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THE GALACTIC SYSTEM OF OLD STAR CLUSTERS: THE DEVELOPMENT OF THE GALACTIC DISK

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ABSTRACT

The vast majority of open clusters persist as clusters for no more than a few hundred million years, but the few which survive for much longer periods constitute a unique sample for probing the evolution of the galactic disk. In a CCD photometric survey for possible old open clusters combined with previously published photometry, we have developed a list of 72 clusters of the age of the Hyades or older [Phelps *et al.*, AJ, 107, 1079 (1994)]. Using our version of parameters based on the luminosity difference between the main sequence turnoff and the horizontal branch and on the color difference between the turnoff and the giant branch, we have calculated a "Morphological Age Index" (MAI) for the clusters in our list and for a sample of globular clusters. We find that the MAI is well correlated with the logarithm of cluster ages, as determined by fitting to theoretical isochrones. We conclude that the index is a good measure of the *relative* ages of both globular and open clusters, although uncertainties in the models and residual metallicity effects prevent the use of the MAI as a definitive calibration of actual cluster ages. The age distribution of the open clusters overlaps that of the globular clusters, indicating that the galactic disk began to develop toward the end of the period of star formation in the galactic halo. The open cluster age distribution can be fit approximately with a two-component exponential decay function; one component can be identified as the tail of the dominant population of thin disk open clusters with an age scale factor of 200 Myr, and the other consists of longer-lived clusters with an age scale of 4 Gyr. The young open clusters are distributed on the galactic plane almost symmetrically about the Sun with a scale height perpendicular to the galactic plane of 55 pc. The old population consists of rich clusters found only in the outer disk, more than R_{GC}=7.5 kpc from the galactic center; this population has a scale height of 375 pc. After accounting for the two exponential distributions of cluster ages, there are indications of an excess of clusters in the age range of 5–7 Gyr; there may have been large bursts of star formation in that period, or perhaps a larger proportion of the clusters forming at that time had advantageous orbits for survival. Either circumstance is consistent with the idea that the galactic disk has been repeatedly disturbed, possibly in collisions or other interactions with external systems, resulting in the occasional formation of clusters with relatively large velocities perpendicular to the plane; these are the clusters that have survived until the present. Finally, the repeated accretion of low angular momentum material onto the disk from the halo or beyond would also explain the observed radial composition gradient and the lack of a correlation between open cluster metallicity and age found by Friel & Janes [A&A, 267, 75 (1993)].

1. INTRODUCTION

Although the oldest stars in our galaxy may have formed early in the life of the Universe, there is growing evidence that the galaxy did not collapse rapidly out of a simple, homogeneous gas cloud soon after the Big Bang. Instead, it is likely that the galaxy formed in a prolonged, perhaps chaotic process. The evidence for a prolonged period of development of the halo is derived primarily from studies of the globular clusters (Searle & Zinn 1978); we now know that some of them are indeed several billion years younger than the majority (Sarajedini & Demarque 1990; VandenBerg *et al.* 1990, hereafter referred to as VBS; Chaboyer *et al.* 1992, hereafter CSD). The age spread found among the globulars rules out a rapid general collapse such as that proposed by Eggen *et al.* (1962), but Zinn (1993) has suggested that there may be two populations of halo star clusters, an "Old Halo" of clusters which formed during a rapid collapse phase, and a "Younger Halo" consisting of clusters that formed out of satellite systems accreted by the galaxy.

How does the galactic disk fit into this picture? The oldest

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white dwarfs in the galactic disk are thought to have ages between 7.5 and 11 Gyr (Wood 1992), and the open cluster NGC 6791, has an age of almost 10 Gyr (Montgomery *et al.* 1994), only slightly less than the ages of the youngest halo clusters (see, e.g., CSD). If these white dwarf and open cluster ages represent the age of the galactic disk, then some degree of continuity between the formation of the halo and that of the disk is suggested. Observations by Carney *et al.* (1990), however, give the distinct impression that the disk and halo are rather disconnected from one another. If we are to establish the complete formation history of the galaxy, it is crucial to find at least the relative ages of stars in the halo, the thick disk, and the thin disk.

Searle & Zinn (1978) hypothesized that the halo formed over a prolonged period from pre-galactic fragments of the size of globular clusters or perhaps an early generation of dwarf galaxies. An obvious extension of their hypothesis is that the disk also developed gradually as material continued to rain onto the galaxy for a long period of time. Indeed, there have been several suggestions recently (Quinn & Goodman 1986; Sommer-Larsen & Antonuccio-Delogu 1993) that major impacts onto the galaxy disrupted the disk enough to form what we now see as the thick disk; the thin disk then reorganized after that event. Theoretical simulations by Quinn *et al.* (1993) indicate that early mergers of LMC sized objects with the galaxy would have heated whatever galactic thin disk might have existed at the time, giving rise to a thick disk with a large scale height.

An alternative view is that of Burkert *et al.* (1992), who have developed a model for the evolution of the galaxy in which a hot thick disk and an "old thin disk" coexist for the first 4–6 Gyr of galactic history, as the thin disk gradually condensed out of the thick disk. This model would explain the distribution of white dwarf ages, since older white dwarfs, members of the thick disk, would not be common in the solar vicinity.

The principal uncertainty in establishing the connection between the disk and halo remains the age and early evolution of the galactic disk. Since the old open clusters provide the only reliable way to date disk stars, they remain the best hope for probing the disk–halo connection. Unfortunately, however, most open clusters are destroyed by interactions with molecular clouds on time scales of a few hundred million years or less (Spitzer 1958), meaning that few very old open clusters are known to have survived to the current epoch.

In an extensive CCD photometric survey of potential old open clusters, we completed a search for the oldest open clusters (Phelps *et al.* 1994, hereafter referred to as Paper I). Using our versions of two well known morphological parameters of color–magnitude diagrams which are described in detail in Paper I and summarized below in Sec. *3.1*, we ranked the open clusters in approximate order of age. The complete list of old clusters, compiled from our photometry as well as previously published data is presented in Table 1, and brings the total number of open clusters known to be as old or older than the Hyades to 72, with 19 of the clusters being as old or older than the ~5 Gyr old M67.

This population of old thin disk clusters represents a unique sample of "test particles" for probing the galactic ages–metallicity relation, the metallicity gradient, and the earliest stages of the formation of the galactic disk. The present paper represents a first reconaissance of this sample of clusters, whose ages span the lifetime of the galaxy. As will become evident, a lot of the available information is in a rather primitive state—the photometry, the reddenings, and the metallicities of most of the clusters are much in need of improvement. Nevertheless, the broad outlines for the development of the galactic disk can be discerned from the existing data. In Sec. 2 we discuss issues of completeness and possible selection effects of the old cluster sample, relative to the dominant open cluster population; in Sec. 3 we derive an index related to the ages of the old clusters; Section 4 is a discussion of the galactic distribution of the old clusters; Section 5 is an evaluation of the implications of the old cluster age and galactic distributions for current ideas of the evolution of the galaxy; and Sec. 6 is a summary and comments on future work.

2. THE GALACTIC OPEN CLUSTER POPULATION

Virtually all the known old open clusters are listed in Table 1, but how representative is this list? Does it constitute a random sample of the galactic population of old clusters, or are there significant selection biases, as a function of age or position in the galaxy?

For purposes of this investigation, an "old" cluster is considered to be any cluster with the age parameter, δV, greater than zero, that is, approximately the age of the Hyades or greater. The clusters in Table 1 represent all those known to be old according to this definition, except for a small number that were not included for various reasons given in Paper I. Although this definition of an old cluster is a bit arbitrary, it does encompass clusters whose ages sample almost the entire lifetime of the galaxy. Furthermore, all of them contain red giant stars, so that in the future, it will be possible to compare their chemical compositions relatively easily.

The structural parameters of a Hyades-age cluster are not much different from a cluster like NGC 188. By the time a cluster reaches the age of the Hyades (800 Myr or so), the main sequence turnoff luminosity is fainter than the red giant stars, and furthermore, on photographic (blue) sky surveys, all the red giants will appear similar in magnitude. Furthermore, any open cluster of the age of the Hyades or greater will be fully relaxed, and the mass differences between the giants and stars at the brightest couple of magnitudes of the main sequence are not very large. Thus, a Hyades age cluster will look about the same on blue sky surveys as a much older cluster such as NGC 188. Both will appear to consist of a considerable number of stars of roughly the same magnitude. In contrast, a young cluster will be dominated by just a few very bright stars, those at the top of the main sequence.

The Lyngå (1987) "Catalog of Open Cluster Data" (hereafter COCD) lists about 1200 clusters, and since the entire sky has been searched systematically several times for stellar systems, it is unlikely that very many more optically visible

TABLE 1. Old open cluster properties.

Name	l	b	δV	Dist.	E(B-V)	Source	Name	l	b	δV	Dist.	E(B-V)	Source
NGC 188	122.78	+22.46	2.4	1.52	0.08	L	Melotte 71	228.96	+4.45	0.5	2.69	0.01	L
King 2	122.88	−4.67	2.2	6.24	0.32	11	NGC 2420	198.11	+19.65	1.6	2.28	0.05	4
IC 166	130.08	−0.19	1.0	3.08	0.80	L	AM 2	246.89	−5.09	2.5	8.35	0.56	9
NGC 752	137.17	−23.36	0.9	0.36	0.03	L	Berkeley 39	223.47	+10.09	2.4	4.01	0.12	15
NGC 1193	146.81	−12.18	2.1	4.01	0.12	10	NGC 2477	253.58	−5.83	0.5	1.15	0.27	L
King 5	143.75	−4.27	0.4	2.19	0.78	C	NGC 2506	230.57	+9.91	1.5	3.22	0.05	L
NGC 1245	146.64	−8.93	0.7	2.23	0.27	L	Pismis 2	258.83	−3.29	1.1	2.84	1.48	C
Hyades	180.05	−22.40	0.4	0.05	0.00	L	NGC 2627	251.58	+6.65	1.6	1.91	---	D
NGC 1798	160.76	+4.85	1.0	3.44	---	D	Praesepe	205.54	+32.52	0.3	0.16	0.00	L
NGC 1817	186.13	−13.13	0.8	1.81	0.28	L	NGC 2660	265.86	−3.03	0.4	2.89	0.38	L
Berkeley 17	175.65	−3.65	2.8	2.63	0.72	C	M 67	215.58	+31.72	2.3	0.77	0.05	20
Berkeley 18	163.63	+5.01	2.3	1.43	---	D	NGC 2849	265.27	+6.33	0.5	5.73	---	D
Berkeley 20	203.50	−17.28	2.1	8.14	0.14	18	092-SC18	287.1	−6.7	2.2	6.32	0.28	C
King 8	176.40	+3.12	0.2	3.35	0.68	L	NGC 3680	286.77	+16.93	1.0	1.07	0.05	3,5
Berkeley 21	186.83	−2.50	1.6	5.80	0.62	C	NGC 3960	294.41	+6.18	0.2	1.68	0.29	L
Berkeley 22	199.80	−8.50	2.1	5.55	0.65	C	Cr 261	301.69	−5.64	2.6	2.56	0.33	C
NGC 2141	198.07	−5.79	1.6	4.25	0.30	L	NGC 4815	303.63	−2.09	1.1	2.20	0.37	C
NGC 2158	186.64	+1.76	1.4	3.88	0.49	L	096-SC04	305.35	−3.17	0.2	7.57	0.72	C
NGC 2194	197.26	−2.33	0.5	2.65	0.42	L	NGC 5822	321.71	+3.58	0.8	0.73	0.19	L
NGC 2192	173.41	+10.64	0.6	3.44	---	D	IC 4651	340.07	−7.88	1.2	0.92	0.09	2
NGC 2204	226.01	−16.07	1.4	4.33	0.08	L	IC 4756	36.37	+5.26	0.4	0.39	0.20	L
NGC 2236	204.37	−1.69	0.4	3.32	0.37	L	Berkeley 42	36.17	−2.19	0.4	1.15	0.65	6
NGC 2243	239.50	−17.97	2.2	3.66	0.06	7,8	NGC 6791	70.01	+10.96	2.6	4.20	0.12	16,19
Tr 5	202.86	+1.05	2.3	0.98	0.64	L	NGC 6802	55.34	+0.93	0.4	1.02	0.81	L
NGC 2266	187.78	+10.28	0.5	3.36	0.10	13	NGC 6819	73.98	+8.47	1.7	2.05	0.27	L
Berkeley 29	197.98	+8.03	2.1	8.60	---	D	NGC 6827	58.24	−2.35	0.5	8.60	---	D
Berkeley 31	206.26	+5.12	2.3	3.68	0.24	C	IC 1311	77.70	+4.25	0.2	4.71	0.62	1
Berkeley 30	210.80	+2.89	0.3	2.34	0.61	C	NGC 6939	95.88	+12.30	1.4	1.20	0.50	L
Berkeley 32	207.95	+4.40	2.4	3.07	0.16	12	NGC 6940	69.90	−7.16	0.2	0.81	0.26	L
Tombaugh 2	232.90	−6.84	1.5	6.08	0.40	17	Berkeley 54	83.13	−4.14	2.5	5.30	0.90	C
NGC 2324	213.45	+3.31	0.3	3.18	0.28	L	NGC 7044	85.87	−4.13	0.7	3.86	0.74	11
NGC 2354	238.42	−6.80	0.8	1.80	0.14	L	Berkeley 56	86.04	−5.18	2.3	5.73	---	D
NGC 2355	203.36	+11.80	0.4	2.20	0.12	14	NGC 7142	105.42	+9.45	2.0	2.95	0.41	L
NGC 2360	229.80	−1.42	0.5	1.14	0.07	L	King 9	101.45	−1.84	2.0	4.56	0.72	C
Melotte 66	259.61	−14.29	2.3	2.88	0.17	L	King 11	117.16	+6.47	2.3	2.19	1.00	6
NGC 2423	230.47	+3.55	0.1	0.75	0.21	L	NGC 7789	115.49	−5.36	1.1	1.84	0.25	L

References to TABLE 1

(1) Alfaro, *et al.* (1992); (2)Anthony-Twarog, *et al.* (1988); (3) Anthony-Twarog, *et al.* (1989); (4) Anthony-Twarog, *et al.* (1990); (5) Anthony-Twarog, *et al.* (1991); (6) Aparicio, *et al.* (1991); (7) Bergbusch, *et al.* (1991); (8) Bonifazi, *et al.* (1990); (9) Gratton & Ortolani (1988); (10) Kaluzny (1988); (11) Kaluzny (1989); (12) Kaluzny & Mazur (1991a); (13) Kaluzny & Mazur (1991b); (14) Kaluzny & Mazur (1991c); (15) Kaluzny & Richtler (1989); (16) Kaluzny & Udalski (1992); (17) Kubiak, *et al.* (1992); (18) MacMinn, *et al.* (1994); (19) Montgomery, *et al.* (1994); (20) Montgomery, *et al.* (1993).

clusters will be found.[4] Well over half the clusters have never been studied in any detail, but most of the unstudied ones are faint, sparsely populated, or located in dense or obscured directions in the galaxy. The reliability of the photometric data for many of the clusters that have been studied is somewhat suspect, not so much because of the quality, but again because many clusters are sparse or located in confused regions. Nevertheless, it is possible to derive the basic character of a cluster even from a rather poor color–magnitude diagram.

There are, then, useful age estimates for somewhat fewer than half of the known open clusters; but how many *old* clusters remain to be identified among the unstudied clusters of the COCD? To address this question, we need to examine the catalog to see which of the properties of clusters can be used to separate the old ones from the younger ones. The answer is to turn to the classic paper of Trumpler (1930). In the course of his work, Trumpler derived a three-part classification of the visual appearance of a cluster: a concentration class, a magnitude range class, and a richness class. This information has been incorporated into the COCD catalog, with a reclassification of almost all open clusters based on modern sky surveys, but following Trumpler's criteria. Table 2 is a summary of the statistics of Trumpler richness and concentration classes for 70 of the old clusters listed in the COCD (all but 2 of those in Table 1), all clusters with age estimates given in the COCD except those that appear in Table 1 (i.e., young clusters—368 of them), and finally all clusters in the COCD without age estimates (644 clusters). The most obvious characteristic of the old clusters is the fact that they are all at least relatively rich; presumably, if a cluster were not rich, it would not last very long. Of the 438 clusters with ages, 39 percent of those classified as "r" are old, 13 percent of the "m" clusters are old, and only 3 percent of the "p" clusters are old. If these same proportions of

[4]In the COCD and in this paper, the term "cluster" is taken to be any apparently significant concentration of stars above the local background density, based on visual inspection of wide-field survey photographs. In this context, the term cluster does not necessarily imply a gravitationally bound system.

TABLE 2. Open cluster statistics.

Richness / Concentration	Old p	Old m	Old r	Old All	Young p	Young m	Young r	Young All	Unknown p	Unknown m	Unknown r	Unknown All
I	2	13	15	30	22	40	27	89	29	24	9	62
II	2	12	20	34	41	67	32	140	64	59	6	129
III	0	0	5	5	38	54	5	97	126	83	14	223
IV	0	0	1	1	29	12	1	42	170	57	3	230
All	4	25	41	70	130	173	65	368	389	223	32	644

old vs young were to hold in the three richness classes among the 644 "unknown" clusters, then there could be as many as 54 undetected old clusters. But in fact, this is likely to be a significant overestimate. All but six of the old clusters are of Trumpler concentration classes I or II, whereas only 27% of the unknown clusters fall in classes I or II. A full one third of all unstudied clusters are in Trumpler class IV, almost all of those being irregular, poorly defined patterns, unlikely to be old clusters.

The three groups of clusters also differ in their distributions with galactic latitude. The median distances from the galactic plane are 5.72°, 2.24°, and 1.53° for the old, young, and unknown samples, respectively. That is, the latitude distribution of the unknown clusters more closely resembles that of the young clusters rather than that of the old clusters.

It appears that we have identified the majority of the old clusters in our part of the galaxy. In round numbers, there could be as many as 50 undetected old clusters, although a much smaller number is more likely. Even the addition of another 50 clusters is unlikely to have a major effect on the age distribution, although there would be some effect on the distribution perpendicular to the galactic plane, as the unknown sample is dominated by clusters very close to the plane.

TABLE 3. Globular cluster morphological age parameters.

Cluster	δV	δ_1	$<\delta V>$	Source	Cluster	δV	δ_1	$<\delta V>$	Source
47 Tuc	3.1	0.29	2.90	19	NGC 5897	2.9	0.23	2.91	21
NGC 288	3.0	0.25	2.92	5	M 5	2.77	0.27	2.77	VBS
	3.07	0.24	2.98	VBS	Ru 106	2.7	0.23	2.81	8
NGC 362	2.82	0.27	2.79	VBS	Pal 14	2.9:	0.22:	2.93	20
	2.75	0.26	2.78	4	NGC 6101	2.85	0.23	2.89	23
NGC 1261	2.72	0.26	2.76	VBS	NGC 6171	3.0	0.23	2.96	13
	2.7	0.25	2.77	3	M 13	3.05	0.25	2.95	VBS
NGC 1851	2.8	0.22	2.88	24	M 12	2.80	0.25	2.82	VBS
NGC 1904	2.8	0.22	2.88	15	NGC 6229	2.85	0.23	2.89	9
NGC 2298	2.83	0.24	2.86	VBS	M 10	3.22	0.23	3.07	VBS
NGC 2808	2.81	0.28	2.77	VBS	M 92	2.95	0.24	2.92	VBS
NGC 3201	2.9	0.27	2.83	6	NGC 6366	3.05	0.24	2.97	16
	2.77	0.25	2.81	VBS	NGC 6297	2.92	0.22	2.94	VBS
NGC 4147	2.95	0.24	2.92	VBS	NGC 6752	2.93	0.25	2.89	VBS
NGC 4372	2.8	0.20	2.92	1	M 55	3.05	0.23	2.99	2
NGC 4590	2.84	0.22	2.90	VBS		2.89	0.22	2.93	VBS
M 53	2.8	0.23	2.86	18	M 71	3.1	0.28	2.91	17
NGC 5053	2.8:	0.20	2.92	18	NGC 7006	2.8	0.23	2.86	7
	2.9	0.23	2.91	12	M 15	2.8	0.22	2.88	11
M 3	2.76	0.26	2.78	VBS	M 30	2.95	0.23	2.94	VBS
IC 4499	2.9	0.21:	2.95	22	NGC 7492	2.9	0.22	2.93	10
Pal 5	2.84	0.26	2.82	VBS		3.02	0.25	2.93	VBS
NGC 5897	2.9	0.21	2.95	14	Pal 12	2.77	0.32	2.67	VBS

References to TABLE 3

(VBS) Vandenberg, *et al.* 1990; (1) Alcaino, *et al.* 1991; (2) Alcaino, *et al.* 1992a; (3) Alcaino, *et al.* 1992b; (4) Bolte 1989; (5) Bolte 1992; (6) Brewer, *et al.* 1993; (7) Buonanno, *et al.* 1991; (8) Buonanno, *et al.* 1993; (9) Carney, *et al.* 1991; (10) Côté, *et al.* 1991; (11) Durrell & Harris 1993; (12) Fahlman, *et al.* 1991; (13) Ferraro, *et al.* 1991; (14) Ferraro, Fusi Pecci and Buonanno 1992; (15) Ferraro, *et al.* 1992; (16) Harris 1993; (17) Heasley & Christian 1991a; (18) Heasley & Christian 1991b; (19) Hesser, *et al.* 1987; (20) Holland & Harris 1992; (21) Sarajedini 1992; (22) Sarajedini 1993; (23) Sarajedini & Da Costa 1991; (24) Walker 1992.

3. THE AGES OF OLD CLUSTERS

3.1 Deriving Ages from Cluster Color–Magnitude Diagrams

The difficulties inherent in fitting theoretical isochrones to observed star cluster color–magnitude diagrams have prompted a number of attempts to parametrize the morphology of either the theoretical diagrams (Janes & Demarque 1983) or the observational diagrams (Anthony-Twarog & Twarog 1985). The concept of the "morphological age" of a cluster was introduced by Anthony-Twarog & Twarog, who computed the ratio of the difference between the luminosity of the main-sequence turnoff and that of the horizontal branch to the color difference between the turnoff and the giant branch. Similar strategies were used by Buonanno *et al.* (1989), VBS, and Sarajedini & Demarque (1990) to study globular clusters. All of these morphological indices are attempts to quantify the visible differences in the color–magnitude diagrams for stellar systems of different ages in a way that bypasses the many observational and theoretical calibration problems.

In Paper I, we adopted as our primary age parameter, an index δV, defined as the magnitude difference between the main-sequence turnoff and the clump, along with a second age parameter, independent of δV, that is based on color differences. Our color index parameter, $\delta 1$, is the difference in color index between the bluest point on the main sequence at the luminosity of the turnoff and the color of the giant branch one magnitude brighter than the turnoff luminosity. The $\delta 1$ values were transformed onto the scale of δV and the two indices merged to yield a single δV estimate for each cluster (see Paper I for details of the derivation of δV). The δV values listed in Table 1 are taken from Paper I.

The uncertainty in the δV values depends on the quality of the photometry, the cluster richness, and to a lesser extent on the cluster morphology. The reddening and distance can also be considered as factors, since clusters with large reddening and large distances will tend to have less well defined color–magnitude diagrams. In Paper I we assigned a quality index to each cluster to provide a relative ranking of the precision in δV (see Table 5 of Paper I). Our subsequent analysis showed that the δV values for the "a" clusters are defined with a precision of better than 0.1 mag, the "b" clusters between 0.1 and 0.2 mag, and finally, the "c" clusters are generally worse than 0.2 mag.

We have followed the same procedures as in Paper I to derive δV and $\delta 1$ indices for globular clusters (Table 3). To calculate the globular cluster indices, we used the color–magnitude diagram fiducial lines from VBS, supplemented by other recent published color–magnitude diagrams, as given in the references to Table 3. As in the case of the open clusters, the two indices were merged onto the scale of the δV index, using the relation developed in Paper I. These are listed as $\langle \delta V \rangle$ in the table.

The δV values for the globular clusters should all be considered to be of quality grade "a," as described above. Because the globulars are very much more populous, do not have a binary star sequence, and are generally less reddened, and because they have been observed with larger telescopes, δV can be estimated with substantially greater precision than in the typical open cluster.

3.2 The Morphological Age Index

Indices similar to the photometric index δV have already been shown to be highly correlated with cluster ages,

TABLE 4. Published open cluster ages.

Cluster	Publ. Age	Ref.	Adopted Age	Cluster	Publ. Age	Ref.	Adopted Age	Cluster	Publ. Age	Ref.	Adopted Age
NGC 188	6.5	12		Be 31	6.0	15	6.0	NGC 2660	0.8	24	
	6.6	29		NGC 2360	0.8	24			1.1	24	
	9.0	6			0.8	32			1.2	16	1.0
	9.0	34	7.8		1.0	29		Praesepe	0.7	22	
King 2	5.0	19			1.2	22			0.8	24	
	6.0	4	5.5		1.3	26			0.9	36	
NGC 752	1.0	24			1.4	24			1.1	24	0.9
	1.0	32			2.2	28	1.2	NGC 3680	1.0	24	
	1.1	9		Mel 66	6.5	2			1.2	32	
	1.3	22			7.0	6	6.8		1.3	24	
	1.4	24		Mel 71	0.9	33	0.9		1.4	22	
	1.5	9		NGC 2420	2.4	12			1.8	26	
	1.7	26			3.3	25			1.9	9	1.9
	1.8	29			3.4	3		IC 4651	1.0	24	
	2.2	35	1.5		5.5	6	2.4		1.3	24	
NGC 1193	6.5	18	6.5	Be 39	8.0	20	8.0		1.9	29	1.5
Hyades	0.6	32		NGC 2506	3.4	27		NGC 6791	6.0	11	
	0.7	23			6.0	6	4.7		7.0	6	
	0.8	24		M 67	3.4	30			8.0	21	
	1.2	24	0.8		3.6	30			8.9	29	
NGC 2141	6.0	6	6.0		4.0	12			9.0	13	7.8
NGC 2158	3.0	6			4.0	14		IC 1311	1.0	1	
	3.0	10	3.0		4.0	29			2.0	1	1.5
NGC 2204	4.0	6	4.0		5.0	31		NGC 7142	4.5	6	4.5
NGC 2243	3.0	8			5.2	17		King 11	5.0	5	5.0
	5.0	7			5.5	30		NGC 7789	0.8	24	
	5.0	8			6.0	6			1.1	24	
	7.0	6	5.0		6.0	30	4.7		1.6	26	1.2

References to TABLE 4

(1) Alfaro *et al.* 1992; (2) Anthony-Twarog *et al.* 1979; (3) Anthony-Twarog *et al.* 1990; (4) Aparicio *et al.* 1990; (5) Aparico *et al.* 1991; (6) Barbaro & Pigatto 1984; (7) Bergbusch *et al.* 1991; (8) Bonifazi *et al.* 1990; (9) Carraro, *et al.* 1993; (10) Christian *et al.* 1985; (11) Demarque *et al.* 1994; (12) Demarque *et al.* 1992; (13) Garnavich *et al.* 1994; (14) Gilliland & Brown 1992; (15) Guetter 1993; (16) Hartwick & Hesser 1973; (17) Hobbs & Thornburn 1991; (18) Kaluzny 1988; (19) Kaluzny 1989; (20) Kaluzny & Richtler 1989; (21) Kaluzny & Udalski 1992; (22) Maeder 1974; (23) Maeder & Mermilliod 1981; (24) Mazzei & Pigatto 1988; (25) McClure *et al.* 1974; (26) McClure & Twarog 1978; (27) McClure *et al.* 1981; (28) Mermilliod & Mayor 1990; (29) Meynet *et al.* 1993; (30) Montgomery *et al.* 1993; (31) Nissen *et al.* 1987; (32) Patenaude 1978; (33) Pound & Janes 1986; (34) Sandage & Eggen 1969; (35) Twarog 1983; (36) VandenBerg 1985.

(Buonanno *et al.* 1989), and may also be independent, or nearly independent, of composition effects. Similarly, VBS and VandenBerg & Stetson (1991) showed that an index very much like the present $\delta 1$ index is an excellent age indicator, although there are indications that it may be a slight function of metallicity. Salaris *et al.* (1993) have examined the problem of α-enhanced theoretical isochrones, and find that α enhancement has little effect on ages derived from indices such as δV or $\delta 1$.

Unfortunately, the correlation between δV and age is not at all linear, the slope of the relation increasing dramatically with age. Furthermore, uncertainties in theoretical models, particularly the well known problem of the mixing length and, for open clusters, the question of whether convective overshooting must be taken into account (see, e.g., Demarque *et al.* 1994), make any attempt at calibration suspect. On the observational side, the poor photometry and unknown compositions of most clusters add to the confusion.

Consequently, there have been no comprehensive studies of open cluster ages, nor are there any immediate prospects for such a study. To derive at least an approximate relation between δV and cluster age, we have done an extensive, although not exhaustive, literature search for published open cluster age estimates (Table 4). Except for the ages determined by Barbaro & Pigatto (1984), which are based on a theoretical calibration of the ratio of the numbers of clump stars to giant branch stars, we selected only references where the ages were derived from a match of theoretical isochrones to cluster photometry. When, in a particular study, a range in ages was given, based on a single set of isochrones, we took the average of the extremes, but if different ages resulted from comparison with different types of isochrones, we treated each value as an independent estimate. In most cases, the adopted age for each cluster is a simple mean of the ages found in the literature search. For a few of the best-studied clusters, we adopted other values for the age: for NGC 752 and NGC 3680, we took the convective overshooting ages from Carraro *et al.* (1993); for the Hyades, we used the mean of the published values; for NGC 2420, we used the recent convective overshooting values from Demarque *et al.*; and for M67, NGC 188, and NGC 6791, we took a simple mean of all the published values.

The ages derived in this fashion should be considered as representative, based on our "average" understanding of stellar evolution over the past 20 years or so. We made no attempt to emphasize ages based on any single type of evolutionary models, such as standard models, models with convective overshooting, O-enriched models and so on, nor have we made any attempt to account for cluster compositions. An examination of Table 4 will show that there is rather wide disagreement as to the ages of individual clusters. Even for some of the best-known clusters, such as M67, there is a range in age estimates of almost a factor of two, even though in this case at least the photometry itself is extremely well

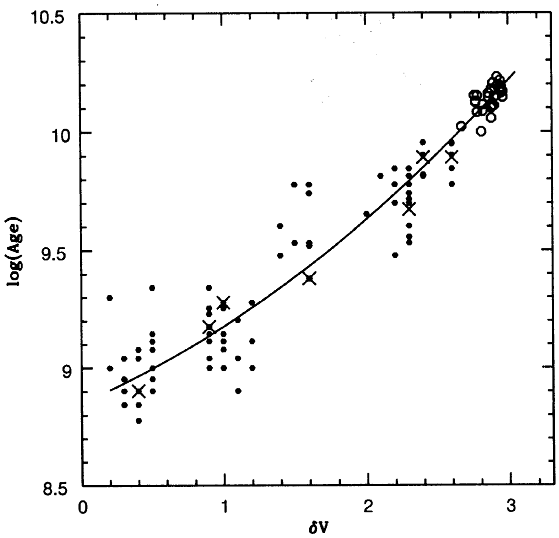

FIG. 1. Correlation between the color–magnitude diagram morphological parameter, δV, and the log of cluster ages. The dots refer to the individual open cluster age estimates, listed in Table 4; the open circles represent the globular cluster data from Table 3, with ages from Chaboyer *et al.* (1992); and the X's show the adopted ages of the "best" clusters from Table 4. The solid line is a quadratic fit to the globular clusters and the best open clusters.

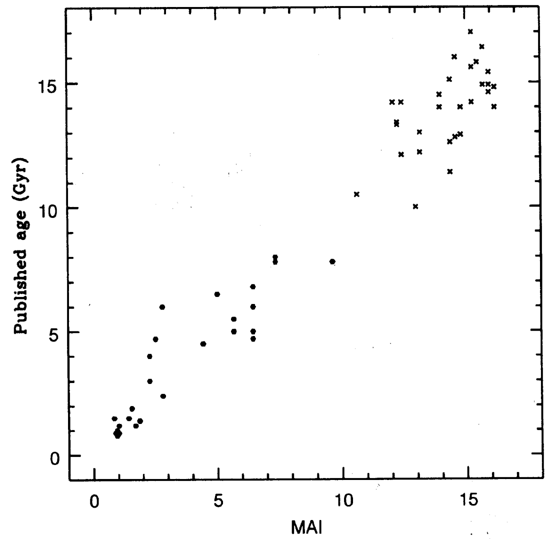

FIG. 2. The derived morphological age index (MAI) vs cluster age for the open clusters (dots) and globular clusters (crosses). The globular cluster ages are from Chaboyer *et al.* (1992).

defined (Montgomery *et al.* 1993). Differences in the models, different assumptions about reddening and metallicity, and different approaches to comparing models with the observations account for most of the disagreements that can be found in Table 4.

In spite of the uncertainties in cluster ages, Fig. 1 shows a good correlation, albeit with considerable scatter, between δV and the *logarithm* of cluster age. In this figure, each separate age estimate listed in Table 4 is plotted, so that many of the clusters are represented by multiple points in the figure. For the globular clusters, indicated with open circles, the ages are taken from a single source, Chaboyer *et al.* (1992). The large x's in the figure represent the mean age estimates from Table 4 for the small subset of the best-studied clusters (Hyades, NGC 188, NGC 752, NGC 2420, NGC 3680, NGC 6791, and M67).

In order to cast the δV index into an approximately linear relationship with age, we made a quadratic least squares fit of the δV measures for the globular clusters plus the best-known open clusters to log(Age), shown as the solid line in the figure. From the shape of that line, we then derived a "morphological age index" (MAI):

$$\mathrm{MAI}=0.73\times10^{(0.256\ \delta V+0.0662\ \delta V^2)}.$$

This index was scaled so that the oldest globular clusters have a typical MAI value of about 15, corresponding to the approximate age of the oldest globulars. As shown in Fig. 2, there is a linear relationship between cluster age and the MAI. In this figure, the mean open cluster ages given in Table 4 are used. The rms difference between the MAI and the tabulated open cluster ages is 1.1 Gyr, whereas the rms difference between the MAI and globular cluster ages is 1.3 Gyr. The expected age error for a given uncertainty in δV is a strong function of δV itself, but as an example, for an open cluster with a δV error of 0.15, the equivalent age error at $\delta V=2$ (corresponding to MAI=4.4 Gyr) is approximately 0.8 Gyr. At $\delta V=2.3$ (corresponding to MAI=6.5 Gyr) the age error rises to 1.4 Gyr. These numbers are consistent with the observed rms differences between MAI and the published ages, when consideration is given for the substantial uncertainty in the published ages.

The MAI was scaled so that its value corresponds approximately to the actual ages of star clusters and Fig. 2 indicates a good, approximately linear correlation with age. *Nevertheless, the heterogeneity of the calibration material, the problem of convective overshooting at intermediate ages, and residual correlations with composition demand caution. The sole purpose of the MAI is to permit the ranking of clusters in order of relative age in an approximately linear relationship in the following section.*

3.3 The Age Distributions of Old Clusters

Figure 3 shows histograms of the numbers of open clusters and globular clusters as a function of the MAI. Assuming that the MAI is even approximately related to the actual ages, then the galactic disk is at least 10 Gyr in age, and the oldest open clusters are similar in age to the youngest globulars. There is an apparent peak in the numbers of clusters between 5 and 7 Gyr, or alternatively, a possible dip in the distribution between 3.5 and 5 Gyr.

The distribution of open cluster ages depends on the cluster birthrate and on the destruction rate, neither of which is known. In any case, the substantial number of very old clusters in the sample is not expected, since the lifetimes of *typical* open clusters are 200 Myr or less (Janes *et al.* 1988). The simplest model for the numbers of clusters would combine a uniform formation rate with an exponential destruction rate; the number of clusters surviving to the present will

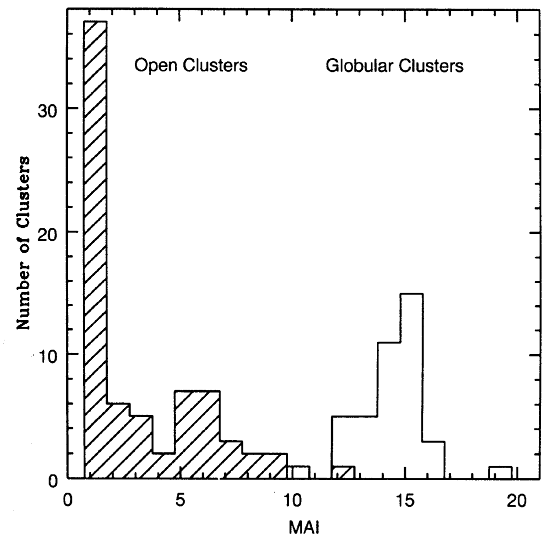

FIG. 3. Histogram of the numbers of clusters vs MAI, for open clusters (crosshatching) and for globular clusters (clear).

also be an exponential function of the cluster age. However, as Fig. 4 shows, a single exponential function cannot explain the cumulative count of the number of clusters surviving from a given age. The dashed line represents an exponential with an age scale factor of 4 Gyr. When a second exponential function, with a scale factor of 200 Myr is added, the combined relation, shown with the solid line in Fig. 4, makes a reasonable, although not precise fit to the observed distribution. There is still a possible excess in the numbers of clusters with ages between 5 and 7 Gyr, relative to both younger and older clusters; we will return to this excess later.

An alternative solution, deliberately chosen to fit the data between 2 and 6 Gyr, is shown in Fig. 5. In this solution, the long-lived population has an age scale of 5.2 Gyr. This "model" suggests a sharp cutoff in the number of clusters at 7 Gyr.

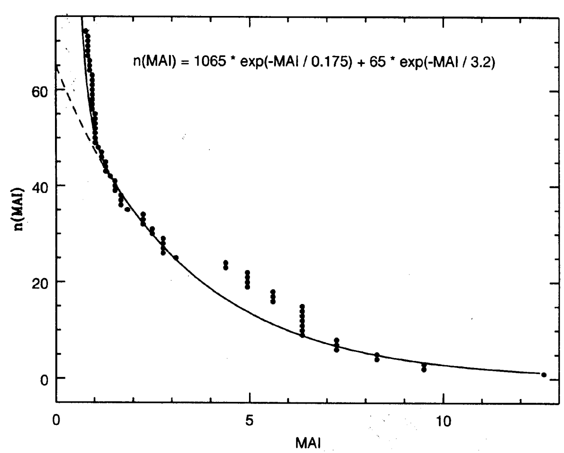

FIG. 4. Cumulative distribution of numbers of clusters with ages greater than the value, MAI. The solid line in the figure represents the function shown at the top of the figure. The dashed line shows the second term in the equation only, that is, the old disk population of open clusters.

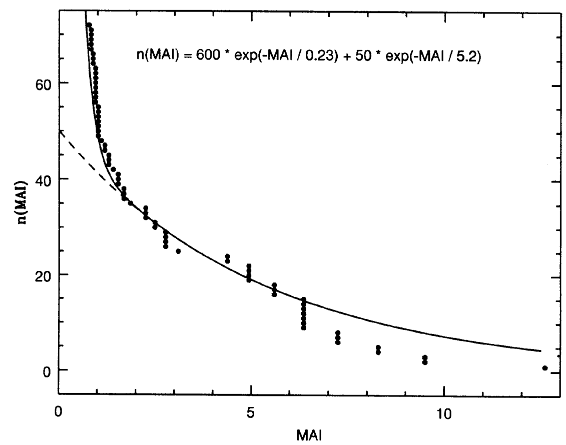

FIG. 5. Same as Fig. 4, except that the function was adjusted to fit the youngest clusters and those with ages up to about 7 Gyr only.

The conclusion that there exists a population of disk clusters with typical lifetimes of several Gyr is contrary to current ideas of cluster dynamics (see Wielen 1977), which require systems moving near the galactic plane to have rather short lifetimes. In order for these clusters to have survived to the present, there has to be something special about them. In fact, as van den Bergh & McClure (1980) pointed out, there are two things that make this group of clusters special: they are located mostly in the outer regions of the galactic disk, and their orbits carry them far from the galactic plane. But the question now becomes, how did they get into those sorts of orbits?

4. THE GALACTIC DISTRIBUTION OF OPEN CLUSTERS

To find the distribution of clusters in the galaxy, their distances are needed. For many of the clusters in Table 1 the distances and reddening are tabulated in the COCD; these are identified by "L" in the "Source" column of Table 1. More recent published sources than the COCD are identified with a source number referring to the list of references in the footnote to the table.

For the distances to most of the remaining clusters, we made use of the fact, first noted by Cannon (1970), that the luminosity of the red giant clump is nearly independent of age in clusters older than a few hundred million years. We used the published data listed in Table 1 to derive M_V and $(B-V)_0$ for the clump in all clusters where these quantities can be measured (Table 5). Because of slight differences in the clump luminosity and color between the older clusters and the younger ones, we calculated the mean luminosities and colors for the younger and older clusters separately; the errors quoted in Table 5 reflect simply the total variance in

TABLE 5. The red giant clump.

δV	M_V	$(B-V)$	n
<1.0	0.59±0.46	0.87±0.12	24
>1.0	0.90±0.40	0.95±0.10	23

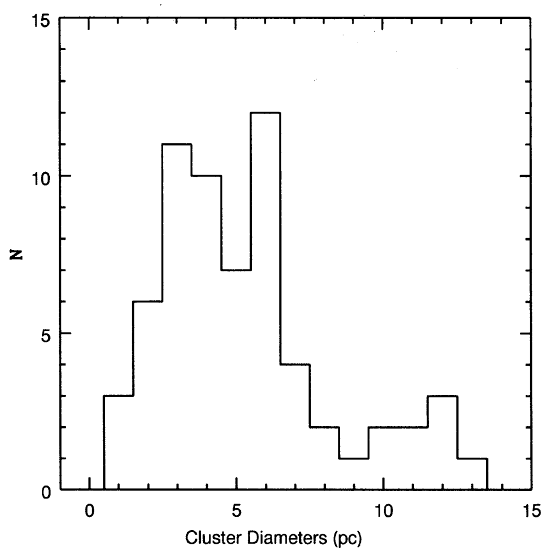

FIG. 6. Histogram of open cluster diameters. The median value is approximately 5 pc.

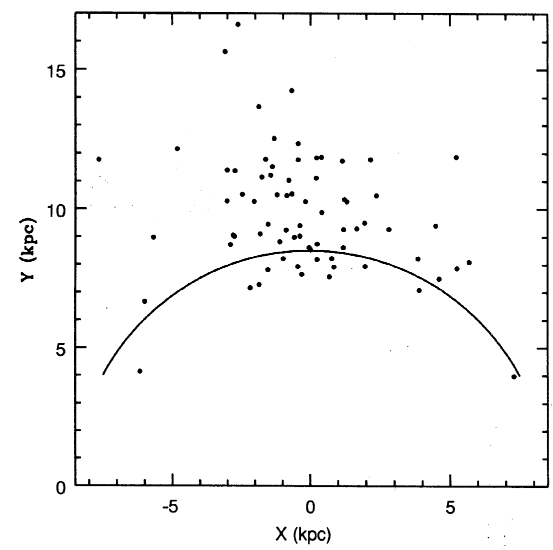

FIG. 7. Distribution of the old clusters on the galactic plane. The Sun is at $X=0$, $Y=8.5$ kpc, and the galactic center is at (0,0). The circle has a radius of 8.5 kpc, centered at the galactic center.

m_V and $B-V$, including both photometric errors and the uncertainties in making visual estimates of the critical quantities, as well as a probable intrinsic spread in HB luminosities and colors among the old open clusters. The dispersion in these quantities is small enough for estimating the approximate distances to clusters that would be otherwise unknown, and from the mean clump color indices given in the table compared to the observed clump colors, estimates of reddening to the individual clusters can also be made. In Table 1, the distances and reddenings to clusters found in this way are indicated by "C" in the source column.

Finally, the MAI indices for a few clusters discussed in Paper I were derived from uncalibrated photometry; for those clusters, we have estimated their distances by relating their angular diameters (taken from the COCD) to an assumed value for the linear diameter. As is well known (Trumpler 1930; Janes *et al.* 1988), there is a relatively small range in the linear diameters of open clusters. The distribution of linear diameters of the clusters of Table 1 is shown in Fig. 6; the median value is 5.3 pc. The COCD lists two values for the angular diameters of most clusters, and an inspection of the catalog shows some large differences between the two values. Nevertheless, the lower quartile of the distribution in Fig. 6 is 3.3 pc and the upper quartile is 6.9 pc. Only a few clusters have diameters more than twice the median value. Several of these are well known clusters whose distances are well determined, and in some cases their angular diameters appear to have been substantially overestimated. It is likely, therefore, that the actual distribution in cluster diameters has a smaller dispersion than indicated by Fig. 6. We have adopted 5 pc as the typical old cluster diameter, and estimate that the probable error of the distances found in this way will be of the order of 30 percent; they are indicated by a "D" in the source column of Table 1.

Figure 7 shows the distribution of the old clusters in the galactic plane; the clusters are shown on an x,y coordinate system, with the zero point in y at the galactic center (the Sun is assumed to be at 8.5 kpc) and the Sun on the x axis. The circle in the figure represents the solar circle about the galactic center. Only a few clusters are found inside the solar circle, and those few are not far inside. Another representation of the galactocentric distribution of the old clusters can be seen in the histogram of Fig. 8. The sharp edge to the distribution at $R_{GC}=7.5$ kpc is particularly striking. It has been noted before (e.g., van den Bergh & McClure 1980) that most of the old clusters are in the outer disk; van den Bergh and McClure attributed the lack of old clusters in the inner disk to the destructive power of the large numbers of giant molecular clouds in the inner regions of the galaxy, but

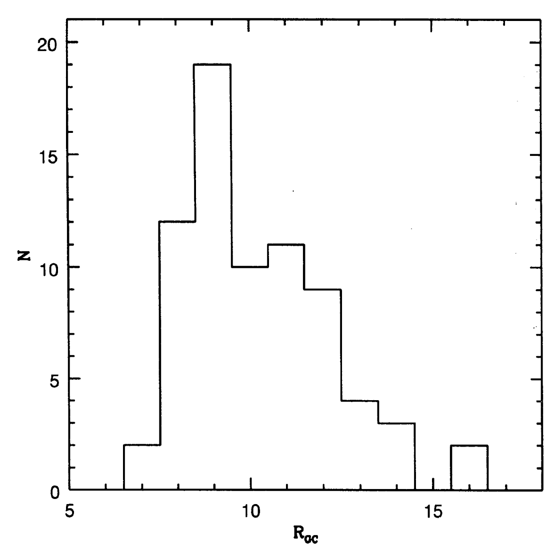

FIG. 8. Histogram of distances of open clusters from the galactic center (R_{GC}). Note the sharp edge to the distribution at $R_{GC}=7.5$ kpc.

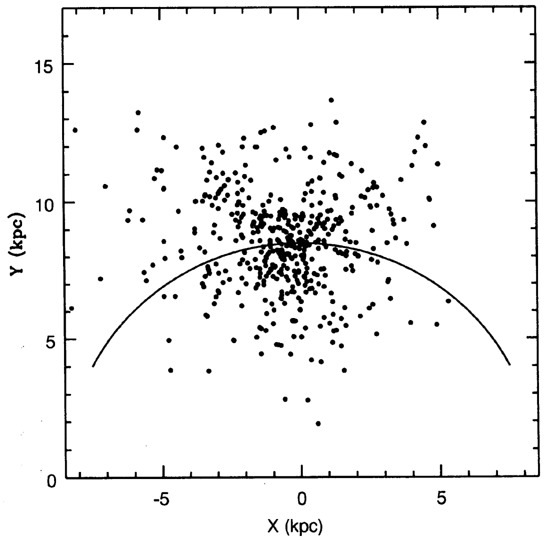

FIG. 9. Distribution of the young clusters on the galactic plane. The scale is the same as Fig. 7.

a possible additional factor will be discussed in the following section.

In stark contrast is the diagram in Fig. 9 showing the distribution of all clusters in the COCD with Trumpler classes "m" and "r," after deleting the old clusters of Table 1. Presumably, the vast majority of these clusters are young. Their distances were derived on the assumption that they all have diameters of 5 pc. Although the individual cluster distances in this figure may not be well determined, the fact that their apparent distribution is centered nearly on the Sun, whereas the old clusters are almost all further from the galactic center than the Sun could not be explained by any distance errors.

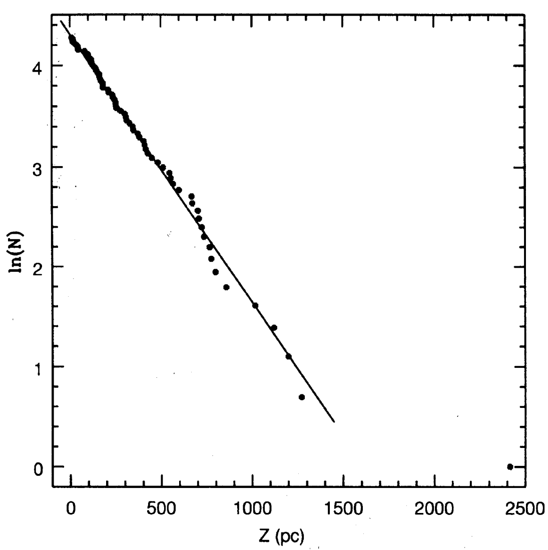

FIG. 10. Cumulative distribution of the ln of the numbers of clusters with distances from the galactic plane, z, plotted vs z. The solid line has a slope of -375 pc.

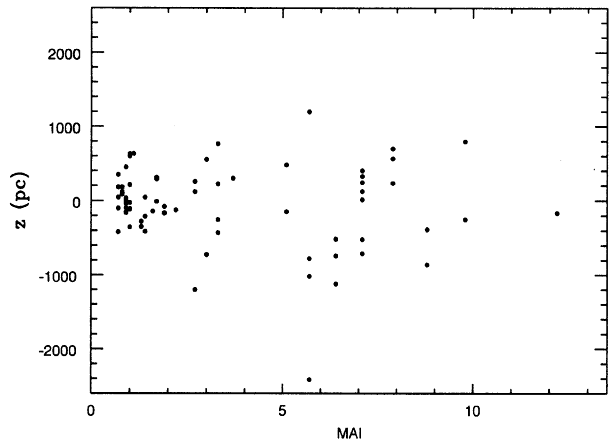

FIG. 11. Distribution of the distances of clusters from the galactic plane, z, as a function of the MAI. Note the lack of a correlation between the two.

The distribution of the old open clusters perpendicular to the galactic plane is well fit by a simple exponential law. Figure 10 shows the logarithms of the numbers of old clusters with distances from the plane greater than distance, z, plotted vs z. The straight line in the figure represents an exponential function with a scale height of 375 pc. In contrast is the distribution of the young clusters. The scale height of this group of clusters is approximately 55 pc, a much thinner distribution than that of the old clusters.

The relation between cluster age and distance, z, from the galactic plane is shown in Fig. 11. A small group of youngest clusters is relatively close to the galactic plane; these are the same clusters that follow the 200 Myr exponential decay curve of Fig. 4. Otherwise, there is no evident correlation of age with distance from the plane. This figure is very different in character from the distribution of individual stars about the galactic plane as a function of age. For example Wielen (1977) found the velocity dispersion of 1 Gyr old stars to be 8 km s^{-1}, increasing gradually to 25 km s^{-1} at 5 Gyr in age. For comparison, a star in the plane with a velocity perpendicular to the plane of 9 km s^{-1} will travel to a maximum of 100 pc from the plane, and a star with a velocity of 37 km s^{-1} will reach 500 pc (Mihalas & Routly 1968).

As Fig. 12 shows, there is also no correlation of cluster age with distance from the galactic center. One might expect that if clusters are destroyed by giant molecular clouds, then the oldest clusters should be well into the outer disk of the galaxy where there are far fewer giant molecular clouds. Yet, some of the oldest and some of the youngest clusters in our sample are found near the solar radius in the galaxy.

The observed galactic distribution of the old clusters explains why they have survived for so long: their orbits in the outer disk, with large z velocities as they pass through the plane, greatly enhance their survivability, relative to the bulk of the open clusters. But we still do not have an explanation as to how these clusters acquired their kinematic properties.

5. THE ORIGIN OF THE OLD CLUSTER POPULATION

The age distribution of the open clusters, overlapping that of the globular clusters as shown in Fig. 3, demonstrates that

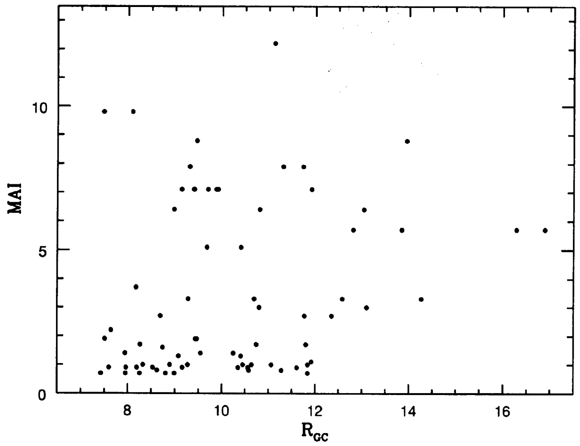

FIG. 12. Distribution of the distances of clusters from the galactic center, R_{GC} as a function of the MAI. Note the lack of a correlation between the two in this diagram as well.

star formation has proceeded more or less continuously since the time of formation of the galaxy. The characteristic lifetimes of the old clusters are long enough (4–5 Gyr, see Figs. 4 and 5) that a significant number of them should have survived from earliest times, and indeed, we find a small number of clusters as old as 10 Gyr in age.

As mentioned previously, there appears to be an excess of clusters between 5 and 7 Gyr in age, relative to the numbers before and after. The excess is of the order of ten clusters, which is significant at roughly the two sigma level, depending on what the expected background level is. If the excess is real, a possible inference from Fig. 4 would be that a major burst of star formation took place in the galactic disk between 5 and 7 Gyr ago. Alternatively, Fig. 5 suggests the possibility that there was very little cluster formation activity until about 7 Gyr ago, when rather suddenly, things began to happen in the disk. In actuality, these two "models" are really rather similar to one another, the essential point being that the star formation rate in the galactic disk, or to be more precise, the rate of formation of *long-lived star clusters*, may not have been uniform with time.

In fact, Figs. 4 and 5 may not actually tell us much about the *overall* rate of star or star cluster formation, for, as we have already seen, the old open cluster population, as sampled by the clusters of Table 1, is very different from the general galactic open cluster population in its distribution with distance from the galactic plane and position projected onto the plane. Yet at the same time, the chemical compositions of the old clusters appear to be entirely in accordance with the compositions of field disk stars at the same location and age (Friel & Janes 1993). The old clusters must have formed from the same material as other stars and clusters, but either their kinematic properties at birth or subsequent changes in their orbits dramatically enhanced their survivability, relative to the majority of open clusters.

Three possible processes could be invoked to explain the existence of this old cluster population:

(1) The old clusters represent simply the long-lived, high z tail of the general open cluster population.

(2) The old clusters have survived because they diffused away from the galactic plane through encounters with giant molecular clouds or other large objects, as part of the general heating of the galactic disk (Lacey 1984; Carlberg & Sellwood 1985).

(3) The old clusters belong to a population of stars that formed as a result of disturbances to the galactic disk, possibly caused by infalling gas or tidal interactions with other galaxies.

5.1 Could the Old Clusters be the Tail of the General Cluster Distribution?

The characteristic lifetime of the dominant population of open clusters is less than 200 Myr, and follows an approximately exponential decline in number (Fig. 4) with time. Yet, there are 24 clusters in our sample older than about 5 Gyr, which is about 25 or more e-folding times. If the old clusters represented simply the tail of this distribution, then they would have to be drawn from a total population of some 7×10^{10} clusters over that period of time for even *one* cluster to have survived from 5 Gyr ago until the present.

To take another perspective, the scale heights of the young and old clusters are 55 and 375 pc, respectively (see Sec. 4), with one moderately old cluster, Be 20, located approximately 2.5 kpc below the galactic plane (MacMinn *et al.* 1994), and 17 old clusters being more than 550 pc (10 times the 55 pc scale height) from the galactic plane. Although the scale height of the young clusters increases with increasing galactocentric radius, the old clusters show no variation in scale height with distance from the galactic center. In effect, these scale height figures refer to the solar galactocentric radius, where the 55 pc scale height is applicable.

If these 17 clusters represent the high z tail of the same exponential distribution characteristic of the young clusters, then they would have to have been drawn from a population of some 375 000 *rich* clusters. (Since all of the clusters far from the plane are populous, whereas most young clusters are not, then unless there is a correlation between z and the *formation* masses of clusters, the high z clusters would have to be drawn from a far larger number of clusters of all masses.) Assuming a uniform cluster formation rate, 375 000 clusters in 10 Gyr corresponds to a formation rate in the region sampled of 7500 rich clusters per 200 Myr. The high z clusters are drawn from a region approximately 5 kpc in radius around the Sun (see Fig. 7); so one would expect to see perhaps 300 rich clusters within 1 kpc of the Sun with ages less than 200 Myr. The total number of clusters within 1 kpc of the Sun tabulated in the COCD is 92, the majority of them being not at all rich.

That portion of the old cluster population with large distances from the galactic plane cannot be explained as just the high z tail of the normal 55 pc thin disk population.

5.2 Scattering of Open Clusters

Perhaps instead, the old clusters have been scattered into the near halo after their formation. Encounters between stars and massive irregularities in the disk, such as giant molecular clouds or spiral arms, have been invoked to explain the heating of the galactic disk (Lacey 1984; Carlberg & Sellwood 1985). Could a cluster survive the buffeting long enough to be ejected from the galactic disk, or do such encounters inevitably disrupt clusters?

Spitzer (1958) considered the tidal effects on a cluster due to encounters with interstellar clouds. If the time the cluster takes to pass by the cloud is short compared the time it takes the stars within the cluster to move a significant distance, then one can make an impulsive approximation to the tidal interaction. With this approximation, Spitzer derived relations for the increase in cluster internal energy, and for the survival time for star clusters against disruption by gas clouds. This process has been reconsidered many times (see e.g., Wielen & Fuchs 1988). As Wielen & Fuchs showed, the lifetimes of clusters are actually determined by a combination of encounters with giant molecular clouds and the tidal effects of the general galactic gravitational field. In the solar vicinity, these disruptive forces result in the destruction of a typical cluster in a few hundred million years or less.

But it is precisely these same encounters with molecular clouds or other gravitational irregularities of similar mass that are believed to be responsible for the general diffusion of stellar orbits (Lacey 1984; Carlberg & Sellwood 1985). However, the time scale for heating of the disk is of the order of billions of years (Wielen 1977; Carlberg *et al.* 1985), not hundreds of millions of years.

It is not likely that clusters will be ejected from the galactic disk after they form; they will be disrupted instead.

5.3 Disturbances to the Galactic Disk

As mentioned in the introduction, Zinn (1993) has suggested that there may be two populations of halo star clusters; an "Old Halo" of clusters which formed in a collapse of the galaxy, leading to the formation of the disk, and a "Younger Halo" consisting of clusters that formed out of satellite systems accreted by the galaxy. But the accretion of these same satellite systems must have disrupted the nascent disk (see Quinn *et al.* 1993), and there may have been a prolonged period of time when the disk was kept in a disturbed state, producing what we now call the thick disk.

We propose that the period of accretion of smaller systems by the galaxy did not end with the formation of the thick disk. Instead, our open cluster data can be explained if there have been repeated events stirring up the disk right up until relatively recent times. We now know that the Universe is full of intergalactic flotsam and jetsam—the "Lyman α forest" of small hydrogen clouds seen even at small redshifts in the spectrum of the quasar 3C 273 (Morris *et al.* 1992); large numbers of blue galaxies found at only at moderate redshifts (Cowie *et al.* 1991) and even near our own galaxy, the Magellanic Clouds, the Magellanic Stream, and the mysterious high velocity hydrogen clouds which are all heading our way. Whatever thin disk may have existed before 8–10 Gyr ago was disrupted, possibly repeatedly, by major events. Once the period of accretion of substantial systems ceased, the disk began to stabilize, with only relatively minor disturbances since then. Even after the disk formed, its subsequent evolution was determined not just by the continued evolution of a thin, rotating disk, but by the continued drizzle of small fragments onto the disk.

There are direct indications suggestive of this process in other nearby galaxies. Rubin & Graham (1990) found a drizzle of high-velocity gas onto the disk of the galaxy NGC 4258, and van der Hulst & Sancisi (1988) have detected neutral hydrogen moving perpendicular to the disk of M101, in a region where the spiral structure of the galaxy appears to be disturbed. They interpret their observations as evidence for a recent impact of an extragalactic gas cloud with with the disk of M101.

Calculations by Tenorio-Tagle *et al.* (1986, 1987) and by Comorón & Torra (1992) show that is if possible for the impact of a relatively small cloud onto the galactic disk to trigger vigorous star formation, with the stars being formed retaining at least some of the vertical (z) motion of the original infalling gas cloud. Some of those clusters we now call "old" open clusters could have formed in such impacts, their survival as clusters being the direct consequence of being formed with a substantial z component of velocity.

6. SUMMARY

For the first time, we have a significant sample of objects whose ages can be measured reliably, and which span the lifetime of the galaxy. This first examination of the old open cluster system as a distinct population shows that the galactic disk (what is generally called the "old, thin disk") began to develop about 10 Gyr ago, at the end of the period of cluster formation in the halo. The clusters that have survived from that era have done so simply because they were formed in favorable orbits, and they may have acquired such orbits because they were formed as the result of unusual events such as infalling gas, mergers of dwarf galaxies, or tidal interactions with other galaxies.

The Zinn (1993) "younger halo" and the thick disk are the consequences of interactions of the galaxy with other galaxies and fragments of galaxies at a time when such interactions were much more common and violent than they are now. The old clusters we have observed could well have been formed in some of the smaller and more recent disturbances that were not severe enough to disrupt the disk completely. There is a possibility that the oldest cluster in our sample, Be 17, as well as another old cluster of ambiguous status, Lyngå 7, (Ortolani *et al.* 1993), and one or two of the "globular" clusters could actually be members of the thick disk population.

If this picture for the development of the galaxy is correct, then the only direct remnant of the initial collapse phase of the galaxy is Zinn's "old halo" and possibly some fraction of the central bulge population of the galaxy. The rest of the galaxy has been substantially disrupted since then; the thick disk is an artifact of that period, and the thin disk developed gradually as the frequency and severity of interactions and impacts decreased.

This model for the development of the galactic disk can also explain several aspects of the chemical evolution of the galaxy:

(1) There is a strong radial gradient in metallicity, which shows up in a variety of disk objects of various ages, including the old cluster system (Friel & Janes 1993).

(2) The overall gradient notwithstanding, the Friel & Boesgaard (1992) study of local open clusters shows convincingly that there are significant local variations in metallicity among relatively young objects (i.e., objects whose ages are small compared to the age of the galactic disk).

(3) The metallicities of open clusters show no correlation with distance from the galactic plane, and their radial velocities are entirely consistent with the velocities of other old disk objects (Friel & Janes 1993).

(4) There is no correlation between the age and metallicity of open clusters. After correction for the radial gradient, four of the oldest clusters (NGC 6791, Be 39, NGC 1193, and NGC 188) all have abundances equivalent to the solar value or higher (Friel & Janes 1993).

The continued rain of material onto the galactic disk explains both the lack of an age–metallicity correlation and the continued maintenance of a radial metallicity gradient. If the material colliding with the disk is metal-poor, local irregularities in abundances, the age–metallicity relation, and the radial gradient are explained naturally through the dilution and mixing of disk gas with the infalling material. Even if the infalling material is metal-rich, it will tend to land on the disk with a small angular momentum, on the average, resulting in the inward spiral of disk gas. The lack of an age–metallicity correlation and the steep radial abundance gradient are a natural consequence of chemical evolution models for the galaxy which include radial flows, which Mayor & Vigroux (1981) showed are a necessary consequence of any accretion of matter onto the galactic disk (see also, Pitts & Tayler 1989; Sommer-Larsen & Yoshii 1990).

The key to understanding the evolution of the galactic disk is to improve the quality and quantity of data for the old open clusters. Their reddenings, color–magnitude diagrams, compositions, and velocities all need to be determined, before these ideas can be properly tested.

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