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Evolution of old populations of our Galaxy

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Abstract

New accurate data on the chemical composition and ages of F and G main sequence stars in the solar neighborhood based on high resolution spectroscopy and Strömgren photometry is discussed and compared with kinematical data. The results point to the existence of three old, kinematically discrete populations:

(i) The old disk stars with ages between 3 and approximately 10 Gyr, [Fe/H] between −0.6 and +0.3, and α-element/iron ratios close to the solar ratio.

(ii) The thick disk stars with ages >10 Gyr, [Fe/H] between −1.2 and −0.4, and non-solar α-element/iron ratios that depend on the galactocentric distance of the birthplace of the star.

(iii) The halo stars with ages > 10 Gyr, [Fe/H] less than about −1.0, and a non-solar α-element/iron ratio that seems to be independent of [Fe/H].

The three populations overlap in [Fe/H] and age. For each population the velocity dispersions and $< V >$ are nearly independent of age and [Fe/H]. The large majority of the thick disk stars in the solar neighborhood appear to have been formed in the inner parts of the Galaxy.

Some implications of these results for evolutionary scenarios of the Galaxy are discussed.

1.1 Introduction

F and G main sequence stars in the solar neighborhood (d < 200 pc) are bright enough that the detailed chemical composition of their atmospheres can be determined from high resolution spectroscopy. Hence, the abundances of elements representing various sites and time scales of nucleosynthesis can be studied, *e.g.* (i) the α-elements (O, Mg, Si, Ca and Ti) produced

by massive stars exploding as SNeII on a short time scale, (ii) the iron-peak elements produced by SNeII *and* less massive stars exploding as SNeI on a time scale of typically 1 Gyr, and (iii) the s-process elements synthesized in AGB stars on a time scale of 3-5 Gyr.

The F and G stars have deep outer convection zones. This probably prohibits significant changes of the abundances of the heavier elements in their atmospheres as a function of time. The observed composition of a star therefore represents the composition of the matter in the Galaxy at the time and at the place of the birth of the star. The very good agreement between solar photospheric and meteoritic abundances and the constancy of abundances of various elements as a function of $T_{\rm eff}$ in star clusters like Hyades and Coma support this assumption. Furthermore, the F and G stars have ages ranging over the whole lifetime of the Galaxy. Thus, by studying the relations between chemical composition, ages and kinematics for F and G stars in the solar neighborhood we may learn a lot about the chemical and dynamical evolution of the Galaxy. In the following some new studies in this field are briefly reviewed and discussed.

1.2 The Edvardsson et al. sample of disk stars

A survey of the chemical composition, ages and kinematics of 189 F and G stars has recently been completed by Edvardsson et al. (1993a). Details about this work may be found in their rather extensive paper. The stars were selected from the Olsen (1988) catalogue of *uvby*-β photometry, which contains nearly all F and early G-type 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] intervals ranging from −1.0 to +0.3 by the aid of the m_1 index. High resolution, high S/N spectroscopy were obtained for the ~ 20 brightest stars in each metallicity range. Hence, the stars are evenly distributed in [Fe/H] but the sample is without any kinematical bias.

From a model atmosphere analysis of the observed spectra the abundances of 13 different elements were determined. As discussed by Edvardsson et al. the error of [Fe/H] is 0.05 dex, whereas the error of $[\alpha/\mathrm{Fe}] \equiv \frac{1}{4}([\mathrm{Mg/Fe}] + [\mathrm{Si/Fe}] + [\mathrm{Ca/Fe}] + [\mathrm{Ti/Fe}])$ is 0.03 dex only. The error of $T_{\rm eff}$ as determined from $b - y$ is less than 100 K.

The age of a star is determined from comparing its position in the $\log T_{\rm eff}$-δM_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 esti-

mated to be about 25%, corresponding to an error of the logarithmic age, $\sigma(\log Age) = 0.10$. The absolute values of the ages are, however, more uncertain.

The kinematical parameters are computed from accurate radial velocities ($\pm 1\,\mathrm{km\,s^{-1}}$) and proper motions based on second epoch observations with the Carlsberg Automatic Meridian Circle for the large majority of the stars. The distances of the stars follow from absolute magnitudes as determined with 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 ($\sigma < 5\ \mathrm{km\,s^{-1}}$) comes from the error of the distance determination.

Binaries for which the light from the secondary component affects the photometric or spectroscopic data by a significant amount were excluded. Each star was checked for interstellar reddening by comparing the β and $b-y$ indices of the star, but in all cases the amount of reddening was negligible.

As the distances are critical for the accuracy of the space velocities we have compared the photometric distances with distances from the new General Catalogue of Trigonometric Parallaxes by van Altena et al. (1993). Fig. 1 shows the comparison for stars having $\sigma(\pi)/\pi < 0.20$. Taking into account the errors the agreement is quite satisfactory although a few stars deviate by more than 3σ.

1.3 The age-abundance-kinematics relations in the disk

The radial velocity, distance and proper motion data were used to calculate velocity components U, V, and W relative to the sun. Furthermore, galactic orbits were computed as described in Edvardsson et al. (1993a). The mean value of the apogalactic and the perigalactic distance of a star is called R_m. As discussed by Grenon (1987) R_m only changes by about ± 0.5 kpc as a result of 'orbital diffusion' (Wielen 1977). Hence, it seems reasonable to adopt R_m as a best estimate of the distance from the galactic center at which the star was originally formed in a nearly circular orbit.

The Edvardsson et al. paper contains a detailed discussion of the relations between various abundance ratios. Here we limit ourselves to a few of the more important results. In Fig. 2 [α/Fe] is plotted versus [Fe/H] with different symbols for stars formed in (i) the inner regions of the Galaxy, $R_m \leq 7$ kpc, (ii) the 'solar cylinder', $7 < R_m < 9$ kpc, and (iii) the outer regions, $R_m \geq 9$ kpc. For [Fe/H] > -0.4 [α/Fe] is close to zero, and the scatter in [α/Fe] is 0.04 dex only. For [Fe/H] < -0.4 both [α/Fe] and the scatter increase. It is, however, interesting that the degree of 'overabundance' of

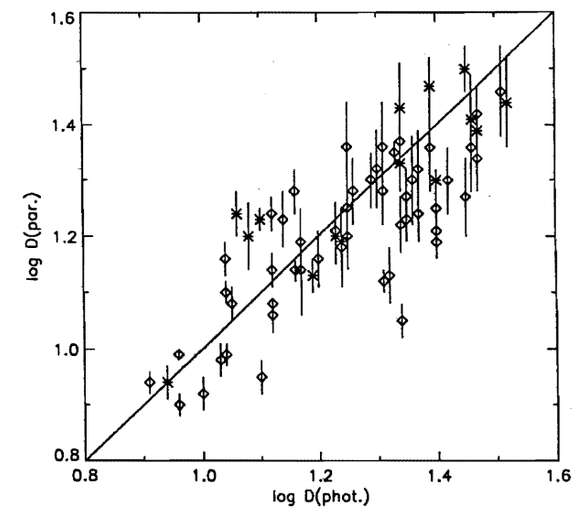

Fig. 1.1. Comparison of logarithmic distances (in pc) determined from Strömgren photometry and from parallaxes in the new catalogue of van Altena et al. (1993). Error bars indicate ± the standard error. ◇ refers to stars with $-0.4 <$ [Fe/H] $< +0.3$ and $*$ to stars with $-1.0 <$ [Fe/H] < -0.4.

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 [α/Fe] values than stars formed in the outer regions. Assuming that the transition from a high value of [α/Fe] to a solar value is due to the appearance of supernovae of type I we conclude that the the chemical evolution has proceeded faster in the inner regions of the galactic disk. This is consistent with models of disk formation by Burkert et al. (1992) implying that the disk formed from inside out.

Another interesting result from the Edvardsson et al. survey is the large scatter in the age-metallicity relation as shown in their figure 14. At a given age and R_m the rms scatter in [Fe/H] is about 0.20 dex, *i.e.* four times larger than the estimated error of [Fe/H]. The corresponding very small scatter in [α/Fe] makes it difficult to explain the large scatter in the age-metallicity relation by local bursts of star formation, because such bursts would produce an even larger scatter in [α/Fe] (Gilmore & Wyse 1991). As discussed by Edvardsson et al. (1993a) there is no obvious explanation of

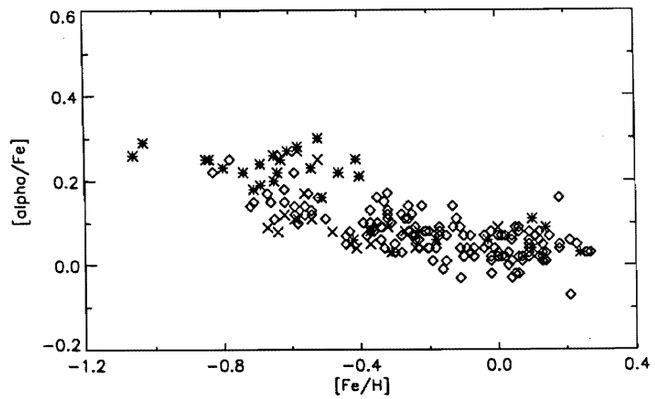

Fig. 1.2. [α/Fe] versus [Fe/H]. The symbols refer to the following mean galactocentric distances of the stars: $*, R_m \leq 7$ kpc; $\diamond, 7 < R_m < 9$ kpc; $\times, R_m \geq 9$ kpc.

the large scatter in the age-metallicity relation as due to observational errors or 'orbital diffusion'.

In Fig. 3 the V and W velocity components of the stars in the Edvardsson et al. sample are plotted versus the logarithm of the age with different symbols according to R_m. As expected from simple dynamical considerations there is a tight relation between R_m and V. In particular, we note that the majority of stars older than 10 Gyr appear to have been formed in the inner regions of the Galaxy.

The distribution of W velocities shows an interesting structure. For ages between 3 and 10 Gyr, *i.e.* $0.5 < \log Age < 1.0$ the velocity dispersion in W is approximately constant (± 21 km s^{-1}), whereas it is nearly a factor of two higher (± 38 km s^{-1}) for the group of stars with $Age > 10$ Gyr. Freeman (1991) has analyzed the same data by plotting $\Sigma|W|$ versus the age rank of the star. He found evidence for a division of the stars in three kinematically discrete populations: (i) the thin disk with $\sigma(W) \simeq 10$ km s^{-1} and $Age < 3$ Gyr, (ii) the old disk with $\sigma(W) \simeq 20$ km s^{-1} and $3 < Age < 12$ Gyr, and (iii) the thick disk with $\sigma(W) \simeq 40$ km s^{-1} and $Age > 12$ Gyr. Edvardsson et al. (1993b), on the other hand, show that if the analysis is limited to stars actually formed in the 'solar cylinder' ($7 < R_m < 9$ kpc), then the data is consistent with a heating mechanism, which increases the velocity dispersions as $(Age)^{0.4}$. We conclude that the thick disk stars now observed in the solar neighborhood have primarily been formed in the inner regions

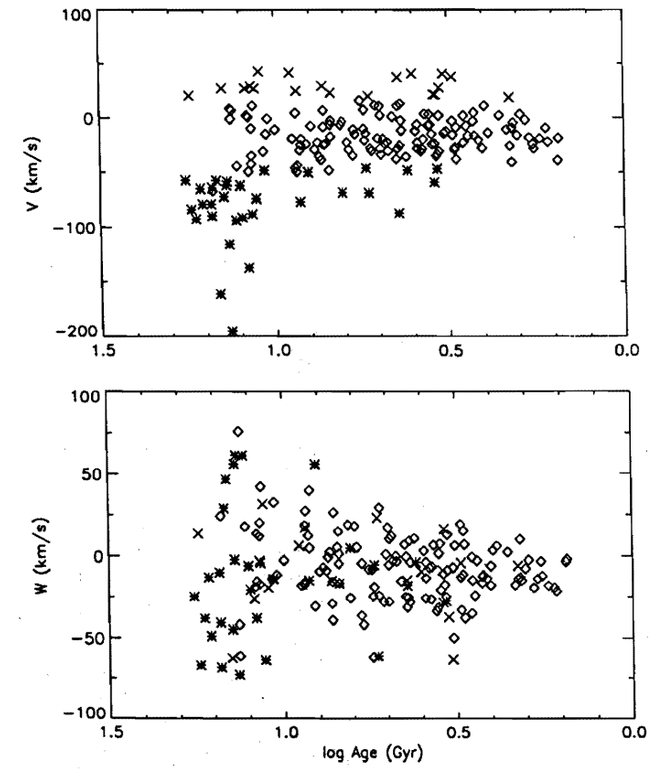

Fig. 1.3. The velocity components V, and W versus the logarithm of the stellar age. The symbols refer to the following mean galactocentric distances of the stars: $*, R_m \leq 7$ kpc; $\diamond, 7 < R_m < 9$ kpc; $\times, R_m \geq 9$ kpc.

of the Galaxy with a few coming from the outer parts. Surprisingly few, if any, of the thick disk stars have been formed in the 'solar cylinder'.

1.4 The halo stars

Several extensive studies of the kinematics and metallicities of high proper motion stars have been completed recently. Carney et al. (1990a, 1990b) used high resolution, low S/N spectra and (mainly) UBV photometry to study metallicities and kinematical parameters for a sample of 740 stars. Nissen & Schuster (1991) and Schuster et al. (1993) used *uvby*-β photometry

to make a similar study of 1214 stars. In both works the distribution of stars in the V-[Fe/H] diagram indicates the existence of three discrete populations: the old disk, the thick disk and the halo. It is unlikely that this structure of the V-[Fe/H] diagram is due to the kinematical bias of the samples selected.

The most important result from these works is that there is no evidence of a radial or vertical chemical gradient in the halo. Furthermore, there is no significant change in $<V>$ as a function of [Fe/H] for the halo stars.

Schuster & Nissen (1989) also determined ages of the turnoff stars from their position in the c_1-$(b-y)$ diagram (the HR-diagram of the Strömgren system). A mean age of about 16 Gyr was found with indication of a cosmic scatter (± 2.5 Gyr) and a weak trend with [Fe/H].

The detailed chemical composition of halo stars has been the subject of several studies, most recently by Nissen et al. (1993). A significant overabundance of α-elements is found ($[\alpha/\mathrm{Fe}] = 0.4$) with a very small scatter, ± 0.06 dex. Considering that the stars analyzed are likely to have been formed in widely different parts of the Galaxy, the small dispersion in $[\alpha/\mathrm{Fe}]$ suggests that the IMF was similar in different regions of the halo and that the mixing of nucleosynthesis products was very efficient like in the disk.

1.5 Discussion and future work

It seems fairly well established that the old stars in the solar neighborhood consist of at least three discrete populations: the old disk, the thick disk and the halo stars, with entirely different explanations of their kinematical properties. The velocity dispersion of the old disk is probably due to a 'heating' mechanism that saturates in about 3 Gyr. The thick disk stars have either been formed with their high velocity dispersion, mostly inside the solar orbit, or have been accelerated by a more violent event, *e.g.* a merger of a satellite galaxy. The halo stars have a negligible net angular momentum and insignificant gradients in their kinematical parameters as a function of metallicity. All of this support the scenario by Searle & Zinn (1978), according to which the outer galactic halo was formed independent of the disk by accretion of smaller satellite galaxies, rather than the dissipational collapse model of Eggen, Sandage & Lynden-Bell (1962).

Much work is, however, needed before a clear picture of the formation and evolution of the Galaxy can be reached. Ages, metallicities and kinematics are needed with the same high accuracy as obtained by Edvardsson et al. for thousands of stars. Work in this direction is in progress based on the big catalogues of Strömgren photometry of F and G stars. In particular

it will be interesting to look for structure in the age-metallicity-kinematics space that relates to merger events and maybe explains the puzzling large spread in the age-metallicity relation. Accurate dating of the thick disk stars relative to the halo stars is another fundamental problem.

For the halo stars it would be particular important to extend the studies of the detailed chemical composition and ages to a sample of say 200 stars, including a fair sample of stars with metallicities in the range $-4.5 <$ [Fe/H] < -2.5. Such work is in progress with the very metal poor stars being selected from the Beers et al. (1992) survey. In particular, it would be interesting to see if $[\alpha/\mathrm{Fe}]$ is strictly constant or slightly dependent on [Fe/H], and if an age-[Fe/H] relation is present among the halo stars. A search for clustering in the abundance-kinematics plane as a relic of satellite accretion should also be carried out.

Acknowledgements

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