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CHEMICAL COMPOSITION OF OPEN CLUSTERS. II. C/H AND C/Fe IN F DWARFS FROM HIGH-RESOLUTION SPECTROSCOPY

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ABSTRACT

We have determined carbon abundances for F dwarfs in open clusters and moving groups of a variety of ages and [Fe/H] abundances to investigate the homogeneity of chemical mixing within the Galactic disk. The stars studied range in age from 5×10^7 to 2×10^9 years, and in metallicity from [Fe/H] = −0.2 to +0.15; our sample of F dwarfs comes from the α Per, Pleiades, and Hyades clusters, and the UMa, Hyades, and Wolf 630 moving groups, as well as a selection of bright field F dwarfs.

Carbon abundances were determined from high-excitation C I lines near 7110 and 6590 Å measured in high-resolution, high signal-to-noise coudé spectra. Observations were obtained with both the CFHT Reticon at a spectral resolution of 0.11 Å and the Palomar 200 inch (5.1 m) TI CCD with a resolution of 0.21 Å. Stellar carbon abundances determined from a model atmosphere analysis are estimated to be accurate to 0.08 dex.

We find that the observed dispersion about the mean cluster carbon abundances is consistent with observational error alone, and we conclude that the intrinsic dispersion in the carbon abundances in each cluster or group is extremely small, probably less than ∼0.05 dex. We also find that, to within the observational error, [C/Fe] = 0.0 for all clusters and groups, with an observed dispersion of only 0.09 dex over the entire sample of 69 stars.

There is no evidence for a trend of [C/H] with age for these young stellar groups, but there are real cluster-to-cluster variations, implying differences in the C content in the precluster gas. The [C/H] cluster differences follow the same pattern as the [Fe/H] cluster differences and yield [C/Fe] values which are constant, and equal to the solar value, in all the groups. Thus in agreement with previous studies of field dwarfs, there is no trend of carbon-to-iron ratio with metallicity. These data indicate that the production of carbon in the Galactic disk over the last ∼1 billion years has kept pace, to an extremely high degree, with the production of iron.

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

I. INTRODUCTION

Carbon and oxygen are among the most abundant elements in stars. Because they are the result of α-processing in stellar interiors and are typically formed in stars of different mass ranges, carbon and oxygen are key elements in the nucleosynthetic history of the Galaxy. By tracing the production of C and O throughout the Galactic disk, we may trace the mass spectrum of past generations of stars and document the extent of chemical mixing in the disk.

Studies of C and O in unevolved stars in disk clusters are especially important. Stars in clusters are thought to be coeval and can be dated accurately. By determining C and O abundances in stars in clusters of different ages we can address questions of the magnitude of intrinsic dispersion in abundance in stars of a given age, the extent of mixing within clusters, and the existence of global trends in abundance and dispersion with age, metallicity, [Fe/H], and position in the disk. By limiting ourselves to stars on or near the main sequence, we should be seeing stellar abundances unaffected by mixing processes that dominate the abundances of C and O in giant stars.

Previous studies of carbon abundances in F and G dwarfs (Clegg, Lambert, and Tomkin 1981; Laird 1985; Carbon *et al.* 1987) have concluded that [C/Fe] = 0.0 over large ranges in [Fe/H]. These studies show an observed dispersion of ∼0.2 dex in [C/Fe] at a given [Fe/H], which, being comparable to, or only slightly larger than the observational errors, suggests that the intrinsic dispersion is less than ∼0.1 dex. However, Nissen, Edvardsson, and Gustafsson (1985) have found that although relationships with [Fe/H] are tight, O/H and Fe/H ratios in F and G dwarfs of a given age show a dispersion larger than that expected from observational errors; they have no similar data for carbon abundances.

We describe here results on carbon abundances obtained as part of a program to investigate Fe, C, and O abundances from high-resolution spectroscopy in galactic open clusters. Results for Fe abundance determinations are discussed in Boesgaard and Friel (1990; Paper I), and those for oxygen will appear in a later paper in this series (Boesgaard, Friel, and Budge 1990). The three clusters studied in our program (α Per, Pleiades, and Hyades) cover a range in age of 5×10^7 to 7×10^8 yr; they are augmented by observations of stars in several proposed moving groups (UMa, Hyades, and the Wolf 630 groups) and bright field dwarfs which extend the age range to about 2 billion years. Later observations are planned to move this age limit to 5 billion years with data from M67.

II. OBSERVATIONS

Carbon abundances were determined from observations of six C I lines in the λλ7048–7182 region and one line in the Hα

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region λλ6540–6655. The source for carbon abundances in the 7110 Å region is Reticon data obtained at the Canada-France-Hawaii telescope with the coudé spectrograph; these spectra have a dispersion of 0.072 Å pixel^{-1} resulting in a resolution of 0.11 Å. The strength of atmospheric water vapor lines present in this spectral region was monitored by observations of rapidly rotating B stars taken at air masses similar to those of our cluster stars. However, at the dry CFHT site on Mauna Kea no atmospheric water vapor lines were detected except those near 7170 Å, well outside the region of interest. The 7110 Å data were supplemented for about half the stars with data from the Hα region; spectra in this region were obtained with a TI CCD and coudé spectrograph of the Palomar 200 inch telescope at a slightly lower dispersion of 0.14 Å pixel^{-1} or 0.21 Å resolution. Details of the instrumentation used and the data reduction procedures are given in Paper I. Data were flat-fielded by the appropriate mean nightly flat field, placed on a linear wavelength scale established by comparison spectra taken each night, and finally continuum-fitted (via IRAF[3] routines) before equivalent widths were measured. The spectra of the fainter cluster stars typically had S/N ratios of 150–200; the brighter stars were observed at much higher S/N ratios of 500–600.

The list of stars observed for carbon abundances and basic data for them are given in Table 1, along with the S/N ratio of each observation. Figure 1 shows representative spectra in the 7110 Å region, and indicates the C I lines that were measured. Figures 1 and 2 of Paper I give further examples of spectra in the same 7110 Å region as well as sample spectra in the Hα region.

Equivalent widths of the carbon lines were measured from the continuum-fitted spectra using IRAF; they are listed in Table 2. Repeat measurements of equivalent widths from the same spectra indicate that we can reproduce our measurements to within 1 mÅ. For six stars we had observations in the 7110 Å region from both the August and the October CFHT runs; measurements of equivalent widths in these stars agree within typically 2 mÅ. Although the data are limited, there is no indication that the errors vary with line strength. Generally, however, the measurements of equivalent width for stars of high rotational velocity are less reliable than those for sharp-lined stars. The five C I lines in the region λλ7111–7117 are particularly affected by rotational blending.

We conclude that we can measure equivalent widths to an accuracy of better than 2 mÅ, except in the case of stars with rotational velocities, $v \sin i$, greater than 20 km s^{-1}.

[3] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

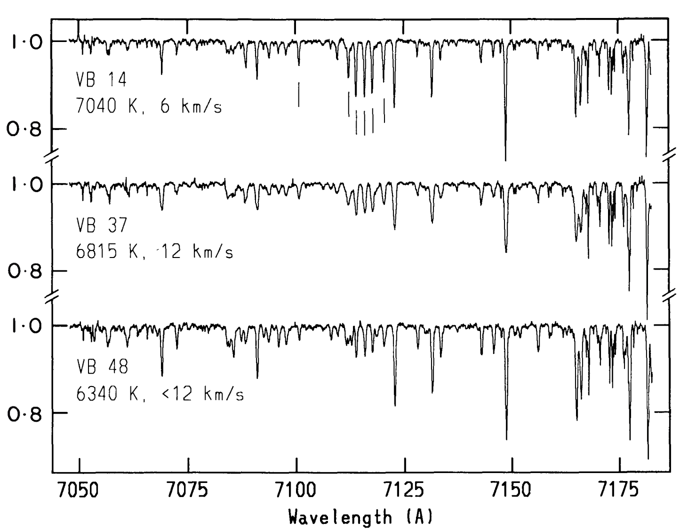

FIG. 1.—Sample Reticon spectra of Hyades stars in the 7110 Å region from the CFHT coudé. The six C I lines used in this region to determine carbon abundances are indicated in the top spectrum.

III. ANALYSIS

To determine carbon abundances we require effective temperatures and surface gravities for these stars. We use temperatures derived in previous papers; Paper I provides references for the cluster temperature determinations and gives the details of the determination of temperatures for the field stars. Final adopted temperatures are generally a mean of those derived from the calibrations of Strömgren Hβ and $b-y$ and of $B-V$ colors in Saxner and Hammarbäck (1985). In most cases, temperatures are accurate to ± 50 K.

Surface gravities for these stars are also derived from Strömgren and Hβ photometry. The prescription follows that used in Boesgaard and Tripicco (1986). The Hβ and c_1 photometric indices are used in the standard relations for F stars (Crawford 1975) to determine absolute magnitudes, M_V. Following Duncan (1984) we take $\log g = 4.3$ for the ZAMS and determine deviation from the ZAMS as $\Delta \log g = \Delta M_V/2.5$. For the handful of stars in our sample which have no Strömgren measurements, we have adopted a value of $\log g = 4.3$; these values are indicated by colons in Table 1. The quoted errors in the Strömgren and Hβ photometry translate into typical uncertainties of 0.05 dex in the log of the surface gravities, to which must be added any source of uncertainty from the calibration itself. We judge the log g values given in Table 1 to be accurate to 0.1 dex.

As discussed in Paper I, abundances were determined with the model atmosphere program of M. Spite, using the grid of Kurucz (1979) model atmospheres. At $\log g = 4.5$, abundances for each carbon line were calculated over the grid of $T_{\rm eff} =$ 7000, 6500, and 6000 K with the microturbulence $\xi = 1.45$, 1.30, 1.10 km s^{-1}, respectively. Calculations were also made for a solar model with $\log g = 4.4$, $T_{\rm eff} = 5770$ K, and $\xi = 1.14$ km s^{-1}. The full set of models was not run over a grid of log g values because of the large number of models necessary, but instead sample lines were calculated at $\log g = 4.0$ and 3.5 over the grid of temperatures to obtain the dependence of the model abundances with log g, which is -0.35 dex in [C/H] for each 1.0 dex decrease in log g. Individual stellar abundances determined via the full grid of $\log g = 4.5$ models were adjusted for the difference between the observed log g and the model value of 4.5. The only sublety in this procedure arises from the translation of the model log g values to the observed scale given by the Crawford/Duncan calibration. Lester, Gray, and Kurucz (1986) have calibrated theoretical Strömgren and Hβ photometric indices for both the published and unpublished grid of Kurucz models; we find from these theoretical colors that the "observed" gravities corresponding to the $\log g = 4.5$ model are a modest function of temperature for the range of the F stars considered here. Consequently, our correction for the deviations in surface gravity are a slight function of temperature through this change in zero point. The effect of this temperature-dependent correction on the carbon abundances

TABLE 1

STARS OBSERVED

a. Hyades

VB	V	B–V	Sp. Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	CFH(C I) S/N	Pal(Hα) S/N
11	6.01	0.40	F3V	6850	4.17	25	530	...
13	6.62	0.42	F6V	6725	4.23	18	370	185
14	5.73	0.36	F4V	7040	3.98	6	550	210
19	7.10	0.51	F8V	6300	4.15	<12	430	215
37	6.61	0.41	F4V	6815	4.17	12	570	180
48	7.14	0.52	F5	6245	4.16	<12	550	275
57	6.46	0.49	F7V	6370	4.25	15	460	235
61	7.10	0.51	F5V	6260	4.16	18	580	...
62	7.50	0.54	F8V	6185	4.12	<6	530	...
78	6.92	0.45	F6V	6510	4.18	20	460	...
81	7.10	0.47	F6V	6470	4.25	18	470	...
86	7.04	0.47	F5	6485	4.34	20	560	...
121	7.29	0.50	F8	6340	4.24	12	400	170

b. Pleiades

H II	V	B–V	Sp. Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	CFH(C I) S/N	Pal(Hα) S/N
233	9.66	0.53	F5V	6485	4.30	<20	180	166
470	8.95	0.39	F5V	6845	4.38	<40	170	150
530	8.95	0.39	F3V	6770	4.30	<12	170 200	200
627	9.68	0.50	F7V	6335	4.26	25	185	...
739	9.56	0.62	G1V	5870	4.30	<12	160	...
948	8.66	0.60	F9V	5960	4.07	<12	...	230
1122	9.29	0.46	F5V	6610	4.46	28	160	...
1200	9.99	0.54	F6V	6470	4.18	<20	105 165	...
1613	9.88	0.54	F6V	6250	4.43	18	155	...
1726	9.25	0.55	F7V	6365	4.34	<12	190	155
1766	9.13	0.47	F5V	6730	4.49	20	185	160
1856	10.02	0.56	F7V	6155	4.32	12	160	

c. α Persei

He	V	B–V	Sp. Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	CFH(C I) S/N	Pal(Hα) S/N
135	9.71	0.41	F5V	6710	4.31	<20	210	...
361	9.68	0.36	F4V	6730	4.3:	30	170	...
490	9.56	0.37	F3IV–V	6805	4.24	<20	220	...
635	9.05	0.26	A8V	7285	4.3:	<20	170 145	...
799	9.69	0.37	F4V	6705	4.20	20	200	...
1225N	8.88	0.41	F7IV–V	6415	4.3:	20	165	...
1225S	8.88	0.41	F7IV–V	6415	4.3:	<20	150	...

is small; the maximum difference in log g from the model value of 4.5 is only 0.15 dex, which translates into 0.05 dex in [C/H].

A minor complication may arise in the interpretation of the surface gravities derived from the c_1 for the Hyades stars. Unevolved stars in the Hyades show c_1 indices some 0.035 magnitudes higher than those for the local field stars of the same metallicity and temperature (Strömgren, Olsen, and Gustafsson 1982). The reason for this "Hyades anomaly" is still not clear (Campbell 1984; Nissen 1988), but the Hyades c_1 values, interpreted directly in terms of surface gravities, yield a cluster mean log g roughly 0.1 dex lower than the mean values for the Pleiades and the α Per clusters. If the high c_1 values for

TABLE 1—*Continued*

d. Hyades Moving Group

Name	V	B–V	Sp. Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	CFH(C I) S/N	Pal(Hα) S/N
HR 88	6.39	0.66	G2V	5785	4.47	7	590	...
							560	
HR 410	6.31	0.47	F7V	6385	4.09	32	570	425
HR 878	5.80	0.41	F5IV	6620	4.3:	20	550	...
HD 197039	6.74	0.45	F7V	6510	4.3:	...	520	...
HR 8548	5.75	0.52	F7V	6170	3.84	7	530	400
							590	
HR 8772	6.68	0.58	F8V	5965	4.07	...	520	...
HR 8788	6.13	0.44	F6V	6500	4.02	...	600	...
							580	
HR 8792	6.30	0.49	F7V	6150	4.08	7	570	...
							540	

e. UMa Moving Group

Name	V	B–V	Sp. Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	CFH(C I) S/N	Pal(Hα) S/N
HR 235	5.19	0.50	F7IV–V	6200	4.19	0	580	...
HD 11131B	6.76	0.43	G1V	5820	4.27	...	600	...
HR 534	5.94	0.30	F2V	7100	4.06	...	660	...
HR 647	6.06	0.40	F4V	6500	4.07	<26	600	...
HR 2047	4.41	0.59	G0V	5900	4.21	6	...	460
HR 5634	4.93	0.43	F5V	6600	4.20	45	660	...
HD 151044	6.60	0.48	F8V	6130	4.3:	...	600	...
HR 7061	4.19	0.46	F6V	6370	3.89	14	600	...
							500	
HR 7172	5.23	0.53	F8V	6115	3.73	26	680	...
HR 7451	5.73	0.48	F7V	6240	4.10	6	590	...
HR 8170	6.40	0.53	F8V	6125	4.31	12	590	...

f. Wolf 630 Group

Name	V	B–V	Sp. Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	CFH(C I) S/N	Pal(Hα) S/N
HD 6479A	6.35	0.38	F3	6700	4.13	...	600	...
HD 6480B	7.25	0.49	F6–7	6265	4.23	...	530	...
HR 7947	5.14	0.49	F7V	6330	4.3:	<25	590	...
HR 8077	5.94	0.54	F8V	6130	3.91	<6	590	...

g. Stars of Known Age

Name	V	B–V	Sp. Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	CFH(C I) S/N	Pal(Hα) S/N
HD 16232B	6.50	0.41	F6V	6440	4.39	30	550	...
HD 196310A	7.98	0.38	F0	6760	4.53	...	450	...
HD 206751A	7.90	...	F2V	6785	4.00	...	530	...
							520	
HD 216582B	7.80	...	F5V	6390	4.14	...	560	...

TABLE 1—*Continued*

h. Boesgaard and Tripicco Field Stars

Name	V	B–V	Sp. Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	CFH(C I) S/N	Pal(Hα) S/N
HR 7496	5.49	0.46	F5IV	6470	3.90	21	510	...
HR 7697	5.85	0.39	F5V	6635	4.10	<10	590	...
HR 7756	5.91	0.38	F5V	6570	4.10	<10	560	...
HR 7925	6.01	0.46	F6IV	6475	4.20	30	610	...
HR 7936	4.14	0.43	F4V	6590	4.10	37	470	...
HR 8205	6.13	0.44	F5V	6525	4.20	12	550	...
HR 8222	6.57	0.41	F0V	6600	3.60	<15	510	...
HR 8805	5.70	0.44	F5V	6550	4.10	9	650	...
HR 8885	5.77	0.46	F5V	6475	4.00	12	650	410
HR 8907	5.52	0.40	F4V	6640	4.10	0	530	...
HR 8977	6.23	0.39	F1V	6660	4.10	30	610	425

the Hyades are due to some parameter which does not actually affect the surface gravities, our log g values and hence derived C abundances may be systematically too low by up to 0.04 dex in [C/H] and [C/Fe] in the mean.

Carbon abundances were determined from each line for all program stars and the ratio of stellar to solar values were found from measurements of the same lines in sky spectra taken during the runs. The sky spectra were of high S/N ratios of 700, and multiple observations showed that the measurements from these spectra repeated to better than 0.5 mÅ. By taking stellar abundances relative to similarly measured solar values we minimize the impact of uncertainties in gf-values for individual lines. Resulting mean abundances and standard deviations of both the ratio $(C/H)_*/(C/H)_\odot$ and its logarithmic value for each star are given in Table 3. Lines that showed evidence of blends or interference by cosmic rays, which were not subtracted from the CFHT spectra, were omitted in forming these mean abundances. Also in Table 3 are given the values of [C/Fe] for each star, assuming the [Fe/H] values determined in Paper I; the σ in [C/Fe] for each star was obtained by adding the rms deviations in [C/H] and [Fe/H] (from Paper I) in quadrature.

Based on our estimate of a 2 mÅ measuring error, we would expect the standard deviation about our mean carbon abundances to be roughly 0.05 dex, while the observed values given in Table 3 are typically much larger, at 0.15 dex. Clearly, some other effect is contributing to this scatter. We attempted to minimize the impact of uncertainties in the atomic line parameters by taking ratios to the solar values. The solar equivalent widths listed in Table 2 are measurements from our very high S/N spectra of the daytime sky taken with the same equipment during our observing run. If these solar values are not "correct," they will introduce some scatter. Although we are not attempting to measure absolute C abundances, it is interesting to note that the solar C/H determined from the mean of the seven lines measured in our sky spectra is $2.3 \pm 0.5 \times 10^{-4}$, or a dispersion in the log of ~ 0.10 dex.

In Figure 2 each panel shows the [C/H] ratio for stars in a cluster or group plotted against effective temperature; these show that the carbon abundances are free from systematic effects with temperature. This is reinforced by the [Fe/H] results in Paper I. Since the C I lines become weaker with decreasing temperature and the Fe I lines become stronger, and neither show any temperature dependence, the temperatures we have used are valid. Error bars give the standard error in the mean abundance for each star. The horizontal line shows the mean value of [C/H] for each cluster or group. These means are averages weighted inversely by the rms deviations for stars judged to be members. Note the small range in [C/H] for stars in a given cluster/group.

The mean stellar abundances are affected by random errors from a variety of sources, including uncertainties in the temperatures and the gravities adopted, in the measurement of the equivalent widths, and in the intrinsic accuracy of the spectra. The model calculations show that there is virtually no dependence on microturbulent velocity. The estimated error in the temperatures of ± 50 K translates into uncertainties in the deduced [C/H] of 0.02 to 0.03 dex. The expected random error in log g of 0.1 dex implies an uncertainty in the [C/H] values of 0.035 dex. The additional source of uncertainty in the translation of the model surface gravities to the observed Strömgren gravities can introduce no more than 0.05 dex error in the final abundances. The total effect of random errors from the other sources can be judged from repeat observations; these indicate that the typical error is no more than 0.05 dex. Adding all these sources in quadrature, we obtain a final estimate of the random errors in a single stellar abundance of 0.08 dex.

Few of these stars have been analyzed for carbon abundances previously, but we can compare our determinations for two Hyades stars, VB 14 and 37, with the results of Tomkin and Lambert (1978), as revised by Clegg, Lambert, and Tomkin (1981, CLT). They determined [C/H] values from high-excitation C I lines with resolutions of 0.2 and 0.4 Å and S/N ratios of 200, and found [C/H] of +0.08 and +0.21 for VB 14 and 37, respectively. For comparison, we obtain −0.09 and +0.03. Effects of differences in adopted temperatures and surface gravities for these stars combine to make minor differences in the final [C/H] values. We have four to five C I lines in common with Tomkin and Lambert; for VB 14 our equivalent widths are systematically smaller by 5 mÅ and for VB 37, which they observed at the lower resolution, ours are 15 mÅ smaller. This difference in measured equivalent widths alone can account for the differences in [C/H]. Our higher resolution and much higher S/N ratios (550 and 570) indicates that our equivalent widths should be more accurate. The difference in final abundances is consistent, however, with the estimates of errors both in this study and for their data (0.1 dex). There is no evidence, as we will see later, for any systematic differences

TABLE 2

C I EQUIVALENT WIDTHS IN MILLIANGSTROMS

a. Hyades

VB	T(K)	6587	7100	7111	7113	7115	7117	7119
14	7040	56.9	26.1	39.7	64.5	62.2	58.8	46.6
11	6850	...	27.3	54.8	69.8	62.4	65.5	46.0
37	6815	41.7	24.8	47.0	57.0	54.6	50.5	39.6
13	6725	45.7	...	...	57.9	53.4	54.4	39.3
78	6510	...	13.5	...	50.8	46.0	41.4	31.3
86	6485	...	18.0	...	41.7	39.3	44.3	29.3
81	6470	...	14.5	...	44.0	42.6	36.0	30.5
57	6370	30.6	12.1	...	44.3	40.2	35.2	30.8
121	6340	34.5	18.1	...	45.3	43.0	35.2	36.1
19	6300	33.7	16.1	...	42.3	41.0	35.1	30.6
61	6260	...	17.9	...	36.4	34.7	...	28.1
48	6245	30.0	15.5	...	38.2	35.0	32.2	28.5
62	6185	...	19.2	25.3	45.5	41.0	35.4	24.9

b. Pleiades

H II	T(K)	6587	7100	7111	7113	7115	7117	7119
470	6845	36.7	...	29.7	42.3	45.2	34.6	...
530	6770	33.8	12.3	...	31.1	39.0	34.2	29.0
1766	6730	30.9	11.9	31.0	39.1	35.9	42.5	32.4
1122	6610	...	15.1	...	...	42.2	31.1	25.2
233	6485	30.7	20.3	...	39.4	35.6	34.4	29.3
1200	6470	...	15.1	24.4	34.8	32.2	32.0	22.6
1726	6365	19.2	15.7	18.5	36.7	31.3	28.4	27.0
627	6335	...	...	...	29.0	32.3	31.3	24.6
1613	6250	...	19.9	...	26.8	25.0	28.6	21.2
1856	6155	...	...	...	25.2	24.0	24.5	22.3
948	5960	19.9	...	...	...	...	...	...
739	5870	...	...	13.1	20.3	20.6	15.0	13.5

c. α Persei

He	T(K)	7100	7111	7113	7115	7117	7119
635	7285	...	29.5	53.6	53.3	49.3	36.2
490	6805	...	31.3	45.8	39.7	46.6	34.2
135	6710	10.9	30.7	38.7	37.2	36.1	22.6
799	6705	11.5	22.7	23.1	23.4	39.0	20.2
1225N	6415	10.8	...	28.8	36.2	38.6	34.2
1225S	6415	...	19.1	37.9	30.5	32.3	27.7

d. Hyades Moving Group

Name	T(K)	6587	7100	7111	7113	7115	7117	7119
HR 878	6620	...	24.7	...	55.6	52.5	50.5	39.4
HD 197039	6510	...	19.0	44.2	42.7	53.0	47.7	33.7
HR 8788	6500	...	30.0	...	66.8	58.9	57.0	47.5
HR 410	6385	43.1	24.8	...	55.9	45.5	48.9	39.4
HR 8548	6170	31.2	16.6	...	37.7	36.8	32.2	...
HR 8792	6150	...	17.2	20.5	37.8	35.3	29.6	...
HR 8772	5965	...	10.2	12.6	22.8	20.7	19.4	14.5
HR 88	5785	...	14.3	...	30.0	27.9	19.6	...

e. UMa Moving Group

Name	T(K)	6587	7100	7111	7113	7115	7117	7119
HR 534	7100	...	16.1	23.5	42.1	40.9	40.8	26.3
HR 5634	6600	...	21.9	...	43.3	33.8	35.4	32.0
HR 647	6500	...	10.2	...	36.3	32.8	33.2	25.8
HR 7061	6370	...	16.4	...	38.4	39.2	38.3	28.3
HR 7451	6240	...	12.0	...	27.8	30.5	25.7	20.1
HR 235	6200	...	10.4	14.3	27.0	26.0	22.0	15.7
HD 151044	6130	...	12.8	15.2	27.0	26.4	24.6	...
HR 8170	6125	...	10.7	...	26.0	26.3	19.6	18.0
HR 7172	6115	...	16.7	...	35.8	30.6	28.7	23.1
HR 2047	5900	18.9	...	...	...	...	...	...
HD 11131B	5820	...	9.6	11.8	18.5	19.7	14.6	11.5

f. Wolf 630 Group

Name	T(K)	7100	7111	7113	7115	7117	7119
HD 6479A	6700	18.7	...	40.1	38.6	38.5	...
HR 7947	6330	19.8	28.0	43.9	43.5	40.2	32.8
HD 6480B	6265	11.2	13.2	26.5	25.0	22.8	...
HR 8077	6130	16.3	...	36.7	34.9	31.5	...

g. Stars of Known Age

Name	T(K)	7100	7111	7113	7115	7117	7119
HD 206751A	6785	18.2	26.0	44.9	42.8	42.9	29.0
HD 196310A	6760	17.6	32.1	49.9	51.8	46.9	37.8
HD 16232B	6440	...	...	...	39.7	34.9	29.8
HD 216582B	6390	16.7	...	33.7	33.4	33.3	27.2

h. Boesgaard and Tripicco Field Stars

Name	T(K)	6587	7100	7111	7113	7115	7117	7119
HR 8977	6660	46.6	24.7	39.0	53.3	58.4	51.6	36.1
HR 8907	6640	...	19.0	29.1	45.8	43.1	47.2	29.2
HR 7697	6635	...	21.7	26.3	52.7	46.9	45.2	33.4
HR 8222	6600	...	20.1	29.9	52.7	50.7	46.9	35.0
HR 7936	6590	...	16.9	36.1	55.8	40.4	52.5	30.6
HR 7756	6570	...	17.7	26.7	43.5	41.7	41.2	30.4
HR 8805	6550	...	15.2	21.5	37.0	37.1	34.1	26.5
HR 8205	6525	...	21.6	37.6	48.0	45.3	46.8	30.9
HR 7925	6475	...	15.9	...	43.3	40.6	37.3	28.8
HR 8885	6475	30.9	17.9	18.4	44.8	46.0	37.4	32.6
HR 7496	6470	...	20.9	32.5	46.6	48.3	45.1	33.1

i. Sun

Name	T(K)	6587	7100	7111	7113	7115	7117	7119
Sun	5770	13.1	13.0	11.5	17.9	22.4	13.6	15.1

TABLE 3

MEAN CARBON ABUNDANCES

a. Hyades

VB	T_{eff}	$v \sin i$	<C/H>	σ	[<C/H>]	σ	N lines	[C/Fe]	σ
11	6850	25	1.517	0.604	+0.18	0.23	6	+0.07	0.24
13	6725	18	1.362	0.422	+0.13	0.14	5	−0.04	0.18
14	7040	6	0.823	0.315	−0.09	0.19	7	−0.16	0.23
19	6300	12	1.211	0.393	+0.08	0.17	6	−0.09	0.20
37	6815	12	1.063	0.357	+0.03	0.17	7	−0.14	0.21
48	6245	12	1.141	0.360	+0.06	0.16	6	−0.06	0.17
57	6370	15	1.143	0.440	+0.06	0.23	6	−0.05	0.24
61	6260	18	0.956	0.256	−0.02	0.12	4	−0.13	0.14
62	6185	6	1.342	0.459	+0.13	0.15	6	−0.03	0.17
78	6510	20	1.017	0.486	+0.01	0.26	5	−0.12	0.28
81	6470	18	0.964	0.369	−0.02	0.20	5	−0.14	0.22
86	6485	20	1.107	0.567	+0.04	0.21	5	−0.09	0.23
121	6340	12	1.342	0.390	+0.13	0.16	6	−0.01	0.19
Weighted means:			1.100	±0.196	+0.04	±0.07		−0.08	±0.06

b. The Pleiades

HII	T_{eff}	$v \sin i$	<C/H>	σ	[<C/H>]	σ	N lines	[C/Fe]	σ
233	6485	<20	1.015	0.275	+0.01	0.13	6	+0.13	0.17
470	6845	<40	0.845	0.140	−0.07	0.07	5	−0.15	0.11
530	6770	<12	0.649	0.285	−0.19	0.21	6	−0.08	0.23
627	6335	25	0.930	0.228	−0.03	0.12	4	+0.03	0.13
739	5870	<12	0.922	0.128	−0.03	0.10	5	−0.01	0.14
948	5960	12	0.594	...	−0.22	...	1	−0.23	...
1122	6610	28	0.755	0.272	−0.12	0.18	4	−0.20	0.21
1200	6470	<20	0.773	0.229	−0.11	0.13	6	−0.04	0.18
1613	6250	18	0.989	0.326	−0.01	0.14	5	+0.04	0.16
1726	6365	<12	0.892	0.245	−0.05	0.12	7	−0.02	0.16
1766	6730	20	0.889	0.381	−0.05	0.23	7	−0.03	0.25
1856	6155	12	0.944	0.276	−0.03	0.13	4	−0.05	0.17
Weighted means:			0.864	±0.127	−0.06	±0.07		−0.05	±0.10

c. α Persei

He	T_{eff}	$v \sin i$	<C/H>	σ	[<C/H>]	σ	N lines	[C/Fe]	σ
135	6710	<20	0.676	0.320	−0.17	0.25	6	−0.16	0.27
490	6805	<20	0.835	0.302	−0.08	0.15	5	+0.04	0.18
635	7285	<20	0.596	0.174	−0.23	0.12	5	−0.18	0.14
799	6705	20	0.481	0.320	−0.32	0.25	6	−0.23	0.29
1225N	6415	20	0.973	0.541	−0.01	0.27	5	−0.08	0.29
1225S	6415	<20	0.938	0.278	−0.03	0.13	5	+0.11	0.16
Weighted Means:[a]			0.632	±0.130	−0.20	±0.09		−0.12	±0.10

[a] Omitting 1225N, S from mean.

between the average abundances for all stars in either of these studies.

IV. RESULTS AND DISCUSSION

Mean values of [C/H] and [C/Fe] have been determined for each cluster and group. In the case of the moving groups, we have examined a variety of indicators including Li, activity, and [Fe/H] abundances, as well as kinematics, in an attempt to distinguish likely members from field stars. A discussion of our choices for membership is given in Paper I. The mean carbon abundances given here assume the same memberships.

Table 3 gives these weighted mean abundances and the rms deviations about each cluster and group mean. The observed dispersions about the mean [C/H] and [C/Fe] for the clusters and groups are consistent with those expected from observational error alone. As a result, we can place a limit of well less than 0.08 dex on the intrinsic dispersion in carbon abundances for stars within these clusters.

TABLE 3—*Continued*

d. Hyades Moving Group

Name	T_{eff}	$v \sin i$	<C/H>	σ	[<C/H>]	σ	N lines	[C/Fe]	σ
HR 88	5785	7	1.844	0.450	+0.26	0.12	4	+0.06	0.15
HR 410	6385	32	1.580	0.591	+0.20	0.18	6	+0.04	0.19
HR 878	6620	20	1.321	0.532	+0.12	0.18	5	+0.05	0.21
HD 197039	6510	...	1.406	0.634	+0.15	0.22	6	−0.00	0.24
HR 8548	6170	7	1.013	0.341	+0.01	0.17	5	+0.05	0.18
HR 8772	5965	...	0.694	0.198	−0.16	0.12	6	−0.06	0.17
HR 8788	6500	...	1.686	0.651	+0.23	0.19	5	−0.02	0.20
HR 8792	6150	7	1.079	0.312	+0.03	0.13	5	−0.06	0.14
Weighted Means:[b]			1.576	±0.236	+0.20	±0.07		+0.05	±0.03

[b] Using *bona fide* members HR 88, 878, and HD 197039 only.

e. UMa Moving Group

Name	T_{eff}	$v \sin i$	<C/H>	σ	[<C/H>]	σ	N lines	[C/Fe]	σ
HR 235	6200	0	0.662	0.210	−0.18	0.14	6	−0.05	0.15
HD 11131B	5820	...	0.770	0.138	−0.11	0.09	6	−0.05	0.12
HR 534	7100	...	0.362	0.145	−0.44	0.17	6	−0.12	0.21
HR 647	6500	<26	0.618	0.281	−0.21	0.24	5	+0.05	0.26
HR 5634	6600	45	0.785	0.242	−0.11	0.14	5	−0.21	0.20
HD 151044	6130	...	0.885	0.292	−0.05	0.14	5	−0.04	0.15
HR 2047	5900	6	1.295	...	+0.11	...	1	+0.16	...
HR 7061	6370	14	0.805	0.326	−0.09	0.18	5	−0.01	0.19
HR 7172	6115	26	0.777	0.239	−0.11	0.13	5	−0.06	0.16
HR 7451	6240	6	0.700	0.222	−0.16	0.15	5	−0.03	0.16
HR 8170	6125	12	0.782	0.206	−0.11	0.13	5	+0.02	0.15
Weighted Means:[c]			0.759	±0.067	−0.12	±0.04		−0.03	±0.03

[c] Omitting HR 534, 647, 5634, and 2047 from mean.

f. Wolf 630 Group

Name	T_{eff}	$v \sin i$	<C/H>	σ	[<C/H>]	σ	N lines	[C/Fe]	σ
HR 7947	6330	<25	1.384	0.422	+0.14	0.14	6	+0.02	0.16
HR 8077	6130	<6	0.978	0.337	−0.01	0.16	4	+0.04	0.17
HD 6479	6700	...	0.660	0.277	−0.18	0.18	4	+0.01	0.21
HD 6480	6265	...	0.639	0.198	−0.20	0.14	5	+0.00	0.16
Weighted means:			[d]0.708	±0.163	−0.15	±0.08		+0.02	±0.02

[d] The values listed on this line exclude HR 7947.

g. Stars of Known Age

Name	T_{eff}	$v \sin i$	<C/H>	σ	[<C/H>]	σ	N lines	[C/Fe]	σ
HD 16232	6440	30	1.179	0.325	+0.07	0.11	3	−0.20	0.24
HD 196310	6760	...	1.210	0.324	+0.08	0.11	6	+0.27	0.15
HD 206751	6785	...	0.579	0.221	−0.24	0.17	6	−0.06	0.18
HD 216582	6390	...	0.792	0.260	−0.10	0.14	5	−0.03	0.16

TABLE 3—*Continued*

h. BT Field Stars

Name	T_{eff}	$v \sin i$	<C/H>	σ	[<C/H>]	σ	N lines	[C/Fe]	σ
HR 7496	6470	21	0.957	0.327	−0.02	0.16	6	−0.04	0.18
HR 7697	6635	<10	0.892	0.353	−0.05	0.17	6	−0.07	0.19
HR 7756	6570	<10	0.807	0.295	−0.09	0.16	6	−0.04	0.17
HR 7925	6475	30	0.914	0.366	−0.04	0.20	5	−0.01	0.21
HR 7936	6590	37	1.054	0.588	+0.02	0.27	6	+0.13	0.29
HR 8205	6525	12	1.171	0.477	+0.07	0.19	6	−0.01	0.23
HR 8222	6600	15	0.674	0.257	−0.17	0.18	6	−0.03	0.19
HR 8805	6550	9	0.656	0.215	−0.18	0.15	6	−0.02	0.17
HR 8885	6475	12	0.832	0.274	−0.08	0.16	7	−0.03	0.20
HR 8907	6640	0	0.827	0.375	−0.08	0.19	6	−0.01	0.21
HR 8977	6660	30	1.174	0.395	+0.07	0.17	7	−0.02	0.19

Table 4 summarizes the mean [C/H] and [C/Fe] values for the clusters and groups, as well as the field stars. Because the accuracy of the final means is heavily influenced by the small number of stars in each group, Table 4 gives the error in the mean rather than the observed rms deviation about the mean as a way of judging the significance of the results. The data of Table 4 show that [C/Fe] = 0.0 to within the observational errors and the observed dispersions for all groups. Figure 3, a plot of [C/Fe] versus [Fe/H], illustrates this uniformity of the carbon-to-iron ratio for the sample. The mean of these 7 points (the three clusters, the three moving groups and the field star sample) gives $\langle[\mathrm{C/Fe}]\rangle = -0.03 \pm 0.05$.

This uniformity of [C/Fe] with [Fe/H] at these abundances has been found in other studies that sampled a much larger range in [Fe/H] (CLT; Laird 1985; Carbon *et al.* 1987), CLT analyzed the same set of C I lines as used here in a sample of 20 F and G main-sequence stars and found their abundances were consistent with solar [C/Fe] over a range of $-0.9 < [\mathrm{Fe/H}] < +0.4$ with an observed dispersion in [C/Fe] of ≤ 0.2 dex. Considering their observational errors were of comparable magnitude, they concluded that the intrinsic dispersion in their sample was ≤ 0.1 dex. Laird (1985) and Carbon *et al.* (1987) used spectrum synthesis techniques to obtain carbon abundances from the CH bands in dwarfs sampling a large range of iron abundance. Their combined results presented in Carbon *et al.* indicate that [C/Fe] = 0 over the range $-2.0 < [\mathrm{Fe/H}] < +0.4$ with an observed scatter slightly larger than the estimated observational errors. Their data also indicate an upper limit to the intrinsic dispersion of about 0.1 dex, calculated from an observed dispersion of 0.18 dex and an observational error of 0.15 dex.

The *observed* dispersion for our sample is roughly half that found in these other studies, and, although our sample covers a much more limited range in metallicity, with $-0.20 < [\mathrm{Fe/H}] < +0.15$, our results indicate that the *intrinsic* dispersion in [C/Fe] is appreciably smaller than the previous upper limits of 0.1 dex. The mean of all 69 stars in our sample, regardless of group or cluster membership is $\langle[\mathrm{C/Fe}]\rangle = -0.04 \pm 0.09$ (rms). Because the observed dispersion is so similar to the expected observational error, any estimate of the intrinsic dispersion in this sample rests crucially on our estimate of the error. A comparison of the observed and expected dispersion, taken at face value, suggests that the intrinsic dispersion in [C/Fe] among all these stars is less than 0.04 dex.

Figures 4*a* and *b* show plots of [C/H] and [C/Fe], respectively, as a function of age for both the clusters and moving

TABLE 4

ABUNDANCE AND AGE DATA FOR CLUSTERS AND GROUPS

Cluster	$\overline{[\mathrm{C/H}]}$	m. e.	$\overline{[\mathrm{C/Fe}]}$	m. e.	$\overline{[\mathrm{Fe/H}]}$	m. e.	n	Age (yr)
α Per	−0.20	±0.08	−0.12	±0.10	−0.057	±0.051	4	5×10^7
Pleiades	−0.06	±0.04	−0.05	±0.05	−0.034	±0.024	12	7×10^7
UMa Group	−0.12	±0.05	−0.03	±0.06	−0.085	±0.021	7	3×10^8
Hyades	+0.04	±0.04	−0.08	±0.06	+0.127	±0.022	13	6.7×10^8
Hyades Group	+0.20	±0.09	+0.05	±0.11	+0.134	±0.052	3	6.7×10^8
Wolf 630 Group	−0.15	±0.09	+0.02	±0.10	−0.137	±0.041	3	1.4×10^9
Known Age[a]	...	...	+0.08	±0.09	−0.154	±0.042	3	1.4×10^9
BT Stars	...	...	−0.02	±0.06	−0.063	±0.025	11	1.9×10^9
Field Stars[b]	...	...	+0.01	±0.05	−0.093	±0.021	14	1.8×10^9

[a] Means exclude HD 16232 because of especially uncertain [Fe/H] value. Age is a mean of individual determinations.

[b] Means include both Known Age and BT field stars. Age given is a mean of individual determinations.

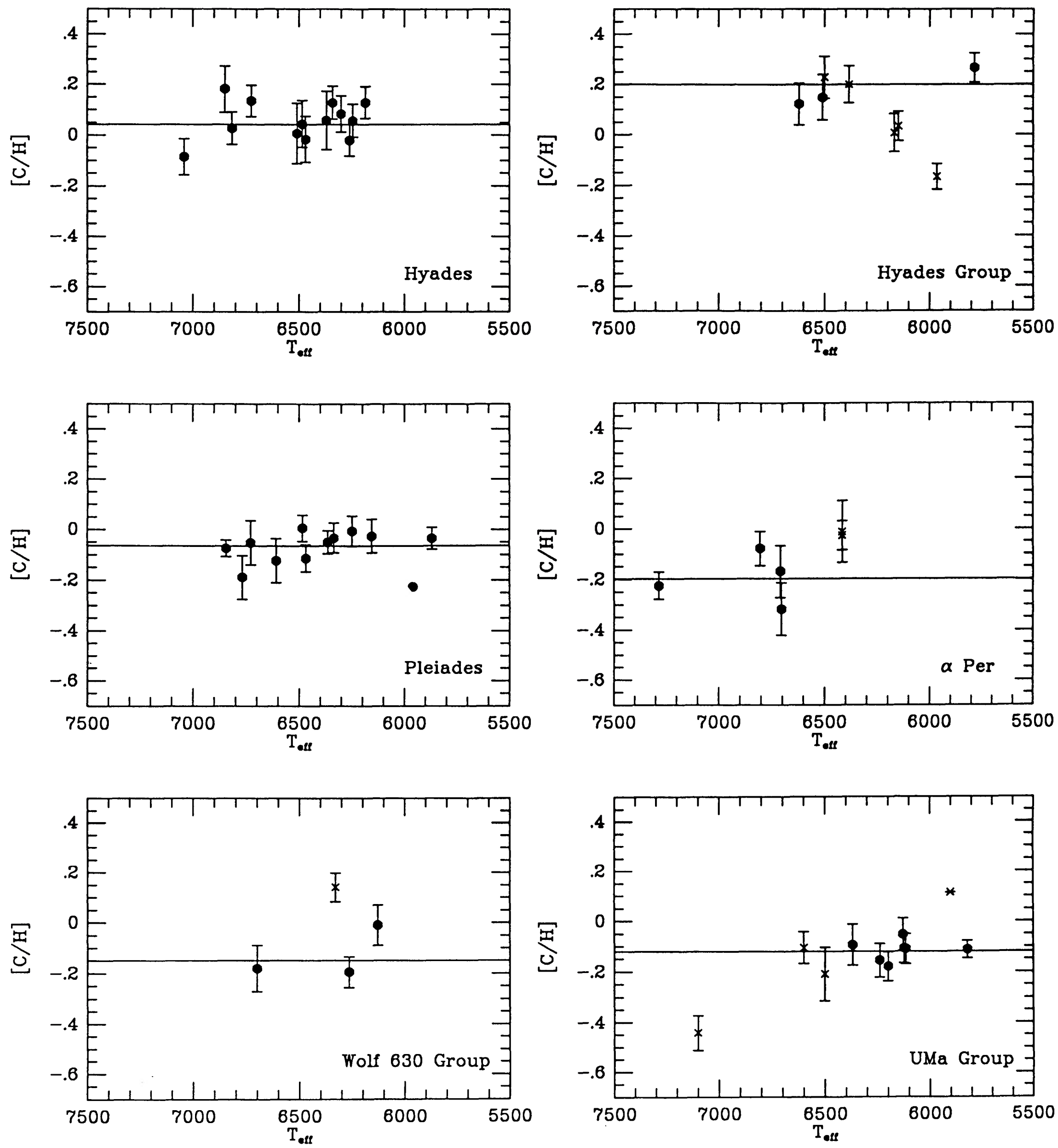

FIG. 2.—Plots of [C/H] against T_{eff} for stars in our sample. Stars judged to be members are indicated by filled circles; those thought to be nonmembers are indicated by crosses. Error bars give the standard error in the mean for each star. Horizontal lines reflect the weighted mean [C/H] abundance for each group. (*a*) For stars from the Hyades; (*b*) for stars from the Pleiades; (*c*) for stars from α Per; (*d*) for stars from the Hyades moving group; (*e*) for stars from the UMa moving group; (*f*) for stars from the Wolf 630 moving group.

groups, and the field stars averaged to one age. Although the global means of [C/H] are not as well determined as those for [Fe/H] as shown in Figure 5 of Paper I, the [C/H] mean values show the same trend of cluster-to-cluster differences at similar ages with no global trends of [C/H] with age. Conversely, the [C/Fe] values show much greater uniformity over all ages sampled.

Consistent with the conclusions of Paper I, the evidence from the carbon abundances, [C/H], indicates that the Galactic disk is unmixed on time scales on the order of at least the age of the Hyades. The uniformity and small intrinsic dispersion of [C/Fe] ratios further indicate that the production of carbon in the disk has kept close pace with the production of iron over a similar time scale.

These facts can be, and have been, explained by a variety of models for galactic nucleosynthesis, as long as carbon and iron are produced in stars of the same mass range and on roughly similar time scales. We do not intend to make a critique of the models here for, in spite of much activity, there remain numerous uncertainties.

Arnett (1978) has presented a successful, standard model in which present-day observed abundances were produced by the nucleosynthesis of all heavy elements in massive stars alone. Work has since developed to recognize the possibility of different IMFs contributing to the halo and disk evolution (Twarog and Wheeler 1982), variable IMFs and yields through the contribution from supermassive stars to the oxygen abundance (Chiosi and Matteucci 1983), the contribution from intermediate mass stars (1–8 $M_{\odot}$) through both stellar winds and planetary nebulae and the C-deflagration of single stars as Type Ib

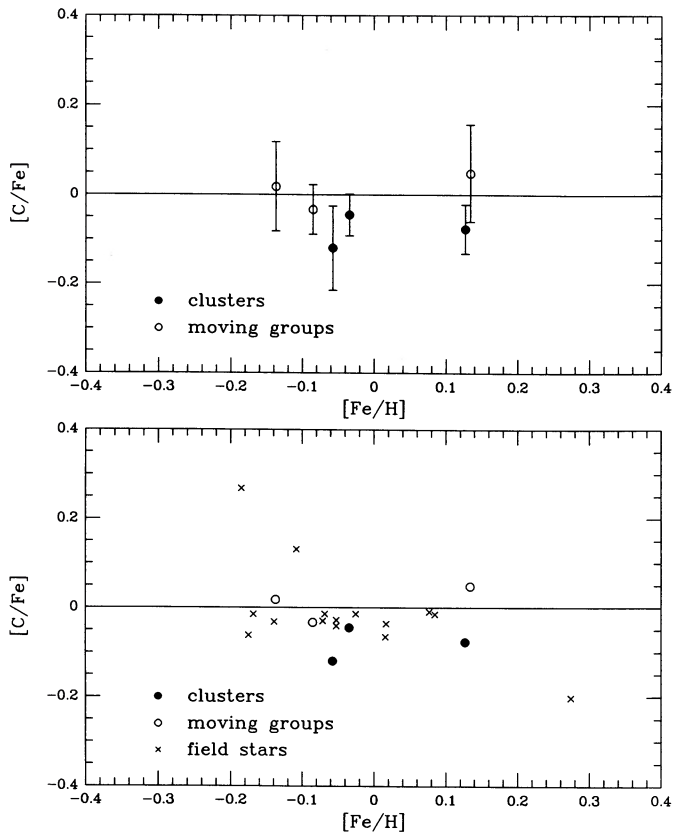

FIG. 3.—Plots showing the distribution of [C/Fe] vs. [Fe/H]. (*a*) Mean points for clusters (*filled circles*), moving groups (*open circles*) with error bars showing the error in the mean. (*b*) As in (*a*) but with individual points for the field stars (*crosses*).

supernovae (Iben and Truran 1978; Renzini and Voli 1981; Matteucci and Tornambé 1985), and, finally, the role of binary star models for Type I supernovae (Matteucci and Greggio 1986). Model results for C and Fe in intermediate mass stars in particular are sensitive to the subtleties of the mass-loss rate, the dependence of parameters on metallicity, the effect of uncertainties in the $^{12}C(\alpha, \gamma)^{16}O$ rate, the structure of the convective envelope, and the extent of hot-bottom burning.

In many cases, the data of CLT have served as the observational constraint for the models. Our data on [C/Fe] for the clusters cover a much larger sample of the young disk and thus are more limited in metallicity range, but are entirely consistent with the CLT data. In addition, the improved limit to the dispersion in [C/Fe] about the solar value for our sample offers some further constraint on the variability of sites of production of C and Fe, and suggests that over the metallicity range within 1.5 times solar and the last 1 billion years, the integrated histories of C and Fe production continue to have been very similar, even for the youngest component of the disk.

Clusters of similar age may have values of [C/H] and [Fe/H] which differ significantly, but still have very similar values of [C/Fe]. These global averaged abundances show that although position in the Galactic disk at the time of formation may be the dominant factor in determining absolute cluster abundances over the ages up to roughly 1 billion years, the ratio of C/Fe abundances has been remarkably constant over the variety of formation sites sampled here.

There are important advantages to using clusters, rather than field stars, to follow the chemical evolution of the Galactic disk by tracing the relationship of elemental abundances with age. Studies of field stars rely on age-metallicity relationships to investigate trends of abundance with time revealed in metal-poor, assumed old, stars. By looking at clusters, which have independently, well-determined ages, we can study abundances patterns with age and position directly and in much more detail. In addition, global averages over many stars in a cluster allow the mean abundances to be of higher precision than those of single field stars. We plan to extend our results, perhaps to reveal a decoupling of C and Fe which could tell us about the possible different sources of these elements, by continuing our observations with older and more metal-poor clusters.

Studies of field stars which have been used to constrain theories of stellar nucleosynthesis and galactic chemical evolution have relied on age-metallicity relationships to investigate the trends of abundances with time revealed by metal-poor stars. By continuing to study galactic open clusters whose ages can be independently dated, we hope to extend our results to older, and to more metal-poor clusters. Enlarging the range of ages and metallicities over those studied here will provide us with more direct evidence for the time dependence of chemical evolution in the Galactic disk.

We are grateful to Monique Spite for her model atmosphere program, RAI10, and to Kent Budge and Deborah Padgett for

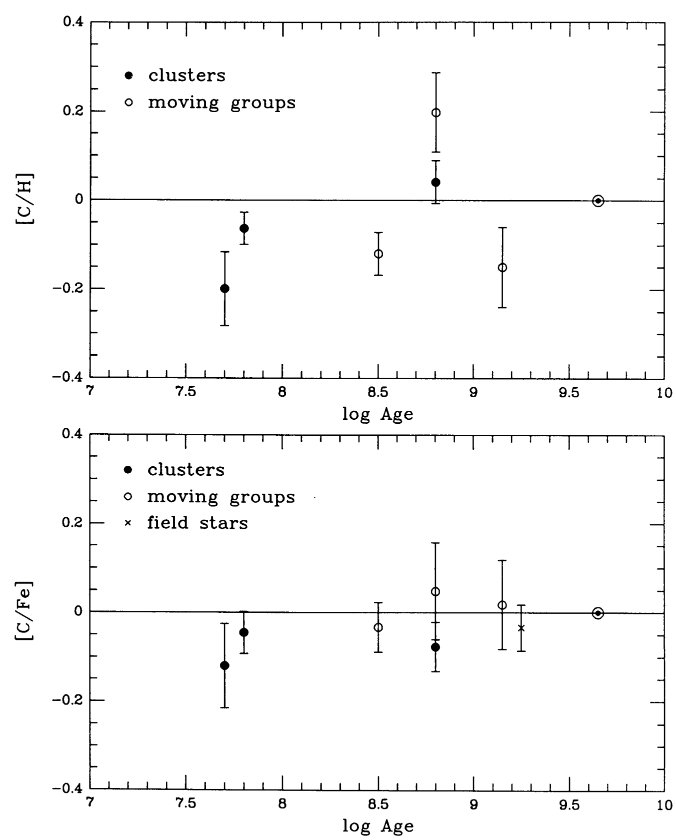

FIG. 4.—Distribution of (*a*) [C/H] and (*b*) [C/Fe] vs. log age for the clusters (*filled circles*), moving groups (*open circles*), and, in (*b*) the field stars binned into a single age group (*cross*). The error bars give the error in the mean cluster or group abundance. The solar value is also indicated at an age of 4.5 billion years.

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