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METALLICITY IN GALACTIC CLUSTERS FROM HIGH SIGNAL-TO-NOISE SPECTROSCOPY

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ABSTRACT

High-quality spectroscopic data on selected F dwarfs in six Galactic clusters have been used to determine global [Fe/H] values for the clusters, in part to investigate ongoing nucleosynthesis in the Galactic disk. The spectra were obtained with (1) the CFHT coudé and the Reticon detector at 0.11 Å resolution and (2) the Palomar coudé and a Texas Instruments CCD with a spectral resolution of 0.21 Å. The signal-to-noise ratios were typically 150–500. Stars in the Hyades, Pleiades, Praesepe, α Per, Coma, and UMa were observed. For the two youngest clusters, Pleiades and α Per, the [Fe/H] values are solar: 0.017 ± 0.055. The Hyades and Praesepe are slightly metal-enhanced at $[\mathrm{Fe/H}] = +0.125 \pm 0.032$, even though they are an order of magnitude older than the Pleiades. Coma and the UMa Group at the age of the Hyades are slightly metal-deficient with $[\mathrm{Fe/H}] = -0.082 \pm 0.039$. The lack of an age-metallicity relationship indicates that the enrichment and mixing in the Galactic disk have not been uniform on time scales less than 10^9 yr. Because of the accuracy of the global spectroscopically determined [Fe/H] of the clusters, a new calibration of the Strömgren $\delta m_0(\beta)$ with [Fe/H] has been made which gives $[\mathrm{Fe/H}] = -13.8\delta m_0(\beta) + 0.15$; this is applicable over a limited range in metallicity, however.

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

I. INTRODUCTION

Open clusters provide important templates to determine the chemical evolution and mixing in the Galactic disk. Their ages are known far more reliably than those of random field stars; with the exception of the Hyades, the stars are rather faint for the high-resolution (0.1–0.2 Å) spectroscopy that is required for chemical abundance analyses. However, new observational and theoretical techniques are making it possible to determine accurate abundances from high signal-to-noise (S/N) and high-resolution spectra of stars at $V \lesssim 10.5$. Therefore, abundance studies in F dwarfs in several open clusters can now be made with unprecedented accuracy. In order to trace the chemical history of the Galactic disk, the abundance of Fe can be used as an indicator of metallicity and metallicity enrichment. The change in [Fe/H] with cluster age shows the chemical evolution, while variations in abundances from cluster to cluster of similar age reveal the success of mixing in the Galactic disk.

It is the advent of linear detectors with high quantum efficiency and high signal-to-noise capabilities, Reticons and CCDs, that has provided new opportunities for precise determinations of stellar chemical composition. For example, Cayrel, Cayrel de Strobel, and Campbell (1985) have used Reticon spectra from the Canada-France-Hawaii Telescope (CFHT) to determine [Fe/H] in the Hyades, and they find a mean of $[\mathrm{Fe/H}] = +0.12 \pm 0.03$ (!) from about 35 Fe lines in ten G dwarfs.

In connection with a program to determine Li abundances in F stars in open clusters, we have observations at spectral resolutions of 0.1–0.2 Å and S/N of 150–800 of several F dwarfs in six open clusters. These spectra have many Fe I lines suitable for use in determining [Fe/H]. The mean metallicity can be found for the cluster from the average metallicity of several stars to accuracies of 10%–20%. In addition to providing primary and accurate data on [Fe/H] in open clusters, this information can be used to calibrate various photometric indices, notably the Strömgren δm_0. These well-calibrated photometric indices can then be used to find more accurate metallicities for fainter open clusters.

II. OBSERVATIONAL MATERIAL

Spectroscopic data have been obtained near 6700 Å for F dwarfs in six Galactic clusters: the UMa Group, the Pleiades, α Per, the Hyades, Praesepe, and Coma. The spectra of the Coma cluster stars are from the CFHT coudé spectrograph and Reticon; of the Pleiades, α Per, and Praesepe from the Palomar 200 inch (5 m) Hale telescope coudé spectrograph and TI CCD, and of the UMa Group and the Hyades from both CFHT and Palomar. The CFHT spectra cover 135 Å and have a spectral resolution of 0.11 Å (see description of Boesgaard 1987*a* for the CFHT instrument and data reduction details). The Palomar spectra cover 110 Å with a resolution of 0.21 Å (see Boesgaard, Budge, and Burck 1988 for a description of the basic data and the reduction procedure).

From the sample of stars observed a subset of the "best stars" has been selected for this work. There are four criteria for inclusion in the "best stars" list: (1) The star must have a low enough value of $v \sin i$ to ensure accurate measurement of the line strengths; in practice this value was ≤ 30 km s^{-1}. (2) The spectrum must have a high S/N; in practice this was usually at least 150, often much higher. (3) The star's temperature must be well known, or, more precisely, the values given by different photometric indices and the calibrations used must agree well; in practice this was usually to within ± 50 K. (4) The star must be a bona fide member of the cluster. Naturally, known spectroscopic binaries were excluded.

Some information about the stars and the clusters observed has been published elsewhere; some information was determined anew, and some is presented here for the first time. For

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the UMa Group the data on the equivalent widths and temperatures are in Boesgaard, Budge, and Burck (1988). For the Pleiades and α Per the data on the temperatures are in Boesgaard, Budge, and Ramsay (1988). For the Hyades there is temperature information in Boesgaard and Tripicco (1986*a*), Boesgaard (1987*b*), and Boesgaard and Budge (1988). The information on temperatures and equivalent widths for Coma is from Boesgaard (1987*a*). The Praesepe data are in Boesgaard and Budge (1988). For the "best stars" of the Hyades, the Pleiades, α Per, and Praesepe new measurements are presented of the equivalent widths of the six Fe I lines $\lambda\lambda$6678, 6703, 6705, 6727, 6750, and 6752.

Table 1 gives the "best stars" in each cluster along with the signal-to-noise ratio of the spectrum, the published $v \sin i$ (from Kraft 1965, 1967*a*, *b*; Anderson, Stoeckly, and Kraft 1966; and Soderblom 1983), and the adopted temperature for each star. The measured equivalent widths for the Fe I lines are given in Table 2. In some cases an Fe I line could not be measured well enough to meet our standards for the accuracy level of these [Fe/H] determinations, e.g., if a cosmic-ray hit perturbed the line, and these lines are excluded from the tables and the abundance results.

III. ANALYSIS AND RESULTS

Temperature determinations and their errors are given in the above-cited papers. With the equivalent widths and temperatures, Fe/H values have been determined for each individual line for each star from the grid of predictions based on Kurucz (1979) model atmospheres and the abundance program described by Boesgaard and Tripicco (1986*b*). For these stars we have used microturbulent velocities for each temperature from Nissen (1981) as described by Boesgaard (1987*a*). The value of $\log g = 4.5$ has been used; with the exception of Fe I λ6678, none of the Fe I lines is affected if $\log g$ is 4.0 or 3.5, and even λ6678 is only mildly dependent on $\log g$. For each line the solar Fe/H was also found. Ratios for each line of $(\text{Fe/H})_*$ to $(\text{Fe/H})_\odot$ were averaged to find $\langle(\text{Fe/H})_*/(\text{Fe/H})_\odot\rangle$ for each star. That value (and the standard deviation of the mean) and the log of that, [Fe/H], are also given in Table 2.

Figure 1 shows the spectra of three of the stars, from each of three clusters, having nearly the same temperature but with definite differences in the strengths of the Fe I lines. The line at 6705 Å, for example, shows an increase in equivalent width from top to bottom of 23, 27, 33 mÅ. Those stars and their respective clusters represent the range of [Fe/H] abundances in our sample. Figure 2 shows the strength of one of the Fe I lines, λ6727, as a function of temperature for stars in the temperature range 5800–6900 K. The symbols group the clusters in pairs by their [Fe/H] abundances, with Hyades and Praesepe at $\sim +0.10$, the Pleiades and α Per at ~ 0.00, and Coma and UMA at ~ -0.10. The slopes are virtually identical, but the vertical displacement of the mean lines of the three groups is clear and results from the Fe/H abundance differences.

The errors from several sources have been estimated. First, the random errors in the equivalent width measurements can be estimated from the repeatability of the equivalent widths from multiple measurements from one spectrum ($\sim$1 mÅ) and from the new measurements on the re-reduced Hyades spectra compared with previous measurements ($\sim$2 mÅ). Second, the errors in the temperatures from the different photometric indices and the calibrations translate into random errors in Fe/H. Third, the internal error in the mean $(\text{Fe/H})_*/(\text{Fe/H})_\odot$ for each star results from equivalent width errors and errors in the input atomic physics and models. Note that the models used for all stars are the same (which may give some systematic error, but the analyses are internally consistent) and that the temperature scales used from cluster to cluster are consistent, and in most cases identical. (For the Hyades we use the scale derived specifically for it by Carney 1983).

For each cluster the average of the $(\text{Fe/H})_*/(\text{Fe/H})_\odot$ values and the error of this mean were found. From those numbers [Fe/H] for the cluster as a whole and σ, the standard deviation about the cluster mean, were determined. These are given in Table 3. It is clear from the error discussion above, from the errors in Table 2, and from the values of σ, that the differences from cluster to cluster are real.

LaBonte and Rose (1985) suggested that the "Hyades anomaly," an excess in c_1 for a given $(b - y)$ relative to field stars, is due to plage emission on the surfaces of the Hyades stars. They report spectral anomalies due to this emission. If the metal lines are indeed filled in by emission, the derived metallicity of the Hyades would be expected to be low, since the lines would appear weakened. However, [Fe/H] for the Hyades is greater than solar. Although the Coma stars have about the same level of activity as the Hyades (Barry, Hege, and Cromwell 1984; Barry, Cromwell, and Hege 1987), and do show lower metallicity than the Hyades, the Pleiades stars, with a higher level of activity according to Barry *et al.*, appear to have solar metallicity, intermediate between the Hyades and Coma. Nissen (1988) has challenged the interpretation of LaBonte and Rose (1985) on the basis that chromospheric activity is known to decrease with age and Coma, at the same age and activity level as Hyades, shows no anomaly, and the Pleiades, which is younger and more active than the Hyades, also shows no anomaly. Therefore it seems unlikely that the measured differences in *metallicity* from these high-resolution, high signal-to-noise spectra could be due to effects of plage emission.

The results are displayed in Figure 3 in six panels showing [Fe/H] as a function of temperature for each star in a given cluster with the mean value for the cluster and the standard deviation of that mean. The panels are arranged into metallicity groups from high (Hyades and Praesepe) to low (Coma and UMa). From the plots we can see that our temperature scales are good, since there is no (spurious) temperature dependence. These plots make it clear that there is little scatter for a given cluster (especially Coma) and that the differences among the three metallicity groups are real. Figure 4 shows the three metallicity groups plotted together with the same symbols used in Figure 3. The three horizontal lines are the means of the three cluster pairs, Hyades + Praesepe, Pleiades + α Per, Coma + UMa, which are given in the bottom part of Table 3.

Each cluster can be characterized by the value of [Fe/H] given in Table 3, and also by the Strömgren δm_1 or δm_0. We have used a sample of F stars in each cluster to find $\delta m_0(\beta)$, that is, the difference in the m_1 that is predicted for the observed β from the standard star relation between β and m_1 given by Crawford (1975) and the m_1 that is observed. For the clusters with differential interstellar reddening these are called $\delta m_0(\beta)$, corrected for reddening. Those cluster-wide values of $\delta m_1(\beta)$ [or $\delta m_0(\beta)$] are also given in Table 3. The photometric data are from Crawford and Perry (1966) for the Hyades; Crawford and Barnes (1969*a*) for Coma and UMa, but also Hauck and Mermilliod (1980) for more UMa stars; Crawford and Barnes (1969*b*) for Praesepe; Crawford and Barnes (1974)

TABLE 1

STARS OBSERVED

A. α PERSEI

He	HD	BD	S/N	$v \sin i$ (km s^{-1})	T (K)
135.........	...	49°868	140	<20	6710
490.........	...	48 892	180	<20	6805
1225.........	22326	47 862	170	20	6415

B. PLEIADES

H II	HD	BD	S/N	$v \sin i$ (km s^{-1})	T (K)
233.........	23195	23°499	145	<20	6485
739.........	23386	24 055	140	<12	5870
948.........	23464	22 549	185	<12	5960
1122.........	23511	23 526	180	28	6610
1139.........	23513	22 551	148	30	6575
1200.........	...	22 553	100	<20	6470
1613.........	...	23 545	130	18	6250
1726.........	23713	23 548	148	<12	6365

C. URSA MAJOR GROUP

NAME	HR	HD	S/N CFHT	S/N Palomar	$v \sin i$ (km s^{-1})	T (K)	MEMBER
ϕ^2 Cet	235	4813	...	360	3.5	6200	?
80 Psc	330	6763	...	450	...	6930	?
... .	...	11131B	...	175	...	5820	Y
χ^1 Ori	2047	39587	1730	...	9.4	5900	Y
π^1 Uma	3391	72905	1360	...	9.5	5850	Y
... .	5830	139798	280	...	...	6930	?
11 Aql	7172	176303A	580	360	26	6115	?
... .	7451	184960	580	200	6.5	6240	Y
... .	8170	203454	700	300	18.0	6125	Y

D. COMA

TR	HD	BD	S/N	$v \sin i$ (km s^{-1})	T (K)
19.........	106103	28°2087	420	<12	6730
58.........	107132	25 2486	270	12	6200
76.........	107399	26 2330	300	...	6060
86.........	107611	28 2109	300	15	6425
90.........	107685	23 2453	230	<12	6350
114.........	108154	24 2457	220	<12	6400
162.........	108976	28 2125	390	12	6345

E. HYADES

VB	HD	BD	S/N CFHT	S/N Palomar	$v \sin i$ (km s^{-1})	T (K)
11.........	26015	14°657	...	370	25	6825
19.........	26784	5 601	...	340	<12	6300
44.........	27731	24 654	340	...	30	6565
48.........	27808	21 641	390	...	<12	6245
51.........	27848	16 591	380	...	30	6595
57.........	27991	15 621	350	...	15	6370
59.........	28034	15 624	...	500	<6	6120
61.........	28069	4 690	...	310	18	6260
65.........	28205	15 627	...	420	9	6200
78.........	28406	17 732	450	295	20	6510
81.........	28483	19 731	400	...	18	6470
86.........	28608	10 588	350	...	20	6485
121.........	30738	15 692	400	...	12	6335
128.........	31845	15 713	500	...	25	6569

F. PRAESEPE

KW	HD	BD	S/N	$v \sin i$ (km s^{-1})	T (K)
227.........	73641	19°2066	150	...	6600
250.........	...	20 2157	150	...	6395
416.........	...	20 2183	125	...	6760

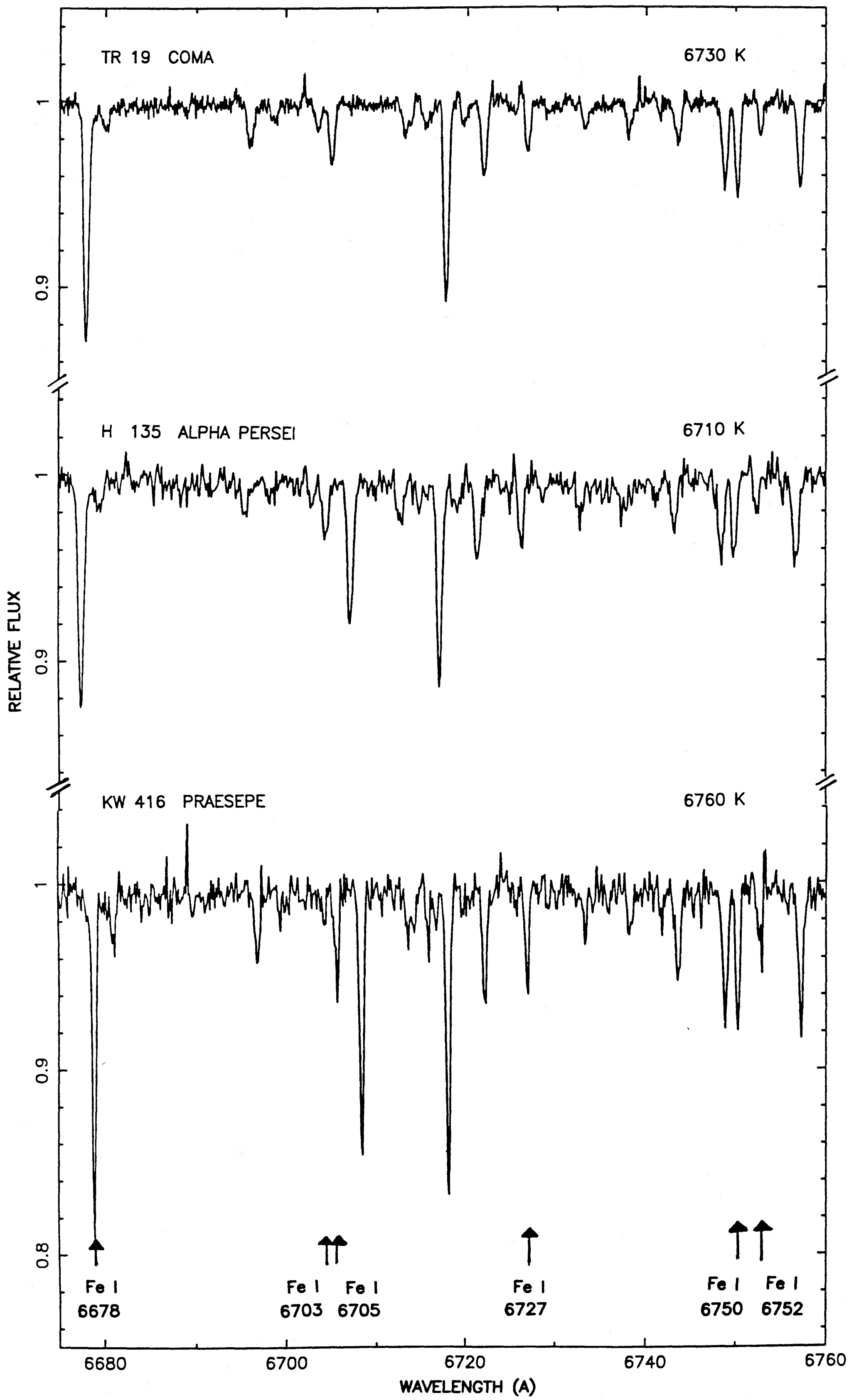

FIG. 1.—Samples of the spectra of three of the faintest stars in this study. (For other examples see the spectra in the other papers referenced in the text.) These stars all have approximately the same temperature, yet there are clear differences in the strengths of the Fe I lines identified near the bottom of the plot. The strong line at 6708 Å in the α Per star and in the Praesepe star is Li I, which is absent in the Coma star.

TABLE 2

EQUIVALENT WIDTHS (mÅ) AND ABUNDANCES

A. α PERSEI

He	Fe I λ6677.993	Fe I λ6703.573	Fe I λ6705.117	Fe I λ6726.668	Fe I λ6750.152	Fe I λ6752.724	$\frac{(Fe/H)_*}{(Fe/H)_\odot}$	σ	[Fe/H]
135.........	103.4	10.5	26.6	27.1	37.5	18.5:	1.097	±0.212	0.040
490.........	86.3	10.2	25.5	24.2	28.2	17.0:	0.955	±0.087	−0.020
1225.........	108.1	16.0	28.2	30.4	45.4	26.0	0.975	±0.084	−0.011

B. PLEIADES

H II	Fe I λ6677.993	Fe I λ6703.573	Fe I λ6705.117	Fe I λ6726.668	Fe I λ6750.152	Fe I λ6752.724	$\frac{(Fe/H)_*}{(Fe/H)_\odot}$	σ	[Fe/H]
233.........	...	14.5	21.1	22.2	34.0	22.3	0.760	±0.130	−0.119
739.........	139.4	29.9	45.5	51.8	75.6	38.5	1.133	±0.178	+0.054
948.........	111.4	33.5	47.4	43.5	68.7	40.5	1.142	±0.238	+0.058
1122.........	89.2	...	39.0	31.0	37.8	...	0.978	±0.240	−0.010
1139.........	103.3	...	30.0	30.8	43.4	...	1.180	±0.064	+0.072
1200.........	...	18.6	24.4	29.1	36.1	28.4:	0.096	±0.271	−0.018
1613.........	107.5	20.7	41.2	37.9	49.3	30.7:	1.050	±0.151	+0.021
1726.........	112.7	25.1	37.4	34.6	48.5	29.5	1.218	±0.146	+0.086

C. URSA MAJOR GROUP

Name	Fe I λ6677.993	Fe I λ6703.573	Fe I λ6705.117	Fe I λ6726.668	Fe I λ6750.152	Fe I λ6752.724	$\frac{(Fe/H)_*}{(Fe/H)_\odot}$	σ	[Fe/H]
ϕ^2 Cet	97.9	16.8	28.0	31.1	50.9	21.7	0.720	±0.117	−0.143
11131B	137.8	29.3	39.3	41.6	65.2	31.0	0.850	±0.178	−0.071
80 Psc	85.6	...	...	19.3	...	...	0.922	±0.067	−0.035
χ^1 Ori	126.8	28.6	41.1	42.6	62.6	29.7	0.888	±0.082	−0.052
π^1 Uma	124.4	30.2	41.0	42.7	65.0	26.8	0.830	±0.088	−0.081
HR 5830	92.3	6.4:	8.6:	17.3	18.5:	...	0.745	±0.338	−0.128
11 Aql	118.5	17.9	32.0	36.6	57.4	24.9	0.852	±0.166	−0.070
HR 7451	100.6	15.3	30.6	30.3	48.8	20.7	0.765	±0.097	−0.116
HR 8170	104.6	16.0	29.0	28.4	47.7	23.4	0.664	±0.057	−0.178

D. COMA

Tr	Fe I λ6677.993	Fe I λ6703.573	Fe I λ6705.117	Fe I λ6726.668	Fe I λ6750.152	Fe I λ6752.724	$\frac{(Fe/H)_*}{(Fe/H)_\odot}$	σ	[Fe/H]
19.........	94.1	11.9	23.1	20.1	34.1	...	0.932	±0.127	−0.031
58.........	...	20.0	36.4	33.4	51.5	23.5	0.852	±0.082	−0.070
76.........	...	25.3	39.4	34.7	61.9	27.4	0.892	±0.091	−0.050
86.........	94.2	15.5	27.2	25.9	43.0:	...	0.806	±0.083	−0.094
90.........	101.4	15.5	28.9	31.5	43.2	...	0.808	±0.059	−0.093
114.........	95.3	15.8	33.3	27.2	47.1	24.7:	0.885	±0.157	−0.053
162.........	103.0	16.6	27.7	31.2	46.7	22.4	0.847	±0.069	−0.072

E. HYADES

VB	Fe I λ6677.993	Fe I λ6703.573	Fe I λ6705.117	Fe I λ6726.668	Fe I λ6750.152	Fe I λ6752.724	$\frac{(Fe/H)_*}{(Fe/H)_\odot}$	σ	[Fe/H]
11	...	12.7	30.5	26.7	37.0	14.8	1.234	±0.261	0.091
19	120.5	26.7	44.6	43.0	60.6	33.8	1.500	±0.100	0.176
44	112.3	14.3	27.1	37.5	51.3	23.5	1.358	±0.350	0.133
48	117.0	26.9	41.3	38.0	55.2	26.7	1.253	±0.215	0.098
51	112.2	18.4	35.5	29.3	50.3	23.9	1.442	±0.267	0.159
57	115.9	18.9	39.4	35.5:	56.6	29.0	1.255	±0.196	0.099
59	127.4	31.1	51.4	45.8	61.0	33.1	1.383	±0.195	0.141
61	116.6	28.0	44.9	39.0	54.9	31.7	1.358	±0.133	0.133
65	124.7	20.7	42.8	42.2	59.7	34.9	1.330	±0.237	0.124
78 (CFH)	112.0	17.4	35.8	34.9	52.0	23.9	1.335	±0.240	0.126
78 (P)	104.1	20.4:	39.3	34.9	53.4	28.2	1.423	±0.150	0.153
81	115.3	22.2	27.8	34.8	56.2	27.7	1.357	±0.301	0.132
86	...	19.4	36.6	25.6	53.1	28.8	1.260	±0.308	0.100
121	112.9	25.4	42.1	43.4	63.0	31.5	1.438	±0.222	0.158
128	112.1	19.5	34.2	27.6	49.0	21.7	1.382	±0.338	0.140

F. PRAESEPE

KW	Fe I λ6677.993	Fe I λ6703.573	Fe I λ6705.117	Fe I λ6726.668	Fe I λ6750.152	Fe I λ6752.724	$\frac{(Fe/H)_*}{(Fe/H)_\odot}$	σ	[Fe/H]
227.........	90.6	11.4	27.7	30.1	...	29.6	1.080	±0.303	0.033
250.........	103.7	20.6	37.3	33.9	59.9	28.7	1.275	±0.288	0.106
416.........	99.6	13.0:	32.9	31.5	42.5	...	1.402	±0.146	0.147

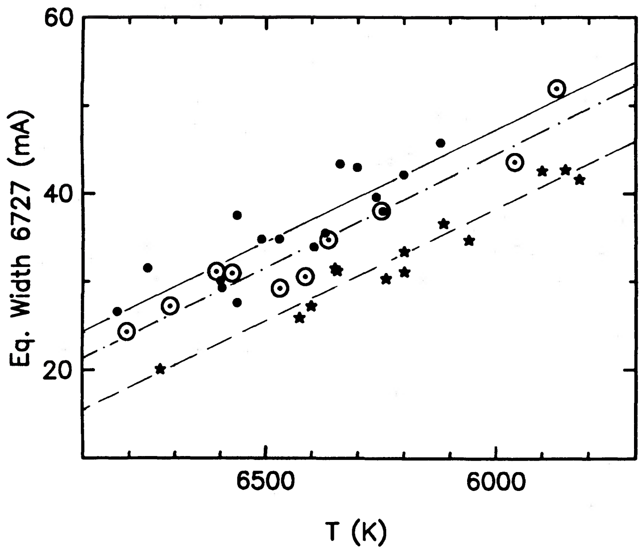

FIG. 2.—Equivalent width of the Fe I λ6727 line as a function of temperature in the stars observed. The filled circles and the solid line are stars in the Hyades and Praesepe clusters, the circled dots and dash-dot line are for the Pleiades and α Per stars, and the star symbols and the dashed line represent the Coma and UMa Group stars. The lines are least-squares fits to their respective data points. This shows that the metallicity differences are clearly measurable among the three cluster groups and that the scatter in the equivalent widths for each group is not large.

for α Per; and Crawford and Perry (1976) for the Pleiades. There are two entries: the upper one is for all stars with $2.73 > \beta > 2.59$ and the lower for stars with $b - y < 0.35$ or $2.73 > \beta \geq 2.625$. Although there is not much range in the values, a calibration can be made because of the precise global [Fe/H] results.

The relationship is

$$[\mathrm{Fe/H}] = -12.7\delta m_0(\beta) + 0.15 .$$

For this the results for all six clusters were used with the δm_0 values from the upper lines of the entries in Table 3.

Following Nissen (1981), we have looked for differences in this relationship due to the dependence of the calibration of δm_0 on T_{eff}. For the early F stars, $2.73 > \beta > 2.66$, the relationship is

$$[\mathrm{Fe/H}] = -15.3\delta m_0(\beta) + 0.11 ,$$

while for the late F and early G stars, $2.66 \geq \beta > 2.59$, it is

$$[\mathrm{Fe/H}] = -13.0\delta m_0(\beta) + 0.17 .$$

Olsen (1984) has found a slight dependence on δc_0 for stars with $b - y > 0.35$. With the lower entries for δm_0 in Table 3, which is from those stars with $b - y < 0.35$, the relationship is virtually identical to Olsen's,

$$[\mathrm{Fe/H}] = -10.0\delta m_0(\beta) + 0.12 .$$

[Olsen found $[\mathrm{Fe/H}] = -11\delta m_0(\beta) + 0.12$.]

If double weight is given to the three clusters with the best [Fe/H], the Hyades, Coma, and the Pleiades, and stars with $b - y < 0.35$ are used, then

$$[\mathrm{Fe/H}] = -11.6\delta m_0(\beta) + 0.13 .$$

In fact, without the δc_0 complication, Olsen's solution is $[\mathrm{Fe/H}] = -10\delta m_0(\beta) + 0.10$, very little different. The preferred solution here, then, is to use all the data (upper entries) and give double weight to the three best clusters. That relationship is

$$[\mathrm{Fe/H}] = -13.8\delta m_0(\beta) + 0.15 ,$$

shown graphically in Figure 5. Note that this calibration is valid only over a small range in metallicity, say $\delta m_0 = -0.01$ to $+0.03$.

Table 3 contains interesting information on the age-metallicity relationship in the young Galactic disk. The clusters are listed in order of increasing age. The ages were determined from the values of $(B-V)_t$, the value of $B-V$ for the cluster turnoff point from Janes and Adler (1982) and their Figure 4. Those ages agree well with those found, for example, by Barry, Cromwell, and Hege (1987), who derive the age used here for the UMa Group. It can be seen that the metallicity does *not* increase uniformly with increasing age. In particular, the young Pleiades and α Per have solar metallicity, while the older Hyades and Praesepe are enriched in metals and the

TABLE 3

CLUSTER AGES AND METALLICITIES

Cluster	Age (yr)	$\overline{[\mathrm{Fe/H}]}$	σ	n	$\overline{\delta m_0(\beta)}$[a]	σ	n
α Per	2×10^7	+0.004	±0.033	3	0.0062	±0.0086	21
					0.0067	±0.0086	19
Pleiades	7×10^7	+0.022	±0.062	8	0.0079	±0.0118	31
					0.0061	±0.0111	28
UMa Group	3×10^8	−0.095	±0.046	9	0.0240	±0.0094	8
					0.0305	±0.0100	3
Coma	4.3×10^8	−0.065	±0.023	7	0.0149	±0.0090	20
					0.0137	±0.0094	14
Hyades	6.7×10^8	+0.130	±0.026	14	0.0031	±0.0073	30
					0.0029	±0.0065	23
Praesepe	7.6×10^8	+0.092	±0.067	3	0.0064	±0.0116	30
					0.0043	±0.0118	21
Pleiades–α Per	5×10^7	0.017	±0.055	11	0.0071	±0.0106	52
Coma–UMa	4×10^8	−0.082	±0.039	16	0.0175	±0.0099	28
Hyades–Praesepe	7×10^8	0.125	±0.032	17	0.0048	±0.0098	60

[a] Upper entry in each case is for stars with $2.59 < \beta < 2.73$; lower entry is for stars with $b - y < 0.35$ or $2.625 \leq \beta < 2.73$.

older Coma and UMa Group are deficient in metals. The plot in Figure 6 shows clearly that there has not been uniform enrichment with time in the solar neighborhood on time scales near 10^8 yr.

The most straightforward interpretation of the lack of an age-metallicity relation for star groups that are $\leq 8 \times 10^8$ years old is that the gas in the Galactic disk where these clusters are formed is not well mixed, i.e., the general enrichment level is nonuniform and the circulation and mixing time of the gas exceeds $\sim 10^9$ yr. This has been suggested by Boesgaard, Budge, and Burck 1988 and Boesgaard, Budge, and Ramsay 1988. The rotation period for the Galaxy at the solar distance, 8.5 kpc (Kerr and Lynden-Bell 1986), and motion, 220 km s^{-1} (Hanson 1987), is 2.4×10^8 yr; apparently even four or five rotations are not sufficient to smooth out the mixture of "local" metal enrichments. Schatzman (1987) has estimated the mixing time scales in the Galactic disk due to diffusion to be 3×10^9 yr over a length scale of 10^{22} cm or ~ 3 kpc.

Different chemical histories can result from infall of intergalactic clouds which will alter the composition of the gas clouds in the disk with which they merge. The influence of infall on the cluster compositions is difficult to determine because the estimates of the flux of matter due to infall and to Galactic fountaining effects differ by orders of magnitude (e.g., Shapiro and Field 1976; Bregman 1978; Twarog 1980; Mirabel and Morras 1984; Carlberg *et al.* 1985).

Palous *et al.* (1977) have presented an interesting study of the places of formation of open clusters using Schmidt's (1965)

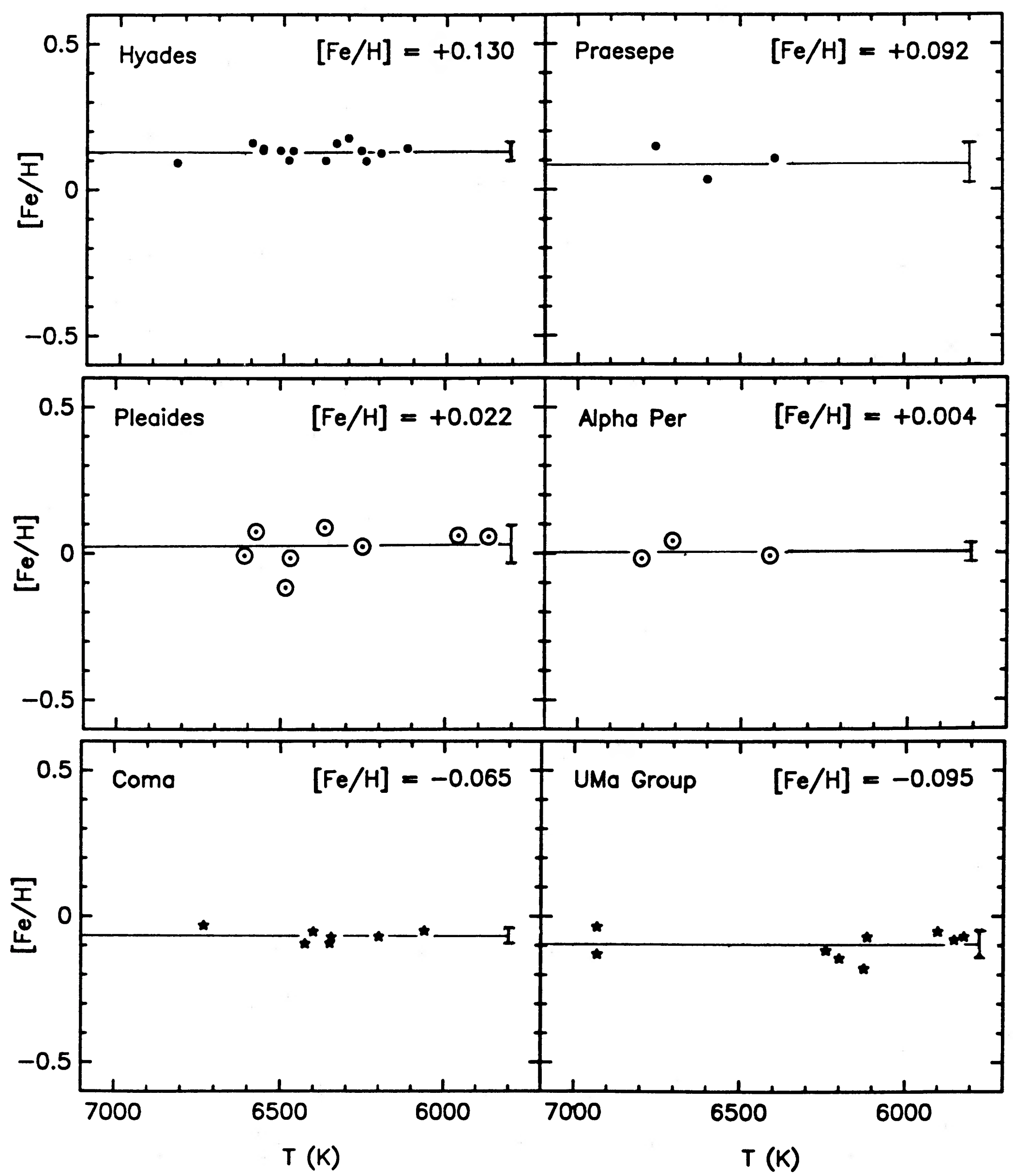

FIG. 3.—The logarithmic Fe/H abundances relative to the Sun, [Fe/H], are shown for each cluster as a function of temperature. There is no systematic temperature error, as indicated by the lack of dependence of abundance on temperature. The horizontal lines are the mean [Fe/H] in each cluster, and the small vertical bar to the right in each panel shows the error in the mean.

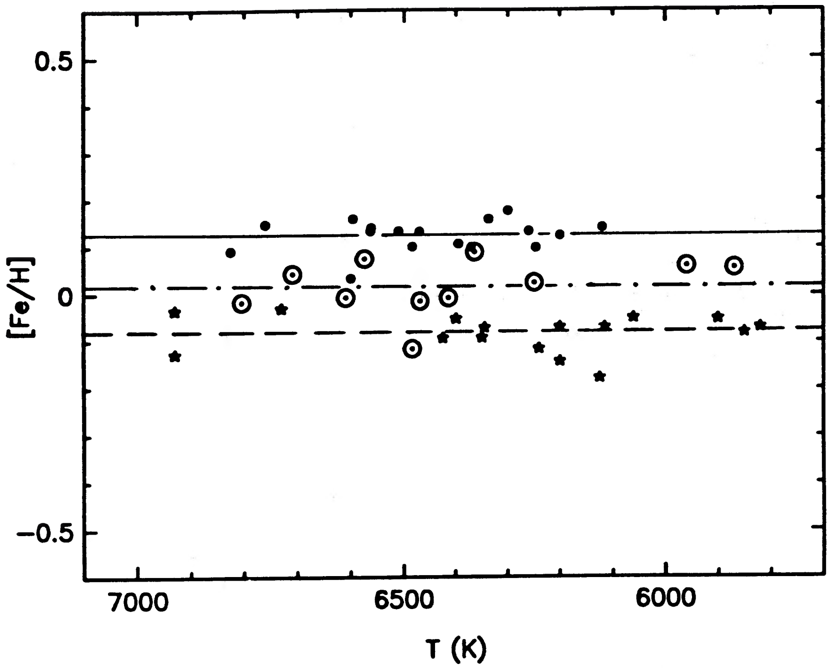

FIG. 4.—Combined results from Fig. 3. The Hyades and Praesepe stars are represented by the filled circles and the solid line, the Pleiades and α Per by the circled dots and the dash-dot line, and Coma and the UMa Group stars by the star symbols and the dashed line. The differences among the three groups are clearly seen.

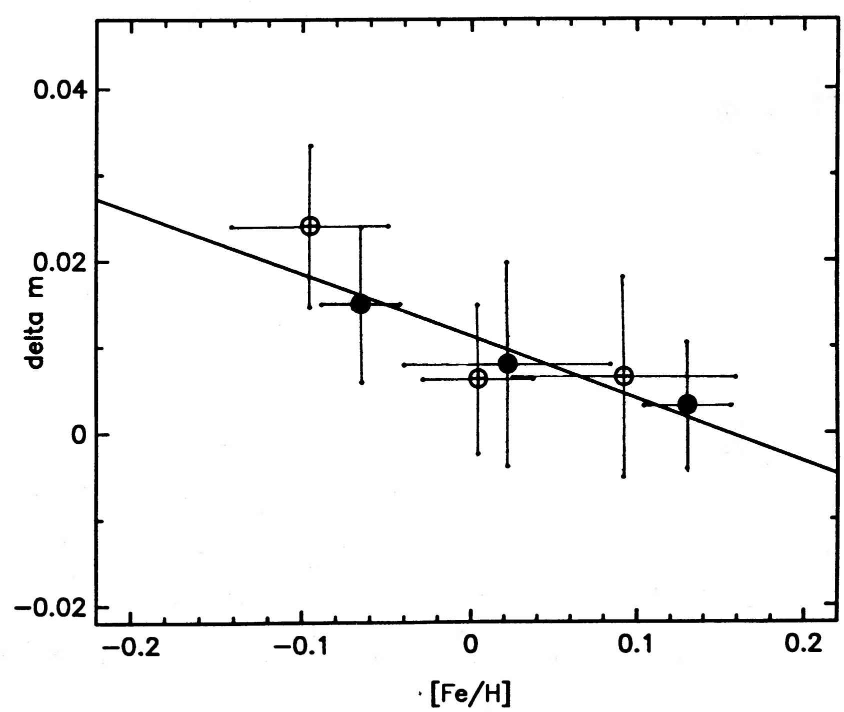

FIG. 5.—Calibration of the global averages for the Strömgren metallicity index, $\delta m_0(\beta)$, with the global [Fe/H] value for each cluster from Table 3. The filled symbols are for Coma, the Pleiades, and the Hyades, which have double weight in the straight-line solution.

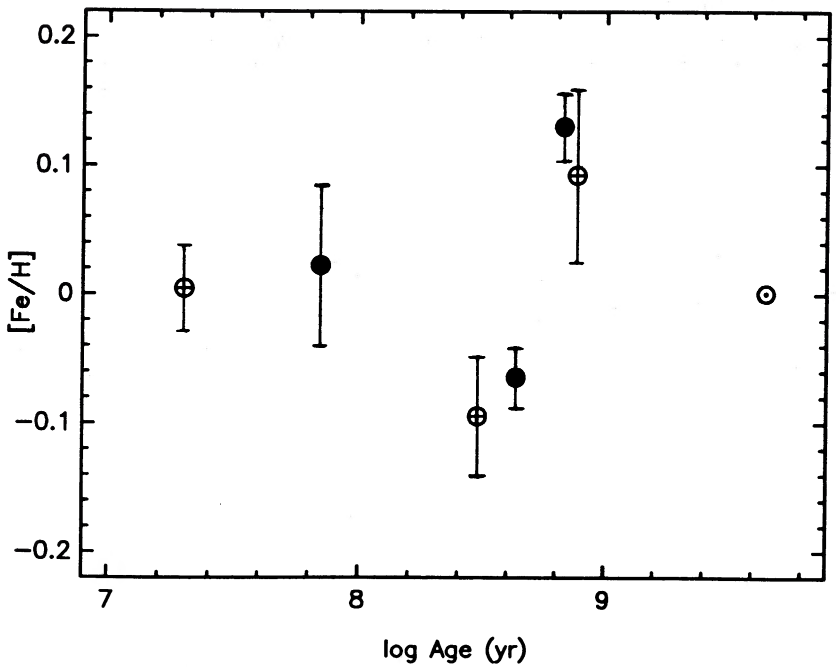

FIG. 6.—Cluster means of [Fe/H] as a function of age estimated from the turnoff point. The error bars are the errors in the mean $(Fe/H)_*/(Fe/H)_\odot$ converted to logs. The differences in the metallicities are clearly real and are *not* a function of age. Mixing of the interstellar matter in the Galactic disk is not thorough on time scales of a few times 10^8 yr.

axisymmetric model of the Galaxy, the spiral density wave theory, and published positions and velocities of Galactic clusters. Their best values for the angular rotation speed of the spiral arms are 13.5 and 20 km s^{-1} kpc^{-1}. Their results show the Hyades and Praesepe formed near to each other, about 120° from Coma, and about −150° from Pleiades and α Per. The last two are so young that they are still near their place of origin near the Sun. In this scheme the composition differences can be the result of the composition that was prevalent at that position and time in the evolution of the Galactic disk. So the Hyades and Praesepe were formed in a slightly metal-rich region, Coma in a slightly metal-poor region, and the Pleiades and α Per in the region of solar composition.

IV. CONCLUSIONS

It is possible to determine precise global values of [Fe/H] for Galactic clusters from high-resolution, high signal-to-noise spectra of F dwarf stars in those clusters. Selecting stars with well-determined temperatures and with low $v \sin i$ values improves the accuracy of the final averages. Results are presented for six clusters where the error in the mean is ≤ 0.05 dex for four of them. Two, the Pleiades and α Per, have solar metallicity: $[Fe/H] = 0.017 \pm 0.055$; two others, the Hyades and Praesepe, are metal-enhanced with $[Fe/H] = +0.125 \pm 0.032$, and the other two, Coma and UMa Group, are metal-deficient with $[Fe/H] = -0.082 \pm 0.039$.

The youngest clusters are the Pleiades and α Per at 7×10^7 and 2×10^7 yr, respectively; these two have solar metallicity. The other four clusters are all about an order of magnitude older and shown a spread in metallicity of 0.2 dex; two are enhanced and two are deficient compared with the Sun. The lack of an age-metallicity relation for these young clusters can be seen clearly in Figure 6. Apparently inhomogeneities in composition exist in the disk on mixing time scales of less than 10^9 yr. The positions where these three groups were formed in the disk were probably quite different, which contributes to their compositional differences.

Due to the accuracy of the global [Fe/H] values for each cluster, they can be used to provide a calibration of the Strömgren metallicity index, $\delta m_0(\beta)$. That result is $[Fe/H] = -13.8\delta m_0(\beta) + 0.15$ from the six clusters; this is applicable over a limited range in metallicity, about δm_0 of -0.01 to $+0.03$. An extension of this method to clusters with lower global metallicity would improve the accuracy of the calibration.

The next step is to expand the cluster base to include some which are older. The most logical clusters for this are M67 and NGC 752, but the main-sequence F stars are fainter and thus are a challenge to observe at the level of spectral resolution and signal-to-noise ratios of this work. Additional Fe I lines could be included, and a greater number of stars could be observed to find global means with smaller errors.

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