

The G dwarf metallicity distribution and the problem of stellar lifetimes lower than the disk age

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Abstract. We examine the possibility of the inclusion of objects having lifetimes lower than the disk age in the database of recent determinations of the G dwarf metallicity distribution for the solar neighbourhood. As a preliminary step, stars with lifetimes potentially lower than the disk age are identified by means of a relation between $(b - y)$, or mass, and $[\text{Fe}/\text{H}]$, from evolutionary models of stars at the zero-age main sequence. We apply these results to the G dwarf samples of Rocha-Pinto and Maciel (1996) and Wyse and Gilmore (1995). We show that the majority of G dwarfs in these samples can be regarded as long-lived objects for chemical evolution purposes, provided the disk age is greater than 12 Gyr. We also find that the G dwarf problem is not an effect of the metallicity dependence of the stellar lifetimes.

Key words: stars: abundances – Galaxy: abundances – Galaxy: evolution – solar neighbourhood

to have lifetimes greater than or equal to the age of the disk, and can be considered as legitimate witnesses of the galactic chemical enrichment. However, there are some evidences indicating that the correspondence between the metallicity distribution of long-lived stars and that of the G dwarfs is not straightforward. Model calculations show that the lifetimes of the earliest G dwarfs could be slightly lower than 12 Gyr, which is a good estimate of the disk age. Pagel and Patchett (1975) avoided this problem by eliminating all stars earlier than G2 from their sample. This simple procedure does not remove all stars with lifetimes lower than the disk age, as the spectral types depend both on the effective temperature and metal content. In fact, stars with the same MK classification may have very different masses (thus different lifetimes), due to variations in the effective temperature T_{eff} and metallicity $[\text{Fe}/\text{H}]$. Moreover, the stellar chemical composition also affects its lifetime. Hence, a metallicity distribution based on a given range of spectral types could include stars that are not long-lived for chemical evolution purposes, even though classified as G dwarfs.

1. Introduction

The simple model (Schmidt 1963) was the first attempt to describe the abundances and the chemical evolution of the Galaxy. It explains fairly well the chemical evolution of closed systems such as the galactic bulge (Pagel 1987), and is able to predict the correct order of magnitude of the radial gradients in the Galaxy (Maciel 1992), but it cannot account for the evolution of open systems like the disk, where gas inflow from external regions seems to have occurred.

One of the best known problems with the simple model is the “G dwarf problem”, or its failure to explain the metallicity distribution of long-lived stars, as represented by the G dwarfs in the solar neighbourhood. The simple model predicts an excess of metal poor stars in the solar vicinity, contrary to what is observed (Pagel and Patchett 1975; Pagel 1989; Wyse and Gilmore 1995; Rocha-Pinto and Maciel 1996; see Tinsley 1980 for a review).

The samples used to build the metallicity distribution of long-lived stars are based on G dwarfs, as these stars are thought

Recently, Rocha-Pinto and Maciel (1996) presented a new metallicity distribution for 287 G dwarfs, using *wby* photometry and up-to-date parallaxes. The adopted sample includes all G dwarfs in the spectral range from G0 to G9 V, based on the argument that the hotter stars are not systematically more metal rich than the redder G dwarfs, as would be expected if they had shorter lifetimes. However, there is no clearcut relation between the spectral types and lifetimes. The G dwarfs may include stars within a given mass range belonging to different stellar generations, thus showing different degrees of evolution on the main sequence. As a result, a given region on the HR diagram may include stars coming from several loci on the zero-age main sequence. According to Nordström (1989), this effect produces an uncertainty of 15% or larger in the relation spectral type-mass. For a typical G5 V star, with an estimated mass of $0.93 M_{\odot}$ (Allen 1973), and a corresponding lifetime of 13 Gyr (Bahcall & Piran 1983), this uncertainty would produce an equivalent uncertainty on the stellar lifetime of the order of 6 Gyr. Thus, some G0 stars can be regarded as long-lived stars, while some G5 stars cannot.

In the present paper, we propose an approximate method to identify stars with lifetimes lower than a given age, by means of a relation between the colour index ($b - y$), or mass, and $[\text{Fe}/\text{H}]$. In section 2, we present the method for estimating the stellar lifetimes, and apply it to the samples of Rocha-Pinto & Maciel (1996) and Wyse & Gilmore (1995). In section 3 we discuss the effect of metallicity dependent lifetimes on the G dwarf problem.

2. Identification of short-lived stars

2.1. The mass-metallicity relation

Stellar models provide lifetimes for stars of a given mass and metallicity $[\text{Fe}/\text{H}]$. As the individual masses of the stars in the samples for which we want to apply our method are not generally known, it is convenient to correlate the stellar mass with some known property. In principle, if we have a temperature indicator for a star, its mass could be estimated by some astrophysical relations.

The method we present here uses the ($b - y$) colour as a temperature indicator, that is, the same index adopted in the samples already mentioned. However, other indices could be used as well, and the same method could be applied to a mass-metallicity diagram. We preferred to use a $[\text{Fe}/\text{H}] \times (b - y)$ diagram, since ($b - y$) is the quantity directly observed. A similar procedure to exclude short-lived G dwarfs was independently developed by Wyse & Gilmore (1995).

We have taken the lifetimes from a set of evolutionary models which cover a wide range in mass M , metallicity Z and helium abundance Y (VandenBerg 1985; VandenBerg & Bell 1985; VandenBerg & Laskarides 1987). These lifetimes were interpolated in order to derive a single relation between the mass and $[\text{Fe}/\text{H}]$ for stars experiencing central hydrogen exhaustion τ_M years after their birth.

The dependence of the lifetimes on the helium abundance was eliminated by means of the relation

$$Y = Y_p + \frac{\Delta Y}{\Delta Z} Z, \quad (1)$$

(Peimbert & Torres-Peimbert 1974, 1976), where we used $Y_p = 0.233$ (Chiappini & Maciel 1994). The helium-to-metals enrichment ratio $\Delta Y/\Delta Z$ was chosen in order to adjust the solar He abundance $Y_\odot = 0.27$ (VandenBerg 1983) at the solar metallicity $Z_\odot = 0.0169$. It results that $\Delta Y/\Delta Z = 2.189$, which is close to the conservative value given in the recent literature (Peimbert 1996, Maeder 1992), and agrees very well with the observed main sequence width $\Delta M_v \approx 0.55$ (Fernandes et al. 1996). The metal abundance Z was converted into the observed abundance $[\text{Fe}/\text{H}]$ by the equation

$$[\text{Fe}/\text{H}] = \log \left[\frac{Z}{1 - Y_p - (1 + \frac{\Delta Y}{\Delta Z})Z} \right] - \log \left[\frac{Z_\odot}{1 - Y_\odot - Z_\odot} \right]. \quad (2)$$

Fig. 1 shows the expected $[\text{Fe}/\text{H}] \times M$ relation for stars having lifetimes of 9, 12 and 15 Gyr. It can be seen that, for a given

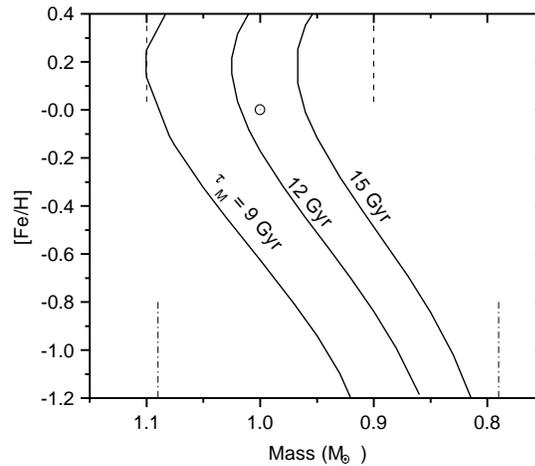


Fig. 1. $[\text{Fe}/\text{H}] \times M$ curves for stellar lifetimes of 9, 12, and 15 Gyr. The vertical lines indicate the G-dwarf mass range according to Bazan and Mathews (1990; dot-dashed lines) and Svechnikov and Taidakova (1984; dashed lines).

metallicity, the lifetimes decrease as the stellar mass increase, corresponding to $\tau_M \geq 12$ Gyr for $M = 1 M_\odot$ and $[\text{Fe}/\text{H}] = 0$, in good agreement with recent calculations for the sun. On the other hand, for a given mass, the lifetimes increase as the metallicity increases, which reflect the fact that the opacities also increase (Bazan & Mathews 1990). At very large metallicities ($[\text{Fe}/\text{H}] \geq 0.1$), the lifetimes tend to decrease, which is an effect of the increase of the helium abundances, according to the adopted evolutionary models.

The mass-metallicity relation can be fitted by a fourth-order polynomial

$$M = \sum_{i=0}^{i=4} a_i [\text{Fe}/\text{H}]^i, \quad (3)$$

and the coefficients a_0, a_1, a_2, a_3 , and a_4 are given in Table 1.

2.2. The colour-metallicity diagram

In order to transform the mass-metallicity relations into colour-metallicity $[\text{Fe}/\text{H}] \times (b - y)$ relations, the following steps have been taken: for each pair $(M, [\text{Fe}/\text{H}])$ we calculate the corresponding luminosity L and radius R at the zero-age main sequence (ZAMS), using the metallicity dependent mass-luminosity and mass-radius relations of Tout et al. (1996). These relations use essentially the same $\Delta Y/\Delta Z$ ratio adopted here, which makes them particularly suitable.

The luminosities and radii thus obtained are combined with the Stefan-Boltzmann law in order to derive the corresponding effective temperature, using $T_{\text{eff}\odot} = 5780$ K. Note that the results of the mass-luminosity and mass-radius relations for a star having $M = 1 M_\odot$ and $[\text{Fe}/\text{H}] = 0$ are not expected to be exactly L_\odot and R_\odot , as they correspond to *zero-age* values. In fact, at the zero-age main sequence the sun had $L = 0.698 L_\odot$ and $R = 0.888 R_\odot$ according to the relations by Tout et al.

Table 1. Coefficients of Eqs. (3) and (5).

τ_M	9 Gyr	12 Gyr	15 Gyr
a_0	1.09226	1.01776	0.96091
a_1	0.08527	0.07701	0.07528
a_2	-0.18696	-0.17460	-0.16527
a_3	-0.15898	-0.14492	-0.14614
a_4	-0.03650	-0.03173	-0.03444
b_0	0.37422	0.40739	0.43930
b_1	0.14870	0.15263	0.14007
b_2	-0.09793	-0.07868	-0.05588
b_3	-0.61373	-0.61850	-0.45216
b_4	-0.58683	-0.61440	-0.40393
b_5	-0.16743	-0.18077	-0.10171

(1996), so that $\log T_{\text{eff}\odot}(\text{ZAMS}) = 3.7486$, in excellent agreement with the result of the solar model by Vandenberg (1985), $\log T_{\text{eff}\odot}(\text{ZAMS}) = 3.7480$.

The colour index $(b - y)$ is related to the effective temperature by the equation

$$(b - y) = - (1.94212 + 0.20792[\text{Fe}/\text{H}] + 0.14239[\text{Fe}/\text{H}]^2) \log T_{\text{eff}} + (7.69792 + 0.81462[\text{Fe}/\text{H}] + 0.54988[\text{Fe}/\text{H}]^2), \quad (4)$$

which is derived from the theoretical colour-temperature relations (Vandenberg & Bell 1985) for dwarfs ($\log g \simeq 4.50$). This equation shows that for a given temperature, the colour $(b - y)$ gets bluer with decreasing $[\text{Fe}/\text{H}]$, which is an effect of the line blanketing.

The derived colour-metallicity relations are shown in Fig. 2, and these relations are fitted to fifth-order polynomials

$$(b - y) = \sum_{i=0}^{i=5} b_i [\text{Fe}/\text{H}]^i. \quad (5)$$

The coefficients b_0, b_1, b_2, b_3, b_4 , and b_5 are also shown in Table 1. It should be stressed that these relations are strictly valid only for zero-age main sequence stars. Real stars show bluer colours as they evolve on the main sequence, so that our results should be considered as preliminary.

We also plotted in Fig. 2 the 287 stars of the sample of Rocha-Pinto and Maciel (1996). Typical uncertainties in this diagram are $\delta[\text{Fe}/\text{H}] \simeq 0.16$ dex and $\delta(b - y) \simeq 0.003$, as shown in the lower right corner of the figure. Stars to the right of a given curve have expected lifetimes longer than indicated by that curve. The dashed lines in this diagram correspond to the $[\text{Fe}/\text{H}] \times (b - y)$ relations for stars of a given mass.

The obvious usefulness of Fig. 2 is that it allows a straightforward identification of potentially long-lived stars. We can divide the diagram into four regions:

- Region I: stars with $\tau_M < 9$ Gyr.
- Region II: stars with $9 < \tau_M < 12$ Gyr.
- Region III: stars with $12 < \tau_M < 15$ Gyr.
- Region IV: stars with $\tau_M > 15$ Gyr.

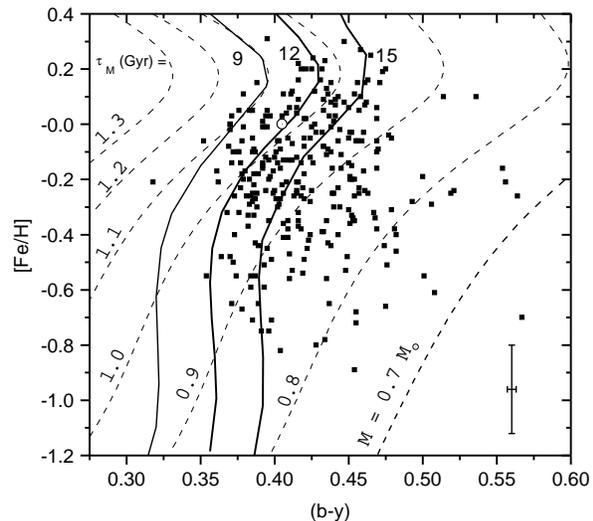


Fig. 2. $[\text{Fe}/\text{H}] \times (b - y)$ relation for stars with lifetimes of 9, 12, and 15 Gyr (solid lines). Also plotted are the 287 stars in the sample of Rocha-Pinto and Maciel (1996, filled squares). An average error bar is shown at the lower right corner. The dashed lines correspond to the $[\text{Fe}/\text{H}] \times (b - y)$ relation for stars of a given mass.

The fraction of stars in each region is, respectively, 3%, 15%, 33% and 49%. The identification of the regions that are populated by long-lived stars depends on the assumed age of the disk. The most probable value for this age is around 12 Gyr, in any case not lower than 9 Gyr (Iben & Laughlin 1989, and references therein; see also Cowan et al. 1991). *We conclude that stars belonging to regions III and IV are certainly long-lived, while stars in region I cannot be regarded as long-lived for chemical evolution purposes.* Therefore, approximately 82% of the stars in the sample by Rocha-Pinto and Maciel (1996) can be safely considered as long-lived. Region II corresponds to the boundary of short-lived and long-lived stars. In view of the uncertainties in the determination of the disk age, we cannot be sure whether or not they are representative of the chemical enrichment of the galactic disk. For a rigorous selection of long-lived stars, region II stars should be avoided.

We have also applied the present method to the sample of Wyse & Gilmore (1995). The corresponding $[\text{Fe}/\text{H}] \times (b - y)$ diagram for this sample is shown in Fig. 3. In this plot, we have used different symbols to represent stars already excluded by Wyse & Gilmore (empty squares), and those potentially long-lived (filled squares) for an adopted disk age of 12 Gyr. In this case, the fraction of stars in regions I, II, III, and IV is 14%, 13%, 37% and 36%, respectively. Note that the percentage of their stars in region I is much larger than in our sample. This can be understood as Wyse & Gilmore included some later F dwarfs in their sample.

Wyse & Gilmore (1995) excluded all stars with bluer colours than the turnoff colour at 12 Gyr, for a given metallicity. They have used the same set of stellar models (Vandenberg 1985; Vandenberg and Bell 1985; Vandenberg and Laskarides 1987), but do not mention how the helium dependence of the lifetimes

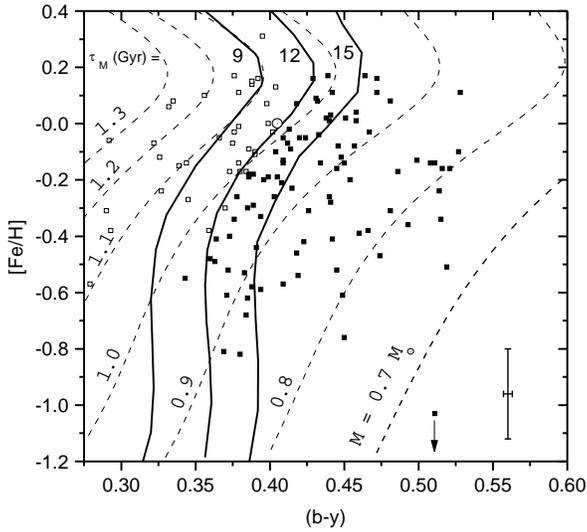


Fig. 3. The same as Fig. 2 for the 128 stars in the sample of Wyse and Gilmore (1995). Different symbols are used to represent potentially short-lived (empty squares) and long-lived stars (filled squares), according to the criterion designed by Wyse & Gilmore.

was treated. In view of the similarities between our treatments, the good agreement between their results and our 12 Gyr curve (see Fig. 3) is not surprising.

The results of figs. 2 and 3 are somewhat affected by the evolution of the stars on the main sequence, as the colour-metallicity relations given by eq. (5) are only valid for ZAMS stars. On the other hand, observational data refer to stars with varying degrees of evolution, that is, their observed colours cannot be taken as zero-age colours. To show this, we have considered the variations in $\log T_{\text{eff}}$ between the ZAMS and the turnoff point given by Vandenberg (1985) and Vandenberg & Laskarides (1987), for stellar masses $M = 0.8$ and $1.0 M_{\odot}$, $Y = 0.25$, and metallicities $Z = Z_{\odot}$, 0.03, 0.01, 0.006, and 0.003. We converted the differences in the effective temperature into colour differences using eq. (4), and the derived results are shown in Fig. 4a. It can be seen that the variation can be large enough to move some stars born in the regions of long-lived stars (regions III and IV) to regions I and II. This can be seen in Fig. 4b for the case of the sun. In Fig. 1, the solar position is slightly to the *right* of the 12 Gyr curve, which would make the sun a long-lived star according to our previous discussion. Taking the present sun colour $(b-y)_{\odot} = 0.405 \pm 0.002$ (Saxner and Hammarbäck 1985), the position of the sun changes to the *left* of the 12 Gyr curve, as can be seen in figs. 2, 3, and 4b. This is basically due to the colour variation on the main sequence. From Fig. 4b, the sun was born on the $1 M_{\odot}$ curve, with approximately $(b-y)_{\odot} = 0.418$, that is, in the region of the long-lived stars, in agreement with Fig. 1. Due to main sequence evolution, it moves to the left, as shown in Fig. 4b. The arrow indicates the expected solar evolution from the variation in the effective temperature according to the models by Vandenberg (1985). As a general conclusion, we can see that some stars located in the regions of short-lived stars could in fact have lifetimes longer than 12 Gyr. Therefore, our results

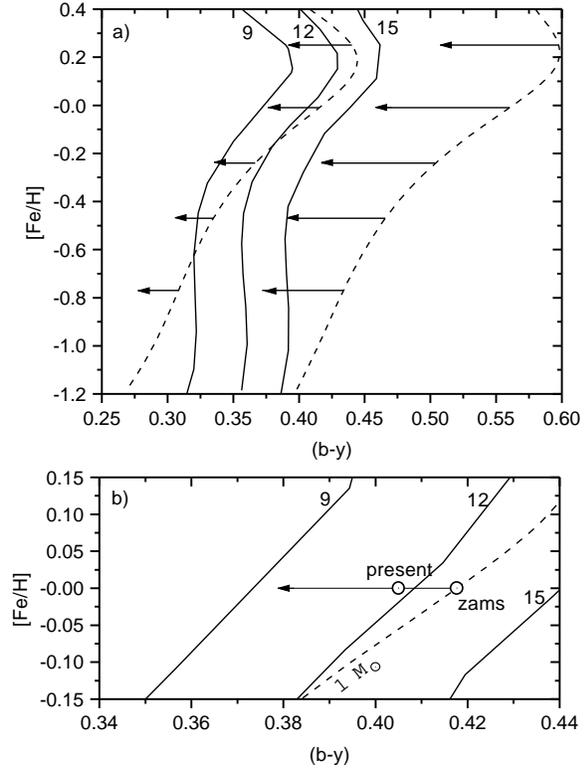


Fig. 4. a The same as Fig. 2, showing the estimated evolution effects on stars of 1.0 and $0.8 M_{\odot}$ with $Y = 0.25$ and initial metallicities Z_{\odot} , 0.03, 0.01, 0.006, and 0.003, respectively. **b** An enlargement of Fig. 4a showing the variation in the solar position from the zero-age main sequence.

should be considered as preliminary, and more accurate estimates are expected to be possible as detailed calculations for evolved stars become available.

3. Effects of metallicity-dependent lifetimes

Fig. 5 shows the metallicity distribution of the sample by Rocha-Pinto & Maciel (1996) in original form (solid line), and after eliminating stars with lifetimes potentially lower than 9 Gyr (dotted line) and 12 Gyr (dashed line). The total number of stars in each distribution is 287, 278, and 236, respectively. As can be seen the elimination of the stars in regions I and II does not affect the shape of the metallicity distribution, except for a decrease in the number of stars at the high metallicity end of the distribution.

These results indicate that, even if the disk age is about 9 to 10 Gyr, our sample is basically composed by long-lived stars. In fact, some investigations on the white dwarf luminosity function (Winget et al. 1987) and the evolution of the abundance ratios of the nucleochronometer pair Th/Nd (Butcher 1987; Morell et al. 1992) yield a disk age of 9-11 Gyr. On the other hand, although our distribution includes essentially long-lived G dwarfs, it still cannot be considered as a complete sample, since most old metal-poor G dwarfs with lifetimes of 12 Gyr or greater are

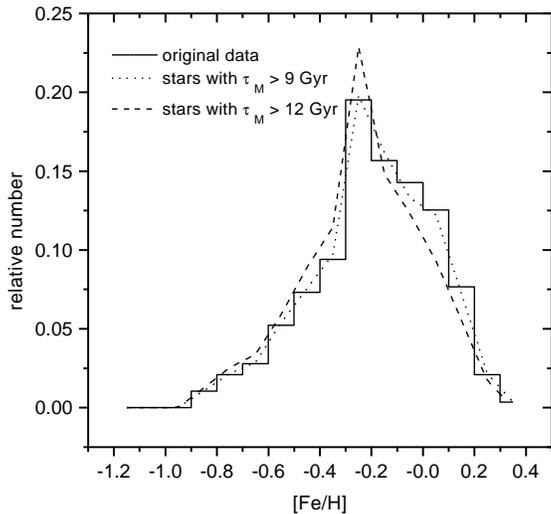


Fig. 5. The original metallicity distribution for the sample of Rocha-Pinto and Maciel (1996, solid line), and after removal of stars with lifetimes lower than 9 Gyr (dotted line) and 12 Gyr (dashed line).

shifted towards the F dwarf range due to the evolution on the main sequence, so that they are not selected as G dwarfs.

The legitimacy of the G-dwarf metallicity distribution as representative of the chemical enrichment history was first questioned by Biermann & Biermann (1977). Taking the disk age as 15 Gyr, they concluded that only stars of type K0 and later can be considered as witnesses of the early phases of the Galaxy, and the customarily used G dwarfs are not old enough to represent these epochs.

More recently, Bazan & Mathews (1990) have suggested that part of the G dwarf problem could be an effect of the metallicity dependence of the stellar lifetimes. Their argument can be summarized as follows: for a given mass, the metal-poor stars should have shorter lifetimes than the metal-rich ones, as a result of lower opacities. Thus, as the older stars are likely to be preferentially the poorest, the number of expected metal-poor G dwarfs today should be smaller than the number of those stars ever born.

However, Meusinger & Stecklum (1992) have pointed out that the results of Bazan & Mathews could not be directly compared with the observational data, because Bazan & Mathews define their theoretical G-dwarf sample by a mass range whereas the observed samples are defined by a spectral range and/or photometric criteria.

According to Bazan & Mathews, the G dwarfs comprise stars between $0.79 M_{\odot}$ and $1.09 M_{\odot}$ (Fig. 1, dot-dashed lines). This range is to be compared with the range predicted by Svechnikov & Taidakova (1984), $0.90 M_{\odot} - 1.10 M_{\odot}$ (Fig.1, dashed lines). The upper mass limit is in very good agreement, but the value of the lower limit seems to be still uncertain.

It is clear that if all stars born within the above mass ranges are G dwarfs, then we should expect that a large number of metal-poor G dwarfs will fall to the left of the 9 Gyr curve (cf. Fig. 1), in the region of short-lived stars. As a result, part of the

G dwarf problem could be originated by the mere absence of the old metal-poor G dwarfs from the data samples, because these stars have already died.

Note that the majority of stars in our sample (which comprises only dwarfs with spectral type G) fall in the region limited by masses $1.1 M_{\odot}$ and $0.8 M_{\odot}$, in good agreement with the predicted G dwarf mass range (Bazan & Mathews 1990), and to a less extent with the results of Svechnikov & Taidakova (1984).

Besides the mass range, the G dwarfs are often defined by a colour range. According to Olsen (1984), G dwarfs have average colours in the range $0.365 \leq (b - y) \leq 0.470$, which is in good agreement with our results of Fig. 2, in the sense that 90% of all objects lie between these extremes.

In fact, the G dwarfs appear to lie in the very intersection between the mass and the colour ranges. Moreover, in spite of being well limited by the curves corresponding to their mass range, the observed G dwarf sample is better defined by the colour range. The dashed lines in Fig. 2 cross regions of the diagram $[\text{Fe}/\text{H}] \times (b - y)$ which are photometrically associated to different spectral types. This indicates that stars of the same mass could have different spectral types. For example, the $0.9 M_{\odot}$ curve shows that $0.9 M_{\odot}$ stars would be F dwarfs [$(b - y) < 0.365$] at lower metallicities, G dwarfs for intermediate metallicities, and K dwarfs [$(b - y) > 0.470$] for $[\text{Fe}/\text{H}]$ above solar.

From Fig. 2 it can be seen that the region corresponding to the metal-poor short lived stars extends beyond the G dwarf range into the F dwarf range. Hence, *metal-poor G dwarfs will not have lifetimes lower than the disk age*, provided that this age does not exceed about 12 Gyr.

The short-lived G dwarfs are to be found mostly amongst the richest stars (see Fig. 2), which is the opposite trend of that predicted by Bazan & Mathews (1990). These G dwarfs are also massive objects, as shown by their location on Fig. 2. If they were also the youngest, probably all of these short-lived G dwarfs ever born would still be alive, as their expected lifetimes are between 9 and 12 Gyr. We conclude that the G dwarf problem is not an effect of the metallicity dependence of the stellar lifetimes.

The question remains as how to define selection criteria to assure the longevity and the completeness of the data samples used to derive the metallicity distribution.

As we have shown, the selection of stars based on a mass range does not isolate the long-lived stars unless we take only stars with $M < 0.9 M_{\odot}$ (see Fig. 2). The same can be said about the selection by a colour range, unless stars redder than $(b - y) > 0.430$ are considered. Selection by spectral type also does not isolate long-lived stars. The G dwarfs could be taken, in a first approximation, as stars that live forever (that is, with $\tau_M \gtrsim T_G$), as we have shown that 82% of the G dwarfs are located in regions III and IV of the diagram $[\text{Fe}/\text{H}] \times (b - y)$. However, a metallicity distribution of K dwarfs could comprise only long-lived stars, as proposed by Biermann & Biermann (1977). The extension of the G dwarf problem to later stars was examined in a few investigations based on small samples (Flynn & Morell 1997; Rana & Basu 1990; Mould 1978), according

to which the lack of metal-poor stars may also occur for redder dwarfs.

An alternative to this question, which we favour, is to make a selection by a lifetime range, for example taking only stars belonging to region III in the $[\text{Fe}/\text{H}] \times (b - y)$ diagram. In this case, not only G dwarfs must be taken in account, but also earlier K dwarfs and late F dwarfs, in order to check their position on the diagram. Once the metallicity dependent mass-luminosity and mass-radius relations are extended to evolved stars, it may be possible to solve the problems associated with stellar evolution on the colour-metallicity diagram.

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