independent of effective temperature; it varies by ± 0.07 dex as $\log g$ is changed ± 0.2. Together, the effective temperature and gravity uncertainties of the iron abundance are therefore about ± 0.1 dex. The total uncertainty of the iron abundances is set at ± 0.2 dex. The internal consistency is higher, and the Hyades-Procyon abundance difference is 0.06 ± 0.1 dex.

V. DISCUSSION

We have found that Procyon, 45 Tau, and HD 27561 have solar carbon, nitrogen, and oxygen abundances. Their iron abundances are also solar.

This situation is in contrast to the abundances of the light elements Li and Be. Danziger and Conti (1966) find that, in 45 Tau, the Li/Ca ratio is 1.6 dex larger than in the Sun; in Procyon, an upper limit of $+0.6$ dex is set. This is converted to $\log N(\mathrm{Li}) = 2.6$ in 45 Tau and $\log N(\mathrm{Li}) < 1.6$ in Procyon, with $\log N(\mathrm{Li}) = 1.0$ in the Sun (Müller, Peytremann, and de la Reza 1975) and the assumption that the Ca abundances of 45 Tau and Procyon are solar. The cosmic abundance of Li is $\log N(\mathrm{Li}) = 3.0$ (Boesgaard 1976*a*). Thus, as compared with its cosmic abundance, Li is mildly underabundant in 45 Tau and very underabundant in Procyon. The same is true of Be. Boesgaard (1976*b*) has determined Be abundances of $\log N(\mathrm{Be}) = 1.04$ and $\log N(\mathrm{Be}) \leq -0.60$ for 45 Tau and Procyon, respectively. The cosmic abundance of Be is $\log N(\mathrm{Be}) = 1.12$. Both Li and Be are destroyed by (p, α) reactions in stellar interiors where the temperature is greater than a few million K. Boesgaard (1976*b*) discussed the depletion of Li and Be in terms of convective overshoot at the base of the convective envelope and diffusion below the convective envelope. Evidently neither of these two mechanisms is affecting the surface abundances of carbon, nitrogen, and oxygen.

Lambert and Ries (1977) find that the four Hyades cluster giants all have C/N ratios that are significantly less than solar. Their average C/N ratio is 0.9, while that of the Sun is 4.8. A deep convective envelope, which mixes up material processed by the CNO cycle to the surface, is responsible for the low C/N ratios of the Hyades giants. The observed C/N ratio results from the mixing of the carbon-poor and nitrogen-rich material processed by the CNO cycle with the unprocessed envelope material. An assumption in this argument is that the unprocessed envelope material had a solar CNO content. Evidence that this assumption is correct is provided by the solar CNO abundances of the Hyades dwarfs.

The CNO cycle does not change the sum of the number of carbon, nitrogen, and oxygen nuclei. Therefore, this interpretation of the observed CNO abundances of the Hyades giants demands that the sum of the CNO abundances of the giants and the dwarfs be the same. The average value of

$$\log [N(\mathrm{C}) + N(\mathrm{N}) + N(\mathrm{O})]$$

for the four Hyades giants is 9.07; for the two Hyades dwarfs it is 9.25. We see that, within the errors of these two results, the requirement that the sum of the CNO abundances be conserved is satisfied.

Our determination of a solar iron abundance in Procyon is in agreement with Griffin (1971). We find that the iron abundance of both the Hyades dwarfs is also solar. This is not a new result. A majority of the previous spectroscopic investigations of the iron abundance of the Hyades dwarfs, which are listed in Table 7, also find that it is solar. The largest iron

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abundance determination, +0.29 dex with respect to the Sun, is that of Alexander (1967), who reanalyzed the equivalent widths for two of the Hyades dwarfs investigated by Wallerstein (1962). A large part of the +0.30 dex difference between Alexander's and Wallerstein's results is caused by Alexander's use of a higher excitation temperature. A criticism of this excitation temperature, which was based on analysis of moderately saturated Fe I lines sensitive to the adopted solar microturbulence, is that the Cowley and Cowley (1964) solar curve of growth—now recognized to have too high a microturbulence (Foy 1972)—was used to derive it. Chaffee, Carbon, and Strom (1971) find an enrichment of +0.18 dex. Their use of saturated lines from the crowded 4200–4900 Å wavelength interval means that this result is of lower weight. Consideration of the abundances in Table 7 shows that the iron abundance of the Hyades dwarfs is *not* significantly different from that of the Sun. What is the accuracy of the spectroscopic abundance determinations? This is difficult to assess. The main source of error is caused by the uncertainty in the temperatures of the stars. An uncertainty of ± 0.02 in the adopted $\theta_{\text{excitation}}$ corresponds to an uncertainty of about ± 0.10 dex in the derived iron abundance. The scatter of the results in Table 7 suggests that the equality of the Hyades and solar iron abundance is accurate to better than 0.2 dex. A Hyades metal enrichment of 0.3 dex appears to be excluded.

We have emphasized the spectroscopic evidence that the iron abundance of the Hyades is *not* significantly greater than that of the Sun because evidence from broad-band photometry that the Hyades *are* metal rich with respect to the Sun is widely accepted as fact. The ultraviolet excess $\delta(U - B)$ of the Sun as compared with the Hyades main sequence (Sandage and Eggen 1959) is the basis of this photometric evidence. This ultraviolet excess is attributed to smaller line blanketing in the Sun than in the Hyades main-sequence stars. The smaller line blanketing of the Sun is in turn explained by the supposition that the metal enrichment of the Sun is less than that of the Hyades. Eggen (1964) uses the ultraviolet excess of the Sun to derive a Hyades metal enrichment of +0.24 dex with respect to the Sun. Bell (1976) adopts a value of +0.3 dex. Nissen (1970) has used very narrow passband photoelectric observations of nine Hyades stars to derive an enrichment of 0.38 dex. This result is in the photometric category because the strength of a group of lines, and not individual lines, was measured. A weakness of Nissen's result is its dependence on the adopted value of the solar $b - y$, for which he used the high value of 0.424. Gustafsson and Nissen (1972) remark that the use of a lower value would reduce the Hyades metal enrichment by about 0.2 dex. They also mention that, if the effects of metal line blanketing on the model atmospheres had been taken into account, the enrichment might be further reduced by 0.1 dex. The large metal enrichment (+0.37 dex) that Nissen (1970) finds for Procyon suggests that his abundances are, indeed, systematically high.

TABLE 7

SPECTROSCOPIC DETERMINATIONS OF THE IRON ABUNDANCE OF HYADES DWARFS

[Fe/H]*	Reference
+0.06........	Wallerstein and Helfer 1959
+0.11........	Parker *et al.* 1961
−0.01........	Wallerstein 1962
+0.29........	Alexander 1967
+0.18........	Chaffee, Carbon, and Strom 1971
+0.05........	Foy 1976
0.0.........	Barry 1978
−0.09........	This work

* $\log (\text{Fe/H})_{\text{Hyades}} - \log (\text{Fe/H})_{\text{Sun}}$.

There is no obvious explanation of the discrepancy between the spectroscopic and photometric results. A possible weakness of the photometric evidence is that abundance effects may not be the only factor involved in the interpretation. An increase of microturbulence affects the colors in the same way as an increase of the abundance of the metals. However, we note that there is no evidence that the microturbulence of the Hyades dwarfs is much greater than the microturbulence of the Sun; so we may not, in fact, be able to explain the discrepancy in terms of the microturbulence. An alternative, and more likely, explanation is that the Sun does *not* have an ultraviolet excess with respect to the Hyades main sequence. Barry, Cromwell, and Schoolman (1978) have determined solar colors ($B - V = 0.66$ and $U - B = 0.20$) which place the Sun on the Hyades main sequence. They find that their colors are in good agreement with the mean of the corrected results of previous investigators.

We thank Larry Testerman of the Kitt Peak National Observatory for sending us the solar scans and Robert Kurucz for the loan of his grid of model atmospheres. This research was supported by the Robert A. Welch Foundation of Houston, Texas, and the National Science Foundation (grant AST 75-21803).

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