AGE AND METALLICITY DISTRIBUTIONS AMONG GALACTIC DISK STARS

P.E. NISSEN

Institute of Physics and Astronomy
University of Aarhus, Denmark
(pen@obs.aau.dk)

Abstract. Observational studies of the relations between ages, metallicities and kinematics of disk stars in the solar neighbourhood are discussed with emphasis on the recent survey by Edvardsson *et al.* (1993), and galactic metallicity gradients inferred from these nearby stars are compared with gradients determined from distant B stars and open clusters.

1. Introduction

F and G main sequence stars in the solar neighbourhood are unique objects in connection with studies of the history of the Galaxy. The abundances of the elements in their atmospheres can be determined with good accuracy from high resolution spectroscopy. For a given star the element composition is likely to represent the composition of the gas in the Galaxy at the time and at the place of the birth of the star. The age can be estimated from the position of the star in an HR-diagram, and the space velocity is determined from the radial velocity, proper motion and parallax. Hence, F and G stars may be used to reveal the chemical and dynamical evolution of the Galaxy.

In the present paper we discuss the age–metallicity–kinematics relations for disk stars in the solar neighbourhood with emphasis on the recent monumental work by Edvardsson *et al.* (1993). Furthermore, galactic metallicity gradients inferred from nearby stars are compared with gradients determined from abundance determinations of distant B stars and open clusters.

P. C. van der Kruit and G. Gilmore (eds.), Stellar Populations, 109–117.

https://doi.org/10.1017/S0074180900108472 Published online by Cambridge University Press

2. The Edvardsson *et al.* Disk Survey

A survey of the chemical composition, ages and kinematics of 189 F and early G main-sequence stars has recently been completed by Edvardsson *et al.* (1993). The stars were selected from the Olsen (1988) catalogue of *uvby*-β photometry, which contains nearly all F stars brighter than $V = 8.3$. Using the β and c_1 indices, stars with $5600 < T_{\rm eff} < 7000$ K and somewhat evolved from the ZAMS were first selected and then divided into nine [Fe/H] groups ranging from -1.0 to $+0.3$ by the aid of the m_1 index. High resolution, high S/N spectra were obtained for the ~ 20 brightest stars in each metallicity group. Thus, the stars have a biased distribution in [Fe/H] but the sample is without any kinematical bias.

From a model atmosphere analysis of the observed spectra the abundances of 13 elements were determined. As discussed by Edvardsson *et al.* the differential error of [Fe/H] is 0.05 dex, whereas the error of $[\alpha/{\rm Fe}] \equiv \frac{1}{4}([{\rm Mg/Fe}] + [{\rm Si/Fe}] + [{\rm Ca/Fe}] + [{\rm Ti/Fe}])$ is 0.03 dex only.

The age of a star was determined from comparing its position in the $\log(T_{\rm eff}) - \delta M_V$ diagram with isochrones computed by VandenBerg (1985). Here δM_V denotes $M_V(ZAMS) - M_V(star)$ as determined from the Balmer discontinuity index, c_1. The error of the *differential* ages of the stars is estimated to be about 25%, corresponding to an error of the logarithmic age, $\sigma(\log({\rm Age})) \simeq 0.10$.

The stellar space velocities were computed from CORAVEL radial velocities ($\pm 1\,{\rm km\,s^{-1}}$) and proper motions. The distances follow from absolute magnitudes determined by the $\delta c_1 - \beta$ method of Crawford (1975). The accuracy of the distance determinations is estimated to be about 15%. Hence, the largest contribution to the error of the space velocity comes from the error of the distance determination. Typical errors of the velocity components U, V and W are $\pm 3\,{\rm km\,s^{-1}}$.

Orbits of the stars were computed for a galactic potential that reproduces the rotation curve. The mean value of the apogalactic and the perigalactic distance of a star is called R_m. As discussed by Grenon (1987) R_m changes by about ± 0.5 kpc only, as a result of 'orbital diffusion' (Wielen, 1977). Hence, it seems reasonable to adopt R_m as an estimate of the distance from the galactic center at which the star was originally formed in a nearly circular orbit.

3. The Age–Velocity-Dispersion Relation

Fig. 1 shows the velocity dispersions in U, V, and W as a function of age for the stars of Edvardsson *et al.* The stars were divided into 7 age groups each corresponding to a bin of 0.15 dex in log(Age). The error bars have been calculated as $\sigma/\sqrt{2N}$, where σ is the velocity dispersion and N the

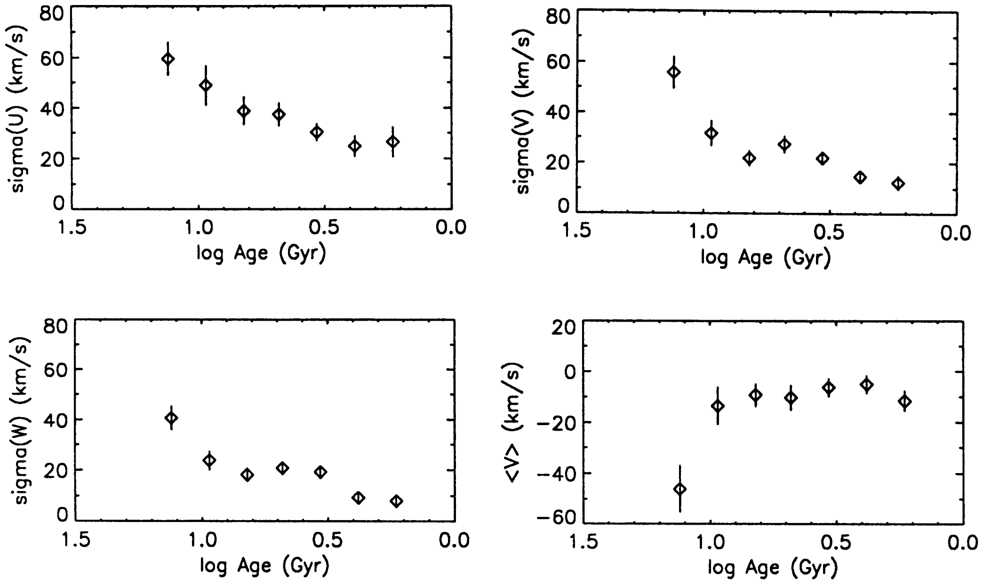

Figure 1. The age–kinematics relations for the sample of 189 disk stars from Edvardsson *et al.* (1993)

number of stars in the bin. Furthermore, Fig. 1 shows the mean value of V vs. log(Age) after a correction of $+6$ km s^{-1} for the solar motion. As seen, $< V >$ is nearly constant at a value of about -10 km s^{-1} up to ages of 10 Gyr, but is dropping to a value of -50 km s^{-1} for the oldest age group. It also interesting that the velocity dispersions in V and W seem to rise abruptly for the oldest age group. Freeman (1991) has analyzed the same data by plotting $\Sigma \mid W \mid$ vs. the age rank, and suggests that the velocity dispersion in W saturates at a value of about 20 km s^{-1} for the age range 3 to 12 Gyr and then increases to about 40 km s^{-1} for ages $>$ 12 Gyr. These results suggest that the oldest age group consists of stars belonging to a thick disk, that is kinematically discrete from the old thin disk.

Possible disk heating mechanisms, e.g. scattering of stars by massive gas clouds, spiral arms or massive black holes, correspond to an exponent p in the age–velocity-dispersion relation, $\sigma \propto (Age)^p$, ranging from $p = 0.2$ to 0.5 (Lacey, 1991). Excluding the oldest group in Fig. 1 the data correspond to $p = 0.45 \pm 0.1$. This is not significantly different from the value of $p \simeq 0.5$ found by Jahreiss and Wielen (1983). On the other hand Strömgren's (1987) data for 558 F dwarfs with metallicities close to the solar value suggest $p = 0.2 \pm 0.1$. It may well be that the samples of Edvardsson *et al.* and Jahreiss and Wielen are contaminated by metal-poor thick stars, for which the kinematics has a different dynamical explanation than in the case of

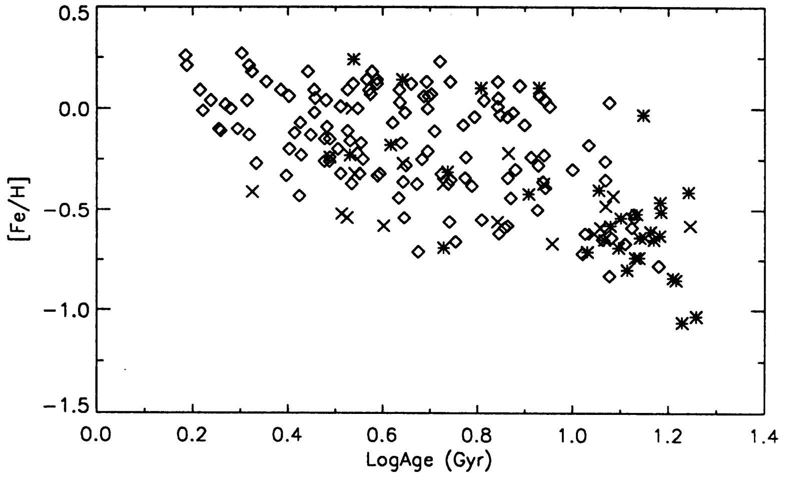

Figure 2. The age–metallicity relation of Edvardsson *et al.* The various symbols refer to the following mean galactocentric distances of the stars: $*, R_m \leq 7$ kpc; $\diamond, 7 < R_m < 9$ kpc; $\times, R_m \geq 9$ kpc.

the thin disk stars. A new study of a sample of F stars sufficiently large to allow binning in both age and metallicity is much needed.

4. The Age–Metallicity Relation

Fig. 2 shows the relation between age and metallicity for the stars of Edvardsson *et al.* Although there is an overall trend of decreasing mean metallicity with increasing age, it is the large scatter in [Fe/H] at a given age that dominates the picture. After correction for the metallicity bias in selecting the stars, as discussed by Edvardsson *et al.*, one gets σ[Fe/H] = 0.20 in the age range 2 to 10 Gyr, where the mean [Fe/H]–age relation is practically flat. This scatter is four times the estimated error of [Fe/H].

What is causing the large scatter in the age–metallicity relation? As seen from Fig. 2, stars presumably formed in the outer parts of the Galaxy ($R_m > 9$ kpc) tend to be distributed along the lower envelope of the distribution, whereas stars formed in the inner parts of the Galaxy ($R_m < 7$ kpc) show a steeper relation between [Fe/H] and age than the rest of the stars. This suggests that part of the scatter in the age–metallicity relation is due to the diffusion of stellar orbits combined with a metallicity gradient. Fuchs *et al.* (1994) have shown that the observed metallicity dispersion in the solar neighbourhood agrees well with the dispersion expected if the radial metallicity gradient is −0.1 dex/kpc and the stellar diffusion process is driven by massive black holes. The corresponding exponent in the age–velocity-dispersion relation is $p = 0.5$. As discussed above it is, however, questionable if p is so high. Other possible explanations of the large dispersion in metallicity, such as star formation triggered by infall of metal-poor gas, are discussed by Edvardsson *et al.*

The data of Edvardsson *et al.* should not be used to determine the mean age–metallicity relation in the solar neighbourhood. The sample of stars is biased with respect to [Fe/H] and there is a temperature cutoff, $T_{\rm eff} \geq 5600$. This means that old, metal-rich stars that may be present in the upper, right part of Fig. 2 have been excluded.

Twarog (1980) has presented a careful and often cited study of the age–metallicity relation in the solar neighbourhood based on Strömgren photometry of about 1000 F stars. His relation agrees well with the data shown in Fig. 2, but it should be noted that his sample also suffers from a temperature cutoff at about 5600 K. Carlberg *et al.* (1985) have used the data of Twarog to derive a very flat age–metallicity relation suggesting that the galactic disk initially had a rather high metallicity. It seems that this result was obtained because all stars with $[Fe/H] < -0.5$ were considered to have an uncertain age determination and therefore excluded from the analysis. Meusinger *et al.* (1991) have reanalyzed Twarog's data assigning weights to each star corresponding to its relative uncertainty in the age determination. The derived age–metallicity relation agrees well with that of Twarog. Furthermore, a dispersion $\sigma[Fe/H] = 0.20$ at a given age is found in agreement with Edvardsson *et al.*

5. Galactic Abundance Gradients

The dependence of [Fe/H] on R_m seen in Fig. 2 is consistent with a radial gradient of -0.1 dex/kpc for old disk stars. Grenon (1987) has derived a similar value from Geneva photometry of a sample of stars from Luyten's NLTT catalogue. Friel and Janes (1993) have recently derived metallicities for 24 open clusters from medium resolution spectroscopy of K giants. The clusters have galactocentric distances ranging from 8 to 16 kpc and ages from 1 to 8 Gyr. The resulting gradient is $\Delta[Fe/H]/\Delta R_{gc} = -0.09 \pm 0.02$ kpc^{-1}. We conclude that both the local stars and the in situ data for open clusters point to a radial metallicity gradient of about -0.1 dex/kpc for the old disk. For comparison, the abundance gradients of O, Ne, S, and Ar as derived from planetary nebulae of Type II with typical ages of 4-6 Gyr are on the order of -0.06 dex/kpc (Maciel and Köppen, 1994).

It is interesting to compare the metallicity gradients determined for old disk stars and planetary nebulae with gradients derived for very young objects. In the last few years accurate abundances of distant B main-sequence stars have been determined by groups in Belfast (Rolleston *et al.*, 1993),

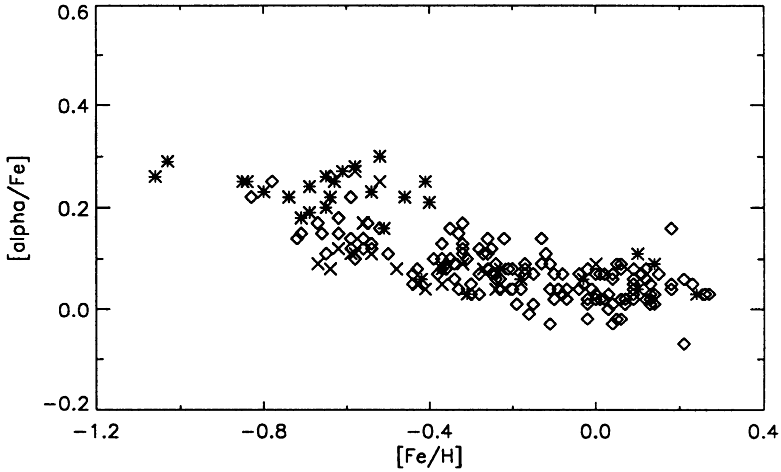

Figure 3. [α/Fe] versus [Fe/H]. The symbols refer to the following mean galactocentric distances of the stars: $*$, $R_m \leq 7$ kpc; $\diamond, 7 < R_m < 9$ kpc; $\times, R_m \geq 9$ kpc.

Munich (Kilian *et al.*, 1994) and Heidelberg (Kaufer *et al.*, 1994). Kaufer *et al.* have summarized the data for 55 B stars well distributed over a range in galactocentric distance from 6 to 16 kpc. Surprisingly flat gradients of oxygen and nitrogen are derived. The values are $\Delta[\mathrm{O/H}]/\Delta R_{gc} = 0.00 \pm 0.01$ kpc^{-1} and $\Delta[\mathrm{N/H}]/\Delta R_{gc} = -0.03 \pm 0.01$ kpc^{-1}. At a first sight these results seem at variance with abundance gradients derived from optical and radio spectroscopy of H II regions (Shaver *et al.*, 1983; Fich and Silkey, 1991). However, as pointed out by Kaufer et al. the steeper gradients from H II regions are mainly due to the very high abundances derived in the innermost parts of the Galaxy. For the H II regions in the range from 6 to 15 Kpc the gradients are: $\Delta[\mathrm{O/H}]/\Delta R_{gc} = -0.04 \pm 0.02$ kpc^{-1}, and $\Delta[\mathrm{N/H}]/\Delta R_{gc} = -0.01 \pm 0.01$ kpc^{-1}, which is not significantly different from the values derived from the B stars.

It is difficult to understand how the metallicity gradient in the disk could change from a value of −0.10 dex/kpc at an age of 5 Gyr to a value of say −0.03 dex/kpc at present. In this connection one should, however, note that the data for the old disk refer to the iron peak elements (except in the case of the planetary nebulae), whereas the data for the B stars and the H II regions refer to O and N. Abundances of Mg, Si and Fe for B stars ranging in galactocentric distance from 6 to 15 kpc have been determined by Kilian-Montenbruck *et al.* (1994) and point to flat gradients as in the case of O and N, but the errors are larger.

The galactic gradients just discussed refer to the thin disk. In the case of the thick disk, i.e. the stars with ages larger than 10 Gyr having $\sigma(W) =$

40 $\mathrm{km\,s^{-1}}$, the Edvardsson *et al.* data are too sparse to say anything about a possible gradient in [Fe/H]. Fig. 3 shows, however, a very interesting observation. For $[Fe/H] < -0.4$ the 'overabundance' of α-elements with respect to iron is correlated with R_m. At a given value of [Fe/H] stars formed in the inner regions of the Galaxy tend to have higher $[\alpha/Fe]$ values than stars formed in the outer regions. Formally, one derives a gradient $\Delta[\alpha/Fe]/\Delta R_m = -0.030 \pm 0.004$ $\mathrm{kpc^{-1}}$. Assuming that the transition from a high value of $[\alpha/Fe]$ to a solar value is due to the appearance of supernovae of type Ia we conclude that the the chemical evolution has proceeded faster in the inner regions of the galactic disk than in the outer regions. This is consistent with models of disk formation by Burkert *et al.* (1992) implying that the disk formed from inside out.

6. Conclusion and Discussion

The new work of Edvardsson *et al.* (1993) points to the existence of two discrete populations of stars in the solar neighbourhood: *i) The Thick Disk* with $10 < Age < 15$ Gyr, $-0.8 < [Fe/H] < -0.4$, $< V > \simeq -50$ $\mathrm{km\,s^{-1}}$, $\sigma(W) \simeq 40$ $\mathrm{km\,s^{-1}}$, and a radial gradient $\Delta[\alpha/Fe]/\Delta R_m = -0.03$ $\mathrm{kpc^{-1}}$. *ii) The Thin Disk* with $Age < 10$ Gyr, $-0.4 < [Fe/H] < +0.3$, $< V > \simeq -10$ $\mathrm{km\,s^{-1}}$, a velocity dispersion that increases with age, and a radial metallicity gradient that probably depends on age. The age and metallicity limits should not be taken too strictly; there may well be considerable overlap of the two populations.

Much work is, however, needed before a clear picture of the formation and evolution of the galactic disk can be reached. Ages, metallicities and kinematics with the same high accuracy as obtained by Edvardsson *et al.* are needed for a much larger sample of stars selected in a well defined way. Work in this direction is in progress based on the big catalogues of Strömgren photometry of F and G stars by Olsen (1983, 1993, 1994). On the basis of these data it will be possible to make a detailed study of the age–metallicity–kinematics relations in the galactic disk and hopefully to get answers to some of the problems raised in this review, such as the reason for the large scatter in the age–metallicity relation, and the explanation of the age–velocity-dispersion relation. In will also be interesting to look for structures in the age–metallicity–kinematics space relating to merger events. Furthermore, the photometry of Olsen can be used for determining the metallicity distribution of G dwarfs and hence for a thorough discussion of the classical G dwarf problem.

With the new photometry of Olsen it will also be possible to investigate if the solar neighbourhood contain a population of Super Metal Rich (SMR) stars. From Geneva photometry of nearby stars in the *Gliese Catalogue* as well as a large sample of NLTT stars, Grenon (1990) concluded that about 4% of the stars in the solar neighbourhood have metallicities in the range $+0.3 < [Fe/H] < +0.6$, ages around 10 Gyr and kinematics indicating that they have been formed in the inner part of the Galaxy. None of these SMR stars were found in the Edvardsson *et al.* survey. This may well be due to the low turnoff temperature of this population ($T_{eff} \simeq 5500$ K), which is below the temperature limit of the Edvardsson *et al.* survey. It is, however, puzzling that no SMR stars are found in the survey by Laird *et al.* (1988) of high proper motion stars and the Strömgren photometry of high velocity stars by Schuster *et al.* (1993). The metallicity distribution of these two samples, which do include G stars, has a sharp cutoff at $[Fe/H] = +0.3$.

References

Burkert A, Truran J.W. and Hensler G., 1992, *Ap. J.* **391**, 651
Carlberg R.G., Dawson P.C., Hsu T. and VandenBerg D.A., 1985, *Ap. J.* **294**, 674
Crawford D.L., 1975, *A.J.* **80**, 955
Edvardsson B., Andersen J., Gustafsson B., Lambert D.L., Nissen P.E. and Tomkin J., 1993, *A. & A.* **275**, 101
Fich M. and Silkey M., 1991, *Ap.J.* **366**, 107
Freeman K.C., 1991, *Dynamics of Disc Galaxies*, ed. B. Sundelius, Gothenburg University, p. 15
Friel, E.D. and Janes, K.A., 1993, *A. & A.* **267**, 75
Fuchs B., Dettbarn C. and Wielen R. 1994, *Ergodic Concepts in Stellar Dynamics*, eds. D. Pfenniger and V.G. Gurzadyan, Springer-Verlag, in press
Grenon M., 1987, *J. Astron. Astroph.* **8**, 123
Grenon M., 1990, *Astrophysical Ages and Dating Methods*, Ed. E. Vangioni-Flam *et al.*, Editions Frontieres, p. 153
Jahreiss H. and Wielen R., 1983, *The Nearby Stars and the Stellar Luminosity Function*, eds. A.G. Davis Philip and A.R. Upgren, L. Davis Press, p. 277
Kaufer A., Szeifert Th., Krenzin R., Baschek B. and Wolf B., 1994, *A. & A.* **289**, 740
Kilian J., Montenbruck O. and Nissen, P.E., 1994, *A. & A.* **284**, 437
Kilian-Montenbruck J., Gehren, T. and Nissen, P.E., 1994, *A. & A.*, in press
Lacey C., 1991, *Dynamics of Disc Galaxies*, ed. B. Sundelius, Gothenburg University, p. 257
Laird J.B., Carney B.W. and Latham D.W., 1988, *A. J.* **95**, 1843
Maciel, W.J. and Köppen, J., 1994, *A. & A.* **282**, 436
Meusinger H., Reimann H.-G. and Stecklum B., 1991, *A. & A.* **245**, 57
Olsen, E.H., 1983, *A. & A. Suppl.* **54**, 55
Olsen, E.H., 1988, *A. & A.* **189**, 173
Olsen, E.H., 1993, *A. & A. Suppl.* **102**, 89
Olsen, E.H., 1994, *A. & A. Suppl.* **104**, 429
Rolleston W.R.J., Brown P.F.J., Dufton P.L. and Fitzsimmons A., 1993, *A. & A.* **270**, 107
Schuster W.J., Parrao L. and Contreras Martinez, M.E., 1993, *A. & A. Suppl.* **97**, 951
Shaver P.A., McGee R.X., Newton L.M., Danks A.C. and Pottasch, S.R., 1983, *M. N. R. A. S.* **204**, 53
Strömgren B., 1987, *The Galaxy*, eds. G. Gilmore and B. Carswell, Reidel Publ. Co., p.229
Twarog, B.A., 1980, *Ap. J.* **242**, 242
VandenBerg D.A., 1985, *Ap. J. Suppl.* **58**, 711

Wielen R., 1977, *A. & A.* **60**, 263

KRAFT: How do you calibrate, for the most metal-rich stars near $\sim$ G0, the ages? If you use galactic clusters to calibrate δc_1, as a function of age, how do you deal with the fact that there are no galactic clusters much older than 7-9 Gyr? Doesn't this make a problem for stars older than 10 Gyr?
NISSEN: The factor f that converts δc_1 to δM_V has been derived from clusters with ages between 1 and 5 Gyr. So the use of the expression of f for older stars is an extrapolation. Its value for the older star is, however, supported by existing trigonometric parallaxes. When HIPPARCOS data become available the calibration can be improved.
BELL: The ages of old galactic clusters e.g. NGC6791 seem consistent with the cooling time ages for white dwarfs. Your ages for some stars are much greater than the 8 Gyr from the white dwarfs. Doesn't this give you pause?
NISSEN: The absolute ages of our stars are quite uncertain due mainly to uncertainties in the mixing length parameter of the models and the $T_{\rm eff}$ temperature scale. The estimated accuracy of 25% in the age determination refers to relative ages of stars with similar metallicities.
CAYREL: There is a single point on which I perhaps disagree, or at least I am sceptical. It is the way you assign a mean place of formation to a star in your survey, i.e. $R_m = \frac{1}{2}(R_{max} + R_{min})$. This does not take into account the time spent by the star in the various parts of the orbit. So assigning a mean distance to a star on an excentric orbit is debatable.
NISSEN: Numerical calculations (Wielen, 1977) of the change of R_m with time due to orbital diffusion show that R_m is conserved within an rms of ± 0.5 kpc.
GRENON: About existence of SMR stars, we can confirm that according to high dispersion analysis by Barbuy, they indeed show [Fe/H] ratios of the order of $+0.30$ dex. The mean maximum [Fe/H] in the solar neighbourhood is around $+0.45$ dex, as in the Bulge according to the Rich revised scale.
The SMRs are normally not detected by objective prism surveys, because of an abundance effect on MK classification. At low dispersion SMR K dwarfs show spectra of normal luminous K giants.
This population was missed in most previous samples because of the temperature cutoffs, namely at G0 for Strömgren photometry, whereas the turn off of SMR population is at G7. Carney's sample is also truncated in favour of metal-poor stars of colour class f or g.
CAYREL DE STROBEL: I agree with the idea of Grenon that there is a fairly large sample of metal-rich unevolved or slightly evolved stars in the solar neighbourhood. But, I contest that his sample is enriched by more than $+0.25$ dex. Our sample of metal-rich stars has been analysed in detail and the errors on [M/H] are better than ± 0.05 dex.