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POPULATION STUDIES. VI. THE TRANSITION FROM HALO TO THIN DISK

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ABSTRACT

DDO observations are presented for a sample of 157 stars towards the south Galactic pole complete in the ranges $0.70 \leq B-V \leq 1.10$ and $V \leq 13.0$. The color and magnitude limits of the survey were chosen to isolate objects of age 1–16 Gyr in their core–helium-burning phase of evolution at distances z from the Galactic plane of up to 3 kpc. Analysis of the results for the 60 giants in the sample leads to the following conclusions: (1) There is a dearth of red horizontal branch stars (of the type in the disk globular cluster population) and a predominance of somewhat cooler giants. For $z > 1$ kpc, we identify these objects with the clump and red giant branch stars in the old, metal-poor open clusters, which are significantly younger than the disk globular clusters. (2) We suggest that the bulk of what Gilmore and his coworkers refer to as the thick disk, and which we prefer to regard as the tail of an extended, continuous Galactic disk, is younger than the disk globular clusters, by at least 3–6 Gyr. There seems no compelling reason to believe that the Galactic disk in the solar neighborhood has any major stellar component as old as the disk globular clusters (which have mean galactocentric distance 4 kpc) to within this age limit. We submit this as evidence that the Galactic disk formed outward from the center on a time scale of several Gyr. (3) We observe a well-defined composition gradient, perpendicular to the Galactic plane, given formally by $[\mathrm{Fe/H}] = -0.19z - 0.16$ (z in kpc). (4) There is no evidence in our work for any stars with $[\mathrm{Fe/H}] > -0.3$ at distances greater than 2 kpc from the plane. Reobservation of a number of stars in the survey of Hartkopf and Yoss for which they report $[\mathrm{Fe/H}] > -0.3$ and $z > 2000$ (and which have been adduced as evidence for solar abundance material far from the plane) suggests that the abundances and distances for these stars have both been significantly overestimated. (5) The lack of such high-abundance stars far from the plane is more in keeping with the continuous extended disk model presented in Paper V of this series than with the thick/thin model proposed by Gilmore and Wyse. This suggests that if the latter is to be accepted, the proportion of higher abundance stars in the thick-disk component should be decreased.

Of the models which have been suggested to explain the thick-disk phenomenon, we submit that pressure-supported collapse models of the type constructed by Larson (1976, predating the term "thick disk") are in best accord with the observations. One important characteristic of these models is that the disk forms first toward the galactic center and then grows outward. In his model 6, for example, one finds that after ~2 Gyr the disk is confined to within ~5 kpc of the center. We identify this as the epoch of disk globular cluster formation in the Galaxy. Only after a further several billion years does the disk form at the solar distance from the center. We suggest that this is the most natural explanation of the apparent relative youth of the disk in the solar neighborhood.

Subject headings: galaxies: The Galaxy — galaxies: stellar content — stars: abundances —
stars: horizontal branch — stars: late-type — stars: stellar statistics

I. INTRODUCTION

The work of Gilmore and Reid (1983) and of Zinn (1985) on the Galactic disk, and the ensuing intense activity in this field (see Freeman 1987 and references therein), show very clearly that the transition from the spheroidal halo population of the Galaxy to its disk population is a complicated matter. Zinn's removal of any reasonable doubt that the Galactic globular cluster system is bimodal, and comprised of spheroidal and disk components, with the latter having spatial, kinematic, and chemical properties intermediate between those of the spheroid and the thin disk, clearly demonstrates the existence of an intermediate population. The stellar number counts of Gilmore and Reid (1983) also suggest the need for an intermediate component. The purpose of the present paper is to investigate the nature of the transition population(s).

a) Historical Perspective

The reader is referred to Sandage (1986) for a detailed description of the development of our understanding of the formation and evolution of the Galaxy. One major contribution was that of Eggen, Lynden-Bell, and Sandage (1962), who, building on the rich observational framework established in the preceding half-century, suggested that a very rapid collapse of a large gas cloud, on a time scale of a few hundred million years, resulted in a system comprising a spheroidal, slowly rotating halo together with a thin, rapidly rotating disk. No mention is made in that paper of an intermediate component; but see Sandage and Fouts (1987, § I) for comment on this point. For a somewhat different suggested origin of the Galactic halo, in terms of star formation separated in space and time (time scale of the order of a few Gyr) from the central collapse, the reader should consult Searle and Zinn (1978). (See Sandage 1987*a* and Norris 1987*a* for a discussion of the implications and relative merits of these two viewpoints.)

It was not until the present decade that the importance of an intermediate component has been emphasized in inescapable and compelling terms. Gilmore and Reid (1983), Gilmore (1984), Gilmore, Reid, and Hewett (1985), Gilmore and Wyse

(1985), and Wyse and Gilmore (1986) have set down the case that there exists such a component, which they designate as "thick disk," and which is argued to be quite distinct from the well-known "thin disk." The basis for their suggestion has been strongly criticized by Bahcall and Soneira (1984), Bahcall and Ratnatunga (1985), and Bahcall *et al.* (1985). Be that as it may, the demonstration by Zinn (1985) that there exists a well-defined group of globular clusters in a disklike configuration with scale height ~1 kpc perpendicular to the Galactic plane and mean galactocentric distance of ~4 kpc establishes without doubt the existence of an intermediate component toward the center of the Galaxy. What remains unclear at this point is the relationship of the disk globular clusters to the Gilmore-Reid-Wyse (GRW) thick disk.

Rose (1985) reported the identification of a rich population of red horizontal branch (RHB) stars toward the north Galactic pole in a thick disklike configuration, which seemed readily identifiable with the GRW thick disk. Since RHB stars represent a major evolutionary component of the disk globular cluster population, it would then follow that the GRW thick disk and the disk globular cluster population are one and the same. The implicit and important corollary of this would be that the GRW thick disk is as old as the disk globular clusters.

b) *Present Investigation*

In Paper IV of the present series (Norris 1987*b*), it was suggested that the Rose RHB candidates could equally well be core–helium-burning "clump" stars (see Cannon 1970) similar to those seen in old, metal-deficient disk clusters such as NGC 2243 and Melotte 66, which have [Fe/H] = −0.6 (Janes 1979). This was based on the observation that Rose found no hot RHB stars ($0.70 < B-V < 0.80$) such as are seen in the disk globular cluster 47 Tuc. If this is true, the Rose candidates need not be identified with the disk globular cluster population and could be somewhat younger (~5–7 Gyr; Hawarden 1975; Anthony-Twarog, Twarog, and McClure 1979) than the disk globular clusters (~14 Gyr; Hesser *et al.* 1987).

Friel (1987, § VII*f*) made a similar suggestion following her work on two high Galactic latitude fields.

The Rose RHB candidates have a velocity dispersion perpendicular to the Galactic plane of $\sigma_z = 40$ km s^{-1} and an abundance [Fe/H] = −0.5. In Paper V (Norris 1987*c*) it was suggested that these were the tail of a continuous Galactic disk distribution, and that the stellar number counts of Gilmore and Reid (1983) could be explained by a disk with continuous, and rather less extreme, properties than the discrete model of Gilmore and his coworkers.

The purpose of the present paper is to investigate further the Rose RHB hypothesis, with a view to placing constraints on the nature of the Galactic disk at distances 1–3 kpc from the plane, at the solar distance from the Galactic center. While in Paper IV the absence of hotter RHB stars from the Rose sample was emphasized, it was also noted that spectroscopic selection effects might have been responsible, at least in part, for the absence of such objects. Accordingly, a survey of a sample of stars toward the south Galactic pole (SGP), complete in the color range $0.7 < B-V < 1.1$, has been undertaken to search for such objects. The magnitude criterion was chosen to be $V < 13$.

The rationale for the choice of this color range is demonstrated in Figure 1, which presents the schematic color-magnitude diagrams of the disk globular cluster 47 Tuc ([Fe/H] = −0.7 dex, age ~14 Gyr), and the old open clusters Melotte 66 (−0.5 dex, 6–7 Gyr), and M67 (~0.0 dex, 6 Gyr; Sandage and Eggen 1969). These clusters were chosen to be representative of the disk globular cluster population and that of the old disk open clusters. The box in the diagram represents (as will be seen in what follows) the region of interest for our investigation. One sees that the range $0.70 < B-V < 1.10$ encompasses the entire color range of the major phase of core–helium-burning (RHB and clump phases) of stars in these clusters. The work of Cannon (1970) suggests that the region of interest encompasses this phase of evolution for all stars of age greater than 500 Myr. A crucial point is that in our color range, core–helium-burning objects, which have lifetimes of order 10^8 yr (see, e.g., Sweigart and Gross 1976), are as common as hydrogen shell–burning red giants, which evolve through the region of interest in about 10^8 yr for the metallicity range we will be considering.[1]

The choice of the magnitude limit of $V = 13$ is such that RHB stars or clump stars (both of which have $M_V \sim 1.0$) should be detected to distances up to ~2–3 kpc from the Galactic plane.

The thrust of the investigation is to establish the relative incidence of RHB stars of the disk globular population and the clump stars of the old open cluster population at heights up to 3 kpc from the plane. It was hoped that such an investigation would place constraints on (1) the age of the bulk of the material at 1–3 kpc from the plane, (2) the nature of the chemical abundance gradient perpendicular to the plane, and (3) the dependence of scale height on abundance. It was also an intention of the investigation to (4) test whether the discrete thin/thick disk formulation of Gilmore and his coworkers or the continuous extended disk formulation presented in Paper V gives a better representation of reality.

The observational data are presented in § II, while the analysis of this material is given in § III. The inferences which may be drawn from the results are discussed in § IV. We conclude with a discussion of the formation of the Galactic disk in § V.

II. OBSERVATIONS

a) *Sample*

As noted above, the absence of relatively hot stars (with colors $0.7 < B-V < 0.8$, as are well represented on the RHB of 47 Tuc) from the Rose RHB candidates might result in part from spectroscopic selection effects. To address this question, all stars having $0.70 \leq B-V \leq 1.10$ and $8.5 \leq V \leq 13.0$ were chosen from the Eriksson (1978) survey of an 11.8 square degree region near the SGP. There are 155 objects in this photometrically complete subsample of Eriksson stars.

b) *Photometry*

To remove dwarfs from the sample, and to determine abundances and absolute magnitudes for the remaining giants, the DDO intermediate-band photometric system (McClure 1976) was employed. Observations were obtained using a pulse-counting GaAs photometer attached to the 2.3 m telescope at Siding Spring Mountain during 1986 May–October and 1987

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[1] From analysis of the stellar evolution data of Sweigart and Gross (1978) and Green, Demarque, and King (1987) we find, for $Y = 0.24$, $Z = 0.01$, and ages in the range 3–14 Gyr, that stars evolve through our region of interest ($0 < M_V < 2$, $0.7 < (B-V)_0 < 1.1$) in $(1.0\text{–}1.1) \times 10^8$ yr in all cases. For $Y = 0.24$, $Z = 0.004$, and ages 7–14 Gr, the corresponding time is $(1.2\text{–}1.3) \times 10^8$ yr.

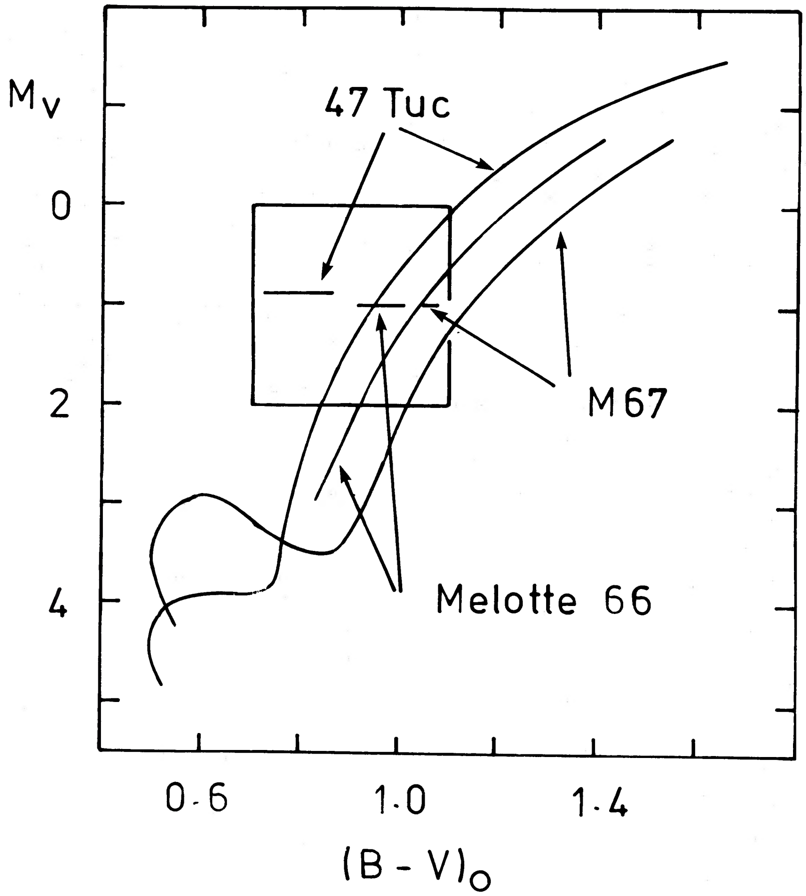

FIG. 1.—Schematic color-magnitude diagrams for the disk globular cluster 47 Tuc (based on data of Hesser *et al.* 1987) and the old open clusters Melotte 66 (following Anthony-Twarog, Twarog, and McClure 1979) and M67 (following Janes and Smith 1984 with $E(B-V) = 0.05$). We note that for Melotte 66 and M67 we have assumed $M_V = +1$ for the clump stars. The box defines the region of interest for the present investigation, and embraces the major core–helium-burning phase of evolution for systems in the Galactic disk having ages in the range ~1–16 Gyr.

June. Standard filters with appropriate blocking for red leaks were used, while reduction to the standard system was effected by also observing stars having well-determined colors from McClure and Forrester (1981) and Norris, Bessell, and Pickles (1985, hereafter Paper I).

The colors $C(4245)$ and $C(4548)$ were obtained for the complete sample and were used as the primary discriminant between dwarfs and giants (see § III*a* below). In 1986 we observed 120 of the sample having $B-V \leq 1.0$, while in 1987 we extended the sample to the 30 objects with $1.0 < B-V \leq 1.1$ and completed the photometry for the hotter group. For the giants in the sample for which $B-V < 1.0$, the colors $C(4142)$, $C(3842)$, and $C(3538)$ were obtained during the 1986 season, while in 1987 $C(4142)$ was observed. These supplementary data are used below (§§ III*a*, III*b*) to check on the luminosity classification and to obtain estimates of absolute magnitude and chemical abundance. For reasons of observational efficiency and convenience some dwarfs were observed in all colors in 1986. The data are given in Table 1, where columns (1)–(3) give the star name, V, and $B-V$ from Eriksson (1978) and columns (4)–(9) give the DDO photometry and the number of observations. From stars with repeated observations we estimate that the internal standard deviations for a single observation are 0.009, 0.009, 0.011, 0.016, and 0.013 for $C(4548)$, $C(4245)$, $C(4142)$, $C(3842)$, and $C(3538)$, respectively.

There are two stars in the Eriksson survey within the color range of our investigation, but with $V < 8.5$. For completeness we include these objects in Table 1, where the tabulated DDO material has been taken from Hartkopf (1981).

Since one of the basic aims of this work was to search for the hotter RHB in the field sample, and since only fragmentary data are available for these objects in clusters, DDO observations were made (during the 1986 season) of four stars on the RHB of 47 Tuc. These objects were chosen to cover the full color range ($0.70 < B-V < 0.90$) of the horizontal branch. The data are presented in Table 2A (where cols. [1]–[9] contain similar information to that given in Table 1) and will be used in the following sections for comparison purposes. The errors of measurement of the DDO photometry are the same as for that of the Eriksson stars.

In anticipation of the criticism that 47 Tuc may not be typical of the disk globular clusters, we also undertook during 1988 May and June observations of RHB stars in the disk globular cluster NGC 6352 while the present paper was in the refereeing process. We doubt that anyone could sustain the case that this cluster, which has $[Fe/H] = -0.52$ (Zinn 1985), is not a member of the disk class. In this case, however, the RHB stars are faint, and we measured only $C(4245)$ and $C(4548)$ for five stars which cover the full extent of the RHB as defined in Figure 3 of Hartwick and Hesser (1972). The observations were again made with the same instrumental setup as

TABLE 1

BV, DDO PHOTOMETRY AND RADIAL VELOCITIES FOR ERIKSSON STARS

Star (1)	V^a (2)	$B-V^a$ (3)	C4548 (4)	C4245 (5)	C4142 (6)	C3842 (7)	C3538 (8)	n^b (9)	v_r (10)	n (11)
29.0.006	12.74	1.01	1.183	0.867	0.087	....	....	11100	..	.
29.0.034	12.53	1.08	1.209	0.954	0.133	....	....	11100	..	.
29.0.044	12.50	0.80	1.069	0.776	....	....	....	11000	..	.
29.0.047	12.21	0.93	1.153	0.887	0.116	-0.420	0.992	22111	-3	1
29.0.049	12.62	1.03	1.176	0.887	0.113	....	....	11100	..	.
29.0.063	12.98	0.83	1.078	0.756	0.080	-0.557	0.980	33111	..	.
29.0.065	12.83	0.72	1.046	0.714	....	....	....	11000	..	.
29.0.069	12.04	0.93	1.149	0.798	0.027	-0.495	1.013	22111	-9	1
29.0.133	11.56	0.87	1.109	0.781	0.079	-0.520	0.969	22111	-6	1
29.0.138	9.38	0.87	1.141	0.765	0.028	-0.677	0.997	22111	-101	2
29.0.173	11.00	1.02	1.192	0.862	0.136	....	....	11100	..	.
29.0.193	12.19	1.02	1.116	0.925	0.013	....	....	11100	..	.
29.0.214	12.18	1.07	1.121	1.047	-0.024	....	....	11100	..	.
29.1.057	12.05	1.05	1.103	1.085	0.074	....	....	11100	..	.
29.1.074	12.92	0.70	1.045	0.668	-0.001	-0.724	0.919	44222	..	.
29.1.075	12.96	0.75	1.046	0.717	....	....	....	11000	..	.
29.1.079	12.84	0.96	1.177	0.754	0.021	-0.635	1.095	33111	-4	3
29.1.090	10.81	0.81	1.062	0.823	....	....	....	11000	..	.
29.1.106	10.90	0.71	1.065	0.705	-0.010	-0.751	0.920	22111	..	.
29.1.129	11.48	0.87	1.113	0.808	0.042	-0.519	0.947	22111	-11	1
29.1.136	12.82	0.92	1.143	0.826	0.032	-0.500	0.990	22111	2	1
29.2.005	11.90	1.02	1.173	0.815	0.046	....	....	11100	..	.
29.2.057	11.83	0.94	1.155	0.809	0.052	....	....	11100	..	.
29.2.065	12.77	0.75	1.104	0.631	0.035	-0.769	1.063	33222	-2	2
29.2.069	12.78	0.72	1.051	0.708	....	....	....	11000	..	.
29.2.104	12.77	0.74	1.049	0.694	....	....	....	11000	..	.
29.2.105	11.81	1.02	1.177	0.890	0.126	....	....	11100	..	.
29.2.107	12.94	0.76	1.052	0.709	....	....	....	11000	..	.
29.2.111	10.37	0.73	1.038	0.700	....	....	....	22000	..	.
29.2.115	12.56	0.72	1.048	0.704	0.043	....	....	11100	..	.
29.2.121	10.98	0.97	1.155	0.854	0.132	-0.382	0.998	22111	-2	2
29.2.137	12.71	0.76	1.053	0.755	....	....	....	11000	..	.
29.2.144	12.87	0.89	1.100	0.896	....	....	....	11000	..	.
29.2.145	12.95	0.71	1.043	0.706	....	....	....	11000	..	.
29.2.154	10.94	0.86	1.081	0.831	....	....	....	11000	..	.
29.2.166	12.97	0.82	1.057	0.746	....	....	....	11000	..	.
29.2.170	11.75	0.70	1.026	0.673	....	....	....	22000	..	.
29.2.179	12.06	0.96	1.113	0.999	....	....	....	11000	..	.
29.2.220	8.96	0.94	1.123	0.844	0.070	-0.522	0.983	22111	..	.
29.3.012	11.93	0.72	1.065	0.691	-0.005	-0.782	0.915	44222	..	.
29.3.019	10.57	0.85	1.110	0.821	0.044	-0.522	0.929	22111	..	.
29.3.048	11.59	0.71	1.050	0.707	....	....	....	22000	..	.
29.3.052	11.67	0.90	1.151	0.760	0.047	-0.567	1.014	22111	30	3
29.3.066	12.76	0.94	1.137	0.815	0.041	-0.498	0.929	22111	12	1
29.3.076	10.82	0.94	1.145	0.808	0.059	-0.533	0.951	22111	32	3
29.3.081	12.52	1.09	1.113	1.122	0.006	....	....	11100	..	.
29.3.083	12.72	0.72	1.045	0.710	....	....	....	11000	..	.
29.3.087	9.51	0.91	1.118	0.303	0.053	-0.551	0.931	33111	-21	1
29.3.088	12.62	0.91	1.100	0.930	....	....	....	11000	..	.
29.3.099	12.51	0.98	1.165	0.819	0.065	-0.469	0.999	22111	49	1
29.3.154	11.70	0.77	1.061	0.738	0.001	-0.656	0.886	22111	..	.
29.3.157	12.77	0.98	1.105	1.012	....	....	....	11000	..	.
29.4.020	12.27	0.95	1.148	0.834	0.073	-0.450	0.994	22111	-17	1
29.4.022	12.90	0.72	1.086	0.740	0.011	-0.682	0.918	22111	..	.
29.4.025	10.44	1.06	1.204	0.946	0.240	....	....	11100	..	.
29.4.039	12.95	0.81	1.069	0.766	....	....	....	11000	..	.
29.4.045	11.76	0.74	1.069	0.790	....	....	....	11000	..	.
29.4.057	12.02	0.81	1.077	0.861	....	....	....	11000	..	.
29.4.076	10.82	0.84	1.100	0.805	0.022	-0.563	0.917	22111	..	.
29.4.090	11.54	0.85	1.101	0.848	0.037	-0.495	0.879	11111	..	.
29.4.132	12.28	0.95	1.199	0.826	0.034	-0.466	0.973	11111	56	1
29.4.146	11.46	0.77	1.074	0.742	0.065	....	....	11100	..	.
29.4.148	6.29	0.94	1.159	0.809	0.078	....	....	Hart[c]	..	.
29.4.170	12.40	0.75	1.019	0.676	0.048	-0.619	0.925	11111	..	.
29.4.179	11.99	0.75	1.023	0.686	....	....	....	22000	..	.
29.4.207	12.11	0.91	1.068	0.942	-0.004	-0.509	0.886	11111	..	.
29.4.223	9.71	1.08	1.200	0.921	0.193	....	....	11100	..	.
29.5.008	12.94	0.89	1.078	0.844	....	....	....	11000	..	.
29.5.015	11.62	1.07	1.223	0.941	0.081	....	....	11100	..	.
29.5.018	12.18	0.70	1.085	0.672	0.010	-0.854	0.853	44333	251	1
29.5.055	10.93	1.06	1.182	0.931	0.194	....	....	11100	..	.
29.5.064	11.14	1.03	1.177	0.886	0.116	....	....	11100	..	.
29.5.076	12.30	0.72	1.098	0.630	0.027	-0.770	1.033	11111	4	2
29.5.137	12.70	1.07	1.191	0.933	0.177	....	....	11100	..	.
29.5.139	12.48	0.70	1.043	0.709	0.021	-0.671	0.943	11111	..	.
29.5.141	11.53	0.90	1.106	0.818	....	....	....	11000	..	.
29.5.173	11.92	0.70	1.009	0.655	....	....	....	11000	..	.
29.5.194	12.61	0.77	1.033	0.699	....	....	....	11000	..	.
29.5.198	12.35	0.83	1.064	0.801	....	....	....	11000	..	.
29.5.209	11.81	1.03	1.174	0.871	0.125	....	....	11100	..	.
29.5.252	12.98	1.01	1.086	0.878	0.000	....	....	11100	..	.
30.0.013	11.75	1.00	1.178	0.890	0.126	-0.349	1.045	22111	41	2
30.0.019	11.81	0.97	1.155	0.825	0.067	-0.489	1.055	22111	29	2
30.0.044	12.70	1.06	1.195	0.890	0.100	....	....	11100	..	.
30.0.055	11.65	0.74	1.035	0.733	....	....	....	11000	..	.
30.0.068	12.78	0.70	1.041	0.732	....	....	....	11000	..	.
30.0.071	10.34	1.01	1.184	0.860	0.182	....	....	11100	..	.
30.0.090	12.84	0.70	1.038	0.693	....	....	....	11000	..	.
30.0.120	12.13	0.98	1.157	0.879	0.098	-0.357	0.999	22111	42	1
30.0.151	12.77	0.72	1.046	0.670	....	....	....	11000	..	.
30.0.181	11.22	0.97	1.092	0.946	....	....	....	11000	..	.
30.0.203	12.45	0.90	1.155	0.774	0.058	-0.547	1.061	22111	31	1
30.0.214	12.25	0.89	1.096	0.884	....	....	....	11000	..	.
30.0.228	10.37	1.01	1.169	0.851	0.092	....	....	11100	..	.
30.1.023	11.81	0.81	1.063	0.775	....	....	....	11000	..	.
30.1.080	12.70	0.99	1.186	0.874	0.072	-0.385	1.044	22111	105	2
30.1.088	12.54	0.76	1.085	0.806	....	....	....	11000	..	.
30.1.092	9.88	0.89	1.137	0.753	0.035	-0.614	1.012	22111	45	2
30.1.094	11.64	0.85	1.126	0.750	0.030	-0.651	1.012	22111	39	2
30.1.095	12.49	0.77	1.066	0.743	....	....	....	11000	..	.

TABLE 1—*Continued*

Star (1)	V^a (2)	$B-V^a$ (3)	C4548 (4)	C4245 (5)	C4142 (6)	C3842 (7)	C3538 (8)	n^b (9)	v_r (10)	n (11)
30.1.100	12.84	0.78	1.036	0.757	....	....	....	11000	..	.
30.1.103	12.29	0.76	1.050	0.752	....	....	....	11000	..	.
30.1.128	9.34	0.90	1.119	0.785	0.133	-0.472	0.986	22111	..	.
30.1.142	12.93	0.94	1.093	0.899	....	....	....	11000	..	.
30.1.143	12.42	0.98	1.112	0.847	0.087	-0.433	0.935	22111	..	.
30.1.145	12.79	1.03	1.188	0.866	0.146	....	....	11100	..	.
30.1.162	12.53	0.76	1.023	0.711	0.075	-0.601	0.933	11111	9	1
30.1.171	11.92	0.98	1.170	0.827	0.100	-0.420	1.024	22111	5	1
30.1.193	12.75	0.74	1.043	0.694	....	....	....	11000	..	.
30.2.015	11.65	0.71	1.040	0.698	....	....	....	44000	..	.
30.2.024	11.58	1.00	1.177	0.853	0.124	-0.394	1.030	22111	-16	1
30.2.057	11.80	0.99	1.095	0.995	....	....	....	11000	..	.
30.2.088	12.60	0.87	1.096	0.844	....	....	....	11000	..	.
30.2.107	11.66	0.72	1.034	0.682	....	....	....	22000	..	.
30.2.110	11.67	0.82	1.075	0.754	....	....	....	11000	..	.
30.2.156	12.64	0.98	1.111	0.951	0.183	-0.332	0.990	11111	..	.
30.2.173	11.83	1.07	1.149	0.927	0.240	....	....	11100	..	.
30.2.178	12.18	0.76	1.025	0.744	0.010	-0.662	0.867	11111	..	.
30.2.183	12.07	0.80	1.075	0.745	....	....	....	11000	..	.
30.3.008	10.21	1.09	1.245	0.985	0.304	....	....	11100	..	.
30.3.011	12.03	0.74	1.028	0.689	....	....	....	22000	..	.
30.3.029	11.81	0.72	1.056	0.722	....	....	....	22000	..	.
30.3.033	12.13	0.83	1.066	0.813	....	....	....	11000	..	.
30.3.038	12.44	0.82	1.078	0.860	....	....	....	11000	..	.
30.3.057	12.63	0.92	1.143	0.819	0.059	-0.485	1.008	22111	126	1
30.3.062	7.17	0.92	1.109	0.965	-0.003	....	....	Hart[c]	..	.
30.3.078	12.62	0.80	1.124	0.710	0.018	-0.690	1.037	33222	-42	2
30.3.088	12.99	0.85	1.088	0.885	-0.051	-0.594	0.840	11111	..	.
30.3.091	11.85	1.03	1.205	0.907	0.183	....	....	11100	..	.
30.3.128	9.21	1.07	1.204	0.918	0.188	....	....	11100	..	.
30.3.154	11.84	0.90	1.117	0.772	0.000	-0.614	0.886	33111	..	.
30.3.186	11.40	1.05	1.109	1.054	0.009	....	....	11100	..	.
30.4.003	12.65	0.71	1.038	0.699	0.059	-0.627	0.962	11111	..	.
30.4.016	11.56	0.96	1.159	0.796	0.073	-0.511	0.967	11111	26	2
30.4.050	12.13	0.75	1.069	0.728	0.021	-0.675	0.934	11111	..	.
30.4.051	12.69	0.85	1.086	0.837	0.083	-0.471	0.925	11111	..	.
30.4.114	11.71	0.73	1.054	0.708	0.017	-0.651	0.931	11111	..	.
30.4.190	12.64	1.10	1.168	0.924	0.165	....	....	11100	..	.
30.4.192	12.06	0.70	1.044	0.635	-0.004	-0.815	0.950	22111	..	.
30.4.203	12.45	0.70	1.066	0.681	-0.020	-0.819	0.869	33222	..	.
30.4.221	9.58	0.96	1.124	0.812	0.040	-0.546	0.942	22111	46	3
30.4.226	11.74	0.93	1.082	0.836	0.039	....	....	11100	..	.
30.5.004	9.45	0.94	1.149	0.829	0.175	-0.358	1.025	33222	11	1
30.5.026	10.07	0.75	1.052	0.773	-0.008	-0.672	0.852	11111	..	.
30.5.042	11.22	1.09	1.212	0.897	0.182	....	....	11100	..	.
30.5.045	12.12	0.95	1.109	1.036	0.048	-0.366	0.914	11111	..	.
30.5.084	12.52	0.99	1.188	0.853	0.050	-0.489	1.068	22222	-48	2
30.5.092	11.00	0.70	1.051	0.709	-0.011	....	....	11100	..	.
30.5.104	12.34	0.73	1.039	0.686	0.018	-0.653	0.898	11111	..	.
30.5.113	12.61	0.85	1.088	0.806	0.001	-0.583	0.890	11111	..	.
30.5.125	12.28	1.00	1.151	0.887	0.122	-0.339	0.996	11111	..	.
30.5.144	12.42	0.83	1.066	0.795	-0.012	-0.658	0.874	22222	..	.
30.5.169	12.63	0.85	1.087	0.757	0.004	-0.619	0.893	11111	..	.
30.5.189	11.99	0.70	1.021	0.666	0.002	-0.781	0.864	11111	..	.
30.5.194	11.43	1.09	1.192	0.927	0.171	....	....	11100	..	.
30.5.208	12.71	0.73	1.021	0.661	-0.005	-0.806	0.889	11111	..	.
30.5.223	11.87	0.70	1.047	0.703	....	....	....	11100	..	.

[a] From Eriksson 1978.

[b] Five-digit positional code giving number of observations for *C*(4548), *C*(4245), *C*(4142), *C*(3842), and *C*(3538), respectively.

[c] DDO data from Hartkopf 1981.

TABLE 2

BV, DDO PHOTOMETRY FOR RED HORIZONTAL BRANCH STARS IN 47 TUC AND NGC 6352

Star (1)	V^a (2)	$B-V^a$ (3)	C(4548) (4)	C(4245) (5)	C(4142) (6)	C(3842) (7)	C(3538) (8)	n^b (9)
A. 47 Tuc								
C16	14.00	0.80	1.123	0.626	0.125	−0.605	1.119	22222
C17	13.94	0.82	1.135	0.651	0.108	−0.556	1.126	22222
C18	14.06	0.87	1.144	0.721	0.056	−0.631	1.065	11111
C31	14.00	0.77	1.094	0.584	0.120	−0.587	1.155	11111
B. NGC 6352								
HH 149	15.26	1.01	1.212	0.717	...	...	...	22000
HH 150	15.20	1.13	1.206	0.755	...	...	...	22000
HH 154	15.15	1.02	1.179	0.670	...	...	...	22000
HH 155	15.27	1.16	1.234	0.868	...	...	...	22000
HH 160	15.23	1.07	1.262	0.706	...	...	...	22000

[a] From Cannon 1974 and Hartwick and Hesser 1972 for 47 Tuc and NGC 6352, respectively.

[b] Five-digit positional code giving number of observations for C(4548), C(4245), C(4142), C(3842), and C(3538), respectively.

described above. Our data are given in Table 2B. From the repeated measures we estimate an internal accuracy of 0.01 and 0.03 for C(4548) and C(4245), respectively. It should be appreciated that NGC 6352 is a much more difficult object to observe than is 47 Tuc, because of the crowded nature of the field. Our observations were made through apertures of diameter 7″–10″ and probably suffer to some extent from cluster contamination problems. The cluster is also appreciably reddened, having $E(B-V) = 0.24$–0.32 (Hartwick and Hesser 1972; Zinn 1985). We have no doubt that these observations are not of the same caliber as the other data presented in this paper.

Finally, as a check on the Eriksson V, $B-V$ values (which were used not only in defining the limits of our sample but also in the discussion of color distribution in § IV), we observed 18 of the stars in Table 1 in the BV system with the 1 m telescope on Siding Spring Mountain. The mean difference for both V and $B-V$ (in the sense present work *minus* Eriksson) was found to be −0.02, with the dispersion of the differences being 0.04 and 0.03, respectively. We are confident, therefore, that the Eriksson data are quite adequate for the purposes of the present work.

c) Radial Velocities

For the giants in the sample (as determined in § III*a*) that have $B-V \leq 1.0$, radial velocities were obtained in 1986 November–December with the 1.9 m telescope at Mount Stromlo. Two data sets were obtained, the first with the Cassegrain and the second with the coudé spectrograph. Stars of known velocity were also observed. Both sets employed a blue-sensitive photon-counting array (Stapinski, Rodgers, and Ellis 1979) as detector and covered (approximately) the wavelength range 3800–4200 Å. Cross-correlation techniques following Da Costa *et al.* (1977) were used to determine radial velocities, which are given, together with the number of observations, in columns (10) and (11) of Table 1. The standard deviation of a single observation is estimated to be 7 km s^{-1}.

III. ANALYSIS

a) Selection of Sample Giants

The DDO [C(4548), C(4245)]-plane provides a powerful means of discriminating between giants and dwarfs, being essentially a (log g, $T_{\rm eff}$)-diagram for late-type stars (see McClure 1979). Figure 2*a* presents data for all stars in the *Bright Star Catalogue* (Hoffleit and Jaschek 1982, hereafter BSC) having $0.70 \leq B-V \leq 1.10$ and for which McClure and Forrester (1981) give DDO photometry. The Population I luminosity class III and V loci from their Table 1 are also superposed (*solid lines*), together with the locus of stars having $M_V = 2$ and solar abundance (*dashed line*) from the work of Janes (1975). (Stars more luminous than $M_V = 2$ fall above the latter line.) Note the strong concentration of class III objects (giants) in the diagram.

Our data for the Eriksson stars are shown in Figure 2*b*. Here the relative numbers of giants and dwarfs have changed from that seen in Figure 2*a*—a result of the fact that in our much fainter, magnitude-limited sample one quickly runs out of disk giants as one looks farther from the Galactic plane, relative to disk dwarfs, which one still sees closer to the plane. Two sets of symbols are employed in Figures 2*a* and 2*b*, depending on luminosity. Filled symbols are used to denote giants and represent the stars for which full DDO photometry was obtained in the present investigation. Open symbols are used for the subgiants and dwarfs. As noted above, complete DDO data were obtained for only a subgroup of the latter stars. We comment, for completeness, that the reddening at the SGP is small, and of order 0.02 ± 0.02 (Philip 1974; Rodgers, Harding, and Sadler 1981; McFadzean, Hilditch, and Hill 1983), and that we adopt $E(B-V) = 0.0$. See § IV*b* for further discussion of this point.

Finally, the data for the 47 Tuc RHB stars (*filled squares*, from Table 2) and the two field RHB stars HD 79452 and Coma A14 (Rose 1985; *filled diamonds*, from Paper IV) are presented in Figure 2*c*. Also shown are the positions of the clump stars in the old (~5 Gyr), metal-poor ([Fe/H] ~ −0.5) open clusters NGC 2243 (*open triangles*, from Paper IV) and NGC 2420 (*open circles*, from McClure, Forrester, and Gibson 1974), the clump stars in M67 (*asterisks*, from Janes and Smith 1984), and the Rose RHB candidates (*filled triangles*, from Paper IV). [Reddening corrections corresponding to $E(B-V) = 0.04, 0.05, 0.02, 0.05$, and 0.00 have been applied to the data for 47 Tuc (following Zinn 1985), NGC 2243 (Janes 1979), NGC 2420 (McClure, Forrester, and Gibson 1974), M67 (Janes 1979), and the Rose RHB candidates (see Paper IV), respectively. The field RHB stars have been assumed to be unreddened.] The box surrounding the RHB stars in this

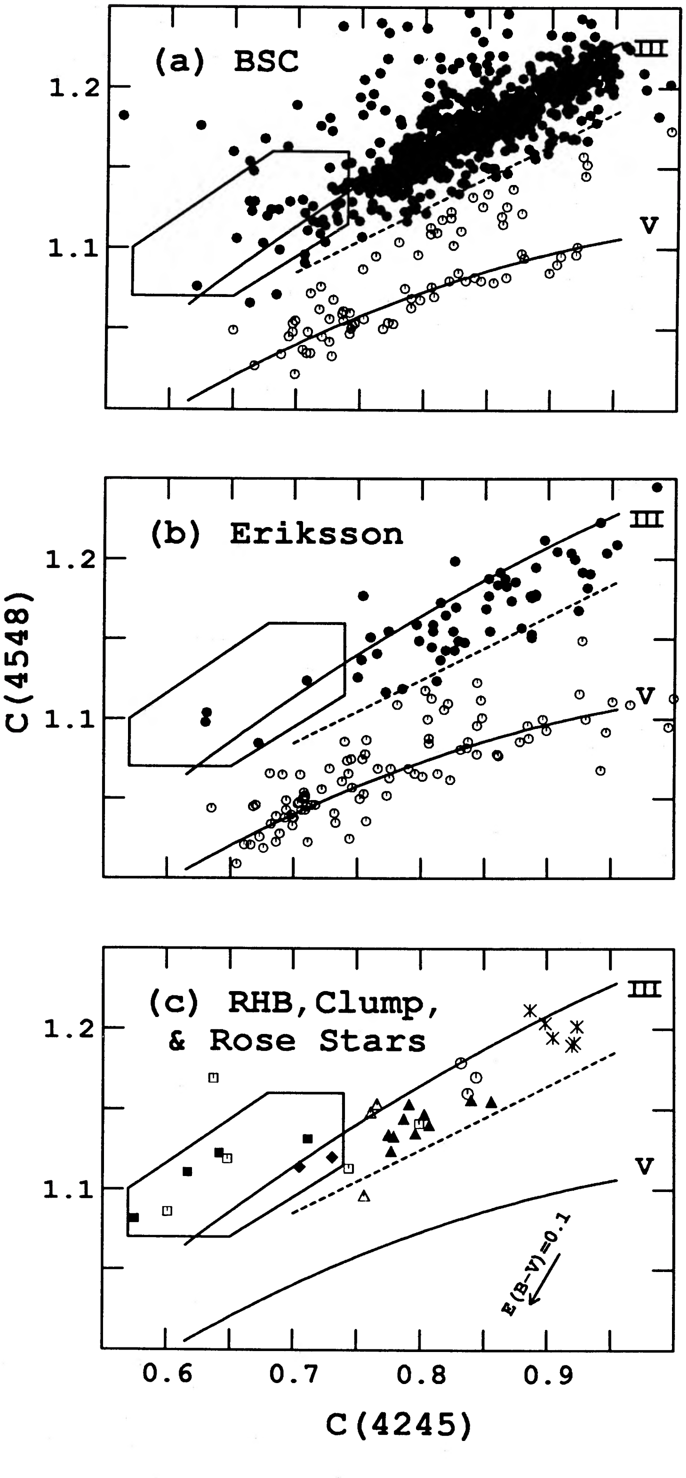

FIG. 2.—The [$C(4548)$, $C(4245)$]-diagram for (*a*) objects in the *Bright Star Catalogue* having $0.7 \leq B-V \leq 1.1$ and DDO photometry from McClure and Forrester (1981), (*b*) the Eriksson sample from Table 1, and (*c*) RHB stars in 47 Tuc (*filled squares*), NGC 6352 (*open squares*), field RHB stars (*diamonds*), clump stars in NGC 2243 (*open triangles*), NGC 2420 (*open circles*), and M67 (*asterisks*), and Rose EHB candidates (*filled triangles*). The continuous lines are the Population I luminosity class III and V loci from McClure and Forrester, while the dashed line is the boundary along which $M_V = +2$. In (*a*) and (*b*) filled and open circles are used to denote giants and less luminous objects, respectively, for future reference. The boxes in the diagram are adopted as the region occupied by 47 Tuc–like RHB stars. In the bottom panel the dereddening trajectory for $E(B-V) = 0.10$ is also shown.

diagram will be adopted in what follows to delineate the region occupied by the RHB stars of the 47 Tuc–like component of the disk globular cluster population. This box has also been superposed on Figures 2*a* and 2*b*.

We also show as open squares in Figure 2*c* the positions for the RHB stars in NGC 6352, which were obtained after the above definition of the RHB region had been made. Reddening corrections corresponding to $E(B-V) = 0.28$, the average of the values given by Hartwick and Hesser (1972) and Zinn (1985), have been applied to the data. Four of the five stars lie in or very close to the RHB region. The fifth, HH 155, lies somewhat redder, at C_0 (4245) = 0.81. [It is perhaps worth noting that the reddening one determines for HH 155 using the data of Table 2B and the technique of Janes 1977 is $E(B-V) = 0.16$, suggesting perhaps that all is not in order with either the photometry or the cluster membership of this star. For HH 150, the only other star inside the Janes calibration, one finds the more reasonable value of $E(B-V) = 0.27$.] We make two points from these data. First, the bulk of the RHB of NGC 6352 falls within the region defined by 47 Tuc, and, as far as the blue end of the RHB is concerned, occupies the same region as that of 47 Tuc. The second point is that radial velocities should be obtained for all of these stars to investigate the not unlikely possibility that some are not members of the cluster.

Examination of Figure 2 then yields the basic observational results of this paper. First, comparison of Figures 2*b* and 2*c* shows that a large number of the giants in the Eriksson sample have an effective temperature–surface gravity distribution similar to that of the Rose RHB candidates, and more like that of the clump stars in the old open clusters NGC 2243 and NGC 2420 than that of the RHB stars in 47 Tuc. Second, and more important, one sees that among the (unbiased) Eriksson sample of giants there are at most four stars which belong to a 47 Tuc–like RHB population, compared with the much larger number of cooler objects, which are presumably clump and first-ascent red giant branch stars, in roughly equal numbers, of either a younger and/or a more metal-rich population. As we shall see in the following paragraph, one of the four possible hot RHB stars (29.5.018) is actually a metal-poor dwarf of the halo population, to which the present calibrations do not apply. The relative rarity of hot RHB stars among the Eriksson sample immediately leads us to doubt the correctness of the Rose (1985) hypothesis—that there exists a large proportion of metal-poor giants in the Upgren catalog which are the field counterparts of the RHB of the disk globular cluster population. We shall return to examine this point in § IV*b*, when we have determined abundances for the Eriksson giants.

The [$C(3538)$, $C(4245)$]-plane is also useful in discriminating between giants and dwarfs. The data for the BSC and Eriksson samples, in the color range $0.7 \leq B-V \leq 1.0$, are shown in Figures 3*a* and 3*b*, where the same notations as in Figure 2 have been adopted. [Note that we have restricted the color range because no $C(3538)$ measurements were made for Eriksson stars with $B-V > 1.0$.] As before, the filled and open circles refer to giants and objects with $M_V > 2$, respectively. With only two exceptions, the dwarf/giant separation of Figure 2 is maintained for the Eriksson stars. The discrepant stars are 29.5.018 and 30.3.154. The first of these has a radial velocity of 251 km s^{-1} and is therefore almost certainly a halo object to which the giant/dwarf calibrations of Figures 2 and 3 do not apply. Its DDO colors are similar to those of the metal-deficient dwarf BD −14°363 (see Paper I). Slight extrapolation

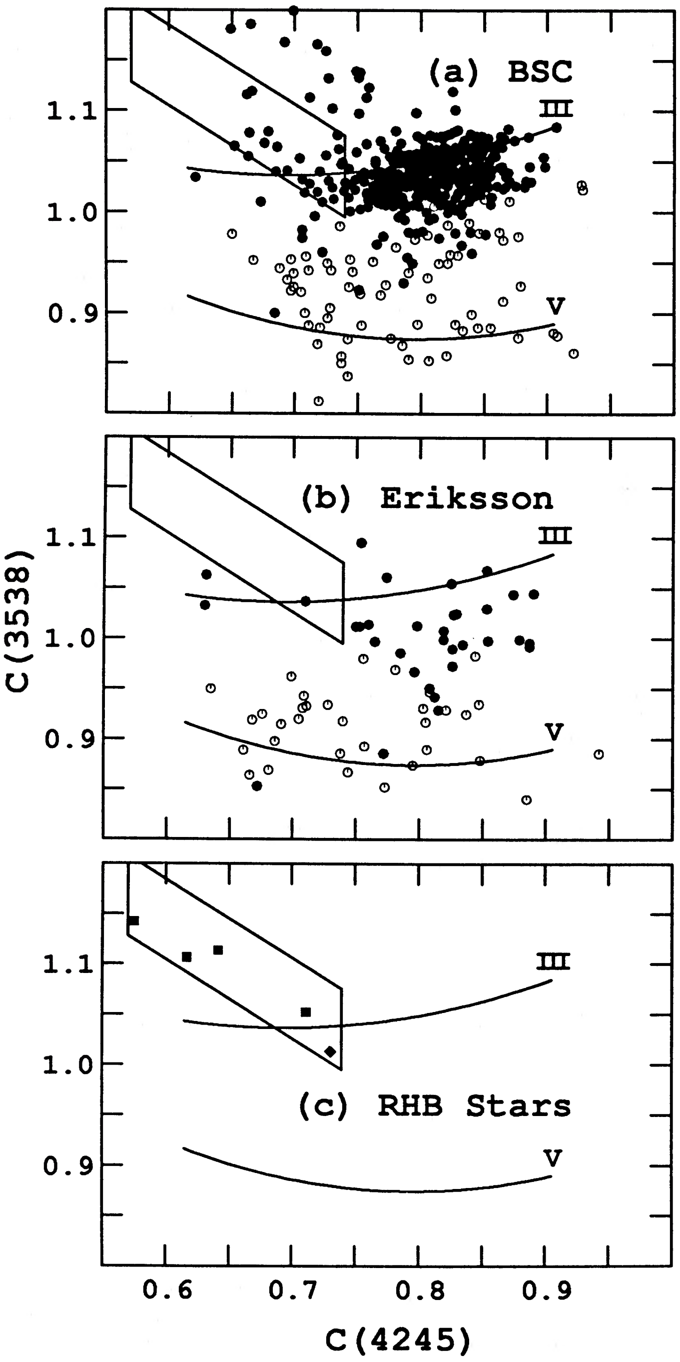

FIG. 3.—The [$C(3538)$, $C(4245)$]-diagram for the same groups of stars as are shown in Fig. 2, and for which data are available. No data are plotted in this diagram for stars with $B-V > 1.0$. The curves are similar to those described in Fig. 2. As with Fig. 2, this is also a (gravity, $T_{\rm eff}$)-diagram. Note that in the large majority of cases in (*a*) and (*b*) the giants (*filled circles*) are still separated from the nongiants (*open circles*) as defined in Fig. 1.

of the calibration of DDO indices in Paper I yields an abundance of [Fe/H] ~ -1.0 for the Eriksson star. The cause of the discrepancy for 30.3.154 is not understood. A possible explanation is that it is a metal-deficient subgiant, to which the Population I calibrations again do not apply.

b) Absolute Magnitudes and Abundances for Sample Giants

The data of Table 1 have been analyzed using the precepts of Janes (1975, 1977, 1979) and Paper IV to determine absolute magnitudes and abundances for the disk giants (or, more correctly, giants with [Fe/H] ≥ -0.8) in the sample. As noted in the previous section, we have assumed that there is negligible reddening toward the SGP. (We mention here for completeness that application of the Janes techniques yields $\langle E(B-V) \rangle = 0.00 \pm 0.004$ for the 52 giants having $C(4245) > 0.74$ and lying within the calibrated regions.) Two stars in the sample (29.1.079 and 29.4.132) appear to be giants of the halo population, and for these we have used the techniques of Paper I (§§ IV and V). The results of the analysis are given in Table 3, where columns (1)–(5) contain the identification, absolute magnitude, distance (in pc), DDO cyanogen excess δCN, and [Fe/H], respectively. We adopt the relation [Fe/H] $= 4.5\delta\text{CN} - 0.13$, following McClure (1979), between the cyanogen excess δCN and [Fe/H]. For completeness we comment that the three giants in Table 3 bluer than $C(4245) = 0.74$ (29.2.065, 29.5.076, and 30.3.078) are *assumed* to be RHB stars (see Figs. 2 and 3). These objects are hotter than may be handled by the Janes techniques, and are treated as in Paper IV, where one adopts $M_V = 1.0$.

The reader may question the validity of adopting the (δCN, [Fe/H])-relationship as a reliable indication of heavy-element abundance for objects at the low-abundance end of our sample (viz., [Fe/H] $= -0.4$ to -0.8). We have addressed this question by applying the above techniques to the sample of metal-poor disk giants which have been the subject of high-dispersion fine analysis by Cottrell and Sneden (1986), and for which McClure and Forrester (1981) give DDO photometry. The results are shown in Figure 4, which compares the DDO abundances with those of Cottrell and Sneden (*filled circles*). For heuristic purposes we also show the results for the (roughly solar abundance) giants from Table 1 of Lambert and Ries (1981) as open circles. (Note that in both cases we consider only stars having $0.7 < B-V < 1.1$.) The agreement between spectroscopic and photometric results is excellent and suggests that the abundances presented in Table 3 are accurate at the 0.2 dex level. We may conclude also that at this abundance resolution the field stars are free from the cyanogen variations which occur in globular clusters. For comparison we note that in 47 Tuc there is a a range in the $C(4142)$ index of order 0.2–0.3 at the luminosities that concern us (see Norris and Freeman 1979, Fig. 1), which, with the Janes calibration, corresponds to Δ[Fe/H] = 0.9–1.2 dex.

IV. INFERENCES CONCERNING THE GALACTIC DISK

a) Comparison of the Rose RHB Candidates with the Eriksson Giants

The Rose RHB candidates are situated roughly 1 kpc from the Galactic plane and have $\langle B-V \rangle \sim 0.9$, $\langle[\text{Fe/H}]\rangle \sim -0.5$, and a velocity dispersion $\sigma_z = 40$ km s^{-1} (Rose 1985; Paper IV). For the Eriksson giants between 500 and 1500 pc from the plane the data from Tables 1 and 2 yield $\langle B-V \rangle = 0.92$, $\langle[\text{Fe/H}]\rangle = -0.43$, and $\sigma_z = 41 \pm 8$ km s^{-1}. The data are consistent with the view that both samples are drawn from the same population.

b) Color Distribution of the Eriksson Giants: RHB or Clump Stars?

Figures 5*a*–5*c* show the $(B-V)_0$ histograms from Paper IV of the RHB stars in 47 Tuc ([Fe/H] $= -0.7$, age 14 Gyr), the clump stars in the old, metal-poor open clusters NGC 2243 and Melotte 66 ([Fe/H] $= -0.6$, ages $\sim$5–7 Gyr), and the Rose RHB candidates ([Fe/H] $= -0.5$), respectively. As noted

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TABLE 3

ABSOLUTE MAGNITUDES, DISTANCES, AND ABUNDANCES FOR ERIKSSON GIANTS

Name (1)	M_V (2)	Distance (3)	δCN (4)	[Fe/H] (5)
29.0.006.........	0.52	2779	−0.109	−0.62
29.0.034.........	1.17	1867	−0.088	−0.53
29.0.047.........	2.32	950	−0.021	−0.22
29.0.049.........	1.30	1836	−0.066	−0.43
29.0.069.........	0.88	1706	−0.128	−0.71
29.0.133.........	2.27	721	−0.013	−0.19
29.0.138.........	0.35	641	−0.124	−0.69
29.0.173.........	0.02	1567	−0.076	−0.47
29.1.079.........	−0.55	4757	...	−1.72
29.1.129.........	2.58	601	−0.048	−0.35
29.1.136.........	1.58	1768	−0.104	−0.60
29.2.005.........	−0.11	2523	−0.146	−0.79
29.2.057.........	0.74	1655	−0.110	−0.63
29.2.065.........	1.00	2259	−0.051	−0.36
29.2.105.........	1.32	1253	−0.054	−0.37
29.2.121.........	1.48	794	−0.017	−0.21
29.2.220.........	2.76	173	−0.025	−0.24
29.3.052.........	−0.41	2606	−0.124	−0.69
29.3.066.........	1.70	1629	−0.088	−0.53
29.3.076.........	1.22	831	−0.086	−0.52
29.3.087.........	2.33	272	−0.048	−0.34
29.3.099.........	0.43	2606	−0.112	−0.63
29.4.020.........	1.47	1444	−0.069	−0.44
29.4.025.........	1.22	696	0.025	−0.02
29.4.132.........	0.00	2857	...	−1.22
29.4.148.........	0.53	141	−0.091	−0.54
29.4.223.........	1.02	547	−0.021	−0.22
29.5.015.........	0.50	1674	−0.166	−0.88
29.5.055.........	1.94	628	0.014	−0.07
29.5.064.........	1.24	954	−0.065	−0.42
29.5.076.........	1.00	1819	−0.059	−0.39
29.5.137.........	1.59	1667	−0.018	−0.21
29.5.209.........	1.02	1436	−0.054	−0.37
30.0.013.........	1.28	1241	−0.056	−0.38
30.0.019.........	1.00	1452	−0.090	−0.54
30.0.044.........	0.65	2570	−0.112	−0.63
30.0.071.........	0.34	999	−0.017	−0.21
30.0.120.........	1.99	1066	−0.048	−0.35
30.0.203.........	−0.34	3613	−0.116	−0.65
30.0.228.........	0.86	797	−0.083	−0.50
30.1.080.........	0.58	2654	−0.128	−0.70
30.1.092.........	0.29	827	−0.114	−0.64
30.1.094.........	0.90	1406	−0.102	−0.59
30.1.128.........	1.94	301	0.025	−0.02
30.1.154.........	0.30	3147	−0.059	−0.39
30.1.171.........	0.34	2070	−0.084	−0.51
30.2.024.........	0.51	1636	−0.065	−0.42
30.3.008.........	0.40	916	0.037	0.04
30.3.057.........	1.47	1708	−0.079	−0.49
30.3.078.........	1.00	2108	−0.103	−0.60
30.3.091.........	0.65	1733	−0.043	−0.32
30.3.128.........	0.82	476	−0.033	−0.28
30.4.016.........	0.20	1867	−0.100	−0.58
30.4.190.........	2.40	1114	0.009	−0.09
30.4.221.........	2.26	291	−0.068	−0.44
30.5.004.........	1.34	418	0.029	0.00
30.5.042.........	0.07	1695	−0.057	−0.39
30.5.084.........	−0.02	3215	−0.157	−0.84
30.5.125.........	2.40	946	−0.011	−0.18
30.5.194.........	1.46	986	−0.027	−0.25

in Paper IV, the Rose RHB candidates appear to have a distribution more like that of clump stars than that of the RHB of 47 Tuc. Figure 5*d* then presents the $B-V$ distribution of the Eriksson giants having $[Fe/H] \leq -0.4$ and $0 \leq M_V \leq 2$. Here, too, one sees that the distribution of the Eriksson stars is more like that of the clump stars than that of the RHB of 47 Tuc.

It should be noted that the Eriksson giant sample in Table 3 will include not only clump/RHB stars but also a number of objects on the giant branch, so that strictly speaking we should compare their distribution with that of a magnitude-limited sample of stars chosen from a 47 Tuc-like or an old, metal-poor open cluster population, rather than with pure RHB or clump samples. We have therefore performed Monte Carlo simulations based on the Revised Yale Isochrones of Green, Demarque, and King (1987) with parameters appropriate for such an exercise and have found no fundamental difference from the result seen in Figure 5.

The simulations are shown in Figure 6, where the left-hand panel (with $[Fe/H] = -0.6$, age = 14 Gyr) represents 47 Tuc, the middle panel presents the observational material for the Eriksson giants having $[Fe/H] \leq -0.3$, and the right-hand panel represents the old, metal-poor open clusters ($[Fe/H] = -0.6$, age = 7 Gyr). The Revised Yale Isochrones give luminosity functions for evolution up to the tip of the giant branch. We have assumed that the numbers of RHB stars and clump stars in the two simulations are both equal to 1.7 times the number of red giants brighter than $M_V = 1.15$ (following Lee 1977 for 47 Tuc), and set $M_V = 1.0$ for the core–helium-burning phase. We have adopted the observed $[(B-V)_0, M_V]$-relations of Hesser *et al.* (1987) for 47 Tuc and of Anthony-Twarog, Twarog, and McClure (1979) for Melotte 66 to associate $B-V$ values with the luminosity functions of the Revised Yale Isochrones. [With this procedure we may be sure that our simulated colors match those of the clusters in question, obviating the question of the appropriate $(T_{\mathrm{eff}}, B-V)$-calibration.] For the RHB of 47 Tuc we assume a flat color distribution between $B-V = 0.75$ and $B-V = 0.85$, while for the old open cluster we adopt a flat distribution with limits of 0.91 and 1.01. Finally, in producing Figures 6*a* and 6*c*, we have assumed Gaussian errors with dispersion 0.5 and 0.02 mag for M_V and $B-V$, respectively, which are appropriate to the present investigation. In the table the histograms include the stars in the rectangular boxes superposed on the lower panels.[2]

We believe that the old open cluster simulation better represents the observations; the correspondence could readily be improved by incorporating a realistic abundance spread into the simulation.

The reader might object that the RHB of 47 Tuc may not be typical of that of the disk globular cluster population. For $[Fe/H] = -0.5$ (the mean abundance found for the Eriksson giants with $z > 1$ kpc) we believe that 47 Tuc is indeed representative. Among the disk globular clusters (see Zinn 1985, Table 1) there are some three objects with $[Fe/H] \sim -0.5$, $E(B-V) \leq 0.30$ and for which well-defined color-magnitude diagrams exist, extending below the level of the horizontal branch. These are NGC 6352 (Hartwick and Hesser 1972 and Nemec, Hesser, and Ugarte 1981; $[Fe/H] = -0.51$), NGC 6624 (Liller and Liller 1976 and Liller and Carney 1978; $[Fe/H] = -0.35$), and NGC 6838 (see Cudworth; $[Fe/H] = -0.58$). All clusters show a well-defined RHB, extending

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[2] Each of the simulations contains the same number of stars within the rectangular boxes as for the observed Eriksson subsample. To address the question of possible small sample effects in the simulations, we produced (for each cluster) one run containing 900 stars and 10 runs of 42 stars. The results shown in Fig. 6 are for the small sample run having the histogram most closely resembling that of the large sample case.

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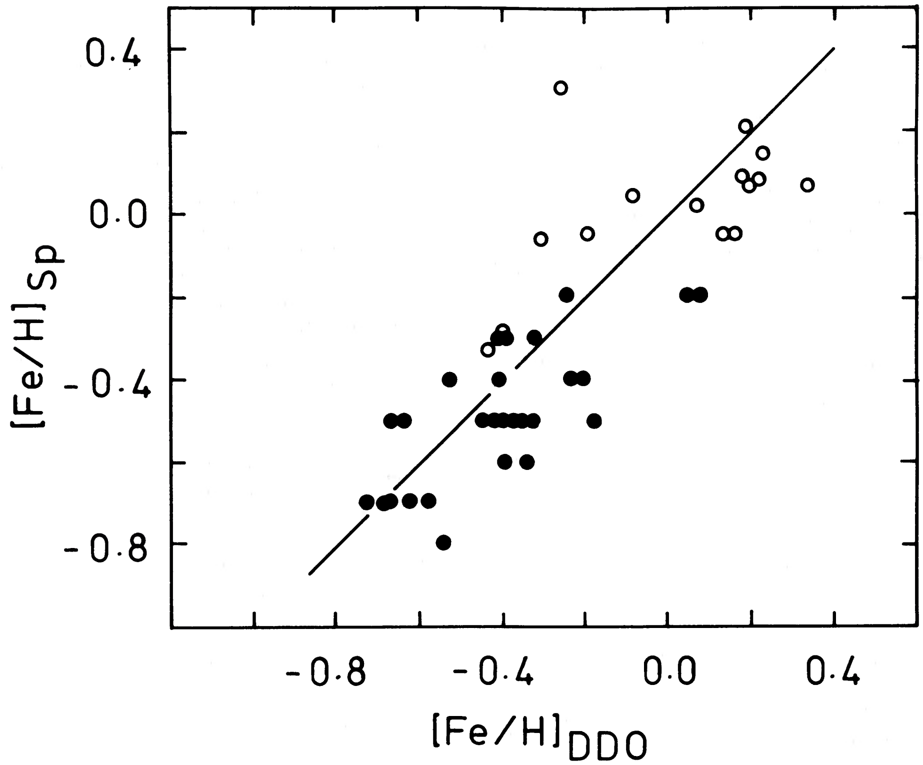

FIG. 4.—Comparison between high caliber spectroscopic values for [Fe/H] (from Cottrell and Sneden 1986 [*filled circles*] and Lambert and Ries 1981 [*open circles*]) and photometrically determined values based on the DDO colors of McClure and Forrester (1981) and the techniques adopted in the present work. (The line is the one-to-one relation.) The agreement is excellent and suggests that in the range $-0.8 < [Fe/H] < 0$ the abundances determined for the Eriksson stars should be accurate at the 0.2 dex level.

over approximately $0.7 \leq (B-V)_0 \leq 0.9$ and well separated from the giant branch, similar to what is seen in 47 Tuc. We would emphasize the case of NGC 6624 to the reader. Even though this cluster has $[Fe/H] = -0.35$ (a value found also in the newer and independent analysis of Armandroff and Zinn 1988), the data of Liller and Carney (1978) show that its RHB has $0.75 < (B-V)_0 < 0.85$—very similar to that of 47 Tuc.

The referee has suggested to us that we should also consider the case of NGC 5927 ($[Fe/H] = -0.30$, $E(B-V) = 0.45$; Zinn 1985), which he proposes to have an RHB covering the range $0.75 < (B-V)_0 < 1.00$ in the color-magnitude diagrams of Menzies (1974). We believe that it is not possible to reach any conclusion on this matter because of the variable reddening that Menzies reports across the cluster—which probably contributes to the giant branch having a width of $\Delta(B-V) = 0.15$–0.20 in these diagrams. If one agrees that the giant branches of globular clusters are intrinsically quite narrow, of order 0.02 mag as is found for all well-studied clusters except ω Cen and M22, this large spread must also be superposed on the RHB distribution. We would also suggest to the reader that in Figure 4 of Menzies (1974), which he regards as not suffering from differential reddening, one sees a reasonably well-defined RHB covering $1.15 < (B-V) < 1.35$, or $0.70 < (B-V)_0 < 0.90$. It would clearly be valuable to have a second color-magnitude diagram of this region.

Thus, from the DDO results, the $B-V$ histograms, and the simulations presented above, we conclude that the Rose RHB hypothesis is no longer tenable, and submit that his RHB candidates and a large proportion of the Eriksson giants observed here are counterparts of the clump stars in the old, metal-poor open clusters rather than belonging to the field counterpart of the RHB stars in the disk globular clusters.

c) Age of Disk Material More than 1 Kiloparsec from the Galactic Plane

No more than three (some 9%) of the 35 Eriksson giants having distances greater than 1000 pc from the Galactic plane are RHB stars. For a disk globular cluster–like population one would have expected the proportion to be ~50%. It seems reasonable to suggest that this relative absence of RHB stars from the sample places an important constraint on the age of the bulk of the so-called thick disk. The simplest explanation is to identify most of the observed sample giants with the population of old, metal-poor open clusters such as NGC 2420, NGC 2243, and Melotte 66, which have $[Fe/H] \sim -0.5$.

In Table 4 we compile recent age and metallicity estimates for these objects, and a number of other old open clusters. Columns (1)–(3) give identifications and metal abundances based on DDO and Washington photometry. Age estimates determined from comparison of observed color-magnitude diagrams with the isochrones of VandenBerg (1985) and the Revised Yale Isochrones are given in columns (4) and (5). Each column of the table presents results that have been determined in precisely the same manner, in keeping with our philosophy that differential results are more reliable than comparing numbers obtained from different systems. (We note that the ages in col. [4] [from VandenBerg 1985 and Christian, Heasley, and Janes 1985] were all determined assuming $Y = 0.25$.)

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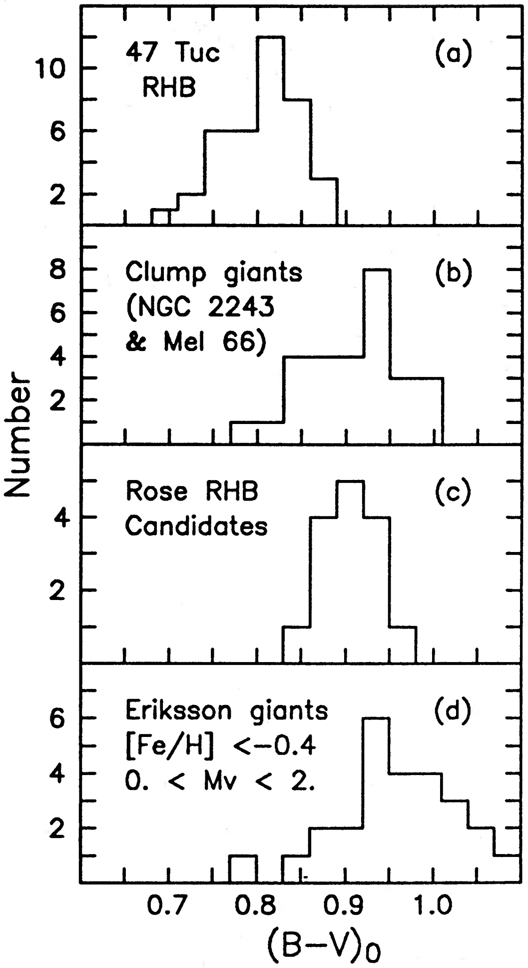

FIG. 5.—(*a–c*) $(B-V)_0$ histograms from Paper IV for (*a*) the RHB of 47 Tuc, (*b*) the clump stars in NGC 2243 and Melotte 66, and (*c*) the Rose RHB candidates. (*d*) Results of the present investigation for Eriksson giants with $0 < M_V < 2$ and $[\mathrm{Fe/H}] < -0.4$. Note that both the Eriksson giants and the Rose RHB candidates have a color distribution more like that of the clump stars in the old open clusters than that of the RHB of 47 Tuc.

TABLE 4

AGES FOR OLD OPEN CLUSTERS

NGC/Other (1)	[Fe/H]^a (DDO) (2)	[Fe/H]^b (Washington) (3)	Age (Gyr)^c (VandenBerg) (4)	Age (Gyr)^d (Revised Yale) (5)
188	−0.18	−0.05	10	6.5
2158	−0.64	−0.88	3	3
2243	−0.64	−0.93	...	5.5
Mel 66	−0.49	−0.35	...	6
2420	−0.44	−0.6	4	4.5
2506	−0.41	−0.46	...	3.5
M67	−0.05	−0.05	5	4

[a] From Janes 1979, except for M67 (Janes and Smith 1984).

[b] From Canterna *et al.* 1986 and Geisler 1987.

[c] From VandenBerg 1985, except for NGC 2158 (Christian, Heasley, and Janes 1985).

[d] From Green, Demarque, and King 1988.

One sees that the old, metal-poor open clusters have an age of 3–6 Gyr. The cluster 47 Tuc, on the other hand, has an age of 14 Gyr (Hesser *et al.* 1987, using VandenBerg isochrones) or 12–14 Gyr (Green, Demarque, and King 1988, using Revised Yale Isochrones). If one identifies the metal-poor Eriksson giants with the old, metal-poor open clusters, one concludes that they are younger than the disk globular cluster population by at least 6 Gyr. We emphasize that this estimate is insensitive to the set of isochrones one adopts. To reinforce the point, we show in Figure 7 age determinations for the four clusters 47 Tuc, NGC 2243, NGC 2420, and M67 (for which the colors of core–helium-burning stars were plotted in Fig. 2*c*) based on fitting published color-magnitude diagrams to the Revised Yale Isochrones. For this paper, we chose metallicities given by the average of columns (2)–(3) in Table 4, and reddenings from Janes (1979), and then adjusted the distance moduli for the best fits. The ages determined for these systems are about 13, 5.5, 4.5, and 4 Gyr, respectively, for the parameters given in the figure. While we cannot emphasize strongly enough that any reasonable variations of [Fe/H], Y, $E(B-V)$, and other parameters will usually result in some sort of match to the isochrones for some distance modulus (and that this does not mean that a given combination of parameters is necessarily correct, on the strength of fit alone), all of the best fits for a given cluster result in ages that are the same to within 10%–15%.

It may be argued that the Eriksson giants do in fact have ages close to 14 Gyr, but have no counterparts in the old open cluster population of the Galaxy because any such cluster formed around this epoch would have been tidally disrupted, and that therefore the above identification is invalid. Such a criticism begs the question as to why the colors of the Eriksson giants are not as blue as the RHB stars in 47 Tuc.

A second very rough estimate of the age difference implied by the observations may be gleaned as follows. Figure 8 presents the dependence of the color of the zero-age horizontal-branch (ZAHB) models of Sweigart (1987) on stellar mass for the case $Y = 0.25$, $Z = 0.01$, where we have adopted the (T_{eff}, $B-V$)-relationship of Green *et al.* (1988) for $[\mathrm{Fe/H}] = -0.5$.[3] Inspection of the stellar evolution calculations of Sweigart (1987) shows that for parameters appropriate to 47 Tuc the red end of the horizontal branch corresponds to the ZAHB position, for which we adopt an observed value of $(B-V)_0 = 0.85$ (see Fig. 5). The mean color of Eriksson giants with $[\mathrm{Fe/H}] \leq -0.5$ is $(B-V)_0 = 0.96$, which (given the extremely small spread predicted by theory for the temperatures appropriate to this color) will approximate the ZAHB position for these objects. It may be argued, however, that some of the stars in the Eriksson sample are in fact slightly cooler red giants at the luminosity of the clump stars. To be conservative in our age-difference estimate, then, let us agree that the appropriate ZAHB position of the Eriksson giants with $[\mathrm{Fe/H}] = -0.5$ is $(B-V)_0 = 0.90$. That is, the difference in ZAHB position for the two groups is at least $\Delta(B-V) = 0.05$. Figure 8 then shows that the mass difference corresponding to this color difference is $\Delta M \sim 0.23\ M_\odot$. We would emphasize that this is an extremely model-dependent estimate; it is sensitive to (among others) the (T_{eff}, $B-V$)-transformation, the O/Fe ratio in these

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[3] We note that $[\mathrm{Fe/H}] = -0.5$ corresponds to $Z = 0.005$ for $Z_\odot = 0.017$. If, following Schuster and Nissen (1987), one adopts $\log Z = \log Z_\odot + 0.6[\mathrm{Fe/H}]$ (based on recent investigations of the [nonsolar] oxygen/iron ratio for $[\mathrm{Fe/H}] < 0$), one finds $Z = 0.009$, closer to the value used here.

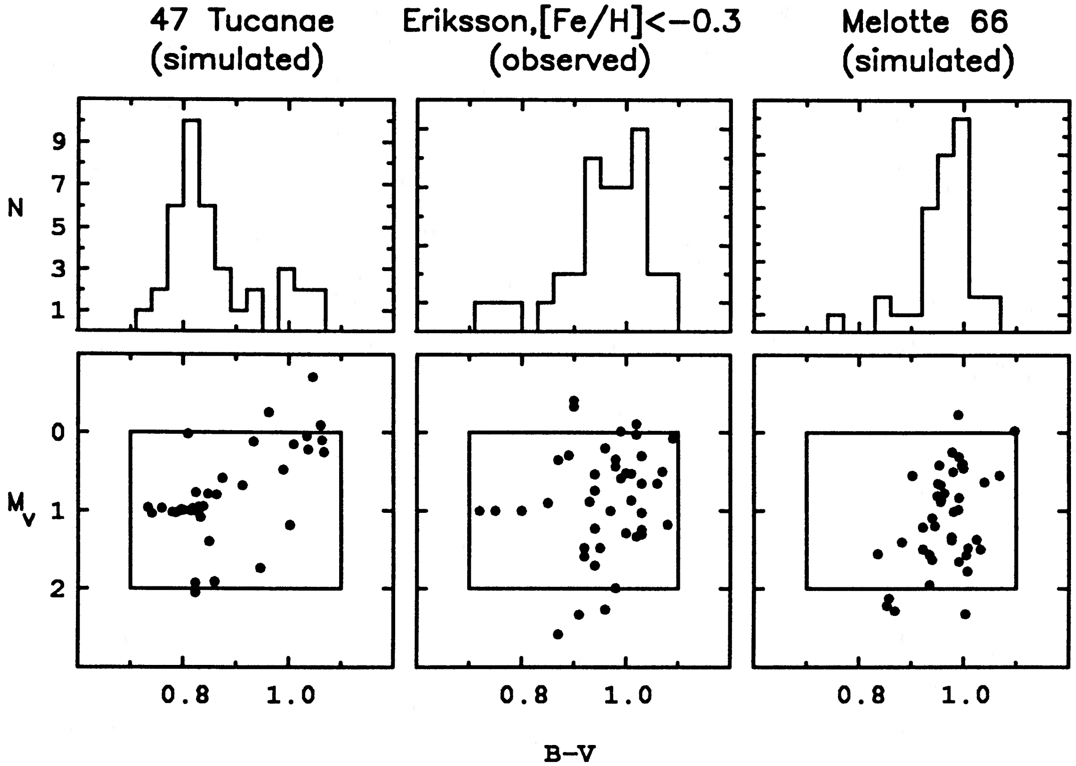

FIG. 6.—On the left is shown the color-magnitude diagram and $B-V$ histogram for a Monte Carlo simulation of a 47 Tuc–like population as described in the text. The simulation attempts to reproduce as closely as possible the observational situation pertaining to the present work in an effort to investigate the contamination effects of shell–hydrogen-burning red giants. The middle panel gives the results of the present investigation for Eriksson giants with $[Fe/H] < -0.3$. Finally, the right-hand panel presents the results of a Monte Carlo simulation for a Melotte 66–like population. The histograms refer to the region inside the boxes, which all contain the same number of stars. Note that the observations more closely resemble the Melotte 66 simulation than that representing 47 Tuc.

objects, and possible helium abundance differences. Given the steepness of the curve at lower masses in Figure 8, values of $\Delta M \sim 0.05\ M_\odot$ could also be possible. We therefore seek to estimate the age difference implied at the main-sequence turnoff by a mass difference 0.05–0.2 $M_\odot$. To proceed, of course, one needs to make assumptions about the relative mass losses between the two groups during their ascent of the RGB. We note that the stellar evolution calculations of Sweigart and Gross (1978) show that, for a given metal abundance, the luminosity of the helium flash is independent of age at the turnoff in the range of relevance here. If one were to assume that mass loss depended only on metal abundance and luminosity, it would follow that at least to first order the two groups have undergone similar degrees of mass loss. To proceed further, we make this assumption. Inspection of the isochrone data of Green, Demarque, and King (1987) shows that the inferred age difference is of order 3–8 Gyr.

In the light of the above discussion, we submit, then, that the bulk of the disk at $z = 1$–3 kpc is characterized by ages at least 3–6 Gyr younger than those of the globular clusters. It should be noted that this result may well be at odds with the suggestion of Sandage (1982) that the $\Delta S = 0$ RR Lyrae stars, which have disklike characteristics, are as old as the disk globular clusters. We make no comment on this matter. We would add, however, that we do not find compelling the suggestion of Sandage (1982, § III*b*) that there is a significant proportion of field giants in the solar neighborhood which are as old as 47 Tuc. From his Figure 2 one sees that for this cluster $(B-V)_{0,g} = 0.98$ and that the horizontal branch has $M_V = 1.1$. The reader will find that the argument turns on the implicit assumption that giants with this magnitude and color must be as old as 47 Tuc. Inspection of the schematic results for the clump stars in Melotte 66 (which has an age of 6–7 Gyr) in our Figure 1 shows that this is not necessarily so, hence invalidating his conclusions.

The referee has noted to us that Gilmore and Wyse (1987, § 8) have interpreted the results of Sandage and Fouts (1987) to infer that their halo and thick-disk stars are "approximately as old as the globular clusters." Further work is obviously needed to see just how close the approximate is.

d) *Evidence for a Young Galactic Disk* (*in the Solar Vicinity*)

In Paper V it was suggested that the Galactic disk (in the solar vicinity) comprises a number of abundance components in the range $-0.8 < [Fe/H] < 0.2$ with velocity dispersions which increase continuously with decreasing abundance and increasing age, and that the thick disk is merely the low-abundance, high velocity dispersion, greater scale height component of this disk. If the concept of a disk age-metallicity relationship is correct (see Twarog 1980; Carlberg *et al.* 1985; Nissen, Edvardsson, and Gustafsson 1985; Strömgren 1987), in which the stars of lowest abundance are the oldest, and one accepts the above submission on the age of the Eriksson giants having $[Fe/H] \sim -0.5$, it immediately follows that the entire Galactic disk at the distance of the Sun from the Galactic center is significantly younger than the disk globular cluster population.

There are two further independent results which are consistent with this view. First, Liebert *et al.* (1979) find a deficit of very low luminosity ($M_{\rm bol} \geq 16$) white dwarfs and conclude

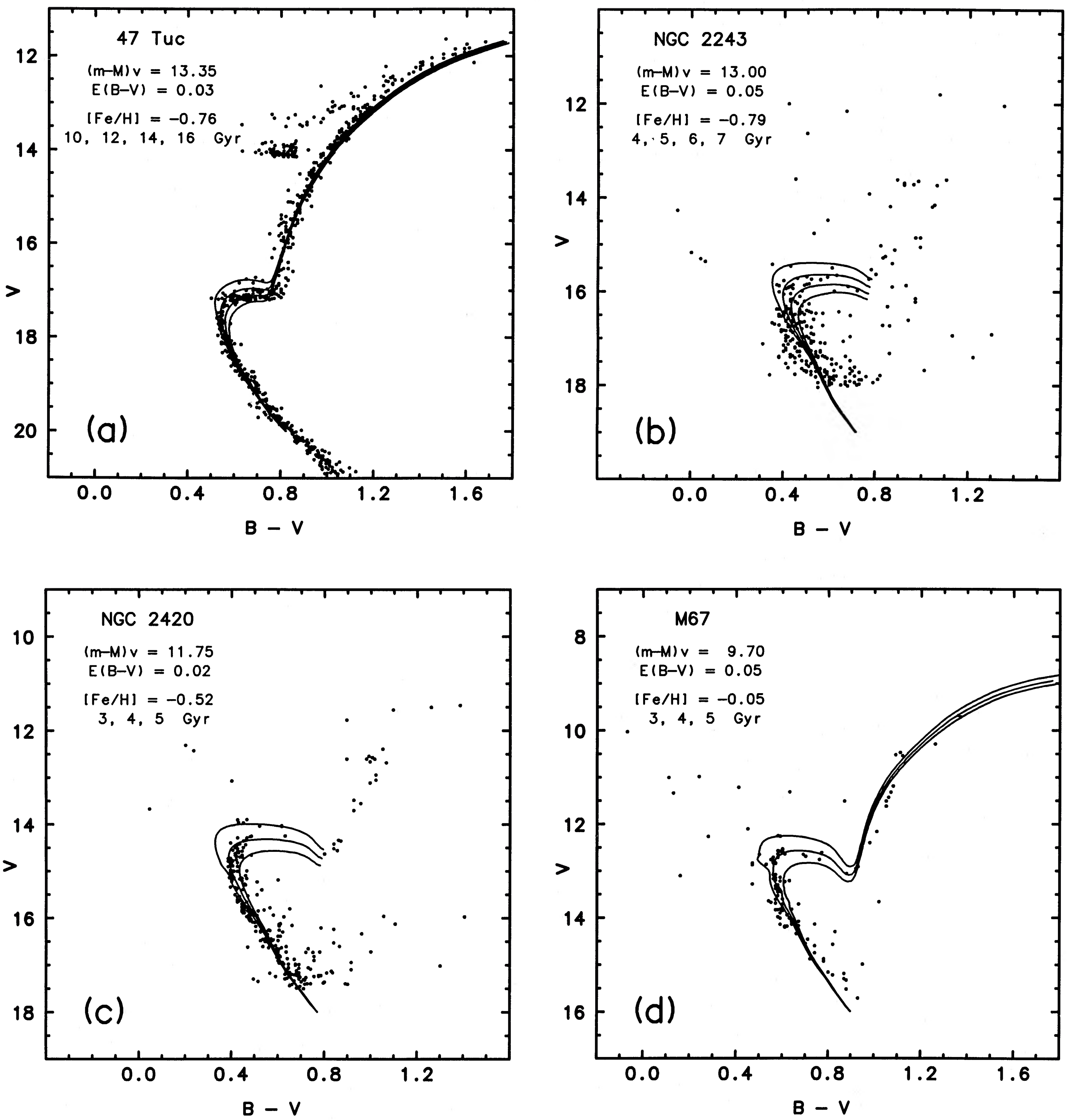

Figure 7.—Fits of the Revised Yale Isochrones to the color-magnitude diagrams of the clusters for which the colors of core–helium-burning stars were plotted in Fig. 2*c*. (*a*) 47 Tuc (data from Hesser *et al.* 1987), (*b*) NGC 2243 (van den Bergh 1977), (*c*) NGC 2420 (McClure, Newell, and Barnes 1978), and (*d*) M67 (Eggen and Sandage 1964).

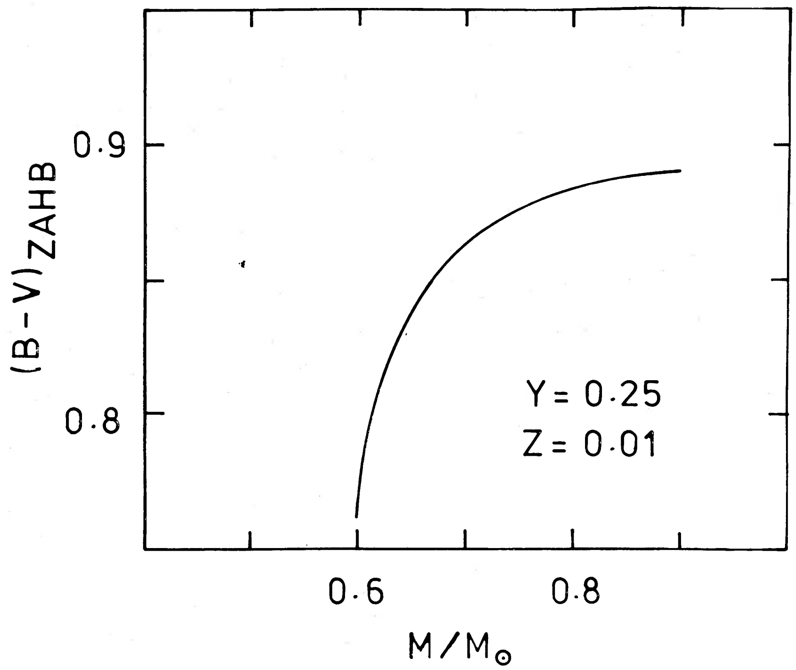

FIG. 8.—Dependence of $B-V$ on total mass for the zero-age horizontal-branch (ZAHB) models of Sweigart (1987) for $Y = 0.25$ and $Z = 0.01$

that "these results thus support the view that the stellar disk is effectively much younger than the currently accepted age of the halo." An age difference of ~5 Gyr is indicated. Second, in an analysis of stars having space velocities greater than 80 km s^{-1}, Schuster and Nissen (1987) find ages of 18 Gyr for objects with $[Fe/H] < -0.8$. For higher abundances, however, they report 9–12 Gyr, and conclude that "there seems to be a significant age difference between the metal-poor halo population and the old (thick?) disk population."

e) Abundance Gradient Perpendicular to the Galactic Plane

Figure 9*a* shows [Fe/H] as a function of distance z from the Galactic plane for the 58 Eriksson giants. (Note that the two halo giants have been excluded from the analysis.) Also shown in the diagram are error bars which result from errors of 0.010 in each of $C(4548)$, $C(4245)$, and $C(4142)$, treated independently. There appears to be a strong and well-defined abundance gradient, as has been reported by many other workers. We refer the reader to Hartkopf and Yoss (1982, hereafter HY) for a summary of earlier results.

In Table 5 we present the average dependence of metallicity on z, where the data have been binned in 500 pc intervals. Neglecting the error in z, the weighted linear least-squares fit to the material in the table is $\langle[Fe/H]\rangle = -0.16 - 0.19\,\langle z(\mathrm{kpc})\rangle$, where the errors in the zero point and gradient are 0.05 and 0.02, respectively. The linear correlation coefficient is −0.97.

TABLE 5

DEPENDENCE OF [Fe/H] ON DISTANCE z FROM THE GALACTIC PLANE

$\langle z\rangle$ (1)	$\langle[Fe/H]\rangle$ (2)	n (3)
296 ± 47	−0.27 ± 0.08	7
802 ± 68	−0.29 ± 0.05	16
1302 ± 48	−0.39 ± 0.06	8
1722 ± 138	−0.50 ± 0.06	15
2146 ± 65	−0.49 ± 0.08	3
2623 ± 41	−0.68 ± 0.03	6
3325 ± 159	−0.63 ± 0.15	3

It is instructive to compare the present results with those of the survey of the Galactic poles by HY, whose data are shown in Figure 9*b*. Here, too, one sees an abundance gradient (HY report $d[Fe/H]/dz = -0.18$ dex kpc^{-1} for their total sample), but one receives the impression of a much greater dispersion in abundance than that found in the present work. One also sees, in their diagram, stars with roughly solar abundance at 1.5–5 kpc from the Galactic plane, contrary to the present result.[4]

There are several possible explanations for the latter effect. One is that the difference is merely illusory, resulting from the much smaller sample size available in the present work. That is, had the sample been larger, we might perhaps have discovered some of these relatively rare objects. While in principle this may be a reasonable argument, we wish to suggest that much of the scatter seen in the HY data results from observational error. We note first that we claim a higher photometric accuracy for our DDO material (~0.010 mag) than that applicable to the survey of HY (up to 0.03; Hartkopf 1981, chap. 2, § D). We wish to emphasize as strongly as possible that the question of errors is critical to this issue. In Figure 9*b* we show how uncertainties of 0.02 mag in $C(4548)$, $C(4245)$, and $C(4142)$ (treated as independent) propagate into the ([Fe/H], z)-plane for the stars UP 26121 and BOK II-138, which HY find to have relatively high abundance and to lie well away from the Galactic plane. (Our values of [Fe/H] and z differ slightly from those of HY because of slight differences in the formalisms of absolute magnitude and abundance determination.) As may be seen from inspection of the error bars, the

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[4] Dr. K. M. Yoss has emphasized to the present authors that Fig. 1 of Yoss, Neese, and Hartkopf (1987) represents their efforts more clearly. Their Fig. 1*a* is certainly more consistent with the view expressed here, while the combined sample in Fig. 1*b* still appears to suffer from the problem we are addressing, albeit to a smaller extent than is seen in our Fig. 9*b*.

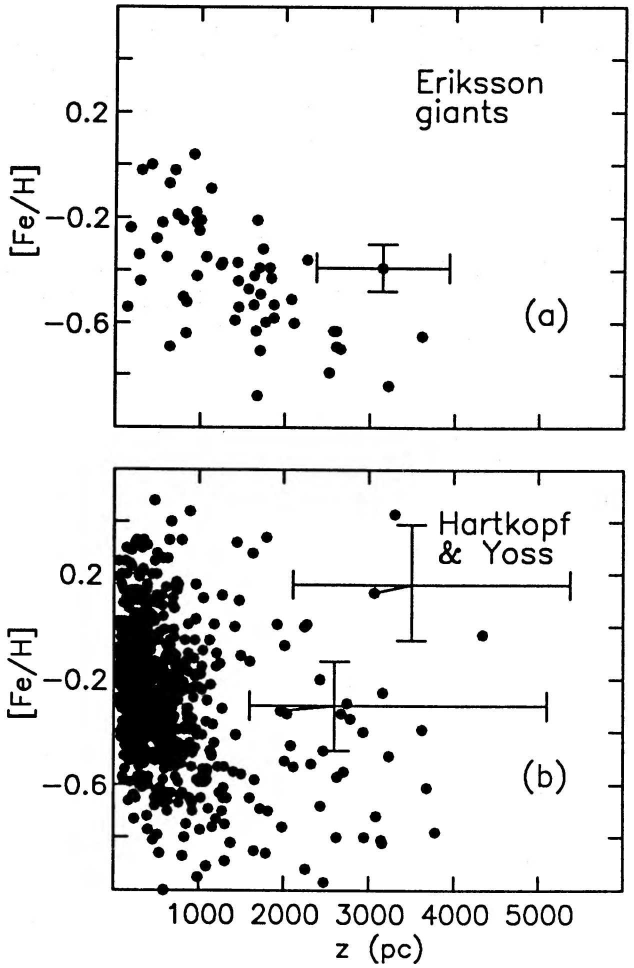

FIG. 9.—Dependence of [Fe/H] on distance *z* from the Galactic plane for (*a*) the Eriksson giants, with error bars corresponding to independent errors of 0.01 in each of *C*(4548), *C*(4245), and *C*(4142), and (*b*) the Hartkopf-Yoss sample, with error bars corresponding to photometric errors of 0.02 in the DDO colors. (The abundance and distance values obtained with the present formulation are connected to those of Hartkopf and Yoss, from which they differ slightly.) Note that the photometric errors are those appropriate to the two investigations.

errors in *z* [driven principally by the sensitivity of distance to errors in *C*(4548)] are very large.

It seems reasonable to suggest that somewhat more accurate DDO observations are necessary for the stars in Figure 9*b* with large values of [Fe/H] and *z* before the HY data may be used to infer far-reaching conclusions about the Galactic disk.

f) *On the Incidence of Stars with* [Fe/H] > −0.3 *and* $z > 2000$ pc

To investigate the question of the existence of high-abundance stars far from the Galactic plane, we obtained DDO photometry on 1987 March 27 and 1987 September 30 (with the same instrumental setup as described in § II) for several of the problematic stars seen in the HY data. The stars were chosen from Table II of HY to have $z > 2000$ pc and [Fe/H] > −0.3. The results are presented in Table 6A, together with the values from Hartkopf (1981) upon which the results of HY are based. The final three columns present the comparison between the two data sets.

For our March data the (internal) standard deviations of a single observation are 0.006, 0.005, and 0.006 for *C*(4548), *C*(4245), and *C*(4142), respectively, while for the September material the corresponding numbers are 0.007, 0.014, and 0.014. As a check on the external accuracy of our measurements, we also observed in March two NGP stars (UP 25102 and UP 27127 from Table II of HY), for which McClure and Crawford (1971, hereafter MC) have presented DDO colors. For their data MC report internal standard errors of 0.004, 0.004, and 0.006 for *C*(4548), *C*(4245), and *C*(4142), respectively. The comparison of our results with those of MC is presented in Table 6B.

We make the following points. First, the mean absolute differences between our results and those of MC are 0.003, 0.005, and 0.015 for *C*(4548), *C*(4245), and *C*(4142), respectively, suggesting that our internal error estimates are reliable, and that our colors are on the DDO system. Second, there are relatively large errors in the DDO photometry of Hartkopf (1981) for the problematic stars of HY. In Table 7 we present distances and abundances determined for these objects from both the Hartkopf and the present data in Table 6, using the formalisms described in § III*b*. (We note again that the small differences

TABLE 6

DDO PHOTOMETRY FOR APPARENTLY PROBLEMATIC STARS AT THE GALACTIC POLES

	OTHER INVESTIGATOR			PRESENT WORK				OTHER *minus* PRESENT		
NAME (1)	*C*(4548) (2)	*C*(4245) (3)	*C*(4142) (4)	*C*(4548) (5)	*C*(4245) (6)	*C*(4142) (7)	*n* (8)	Δ(4548) (9)	Δ(4245) (10)	Δ(4142) (11)
A. Comparison with Hartkopf (1981)										
HD 3539	1.286	0.949	0.365	1.260	1.004	0.376	2	0.026	−0.055	−0.011
HD 3966	1.267	0.940	0.436	1.242	1.002	0.352	2	0.025	−0.062	0.084
HD 5424	1.286	0.948	0.309	1.253	0.966	0.289	1	0.033	−0.018	0.020
BD +31°2423	1.276	0.923	0.348	1.250	0.944	0.328	2	0.026	−0.021	0.020
MA 30123	1.214	0.933	0.273	1.217	0.981	0.171	2	−0.003	−0.048	0.102
MA 32276	1.243	0.944	0.294	1.242	1.002	0.280	2	0.001	−0.058	0.014
BOK II-39	1.286	1.046	0.340	1.100	0.919	0.076	1	0.186	0.127	0.264
BOK II-158	1.291	1.010	0.311	1.253	1.077	0.273	1	0.038	−0.067	0.038
BOK II-269	1.210	0.835	0.312	1.185	0.948	0.214	2	0.025	−0.113	0.098
B. Comparison with McClure and Crawford (1971)										
UP 25102	1.211	0.927	0.227	1.216	0.924	0.217	2	−0.005	0.003	0.010
UP 27127	1.258	1.039	0.386	1.259	1.032	0.366	2	−0.001	0.007	0.020

TABLE 7

DISTANCES AND ABUNDANCES FOR APPARENTLY PROBLEMATIC STARS AT THE GALACTIC POLES

	HARTKOPF-YOSS		PRESENT WORK	
NAME (1)	Distance (pc) (2)	[Fe/H] (3)	Distance (pc) (4)	[Fe/H] (5)
HD 3539	2344	0.07	539	0.29
HD 3966	3147	0.47	879	0.28
HD 5424	3579	−0.18	1362	−0.15
BD +31°2423	5180	0.02	1636	0.08
MA 30123	2135	0.04	1604	−0.39
MA 32276	2322	−0.03	1348	−0.04
BOK II-39	2474	0.04	[a]	[a]
BOK II-158	3206	−0.15	859	−0.08
BOK II-269	12302	0.16	1412	0.07

[a] Outside calibration.

between our values of [Fe/H] and z determined from the Hartkopf data and those published by HY are undoubtedly due to small differences in the adopted formalisms of the two works.) One sees that in all cases the present data yield values in the ([Fe/H], z)-plane less extreme than those of HY, and also that we find no object with $z > 2000$ and $[\mathrm{Fe/H}] > -0.3$, consistent with the result found for the Eriksson giants in Figure 9*a*.

We submit that the present data for the Eriksson stars, and our reobservations of critical stars from the HY sample, are consistent with the view that, as far as the available DDO material is concerned, there is no compelling evidence for a significant proportion of stars having $[\mathrm{Fe/H}] > -0.3$ at distances $z > 2$ kpc. We also stress that this claim pertains to material at the radial distance of the Sun from the Galactic center.

g) Continuous Extended Disk versus Discrete Thick/Thin Disk

Gilmore and Wyse (1985) have suggested that their thick-disk component has $\langle[\mathrm{Fe/H}]\rangle = -0.6$, with a dispersion of ~0.3 dex. Their preferred scale height of the thick disk is ~1350 pc. An abundance dispersion this large is difficult to reconcile with the present results, since for large distances from the plane one would then expect (for a Gaussian distribution) that some 14% of stars would have $[\mathrm{Fe/H}] > -0.3$.

The problem is illustrated in Figure 10*a*, where the thick line shows the percentage of Eriksson giants having $[\mathrm{Fe/H}] > -0.3$ as a function of z. The thin line is the result of Monte Carlo simulation of a two-component thin/thick disk model defined by scale heights of 300 and 1350 pc, $\langle[\mathrm{Fe/H}]\rangle = -0.3$ and -0.6, $\sigma([\mathrm{Fe/H}]) = 0.2$ and 0.3, and relative densities at the plane of 1.00 and 0.02, respectively, as advocated by Gilmore and Reid (1983) and Gilmore and Wyse (1985). (We note that our simulation includes errors of 0.5 mag and 0.1 dex for absolute magnitude and abundance, respectively.) Clearly, if the present data are correct, and the Gilmore-Wyse model is to stand, the abundance parameters of their thick-disk component need to be revised.

In Paper V of this series a continuous extended disk having less extreme parameters than those of Gilmore and his coworkers was advocated, and a very simple model was presented. In Figure 10*b* we present the confrontation of the original model with the observations. As before, the thick line represents the observations, while the thin line shows the results of Monte Carlo simulations of the four-component model of Table 2 of Paper V. As emphasized there, the four-component model was seen as a convenient mathematical representation of a *continuous* system. The agreement between observation and model is quite satisfactory.

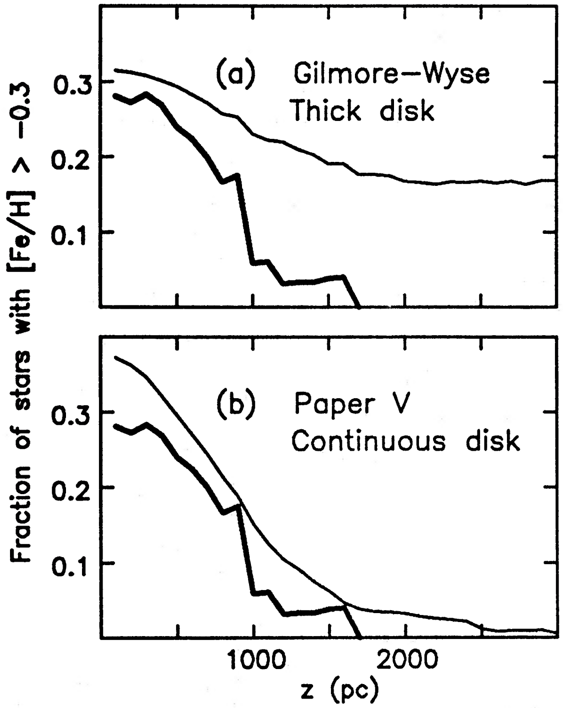

FIG. 10.—In each panel the thick line shows the fraction of stars having $[\mathrm{Fe/H}] > -0.3$ as a function of distance z from the Galactic plane for the Eriksson giants. In (*a*) the thin line shows the result of a Monte Carlo simulation based on the thick/thin model of the Galactic disk of Gilmore and Wyse as described in the text, while in (*b*) it represents a simulation based on the continuous Galactic disk model presented in Paper V.

h) Dependence of Exponential Scale Height on Abundance

The data in Table 3 are sufficient to permit a rough estimate of the dependence of scale height on abundance. The procedure is as follows. First we determine the density in the solar neighborhood of giants having colors in the range $0.7 \leq B-V \leq 1.1$ as a function of [Fe/H]. Then for a given abundance bin an estimate is made of the exponential scale height consistent with the number of giants observed in that bin in the Eriksson sample.

Densities in the solar neighborhood were obtained by selecting all stars in the BSC in the stated color range for which McClure and Forrester (1981) give DDO colors. This sample was analyzed in the same manner as was the Eriksson sample (§ III*b*) to isolate the giants and to determine distances and abundances. Then, allowing for the fact that only approximately half of the stars in the BSC have DDO photometry, the stellar densities were determined for several abundance bins. The results are given in Table 8, where columns (1)–(4) give the abundance bin, mean abundance, stellar density, and number of stars, respectively. It should perhaps be emphasized that the densities given in the table refer to stars in the stated color and abundances ranges, and also in the DDO color ranges over which the techniques described in § III are applicable. Since we apply the same techniques to the BSC and Eriksson samples, it does not matter that the densities refer to a select subset of stars. What makes the technique defensible is that the same

TABLE 8

DEPENDENCE OF EXPONENTIAL SCALE HEIGHT ON [Fe/H]

[Fe/H] Range (1)	⟨[Fe/H]⟩ (2)	Density (pc^{-3}) (3)	n_{BSC} (4)	n_{Erik} (5)	z_0 (pc) (6)
0.0 to 0.1..............	0.02	3.08E−05	126	2	200 ± 60
−0.1 to 0.0..............	−0.05	3.21E−05	165	4	260 ± 50
−0.2 to −0.1..............	−0.18	3.53E−05	135	2	200 ± 60
−0.3 to −0.2..............	−0.23	2.19E−05	100	8	370 ± 50
−0.4 to −0.3..............	−0.36	2.09E−05	80	11	420 ± 50
−0.5 to −0.4..............	−0.45	6.13E−06	29	8	600 ± 100
−0.7 to −0.5..............	−0.60	3.15E−06	20	19	1360 ± 350

selection effects apply to both samples.[5] As noted above, the Eriksson sample covers 11.8 square degrees at the SGP. Given the stellar density at the plane, an assumed exponential scale height, and a knowledge of the absolute magnitude distribution of the sample, it is straightforward to estimate the number of stars which would be expected in the Eriksson sample. This exercise was performed for each abundance bin. The procedure was simplified somewhat by the fact that the (differential) luminosity function of the above BSC sample is roughly Gaussian with $\langle M_V \rangle = 0.6$ and $\sigma(M_V) = 0.8$, while for the Eriksson giants $\langle M_V \rangle = 1.0$ with $\sigma(M_V) = 0.8$. We have therefore assumed that all giants in the sample have $M_V = 0.8$. Columns (5)–(6) in Table 8 then give the resulting numbers of Eriksson giants and the exponential scale heights necessary to reproduce these numbers as a function of abundance. Column (6) includes an attempt to assess the error in the scale height on the assumption that the observed numbers of giants in the Eriksson sample obey Poissonian statistics.

Figure 11*a* then shows the dependence of scale height on abundance, while for comparison purposes Figure 11*b* presents the velocity dispersion, σ_z, as a function of [Fe/H], based on the data of Janes (1975) and Strömgren (1987). Finally, in Figure 11*c*, the age-metallicity relations of Twarog (1980), Carlberg *et al.* (1985), Nissen, Edvardsson, and Gustafsson (1985), and Strömgren (1987) for the Galactic disk are also presented.

As noted above, it was suggested in Paper V that the Galactic disk comprises a number of abundance components in the range $-0.8 < [Fe/H] < 0.2$ with velocity dispersions which increase continuously with decreasing abundance and increasing age, and that the thick disk is merely the low-abundance, high velocity dispersion, greater scale height component of this disk. We submit that the monotonic increase of scale height with abundance in Figure 11*a* is quite consistent with this concept. It may well be that a discrete thin/thick disk configuration, smeared by errors of observation, is also consistent with the data. The point we would make is that such a configuration, with its attendant implications for the formation of the Galactic disk, is not *necessarily* required by the observations.

V. THE FORMATION OF THE GALACTIC DISK

a) *Constraints*

We seek to understand the following basic facts concerning the Galactic disk:

1. The population of disk globular clusters has scale height ~1 kpc (Zinn 1985) and age ~14 Gyr (Hesser *et al.* 1987). We note for future reference that for the Zinn sample (1985,

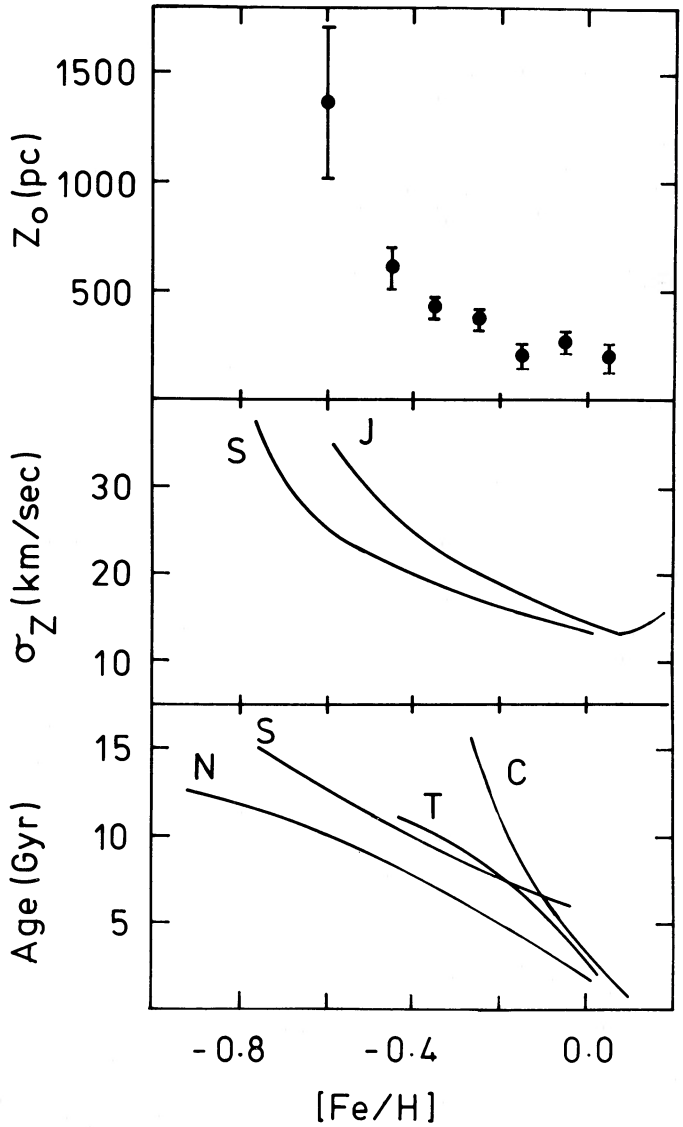

FIG. 11.—(*Top*) Dependence of exponential scale height on [Fe/H] determined in the present investigation. (*Middle*) Dependence of σ_z on [Fe/H] based on Janes (1975, labeled J) and Strömgren (1987, labeled S). (*Bottom*) Age-metallicity relations of Twarog (1980, labeled T), Carlberg *et al.* (1985, labeled C), Nissen, Edvardsson, and Gustafsson (1985, labeled N), and Strömgren (1987, labeled S).

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[5] In Fig. 2 one sees that the BSC sample contains a number of supergiants not present in the Eriksson sample for obvious reasons. Redder than $C(4245) = 0.74$ these are excluded by the Janes formalism. Forcible exclusion of presumed supergiants bluer than this limit was effected by accepting only those stars with $C(4548) < 0.53C(4245) + 0.78$. The inclusion or exclusion of these stars causes no essential change to the results presented here, since their number is quite small.

Table 1, with [Fe/H] < -0.8) one finds a mean distance from the Galactic center, projected onto the plane, of 4.9 kpc. If Pal 8 (which has $z = 18.9$) is omitted, this value is reduced to 4.2 kpc. Consideration of selection effects due to interstellar absorption toward the Galactic center suggests that these values are an overestimate of this parameter for the entire population.

2. The bulk of the material at the solar distance from the Galactic center and with $z < 3$ kpc is at least 3–6 Gyr younger than the disk globular cluster population. For $z = 1$–3 kpc, at most $\sim 10\%$ of the stellar material may be identified as belonging to the same population as the disk globular clusters.

3. There is a well-defined gradient of chemical abundance perpendicular to the plane, given by ~ -0.2 dex kpc^{-1} for $0 < z < 3$ kpc.

4. There is a continuous metallicity–age–velocity dispersion for material in the range $-1 <$ [Fe/H] < 0. For the most metal-weak material in this range, $\sigma_z \sim 40$ km s^{-1}, which corresponds to an exponential scale height $z_0 \sim 1$ kpc.

We bear in mind the following constraints on the relationship between the disk and halo populations:

5. There are two distinct populations of globular clusters—halo and disk (Zinn 1985).

6. Following Zinn (1985), we accept that for the globular clusters "there is a shallow, but significant, metallicity gradient with R [galactocentric distance] in the halo population that either disappears or becomes too shallow to measure beyond $R = R_\odot$ kpc. There is some evidence of metallicity gradients with R and with distance from the galactic plane among the disk clusters."

7. The second-parameter problem of horizontal branch morphology is a function of galactocentric position (see, e.g., Searle and Zinn 1978).

8. The halo and disk populations of the Galaxy are kinematically decoupled, there being no dependence of kinematics on abundance in the halo. This point is controversial: see Searle and Zinn (1978), Norris (1986, hereafter Paper II), Sandage and Fouts (1987), Sandage (1987*a*), Norris (1987*a*), Zinn (1987), Carney (1987), and Yoss, Neese, and Hartkopf (1987) for evidence and argument. We shall return to this problem in Paper VII. It is, however, not central to the present discussion.

b) Competing Scenarios

Gilmore and Wyse (1985) have listed several hypotheses which may explain the thick disk of the Galaxy. While we refer the reader to their work (and references therein) for details, the basic mechanisms are the following:

1. Acceleration processes operating on the thin disk over the lifetimes of objects in that disk.
2. The infall of large objects (other galaxies, fragments of the initial system) onto the thin disk.
3. The collapse of gas into the nonspherical potential wells of underlying dark halos.
4. The response of the halo component of the Galaxy to the gravitational potential of the thin disk.

In Gilmore and Wyse (1985) and Paper II shortcomings of processes 3 and 4 were noted. We shall not repeat the discussion here and in what follows will not consider them further.

Gilmore and Wyse (1986) examine the question in terms of a three-phase scenario for the formation via gravitational collapse of the Galaxy which proceeds halo → thick disk → thin disk.

Sandage (1987*a*) envisages the thick-disk component in terms of "a change in the collapse rate (due to partial pressure support after the main halo phase) relative to the metal enrichment rate, giving the appearance of a separate spatial, kinematic, and metallicity structure."

Within this framework it is interesting to note that some years before the term "thick disk" had been coined by Burstein (1979), Larson (1976, hereafter Larson) had explored the physical processes which were necessary to produce disk galaxies, in an effort to understand the factors which are important in determining the different bulge/disk ratios found among spiral galaxies. In that endeavor he produced models which he felt in large part reproduced the available observational constraints for the Galaxy. Tinsley and Larson (1978) extended this work for two of the Larson models. It is then important to note that the preferred models contain a thick-disk component. We shall argue below that these models can explain the majority of the above constraints.

c) Discussion

In the above suggestions there are two basically different concepts. The first envisages that an extant thin Galactic disk has been thickened by gravitational processes following its formation. The second involves the formation of a disk which is thick, with the bulk of the material currently being highly concentrated to the plane.

The difficulties with the former concept are well known. While the phenomenon undoubtedly occurs, no acceleration mechanism (acting continuously over the lifetime of the Galaxy) has been proposed which can satisfactorily produce values of $\sigma_z \sim 40$ km s^{-1}. See Gilmore and Wyse (1985) for discussion of this point. It is also difficult (but presumably not impossible) to envisage how the thickening of an already formed thin disk by a stochastic process such as the accretion of satellites could lead to the observed, well-defined abundance–age–velocity dispersion relation, together with the vertical abundance gradient, unless it were an ongoing, continuous process.

Be this as it may, the concept of a very rapid time scale of a few times 10^8 yr for the collapse of the Galaxy from protocloud to thin disk, put forward by Eggen, Lynden-Bell, and Sandage (1962), has had a profound effect on the way many astronomers think about the origin of the Galactic disk. We believe we see this in the desire to thicken a thin disk by acceleration processes, and in suggestions to add a third component to meet perceived inadequacies of the model.

It should be noted, then, that Rood and Iben (1968, § IV) have suggested that the theoretical basis for such a short time scale is not unique, and that any pressure support exerted against the collapse by gaseous material would lead to a longer time scale and still be compatible with the observed large eccentricities of halo stars, upon which the short time scale is essentially based. These authors advocate formation of the Galaxy over a considerably longer time scale, of order a few times 10^9 yr.

The models of Larson for the formation of disk galaxies are of this type. It should perhaps be recalled that the essential conclusion which he reached was that in order to produce a disk containing more than half of the mass of the system, the star-formation rate must have decreased substantially following the initial formation of a spheroidal component. When this condition was met, he produced models with many of the characteristics of the Galaxy. We refer the reader to Larson and to Tinsley and Larson (1978) for the comparison of his results with the observational constraints listed above. Suffice it to say here that these models already contain the concepts of an age–abundance–velocity dispersion relation in the solar neighborhood, of the old disk open clusters being significantly younger than the halo of the Galaxy, and of the existence of an abundance gradient perpendicular to the plane.

The models also naturally explain the observed age difference between the disk globular clusters and the bulk of the disk in the solar neighborhood reported here. The essential fact of the Larson models, contained in no other scenario for the formation of the thick disk of the Galaxy, is that the disk begins to form toward the center of the Galaxy. In Figure 12 we reproduce his Figure 6, which shows the density profile in a meridional plane for three epochs during galaxy formation of his model 6. Here one sees that at time 2 Gyr the disk exists only within the central 5 kpc. It seems natural to identify this as the time and place for the formation of the disk globular clusters. Such a suggestion is consistent with the mean galactocentric distance of 4 kpc for Zinn's disk globular clusters and the age estimate of 14 Gyr for 47 Tuc (accurate to at best 2 Gyr), which is at present indistinguishable from that of the halo globular clusters. According to Larson, it is only after a delay of several more Gyr that a disk is formed at the distance of the Sun from the Galactic center in models of this type.

There are two other comparisons which may be made concerning the thick disks produced in these models. Figure 13 presents the run of stellar density with height above the plane of the Galaxy (at the radial distance of the Sun) as given by Sandage (1987*b*) together with the predictions (at a galactocentric distance of 8 kpc) of Larson's models 6 and 9. The agreement is by no means perfect, but conceptually the comparison is excellent. The second interesting point is that Larson predicts for his model 9 an abundance gradient at $r = 8$ kpc and $z = 1$–3 kpc of -0.2 dex kpc^{-1}, in (fortuitously perhaps) rather close agreement with the value of -0.18 found in the present work.

Tinsley and Larson (1978) explore further the properties of Larson's models 6 and 9, and conclude that the characteristics not only of the disk but also of the halo, which is predicted to form over a period of several billion years, can be understood in this way. Constraints 5, 7, and 8 above are readily explained within their framework. It would be interesting to know whether the models predict an abundance gradient for the halo population. One receives the impression from Larson's Figure 9 that such an effect is present. If this is indeed the case, one is still faced with the need for a mechanism such as that of Searle and Zinn (1978) to explain the absence of such a gradient for galactocentric distances greater than ~8 kpc. It would also be interesting to see whether the model reproduces the dependence of systemic rotation of the Galaxy as a function of abundance reported in Paper II, or one that favors the results of Sandage and Fouts (1987). The statement of Larson that " the distribution of average rotational velocity ... shows a distinction between a rapidly differentially-rotating disc component and a much more slowly and more uniformly-rotating halo " seems more consistent with the claims of Paper II.

d) An Objection

Wielen (1977) has argued that the age–velocity dispersion relation for disk stars is difficult to explain in terms of conditions which were established during the formation of the disk. He emphasizes that the rapid change of velocity dispersion for ages less than 1 Gyr, compared with the slower change at greater ages, would then be inconsistent with the general cosmological principle that neither our position nor our epoch is of special significance. The implicit assumption in this suggestion is that the disk of the Galaxy had already reached an equilibrium configuration when the stars under consideration

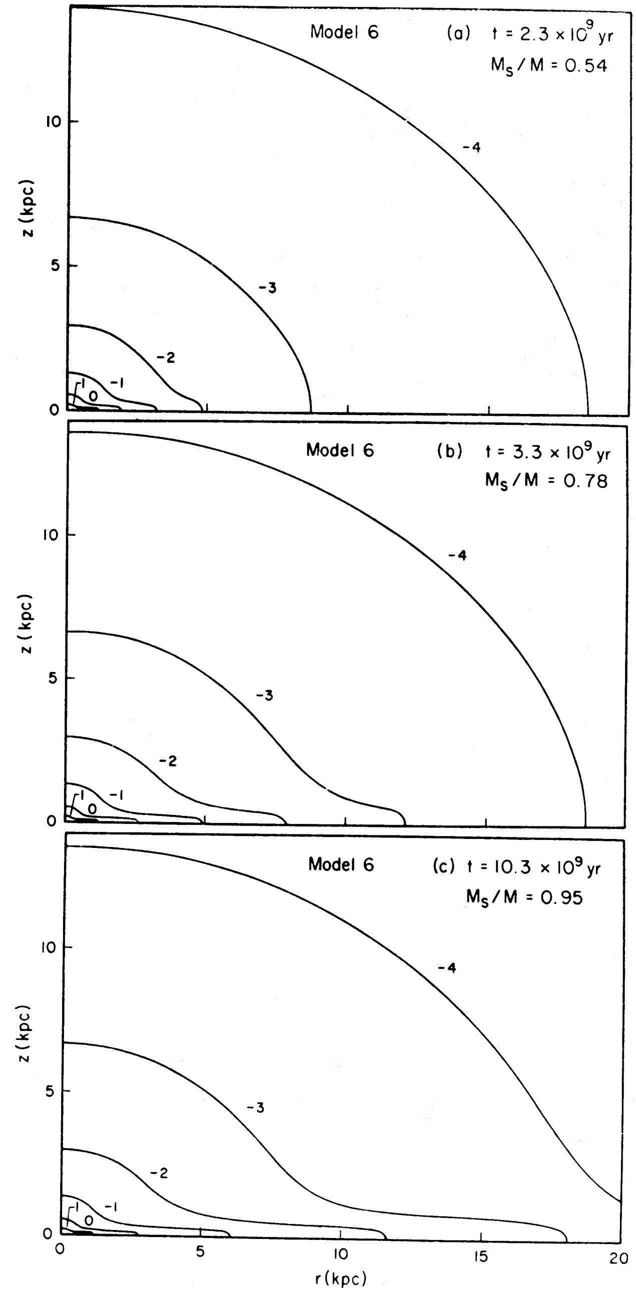

FIG. 12.—Density contours of model 6 of Larson (1976; his Fig. 6) through a meridional plane for three times during the formation of a galaxy. The curves are labeled with the logarithm of the stellar density. (At top right in each panel is given the time since the collapse began and the fraction of gas that has been transformed into stars.) Note the important result that in models of this kind the disk first forms close to the galactic center, and only after several billion years more does it become evident at distances equal to that of the Sun from the Galactic center.

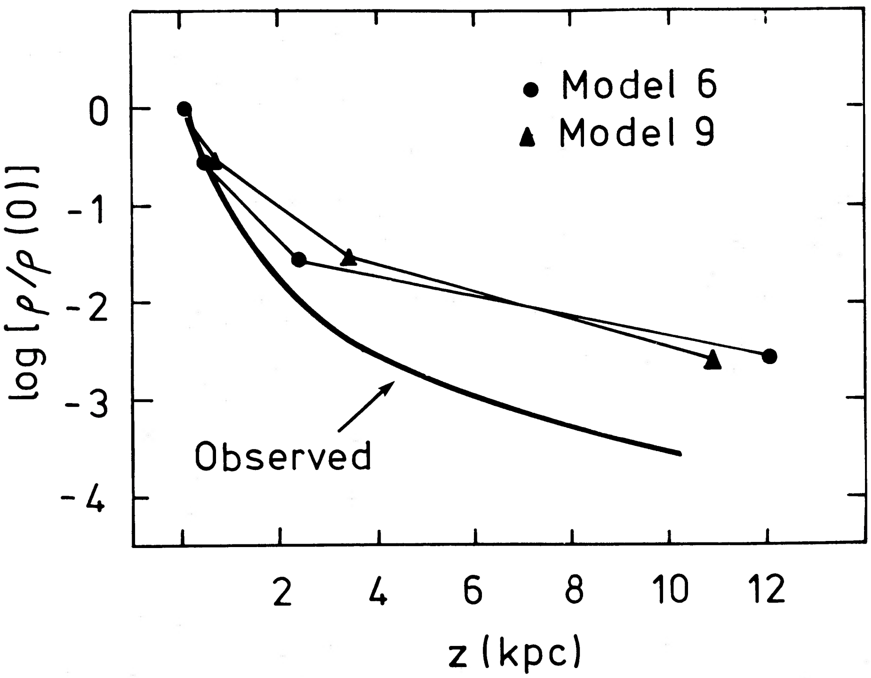

FIG. 13.—Dependence of stellar density on distance z from the Galactic plane. The thick line represents the observational results discussed by Sandage (1987*b*) toward the Galactic poles, while the thin lines show the results for the Larson (1976) models 6 and 9. The purpose of this diagram is to emphasize that the Larson collapse models contain a thick-disk component, in spite of the fact that they predate the emphasis on that Galactic component by observers by several years.

were formed. If our contention concerning the age of the disk in the solar neighborhood is correct and Larson's models 6 and 9 represent the way in which the disk formed, this assumption is unwarranted. We refer the reader also to Larson and Tinsley (1978) for further rebuttal of the Wielen argument.

This is not to say that acceleration mechanisms as discussed by Wielen do not operate. It seems not unreasonable to suggest that the observed age–velocity dispersion relationship results from a combination of initial conditions *and* acceleration mechanisms.

e) Predictions

Assuming that the above suggestions are correct, we make the following two predictions. First, if one examines material 1–3 kpc above the Galactic plane (toward the Galactic poles), one will find a significant component of dwarfs with $B-V = 0.4$–0.5 with abundances $-0.8 < [\mathrm{Fe/H}] < -0.4$. These are the counterparts of the turnoff stars in the old, metal-poor open clusters such as Melotte 66 and NGC 2243, and should not be present in a thick-disk model in which the stars have properties similar to those of the disk globular cluster population (and for which the main-sequence turnoff occurs at $(B-V)_0 = 0.50$; Hesser *et al.* 1987). The number of such stars in the stated color range will become more marked the greater the age difference between the disk in this region and the disk globular clusters.

Second, if one were to repeat the observational program performed in the present work, but instead understood the investigation at $l = 0°$ and $b = \pm 30°$ in the same color range ($0.7 < B-V < 1.1$) but with $V \sim 15$, one would find an increase in the proportion of the RHB stars. At that position and apparent magnitude, core–helium-burning giants with $M_V = 1.0$ and $E(B-V) = 0.2$ will be located some 4 kpc from the Galactic center, some 2.5 kpc from the Galactic plane. If our suggestion is correct, the disk at this point should have an age closer to that of the disk globular clusters and therefore contain a higher proportion of RHB stars than was found in the Eriksson sample.

It is a pleasure to thank Ms. H. L. Morrison for assistance in obtaining some of the data presented in this work. We are also grateful to Professor R. B. Larson and the Editor of the *Monthly Notices of the Royal Astronomical Society* for permission to reproduce Figure 12.

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