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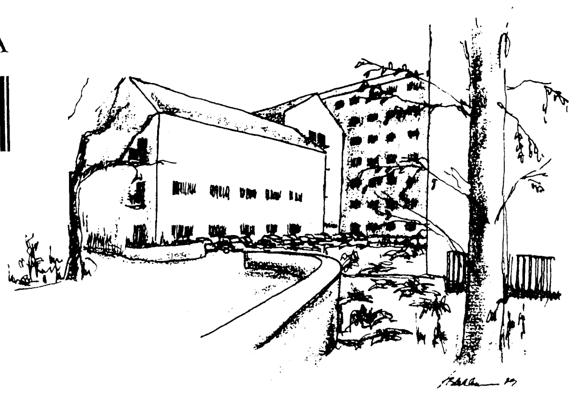
AARHUS - ASTRO - 1991 - 2
ISSN 0906-3870



uvby-β PHOTOMETRY OF HIGH-VELOCITY AND METAL-POOR STARS
V. DISTANCES, KINEMATICS AND AGES OF HALO AND DISK STARS

P.E. Nissen and W.J. Schuster

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Using the new distances and published radial velocities and proper motions, space velocities have been calculated for 611 high-velocity stars to an accuracy of typically $20\,\mathrm{km\,s^{-1}}$. The distribution of these stars in the V_{rot}–[Fe/H] diagram (V_{rot} denoting the velocity component in the direction of Galactic rotation) shows two discrete populations: a fast rotating disk component with an asymmetric (Strömberg) drift of $50\ \mathrm{km\,s^{-1}}$, and a slow rotating halo component with a large, anisotropic velocity dispersion. The two populations overlap in metallicity in the range $-1.4 <$ [Fe/H] < -0.6, but can be separated in the V_{rot} – [Fe/H] diagram due to a scarcity of stars with [Fe/H] $\simeq -1.0$ and $V_{rot} \simeq 100\,\mathrm{km\,s^{-1}}$.

Ages of turn-off stars have been derived by using isochrones of VandenBerg (1985). It is found that the large majority of the high-velocity disk stars with $-1.2 <$ [Fe/H] < -0.5 are as old as the halo stars. The significance of this result for models of Galactic formation and evolution is discussed.

In press, **Astron. Astrophys.** 1991.

uvby-β photometry of high-velocity and metal-poor stars

V. Distances, kinematics and ages of halo and disk stars

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Using the new distances and published radial velocities and proper motions, space velocities have been calculated for 611 high-velocity stars to an accuracy of typically 20 km s^{-1}. The distribution of these stars in the $V_{\rm rot}$-[Fe/H] diagram ($V_{\rm rot}$ denoting the velocity component in the direction of Galactic rotation) shows two discrete populations: a fast rotating disk component with an asymmetric (Strömberg) drift of 50 km s^{-1}, and a slow rotating halo component with a large, anisotropic velocity dispersion. The two populations overlap in metallicity in the range $-1.4 <$ [Fe/H] < -0.6, but can be separated in the $V_{\rm rot}$-[Fe/H] diagram due to a scarcity of stars with [Fe/H] $\simeq -1.0$ and $V_{\rm rot} \simeq 100$ km s^{-1}.

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Key words: Galaxy (the): evolution of – Galaxy (the): halo of – Galaxy (the): disk of – Galaxy (the): kinematics and dynamics of – Stars: luminosities of

1. Introduction

The understanding of stellar populations is fundamental to the study of Galactic structure and dynamics. To comprehend fully the populations and their differences would take us a long way toward a complete theory of Galactic evolution. Yet, very subtle and difficult questions arise that have been very unyielding to final solutions, such as, how can we define the populations in a way that is physically meaningful, how many discrete populations really are there, and how can we unambiguously separate the stellar constituents of the populations for detailed analyses?

The pioneering work on populations was carried out by Baade (1944) during the 1940's and 1950's using mostly observations of galaxies in the Local Group. Baade proposed two populations: a globular-cluster-like Population II found in the bulges of spiral galaxies and in centers of elliptical galaxies and a low-velocity solar-neighborhood-like Population I found in the disks of spiral galaxies. Since then the study of stellar populations has nearly always been beset by controversy and flux. By 1957 the Vatican conference on stellar populations (O'Connell 1958) proposed a compromise scheme of five populations: Extreme Population I, Older Population I, Disk Population, Intermediate Population II, and Halo Population II. More recently the divisions have once again alternated between the coarse simplicity of "halo" and "disk", used in the review by Mould (1982) to the somewhat higher complexity of Young (thin) Disk, Old (thin) Disk, Thick Disk, and Halo, discussed by Croswell (1990).

Baade's work concerned mostly the colors, spatial distributions, kinematics, and association with interstellar material of the two stellar components. Later work showed that the stellar ages and chemical compositions are fundamentally related to the differences between populations. The classification schemes became more complicated, but it was not always obvious that the different categories really correspond to physically discrete components of the Galaxy. For example, the sequence Extreme Population I → Older Population I → Disk Population may merely reflect the *continuous* process of dynamical heating of the disk by molecular clouds and spiral arms. The main complication against resolving these questions is that in the solar vicinity the populations overlap considerably in terms of spatial distribution, kinematics, and metallicity. For example, the Sun lies near the plane of the Galaxy, and in the solar neighborhood nearly 98% of the stars belong to the thin disk; these stars, especially their high-velocity tail, swamp our attempts to study cleanly the thick disk and halo populations. Another example, recent work by Morrison et al. (1990) suggests that some thick disk stars have metallicities as low as [Fe/H] ≈ -1.6, near the median value of the halo, thereby

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frustrating also our attempts to separate and to study well the halo and thick disk populations.

A fundamental problem is whether the populations overlap also in age or rather have significant age differences. The oldest open clusters seem to be perhaps several gigayears younger than the youngest globular clusters, but this difference may be only apparent due to the disruption by tidal forces of many clusters, especially the oldest open clusters. The measurement of age for field stars is more difficult, and very little information is available until now.

These complications have led to some interesting controversies concerning stellar populations, even quite recently. For example, Gilmore & Reid (1983) argued that a two component Galaxy, thin disk plus halo, could not fit star-count data near the SGP, that a "thick disk" component, representing about 2% of the stars in the solar vicinity, is needed. Bahcall & Soneira (1984) countered that the standard two-component Galactic model fit the star-count data quite well. Further star-count studies in several directions by these and other investigators led to conflicting conclusions, the main problem being that star counts constrain the final solution only weakly. Many more recent studies by several groups making use of radial velocities, metallicities, and proper motions in selected areas and in the solar vicinity have in general concluded that the thick disk *does* exist. For example, Sandage & Fouts (1987, hereafter SF) using a large kinematically selected sample of stars find that nearly half of their sample belongs to a Galactic component with a Strömberg drift velocity of $\sim$ 30 km s^{-1}, a mean velocity dispersion perpendicular to the plane of $\sigma(W) \simeq$ 40 km s^{-1}, and a mean metallicity of $<$ [Fe/H] $> \simeq -0.5$, and they identify this stellar population with the Gilmore-Reid-Wyse thick disk.

But the controversy concerning the thick disk continues. The identification of many giants in the direction of the SGP with the clump and red giant members of old open clusters has led Norris & Green (1989) to conclude that the thick disk is fairly young, 3-6 Gyr younger than the "disk" globular clusters. They favor the idea that the thick disk is a continuous extension of the old thin disk produced in a pressure-supported collapse similar to that described in the models of Larson (1976). These models predict that the disk formed outward from the Galactic center after the formation of the halo thereby explaining the difference in age found locally by Norris & Green (1989). In contrast, Carney et al. (1989) using the metallicity and color histograms of another large kinematically-selected survey conclude that the thick disk probably is a third discrete population in the Galaxy, that it is old like the "disk" globular 47 Tuc, and that a merger event early in the Galaxy's history is a likely explanation of the thick disk.

In the present series of articles *uvby-β* photometry of high-velocity and metal-poor stars has been presented and analyzed. The new aspect of our work as compared to other recent investigations of large samples of high-proper-motion stars is that the *uvby-β* photometry makes it possible to determine relative ages of individual turn-off stars with a reasonable accuracy. Adding this age dimension to our knowledge about the metallicities and kinematics of stellar populations is crucial for understanding Galactic formation and evolution.

In Schuster & Nissen (1988, Paper I) *uvby-β* photometry was published for 711 stars, 607 of these from various high-velocity star catalogues and 104 from the catalogue of metal-poor stars selected spectroscopically of Bartkevičius (1980). This sample spans the older populations, such as old thin disk, thick disk, and halo. The *uvby-β* data were transformed closely onto the standard system of Olsen (1983, 1984) and are uniform over the sky. For the large majority of stars the mean errors of V, m_1, c_1, and β are less than $\pm 0^{m}\!.008$, and the error of $b-y$ less than $\pm 0^{m}\!.005$.

In Paper II (Schuster & Nissen 1989a) the intrinsic color and metallicity calibrations, needed to estimate $E(b-y)$ and to measure [Fe/H] for the majority of the stars of Paper I, were presented. In Paper III (Schuster & Nissen 1989b) the absolute and relative ages and a possible metallicity-age relation for the halo stars, defined as those with [Fe/H] ≤ -1.0, were examined. Significant evidence for a cosmic age scatter of $\pm$ 2.5 Gyr at a given metallicity was found. In Paper IV (Allen et al. 1991) a detailed look at the kinematics and Galactic orbits for those stars with [Fe/H] ≤ -2.0 was made. Evidence for a chaotic, non-rapid formation of the halo and for a difference between the inner and outer halo ($R_{\max} > 20$ Kpc) was discovered.

In this Paper V we concentrate on the interface between the disk and halo populations. First, a new distance calibration using *uvby-β* photometry is derived which covers the full metallicity range of the stars of Paper I, $-3.5 \lesssim$ [Fe/H] $\lesssim +0.2$. This calibration is based upon the c_0-$(b-y)_0$ and M_V-$(b-y)_0$ diagrams and includes an evolutionary correction of the form $f\,\delta c_0$. The resulting distances for parallax stars show that our calibration contains no significant systematic errors as a function of metallicity. We also calculate distances using our calibration for many overlapping stars from Laird, Carney, and Latham (1988, hereafter LCL) and from SF. These comparisons show very good agreement between the zero points of the different distance calibrations and indicate that our distances are more accurate for evolving main sequence and subgiant stars due to the inclusion of the evolutionary correction.

Radial velocities and proper motions have been selected carefully from the literature for the stars of Paper I. The space velocities U', V', and W', have been calculated using a computer program based on the precepts discussed by Johnson & Soderblom (1987). Complete kinematic data for 611 stars have resulted.

In the $V_{\rm rot}$-[Fe/H] diagram clear evidence for two discrete populations is noted. We prefer to call these populations *high-velocity disk* and *halo*, due mainly to our selection criteria. These two populations overlap in metallicity in the range $-1.4 \lesssim$ [Fe/H] $\lesssim -0.6$ and in kinematics in the range 25 km s$^{-1} \lesssim V_{\rm rot} \lesssim$ 200 km s^{-1}. We suggest that a fairly clean and unambiguous way of separating the two populations is a diagonal cut in the $V_{\rm rot}$-[Fe/H] diagram. This cut passes through an obvious scarcity of stars at [Fe/H] $\simeq -1.0$ and $V_{\rm rot} \simeq$ 100 km s^{-1}; this scarcity is also obvious in the V-[Fe/H] diagram of Carney et al. (1990). Such a criterion for separating the two populations has the advantage that it combines both kinematic and metallicity information.

Finally, ages are derived using the isochrones of VandenBerg (1985) for all turn-off stars with [Fe/H] > -1.5 and M_V(ZAMS) $- M_V$(star) > 0.4. It is found that the large majority of high-velocity disk stars in the range $-1.2 <$ [Fe/H] < -0.5 (i.e. the thick disk stars) are as old as the halo stars. We suggest that a scenario for Galactic formation and early evolution discussed by Freeman (1990) explains these results. According to this scenario the globular clusters and halo stars were formed in dwarf galaxies close to the Galaxy. These were then accreted by a thin, fast-rotating Galactic disk, and the dynamical heating of the stellar components of this disk by the accretion process produced the thick disk.

2. Distances

2.1. Determination of absolute magnitudes

Two methods for determining visual absolute magnitudes for high-velocity and metal-poor stars are discussed here. For both methods

$$M_V(\text{star}) = M_V(\text{ZAMS}) - f\,\delta c_0\,, \quad (1)$$

where M_V(ZAMS) is the absolute magnitude of that zero-age-main-sequence (ZAMS) with same metallicity as a given star, measured at the star's $(b-y)_0$, and where $\delta c_0 = c_0(\text{star}) - c_0(\text{ZAMS})$ is the displacement of the star from the corresponding ZAMS in the c_0-$(b-y)_0$ diagram. The coefficient f may depend on $(b-y)_0$ and [Fe/H]. The main difference between our two methods concerns the zero points of the M_V(ZAMS)'s; in method 1 the zero point is provided by the standard relations of Crawford (1975) and of Olsen (1984) and in method 2 by the models of VandenBerg & Bell (1985, hereafter VB). A preliminary version of method 1 was used in Paper II to obtain rough distances for selecting the stars used in the $(b-y)_0$-β calibration. In Paper IV a limited version of method 2 gave reliable distances for stars with $[\text{Fe/H}] \leq -2.0$.

Of prime importance for both methods is the displacement of the ZAMS's with metallicity in the c_0-$(b-y)_0$ and M_V-$(b-y)_0$ diagrams. The former displacement, Δc_0, has been measured observationally using the *uvby-β* observations of the 711 high-velocity and metal-poor stars of Paper I. These stars were divided according to their [Fe/H] values into 23 overlapping groups, and the ZAMS loci taken to be the lower envelopes in the c_0-$(b-y)_0$ diagram, corrected slightly for the expected observational errors of c_0 and $(b-y)_0$. The Δc_0's were measured with respect to the combined standard c_0-$(b-y)_0$ relations, c_0(std), of Crawford (1975) and Olsen (1984), see Table 1. Our most metal-rich group corresponds to $+0.10 \leq [\text{Fe/H}] < +0.20$ and the two most metal-poor groups to $-2.9 \leq [\text{Fe/H}] \leq -2.4$ and $[\text{Fe/H}] < -2.9$.

It became obvious that over a wide [Fe/H] range the displacement of the ZAMS in the c_0-$(b-y)_0$ diagram is *not* a simple function of [Fe/H] only but that the ZAMS changes shape. That is, Δc_0 is a function of both [Fe/H] and $(b-y)_0$. A fourth-order polynomial in [Fe/H] and $(b-y)_0$ was fit to the Δc_0 data by the aid of the same mathematical package as discussed in Paper II, using T-ratios to eliminate insignificant terms. Nine terms, including the zero point, were retained in the final expression, all terms have T-ratios with absolute values greater than or equal to 3.95, and the final solution gives a standard deviation about the regression line of $\pm 0\overset{m}{.}015$. The final calibration equation is

$$\begin{aligned}\Delta c_0 \;=\; & -0.346 - 0.751[\text{Fe/H}] + 1.804(b-y)_0 - 0.196[\text{Fe/H}]^2 \\ & -2.006(b-y)_0^2 + 4.261(b-y)_0[\text{Fe/H}] \\ & +1.057(b-y)_0[\text{Fe/H}]^2 - 4.890[\text{Fe/H}](b-y)_0^2 \\ & -1.201[\text{Fe/H}]^2(b-y)_0^2\,, \end{aligned} \quad (2)$$

where $\Delta c_0 = c_0(\text{ZAMS}) - c_0(\text{std})$. An additional *a posteriori* correction is also applied for stars with $[\text{Fe/H}] \geq -0.34$, see Eq. (5).

For various reasons the observational data of Paper I have very definite blue and red limits, beyond which there are few or no stars useful for measuring Δc_0. Beyond these limits the mathematical expression for Δc_0 may not be realistic and may even be unstable. The blue limits are $(b-y)_0 = 0.275$ if $[\text{Fe/H}] \leq -1.65$, $(b-y)_0 = 0.296 + 0.0125\,[\text{Fe/H}]$ when $-1.65 < [\text{Fe/H}] \leq -0.45$ and $(b-y)_0 = 0.332 + 0.0923\,[\text{Fe/H}]$ when $[\text{Fe/H}] > -0.45$. The red limits are 0.55 when $[\text{Fe/H}] > -0.60$ and 0.58 otherwise. A few of the high-velocity and metal-poor stars are redder than these limits and are obviously not subgiants, but there are not enough of them to define well Δc_0. For these stars we have assumed $M_V(\text{star}) = M_V(\text{ZAMS})$.

Once the positions of the ZAMS's in the c_0-$(b-y)_0$ diagram have been defined as a function of [Fe/H], δc_0 can be calculated for a given star. Finally, $f\,\delta c_0$ gives the star's evolutionary correction $\delta M_V = M_V(\text{ZAMS}) - M_V(\text{star})$. This evolutionary correction can be very important as can be seen in globular cluster C-M diagrams, for example Fig. 6 of Sandage & Kowal (1986). For evolving main-sequence stars near the turn-offs and for subgiants δM_V can approach 2 magnitudes.

The f coefficient of the evolutionary correction has been determined by Nissen et al. (1987) using *uvby-β* data for the old open cluster M67 combined with data for NGC 752 and NGC 3680 (Nissen 1988). They find

$$f = 9.0 + 38.5((b-y)_0 - 0.22) \quad (3)$$

for stars over the range $0.22 \leq (b-y)_0 \leq 0.47$. Since these clusters have $[\text{Fe/H}] \simeq 0.0$ we cannot be sure that this expression is valid for metal-poor stars. However, the CCD *uvby* photometry of Anthony-Twarog (1987) for the globular cluster NGC6397, which has $[\text{Fe/H}] \simeq -2.0$, gives $f \approx 17 \pm 6$ at $(b-y)_0 = 0.42$, only slightly larger than the value $f = 16.7$ derived from Eq. (3). The large error of this confirmation is due mainly to the low sensitivity of the CCD detector in the ultraviolet.

As mentioned above, the absolute visual magnitudes of our first method depend directly upon the $(b-y)_0$-M_V standard relation of Crawford (1975, Table 1) for Population I F stars and upon the corresponding relation of Olsen (1984, Table VI) for G and K stars. Both these authors used stars with trigonometric parallaxes satisfying $\sigma_\pi/\pi \leq 0.175$ to fix the zero points of their M_V(std) calibrations. Also, Crawford derived $f = 10$ and used this value to correct M_V for the evolved parallax stars. Recently Olsen (1989) has revised the M_V(std) calibration for F stars using the expression for f given above. The changes to Crawford's M_V(std) values are minor, $+0.06$ at $(b-y)_0 \approx 0.30$ and $+0.14$ at $(b-y)_0 \approx 0.40$. These revised values are given in Table 1 and used in all of the following work.

Also needed for the first method is the displacement of the ZAMS in the M_V-$(b-y)_0$ plane as a function of metallicity. An expression for this displacement has been derived from the models of VB at $(b-y)_0 = 0.38$ and with the helium mass fraction Y interpolated to a value of 0.25. This $(b-y)_0$ has been chosen to avoid the evolutionary effects in the models at the hotter temperatures and to avoid as much as possible the systematic effects discussed by VB (see their Fig. 1), which are probably due to missing line blanketing data and which are more severe for the cooler models, $T_{\text{eff}} \leq 5500$K. The resulting expression is

$$\Delta M_V = -35.68(Z - 0.0169) + 1734.6(Z - 0.0169)^2 \quad (4)$$

Table 1. The standard relations between $(b-y)_0$, c_0 and M_V used in the present paper

$(b-y)_0$	c_0	M_V	$(b-y)_0$	c_0	M_V
0.271	0.465	3.52	0.480	0.246	5.90
0.284	0.440	3.65	0.490	0.250	5.99
0.298	0.415	3.80	0.500	0.252	6.08
0.313	0.390	3.95	0.510	0.252	6.17
0.328	0.370	4.12	0.520	0.251	6.25
0.344	0.350	4.29	0.530	0.249	6.34
0.360	0.330	4.46	0.540	0.246	6.42
0.377	0.310	4.63	0.550	0.242	6.50
0.394	0.290	4.82	0.560	0.237	6.58
0.412	0.270	5.04	0.570	0.230	6.66
0.430	0.254	5.27	0.580	0.221	6.74
0.450	0.241	5.57	0.590	0.211	6.82
0.455	0.240	5.63	0.600	0.199	6.90
0.460	0.241	5.69	0.610	0.188	6.97
0.470	0.243	5.80			

where $\Delta M_V = M_V(\text{ZAMS}) - M_V(\text{std})$ and Z is the mass fraction of heavy elements given in Eq. (7) as a function of [Fe/H].

The second method for deriving M_V(ZAMS)'s depends upon the isochrones of VB both for setting the zero point and the displacement of the ZAMS in the M_V-$(b-y)_0$ plane. A third-order polynomial was fit, using the same mathematical routine as described in Paper II, to give M_V(ZAMS) as a function of the metallicity and $(b-y)_0$. The $(b-y)_0$'s of VB were shifted to the red by +0.025 as according to the discussions of Papers III and IV. Nine terms were retained in the final polynomial, all have T-ratios with absolute values greater than or equal to 5.77, and the standard deviation about the regression is ±0.043 magnitudes. The least-evolved (8 Gyr) isochrones of VB have been used to provide the M_V(ZAMS) values. For $(b-y)_0 > 0.30$, the M_V-$(b-y)_0$ relations of the 8 and 10 Gyr isochrones of VB differ by less than $0^{\rm m}\!.2$, and so the 8 Gyr relation should correspond fairly closely to a little-evolved main sequence in this $(b-y)_0$-range.

A comparison of the M_V's from the two methods for the high-velocity and metal-poor stars shows a systematic difference of about $0^{\rm m}\!.3$, with the absolute magnitudes from the second method, the M_{V2}'s, being brighter. This difference depends little upon the metallicities or the M_V's of the stars. It is shown below that the M_{V1}'s and D_1's, the absolute magnitudes and distances from the first method, agree well with the values from the trigonometric parallaxes and with the values of LCL and SF. Also the second method is usable only for [Fe/H] ≤ -0.75, the approximate metallicity of the most metal-rich isochrone of VB. In the following analyses and discussions, the results of the first method are therefore used exclusively.

A detailed, inclusive propagation of errors analysis for the M_{V1}'s has been made. This analysis covered all of the factors mentioned above, such as Δc_0, ΔM_V, the f-coefficient, and interpolations for the standard values of c_0 and M_V(std). The observational errors were taken to be $\sigma_{b-y} = \pm 0.005$, $\sigma_{c_1} = \pm 0.008$, according to the values given in Paper I and $\sigma_{[\text{Fe/H}]} = 0.05 - 0.1[\text{Fe/H}]$ when [Fe/H] ≤ -1.0 and 0.15 otherwise as estimated in Paper III. The analysis covered the ranges $0.30 \leq (b-y)_0 \leq 0.50$, $-2.75 \leq$ [Fe/H] ≤ 0.00, and $0.00 \leq \delta c_0 \leq 0.20$. The final values for σ_{M_V} range between 0.16 and 0.48, the larger errors occurring for the redder, more metal-rich stars, and the smaller for the bluer, metal-poor ones. The biggest contribution to these errors comes generally from the $f \frac{\partial \Delta c_0}{\partial [\text{Fe/H}]} \sigma_{[\text{Fe/H}]}$ term and the second largest contribution from $f\sigma_{c_0}$. The above analysis does not take into account systematic errors, such as those due to the extrapolation of the expression for f to metal-poor stars, small systematic errors in the standard relations, errors in the ΔM_V expression due to uncertainties in the theoretical models, and incorrectly located ZAMS's in the c_0-$(b-y)_0$ diagram, as will be discussed below. We estimate that rough rules of thumb for the metal-poor stars, those with [Fe/H] ≤ -0.75, are the following: for main sequence and subgiant stars the *random* absolute visual magnitude errors, the σ_{M_V}'s, fall between $\pm 0^{\rm m}\!.15$ to $\pm 0^{\rm m}\!.30$ corresponding to distance errors of 10-15%, while for the metal-poor subgiants the *total* errors, including the systematic contributions, are 20-30% in the distances. These estimates are corroborated by the comparisons made below.

2.2. Comparison of photometric and trigonometric distances

In Figs. 1 and 2 are compared the $M_{V1}(uvby)$'s, the absolute visual magnitudes from our first photometric method, to $M_V(\pi)$'s, the values from trigonometric parallaxes. The parallax stars have been taken from Crawford (1975), Carney (1979), Olsen (1984), LCL, and Stetson & Harris (1988). The parallax stars of Crawford and Olsen were chosen to have $\sigma_\pi/\pi \leq 0.175$, those of Carney and LCL, $\sigma_\pi/\pi \leq 0.20$, and those of Stetson & Harris, $\sigma_\pi/\pi \leq 0.22$. In most cases Lutz-Kelker corrections have been applied (Lutz & Kelker 1973 and Lutz 1979). We have also checked various parallax series in the literature and have found parallaxes satisfying $\sigma_\pi/\pi \leq 0.175$ for an additional 8 of the high-velocity and metal-poor stars of Paper I. Two of these stars deserve special note: G190-015 from Vilkki et al. (1986) and G026-009 from van Altena & Vilkki (1973) have [Fe/H] ≤ -1.0.

The comparison in Fig. 1 for parallax stars with [Fe/H] ≤ -0.50 shows that any systematic errors of our photometric calibration are less than 0.2 magnitudes. For [Fe/H] ≤ -0.50 the average difference $< \Delta M_{V1} > \, = \, < M_V(\pi) - M_{V1} >$ is -0.09 ± 0.65 for 26 stars; if 4 stars with $|\Delta M_{V1}| \geq 1.0$ are eliminated, the average difference becomes -0.09 ± 0.43. For [Fe/H] ≤ -1.0 the corresponding average differences are $+0.02 \pm 0.66$ and -0.18 ± 0.47, for 14 and 12 stars, respectively.

In making a similar comparison between $M_V(\pi)$ and $M_{V1}(uvby)$ for the more metal-rich parallax stars, it became obvious that there was a systematic displacement for the brighter metal-rich stars, $M_V(\pi) < 5.0$ and [Fe/H] ≥ -0.34; our $M_{V1}(uvby)$'s were too positive. We attribute this to the evolved status of all of the hotter high-velocity stars used to position the ZAMS's in the c_0-$(b-y)_0$ plane. That is, the lower limits used to define the ZAMS's really correspond to an evolving main sequence, not the ZAMS, and so the evolutionary corrections, $f\delta c_0$, were underestimated. This effect was also obvious in the empirically obtained values of Δc_0 used to derive Eq. (2); the values were considerably more positive than expected, $\geq +0.03$, for [Fe/H] ≥ -0.15. An *a posteriori* correction,

$$\Delta(\Delta c_0) = 0.728(-0.34 - [\text{Fe/H}])(0.562 - (b-y)_0), \quad (5)$$

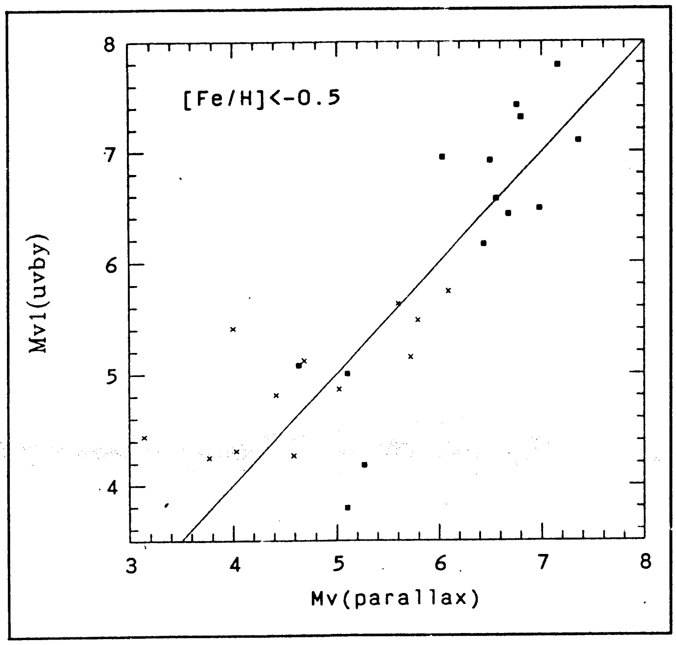

Fig. 1. A comparison of our photometric visual absolute magnitudes with parallactic ones. Crosses represent stars with $-1.0 < [Fe/H] \leq -0.5$, and filled squares those with $[Fe/H] \leq -1.0$

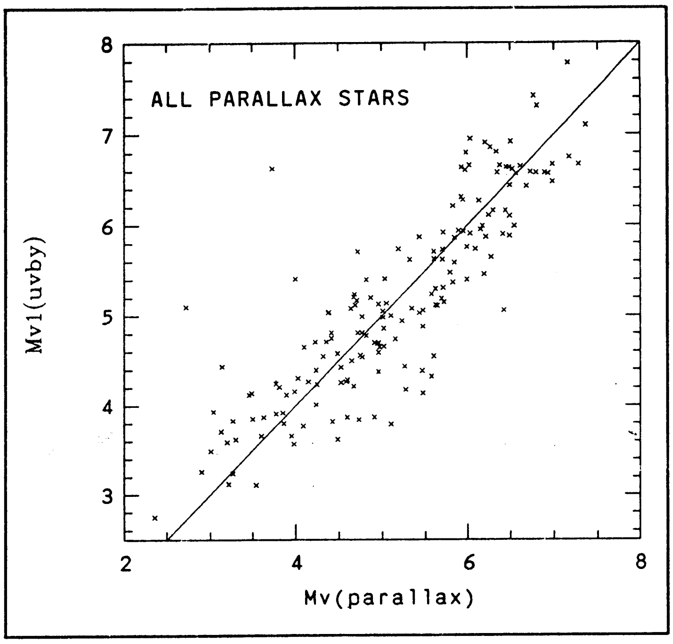

Fig. 2. A comparison of photometric and parallactic visual absolute magnitudes for all of the parallax stars

has been derived to remove this effect from the photometric calibration. It is applied only for stars with $[Fe/H] > -0.34$ and $(b-y)_0 < 0.562$; it has been normalized using $<[Fe/H]> = -0.09$, the mean metallicity of the parallax stars with $[Fe/H] \geq -0.34$; and, for example, it provides a correction of $-0^m.45$ for M_{V1} at $(b-y)_0 = 0.40$ and $[Fe/H] = -0.1$.

In Fig. 2 is shown the final comparison between $M_{V1}(uvby)$ and $M_V(\pi)$ for our total sample of 169 parallax stars covering all metallicities. For this sample $<\Delta M_{V1}> = 0.00 \pm 0.58$ for all 169 stars and -0.01 ± 0.42 for 157 stars with $|\Delta M_{V1}| < 1.00$. If we restrict our attention to only stars with $[Fe/H] \geq -0.34$, then $<\Delta M_{V1}> = +0.14 \pm 0.50$ for 62 stars with $M_{V1} \leq 5.0$ and -0.07 ± 0.63 for 69 stars with $M_{V1} > 5.0$. The values change to $+0.05 \pm 0.41$ and -0.01 ± 0.43, respectively, if we remove the more discrepant stars.

Twelve stars with large deviations, $|\Delta M_{V1}| \geq 1.00$, are seen in Figs. 1 and 2. Two of these, HD84937 and HD140283, with $[Fe/H] \leq -2.0$, have already been discussed in detail in Paper IV. Eight of the other ten stars also have residuals greater than $0^m.7$ according to the absolute magnitude calibration of Olsen (1984). The stars HD23249, HD82885AB, HD142373, HD144087A, and HD188512AB are probably discrepant due to duplicity, variability or circumstellar shells according to the notes of Hoffleit & Jaschek (1982) and Hoffleit et al. (1983). In general the discrepant parallax stars are so due to atypical characteristics or to unusually large parallax errors.

Also it can be seen in Figs. 1 and 2 and in the above discussions that the scatters are totally compatible with the expected errors. The criterion $\sigma_\pi/\pi \leq 0.175$ corresponds to $\sigma_{M_V} \leq 0.38$. Our propagation of errors analysis has given $0.25 \leq \sigma_{M_V} \leq 0.48$ for metal-rich stars and $0.15 \leq \sigma_{M_V} \leq 0.25$ for metal-poor ones, $[Fe/H] \leq -1.0$. These values give us a total standard deviation of the comparison of $\sigma_{M_V}(\text{total}) \leq 0.60$ for metal-rich stars and $\sigma_{M_V}(\text{total}) \leq 0.45$ for metal-poor. Nearly all of our parallax stars have ΔM_{V1} within $\pm 2\sigma_{M_V}(\text{total})$, and if the twelve stars with $|\Delta M_{V1}| \geq 1.0$ are removed, the expected and observed standard deviations agree quite satisfactorily.

The above comparisons show that there are no significant systematic errors in our absolute magnitude calibration, especially as a function of metallicity. Any such errors are less than $0^m.2$.

2.3. Comparison with the distances of LCL and SF

In Figs. 3 and 4 our distances from the first method are compared to those of LCL and of SF, respectively. We have 130 stars in common with LCL and 158 stars with SF. In these figures $\Delta M_{V1} = M_V(\text{other}) - M_{V1}(uvby) = 5\log(D_1/D_{\text{other}})$ is plotted versus the evolutionary correction, $f\,\delta c_0$. Figure 3 appears very similar to Fig. 1 of paper IV; a strong correlation between ΔM_{V1} and $f\,\delta c_0$ is seen, as expected. LCL have in general made their distance determinations conservatively. They have attempted no evolutionary correction, assuming that all their stars are little-evolved dwarfs and fitting them to the appropriate dwarf sequence in their color-magnitude diagrams. For this reason ΔM_{V1} correlates strongly with δc_0, but despite this correlation, a line fitting the points passes very near the origin, indicating no significant difference in the zero points for the different calibration procedures. Our evolutionary corrections will allow us to provide more accurate distances for evolving main-sequence stars and for subgiant stars; for these stars the methods of LCL give underestimates for the stellar distances.

The distances of SF were derived (see Sandage & Kowal 1986, section IVa) by assuming that the metal-poor stars lie on the "evolved main sequence". Theirs is a strictly empirical procedure that has been shown to give reliable distances for main sequence parallax stars, but not necessarily for metal-

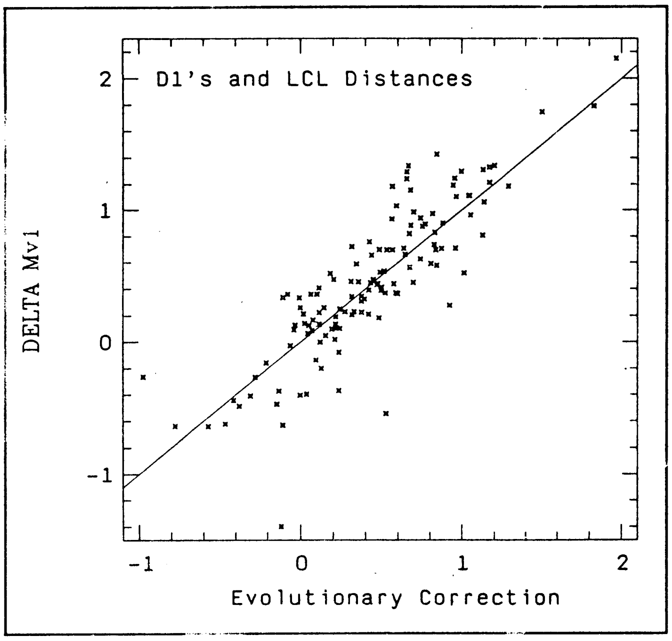

Fig. 3. The differences in absolute visual magnitudes, corresponding to the differences in distances between those of LCL and those of this paper, plotted as a function of the evolutionary correction. That is, $\Delta(M_{V1}) = M_V(\mathrm{LCL}) - M_{V1} = 5\log(D_1/D_{\mathrm{LCL}})$ as a function of $f\,\delta c_0$

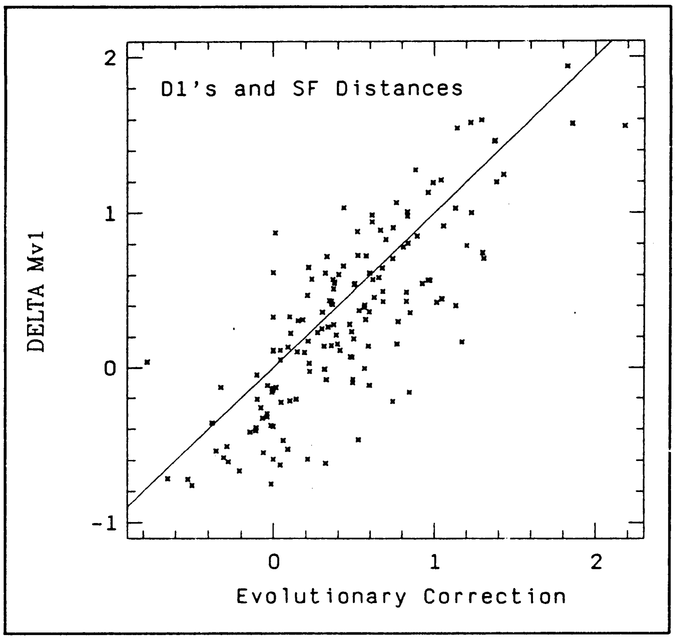

Fig. 4. The same as Fig. 3, but for the distances of SF

poor subgiants. Figure 4 shows considerably more scatter than Fig. 3, but there is still some correlation between ΔM_{V1} and the evolutionary correction. For 90 stars with $f\,\delta c_0 < 0.50$, $<\Delta M_{V1}> = +0.01 \pm 0.42$; for 136 stars with $f\,\delta c_0 < 1.00$, $<\Delta M_{V1}> = +0.20 \pm 0.48$; and for the full sample $<\Delta M_{V1}> = +0.32 \pm 0.57$. So, on the average the procedure of SF does correct for the evolutionary status of high-velocity and metal-poor stars, at least for those that are not too evolved. For those with $f\,\delta c_0 > 0.50$ their method provides distances that are underestimates, the more so, the larger the evolutionary correction.

To appreciate the possible effects of ignoring or underestimating evolutionary corrections in the derivation of stellar distances, the samples of Figs. 3 and 4 are taken to be representative subsets of the stars of LCL and SF, respectively. For the 130 stars of Fig. 3, $<\Delta M_{V1}> = +0.45$, which means that LCL underestimate distances and tangential velocities on the average by $\approx 20\%$. For the 158 stars of Fig. 4, $<\Delta M_{V1}> = +0.32$, corresponding to underestimates of $\approx 15\%$. Assuming equal contributions, on the average, from tangential and radial velocities to the total space velocities, these underestimates may lead LCL and SF to derive local escape velocities that are as much as 15% too low, and lower limits for the mass of the Galaxy 30% too low, see Carney et al. (1988). Model-dependent attempts to measure the total mass of the Galaxy may lead to even larger errors. For example, the model of Carney et al. (1988) assumes that $M(r)$ scales linearly with r for $r > R_\odot$ out to some limiting radius, R_{limit}, which is the outer boundary of the Galaxy. Then $\Delta M_{\mathrm{total}}/M_{\mathrm{total}} = (V_{\mathrm{esc}}/\theta_\odot)^2\,\Delta V_{\mathrm{esc}}/V_{\mathrm{esc}}$ and errors larger than 50% in the total mass are possible.

3. Kinematics

3.1. Space velocities

The radial velocities and proper motions used to derive the space velocities were taken from many sources. An attempt was made to select always the most recent, most reliable and most accurate values, or, if several equally reliable sources were available, an average value was used.

For the radial velocities the following sources were used: (a) Norris & Ryan (1989), (b) Latham et al. (1988), (c) Carney & Latham (1987), (d) Barbier-Brossat & Petit (1986), (e) Norris (1986), (f) Fouts & Sandage (1986), (g) Norris et al. (1985), (h) Sandage (1981), (i) Eggen (1979, 1980), (j) Augensen (1979), (k) Augensen & Buscombe (1978), (l) Abt & Biggs (1972), (m) Sandage (1969), and Eggen (1964). The standard deviations of the observed radial velocity values range from less than $1\,\mathrm{km\,s^{-1}}$ in papers (b) and (c) to approximately $7\,\mathrm{km\,s^{-1}}$ in papers (a) and (f), and to $\lesssim 10\,\mathrm{km\,s^{-1}}$ in papers (g) and (j).

The proper motions were taken from the following sources: (a) the SAO Catalogue (Ochsenbein 1979), (b) Sandage (1969), (c) Giclas et al. (1971, 1978), (d) Luyten (1957, 1961), (e) Eggen (1964, 1979, 1980, 1987), (f) Rodgers & Eggen (1974), (g) Norris & Ryan (1989), (h) Norris et al. (1985), (i) Augensen & Buscombe (1978), and (j) Buscombe & Morris (1958). Frequently the proper motions in c) were averaged with those in d). Typical errors in μ_α and μ_δ fall in the range $0.''01$ to $0.''03\ \mathrm{yr^{-1}}$.

The computer program for calculating the Galactic space velocities, U', V' and W', was kindly loaned to us by C. Allen. The precepts, matrix equations, and Galactic coordinate system used in this program are the same as those given by Johnson & Soderblom (1987). However, we prefer to work with a left-handed system so that U' here is positive toward the Galactic anti-center. The adopted corrections for the solar motion are $(-10.0, +14.9, +7.7)\ \mathrm{km\,s^{-1}}$ for (U, V, W), and the rotation velocity of the LSR about the Galactic center is taken to be 225 $\mathrm{km\,s^{-1}}$ (Allen & Martos 1986) so that $V_{\rm rot} = V' + 225\,\mathrm{km\,s^{-1}}$ is the rest-frame rotation velocity of a given star.

For the majority of stars the largest contribution to the uncertainty of the space velocity arises from the uncertainty of the distance determination. In the case of a metal-poor star having a typical tangential velocity of $V_t = 100\,\mathrm{km\,s^{-1}}$ a distance error of 20% corresponds to an error of $\sigma(V_t) = 20\,\mathrm{km\,s^{-1}}$, whereas a proper motion error of $\sigma(\mu) = 0\farcs02\,\mathrm{yr^{-1}}$ corresponds to $\sigma(V_t) \simeq 10\,\mathrm{km\,s^{-1}}$ for a typical distance of 100pc. As mentioned above the error of the radial velocity is smaller. Hence, representative errors of the space velocity lie in the range 10 to 30 $\mathrm{km\,s^{-1}}$.

3.2. The $V_{\rm rot}$- [Fe/H] diagram

The relation between Galactic rotational velocity, $V_{\rm rot}$, and chemical composition, [Fe/H], is of fundamental importance for our knowledge of the formation and evolution of the Galaxy. An extensive debate on this relation has arisen in the past few

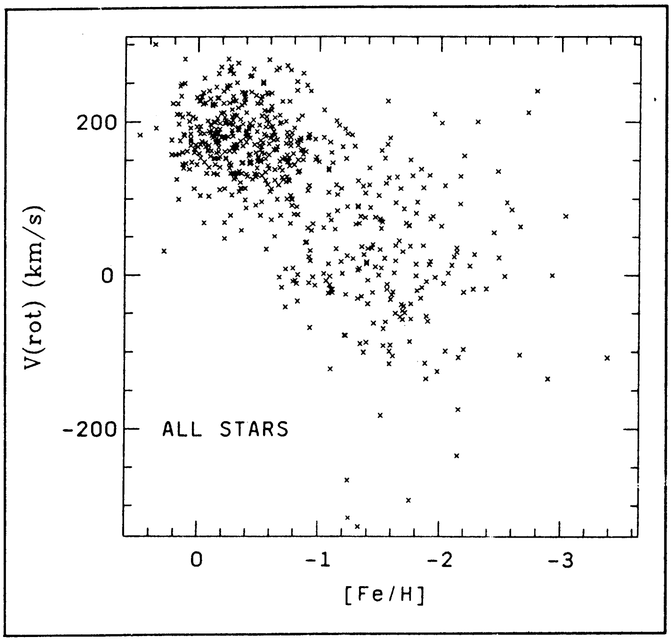

Fig. 5. The $V_{\rm rot}$ versus [Fe/H] plot for 611 stars with kinematical parameters determined. $V_{\rm rot} = V' + 225\,\mathrm{km\,s^{-1}}$

years as a result of several new studies of the kinematics and metallicities of rather large samples of stars. Sandage & Fouts (1987) argue that there is a smooth increase of the mean $V_{\rm rot}$ from zero at [Fe/H] $\simeq -2.0$ to about 200 $\mathrm{km\,s^{-1}}$ at [Fe/H] $\simeq$ 0.0. Norris (1986) and later Norris & Ryan (1989) find that $< V_{\rm rot} >$ is constant at about 25 $\mathrm{km\,s^{-1}}$ for $-2.5 <$ [Fe/H] $<$ -1.5 and then raises steeply to about 200 $\mathrm{km\,s^{-1}}$ at [Fe/H] $\simeq$ -0.5. Gilmore et al. (1989) have shown that there is really no statistically significant difference between the two data sets of $< V_{\rm rot} >$ versus [Fe/H]. Rather, the differences between the conclusions of the two groups result largely from different ways of binning the data and from the larger errors in the [Fe/H] values of Sandage and Fouts (see Norris & Ryan 1989). On the other hand Gilmore et al. (1989) draw attention to the fact that the $V_{\rm rot}$-[Fe/H] diagram of individual stars contains more information than can be presented in terms of $< V_{\rm rot} >$ (and its standard deviation) as a function of [Fe/H]. Thus, the V-[Fe/H] diagram of Carney et al. (1990) for 740 high proper motion stars clearly shows two distinct groups: one metal poor slowly rotating and one more metal rich, fast rotating group. There is a scarcity of stars with [Fe/H] $\simeq -1.0$ and $V_{\rm rot} \simeq 100\,\mathrm{km\,s^{-1}}$

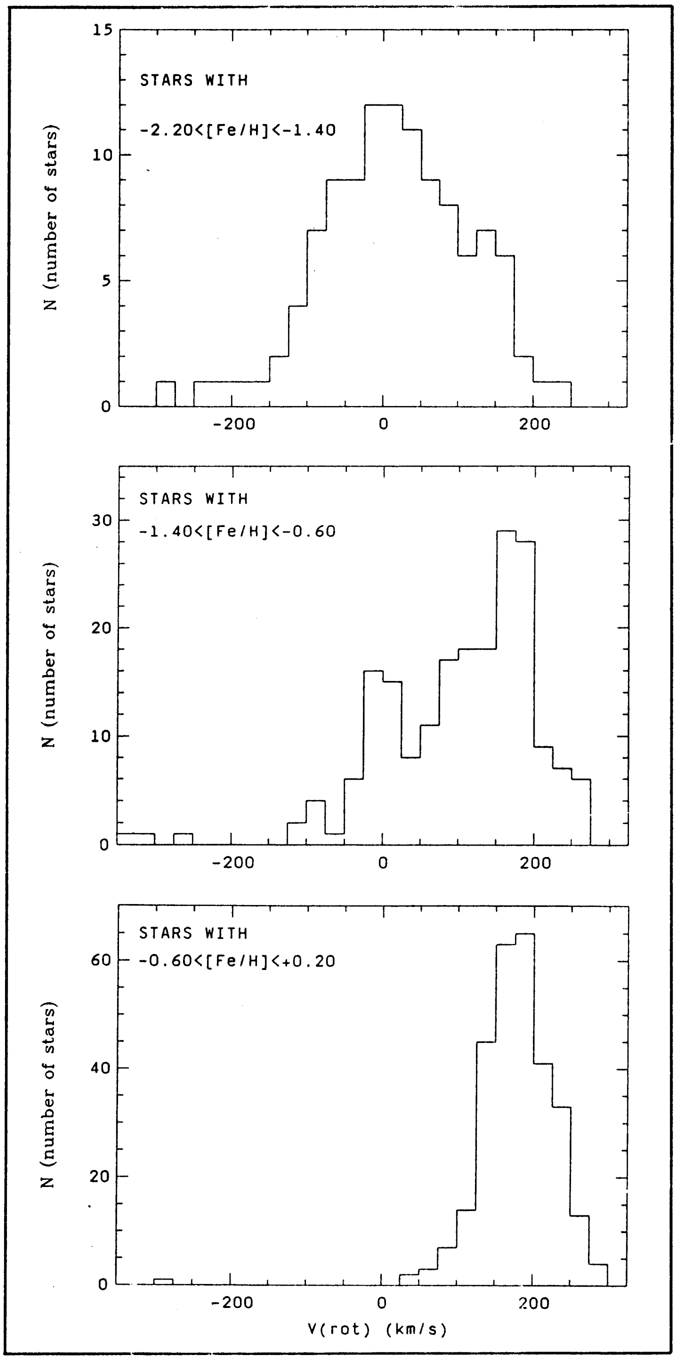

Fig. 6. Histograms of $V_{\rm rot}$ for 3 intervals in [Fe/H].

The $V_{\rm rot}$-[Fe/H] diagram for stars in the present work is shown in Fig. 5. The similarity of this diagram to the one published by Carney et al. (1990) (their Fig. 3) is striking; we note in this connection that only about 130 stars are in common between the two diagrams. Two discrete populations are seen: one centered around $V_{rot} \simeq 0\,\mathrm{km\,s^{-1}}$ and [Fe/H] $\simeq -1.6$ with large dispersions in the two parameters; the other population is centred around $V_{rot} \simeq 175\,\mathrm{km\,s^{-1}}$ and [Fe/H] $\simeq -0.4$ with smaller dispersions.

It is interesting that the two populations seen in Fig. 5 tend to overlap in the range $-1.4 <$ [Fe/H] < -0.6. Figure 6 shows the histograms of V_{rot} for three [Fe/H] intervals. In the ranges $-2.2 <$ [Fe/H] < -1.4 and $-0.6 <$ [Fe/H] $< +0.2$ the distributions are close to Gaussians, whereas the distribution for $-1.4 <$ [Fe/H] < -0.6 is clearly non-Gaussian with two separate peaks at $0\,\mathrm{km\,s^{-1}}$ and $175\,\mathrm{km\,s^{-1}}$, respectively. In other words, the slow and fast rotating populations overlap in [Fe/H] in the range $-1.4 <$ [Fe/H] < -0.6. A similar result has recently been found by Morrison et al. (1990). From a study of K-giants they find a significant overlap in abundance between halo and disk stars in the range $-1.6 <$ [Fe/H] < -0.8.

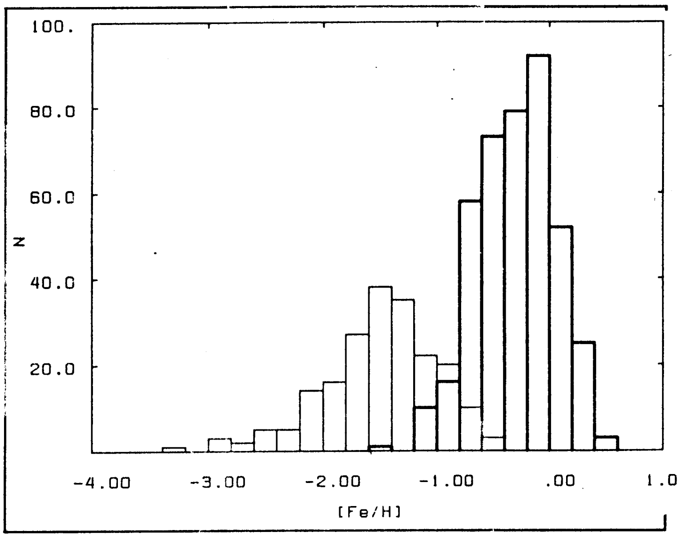

Fig. 7. The [Fe/H] distributions for the halo stars (thin line) and the high-velocity disk stars (thick line)

Due to the overlap in abundance for the two populations seen in Fig. 5 it is not possible to separate them by [Fe/H] alone. Neither it is possible to use V_{rot} alone as a population criterion because a significant fraction of the halo group have $V_{rot} \simeq 200\,\mathrm{km\,s^{-1}}$. Instead we have drawn a straight line of separation through the points ([Fe/H], V_{rot}) $= (-0.3, 0\,\mathrm{km\,s^{-1}})$ and $(-1.5, 175\,\mathrm{km\,s^{-1}})$. Stars below this line are called *halo* stars and stars above the line are called *high-velocity disk* stars. We note that the line defined in this way also separates the two populations seen in the V-[Fe/H] diagram of Carney et al. (1990) very nicely.

The [Fe/H] distributions of the two populations just defined are shown in Fig. 7. The Bottlinger diagrams are shown in Fig. 8 and the W' distributions in Fig. 9. In Table 2 the mean values and standard deviations of U', V' and W' and [Fe/H] are given. In the following we compare these data with similar data derived for non-kinematically selected samples of halo and disk stars.

The [Fe/H]-distribution of the halo stars (see Fig. 7) is very similar to that of the halo globular cluster system (Zinn 1985), except maybe for a more extended tail of very metal-poor stars in our sample. The number distributions of V' and W'

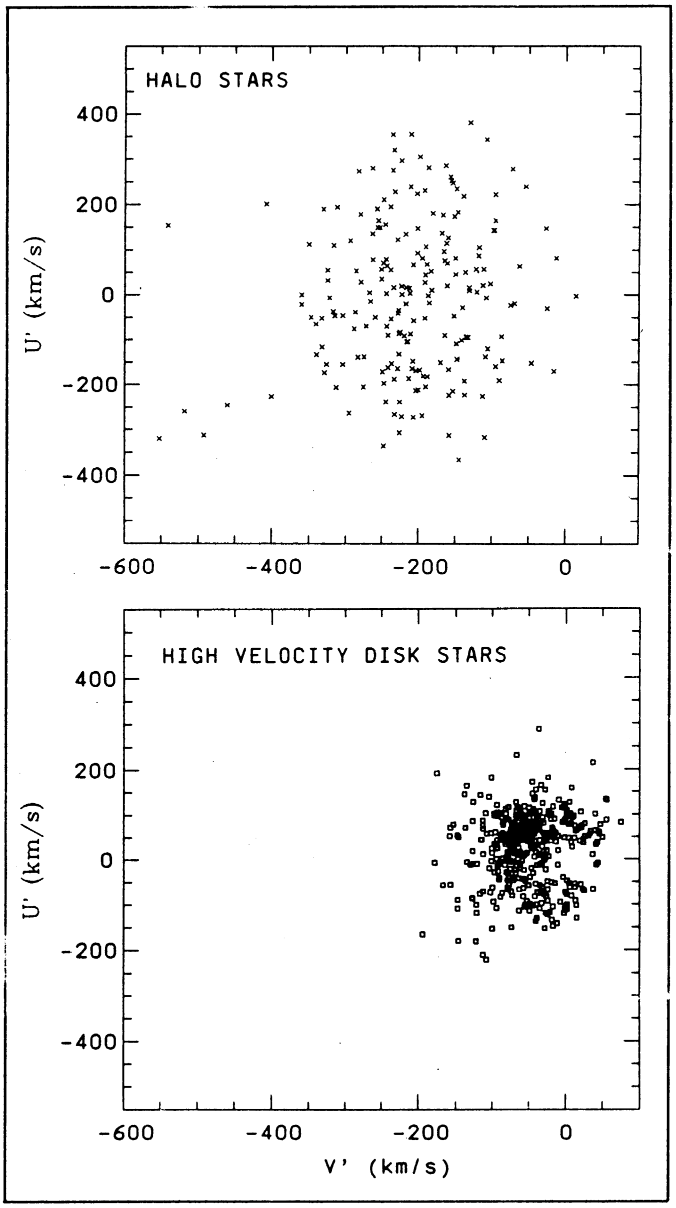

Fig. 8. The Bottlinger diagrams for the halo stars and the high-velocity disk stars

are approximately Gaussians, whereas the distribution of U' is quite flat as also seen from the Bottlinger diagram, Fig. 8. For comparison we quote the velocity dispersions derived for non-kinematically selected samples of halo stars $(\sigma_{U'}, \sigma_{V'}, \sigma_{W'}) = (131, 102, 89\,\mathrm{km\,s^{-1}})$ as given by Gilmore et al. (1989). Within the uncertainty (typically $10\,\mathrm{km\,s^{-1}}$) the dispersions in V' and W' agree with the values given in Table 2 for our halo sample. The dispersion in U' ($171\,\mathrm{km\,s^{-1}}$) is however much larger than the value of $131\,\mathrm{km\,s^{-1}}$ found for the non-kinematically selected samples. Evidently, our halo sample has a bias towards radial orbits, and we note that Carney et al. (1990) find the same bias for their sample of high proper motion stars.

As seen from Fig. 8 the distribution of high-velocity disk stars in the (U', V') plane is somewhat irregular. The "hole" in the distribution centred on $(U', V') \simeq (0, 0\,\mathrm{km\,s^{-1}})$ is due to

Table 2. Mean values and rms dispersion for the kinematical parameters and metallicity of the two populations seen in the V_{rot}-[Fe/H] diagram

	$<U'>$ $\mathrm{km\,s^{-1}}$	$\sigma_{U'}$ $\mathrm{km\,s^{-1}}$	$<V'>$ $\mathrm{km\,s^{-1}}$	$\sigma_{V'}$ $\mathrm{km\,s^{-1}}$	$<W'>$ $\mathrm{km\,s^{-1}}$	$\sigma_{W'}$ $\mathrm{km\,s^{-1}}$	$<$[Fe/H]$>$	$\sigma_{[Fe/H]}$	N_{star}
Halo	1	±171	−211	±93	−7	±86	−1.60	±0.56	202
Disk	24	±80	−50	±46	−3	±46	−0.40	±0.34	409

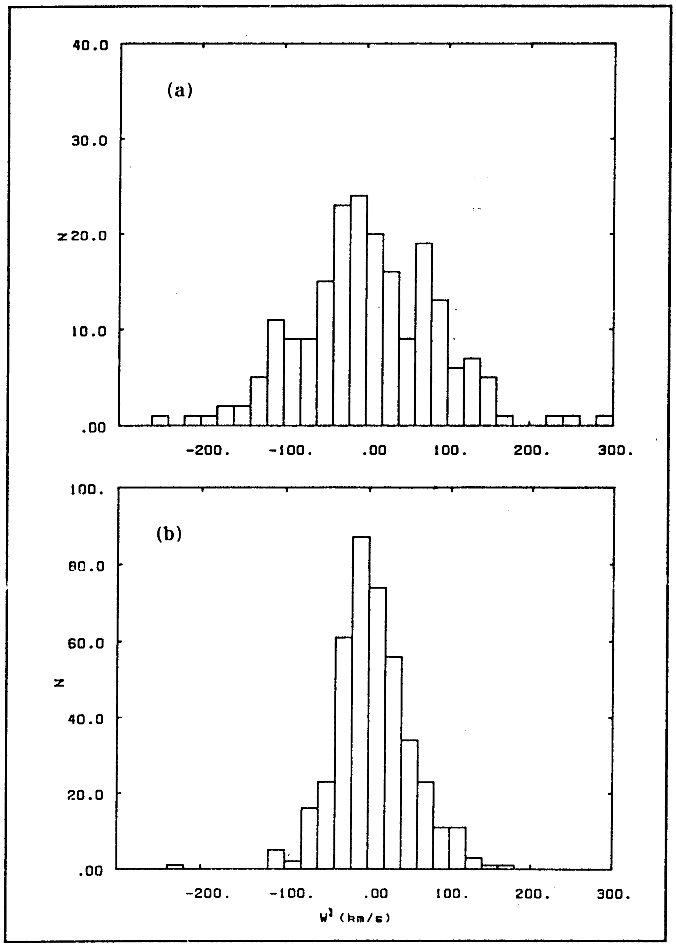

Fig. 9. The W' distributions for the halo stars (a), and the high-velocity disk stars (b)

our original selection of stars with space velocities larger than $80\,\mathrm{km\,s^{-1}}$ as given in various catalogues (see Paper I). The redetermination of space velocities – in particular the effect of improving the distances – has diminished the actual limit to about $50\,\mathrm{km\,s^{-1}}$, which is also the approximate radius of the "hole" seen in Fig. 8. Another interesting feature of Fig. 8 is the concentration of stars around $(U', V') \simeq (80, -50\,\mathrm{km\,s^{-1}})$ probably reflecting some kind of group motion of stars in the solar vicinity. Thus, Eggen (1965) discusses the probable 61 Cygni moving group, which has $(U', V') = (91, -53\,\mathrm{km\,s^{-1}})$; within the errors of the space velocities this is the same group as seen in Fig. 8. Despite these irregularities in the (U', V') plane the distribution of W' velocities is close to a Gaussian with a velocity dispersion ($46\,\mathrm{km\,s^{-1}}$) similar to that of the thick disk (Gilmore et al. 1989). Also the asymmetric (Strömberg) drift ($50\,\mathrm{km\,s^{-1}}$) of our sample corresponds closely to that of the thick disk. On the other hand, the average [Fe/H] of our sample (−0.40) is somewhat higher than the value of [Fe/H] = −0.6 normally quoted for the thick disk. Probably, our sample contains a mixture of metal-poor thick disk stars and a high-velocity tail of more metal-rich old thin disk stars. This is why we don't name the group *thick disk* but prefer to use the designation *high-velocity disk*

We conclude that although our sample of stars has some bias towards extreme U' velocities it contains rather well-defined groups of halo, and (thick plus old thin) disk stars. In particular it is of interest to study the relative ages of these presumably very old groups of stars in order to learn more about the early evolution of the Galaxy. This is the subject of the next section.

4. Ages

In Paper III ages of turn-off stars with [Fe/H] < -1.0 were derived by the aid of isochrones in the c_0-$(b-y)_0$ diagram computed by VandenBerg & Bell (1985). The maximum heavy element abundance of these isochrones, $Z = 0.006$ corresponds to [Fe/H] $= -0.75$ according to the relation between [Fe/H] and $\log Z/Z_\odot$ given below in Eq. (7). Thus, we cannot use this set of isochrones transformed to the c_0-$(b-y)_0$ diagram for an age determination of the more metal-rich stars in our sample. Instead, the ages given in the present paper are determined from the position of the stars in the δM_V-$\log T_{\rm eff}$ diagram; $\delta M_V = M_V(\mathrm{ZAMS}) - M_V(\mathrm{star})$ being defined in Sect. 2.1. Among others Twarog (1980) has applied this method to derive an age-metallicity relation for disk population stars. Recently, Strömgren (1987) has discussed the method and reached the conclusion that ages of Population I stars can be determined with an accuracy of about 25%.

The isochrones used for the age determinations are those of VandenBerg (1985). They refer to stellar models with a helium mass fraction of $Y = 0.25$ and heavy element mass fractions of $Z = 0.0169$, 0.01, 0.006, 0.003 and 0.0017. Using the $M_{V,\mathrm{ZAMS}}(\log T_{\rm eff})$ relations computed by VandenBerg for the various Z values we have transformed the isochrones from the M_V-$\log T_{\rm eff}$ plane to the δM_V-$\log T_{\rm eff}$ plane.

As discussed by VandenBerg & Poll (1989) the surface temperatures of the stellar models of VandenBerg (1985) are probably slightly too high due to problems with the model atmospheres used to provide the boundary conditions. Thus, the solar model is too hot by $\Delta \log T_{\rm eff} \simeq 0.01$. In order to correct for this we have shifted the isochrones of VandenBerg (1985) by $\Delta \log T_{\rm eff} = -0.013$, which corresponds to the shift of $\Delta(b-y)_0 = 0.025$ applied to the isochrones of VandenBerg & Bell (1985) in Paper III.

The computation of δM_V from the position of the star in the c_0-$(b-y)_0$ diagram has already been described in Sect.

2.1. For the computation of T_{eff} we have used the calibration of Magain (1987),

$$T_{eff} = 8330 - 7040(b-y)_0(1.0 - 0.099\ 10^{[Fe/H]})\,. \quad (6)$$

The heavy element mass fraction, Z, of a star is determined by:

$$\log Z/Z_\odot = 0.6[Fe/H] \quad \text{for } [Fe/H] \geq -1.0$$
$$\log Z/Z_\odot = 0.4 + [Fe/H] \quad \text{for } [Fe/H] < -1.0 \quad (7)$$

These formulae take into account the increasing ratios of oxygen and α-elements to iron as a function of decreasing values of [Fe/H] (Nissen 1990).

The individual stars have been plotted in δM_V-$\log T_{eff}$ diagrams with sets of isochrones approximating the [Fe/H] values of the stars. As an example Fig. 10 shows the position of all stars having $-0.45 <$ [Fe/H] < -0.30 i.e. $-0.27 < \log(Z/Z_\odot) < -0.18$ according to Eq. (7). The isochrones drawn correspond to $Z = 0.01$, i.e. $\log Z/Z_\odot = -0.227$. It is seen that a large fraction of the stars are distributed along the ZAMS ($\delta M_V \simeq 0.0$). The ages of these stars cannot be determined with any significant accuracy. Hence, only for stars with $\delta M_V > 0.4$ has the age been determined. By graphical interpolation the logarithmic age, $\log A$, is determined from the figure and then corrected for the difference between the heavy element abundance of the star and that of the set of isochrones. This rather small correction is determined from the shift of isochrones as a function of Z.

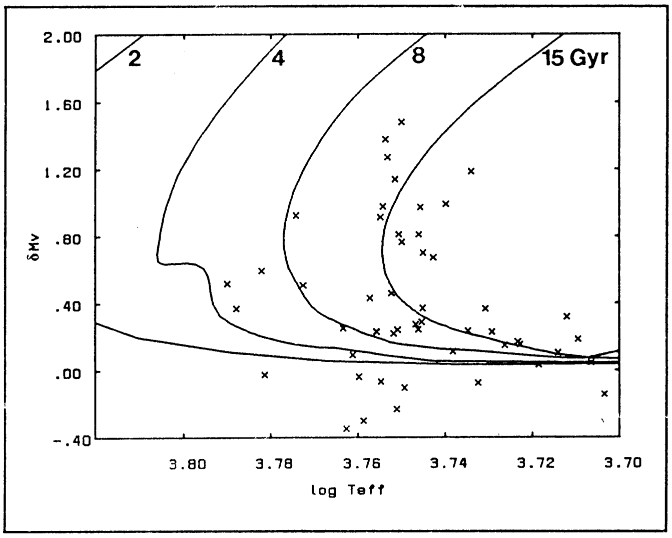

Fig. 10. The δM_V-$\log T_{eff}$ diagram for stars with $-0.45 <$ [Fe/H] < -0.30. Isochrones computed from VandenBerg (1985) with ages of 2, 4, 8 and 15 Gyr are also shown

As discussed by Nissen (1990) differential effective temperatures of F and early G type stars at a given metallicity can be determined with an accuracy of ±50K from $(b-y)_0$ when using Eq. (6). The corresponding error of $\log T_{eff}$ is ±0.004 dex. Systematic errors in T_{eff} as a function of [Fe/H] may be larger, up to ±100K at [Fe/H] $\simeq -1.0$. The error of δM_V was discussed in Sect. 2.1 and estimated to be of the order of ±0.2 magnitudes for turn-off stars. The corresponding error of the age determination depends somewhat on the position of the stars in the diagram but are on the order of ±0.10 dex in $\log A$ if $0.4 < \delta M_V < 2.0$. We emphasize, however, that the systematic errors in the age determination as a function of [Fe/H] may be somewhat larger, due to possible systematic errors in the calibrations leading to T_{eff} and δM_V and to possible systematic errors in the computation of the isochrones.

In some [Fe/H]-ranges a few stars fall in the "forbidden" region to the right of the 15 Gyr isochrone, apparently having ages larger than say 25 Gyr. Such stars could be unresolved binaries. As discussed in Paper III duplicity effects may cause the age to be overestimated by as much as 6 Gyr. For this reason we consider stars with $A \geq 25$ Gyr as potential binaries and exclude them from the final list of stars with an age determination.

As the lowest Z-value for which VandenBerg (1985) has computed a set of isochrones, $Z = 0.0017$, corresponds to [Fe/H] $= -1.4$ according to Eq. (7), we have not attempted any age determination for stars with [Fe/H] < -1.5. The metallicity range $-1.5 <$ [Fe/H] < -1.0 is common for the age determinations in Paper III and in the present work. Altogether 19 stars have ages determined by both methods. For two of these (BD−45°12460 and HD179626) the error estimate given in Paper III is rather high, $\sigma(A) \simeq 4$ Gyr. The remaining stars have error estimates $\sigma(A) \leq 2.2$ Gyr. Excluding BD−45°12460 and HD179626, we find the average age difference (Present work - Paper III) to be $< \Delta A > = 3.0$ Gyr with a standard deviation $\sigma(\Delta A) = 2.2$ Gyr. Whereas the standard deviation is as small as could be expected, the average age difference is surprisingly large. Part of this difference is due to the fact that the isochrones used in Paper III were computed for a helium mass fraction of $Y = 0.20$, whereas the isochrones used in the present work have $Y = 0.25$. As seen from Fig. 5 in Paper III the corresponding change of age is about 1 Gyr. The remaining 2 Gyr of the age difference between Paper III and the present work may be due to accidental errors or to the different calibrations and methods applied.

5. Discussion and conclusion

In Fig. 11 the metallicity [Fe/H] is plotted as a function of the logarithmic age with different symbols for the halo and the high-velocity disk stars. As seen all halo stars except one are confined to a rather narrow age range. Excluding this comparatively young and metal-rich halo star we find a mean age of the halo stars, $< A > = 18.5$ Gyr, and a standard deviation of 3.2 Gyr. It is furthermore seen from Fig. 11 that the large majority of high-velocity disk stars in the metallicity range $-1.2 <$ [Fe/H] < -0.5 are as old as the halo stars. Even among high-velocity disk stars, with [Fe/H] ≥ -0.5 a significant fraction appear nearly as old as the halo stars, but in this range the age distribution is relatively flat from 4 to 15 Gyr.

From these results we conclude that the Galactic halo and the metal-poor, high-velocity component of the Galactic disk (the thick disk in Gilmore's notation) are nearly coeval. Any possible age difference between the two populations is at most 2-3 Gyr, which equals the age scatter found among the halo stars in Paper III. This suggests that the formation of the halo and the thick disk are closely related. An interesting scenario that establishes such a connection is discussed in some detail by Freeman (1990). It is based on the idea of Searle & Zinn (1978) that globular clusters and halo stars form in small satellite galaxies, which are then accreted by a thin, fast rotating,

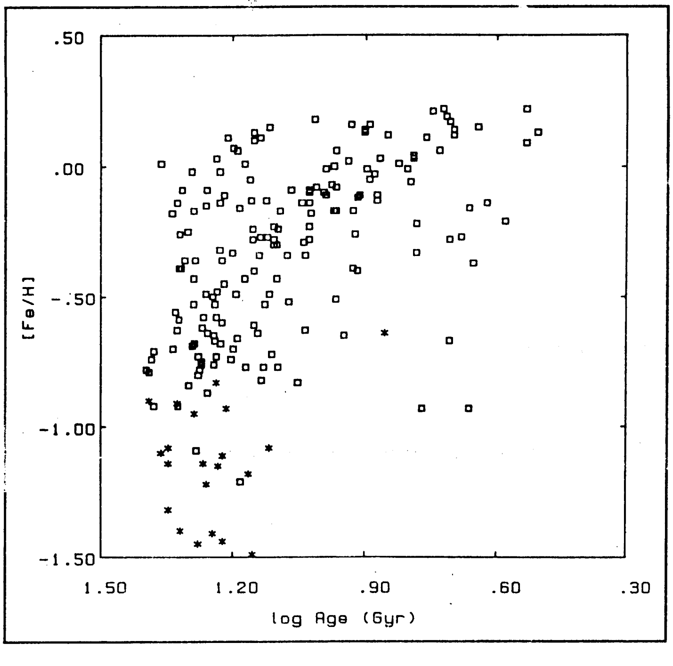

Fig. 11. The [Fe/H]-log Age diagram of turn-off stars in the present paper. *, halo stars; □, high-velocity disk stars

Galactic disk. The dynamical heating of the stellar component of this disk in connection with the accretion process produces the thick disk. The kinematics of the halo depends on the dynamics of the merging satellites, whereas the kinematics of the thick disk are determined by the heating of a rotating disk. Thus, this scenario offers a natural explanation for the striking kinematical discontinuity between the halo and thick disk stars as seen in Fig. 5. The formation of the two populations occurs simultaneously and nothing prohibits it to take place over an extended period of several gigayears in agreement with the age data presented in Fig. 11. Finally, an overlap in abundance as discussed in Sect. 3.2 may occur, because the satellite galaxies and the Galactic disk have separate chemical evolutions.

Some collapse models of Galactic formation may also be compatible with the age and kinematical data presented in this work. As suggested by Wyse & Gilmore (1986) a rapid increase in the dissipation and star formation rates due to enhanced cooling once [Fe/H] has passed -1.0 could explain the kinematical discontinuity between the non-rotating halo and the rapidly rotating thick disk. In this scenario the age difference between the two components may well be less than a few gigayears and the model is therefore compatible with our age data. On the other hand a slow, pressure-supported collapse model, like Larson's (1976) hydrodynamical model of disk galaxy formation, in which the disk forms first towards the Galactic center and then grows outwards on a time scale of many gigayears, does not agree with our age data. As mentioned in the introduction Norris & Green (1989) have presented evidence in support of Larson's models finding that the thick disk is younger than the disk globular cluster system by at least 3-6 Gyr, in clear disagreement with the high age for the thick disk found in the present work. We note in this connection that Norris and Green predict that if their suggestion for the age of the thick disk is correct, then significant numbers of dwarfs with $+0.4 \leq B-V \leq +0.5$ and with $-0.8 \leq$ [Fe/H] ≤ -0.4 should be found 1-3 kpc above the Galactic plane. However, Croswell (1990) doing *uvby* photometry to $V \approx 17.0$ in Selected Area 57 (near the NGP) finds only *one* dwarf or subgiant with $+0.4 \leq B-V \leq +0.5$ over the range 1 kpc$\leq z \leq$5 kpc, and this one star has [Fe/H] $\simeq -0.28$ and $z = 1.3$ kpc. The main peak occurs for $+0.6 \leq B-V < +0.7$ with some stars having $+0.5 \leq B-V < +0.6$; this indicates a larger average age than that proposed by Norris & Green (1989) in agreement with our results.

Recently, Eggen (1990) has published an interesting paper on astrometric and astrophysical discontinuities between old disk and halo stellar populations. On the basis of intermediate, *RI* and *DDO* photometry of weak-lined stars from the Michigan spectral type catalogues he finds a dichotomy between old disk stars, all having [Fe/H] > -0.8 and halo stars, all having [Fe/H] < -1.2 and $V' < -100\,\mathrm{km\,s^{-1}}$, i.e. $V_{\rm rot} < 125\,\mathrm{km\,s^{-1}}$ (see Eggen's Fig. 6). Although our Fig. 5 also shows a discontinuity between disk and halo stars, as discussed in Sect. 3.2, we do find stars that violate the dichotomy seen in Eggen's Fig. 6. In particular our Fig. 5 shows a significant number of stars with $V_{\rm rot} \simeq 0\,\mathrm{km\,s^{-1}}$ and $-1.2 <$ [Fe/H] < -0.8 as well as stars with $V_{\rm rot} > 125\,\mathrm{km\,s^{-1}}$ and [Fe/H] < -1.2. The fraction of stars falling in these intervals cannot be explained as due to our errors of [Fe/H] (±0.15 dex) and of $V_{\rm rot}$ ($\pm 20\,\mathrm{km\,s^{-1}}$).

It may be asked to what extent the results discussed above are influenced by selection effects. As explained in detail in Paper I we have been observing a kinematically selected sample of 607 high velocity stars supplemented with 104 metal-poor stars from the catalogue of Bartkevičius (1980). This means that one should be very cautious about determining velocity dispersions and metallicity distributions for stellar populations from our sample. The approach followed in the present paper has therefore been to show that our sample contains groups of stars with kinematical parameters and metallicities similar to those currently accepted for the halo and thick disk populations, and then to determine the age distributions of the two groups (Fig. 11). Hence, our main conclusion that the thick disk is nearly coeval with the halo does not depend on our selection criteria, unless there is an age-kinematics relation in the thick disk. If the velocity dispersion increases with age, then our high-velocity selection criterion may lead to an average age for the thick disk that is too high. However, this bias, if it does indeed exist, will not change our result that there is a considerable overlap in ages between the halo and thick disk. Also, the results of Croswell (1990) argue that there is *not* a significant younger component in the thick disk.

The other interesting result, the scarcity of stars with [Fe/H] $\simeq -1.0$ and $V_{\rm rot} \simeq 100\,\mathrm{km\,s^{-1}}$, is more vulnerable to selection effects. However, we don't think that our way of selecting the stars could produce such a fine-structure in the $V_{\rm rot}$-[Fe/H] diagram. If stars with [Fe/H] $\simeq -1.0$ and $V_{\rm rot} \simeq 100\,\mathrm{km\,s^{-1}}$ existed in appreciable numbers they would certainly have $V_{\rm total} > 80\,\mathrm{km\,s^{-1}}$ and hence would have been included in our sample.

The results discussed above have been obtained by comparing metallicities, ages and direct observable kinematical parameters for a sample of high-velocity stars. Another line of approach would be to compute Galactic orbits of the stars from the distances and the space velocities as already done for the most metal deficient stars ([Fe/H] < -2.0) in Paper IV. Possible correlations between metallicities, ages and orbital characteristics like mean galactocentric distance, eccentricity, and maximum height above the Galactic plane may give new insight into the formation and early evolution of the Galaxy. In particular it would be interesting to look for groupings of halo stars with respect to orbital parameters, ages and metallicities. If such grouping exists it would be new evidence for the Searle-Zinn idea that the halo stars have formed in small satellite galaxies and then accreted by the Galactic disk. In the next Paper VI we intend to make such an analysis of the data.

Acknowledgements. We are indebted to C. Allen for kindly loaning us her program for calculating Galactic space velocities and for several fruitful discussions. We thank K. Croswell, P. Pismis, and A. Poveda for their interest and useful comments. E. H. Olsen is thanked for providing the revised M_V-$(b-y)_0$ standard relation in advance of publication. We gratefully acknowledge the use of the computing facilities of the Centro de Investigacion Cientifica y Educacion Superior de Ensenada (CICESE). This work was partially supported by a grant from CONACYT, No P228CCOX880202.

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