Astron. Astrophys. 339, 791–801 (1998)

ASTRONOMY
AND
ASTROPHYSICS

Consistency of the metallicity distributions of nearby F, G and K dwarfs

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Received 24 March 1998 / Accepted 8 September 1998

Abstract. The consistency of the metallicity distributions of F, G and K dwarfs is studied. We present a new metallicity distribution for K dwarfs using metallicities determined from *uvby* photometry. There is a remarkable paucity of metal-poor K dwarfs in analogy with the G dwarf problem. We show that late-type dwarfs have consistent metallicity distributions. We also propose preliminary corrections to these distributions to take into account the contamination of the *uvby* indices due to the chromospheric activity in these stars, since around 30% of the nearby late-type dwarfs have active chromospheres. We consider the possibility that the metallicity distribution of cooler stars may be different from that of the hotter stars due to (i) metal-enhanced star formation and (ii) a metallicity bias in the catalogue of nearby stars. We conclude that these hypotheses are unlikely to produce important differences in the metallicity distributions of late-type dwarfs.

Key words: stars: abundances – stars: late-type

1. Introduction

Thirty six years after its discovery by van den Bergh (1962), the G dwarf problem still presents challenges to the astrophysicists studying Galactic Evolution. Although several mechanisms for decreasing the number of metal-poor dwarfs in the Galaxy have already been devised, the shape of the metallicity distribution is generally not very well reproduced by the majority of models in the literature. In fact, given the uncertainties in the data, obtaining a good fit to the G dwarf metallicity distribution was less significant than to search for an explanation for the paucity of metal-poor objects. However, after the recent derivation of a new G dwarf metallicity distribution (Rocha-Pinto & Maciel 1996, hereafter RPM), the G dwarf problem cannot be regarded as just the paucity of metal-poor stars, compared with Simple Model predictions. RPM showed that, besides the small number of metal-poor objects, there is also a small number of metal-rich dwarfs and an excessive number of dwarfs with intermediate metallicities. These results were already predicted by Malinie et al. (1993) on the basis of an inhomogeneous chemical evolution model. Infall models also seem very suitable to reproduce the shape of the new metallicity distribution, as shown by RPM and Chiappini et al. (1997).

Recently, Favata et al. (1997) have obtained spectroscopic metallicities for a sample of 91 nearby G and K dwarfs. They found a very narrow K dwarf metallicity distribution, in which no stars have [Fe/H] < -0.4, in contrast with the broader G dwarf metallicity distribution they have also derived. They have offered two possible explanations for this discrepancy: the Se cond Catalogue of Nearby Stars (Gliese 1969; Gliese & Jahreiß 1979; hereafter CNS2) from which they have selected their sample could have a metallicity bias, in the sense of favouring metal-rich stars; alternatively, less massive stars should preferably form in metal-rich regions.

In this paper, we make an effort to derive the metallicity distribution of K dwarfs in the solar neighbourhood, along the same lines followed for the G dwarfs (RPM). Our main purpose is to see whether or not these distributions are different from each other. As it will become clear in the following sections, the metallicity distribution by RPM can be taken as representative of the true late-type star metallicity distribution in the solar neighbourhood. We also present preliminary corrections to photometrically derived metallicity distributions that take into account the effect of the chromospheric activity on the *uvby* indices (Giampapa et al. 1979; Basri et al. 1989; Giménez et al. 1991; Morale et al. 1996; Rocha-Pinto & Maciel 1998). The contamination of the photometric indices by the chromospheric activity is one of the most important sources of systematic errors in photometric [Fe/H] surveys, and has been often ignored.

This paper is organized as follows: in Sect. 2, we present the selection criteria for the sample of K dwarfs, and derive the corresponding metallicity distribution. In Sect. 3, the derived distribution is compared with the G dwarf metallicity distribution, and the consistency of the metallicity distributions of late-type dwarfs of types F, G, and K is considered. In Sect. 4, we present the proposed corrections owing to the chromospheric activity, and apply them to both G and K dwarf metallicity distributions. A discussion of the results by Favata et al. (1997), especially regarding the differences between their derived distributions is given in Sect. 5.

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2. The K dwarf metallicity distribution

We have selected a preliminary sample from the Third Catalogue of Nearby Stars (Gliese & Jahreiß 1991; hereafter CNS3). This sample comprises around 870 objects classified as K stars. We searched for *uvby* indices for these stars in the surveys of Olsen (1993, 1994) and in the compilation by Hauck & Mermilliod (1998), favouring the data by Olsen when a star had measurements in both sources. Disregarding unresolved binaries, stars with variable indices, giants and subgiants, our sample has been reduced to 242 objects. For some of these, the spectral types available in the literature do not allow the identification of the star luminosity class. In these cases, the identification was made by checking the star's position on the $(b-y)\times c_1$ diagram. Seventeen objects occupy a region in this diagram which is mainly populated by subgiants, according to Olsen (1984), and were eliminated from the sample. One star (BD +00 3077) was also removed from the sample, as it has a colour $(b-y)=0.972$ of an M dwarf, although being classified as K7 V in the CNS3.

Metallicities were found from the calibrations of Schuster & Nissen (1989) for stars bluer than $(b-y)=0.550$, and from the calibration for K2–M2 dwarfs by Olsen (1984) for the redder stars. The calibrations by Schuster & Nissen are assumed to be valid for $(b-y)<0.590$. However, we decided to apply them for $(b-y)<0.550$ only, since beyond this value the calibrations yield spuriously high metallicities of 0.45–0.75 dex. On the other hand, the calibration by Olsen (1984) is valid for the range $(b-y)>0.514$, but it is rather uncertain for $(b-y)>0.550$, as it is based on a small number of stars with spectroscopic [Fe/H] determinations. Therefore, the accuracy of the metallicity determinations for the cooler stars is poorer than for the hotter objects.

Fig. 1 shows the comparison between our derived photometric metallicities and spectroscopic metallicities taken from the literature (Cayrel de Strobel et al. 1997, Favata et al. 1997) for 42 dwarfs. It can be seen that the photometric and spectroscopic data are in good agreement with each other, especially when data by Favata et al. (1997) is used.

Characterization of the disk population has been made by applying the chemical criterion (see RPM for details), according to which stars with $[\mathrm{Fe/H}]<-1.2$ are considered as halo members. From the application of this criterion, 6 stars were removed from the sample, which comprises 218 K dwarfs in its final form. Detailed data on these stars can be supplied by request to the authors. As discussed by RPM, the chemical criterion is a very simplistic one and does not take into account the recent results on the chemical and kinematical properties of the halo and thick disk (Beers & Sommer-Larsen 1995; Gratton et al. 1996). In fact, the chemical criterion is presently more traditional than astrophysical, as it allows a straight comparison between our distribution and previous studies in the literature. More rigorously, the characterization of a pure thin disk late-type dwarf sample should be made by considering both the chemical composition and spatial velocities of the stars. At present this is not possible, as radial velocities are available only for a few late-type disk stars.

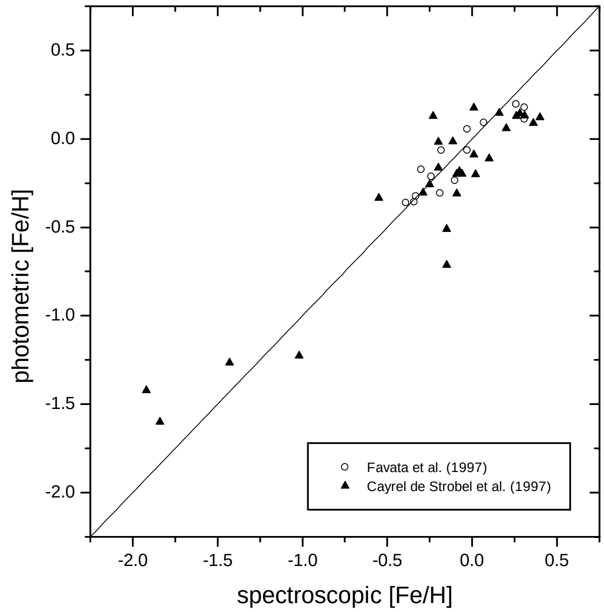

Fig. 1. Comparison between the photometric and spectroscopic metallicities for 42 K dwarfs. The spectroscopic data are from Favata et al. (1997) and Cayrel de Strobel (1997).

Table 1. Metallicity distribution of 218 nearby K dwarfs

[Fe/H]	number
-1.15	0
-1.05	0
-0.95	0
-0.85	0
-0.75	3
-0.65	2
-0.55	5
-0.45	11
-0.35	18
-0.25	39
-0.15	39
-0.05	36
0.05	30
0.15	28
0.25	6
0.35	1

Particular care must be taken in the sense of avoiding any bias towards metal-poor stars in our sample. Some bias could be produced by intrinsic biases in the *uvby* databases we have used. From the 218 K dwarfs in our final sample, 138 have photometric data from Olsen (1993), 40 from Olsen (1994) and 40 from Hauck & Mermilliod (1998). It is difficult to investigate the presence of any bias in the compilation by Hauck & Mermilliod, as it contains objects from several heterogeneous sources. On the other hand, the samples in Olsen's papers are very well described and different subsamples are easily identified, particularly in Olsen (1993). Three subsamples of this last catalogue

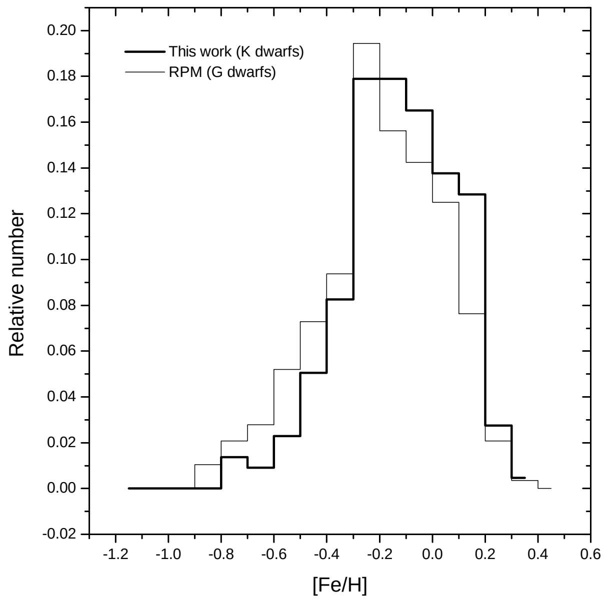

Fig. 2. Comparison between the metallicity distributions for K dwarfs (this work) and G dwarfs (RPM).

are present in our sample: G5-type HD stars, calibration stars and high-velocity stars. Biases could be present in the calibration stars due to selection effects, and high-velocity stars which are likely to be old metal-poor stars. Of the 138 stars in our sample taken from Olsen (1993), 38 are G5-type HD stars, 77 are calibration stars and 23 are high-velocity stars. The average metallicity of G5-type stars is around -0.19 dex, while the calibration and high-velocity stars have average metallicities of -0.10 and -0.07 dex, respectively. The average metallicity of the stars coming from the catalogues of Olsen (1994) and Hauck & Mermilliod (1998) is around -0.15 dex. The standard deviation of the metallicity distributions of all these subsamples is 0.21–0.23 dex. Therefore, no bias towards metal-poor objects is likely to be present in our sample. The differences in the metallicity distribution of the subsamples may suggest a small bias towards metal-rich objects. However, these differences may be caused by the fact that the subsamples have different $(b-y)$ ranges, some of which depend more strongly on the different metallicity calibrations we used.

The resulting metallicity distribution is presented in Table 1. It can be seen that no stars have $[\mathrm{Fe/H}] < -0.80$, in excellent agreement with the previous results by RPM. The data in Table 1 show that the 'G dwarf problem' is not a characteristic of the G dwarfs only, ruling out all previous arguments that the paucity of metal-poor dwarfs could be caused by the non-legitimacy of the G dwarfs as representative of the long-lived stars (see Rocha-Pinto & Maciel 1997a). In fact, the existence of a *K dwarf problem* confirms that the paucity of metal-poor long-lived stars is a real feature of the galactic disk. It is interesting to note that, according to Worthey et al. (1996), the G dwarf problem could even be a universal consequence of the evolution of galaxies.

3. Comparison of the metallicity distributions of F, G, and K dwarfs

Fig. 2 shows a comparison between our K dwarf metallicity distribution and that of the G dwarfs (RPM). It can be seen that there is a very good agreement between these distributions, with only some small differences in the range $-0.7 < [\mathrm{Fe/H}] < -0.4$, and in the amplitude of the peak around $[\mathrm{Fe/H}] \approx -0.25$. Therefore, there seems to be no essential difference in the distributions of hotter and cooler dwarfs, in opposition to the findings by Favata et al. (1997). This conclusion is supported by many independent metallicity distributions in the literature, which agree with the G dwarf metallicity distribution by RPM. This is shown in Fig. 3, where we show, besides the metallicity distribution of RPM:

1. The metallicity distribution of the F dwarf sample studied by Twarog (1980), comprising 936 stars, after applying corrections due to stellar evolution and scale height, assuming the Salpeter initial mass function (IMF). Twarog's (1980) sample was built with the primary purpose of studying the age–metallicity relation. It is composed exclusively by F dwarfs, selected by $T_{\rm eff}$ range, and is expected to be representative of our vicinity. Metallicities are found from *uvby* photometry, but using a very simple calibration in which [Fe/H] depends linearly on δm_1.
2. The metallicity distribution of Wyse & Gilmore (1995), with 128 F and G dwarfs. Wyse & Gilmore (1995) use the same photometric calibrations as RPM. The major difference between these works is that Wyse & Gilmore (1995) have used photometric data by Olsen (1983), while RPM have used the more recent data from Olsen (1993). This last paper is specifically concerned with G stars, while Olsen (1983) gives more attention to stars ranging from A0 to G0. Therefore, their metallicity distribution includes some late F dwarfs, apart from the G dwarfs.
3. The metallicity distribution of Flynn & Morell (1997), comprising 179 G and K dwarfs, after applying the chemical criterion. They have built their sample from G and K dwarfs, listed in CNS3, with $(R-I)$ measurements and Geneva photometric indices available in the literature. Their sample has 179 stars with $[\mathrm{Fe/H}] \geq -1.2$ after applying the chemical criterion, from which 97 are G dwarfs and 82 are K dwarfs. In order to improve the statistics of their database, we have used the metallicity distribution for their combined sample of G and K dwarfs.
4. The metallicity distribution derived by Rocha-Pinto & Maciel (1998), based on the chromospheric activity survey (Soderblom 1985; Henry et al. 1996), with 730 dwarfs of types late F, G and early K. All stars in the chromospheric activity survey are expected to be located within 50 pc from the Sun, and are mostly G dwarfs, with some late F and early K dwarfs. Strömgren photometric indices for these stars were taken from Olsen (1983, 1993, 1994) and used to find metallicities adopting the same calibrations used here.

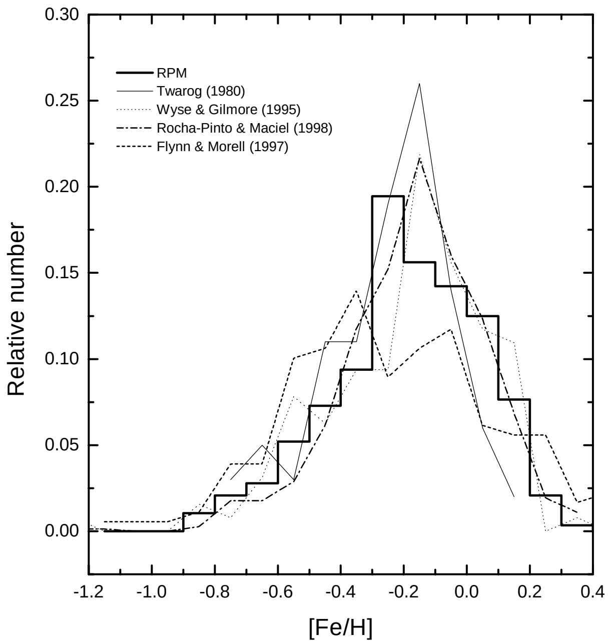

Fig. 3. Comparison of the G dwarf metallicity distribution (RPM) and other distributions in the literature.

Table 2. Fraction of dwarfs with [Fe/H] < -0.40 in the metallicity distribution

This work	9.6%
Twarog (1980)	22%
Wyse & Gilmore (1995)	20.3%
RPM	18.4%
Flynn & Morell (1997)	31.3%
Rocha-Pinto & Maciel (1998)	13.2%

All these distributions use metallicities estimated by photometric data. However, they differ in the selection criteria and calibrations used. In spite of these differences, the agreement of the metallicity distributions (Figs. 2 and 3) is very good. The fraction of stars with [Fe/H] < -0.40, for each distribution, is presented in Table 2. From these data, it can be estimated that around (22 $\pm$ 7)% of the late-type dwarfs in our neighbourhood should have metallicities lower than -0.40 dex

Note also that all distributions, except that by Flynn & Morell (1997), show a prominent single peak around -0.20 dex. As shown by Rocha-Pinto & Maciel (1997b), this feature could be explained by an intense star formation era from 5 to 8 Gyr ago. Therefore, the main conclusion that can be drawn from the comparisons above is that there is a remarkable consistency amongst the distributions of F, G and K dwarfs. This consistency could only be attained if the chemical enrichment and star formation history *have been essentially the same for all late-type dwarfs*.

4. Correction factors owing to chromospheric activity

The raw data of the metallicity distributions are often subject to a variety of corrections due to observational errors, cosmic scatter and scale height effects. When a sample has stars with lifetimes lower than the disk age, corrections due to stellar evolution must also be applied. Such corrections are needed to conve rt the *observed* metallicity distribution into the *true* distribution.

For a distribution based on spectroscopic [Fe/H], these corrections are generally sufficient. However, for photometric distributions there is an additional correction which has been totally neglected in past studies. This correction is needed in order to take into account the effects of the chromospheric activity on the photometric indices.

By studying the metallicity distribution in a sample of 730 late-type dwarfs with varying levels of chromospheric activity, Rocha-Pinto & Maciel (1998) have shown that, for the active stars, the difference between the spectroscopic and the photometric metallicity increases systematically as a function of the stellar activity. This result is a consequence of the m_1 deficiency, which is more pronounced in active binaries (Giménez et al 1991), but actually seems also to be present in normal active stars (Giampapa et al. 1979; Basri et al. 1989; Morale et al. 1996). A metallicity distribution that does not take into account this effect will be biased towards metal-poor stars. The elimination of identified active stars from the sample is not an ideal solution to this problem as, in single late-type dwarfs, the activity is linked to the stellar age (Soderblom et al. 1991). Samples free of active stars will be also free of young stars, which will introduce another bias, in the sense of avoiding the expected metal-richer dwarfs. Even if there was no relation between age and activity, there would always remain some unidentified active stars in the photometric surveys, as we do not know how to identify such stars from their indices. The only way to keep a minimum compromise between the achievement of a non-biased sample and an accurate metallicity distribution is to make use of approximate corrections for the effects of the chromospheric activity.

The corrections we are proposing assume that all active stars, for which the chromospheric index $\log R'_{\rm HK} > -4.75$ (Soderblom et al. 1991), have photometric metallicities lower than the spectroscopic values by a constant amount Δ. In fact, Δ is likely to depend on $\log R'_{\rm HK}$, but for the sake of simplicity we shall adopt here an average value given by

$$\bar{\Delta} = \frac{\int_{-4.75}^{\infty} \chi(\log R'_{\rm HK}) \Delta(\log R'_{\rm HK}) \, {\rm d} \log R'_{\rm HK}}{\int_{-4.75}^{\infty} \chi(\log R'_{\rm HK}) \, {\rm d} \log R'_{\rm HK}}, \quad (1)$$

where $\chi(\log R'_{\rm HK})$ is the distribution of stellar chromospheric activity, that can be found from the combined data of Soderblom (1985) and Henry et al. (1996), and Δ is estimated by using Eq. (5) of Rocha-Pinto & Maciel (1998). Using Eq. (1), we have $\bar{\Delta} = 0.149$ dex.

The normalized photometric metallicity distribution of the active stars, $\mathcal{D}([{\rm Fe/H}])$, from Rocha-Pinto & Maciel (1998), is shown in Table 3. Instead of identifying the active stars in the data sample, the approach we have taken here assumes that a fraction c of the total number of stars in the sample ($N_{\rm tot}$)

Table 3. Metallicity distribution for active stars and corrections

[Fe/H]	$\mathcal{D}$[Fe/H]	r	$r_{\rm G}$	$r_{\rm K}$
−1.15	0	0	0	0
−1.05	0	0	0	0
−0.95	0	0	0	0
−0.85	0	0	0	0
−0.75	0.00508	−0.00009	−0.01	−0.01
−0.65	0.01015	−0.00096	−0.08	−0.06
−0.55	0.01523	−0.00685	−0.58	−0.44
−0.45	0.02030	−0.03097	−2.63	−2.00
−0.35	0.09645	−0.08674	−7.37	−5.60
−0.25	0.20305	−0.14168	−12.04	−9.14
−0.15	0.26396	−0.10795	−9.17	−6.97
−0.05	0.20305	0.02736	2.32	1.77
0.05	0.09645	0.13495	11.46	8.71
0.15	0.07107	0.12700	10.79	8.19
0.25	0.01015	0.06311	5.36	4.07
0.35	0.00508	0.01884	1.60	1.22
0.45	0	0.00352	0.30	0.23

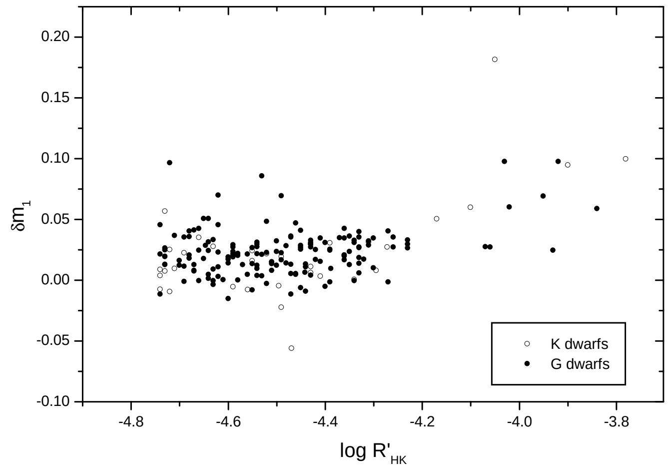

Fig. 4. δm_1 as a function of the chromospheric activity for the active stars in the sample of Rocha-Pinto & Maciel (1998). G dwarfs and K dwarfs are marked by solid and open circles, respectively.

are active stars. Therefore, the number of active stars in each metallicity bin is $cN_{\rm tot}\mathcal{D}([{\rm Fe/H}])$, and to correct the metallicity distribution, these active stars should be allocated to more metal-rich bins by an amount of $\bar{\Delta}$.

The fraction c is likely to depend on the spectral type considered, as the chromospheric activity is thought to be caused by the interaction between the stellar rotation and the convection in the stellar envelope. The decrease of the outer convective zone towards hotter stars indicates that young hotter stars do not show much activity (Elgarøy et al. 1997). For a sample centered on G dwarfs, we can take $c = 0.296$ as a good value, according to Henry et al. (1996).

Table 3 also presents the normalized corrections r to the metallicity distribution. The numbers in the table were found by the subtraction of $\mathcal{D}$[Fe/H] from a gaussian curve fitted to this distribution with a mean shifted by $\bar{\Delta}$. These corrections are to be multiplied first by $cN_{\rm tot}$, before they can be added to the metallicity distribution, and *before* the application of any other corrections due to observational errors, cosmic scatter, stellar evolution or scale height.

The absolute corrections to the G dwarf metallicity distribution of RPM and the K dwarf distribution derived in this work are shown in the last columns of Table 3, where $r_K = rcN_{\rm tot}(K)$ and $r_G = rcN_{\rm tot}(G)$ with $N_{\rm tot}(K) = 218$ and $N_{\rm tot}(G) = 287$. Note that we have assumed the same values for c and $\bar{\Delta}$ for G and K dwarfs, as there is no information about their dependence on the stellar mass.

It should be stressed that these corrections are valid only for distributions binned by 0.1 dex, with each bin centered at the metallicities presented in the first column of Table 3, and for [Fe/H] determined by Strömgren photometry. In order to apply them to a distribution binned in a different way, we provide the equations below:

$$r_X = 0.296\,\delta z\,N_{\rm tot}(X)\left[G([{\rm Fe/H}]-\bar{\Delta}) - G([{\rm Fe/H}])\right], \quad (2)$$

where δz is the bin size in dex, assumed constant, and

$$G([{\rm Fe/H}]) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{([{\rm Fe/H}]-\mu)^2}{2\sigma^2}\right] \quad (3)$$

is the gaussian fit to the normalized distribution in Table 3. According to this fit, $\mu = -0.143$ and $\sigma = 0.152$.

For distributions based on different photometric systems, a new value for $\bar{\Delta}$ should be computed, since the extent of chromospheric activity effects on the photometric indices depends on the spectral range sampled by the filters, as well as on their transmission functions. This could be an explanation for the fact that the metallicity distribution of Flynn & Morell is somewhat different from the others (see Fig. 3), as this distribution uses Geneva photometry, and the indices of the calibrations can be affected in a different way from the *uvby* indices, which are used by all other distributions in Fig. 3.

Morale et al. (1996) report that, in active K dwarfs, δm_1 is systematically greater than in active G dwarfs as a function of the stellar activity, which would indicate a greater $\bar{\Delta}$ for those stars. This is not confirmed for the active stars in the sample studied by Rocha-Pinto & Maciel (1998), as can be seen from Fig. 4. This plot shows that the m_1 deficiency, reflected in a larger value for δm_1, is about the same for G and K dwarfs, as a function of the activity. However, the stars analyzed by Morale et al. (1996) are generally much more active than ours, as they were detected by the X-ray flux-limited *Einstein* Extended Medium Sensitivity Survey (Gioia et al. 1990).

This can be verified from the data in Table 4 where we compare the activity indices, $\log R'_{\rm HK}$ and $\log(f_{\rm X}/f_{\rm V})$, in the chromospheric activity and *Einstein* surveys, respectively, for the four stars in common to these surveys. The bulk of the active

Table 4. Activity indices for common stars in the Einstein and chromospheric activity survey

Name	$\log R'_{\rm HK}$	$\log(f_{\rm X}/f_{\rm V})$
HD 105	-4.36	-3.58
HD 166	-4.33	-3.43
HD 25680	-4.54	-3.93
HD 97334	-4.40	-4.06

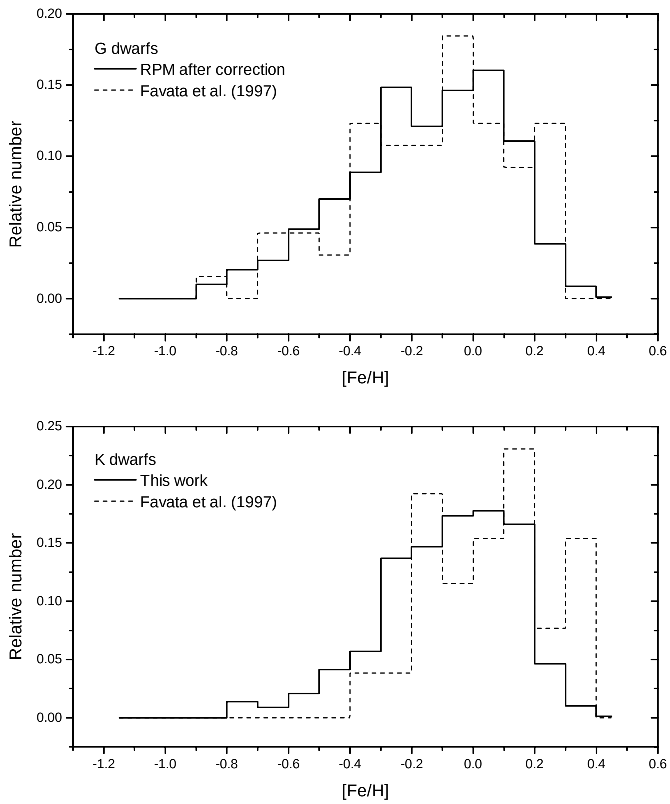

Fig. 5. Comparison between the metallicity distributions for K dwarfs (this work) and G dwarfs (RPM), and Favata et al.'s distributions.

stars, according to the distribution function $\chi(\log R'_{\rm HK})$, has $\langle\log R'_{\rm HK}\rangle \approx -4.50$, which from the values in Table 4 would correspond to $\log(f_{\rm X}/f_{\rm V}) \approx -3.9$ or lower. Thus, our Fig. 4 does not rule out the conclusions by Morale et al. (1996). Note that our most active stars, that would have $\log(f_{\rm X}/f_{\rm V}) \approx -2.8$ if we extrapolate the relation for the stars from Table 4, have $\delta m_1 \approx 0.07$ in good agreement with Fig. 3 by Morale et al.. We can see that at $\log(f_{\rm X}/f_{\rm V}) \approx -3.0$, the G and K dwarfs still present similar δm_1 indices.

From the considerations above, we can conclude that, only for the most active dwarfs, the cooler stars will present larger Δ compared to the G dwarfs. From the function $\chi(\log R'_{\rm HK})$, these very active stars comprise around 5 % of the active stars we are dealing with (that is, $0.05cN_{\rm tot}$ stars), so that their influence on the metallicity distribution will be negligible, and our hypothesis for equal c and $\bar{\Delta}$ is fairly reasonable.

5. Metal-enhanced star formation of K dwarfs or a biased catalogue?

In the last few years, several works have investigated the observational aspects of the G dwarf problem (Wyse & Gilmore 1995; Rocha-Pinto & Maciel 1996, 1997a; Flynn & Morell 1997). All these works have followed the steps delineated by Pagel & Patchett (1975) for the selection of a unbiased metallicity distribution of long-lived dwarfs, by choosing stars in a volume limited sample and using photometric metallicities.

The recent paper by Favata et al. (1997) also analyzes the metallicity distribution of the solar neighbourhood. The major novelty of this work is that the authors made the first attempt to systematically study the local metallicity distribution by using spectroscopic metallicities. In fact, the first local spectroscopic metallicity distribution was made by Rana & Basu (1990). However, their selection criteria were not appropriate to define a unbiased sample, and their metallicity database was largely heterogeneous. Recently, some papers have also made use of a spectroscopic metallicity distribution from the data of Edvardsson et al. (1993). However, this distribution cannot be taken as representative either, as Edvardsson et al. have selected their stars in order to have nearly equal numbers of them in pre-determined metallicity bins.

The results by Favata et al. (1997) are quite peculiar: stars hotter than 5100 K present metallicities spanning the whole range of [Fe/H] values expected for the disk, whereas amongst the cooler objects, no stars show $[{\rm Fe/H}] < -0.40$ dex. Their sample comprises 91 stars, 65 of which are considered as G dwarfs and 26 are K dwarfs, their separation being made at 5100 K.

The authors present two alternative hypotheses to explain the lack of cool metal-poor stars:

1. Low mass stars would preferably form in higher metallicity clouds, due to the efficient cooling driven by the radiation of molecules containing metals.
2. The Catalogue of Nearby Stars could have a metallicity bias, in the sense of favouring metal-rich stars amongst the cooler ones.

In what follows, we shall examine these hypotheses separately.

5.1. Metal-enhanced star formation of K dwarfs

The first hypothesis resembles the metal-enhanced star formation model (MESF; Talbot & Arnett 1973; Talbot 1974; see also Tinsley 1975, 1980). This model was proposed to explain the lack of metal-poor G dwarfs, when the G dwarf problem was identified. The idea of Favata et al. (1997), although not explicitly stated in this way, is that stars of progressively lower masses are generally born with metallicities above than average, just like a mass-dependent metal-enhanced star formation.

There are problems with this hypothesis. If MESF could produce a lack of metal-poor K dwarfs compared to G dwarfs, then the same reasoning indicates that there would be a paucity of metal-poor G dwarfs compared to F dwarfs, and so on. It is not possible to test this hypothesis using stars earlier than F0, since the older earlier stars have already evolved away from the main sequence. However, the F dwarf metallicity distribution corrected by stellar evolution (Twarog 1980) is not different from the distribution of the G dwarfs in the metal-poor range (see Fig. 3). The F dwarf metallicity distribution could have another intrinsic bias towards metal-rich stars due to the accretion of Jupiter-mass planets (Laughlin & Adams 1997). However, the extent of these effects is not presently known. Moreover, as there is a metallicity gradient in the Galaxy (see for example Maciel and Köppen 1994), the fraction of cooler dwarfs related to the other stars should increase towards the Galactic center. Studies of the variation of the IMF as a function of galactocentric radius show just the opposite (Scalo 1986; Matteucci & Brocato 1990).

Fig. 5 compares the metallicity distributions found by Favata et al. (1997) with the G dwarf (RPM) and our present K dwarf metallicity distributions, after the application of the corrections due to chromospheric activity. These corrections were not applied to these distributions in the previous figures, since we were comparing photometric distributions, which are expected to be affected in the same way by chromospheric activity. However, to compare a photometric distribution with a spectroscopic one, the corrections in Table 3 are needed. The G dwarf metallicity distributions show a good agreement (upper panel of Fig. 5), except for [Fe/H] $> +0.10$, where the distribution by Favata et al. (1997) shows a larger number of metal-rich stars. The same occurs in the K dwarf distribution (lower panel of Fig. 5). Note also the lack of metal-poor K dwarfs in the sample by Favata et al. (1997) compared to ours. This difference is not likely to be caused by errors in the photometric calibrations we have used, since Fig. 1 demonstrates the good agreement with the spectroscopic metallicities, which is even closer for their data.

The MESF model was not successful in giving a reasonable explanation to the G dwarf problem, as it requires both very large chemical inhomogeneities in the interstellar medium and very inefficient star formation in metal-poor regions (Tinsley 1980). Our present knowledge of star formation and initial mass function corroborates this, as we shall show below.

Padoan et al. (1997) have recently presented analytical expressions for the initial mass function (IMF) taking into account the dependence of the star formation on the physical parameters of the molecular clouds. Their model shows that cooler clouds form preferably lower mass stars. The IMF has a single maximum and an exponential cutoff below it. For the idea of Favata et al. to be valid, regions with [Fe/H] < -0.4 should form stars with an IMF cutoff just below 1 $M_{\odot}$, and in more metal-rich clouds the IMF cutoff should lie beyond 0.6–0.7 $M_{\odot}$. Using the expressions given by Padoan et al. (1997), and taking average values for cloud density and velocity dispersion, the temperature of the clouds for such cutoffs should be 22 K and 19–17 K, respectively. This is hotter than the mean temperature expected for typical dark clouds, 8–15 K (Goldsmith 1988). However, according to Lin (1997), at the present metallicity of the globular clusters ([Fe/H] $\lesssim -1.0$ dex), the cold dense clouds could cool

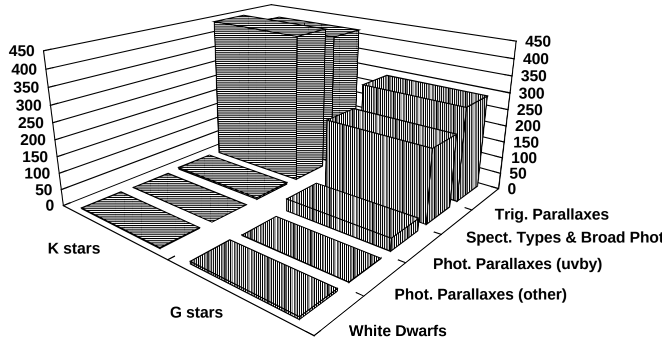

Fig. 6. Sources for the parallaxes in the Third Catalogue of Nearby Star (Gliese & Jahreiß 1991).

to around 10 K, putting the IMF cutoff at 0.2 $M_{\odot}$, according to the formulae by Padoan et al. (1997).

Even if the IMF cutoff were around 0.9–1 $M_{\odot}$ in the hotter clouds, there would be no such a direct relation between the metallicity and the cloud temperature. The temperature in a molecular cloud is not solely determinated by the cooling rate (which can depend on the metallicity), but it depends also on the cloud density and on the existence of internal and external heating sources (Goldsmith 1988; Cernicharo 1991). A difference of 5 K, as that required for the IMF cutoff to be 1 $M_{\odot}$ or 0.6 $M_{\odot}$, could exist even inside the same cloud, where the metallicity is likely to be the same everywhere, as shown by Young et al. (1982) and Cernicharo (1991). There is no strong evidence that the star formation mechanisms would be different for G and K dwarfs. The bump at 0.7 $M_{\odot}$ in the present-day mass function, quoted by Favata et al. (1997) as an evidence favouring a bimodality in the star formation of low mass stars, was more easily explained by Kroupa et al. (1990) as a real feature in the mass–magnitude relation due to the effects of the increasing importance of H^- as an opacity source. Given the considerations above, it is reasonable to conclude that MESF cannot account for the lack of metal-poor K dwarfs in the sample by Favata et al. (1997).

5.2. A metallicity bias in the catalogue of nearby stars

According to Favata et al. (1997), the use of photometric parallaxes could introduce a metallicity bias in the CNS2. Note, however, that our sample does not show this problem, in analogy with the K dwarf metallicity distribution found by Flynn & Morell (1997). The samples by RPM and Flynn & Morell were also selected from the Catalogue of Nearby Stars, although both papers have considered a more recent version.

We decided to investigate the parallax sources in CNS3. This version of the catalogue was used instead of CNS2, as all recent work on the metallicity distributions is based on it. Moreover, any bias in the CNS2 would also be present in the CNS3, since both catalogues were built in the same fashion. We begin by selecting all stars with $(B-V)$ between 0.5 and 1.4, as in Favata et al. (1996). The sample was further divided into 'G stars' and 'K stars' at $(B-V) = 0.8$. There are 1421 objects in this

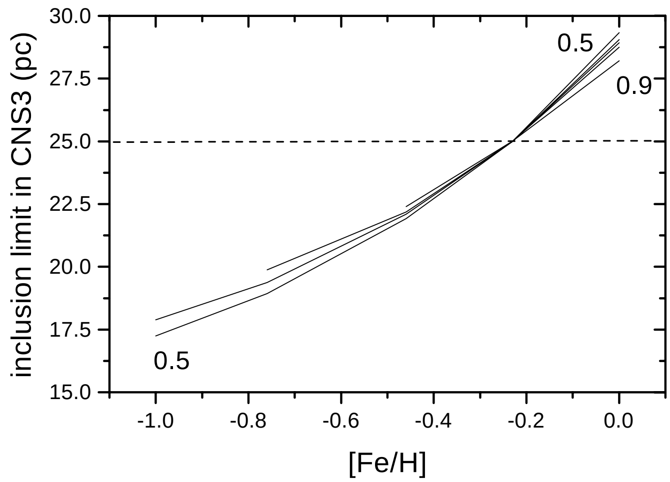

Fig. 7. The real inclusion limit of the CNS3 as a function of [Fe/H] and $(B-V)$ for *UBVRI* parallaxes. The curves correspond to $(B-V)$ of 0.5, 0.6, 0.7, 0.8 and 0.9. The labels indicate the curves for the cooler and hotter stars.

colour range, from which 550 are G stars and 871 K stars. Fig. 6 shows the number of stars included in the CNS3 according to the parallax sources. These sources are: (i) trigonometrical parallaxes; (ii) spectroscopic parallaxes and parallaxes determined from broad-band photometric colours; (iii) photometric parallaxes determined from *uvby* colours; (iv) photometric parallaxes determined from other photometric systems; and (v) photometric parallaxes for white dwarfs. As can be seen, the main sources for the CNS3 are the trigonometrical parallaxes, and parallaxes determined from spectral types or *UBVRI* colours (which we will call *UBVRI* parallaxes). The contribution by photometric parallaxes at this colour range is negligible. Both the spectroscopic and *UBVRI* parallaxes are determined from mean calibrations built using the stars for which accurate trigonometric parallaxes are available (Gliese & Jahreiß 1989). As these calibrations include stars with varying chemical composition, this must refer to an average metallicity. At a given colour, metal-poor stars have higher absolute magnitudes than their richer counterparts, because their main sequences lay below that of the average-metallicity stars in the colour-magnitude diagram. Therefore, metal-poor stars would be estimated to be systematically farther away than they really are by the use of spectroscopic and *UBVRI* parallaxes, as Favata et al. (1997) suggested. Could this effect be large enough to introduce a metallicity bias in the CNS3?

In order to investigate this problem, we need to know how the '25 pc limit' for inclusion in the CNS3 depends on the metallicity as well on the colour of the stars by using an average colour–magnitude relation. We have used the theoretical zero-age main sequences (ZAMS) calculated by VandenBerg (1985). His ZAMS for $[\mathrm{Fe/H}] = -0.23$ was chosen as the mean ZAMS, since this metallicity corresponds roughly to the average metallicity of the solar neighbourhood stars (cf. RPM). In Fig. 7, we show the real limit for inclusion in the CNS3, for $(B-V)$ colours ranging from 0.50 to 0.90. The figure shows that metal-poor stars, with [Fe/H] < -0.4, estimated as being located at 25 pc from the Sun, are in fact closer by 2.5–8 pc. Also, solar-metallicity stars assumed to be within 25 pc from the Sun, could be farther away by up to 5 pc. This effect depends slightly on the stellar colour, being lower for cooler stars. Thus, it is expected that such effects would be slightly more pronounced amongst the G dwarfs, in comparison with the K dwarfs.

We have looked for such effects in the data by comparing the distances from the CNS3 with the distances measured by the HIPPARCOS satelite, both for stars with trigonometric and *UBVRI* parallaxes. The sample of G and K dwarfs, built according to the prescriptions above, was further divided into four samples: (i) G dwarfs included in the CNS3 with trigonometric parallaxes (hereafter tG); (ii) G dwarfs with spectroscopic and *UBVRI* parallaxes (ubvG); (iii) K dwarfs included with trigonometric parallaxes (tK); and (iv) K dwarfs with spectroscopic and *UBVRI* parallaxes (ubvK). The number of stars with distances in both the CNS3 and in the HIPPARCOS database is 236 (tG), 204 (ubvG), 262 (tK) and 272 (ubvK).

Fig. 8 shows a comparison of the CNS3 and HIPPARCOS distances of these four groups. A number of trends can be seen in these panels. Let us consider first the two groups included in the CNS3 with trigonometric parallaxes, tG and tK. It is possible to see that the agreement between the CNS3 and HIPPARCOS distances improves as we consider stars closer to the Sun, reflecting the better accuracy of ground-based parallax measurements of nearby objects. A very small number of stars was also included in the catalogue in spite of having trigonometric parallaxes smaller than 0.039. There are nearly 10% of the stars in each group tG and tK that are located much farther away than 25 pc. This is due to errors in the parallax measurements, so that we do not expect any chemical composition differences between those stars and the stars with accurate distances. The situation is different for the groups ubvG and ubvK, whose distances are shown in the bottom panels of Fig. 8. For these groups, the scatter around the line of same distance does not depend on the actual stellar distance. Such scatter is very likely to be produced by the varying chemical composition of these stars. There is a group of stars with underestimated distances in CNS3, both amongst the G and K dwarfs. We separate these stars by a dot-dashed line. The possibility that the inclusion of metal-rich stars in CNS3 with *UBVRI* parallaxes has an important effect can be checked by comparing the metallicity of the stars at both sides of the dot-dashed lines in the bottom of Fig. 8.

To estimate the metallicities we used the same procedures described in Sect. 2. The number of stars with metallicities in each subgroup is: 185 (tG), 176 (ubvG), 111 (tK) and 121 (ubvK). The number of stars deviating from the line of same distance is 21 G dwarfs and 20 K dwarfs.

In Fig. 9a and b, we show the metallicity distributions of the groups tG, ubvG, tK and ubvK. There is no indication that the metallicity distribution of G stars is different at the extreme metallicities, regardless of the parallax source. However, the metallicity distribution of the group ubvG has a remarkable single peak at $[\mathrm{Fe/H}] \sim -0.20$ dex, which is not present in group tG. This peak is also apparent in the metallicity distributions

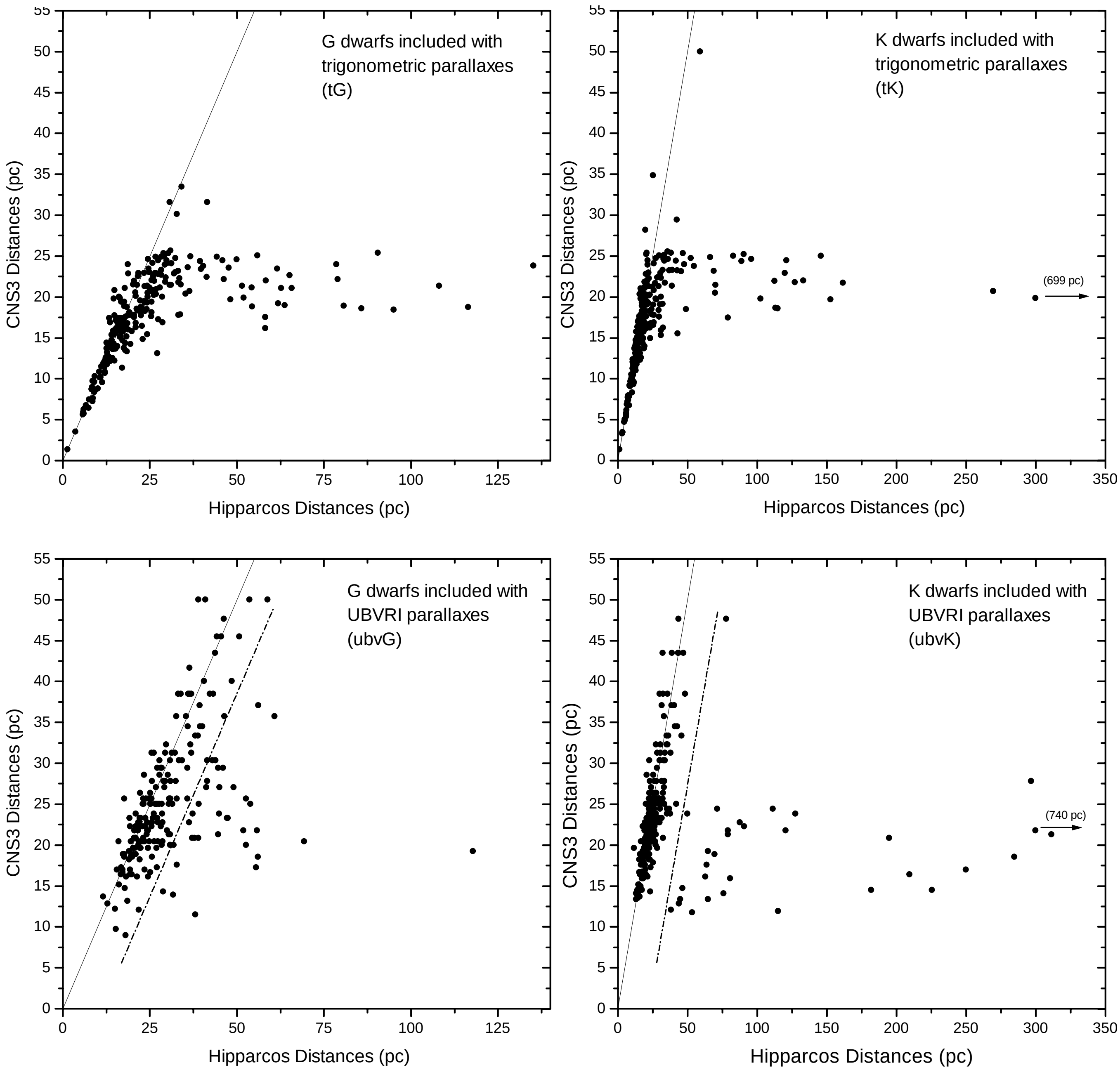

Fig. 8. Stellar Distances from the CNS3 and from the HIPPARCOS database, for different stellar groups defined by their parallax sources. The dot-dashed lines at the bottom panels separate stars with good distance estimates in the CNS3 from those assumed to be closer than they are.

discussed in Sect. 2, but it is not clear whether it is caused by something related to the colour–magnitude calibration, since it is also present in Twarog's (1980) distribution which uses very different selection criteria. On the other hand, the metallicity distributions of K dwarfs seem to depend strongly on the parallax sources of the CNS3. A Kolmogorov-Smirnov test indicates that both distributions are different at a significance level of 99.99%. However, the difference occurs in the opposite sense of what we were expecting as group tK shows much more metal-rich objects than the group ubvK. Also there seems to be more metal-poor stars amongst the ubvK dwarfs. Therefore, these groups do not show any bias derived from *UBVRI* parallaxes, although some excess of metal-rich stars is apparent in the group of K dwarfs with trigonometric parallaxes.

However, this result is not conclusive, since the metallicity distribution of group tK is more strongly dependent on the calibration by Olsen (1984) than group ubvK (the fraction of stars in these groups that have $(b-y) > 0.550$ is 0.55 and 0.37, respectively). It is worth to note that the metallicity distribution of group ubvK agrees better with the groups of G dwarfs. The hypothesis that the metallicity distribution of group ubvK is the

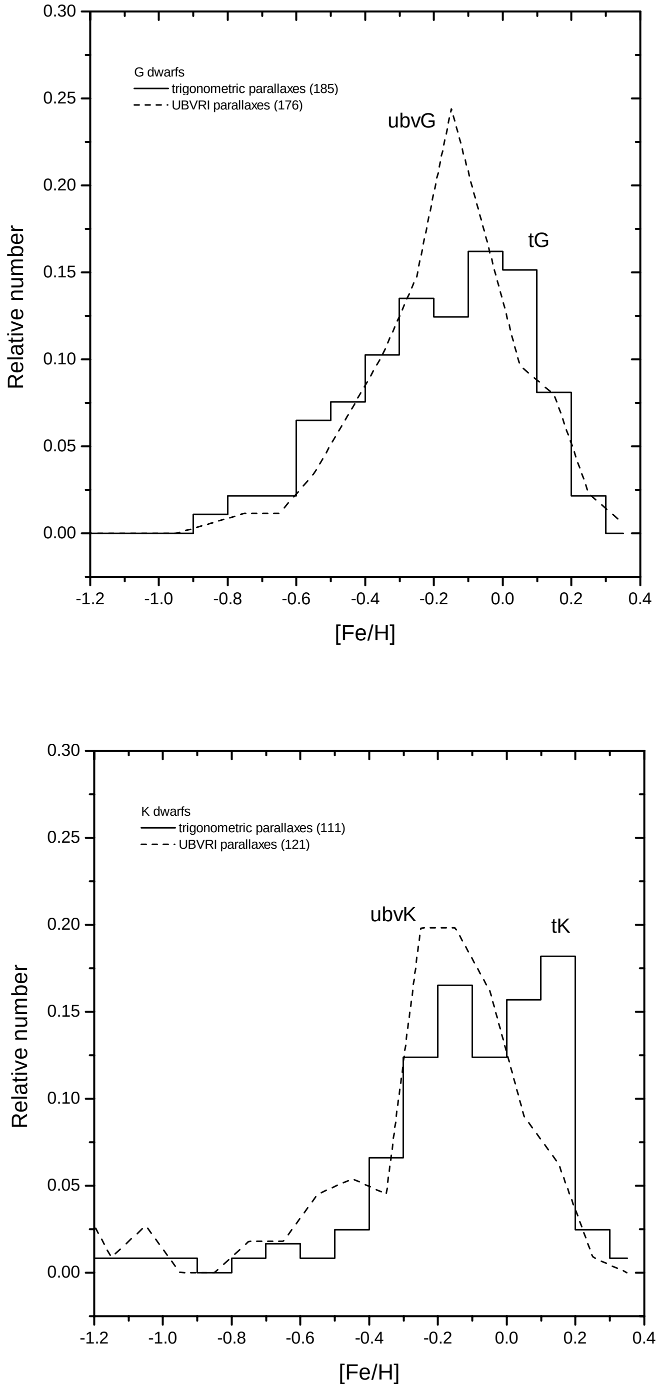

Fig. 9a and b. Comparison of the metallicity distributions of the stellar groups included in the CNS3 with different parallax sources: **a** groups tG e ubvG; **b** groups tK and ubvK.

same as those of groups ubvG and tG can only be rejected at a significance level of 0.2246 and 0.2339, respectively.

It is then particularly important to see whether there are differences amongst the groups of deviating stars, that is, those objects to the right of the dot-dashed lines in Fig. 8, and the remaining groups. The metallicities of the deviating G stars range from -0.5 to $+0.1$ dex, with an average around -0.10 dex. There is no indication that this group has more metal-rich stars compared to the others. The absence of stars with metallicities lower than -0.5 dex can well be ascribed to the size of the sample. As an illustration, the KS test gives significance levels of 0.517 and 0.314 for this distribution not to be taken from the same population of groups ubvG and tG, respectively. The situation is different for K dwarfs. The group of deviating K dwarfs has metallicities ranging from -1.6 to -0.05 dex, with an average around -0.65 dex. This result is very peculiar since it suggests that the stars which have systematically underestimated distances in the CNS3 are metal-poor, while we would expect that metal-poor stars would have overestimated distances according to Fig. 7. However, this question cannot be properly answered because the metallicity of the group of deviating K dwarfs also strongly depends on the metallicity calibration for stars cooler than $(b-y) = 0.550$.

In spite of that, if such bias is likely to be present in the catalogue, it should occur for both G and K dwarfs, being in fact stronger for the hotter stars. The non-existence of such bias amongst the G dwarfs, which have even more accurate photometric metallicities, indicates that it does not affect the content of the CNS3. This can happen because the limit for inclusion of objects in the CNS3 due to spectroscopic and *UBVRI* parallaxes is more flexible than the limit for trigonometric parallaxes. This is evident from Fig. 8. In this plot we see that there are many stars in the CNS3 whose distances in this catalogue are greater than 25 pc, amongst those included with *UBVRI* parallaxes. Thus, in the CNS3 there is not a fixed limit at 25 pc for the inclusion of stars with *UBVRI* parallaxes, and there seems to be no corresponding metallicity-bias.

The simplest hypothesis to account for the results found by Favata et al. (1997) is that their sample is not representative of the galactic population of K dwarfs, due to its small size. The original sample randomly selected from the CNS2, and consisting of around 100 G and 100 K dwarfs (Favata et al. 1996), can be expected to be representative. However, the number of stars that were effectively observed is 63 G dwarfs and 26 K dwarfs. As Favata et al. (1997) themselves state, relatively fewer cooler stars were observed due to their faint magnitudes. This observational selection is not likely to remove the representativeness of a large data sample. However, small samples are much easily affected by statistical fluctuations due to the elimination of some stars. This can explain why the distributions by Favata et al. (1997) show large fluctuations and not a single prominent peak as the other metallicity distributions in the literature.

Acknowledgements. HJR-P thanks Marília Sartori for some helpful discussions. We are indebted to Dr. E. H. Olsen for some important remarks on an earlier version of this paper. We have made use of the SIMBAD database, operated at CDS, Strasbourg, France. This work has been partially supported by FAPESP and CNPq.

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