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The [Fe/H] distribution of a volume limited sample of solar-type stars and its implications for galactic chemical evolution*

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Abstract. We present [Fe/H] determinations for a volume-limited sample of G and K dwarfs from the Gliese catalog of nearby stars. The [Fe/H] values were determined from the Fe I lines present in $\simeq 40$ Å wide high resolution ($R \geq 50\,000$) spectra taken around the Li I 6707.8 Å line, through an equivalent width analysis based on the latest Kurucz model atmospheres.

The resulting abundance distribution, corrected for disk heating effects, is compared to recent models of galactic chemical evolution. The surprising result is that, while the abundance distribution of solar-type dwarfs hotter than $\simeq 5100$ K and the derived chemical evolution parameters (in particular the rate of Fe enrichment and the abundance spread at a given age) are compatible with previous determinations of the same quantities, dwarfs cooler than 5100 K show a lack of metal-poor ([Fe/H] $\lesssim -0.4$) objects, implying chemical evolution parameters (using the same model) not compatible with the ones derived for the hotter stars. Possible explanations for this fact are discussed, critically considering possible biases present in the parent sample, as well as each of the assumptions made in the chemical evolution model and in particular the assumption that the birth rate will be constant with time and independent of stellar mass.

Key words: stars: abundances – stars: late-type – stars: formation – Galaxy: evolution

1. Introduction

The metallicity distribution of unbiased samples of stars is one of the basic observational elements against which theories of the chemical evolution of the Galaxy are tested. Lower mass (K-type) stars are a critical group, in this context, because, in the disk's lifetime, they have not significantly evolved away from the main sequence. Most comparisons between observations and theory have been done using the metallicity distribution of volume limited samples of G dwarfs, which have been available, using photometric abundance determinations, since the '70s. In particular, the sample of Pagel & Patchett (1975), with subsequent corrections, has for a long time been the standard local abundance distribution against which models of galactic chemical evolution have been tested. It has been evident since the early days that simple models of chemical evolution of the Galaxy, which assumed zero initial metallicity and a chemically homogeneous disk, predicted far more low metallicity G dwarfs than what is actually observed. This apparent deficit of low metallicity dwarfs, which has become known as the "G dwarf problem", has been recently mitigated by the inclusion, in the theoretical interpretation, of important effects such as disk heating, which decreases the number of older stars in the solar neighborhood, as they diffuse away toward larger and larger scale heights, and of an initial disk metallicity. However, the problem has not completely disappeared. The reader is referred, for a more detailed discussion, to the review of Rana (1991) where the classical G dwarf problem is extensively discussed, together with the available observational material. As Rana (1991) notices, however, "it is necessary to check that the metallicity distribution for dwarfs of other spectral types do indeed conform with that of the G-dwarfs, given the same age–metallicity relationship. This cannot be accomplished without complete volume-limited data".

Homogeneous metallicity data on volume limited samples of cool dwarfs are not available in the literature. To study the metallicity distribution of spectral types other than G Rana & Basu (1990) used a collection of heterogeneous data, which included 60 K dwarfs, almost all of which came from the catalog of [Fe/H] determinations of Cayrel de Strobel et al. (1985). The uncertain selection criteria of the Cayrel de Strobel et al. (1985) (and subsequent versions) catalog, whose aim is simply to collect all the [Fe/H] determination in the literature, are likely to result in biases in the sample. In particular, as already noted by Rana & Basu (1990), the catalog is likely to be biased toward lower metallicity stars, which tend to be "interesting" for several reasons, and thus studied more often. A volume limited sample is in principle free from selection biases, although comparison

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with theoretical predictions has to include a correction for the already mentioned disk heating effect. This has to be done on the basis of an age-metallicity relationship and of a model of galactic dynamics. By being model dependent such corrections obviously introduce additional uncertainties.

In the present work we have analyzed the spectra of a volume limited sample of 91 G and K dwarfs, determining their [Fe/H] abundance using the available Fe I lines. These spectra were already used to study the lithium abundance of the sample stars (Favata et al. 1996). The sample is free from selection biases, and has been analyzed in a coherent way. It thus forms, with respect to collections of heterogeneous data, an improved starting point for comparison with theoretical models of galactic chemical evolution. In the present paper we compare the resulting metallicity distributions with the work of Rana & Basu (1990), in particular determining the slope of the age–metallicity relationship and the spread in metallicity at a given age, and determining whether the metallicity distributions for G and K are compatible with the same set of galactic evolution parameters.

2. The observed sample

The selection criteria of the sample have been described in detail by Favata et al. (1996) to which the reader is referred for details. The sample considered here is listed in Table 1. The objects in the sample have $B-V$ colors ranging between 0.5 and 1.4, with 0.8 marking the division between G and K dwarfs, and have been selected at random from the Gliese catalog of nearby stars (Gliese & Jahreiss 1979). The sample should in principle be free from any selection bias, and be truly representative of the solar neighborhood population. The observed sample is not however representative of the actual luminosity function of cool dwarfs, as it contains relatively more hotter stars than cooler ones. This is due to a pure observational bias, as cooler stars are on the average fainter, requiring longer exposures, and relatively fewer of them have been observed.

Five objects which appear in Favata et al. (1996) are not in the present paper, because the spectra were not of sufficient high quality for the present analysis or because they fell outside our cooler cut-off at 4300 K. For stars cooler than 4300 K our equivalent width analysis is not sufficiently accurate: the continuum disappears in a maze of molecular lines, and a full spectral synthesis analysis is needed, which is outside the scope of the present work. The loss of these 5 stars from the original sample, being due to accidental reasons, does not modify the characteristics of the original sample.

All the observations used in the course of the present work have been conducted using the CAT 1.4 m telescope at the ESO La Silla observatory in November 1993 and in February and August 1994, with the Coudé Echelle Spectrometer (CES), using the short camera with the RCA CCD (ESO #9), yielding an effective resolution of about 50 000. Seven of the spectra (for GJ 9730, GJ 691, GJ 744, GJ 746, GJ 9019, GJ 183, GJ 664) were acquired with the long camera, yielding an effective resolution of about 100 000. The data reduction procedure has been described in detail in Favata et al. (1996), to which the reader is referred for details. For GJ 664, GJ 183 and GJ 9019 (with $T_{\rm eff}$ of 4525, 4850 and 5375 K, respectively) we acquired spectra at both resolutions, verifying that no systematic differences in the derived abundances are present.

3. The effective temperature scale

There is still no widespread agreement neither on the absolute calibration of the effective temperature scale of cool dwarfs nor on the relationship between the photometric and spectroscopic (i.e. ionization balance) effective temperature scales. Given the dependence of the derived metallicity on the assumed effective temperature, and therefore on the final results of the present work, we review the process of derivation of $T_{\rm eff}$ in detail.

When dealing with a sample of stars of different metallicity, the $B-V$ index is not an appropriate $T_{\rm eff}$ indicator, as for the range of metallicity observed in our sample stars, the $T_{\rm eff}$ derived on the assumption of solar metallicity can be in error by as much as ~ 200 K (see Buser & Kurucz 1992). The $B-V$ versus $T_{\rm eff}$ calibration is also sensitive to interstellar reddening. The $R-I$ index is a much better choice, as it has very little sensitivity to metallicity effects at least down to [Fe/H] $\simeq -1.0$, and, the sensitivity to reddening is very small (although, even for nearby stars, as shown by Gray 1995, reddening induced effects can yield errors on $R-I$ derived $T_{\rm eff}$ as large as 20 K).

The most uncertain issue is the calibration of photometric indices in terms of "absolute" $T_{\rm eff}$. As discussed in detail by Bessel (1979), for more luminous stars absolute determinations of the effective temperature are based on interferometric stellar diameter measurements, which, when coupled with bolometric magnitude measurements, allow for the effective temperature to be derived from first principles, independent from any stellar atmosphere modeling. However, interferometric stellar diameter measurements are not available for the fainter stars, i.e. for late G and K dwarfs. Alternative approaches are possible. The one adopted by Bessel (1979) is to assume, supported by reasonable theoretical assumptions, that the atmospheres of lower gravity stars (giants) behave, from the point of view of the color–$T_{\rm eff}$ relationship, identically to the atmospheres of dwarfs. The $R-I$ versus $T_{\rm eff}$ calibration of Bessel (1979) for dwarfs is, for objects cooler than the Sun, essentially the one derived for giant stars.

The calibration of Bessel (1979) has recently been challenged by Taylor (1992), who determined a $R-I$ versus $T_{\rm eff}$ calibration for G and K dwarfs, using effective temperatures determined both from model atmosphere analysis of Balmer line wings and from infrared flux modeling. While both methods incorporate some degree of model dependence, they have the advantage of being explicitly calibrated on dwarf stars. The Taylor (1992) calibration differs, for cooler dwarfs, from the Bessel (1979) one. While both appear to have essentially the same sort of linear relationship between $1/T_{\rm eff}$ (usually using the variable $\theta = 5040/T_{\rm eff}$) and $R-I$ the difference in slope is large (see Fig. 1 of Taylor 1992), with redder K stars being hotter by as much as 250 K in the Taylor (1992) calibration.

Table 1. The [Fe/H] abundance relative to the solar one determined in the present work. For each star the Gliese (GJ) number is given, as well as the HD number (where available). The effective temperature given is the one of the model atmosphere used in the abundance analysis, while under the heading "Lines" the number of Fe I lines used in the abundance analysis for each object is reported. The derived [Fe/H] values are reported together with the RMS scatter of the abundances computed from the individual Fe I lines.

GJ	HD	$T_{\rm eff}$ (K)	Lines	[Fe/H]	GJ	HD	$T_{\rm eff}$ (K)	Lines	[Fe/H]
9029	4597	6150	10	-0.39 ± 0.04	9177	33811	5425	10	$+0.26 \pm 0.05$
904	222368	6125	8	-0.18 ± 0.06	9792A	214615	5425	9	$+0.00 \pm 0.06$
496A	113415	6125	11	$+0.07 \pm 0.04$	9350	NA	5425	9	-0.32 ± 0.03
9002A	142	6025	6	$+0.04 \pm 0.15$	113	17382	5425	9	$+0.21 \pm 0.06$
504	115383	6025	11	$+0.13 \pm 0.04$	315.0	73667	5400	10	-0.39 ± 0.05
127A	20010	6000	9	-0.35 ± 0.07	9019	3795	5375	7	-0.56 ± 0.02
198	34721	6000	9	-0.10 ± 0.03	559B	128621	5350	11	$+0.28 \pm 0.07$
312	73524	6000	11	$+0.16 \pm 0.04$	9045B	7438	5325	10	-0.24 ± 0.04
243	48938	5950	8	-0.38 ± 0.05	309	72673	5300	11	-0.34 ± 0.04
9209A	44120	5925	11	$+0.06 \pm 0.05$	56.3A	7895	5300	10	-0.03 ± 0.07
9287A	78643	5925	9	-0.06 ± 0.08	9249A	66509	5275	8	-0.67 ± 0.07
77	11112	5925	10	$+0.20 \pm 0.03$	9249AB	66509B	5275	8	-0.64 ± 0.06
404	94444	5900	7	-0.65 ± 0.06	9395.0	106092	5250	10	-0.27 ± 0.07
598	141004	5875	10	-0.03 ± 0.03	491A	112758	5225	9	-0.37 ± 0.03
9730	202628	5850	9	$+0.00 \pm 0.06$	120.1A	NA	5200	7	-0.47 ± 0.05
9802	216435	5850	10	$+0.15 \pm 0.04$	120.1B	NA	5200	7	-0.58 ± 0.04
559A	128620	5850	11	$+0.22 \pm 0.03$	505.0A	115404	5200	11	-0.10 ± 0.07
9819	219709	5825	10	-0.02 ± 0.04	53.1A	NA	5175	9	$+0.15 \pm 0.12$
327	76151	5800	10	$+0.09 \pm 0.04$	9245	64606	5175	8	-0.83 ± 0.08
691	160691	5800	9	$+0.28 \pm 0.04$	613.0	144628	5100	10	-0.33 ± 0.06
9252	67458	5800	11	-0.21 ± 0.04	42.0	5133	5000	11	-0.10 ± 0.05
19	2151	5775	9	-0.12 ± 0.04	368.1A	NA	4975	9	$+0.12 \pm 0.08$
9409	108799	5775	10	-0.10 ± 0.22	86.1	NA	4975	9	$+0.34 \pm 0.12$
9208A	43587	5775	11	-0.08 ± 0.04	165.2	NA	4950	9	$+0.04 \pm 0.10$
9317	88218	5775	9	-0.20 ± 0.06	18.0	2025	4900	9	-0.19 ± 0.08
9273A	73350	5750	10	$+0.09 \pm 0.05$	531.0	120780	4900	10	-0.17 ± 0.07
9037	6434	5750	9	-0.52 ± 0.05	429.0B	99492	4875	10	$+0.31 \pm 0.09$
9075B	13612B	5750	11	$+0.01 \pm 0.05$	118.2A	18143	4850	10	$+0.34 \pm 0.10$
9378A	103432	5725	11	-0.08 ± 0.04	183	32147	4850	9	$+0.31 \pm 0.10$
135	20619	5725	9	-0.21 ± 0.04	118.1A	NA	4825	10	$+0.18 \pm 0.09$
9396	106116	5725	11	$+0.15 \pm 0.04$	429.4	NA	4825	10	$+0.28 \pm 0.11$
9774	210918	5725	11	-0.12 ± 0.04	610.0	144253	4700	10	-0.03 ± 0.09
9092A	16619	5725	10	-0.06 ± 0.03	250A	50281	4700	10	$+0.07 \pm 0.10$
744	177565	5700	7	$+0.07 \pm 0.03$	293.2	NA	4675	10	-0.24 ± 0.07
9223A	53705	5675	9	-0.05 ± 0.03	456.1A	NA	4650	10	$+0.20 \pm 0.09$
9450	117939	5625	10	-0.23 ± 0.02	149	NA	4625	8	$+0.09 \pm 0.09$
9769	210277	5625	11	$+0.22 \pm 0.04$	141.0	21197	4575	8	$+0.26 \pm 0.08$
746	178428	5625	9	$+0.10 \pm 0.04$	868.0	214749	4575	9	$+0.12 \pm 0.12$
9790	213941	5625	8	-0.42 ± 0.07	664	156026	4525	8	-0.18 ± 0.06
9463	121849	5575	10	-0.28 ± 0.08	1106	NA	4475	10	-0.08 ± 0.10
869	214759	5575	11	$+0.25 \pm 0.05$	1176	119291	4475	9	$+0.10 \pm 0.09$
9220B	NA	5575	11	-0.08 ± 0.06	140.1A	NA	4450	10	-0.17 ± 0.09
9223B	53706	5525	9	-0.30 ± 0.05	428A	99279	4375	9	$+0.13 \pm 0.08$
530	120690	5475	11	-0.11 ± 0.06	9347	NA	4375	9	-0.03 ± 0.19
9269	72769	5475	11	$+0.27 \pm 0.06$	1177A	120036	4325	5	$+0.11 \pm 0.05$
580A	135204	5475	11	-0.07 ± 0.03					

We have determined the abundance for the present sample using both temperature scales. The upper envelope of the scatter plot of [Fe/H] versus $T_{\rm eff}$ derived using the Bessel (1979) calibration has a strong slope, with cooler stars having higher abundances with respect to hotter ones by about 0.2 dex. This indicates that the $T_{\rm eff}$ scale adopted is not coherent with the one of the model atmospheres used for the abundance analysis. Such a slope is not present in the data analyzed with the Taylor (1992) $T_{\rm eff}$ scale (see Fig. 1), which is therefore used in the following.

For most of the stars in the sample homogeneous $R-I$ photometry is available (Bessel 1990). For some of the stars however only $B-V$ or $b-y$ data are available (see Favata et al. 1996), for which Taylor (1992) does not offer a calibration. For these objects we have used the Bessel (1979) color–temperature calibration for the $B-V$ and $b-y$ colors and converted it to the Taylor (1992) absolute $T_{\rm eff}$ scale.

4. The abundance determination

The spectra used are $\simeq$ 40 Å wide, centered around the Li I 6707.8 Å line. In this spectral region we have identified 13 Fe I lines with sufficient strength in the spectrum of the Sun to allow a direct determination of the solar $\log gf$ values. Unfortunately, no Fe II lines are present in the limited spectral region under analysis, making it impossible to check the effective temperature through a determination of the Fe ionization equilibrium.

Abundance analyses were performed with the WIDTH9 code, using a grid of stellar models computed with the ATLAS9 code (Kurucz 1993a). For most of the stars in the sample no coherent multicolor photometry is available in the literature, and thus the surface gravity cannot be determined on an individual basis. We have therefore assumed that all stars are main sequence ones and adopted the value of surface gravity appropriate at each temperature for main sequence stars, based on the observed main sequence $\log g$–color relationship of Gray (1992). This introduces a small additional uncertainty for the few slightly evolved hotter stars in the sample. For the microturbulence parameter ξ we have used the relationship of Edvardsson et al. (1993), i.e.

$$\xi = 1.25 + 8 \times 10^{-4}(T_{\rm eff} - 6000) - 1.3(\log g - 4.5)\,{\rm km/s},$$

assuming a constant ξ of 0.2 km/s for the cooler dwarfs for which the relationship predicts values smaller than 0.2 km/s.

An extensive grid of stellar models was computed, spaced by 25 K in $T_{\rm eff}$, with temperature dependent $\log g$ and ξ values, and using the ξ = 2.0 km/s, solar abundance grid of Kurucz (1993a). For each star, the equivalent width of the Fe I lines listed in Table 2 was measured from the spectra, using the *splot* routine from the IRAF software package, and de-blending nearby lines when appropriate and possible (in particular the 6696.30 Å Fe I line is blended with a nearby Al I line. See also Sect. 4.1). The measured equivalent widths, together with the model atmosphere from the computed grid with $T_{\rm eff}$ closer to the actual photometrically determined value, were used as input to WIDTH9, which produces an abundance estimate for each line together with a mean abundance and a scatter. This mean abundance, together with the scatter, is reported in Table 1. Some of the lines could not be measured in some of the spectra, as in some case the radial velocity Doppler shift of the spectrum moved some of the lines outside the spectral region observed. Also, cosmic rays hits rendered, in a few cases, some lines unusable. Therefore in Table 1 we also report the number of Fe I lines contributing to the final abundance determination for each object.

Table 2. The line list. Also reported in the last two columns, for comparison purposes, are the $\log gf$ values from Abia et al. (1988) and Balachandran and Lambert (1988), indicated as ARB+88 and BL88, respectively.

	Å	χ (eV)	$\log gf$	ARB+88	BL88
Fe I	6696.30	4.836	−1.66	–	−1.65
Fe I	6699.16	4.594	−2.42	–	−2.27
Fe I	6703.57	2.759	−3.23	-3.31	−3.15
Fe I	6705.10	4.608	−1.26	–	−1.15
Fe I	6710.32	1.485	−4.69	-4.48	−4.49
Fe I	6713.05	4.608	−1.49	-1.51	−1.61
Fe I	6713.77	4.796	−1.59	-1.53	−1.48
Fe I	6715.38	4.608	−1.61	-1.57	–
Fe I	6716.22	4.581	−1.95	–	–
Fe I	6725.35	4.104	−2.33	-2.30	–
Fe I	6726.66	4.608	−1.24	-1.16	−1.48
Fe I	6732.07	4.585	−2.27	–	–
Fe I	6733.15	4.639	−1.59	–	–

Line data were taken from the extensive lists of Kurucz (1993b). The $\log gf$ values were estimated from each line by using the WIDTH9 code together with the solar model atmosphere of Kurucz (1993b). Individual $\log gf$ values were varied until the computed equivalent widths for each line were found to be in agreement with the equivalent widths measured from a set of high signal-to-noise solar spectra taken with the same instrumental configuration as the stellar spectra. This procedure (which obviously will yield a differential abundance analysis with respect to the Sun) has the advantage of intrinsically allowing some correction for eventual spectrograph peculiarities (such as scattered light). The $\log gf$ values thus determined were found to be in reasonable agreement, as indicated in Table 2, with the values of Abia et al. (1988) and Balachandran & Lambert (1988).

The larger error bars evident for the cooler stars in Fig. 1 are due to the often lower signal-to-noise in the spectra of these typically fainter objects, as well as to the difficulty of determining the continuum reliably in their more crowded spectra.

4.1. Blended lines

Three of the Fe I lines used in the analysis are blended and cannot be separated: Fe I 6705.10 Å is blended with a weak Fe I line at 6705.13 Å, Fe I 6713.05 is blended with a weak Fe I line at

6713.20 Å, and Fe I 6715.04 is blended with a weak Cr I line at 6715.41 Å. None of these blends can be resolved, and thus they have been measured as a single line. The $\log gf$ value determined from the solar spectrum is thus an "effective" $\log gf$ for the blend. This simplifying assumption, however, is only valid if the equivalent width of the two blended lines has the same temperature and abundance dependence. To verify this assumption we have generated a set of synthetic spectra, and determined the difference between the abundance determined by measuring the de-blended line (with an appropriately determined $\log gf$) and the abundance determined by measuring the equivalent width of the blend (with the $\log gf$ value determined as above). An induced error of $\leq 5\%$ has been considered as acceptable. For the 6705.10–6705.13 Å Fe I blend, the induced error is $\leq 1\%$ across the whole temperature range while for the 6713.05–6713.20 Å Fe I blend the error is $\leq 5\%$ across the whole temperature range. For the 6715.04–6715.41 Å Fe I–Cr I blend the error is acceptable for $T_{\rm eff} \lesssim 5000$ (where it is $\leq 5\%$), but it becomes larger for $T_{\rm eff} \gtrsim 5000$. Thus, the 6715.04–6715.41 Å Fe I–Cr I blend has not been used in the determination of the abundance of the objects cooler than 5000 K.

4.2. *The difference between high- and low-excitation potential Fe lines*

While the abundance values determined for hotter stars from all the Fe I lines are usually in very good agreement, with RMS scatters as small as 0.05 dex, for cooler stars the abundance values determined from the two low excitation Fe I lines in our line list (Fe I 6703.57 Å, with $\chi = 2.759$ eV, and Fe I 6710.32 Å, with $\chi = 1.485$ eV) are systematically lower by $\simeq 0.3$ dex than the abundance determined from the rest of the Fe I lines, which are all high excitation lines ($\chi \gtrsim 4.0$ eV). Such difference in the behavior of high and low excitation Fe I lines in cool stars is already well known in the literature, and it is attributed to non-LTE effects (cf. for example Fig. 3 of Drake & Smith 1991). The study of Steenbock (1985) shows that NLTE effects are primarily due to over-ionization of Fe I rather than to non-thermal excitation effects, and that, as a consequence, NLTE effects will increase with increasing line strength and decreasing excitation potential, due to the different depth of formation of the core of these lines. Steenbock (1985) notes that weak, high-excitation Fe I lines are the ones which, in an LTE analysis, yield the abundance closest to the "true" value, with low-excitation lines yielding a much lower abundance (as we indeed observe in the cooler stars in our sample). Therefore we have only used the high-excitation Fe I lines, and discarded the abundance derived from the low-excitation lines for all the stars in the sample, even when it appeared to be in good agreement with the abundance of the high-excitation lines.

5. Comparison with previous abundance determination

We have searched both the Cayrel de Strobel et al. (1992) (an updated version of Cayrel de Strobel et al. 1985) and the Taylor (1994b) (and Taylor 1995 and Taylor 1996 extensions) catalogs of abundance determinations for objects in our sample and have compared in detail our results with previously available abundance determinations. The two catalogs used are of a somewhat different nature. While the Cayrel de Strobel et al. (1992) catalog is essentially an annotated bibliography of literature data, the series of papers from Taylor is part of an organic attempt at reassessing the literature data on [Fe/H] in cool stars. To this end, the [Fe/H] literature values have been converted to a coherent temperature scale (the same one adopted in the present work), thus forming a much more homogeneous data set, against which more meaningful comparisons are possible. For the purpose of assessing the consistence of our [Fe/H] values with previous literature data we have enhanced the data set discussed here with another set of stars (from Favata et al. 1997), which have been taken with the same instrument, and have been reduced and analyzed together with the data discussed here. While they do not form a volume limited sample, and are not discussed here, they can still be used for the purpose of assessing the whole analysis procedure.

We have searched the Taylor series of catalogs for stars in common with our extended sample, and found 35. One object (GJ 27) has been excluded from the comparison as the literature photometric and spectroscopic abundance determination appear strongly discrepant. We have also added a star (GJ 309) for which the abundance has recently been determined by Flynn & Morell (1997). For the 35 objects in common with Taylor and with Flynn & Morell (1997), we have plotted (Fig. 2) our [Fe/H] values against the ones from the Taylor catalogs. Also plotted are the "ideal" 45 deg relationship (dotted line) as well as a least square fit to the data points. Our [Fe/H] values are on the same scale as Taylor's catalog, as the slope of the mean relationship is 1.028 and the zero-point shift is only 0.02 dex. The RMS scatter of the difference between our [Fe/H] values and Taylor's is 0.09 dex. The data points in common with literature values cover the complete range of metallicities represented in the present work, from the most metal-poor object up to the most metal-rich ones.

Some works in the literature also report the actual equivalent widths for some lines in common with our analysis. When possible, we have compared them in detail. Abia et al. (1988) performed an abundance analysis on a number of cool stars using data from the same spectrograph as the one used here, although with an older Reticon detector, and in the same spectral region. Our sample has 3 stars (GJ 19, GJ 559A, GJ 559B) in common with the Abia et al. 1988 sample, and for these 3 stars the equivalent widths for the Fe lines in common agree with the equivalent widths determined in the course of the present work to $\sim 5\%$.

Pasquini et al. (1994) have observed a sample of early G dwarfs in the same spectral region around the Li I line, also with the same instrument and detector combination, with 8 objects in common with our sample. They have also performed a [Fe/H] analysis, however using only two Fe lines, the ones at 6703.57 and 6705.10 Å. While we have decided not to use the 6703.57 Å line in our abundance analysis because of the considerable non-LTE effects in the cooler stars (which however appear to be

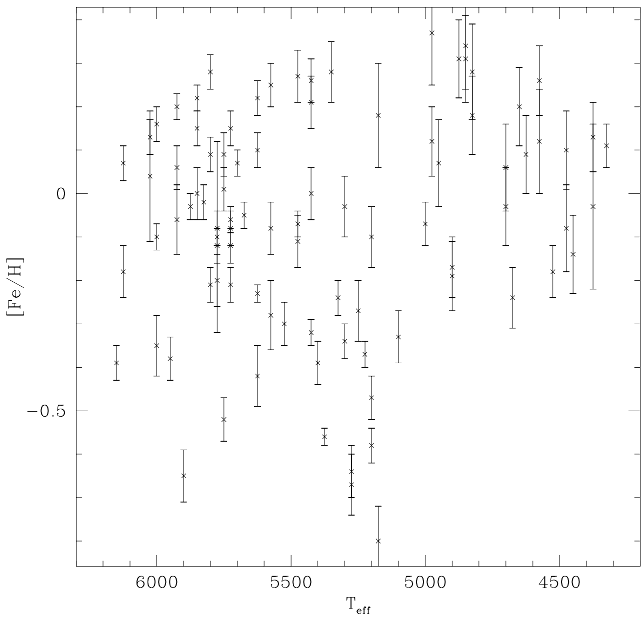

Fig. 1. The Fe abundance, plotted against effective temperature, for the whole sample studied in the present work. The vertical error bars are the formal error on the abundance determined by the spread of the values derived from the individual Fe lines.

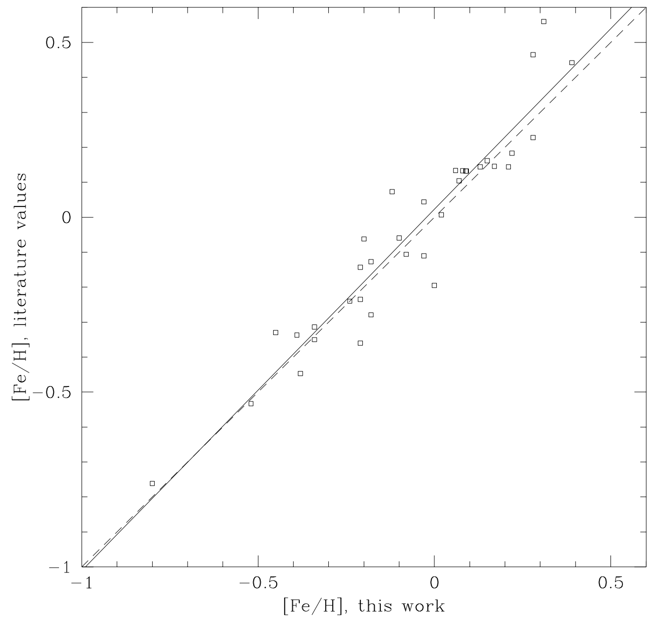

Fig. 2. The [Fe/H] values determined in the present work are plotted against literature [Fe/H] values for the 35 stars present in the Taylor series of catalogs (see main text). The dashed line is the ideal 45 deg relationship, while the continuous line is the actual least square fit to the data points.

negligible in the hotter stars studied by Pasquini et al. 1994), we have compared the equivalent widths reported by Pasquini et al. (1994) for these two lines with ours, finding that they also agree to better than 7% (peak to peak relative dispersion). Two of the stars in common between our work and Pasquini et al. (1994) have differenced in the derived metallicities as large as 0.2 dex. Given the small difference in the measured equivalent widths, these difference are to be attributed partly to the differences in the model atmosphere parameters (specially the $T_{\rm eff}$), and partly to the different set of model atmospheres used. The effective temperatures of Pasquini et al. (1994) differ in some cases from the ones adopted here by as much as 100 K, while the $\log g$ values are mostly close to the main sequence ones adopted in the present work, except in one case (GJ 77) for which Pasquini et al. (1994) assume $\log g = 4.0$, i.e. significantly above the main sequence.

6. The abundance distributions

The Fe abundance, relative to the solar value, for the whole sample studied in the present work, is plotted in Fig. 1. The [Fe/H] values in our sample ranges from $\simeq +0.3$ down to $\simeq -0.8$, the typical range of Pop. I stars. However, the range of metallicities present in the hotter and cooler stars in the sample appears different, with the cooler stars presenting an apparent deficit of metal poor stars, with an apparent break in the distribution at $T_{\rm eff} \simeq 5100$ K, hinting at a lack of metal poor K dwarfs in the solar neighborhood. As the density of stars as a function of $T_{\rm eff}$ in the same plot is not constant (because of the observational bias discussed in Sect. 2), and low metallicity stars are rarer, the apparent lack could be due to worse sampling. To give a quantitative estimation, we have determined the probability that the [Fe/H] distribution of stars cooler and hotter than 5100 K are drawn from the same parent distribution, using Gehan's generalized Wilcoxon test as implemented in the ASURV Rev. 1.2 package (LaValley et al. 1992). The two distributions (in their raw form, i.e. without correction for disk heating effect) are found to be different at the 98% confidence level. We thus find evidence for a lack of metal poor K dwarfs with respect to the G dwarfs in the solar neighborhood.

The two distributions, the one for the stars cooler than 5100 K and the one for the hotter stars are shown, corrected for disk evaporation in Fig. 3 (the correction applied is explained in Sect. 7). The error bar plotted is derived from the raw number of objects per metallicity bin, using the appropriate 1 σ estimate for Poisson statistics in the presence of small numbers, using the approach of Gehrels (1986). It is again evident that the cooler stars show a lack of metal poor objects with respect to the hotter ones. In particular, there appears to be a complete lack of mid and late K dwarfs with [Fe/H] lower than $\simeq -0.4$. In the hotter star group there are 48 stars with [Fe/H] $\gtrsim -0.4$ and 17 with [Fe/H] < 0.4. If we assume that the cooler stars should have the same distribution, then, scaling on the total number of cooler stars (25 objects) we would expect to find 7 cool objects with [Fe/H] < 0.4. We find none, and, assuming a Poisson distribution in each bin, this is significant to the a probability level of 2×10^{-5}.

Before attributing any physical significance to the lack of metal poor cool dwarfs in our sample, we have examined in

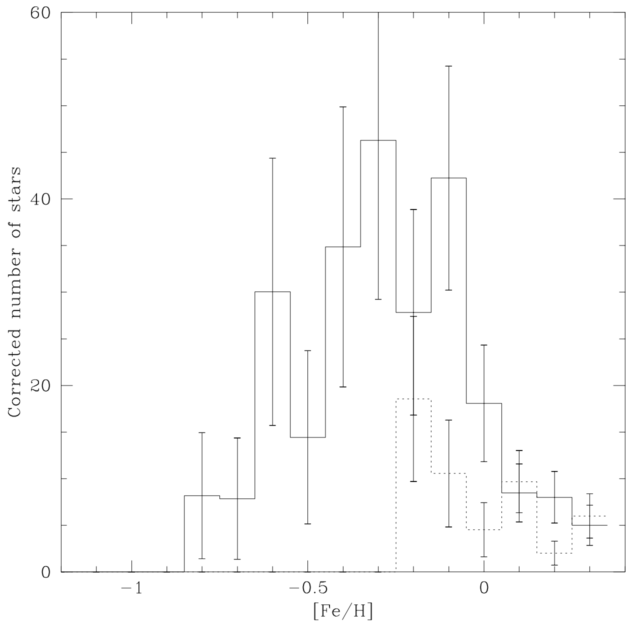

Fig. 3. The histogram of [Fe/H] values, for stars hotter (continuous line) and cooler (dashed line) than 5100 K. The values have been corrected for scale height inflation (see Sect. 7).

detail whether systematic effects or biases in the sample may be responsible for the effect.

6.1. Error analysis

To assess if systematic effects may (at least) partially be responsible for the apparent lack of cool metal poor dwarfs in our sample we have studied the influence of uncertainties in the fundamental parameters of each star on the final abundance value. Assuming a reference value of $T_{\rm eff}$ = 5000 K, log g = 4.5 and ξ = 1.5 km/s, we have derived the following relationships between uncertainties in the atmospheric parameters and derived abundance:

$$\frac{\partial[\mathrm{Fe/H}]}{\partial T_{\rm eff}} = \frac{0.045\,\mathrm{dex}}{100\,\mathrm{K}},$$

$$\frac{\partial[\mathrm{Fe/H}]}{\partial \log g} = \frac{0.15\,\mathrm{dex}}{\mathrm{dex}},$$

$$\frac{\partial[\mathrm{Fe/H}]}{\partial \xi} = \frac{-0.22\,\mathrm{dex}}{1\,\mathrm{km/s}}.$$

The order of magnitude of the effects, as well as their relative importance, are similar across the range of $T_{\rm eff}$ studied here. Random temperature errors will produce a broadening in the resulting [Fe/H] histogram, while systematic errors in the temperature calibration of the cooler dwarfs would shift the whole distribution. This would cause a slope in the upper envelope of the points of Fig. 1 (which is not observed), and would not selectively move the more metal poor stars toward higher abundances (unless the temperature calibration was strongly metallicity dependent). Another additional small uncertainty is introduced by the usage of solar-abundance model atmospheres for all the objects. We have determined the additional uncertainty induced by this as $\leq$ 7% for the most metal poor stars in the sample.

Most of the stars in the present work have $R-I$ colors available (see Favata et al. 1996 for details), which are, as discussed in Sect. 3, almost totally free from metallicity effects. For some of the cooler dwarfs, only $B-V$ colors are available. The $T_{\rm eff}$ versus $B-V$ calibration does show a considerable metallicity effect, with metal poor dwarfs being cooler than derived from their $B-V$ color on the assumption of solar metallicity, with a slope of $\simeq$ 200 K per dex in [Fe/H] for G and K dwarfs (Buser & Kurucz 1992). Therefore, a star with a "true" [Fe/H] of -1.0 for which only the $B-V$ color was available would have its metallicity over-estimated by $\simeq$ 0.05 dex. Even in the hypothesis that all the metal poor cool dwarfs are "hiding" in the less well studied and therefore fainter stars, which would only have $B-V$ colors available (in principle possible, given that they are expected to be rarer, and thus, on average, farther away), the effect is too small to significantly modify the distribution of Fig. 3.

Potentially larger is the effect of the uncertainty in log g. Given that for most stars in our sample (specially for the cooler ones) no gravity data are published, we have performed the metallicity analysis under the assumption of a log g appropriate for main sequence stars. Metal poor dwarfs would have a higher surface gravity, and thus their estimated metallicity would be slightly lower than the correct one. This effect would not subtract stars from the metal poor part of Fig. 1, but rather add them. On the contrary, metal poor cool sub-giants, if at all present, would have their metallicity significantly underestimated (by $\simeq$ 0.15 dex) by the analysis procedure used here. However, the eventual presence of a few higher mass evolved stars would not influence the lack of metal poor objects among the unevolved K dwarfs.

The sensitivity of the derived [Fe/H] value on the adopted micro-turbulence value is also large, and could in principle shift the resulting distribution toward higher metallicity, should metal poor cool dwarfs have consistently lower micro-turbulence values than their metal rich counterparts. However, while we do not have independent determinations of the micro-turbulence parameter, a wrong value of ξ would cause a plot of the abundance derived from each individual line versus the equivalent width of the line to show a significant slope (the slope being zero for the correct micro-turbulence value). We have examined the abundance versus equivalent width plot (which is produced by the WIDTH9 code) for each star in the sample, and in no case was a significant slope found, thus providing evidence for the correctness of the adopted micro-turbulence.

Another effect which might affect the metallicity determination of the cooler stars is the continuum blanketing due to diatomic molecules. The line strength of diatomic molecules (not the hydrides) goes roughly like the square of Z, while the line strength of the atomic lines is roughly linear with Z. The effect of this is to depress the continuum, relative to the atomic lines, more in the metal-rich objects (making them appear of lower Z than they actually are) than in the metal-poor ones, effectively compressing the metallicity scale, and potentially "bunching" the cooler stars together in Fig. 1. To estimate how much this may affect our analysis we have computed a set of synthetic spectra at the cooler effective temperature present in our sample (4325 K). The 4 spectra were computed with $Z = 1.0$ and $Z = 0.1$, both using all the molecular line lists (of C_2, CN, CO, SiO and TiO) present in the CD-ROMs No. 15 and No. 18 of Kurucz's set, as well as using *no* molecular line list at all. These molecular line lists contain very many lines which are predicted from atomic physics calculations, but which have not been experimentally measured. While their wavelength may be significantly wrong, and thus they cannot reliably be used for individual line identification, their combined statistical effect should still be reliable. From these model spectra we have evaluated that the total combined effect of continuum depression due to diatomic molecules is, even at the coolest $T_{\rm eff}$ in our sample, negligible (i.e. less than 0.02 dex).

Last, we have checked the possible effect of using a model grid computed for a ξ value of 2.0 km/s (although we have used the appropriate, $T_{\rm eff}$ dependent value of ξ in the abundance calculation). To this end we have, again for the coolest of our temperatures, verified that the usage of a $\xi = 2.0$ km/s model produces abundances that are within 0.01 dex of the abundance computed using a $\xi = 0.0$ km/s model. Thus, neither diatomic molecule continuum blanketing nor micro-turbulence effects in the model atmospheres can explain the observed deficit of metal-poor cool dwarfs.

6.2. Biases present in the parent sample

The observed lack of metal poor cool stars could in principle be a simple reflection of a similar bias present in the parent sample used in our work. The key point is the assumption that the Gliese catalog (our parent sample) is complete and unbiased. Both of the above assumptions are known not to be true to some extent. The presence in the Gliese catalog of biases dependent on magnitude and spectral type and class has been shown recently by Perryman et al. (1995), who, on the basis of preliminary Hipparcos data show, for example, that most of the giants present in the Gliese catalog are actually much further away than 25 pc. Also, (see their Fig. 8) the number of main sequence stars which, while being in the Gliese catalog are actually much further away, depends on the stellar mass, being larger for the G dwarfs, smaller for the early K dwarfs, and essentially nil for the later K dwarfs.

Could such bias be (at least in part) metallicity-dependent? The presence of stars in the Gliese which are actually further away depends (in addition to the statistical uncertainties in the parallaxes) from the usage, in addition to trigonometric parallaxes, of spectroscopic and photometric parallaxes. The final parallax which is used in the Gliese catalog as a criterion for inclusion is the result of a weighted average between the trigonometric, photometric and spectroscopic value, with the weight being based on the formal error. It is thus possible that spectrophotometric parallaxes with small formal errors, but affected from strong systematics, have induced biases in the catalog.

In particular, a metallicity dependent bias could be induced from the usage of photometric calibrations which are not fully corrected for metallicity effects. If metal-poor G dwarfs had been estimated to be systematically fainter (and therefore closer), or if, conversely, metal-poor K dwarfs had been estimated to be systematically brighter, this could induce a bias in the Gliese catalog which could lead to the present results. The Gliese catalog represents, with its limitations, the best parent sample available at the moment for K dwarfs. However, before the present results can be taken at face value, biases present in the Gliese catalog itself will have to be investigated.

7. Derivation of chemical evolution parameters

Ultimately, the observed abundance distributions reflect the chemical evolution of the Galaxy. By assuming a certain model of chemical evolution it is possible to verify whether the experimental data justify the model's assumptions and, eventually, to derive the model's parameters. Simple models of galactic chemical evolution, in which the metallicity is a single valued function of time and the initial disk metallicity is zero, have since long been shown to be in disagreement with the observed G dwarf metallicity distribution. Here, we follow the simple approach of Rana & Basu (1990), who fit the metallicity distributions by assuming a linear dependence of the mean metallicity with time and a constant gaussian spread in metallicities at any given time, together with a constant stellar birth rate. The age-metallicity distribution is constrained at the present epoch, at a value equal to the Hyades' mean metallicity, while the slope is derived from the data.

To fit the data, we have first corrected the observed raw number of stars in each metallicity bin for the disk evaporation effect, using the correction factor of Rana (1991), which increases the number of stars in the lower metallicity bins, by as much as $\simeq 8$ for the lowest metallicity bin. This also explains the apparently larger error bars for the lower metallicity bins. We have also assumed (as in Rana & Basu 1990) that the disk's age is 12.0 Gyr, while the main sequence lifetime is 11.0 Gyr for the G dwarfs and 15.0 Gyr for the K dwarfs. Also, while Rana & Basu (1990) assume a value of 0.17 for the Hyades' mean metallicity, we have assumed 0.107, the value derived by Taylor (1994a) using the same temperature scale as the one used in the present work. Using their sample of G dwarfs Rana & Basu (1990) derive a slope for the age–metallicity relationship $\alpha = 0.042 \pm 0.020\,{\rm dex\,Gyr^{-1}}$ (implying an initial metallicity for the disk of -0.33 dex), and a metallicity spread at a given age $\sigma = 0.24 \pm 0.10$ dex, which, they find, also satisfactorily fits their heterogeneous sample of K dwarfs. However, as they caution, the G dwarf sample used in their work yields different parameters than previous literature samples, and the resulting parameters, while providing a satisfactory fit to the K dwarf distribution, do not agree with the A and F dwarf metallicity distributions.

The fit to our G dwarf metallicity distribution is shown in Fig. 4. The derived parameters are $\alpha = 0.067 \pm 0.024\,{\rm dex\,Gyr^{-1}}$ and $\sigma = 0.16 \pm 0.12$ dex, i.e. compatible with the parameters

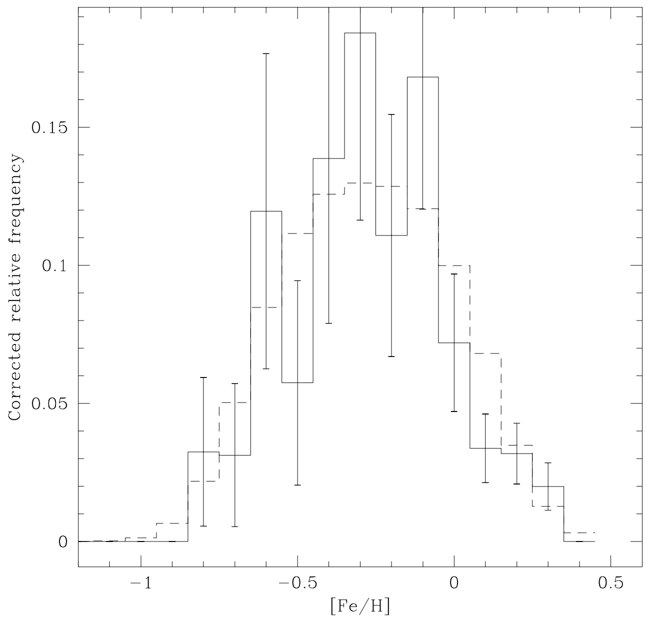

Fig. 4. The histogram of [Fe/H] values, for stars hotter than 5100 K (continuous line), together with the theoretical fit to the data (dashed).

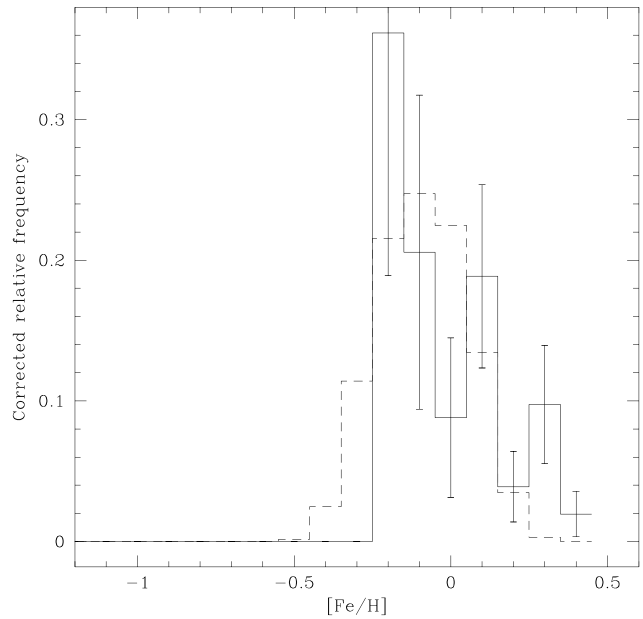

Fig. 5. The histogram of [Fe/H] values, for stars cooler than 5100 K (continuous line), together with the theoretical fit to the data (dashed).

found by Rana & Basu (1990) for their sample. The same parameters do not however provide a satisfactory fit to the metallicity distribution of cooler stars. The fit to that distribution yields $\alpha = 0.034\,\mathrm{dex\,Gyr^{-1}}$ and $\sigma = 0.08$ dex. The inferred initial metallicity for the disk is -0.73 dex for the G dwarfs and -0.30 dex for the cooler dwarfs. The fit to the G dwarf metallicity distribution does not provide a satisfactory fit to the K dwarf metallicity distribution, with a reduced χ^2 of 1.88 with 16 degrees of freedom, corresponding to a probability level of $\gtrsim 98\%$.

Note that a constant star formation rate has been assumed. Possible bumps in the metallicity distribution can be used to trace lulls and peaks in the star formation rate (as done by Rana 1991 for the G dwarf distribution), however our sample is too small to allow such more detailed analysis.

We have also compared the chemical evolution parameters derived here with the ones derived by Edvardsson et al. (1993) for a large (albeit not volume limited) sample of somewhat evolved late F and early G dwarfs for which they carefully determined both the abundances of several elements as well as the individual ages (by fitting evolutionary tracks to the position of each star in the HR diagram). Their sample shows a variation of the mean abundance of $\simeq 0.08\,\mathrm{dex\,Gyr^{-1}}$, i.e. essentially the same value which we find for our G dwarf sample. The estimated scatter at any given age, $\simeq 0.2$ dex, is also in agreement with the result obtained for our G dwarf sample.

8. Discussion

The present results, taken at face value, indicate that the cooler K dwarfs may have had a different chemical evolution than G dwarfs, in particular showing, in their present day metallicity distribution, a deficit of lower metallicity stars. Before any conclusion is drawn from this observational fact, it is important to stress that the samples discussed here are relatively small, so that the two metallicity distributions (for cooler and hotter dwarfs) are only different at the 98% confidence level.

Assuming nevertheless that the difference between the two metallicity distributions is real, and not simply a statistical artifact, or a consequence of biases present in the parent sample, the implications can be far-reaching. If we assume that the simple model that we have used is a good representation of the reality, the different model parameters for the two sub-samples imply that the initial metallicity of the disk was significantly different for cooler and hotter stars. Such a conclusion is, for obvious physical reasons, unlikely, and it would assume the existence of a "cosmic conspiracy" that brings the metallicity of cooler and hotter dwarfs together at the current epoch. It is however interesting to compare our result with Fig. 8 of Eggen (1996), which shows the relationship between the chromospheric age and the photometrically derived metallicity for a sample (not randomly chosen) of Gliese stars in the range of spectral types K5V–M4V (i.e. cooler than considered here). The change in mean metallicity along the disk's lifetime for the sample shown there is of only $\simeq 0.3$ dex, i.e. a value very similar to our result. The spread in Eggen's data is however very large. If we discard the possibility of different initial abundances in the disk for stars of different masses, we have to question the assumptions of the chemical evolution model.

One of the assumptions, namely the one of identical present-day metallicity, is strictly speaking untested, as all the published accurate spectroscopic determinations of metallicity in Hyades stars (as well as in other young and intermediate age open clusters) are limited to stars hotter than $\sim$ 5000 K (see

Taylor 1994a). It is thus in principle possible that the assumption of identical present day abundance for G and K stars is not correct. However, while certainly it would be desirable to have good metallicity determinations for cool Hyades dwarfs, to verify this assumption, the near coincidence of the upper range in metallicity for the cooler and hotter dwarfs (see Fig. 3) can be taken to indicate that the present-day metallicity is not strongly mass-dependent for G and K dwarfs.

The other key assumption of the simple model used here is the constancy of the stellar birth rate, across the Galaxy's lifetime, and for the whole range of masses. This is clearly a simplistic assumption, tantamount to assuming that the IMF is a truly universal function, independent of the physical condition of the star formation environment. In fact, observational evidence is accumulating showing that the IMF from different star-forming regions and embedded young clusters is *not* universal. Meyer (1996) has shown, for example, that the IMF's of two embedded clusters (NGC 2024 and the Ophiuchus cloud core) are actually different, and that more in general the ratio of the number of intermediate (1.0–10 $M_\odot$) to low (0.1–1.0 $M_\odot$) mass stars in various embedded clusters is not constant, and ranges between $\simeq 0.1$ and 0.45, while in the Miller-Scalo IMF (the one observed for the field) has a value of 0.17. On the basis of the available observational evidence Meyer (1996) suggests that higher stellar density embedded clusters would tend to form more intermediate mass stars, and lower density ones would form more low mass stars.

It is not unreasonable to expect that one of the important parameters, driving the development of the star forming process, may be the total metallicity of the parent cloud. In fact, the cooling of a molecular aggregate (the main star forming environments in our Galaxy) is dominated by the radiation of molecules containing elements heavier than He, so that it does not seem far fetched that a different initial abundance may lead to different conditions in the collapsing cloud and thus to a different mass spectrum in the resulting stellar population. Our observed metallicity distribution would seem compatible with a scenario in which low mass stars preferentially form in higher metallicity clouds, while intermediate mass stars form more efficiently in lower metallicity clouds, producing an apparent deficit of low metallicity low-mass stars. Such a scenario would imply a mass-dependent age–metallicity relationship and an age-dependent IMF. In this context, it is also suggestive that the present day mass function (which should be identical to the initial mass function for stars cooler than mid-G, given that their main sequence lifetime is longer than the disk's age) is not smooth in the mass range discussed here, but rather it shows a bump at masses corresponding to $\simeq 0.7$ and $\simeq 0.15\,M_\odot$, implying "two mass scales in the process of star formation" (Rana 1991). The position of the first bump corresponds with the mass range of the cooler sub-sample discussed here.

Again, the sample on which this paper is based is relatively small. Given that the implications of the present results are potentially far-reaching, an effort should be made to enlarge the sample, determining the metallicity of a larger volume limited sample of cool dwarfs. Also, the metallicity of the cooler dwarfs in open clusters (specially the Hyades) should be accurately determined, testing the key assumption that the present day metallicity is not a function of stellar mass.

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