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CHEMICAL COMPOSITION OF OPEN CLUSTERS. III. IRON AND CARBON IN F DWARFS IN COMA, PRAESEPE, AND M67

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ABSTRACT

We have determined iron and carbon abundances for F dwarfs in several open clusters and the field to continue our investigations on the homogeneity of chemical mixing in the Galactic disk. These new data on stars in Coma, Praesepe, M67, and the field complement our previous sample of clusters and moving groups and extend the sample coverage in metallicity and age.

The data are high resolution, high signal-to-noise Reticon observations made with the Canada-France-Hawaii Telescope coudé. Abundances are based on measurements of eight Fe I lines and six high excitation C I lines in the spectral region $\lambda\lambda 7065$–7155 analyzed with model atmospheres. Our results for these new clusters are consistent with the conclusions drawn from our previous sample. Intrinsic dispersions in [Fe/H] and [C/H] in each cluster are consistent with observational error alone, and are extremely small. The [C/Fe] ratio for all clusters is solar to within observational error over the metallicity range $[\mathrm{Fe/H}] \geq -0.50$, and has an intrinsic dispersion of much less than 0.1 dex. Cluster mean values of [Fe/H] and [C/H] show cluster-to-cluster variations well in excess of observational errors, indicating both that the overall metal content of the gas from which these clusters formed preserved small, but significant differences over periods of several billion years, and that the production of carbon closely followed that of iron so that these regions of star formation had the same ratio of C/Fe. The mean value of [C/Fe] for the 84 stars in our three papers with values of $[\mathrm{Fe/H}] > -0.2$ is -0.031 ± 0.009 (error in the mean). Five metal-poor stars which have $-1.3 < [\mathrm{Fe/H}] < -0.5$ have $\langle[\mathrm{C/Fe}]\rangle = +0.140 \pm 0.044$ (error in the mean), indicating, in the absence of systematic errors in adopted parameters, that these stars of intermediate metallicity have slightly enhanced values of [C/Fe], as predicted by some models of Galactic chemical evolution.

Subject headings: open clusters and associations: general — stars: abundances

1. INTRODUCTION

Among the elements of importance for our understanding of the chemical evolution of the Galaxy, iron, carbon, and oxygen play principal roles. Iron is important as the general indicator of chemical enrichment and evolution, and, at least for field stars of the solar neighborhood, appears generally correlated with stellar age (Twarog 1980; Carlberg et al. 1985). Carbon and oxygen are abundant elements, and, as the result of alpha processing, are produced in stars of differenct characteristic masses. Carbon and iron, on the other hand, are thought to be produced in almost the same percentages by the same stellar mass ranges (Matteucci 1989). The abundance ratios of these elements in stars of different ages provide information on the relative rates and time scales of chemical enrichment by stars of different mass ranges. The observed dispersion in abundance ratios also provides some indication of the extent and time-scales of chemical enrichment by stars of different mass ranges. The observed dispersion in abundance ratios also provides some indication of the extent and time scale for mixing in the Galactic disk.

High-resolution spectroscopy at high signal-to-noise ratios of unevolved stars in open clusters yields abundance determinations of high precision essential to discussions of the chemical evolution of the Galaxy. As was shown by Cayrel, Cayrel de Strobel, & Campbell (1985) for the Hyades and Boesgaard (1989) for four clusters, [Fe/H] abundances in clusters can be found to a precision of ± 0.03–0.05 dex. We have been pursuing a program of the determination of Fe, C, and O abundances in main-sequence stars in nearby open clusters to further clarify these issues. Data on abundance ratios in cluster stars are an important complement to survey results for field stars because the ages of the clusters are known with relative certainty. Results on Fe and C abundances for the Hyades, Pleiades, and α Per clusters, the Hyades, UMa, and Wolf 630 moving groups, and bright field F dwarfs have been published in Boesgaard & Friel (1990) and Friel & Boesgaard (1990, hereafter Papers I and II). We concluded that these clusters and groups shown no strong age-metallicity relationship, for either Fe or C, in stars with ages up to 1 billion yr and that clusters of a given age show a modest range in [Fe/H] value over that expected from observational errors. We found, in agreement with other studies, that the (C/H) ratios closely follow (Fe/H) in stars of all ages and metallicities in our sample.

This paper extends these results by presenting new data on both Fe and C abundances for unevolved or only slightly evolved dwarfs in the clusters Coma, Praesepe, and M67, and for additional bright, slightly metal-deficient field stars. The primary goal of these new observations was the determination

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of [Fe/H] and [C/H] for stars in the 5 billion yr old cluster M67. Unfortunately, poor weather prevented us from obtaining high-quality spectra of the faint M67 stars, and our conclusions based on the few stars we could observe are limited.

2. OBSERVATIONS

The data were obtained at the Canada-France-Hawaii Telescope on the nights of 1989 March 15–17, using the Reticon at the coudé spectrograph with the f/8.2 camera and red optics. The observational setup was identical to that used for our previous data set (Papers I and II) with the exception of the use of a slightly lower resolution provided by the 600 l/mm grating, in an effort to reach the fainter M67 stars more efficiently. This arrangement provided a sampling of 0.1 Å pixel^{-1} over the spectral range $\lambda\lambda$7015–7205, at a spectral resolution of 0.25 Å.

Although much of the run was cloudy and the seeing quite poor, for the bright field stars and Coma dwarfs, we obtained spectra with typical S/N ratios of 200–500. The spectra of the fainter Praesepe stars have S/N ratios of 100–200, and the combination of the multiple M67 spectra 30–85.

As in our previous CFH runs, a series of flat fields was obtained at several exposure levels chosen to match those of the program stars, and comparison lamps were taken each night to establish the wavelength scale. We also obtained, periodically through each night, spectra of rapidly rotating B stars to monitor the presence of atmospheric water vapor lines in our program stars. Although there are strong water vapor lines at λ7170, longward of our region, there was no sign of any contaminating lines in the regions of the spectrum containing the carbon and iron lines used for abundance determinations.

The identification and basic observational data for the stars observed in each of the clusters and the field are given in Table 1, along with derived quantities such as the effective temperature and surface gravities. Figure 1 shows a sample of the observed spectra.

The data reduction was carried out with IRAF, and included flat fielding, wavelength linearization and continuum fitting. For the low S/N spectra of M67 stars, the fitting of the continuum level is difficult, and introduces added uncertainty into our measurements.

Eight Fe I lines through the range $\lambda\lambda$6078–7155 and six C I lines from $\lambda\lambda$7100–7120 were measured for abundance determination. From repeated measurements of the same spectrum we judge our measurement errors to be less than 1 mÅ. For several stars we obtained two spectra, and line measurements from these indicate an observational uncertainty in the equiva-

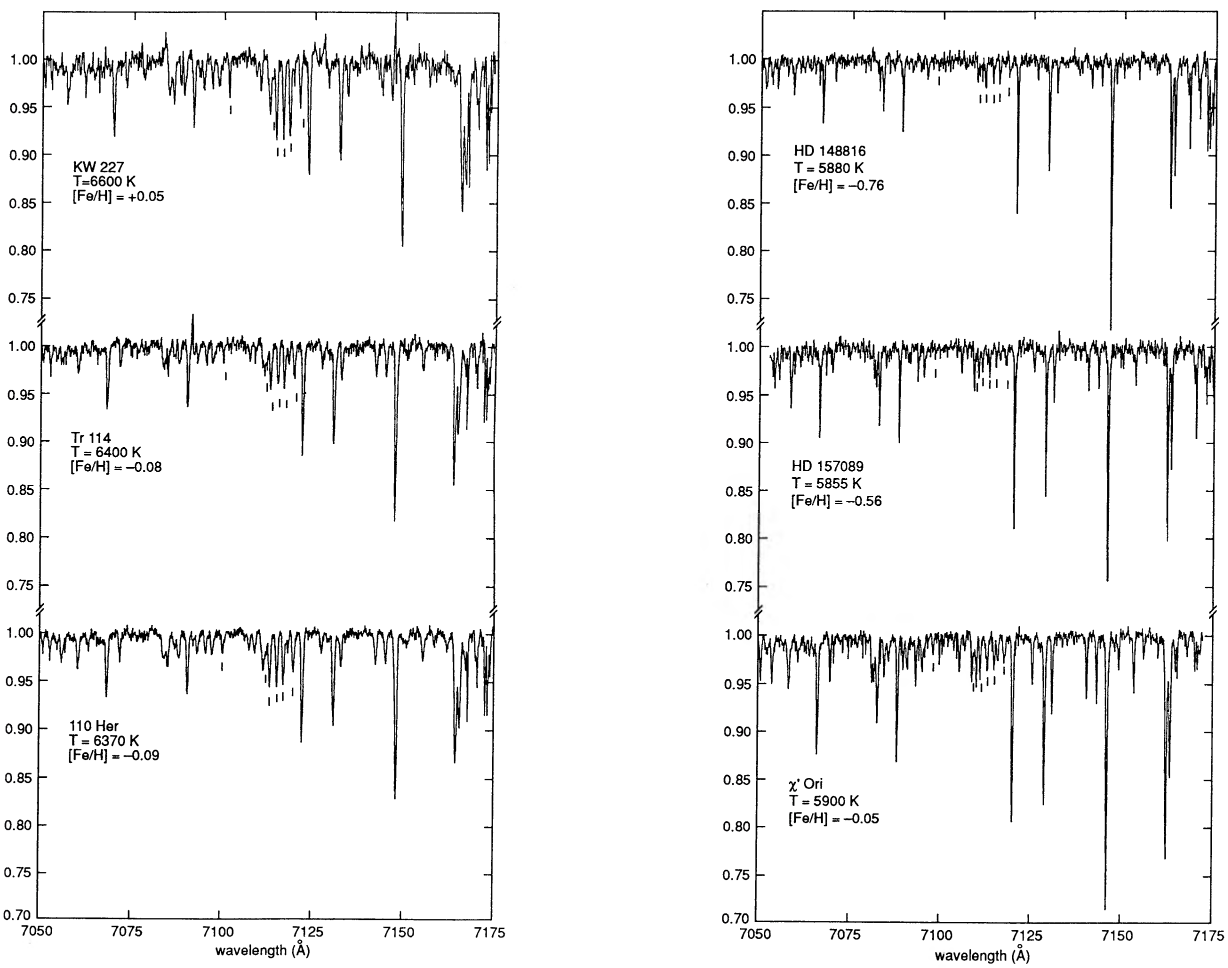

FIG. 1*a* FIG. 1*b*

FIG. 1.—Sample spectra showing the C lines near 7710. (*a*) Cluster stars from Praesepe, Coma, and UMa. (*b*) Stars of similar temperatures, but a range of metallicities.

lent widths of less than 2 mÅ for most objects which increases to 3 mÅ in spectra with S/N < 200.

Measurements of equivalent widths, in mÅ, are given in Table 2 for the eight Fe I lines and the six C I lines in all stars. For stars with more than one observation, the spectra were measured individually but the entries in Table 2 are mean values of equivalent width, weighted by the S/N ratios when the two spectra differed significantly in S/N. We obtained spectra of four stars in M67, all of which were observed more than once, in exposures limited to less than 60 minutes to minimize the contamination by cosmic rays. Individual spectra of M67 stars were added before measurement of equivalent

TABLE 1

STARS OBSERVED

A. COMA

Tr	V	$B-V$	Spectral Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	(S/N
19	8.12	0.397	F5 V	6730	4.32	<12	350
53	8.73	0.525	F8 V	6165	4.29	<12	160
58	8.83	0.510	G0 V	6200	4.29	12	160
65	9.02	0.566	G0 V	5985	4.34	...	150
76	9.10	0.547	G0 V	6060	4.26	...	230, 150
85	9.34	0.589	G0 V	5960	4.20	<12	250
86	8.55	0.463	F6 V	6425	4.38	15	340
90	8.56	0.461	F5 V	6350	4.21	<12	350
92	8.61	0.535	F6 V	6210	4.27	15	230
97	9.12	0.540	F9 V	6095	4.37	...	210, 150
101	8.42	0.443	F5 V	6535	4.39	20	320
114	8.60	0.453	F8 V	6400	4.29	<12	350
118	8.37	0.449	F6 V	6495	4.26	<12	370
162	8.61	0.475	G0 V	6345	4.27	12	360

B. PRAESEPE

KW	V	$B-V$	Spectral Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	S/N
227	9.49	0.414	F5	6600	4.17	15	190
268	9.90	0.473	F6 IV	6400	4.23	20	135
341	10.31	0.521	F8 V	6195	4.14	<20	100
371	10.11	0.505	F8 V	6210	3.98	...	60
416	9.59	0.412	F5 V	6760	4.28	...	170
439	9.42	0.392	F7	6730	4.28	15	170

C. M67

Name	V	$B-V$	Spectral Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	S/N
F124	12.12	0.46	...	6515	...	...	20, 20, 15
F131	11.22	0.40	...	6790	4.12	...	55, 50, 40
F156	11.00	0.11	...	...	...	...	45, 20
I-27	11.32	0.30	...	7300	3.97:	...	35, 30

D. UMa MOVING GROUP

Name	V	$B-V$	Spectral Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	S/N
HR 2047	4.41	0.59	G0 V	5900	4.21	6	480, 480
HD 151044	6.60	0.48	F8 V	6130	4.3:	...	350
HR 7061	4.19	0.46	F6 V	6370	3.89	14	450

E. FIELD STARS

Name	V	$B-V$	Spectral Type	T_{eff} (K)	log g	$v \sin i$ (km s^{-1})	S/N
HR 1673	5.12	0.44	F5 V	6400	3.95	0	520, 450
HR 1729	4.71	0.63	G2 IV–V	5845	4.22	2	270, 450
HR 5447	4.46	0.36	F2 V	6745	4.22	3	460
HR 5533	5.74	0.48	F5 V	6405	4.00	20	470
HR 5758	6.57	0.37	F4 V	6800	4.29	23	450
HR 5933	3.85	0.48	F6 V	6300	4.11	8	450
HR 6189	6.35	0.48	F3 V	6105	3.93	<15	450
HD 148816	7.28	0.54	G2	5880	4.0:	...	270, 220
HD 157089	7.03	0.60	G2	5855	4.0:	...	300, 300
HD 160693	8.41	0.60	G2	5690	4.0:	...	320
HD 194598	8.40	0.49	...	5895	4.0:	...	200

widths, in a sum weighted by the S/N of the spectra. No equivalent widths were measured for the M67 star F156 because its high temperature resulted in Fe lines too weak to detect in the low S/N spectra.

3. ANALYSIS

We require accurate effective temperatures and surface gravities to determine abundances from the line strengths of Table 2. As in our previous papers, temperatures for stars in our sample are based primarily on the calibrations of Strömgren and *UBV* photometry derived by Saxner & Hammärback (1985), supplemented by the calibration from $B-V$ by Böhm-Vitense (1981). Temperatures for most of the sample in Coma are derived by Boesgaard (1987), which also gives references for photometry in the cluster. Parameters for previously observed stars in Praesepe are discussed in Boesgaard & Budge (1988). For the remaining stars in our sample, temperatures based on the Saxner & Hammärback (1985) and Böhm-Vitense (1981)

TABLE 2

Fe I and C I Equivalent widths in mÅ

A. Coma

Tr	*T* (K)	7068	7072	7107	7128	7131	7133	7143	7156	7100	7111	7113	7115	7117	7119
19	6730	35.2	15.2	...	12.7	65.0	21.8	20.3	17.7	...	33.1	41.6	37.6	38.5	29.4
53	6165	57.1	21.3	8.3	...	80.4	30.4	28.2	26.2	11.4	20.2	18.8	12.8	17.3	13.2
58	6200	56.1	20.4	14.9	18.4	87.3	35.2	33.7	17.3	12.2	11.0	19.8	24.2	22.6	18.5
65	5985	46.7	16.4	20.0	16.5	78.9	35.9	33.1	25.0	10.4	15.6	30.1	26.3	20.9	15.6
76	6060	64.0	24.1	20.3	20.8	88.7	40.3	26.1	34.4	12.0	18.0	25.7	25.3	18.8	21.9
85	5690	64.4	26.1	10.7	20.7	96.4	35.3	33.0	30.8	8.7	16.0	19.6	25.6	18.1	18.9
86	6425	48.7	...	12.2	15.7	67.0	25.6	24.9	19.2	9.8	24.0	30.8	34.1	30.3	22.2
90	6350	49.2	16.3	12.6	17.5	76.4	26.1	24.8	23.8	11.3	24.5	32.2	31.4	30.8	23.6
92	6210	54.5	22.1	...	18.6	65.8	29.9	21.8	16.5	...	11.5	27.6	21.1	17.1	16.9
97	6095	56.3	21.1	12.5	23.8	88.1	35.0	28.4	22.7	10.8	19.5	24.7	21.6	21.5	10.3
101	6535	49.8	18.8	8.9	11.9	64.5	21.8	23.7	20.0	5.7	26.3	27.6	29.7	28.9	15.5
114	6400	45.0	15.5	9.8	15.6	77.7	25.2	24.1	20.0	8.7	21.7	30.5	31.1	28.6	23.6
118	6495	50.0	19.1	11.2	18.3	71.9	24.8	29.3	23.4	10.6	31.0	34.9	34.5	28.3	25.4
162	6345	52.5	14.6	13.0	17.9	77.2	25.2	28.8	20.5	11.3	32.8	28.9	31.1	27.7	23.7

B. Praesepe

KW	*T* (K)	7068	7072	7107	7128	7131	7133	7143	7156	7100	7111	7113	7115	7117	7119
227	6600	56.9	16.3	10.3	18.4	74.3	24.0	24.4	17.5	18.4	47.0	57.9	60.4	54.5	31.5
268	6400	56.7	15.6	10.0	20.8	73.0	29.0	27.3	26.7	16.7	31.0	47.9	41.1	36.3	43.2
341	6195	62.0	26.6	11.1:	22.2	86.9	36.5	29.6	...	26.2	28.9:	41.2	37.3	...	32.7
371	6210	63.3	25.0	...	...	102.3[a]	31.8	...	21.5	...	...	23.8	26.2	...	27.3
416	6760	56.6	15.8	13.7	23.3	74.3	27.5	17.3	19.7	23.5	33.6	55.1	56.6	51.4	41.1
439	6730	41.6	14.3	6.6	16.5	67.5	28.5	18.3	...	24.8	39.0	58.6	57.5	61.4	43.6

C. M67

Name	*T* (K)	7068	7072	7107	7128	7131	7133	7143	7156	7100	7111	7113	7115	7117	7119
F124	6515	59.7	20.3	...	...	47.2	31.6	25.7	...	17.4	40.3	31.1	45.9	...	24.9
F131	6790	23.5	9.5	...	23.3	41.0	18.8	26.1	8.3	19.3	...	50.0	51.4	53.0	29.5
I-27	7300	...	...	...	9.5	40.1	14.9	17.4	...	...	...	...	...	...	...

D. UMa Moving Group

Name	*T* (K)	7068	7072	7107	7128	7131	7133	7143	7156	7100	7111	7113	7115	7117	7119
HR 2047	5900	67.5	22.3	18.7	24.5	95.5	37.2	33.5	30.5	8.9	10.8	20.4	19.0	18.9	18.2
HR 7061	6370	47.7	16.7	11.4	13.9	70.5	26.0	24.7	24.2	12.7	31.8	39.4	39.8	36.6	29.3
HD 151044	6130	60.3	20.6	15.2	20.3	84.4	34.6	27.4	27.5	11.5	15.5	30.8	25.3	24.1	22.8

E. Field Stars

Name	*T* (K)	7068	7072	7107	7128	7131	7133	7143	7156	7100	7111	7113	7115	7117	7119
HR 1673	6400	32.6	12.2	5.6	10.5	52.3	16.2	14.2	14.2	9.4	14.7	25.5	23.7	25.0	16.7
HR 1729	5845	82.1	28.4	26.4	30.4	104.8	46.3	37.9	42.9	12.8	15.6	31.6	26.8	24.7	16.3
HR 5447	6745	22.3	6.8	5.5	6.5	38.5	10.2	10.1	9.4	11.4	17.0	24.1	24.5	23.0	16.3
HR 5533	6405	55.6	18.1	13.3	15.9	78.0	31.3	26.7	20.4	16.8	...	42.6	41.7	39.2	32.4
HR 5758	6800	33.6	9.0	6.2	10.9	55.4	16.7	15.6	14.3	22.8	30.9	48.0	44.3	44.9	33.7
HR 5933	6300	46.4	14.4	9.8	15.1	66.0	12.9	20.6	16.7	12.4	18.8	26.3	26.6	24.6	19.3
HR 6189	6105	25.4	5.3	6.7	4.6	42.3	13.7	8.0	6.2	5.1	7.7	13.4	11.3	12.4	10.8
HD 148816	5880	25.9	7.7	6.3	7.6	44.9	9.7	11.0	8.2	2.8	5.9	13.2	8.3	9.6	6.8
HD 157089	5855	36.8	9.9	8.0	10.5	56.0	20.8	14.2	14.9	3.7	4.9	10.1	15.0	8.1	6.3
HD160693	5690	32.8	14.2	9.8	11.1	62.3	21.5	17.4	17.7	2.7	5.5	11.5	10.1	8.3	6.9
HD 194598	5895	...	...	...	...	24.0	3.8	...	...	...	2.5	3.4	2.1	1.9	3.2

[a] Not used in the abundance determination.

TABLE 3

NEWLY DETERMINED TEMPERATURES

Star	T(β)	T(b − y)	T(B − V)	T(adopted)
M67[1] –				
F124	...	6430	6560	6515
F131	...	6790	6785	6790
I-27[2]	...	7360:	7250	7305
Praesepe –				
KW268	6405	6395	6400	6400
KW341	6170	6200	6215	6195
KW371	6105	6255	6275	6210
KW439	6840	6660	6690	6730
Coma –				
Tr85[3]	5825	5965	5955	5960
Field Stars –				
HR 1673	6260	6430	6515	6400
HR 1729	5850	5880	5800	5845
HR 5447	6695	6720	6825	6745
HR 5533	6490	6350	6375	6405
HR 5758	6820	6815	6770	6800
HR 5933	6220	6310	6375	6300
HR 6189	6010	6165	6145	6105
HD 148816	5935	5870	5845	5880
HD 157089	6030	5840	5700	5855
HD 160693[4]	...	...	5660	5690
HD 194598[5]	...	5870	5900	5895

[1] *BV* Photometry generally a mean of Eggen & Sandage 1964 and of Racine 1971; $E(B-V) = 0.04$ adopted. *uvbyβ* Photometry generally a mean of Nissen et al. 1987 and Eggen 1981; $E(b-y) = 0.023$ adopted.

[2] Photometry for this star places it slightly outside the range of the Saxner & Hammärback (1985) calibration.

[3] Estimate from Hβ not included in the mean.

[4] Mean includes an estimate of $T_{\rm eff} = 5720$ from Magain calibration of $V-K$.

[5] Mean includes an estimate of $T_{\rm eff} = 5920$ from Magain calibration of $V-K$.

calibrations are presented in Table 3. Sources for the photometry for Coma and Praesepe stars are given in the papers mentioned above. For stars from M67, *UBV* photometry was taken from Eggen & Sandage (1964) and Racine (1971), and *uvby* Hβ photometry from Nissen, Twarog, & Crawford (1987) and Eggen (1981). Photometry for the field stars was taken from the catalogs of Nicolet (1978) and Hauck & Mermilliod (1980).

The field star sample now includes several stars more metal-poor than [Fe/H] = −0.5, and for them the effect of nonsolar metallicity on the temperature calibration of $B-V$ and $b-y$ must be considered. Magain (1987) has recently applied the calibration methods of Saxner & Hammärback (1985) to a sample of metal-poor stars having [Fe/H] < −1.0, and derived relations between effective temperature and the colors $B-V$, $b-y$, and $V-K$ valid for metal-poor stars. Only one of our field stars has a metallicity low enough ([Fe/H] ∼ −1.3) to require the Magain (1987) calibration; another four stars have metallicities just at the low edge of applicability of the Saxner & Hammärback (1985) calibration. For these four stars, we find good agreement between the effective temperature predicted by the Saxner & Hammärback (1985) and the Magain (1987) calibrations when the [Fe/H] dependence is explicitly included. Values in Table 3 for these stars use the Saxner & Hammärback (1985) calibration, unless noted. This calibration, and the derived temperatures, are good typically to ±50 K.

The surface gravities for these stars were also derived from Strömgren and Hβ photometry, following the procedure outlined in Paper II. For the modestly metal-poor stars in our sample, those with [Fe/H] < −0.5, we have assumed a value of $\log g = 4.0$. Iron abundances derived are insensitive to the surface gravity adopted, but the carbon abundances are affected by ∼ +0.1 dex for every 0.3 dex increase in $\log g$.

Abundances were derived using a grid of Kurucz (1979) model atmospheres incorporated in a program of M. Spite which computes line strengths as a function of abundance. Abundances for each of the Fe I and C I lines were computed at a $\log g = 4.5$ over the grid of $T_{\rm eff} = 7000$, 6500, and 6000 and microturbulence $\xi = 1.45$, 1.30, 1.10 km s^{-1}, respectively. Results for a solar model with $T_{\rm eff} = 5770$ K, $\log g = 4.4$, and $\xi = 1.14$ km s^{-1} were also calculated. The full set of models was not computed for a similar grid of $\log g$ values, but, as discussed in Paper II, sample lines were calculated over a range of $\log g$ to determine corrections to [C/H] as a function of $\log g$. These corrections were applied to the abundances determined from the full set of $\log g = 4.5$ models. Paper II provides more discussion on the method and the sensitivity of the results to $\log g$ values.

Iron and carbon abundances were computed for each of the eight lines of Fe I and the six lines of C I measured. The stellar abundances were ratioed to solar abundances determined from measurements of the same lines in solar spectra obtained in our previous CFHT observations (Papers I and II). The poor conditions during this run prevented us from obtaining high quality sky observations for comparison, and the lower resolution and lower S/N of the sky spectra we did obtain made it difficult to make secure measurements. The use of solar abundances from our previous work also ensures, as we will see later, that we are on the same system of abundances discussed in Papers I and II.

Mean abundances and standard deviations of both the ratios $(\mathrm{Fe/H})_*/(\mathrm{Fe/H})_\odot$ and $(\mathrm{C/H})_*/(\mathrm{C/H})_\odot$ and their logarithmic values are given for all stars in Tables 4A to 4E. Also listed are the number of lines used in forming the respective means, and the [C/Fe] ratio for each star. The standard deviation for the [C/Fe] ratios was calculated by adding, in quadrature, the σ-values for [Fe/H] and [C/H].

The standard deviation about these mean values for each star is typically 0.1 dex for [Fe/H] and 0.17 dex for [C/H]. Our estimated measurement errors of 2 mÅ should produce abundance errors of only 0.04 or 0.05 dex, and, except for the case of the low S/N M67 spectra, errors due to continuum fitting should be well less than 0.02 dex. A major source of the line-to-line scatter appears to be due to the dispersion in the solar values used to form the stellar to solar ratios. The dispersion in the solar abundance for the eight Fe I lines used here is 0.12 dex and for the six C I lines is 0.11 dex. We prefer to continue to use these solar values for reference to minimize the influence of uncertainties in atomic line parameters, and to maintain the same abundance scale as our previous observations.

Uncertainties in the adopted stellar parameters also give rise to random errors in the stellar abundances. The typical uncertainty of ±50 K in the effective temperatures translates into uncertainties in abundance of ± 0.025 dex in [Fe/H] and of ∓ 0.025 dex in [C/H]. Because the sense of dependence on temperature is in opposite directions for [Fe/H] and [C/H], the random error of ± 50 K results in an error of ∓ 0.05 dex in the ratio [C/Fe]. The [C/Fe] ratio is also doubly sensitive to errors in the zero point of the temperature scale. Although the iron abundance determinations are insensitive to the stellar surface gravity, the carbon abundances are not. As discussed in Paper II, we estimate that the [C/H] and [C/Fe] values have an additional random error of 0.06 dex due to uncertainties in log g values and our method of translating from the observed to model scale of log g. Determinations of [Fe/H] and [C/H]

TABLE 4

MEAN IRON AND CARBON ABUNDANCES

A. COMA

Tr	$T_{\rm eff}$	$v \sin i$	⟨Fe/H⟩	σ	[⟨Fe/H⟩]	σ	N lines	⟨C/H⟩	σ	[⟨C/H⟩]	σ	N lines	[C/Fe]	σ
19	6730	<12	0.910	0.174	−0.041	0.086	7	0.848	0.254	−0.07	0.14	5	−0.03	0.16
53	6165	<12	0.833	0.177	−0.079	0.102	7	0.625	0.315	−0.20	0.22	6	−0.13	0.24
58	6200	12	0.991	0.324	−0.004	0.171	8	0.653	0.193	−0.19	0.11	6	−0.18	0.21
65	5985	...	0.739	0.280	−0.131	0.160	8	1.021	0.346	+0.01	0.16	6	+0.14	0.22
76	6060	...	1.051	0.251	+0.022	0.107	8	0.908	0.198	−0.04	0.11	6	−0.06	0.15
85	5960	<12	0.877	0.253	−0.057	0.124	8	0.839	0.231	−0.08	0.14	6	−0.02	0.19
86	6425	15	0.879	0.184	−0.056	0.097	7	0.820	0.316	−0.09	0.21	6	−0.03	0.23
90	6350	<12	0.890	0.162	−0.051	0.080	8	0.822	0.315	−0.09	0.19	6	−0.04	0.21
92	6210	15	0.712	0.194	−0.148	0.129	7	0.649	0.185	−0.19	0.12	5	−0.04	0.21
97	6095	...	0.873	0.206	−0.059	0.107	8	0.843	0.353	−0.07	0.20	6	−0.02	0.23
101	6535	20	0.879	0.164	−0.056	0.084	8	0.720	0.294	−0.14	0.18	5	−0.10	0.20
114	6400	<12	0.833	0.188	−0.079	0.096	8	0.733	0.274	−0.14	0.22	6	−0.06	0.24
118	6495	<12	1.036	0.158	+0.015	0.065	8	0.762	0.325	−0.12	0.23	6	−0.13	0.24
162	6345	12	0.911	0.222	−0.040	0.117	8	0.916	0.475	−0.04	0.22	6	+0.00	0.25
Weighted means			0.887	±0.093	−0.052	+0.047		0.775	+0.112	−0.11	+0.06		−0.05	±0.07

B. PRAESEPE

KW	$T_{\rm eff}$	$v \sin i$	⟨Fe/H⟩	σ	[⟨Fe/H⟩]	σ	N lines	⟨C/H⟩	σ	[⟨C/H⟩]	σ	N lines	[C/Fe]	σ
227	6600	15	1.118	0.301	+0.048	0.125	8	1.384	0.694	+0.14	0.28	6	+0.09	0.30
268	6400	20	0.999	0.186	−0.000	0.089	8	1.279	0.471	+0.11	0.20	6	+0.11	0.22
341	6195	<20	1.137	0.146	+0.056	0.057	6	1.309	0.243	+0.12	0.08	4	+0.06	0.10
371	6210	...	0.989	0.331	−0.005	0.163	4	0.678	0.209	−0.17	0.13	3	−0.16	0.21
416	6760	...	1.457	0.484	+0.163	0.160	8	1.099	0.389	+0.04	0.17	6	−0.12	0.23
439	6730	15	1.063	0.305	+0.027	0.110	7	1.140	0.353	+0.06	0.16	5	+0.03	0.19
Weighted means			1.092	±0.161	+0.038	±0.056		1.028	±0.261	+0.01	±0.10		+0.02	±0.11

C. M67

Name	$T_{\rm eff}$	$v \sin i$	⟨Fe/H⟩	σ	[⟨Fe/H⟩]	σ	N lines	⟨C/H⟩	σ	[⟨C/H⟩]	σ	N lines	[C/Fe]	σ
F131	6790	...	0.860	0.59	−0.07	0.30	7	0.769	0.417	−0.11	0.30	5	−0.05	0.42
F124	6515	...	1.121	0.48	+0.05	0.25	5	0.871	0.507	−0.06	0.23	5	−0.11	0.34
I-27	7300	...	1.060	0.36	+0.03	0.16	4	...	...	...	...	...	...	...
Weighted means			1.039	±0.114	+0.02	±0.05		0.810	±0.052	−0.09	±0.03		−0.09	±0.03

D. UMa MOVING GROUP

Name	$T_{\rm eff}$	$v \sin i$	⟨Fe/H⟩	σ	[⟨Fe/H⟩]	σ	N lines	⟨C/H⟩	σ	[⟨C/H⟩]	σ	N lines	[C/Fe]	σ
HD 151044	6130	...	0.930	0.190	−0.032	0.091	8	0.942	0.305	−0.03	0.16	6	+0.01	0.18
HR 2047	5900	6	0.893	0.195	−0.049	0.099	8	0.802	0.251	−0.10	0.14	6	−0.05	0.17
HR 7061	6370	14	0.829	0.137	−0.081	0.075	8	0.855	0.350	−0.07	0.23	6	+0.01	0.24
Weighted means			0.871	±0.044	−0.060	±0.021		0.858	±0.058	−0.07	±0.03		−0.01	±0.03

E. FIELD STARS

Name	$T_{\rm eff}$	$v \sin i$	⟨Fe/H⟩	σ	[⟨Fe/H⟩]	σ	N Lines	⟨C/H⟩	σ	[⟨C/H⟩]	σ	N Lines	[C/Fe]	σ
HR 1673	6400	0	0.461	0.048	−0.336	0.044	8	0.419	0.160	−0.38	0.17	6	−0.04	0.18
HR 1729	5845	2	1.257	0.311	+0.099	0.109	8	1.268	0.457	+0.10	0.15	6	+0.00	0.19
HR 5447	6745	3	0.414	0.108	−0.383	0.101	8	0.338	0.098	−0.47	0.13	6	−0.09	0.16
HR 5533	6405	20	1.028	0.255	+0.012	0.118	8	0.918	0.343	−0.04	0.19	5	−0.05	0.22
HR 5758	6800	23	0.718	0.118	−0.144	0.074	8	0.842	0.264	−0.08	0.14	6	+0.07	0.16
HR 5933	6300	8	0.650	0.108	−0.187	0.081	8	0.619	0.172	−0.21	0.13	6	−0.02	0.15
HR 6189	6105	<15	0.208	0.089	−0.682	0.169	8	0.278	0.093	−0.56	0.15	6	+0.13	0.22
HD 148816	5880	...	0.180	0.047	−0.755	0.104	8	0.286	0.128	−0.54	0.16	6	+0.21	0.19
HD 157089	5855	...	0.275	0.046	−0.561	0.070	7	0.284	0.086	−0.55	0.14	6	+0.02	0.16
HD 160693	5690	...	0.263	0.050	−0.580	0.088	8	0.341	0.125	−0.47	0.20	6	+0.11	0.22
HD 194598	5895	...	0.053	...	−1.276	...	2	0.119	0.042	−1.04	0.17	5	+0.23	0.22

from repeat measurements of stars taken during this run indicate that remaining observational uncertainty in the logarithmic abundance is on the order of 0.03 dex.

Combining these random effects yields total error estimates of 0.04 dex for [Fe/H] and 0.08 dex for [C/H] for the high S/N observations. Systematic errors in any of these stellar parameters or solar values will, of course, increase these estimates. Uncertainty in the reddening to M67, for example, introduces an additional uncertainty in the zero point of the temperature scale for the M67 stars which may result in errors of 0.03 dex in [Fe/H] or [C/H]. Also in the case of the M67 observations, the low S/N of the spectra, the difficulty of setting the continuum accurately, and the measurement uncertainty, contribute additional uncertainty which is more difficult to quantify.

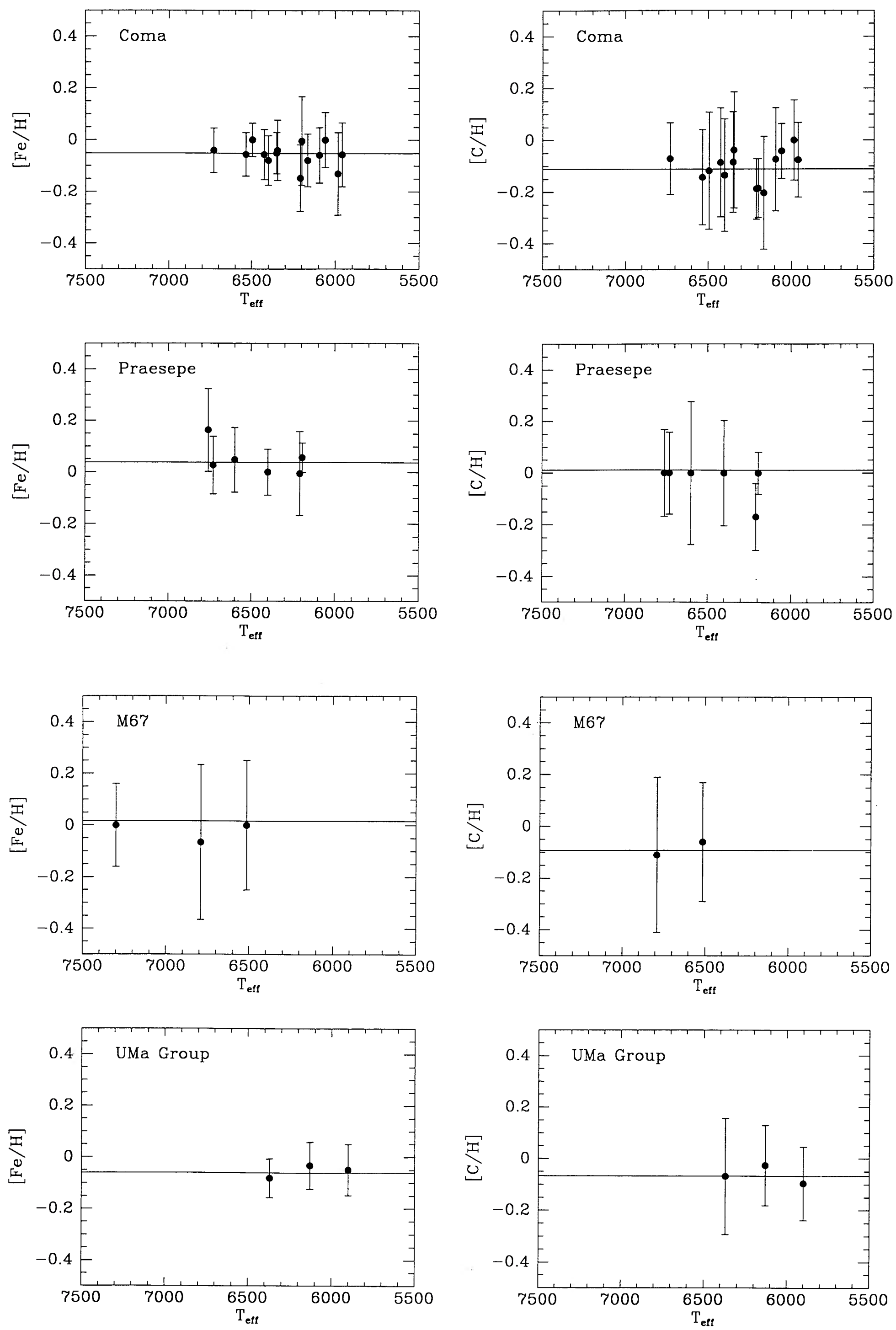

FIG. 2.—Plots of [Fe/H] and [C/H] against $T_{\rm eff}$ for stars in Coma, Praesepe, M67, and the UMa moving group. The error bars for each star show the standard deviation about the mean. Horizontal lines in each panel represent the cluster or group mean [Fe/H] or [C/H], formed by a weighted mean.

That our abundances are free from systematic effects with temperature can be seen in Figure 2 where we plot the logarithmic abundance ratios for stars in Coma, Praesepe, UMa, and M67. Although the range of temperature covered is not large, there appear to be no dependences of either [Fe/H] or [C/H] ratios with effective temperature, reassuring us that the temperature scales are well-chosen and free of large systematic effects. The horizontal lines in each panel of Figure 2 give the mean value of [Fe/H] and [C/H] for each cluster and group; these are means weighted inversely by the standard deviation in the abundance for each star.

The results from our re-observations of the three stars in the UMa Group indicate that our new observations are on the same scale as our previous larger data set. The UMa stars in Table 4 have abundances which deviate from the results in Papers I and II by Δ[Fe/H] $= -0.003 \pm 0.015$ (s.d.) and Δ[C/H] $= +0.027 \pm 0.001$ (s.d.) (in the sense of here minus Paper I or II) for the stars with determinations from several lines.

In comparison with results from other authors, our abundances also agree very well. Our new observations include four bright field stars in common with the sample of Clegg, Lambert, & Tomkin (1981, hereafter CLT). For these stars, our abundances differ in the sense of here minus CLT by only Δ[Fe/H] $= -0.05 \pm 0.06$ (s.d.) and Δ[C/H] $= +0.06 \pm 0.08$ (s.d.). Our metallicities for the moderately and very metal-poor stars in our sample are also in excellent agreement with values from other high-resolution studies as given in the catalog of Cayrel de Strobel et al. (1991). For the four stars which range in metallicity from $-1.3 <$ [Fe/H] $< = -0.5$, our [Fe/H] determinations agree with mean values in the catalog to within 0.1 dex. In particular, each of the stars studied here has a recent determination given in the catalog which rests on observations using electronic detectors. These four recent values from three different authors differ from ours with a slight systematic effect of $\langle [\mathrm{Fe/H}]_{\mathrm{here}} - [\mathrm{Fe/H}]_{\mathrm{catalog}} \rangle + 0.12 \pm 0.02$, which is well within the accidental and systematic errors of any of these studies.

4. RESULTS AND DISCUSSION

We have computed mean iron and carbon abundances for the clusters and the UMa moving group, weighting the individual stellar measurements inversely by their standard deviation. These mean abundances and the standard deviation about the mean are presented at the base of each section of Table 4. The logarithmic mean solar ratios, [Fe/H] and [C/H], in each case are the log of the mean (Fe/H) or (C/H) value.

The dispersions about the mean cluster abundances are typical of what was found in Papers I and II, and in good agreement with what is expected from observational error. As before, we conclude that there is no evidence for intrinsic star-to-star variations in either [Fe/H] or [C/H] in these clusters.

For M67 in particular, where the sample is so small and the determinations for individual stars are so uncertain, the small dispersion about the mean observed is not an accurate estimate of the true observational uncertainty. In Table 5 we present these mean cluster abundances, combined with those from Papers I and II, with their associated error in the mean. These mean errors are a better reflection of the uncertainty of our determinations, particularly in the case of M67 and the moving groups.

Our new determination for the metallicity of Coma, -0.052 ± 0.026, based on a completely different set of Fe I lines in 14 stars, is in excellent agreement with that of -0.065 ± 0.023 previously obtained by Boesgaard (1989). Our value of [Fe/H] for Praesepe, $+0.038 \pm 0.039$, is slightly, though not statistically significantly, lower than that of $\pm 0.092 \pm 0.067$ found by Boesgaard (1989), but is based on twice as many stars, and rests on measurements from typically slightly higher S/N spectra. Results for the two Praesepe stars in common, KW 227 and KW416, agree extremely well, differing by only 0.033 and 0.016 dex, respectively, the present values being the higher. And, finally, although the iron abundance we find from the three M67 stars has a large error associated with it, $+0.02 \pm 0.12$, it is in excellent agreement with the only other published high-resolution determination of $+0.04 \pm 0.04$ (m.e.) by Garcia Lopez, Rebolo, & Beckman (1988) based on seven stars.

The results for carbon abundances for these three additional clusters serve to strengthen the conclusions from Papers I and II. Figure 3 shows the lack of dependence of [C/Fe] ratio upon [Fe/H] for the combined data set of Table 5. These six clusters and three moving groups show a uniformly solar [C/Fe] ratio within the observational errors, with a mean $\langle$[C/Fe]$\rangle = -0.037 \pm 0.057$.

The field star sample over the same range of metallicities also shows solar [C/Fe], but Figure 4*a* indicates that there

TABLE 5

ABUNDANCE AND AGE DATA FOR CLUSTERS AND GROUPS

Cluster	$\overline{[\mathrm{Fe/H}]}$	m. e.	$\overline{[\mathrm{C/H}]}$	m. e.	$\overline{[\mathrm{C/Fe}]}$	m. e.	n	Age (yr)
α Per	−0.057	±0.051	−0.20	±0.08	−0.12	±0.10	4	5×10^7
Pleiades	−0.034	±0.024	−0.06	±0.04	−0.05	±0.05	12	7×10^7
UMa Group[a]	−0.086	±0.021	−0.12	±0.05	−0.03	±0.06	8	3×10^8
Coma	−0.052	±0.026	−0.11	±0.04	−0.05	±0.05	14	4×10^8
Hyades	+0.127	±0.022	+0.04	±0.04	−0.08	±0.06	13	6.7×10^8
Hyades Group	+0.134	±0.052	+0.20	±0.09	+0.05	±0.11	3	6.7×10^8
Praesepe	+0.038	±0.039	+0.01	±0.06	+0.02	±0.07	6	8×10^8
Wolf 630 Group	−0.137	±0.041	−0.15	±0.09	+0.02	±0.10	3	1.4×10^9
M 67	+0.017	±0.123	−0.09	±0.18	−0.09	±0.26	3	5×10^9

[a] Values include averages over determinations in this paper and Papers I and II.

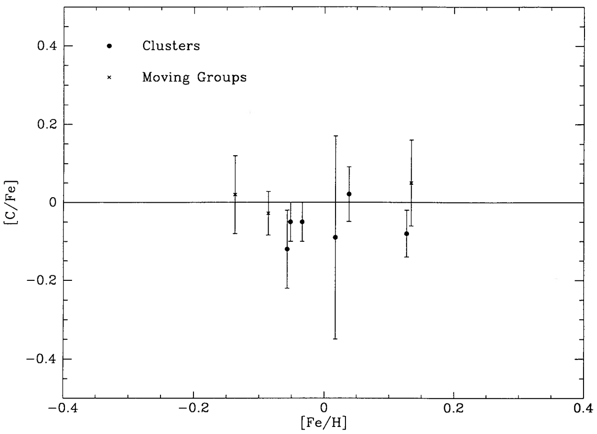

FIG. 3.—Mean cluster and group values of [C/Fe] vs. [Fe/H] for the sample studied here combined with the results for the clusters and groups from Papers I and II. Clusters are designated by filled circles and the moving groups by crosses. The error bars give the error in the mean of [C/Fe] for each cluster or group.

may be a slight systematic trend to higher [C/Fe] values at metallicities [Fe/H] ≤ -0.5 among our data. This systematic effect is modest, but has not been seen in any of the larger samples of field dwarfs which cover metallicities down to [Fe/H] $= -2.5$ (Laird 1985; Carbon et al. 1987; Tomkin, Sneden, & Lambert 1986). In spite of the difficulties in the interpretation of these results, the existence of systematic differences from study to study, and the uncertainty in the behavior of the [C/Fe] ratio at very low metallicities (Wheeler, Sneden, & Truran 1989), these studies have all concluded that at least over the range of metallicities covered by our limited sample, [C/Fe] is solar.

It is possible that the slight offset to positive [C/Fe] values we see in stars more metal-poor than [Fe/H] ~ -0.5 is spurious; it could be explained easily by a slight zero-point error in the temperature scale or in the surface gravities of the metal-poor stars. For example, a 100 K increase in $T_{\rm eff}$ produces a 0.1 dex decrease in [C/Fe], and a 0.2 dex decrease in log g decreases [C/Fe] by 0.07 dex. These metal-poor stars are all also quite cool, and the carbon lines become very weak at these temperatures, while the iron lines remain relatively stronger. The contamination of the carbon lines by remaining weak iron line blends may have contributed to the slight upturn in [C/Fe] as a function of decreasing [Fe/H].

However, the surveys of metal-poor dwarfs showing [C/Fe] ~ 0 in this metallicity range have all relied on measurements of the CH feature, and there is evidence for systematic differences between abundances from CH and C I lines (CLT; Tomkin et al. 1986). Analysis of C I features yields [C/H] ratios 0.2 to 0.3 dex higher than measurements from CH in the same stars. It is interesting to compare our results with those of CLT, who also use the C I lines, for stars in this region of modest metal deficiency. CLT measured [C/H] for four stars with $-0.85 \leq$ [Fe/H] < -0.5 and found enhanced [C/Fe] for all of them: $\langle$[C/Fe]$\rangle = +0.17 \pm 0.10$ (s.d.). The five stars in

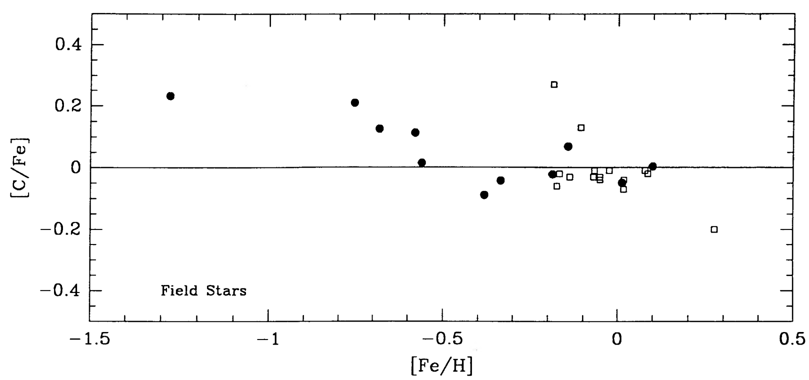

FIG. 4*a*

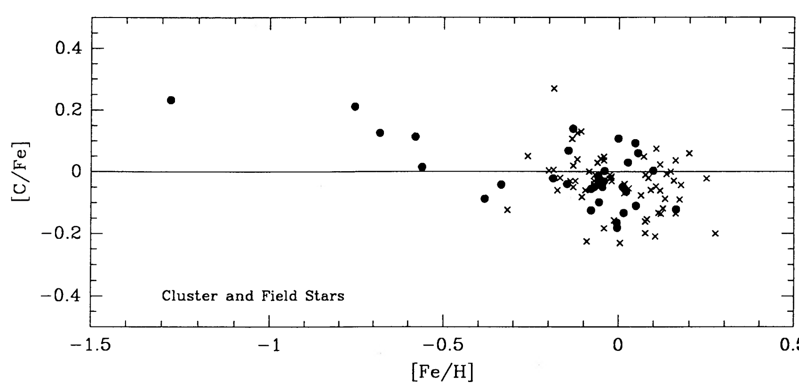

FIG. 4*b*

FIG. 4.—(*a*) [C/Fe] vs. [Fe/H] for the field stars observed in this paper (*filled circles*) and those from Papers I and II (*open squares*). (*b*) [C/Fe] vs. [Fe/H] for all field and cluster stars from this paper (*filled circles*) and those from Papers I and II (*crosses*).

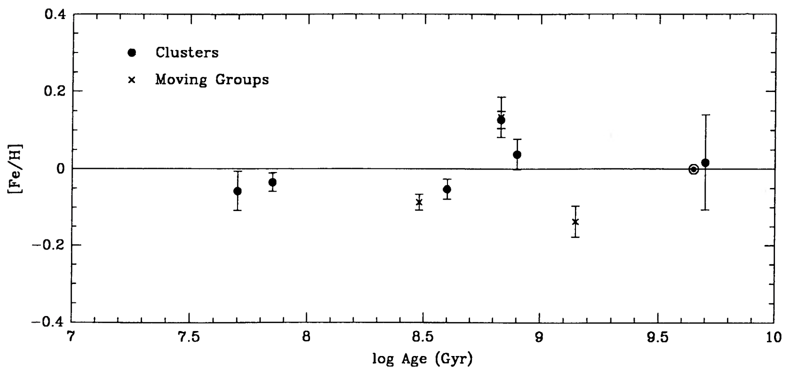

FIG. 5*a*

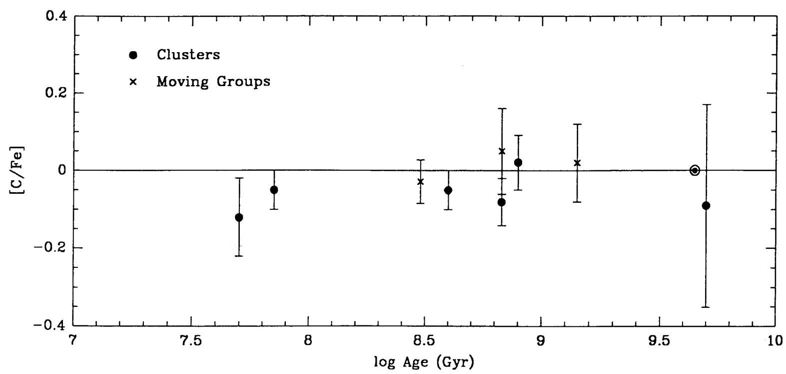

FIG. 5*b*

FIG. 5.—Relationship of (*a*) [Fe/H] and (*b*) [C/Fe] with age for the clusters (*filled circles*), and moving groups (*crosses*) observed here and in Papers I and II. The error bars give the error in the mean cluster or group abundance. The solar value is at a log age of 9.65, or 4.5 billion yr.

our sample with [Fe/H] < -0.5 give $\langle$[C/Fe]$\rangle = +0.14 \pm 0.09$ (s.d.). CLT noted that their C I data suggested that the C and Fe abundances may not vary in unison, but on including the existing CH data for more metal-poor stars, concluded that [C/Fe] was solar.

Whether this apparent enhancement is due to systematic effects or small number statistics, or reflects a real trend in [C/Fe] ratios in moderately metal-poor stars requires a larger sample of metal-poor stars observed for the C I lines. Although the C I lines become too weak to measure in stars more metal-poor than [Fe/H] ~ -1.5, they are clearly visible in the high S/N, high-resolution observations of stars with metallicities in the range -0.5 to ~ -1.3. It would be particularly interesting to increase the sample of stars measured for both C I and CH in this intermediate metallicity range to investigate the nature of these systematic effects.

This upturn in [C/Fe] ratios appears to set in only at [Fe/H] ~ -0.5; the stars more metal rich show no sign of nonsolar [C/Fe] values.

Since C tracks Fe so well, we can use all the stars in both clusters and the field to find the mean [C/Fe] for stars with roughly solar metallicity. Figure 4*b* shows this complete sample of 102 field and cluster stars, taken from Papers I, II and here. Of these, 84 have [Fe/H] > -0.2 and $\sigma \leq 0.25$ for [C/Fe]; for them, $\langle$[C/Fe]$\rangle$ is -0.031 ± 0.009 (error in the mean). Given the difficulty of eliminating systematic errors in the zero point of any study of elemental abundances, we do not consider the slight negative value to be significant. The standard deviation observed about this mean, 0.081 dex, is explained entirely by the expected errors in the observations and adopted stellar parameters, and indicates that the intrinsic variation in [C/Fe] among these solar metallicity stars is extremely small. Although our sample contains only five metal-poor stars (which have a mean [Fe/H] of -0.8), their mean $\langle$[C/Fe]$\rangle$, $+0.140 \pm 0.044$ (error in the mean), is larger by 4 σ than that for the solar metallicity sample, strong statistical evidence that these intermediate metallicity stars have larger than solar values of [C/Fe].

Our new determinations of Fe and C in Coma, Praesepe, and M67 also leaves unaltered conclusions about the age-metallicity relation of these clusters and groups. Figure 5 presents the [Fe/H] and [C/Fe] versus age relationships for the combined cluster data. The points are shown with error bars which reflect the error in the mean abundances given in Table 5. Although at a given age the range seen in [Fe/H] values is highly significant, there is no statistically significant variation in [C/Fe]. The [Fe/H] values of the Hyades and Coma differ at the 5 σ level, although they are roughly the same age, while their [C/Fe] ratios are statistically identical.

Models of galactic chemical evolution predict qualitatively the uniformity of [C/Fe] over a wide range of metallicity because carbon and iron are thought to be produced in roughly the same proportions in stars of similar masses (Matteucci & François 1989). The detailed predictions of the models show, however, a slight increase in [C/Fe] from solar to the level of $\sim +0.3$ dex at [Fe/H] ~ -1.0, followed by a return to solar ratios at lower metallicities. In comparison to the observations indicating solar [C/Fe] for all metallicities [Fe/H] > -2.0, this predicted feature has been dismissed as the result of the assumption of different nucleosynthetic reaction rates in the different mass ranges that correspond to the halo and disk populations (Matteucci 1989). Until predictions are made using consistent reaction rates at all masses, the nature of the systematic effects between abundances from CH and C I features are understood, and the reality of the enhanced [C/Fe] ratios indicated for intermediate metallicities are verified, we cannot make detailed comparisons to these predictions of nucleosynthetic chemical evolution. However, the small dispersion about the mean solar ratio that we find for stars with roughly solar metallicity places tight constraints on the similarity of the chemical evolutionary histories of C and Fe to be matched by models of galactic chemical evolution.

At the same time, the range in [Fe/H], small but highly significant, strengthens the conclusion of Boesgaard (1989) that the timescale of mixing in the Galactic disk near the solar neighborhood must be greater than 1 billion yr. We cannot place very tight limits on this timescale for mixing, but other studies of the radial abundance gradients in the older open cluster population show that the place of formation is of primary importance in determining the overall metallicity of the newly forming cluster stars (Friel & Janes 1990). The importance of the place of formation in determining the composition of the more nearby clusters was discussed by Boesgaard (1989). The high precision of the metallicity determinations for these clusters and the ones studied here show that even within 200 pc of the solar neighborhood, the overall metal content of the gas is not homogenized, so that clusters like the Hyades, Praesepe, and Coma, which formed within less than half a billion years of each other preserve small inhomogeneities in the composition of the gas from which they form.

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