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THE OLD OPEN CLUSTERS OF THE MILKY WAY

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ABSTRACT

The Galactic open clusters, in particular the oldest members, serve as excellent probes of the structure and evolution of the Galactic disk. Individual clusters provide excellent tests of stellar and dynamical evolution. Cluster spatial and age distributions provide insight into the processes of cluster formation and destruction that have allowed substantial numbers of old open clusters to survive. Spectroscopic and photometric data for the old clusters yield kinematic, abundance, and age information that clarifies the relationship between the old open cluster population and other Galactic populations. New samples of old open clusters, which span a large range in distance and age, are used to define disk abundance gradients and the cluster age-metallicity relationship, and they point to a complex history of chemical enrichment and mixing in the disk.

1. CONTEXT AND HISTORY

Open clusters have long been recognized as important tools in the study of the Galactic disk. The young clusters and stellar associations have been used for many purposes, among them to determine spiral arm structure, to map the rotation curve of the Galaxy, to investigate the mechanisms of star formation and its recent history, and to constrain the initial luminosity and mass functions in aggregates of stars. Within the large population of known open clusters, now numbering over 1200, the sample of old clusters has been an especially interesting minority.

The first small samples indicated that old open clusters, those with ages of roughly 1 billion years (Gyr) or greater, had special properties compared to the

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younger, more numerous population. From early statistics it was evident that old clusters were severely underabundant relative to the numbers expected by extrapolating the population of young clusters and assuming a uniform rate of star formation over the lifetime of the disk (Oort 1958). This fact was readily explained by the disruptive effects of encounters with massive clouds in the Galactic disk, which could easily destroy a typical open cluster (Spitzer 1958). When numbers were interpreted with the additional assumption of a uniform destruction rate, it became clear, on the contrary, that there was a significant population of very long-lived open clusters in the disk.

The old open clusters are excellent probes of early disk evolution. They can be dated relatively readily and can be seen to large distances; their brightest members are strong-lined red giants that are well suited for measurements of radial velocity and composition. These open clusters are thus excellent tracers of the structure, kinematics, and chemistry of the Galactic disk.

Until recently, the number of old open clusters known was small and the insights they offered into disk evolution were limited though provocative. However, recent systematic searches and follow-up photometry have revealed a substantial number of old open clusters. Investigations into their properties now provide the best tools for understanding the development and evolution of the Galactic disk. We are still in the early stages of unraveling the picture they provide and relating it to the complex history suggested by the other Galactic stellar populations, but significant progress has been made in the past decade. This review presents an introduction, both to the current status of observation and interpretation, and to the potential these clusters hold for furthering our understanding of disk evolution.

There are many outstanding questions we hope to answer. Why are these clusters so long-lived compared to most open clusters? What does this tell us about how destructive processes work in the disk or about the special circumstances under which these clusters formed? How did old open clusters come to be where they are? Exactly how old are they? How are they related to the other disk populations—the old thin disk, the thick disk, and the globular clusters? And, overall, what does this imply for both cluster and Galactic formation, the history of star formation in the disk, and its continuing chemical evolution?

This review begins with an overview of the properties of old open clusters to provide perspective both on their individual characteristics and their place in the Galaxy. With increased samples, we can look at the age distribution of the clusters and the correlation of properties with age. The chemical abundances of these clusters are reviewed and the disk chemical gradients and age-metallicity relationships as revealed in the old cluster population are discussed and compared to theories of galactic chemical evolution. Finally, we examine the constraints that the old clusters provide for pictures of Galaxy formation and evolution.

2. INDIVIDUAL CLUSTER PROPERTIES

2.1 *Structural Properties*

2.1.1 SIZES AND MASSES The open clusters are commonly thought of as sparsely populated, loosely concentrated, barely gravitationally bound systems of a few tens or hundreds of stars. Although true for many younger clusters and associations, the old clusters present a different impression. Most of our past generalizations rest on results from surveys and catalogs that present visual estimates of membership and apparent diameter. In fact, few open cluster systems have been studied in detail for their structural properties.

Surveys of open cluster properties (Lynga 1982, Janes & Adler 1982, Janes et al 1988, Janes & Phelps 1994) have noted that old clusters distinguish themselves by being relatively richer and more concentrated than younger clusters. However, it is clear from the variety of richness and simple cluster appearance that old clusters must span a wide range in total mass. On the other hand, they show a relatively small range in apparent linear diameters, with a median value of approximately 5 pc (Janes & Phelps 1994).

Early estimates of masses of open clusters derived from luminosity functions by van den Bergh & Sher (1960) gave masses of $900M_\odot$ for NGC 188 and $800M_\odot$ for M67, two of the classic old disk clusters. More recent studies of the luminosity functions of old open clusters (Francic 1989, Montgomery et al 1993, Mathieu & Latham 1986) that rely on star counts over the limited range of masses available in the old clusters render numbers in agreement with these; Francic finds a mass of $550M_\odot$, and Montgomery et al find a mass of $724M_\odot$ for M67. These estimates suggest typical cluster masses of $1000M_\odot$, though, as these authors recognized, and as discussed below, these estimates must be lower limits.

Some clusters are much more massive than these. Two of the most extensive studies of structural properties of open clusters are those by Leonard (1988) for NGC 2420 and by Mathieu (1984) for M11. In his survey of NGC 2420, a typical 3–4 Gyr old cluster in the outer disk, Leonard estimated a total mass of $4000M_\odot$. Mathieu (1984) estimated a mass of at least $5200M_\odot$ and perhaps as large as $9000M_\odot$ for M11, a cluster somewhat younger than the typical Galactic old open cluster. Kaluzny & Udalski (1992) give a best estimate of $4070M_\odot$ for NGC 6791, which is among the two or three oldest open clusters, though they note that even this figure must be a significant underestimate. It appears that some open clusters, particularly those older than about 1 Gyr, are significantly more massive than has been commonly thought.

Direct determination of masses of open clusters by star counts and observed luminosity functions is difficult for a variety of observational and astrophysical reasons. The typical apparent cluster diameter of 5 pc refers to a visual impression of the cluster size, and although it does not relate to a true physical quantity, it is most closely associated with a half-mass diameter. Dynamical models predict that stars will linger around the very much larger tidal radii of these clusters, so one expects to see cluster members well outside the apparent cluster diameters. Most star count data do not reach to these distances and omit many potential cluster members. Furthermore, recent deep CCD studies have shown that most open clusters have substantial binary populations, estimated at a minimum of 38% for M67 (Montgomery et al 1993) and up to 50% for King 2 (Aparicio et al 1990). Star count data and luminosity functions need to be corrected for this large and often uncertain factor. In addition, the observed luminosity functions cover a limited range in mass and call for significant extrapolation of the mass function to low masses, where, potentially, much of the cluster mass resides. And lastly, as discussed below, dynamical evolution in these old clusters is expected to be very effective at causing mass segregation and the evaporation of low mass stars. Flat luminosity functions often observed in the old clusters certainly reflect this preferential loss of low mass stars, but by concentrating on the inner cluster regions where mass segregation has operated to compound the depletion of the low mass stars, these studies can yield a deceptively flat mass spectrum and a significant underestimate of the initial cluster mass.

Compensating for all these effects necessarily makes mass estimates extremely uncertain, but indicates that, in spite of the best of efforts, we are likely to underestimate both the present-day and original masses of these old clusters. Observational selection and dynamical arguments indicate that, although they were likely formed with a range of masses, many of the old clusters that we see today were stellar systems with initial masses in excess of $10^4 M_\odot$.

2.1.2 DYNAMICAL EVOLUTION Observational work on defining the structural and internal dynamical properties of open clusters has not advanced as far as similar studies on the more concentrated, more massive globular clusters, but the available evidence, both observational and theoretical, indicates that open clusters that have survived to ages of at least a billion years have undergone significant dynamical evolution. King (1962, 1966) found that open clusters, like M67, NGC 188, and NGC 7789, followed the surface density profiles expected for isothermal spheres modified by tidal forces, and successfully described them by models with small ratios of tidal to core radii, or concentration parameters, of 6 to 8. Old open clusters typically show core radii of 1–2 pc and tidal radii of up to 10 to 25 pc (King 1962, Mathieu 1984, Leonard 1988).

With initial masses in excess of $10^4 M_\odot$ and ages greater than 1 Gyr, these clusters have had sufficient time to relax dynamically, and we expect to see mass segregation among the cluster members. Hints that mass segregation has occurred were seen in the early data of van den Bergh & Sher (1960), who found flatter luminosity functions in the inner regions of clusters, which suggested fewer low mass stars than in the outer regions. The clearest evidence for mass segregation is seen in the best-studied clusters, M11 (Mathieu 1984) and M67 (Mathieu & Latham 1986), where the higher central concentration of more massive stars, including binaries in the case of M67, is convincingly demonstrated.

There is conflicting evidence, however, that the evolved red giant stars in some old open clusters are less centrally concentrated than the presumably less massive main-sequence stars. Hawarden (1975) found that the He-core burning stars are significantly less centrally concentrated than both the red giant branch stars and the main-sequence stars in a number of old open clusters. Similar results have been found for several other clusters, e.g. NGC 188 (McClure & Twarog 1977) and M11 (Mathieu 1984). This effect runs counter to that expected from mass segregation, unless the evolved stars have suffered a large amount of mass loss after leaving the main sequence. Although this explanation may be appropriate in several clusters (cf Tripicco et al 1993 for M67), the mass loss rates implied for some clusters are high enough to make this unlikely as a universal explanation. As some authors have pointed out, however, the results for a number of these clusters depend on small numbers of stars and may reflect statistical anomalies and possible stellar evolutionary effects (Harris & McClure 1985).

As mentioned above, many observational studies of the luminosity functions and derived mass functions of the old clusters show surprisingly flat distributions (van den Bergh & Sher 1960, Francic 1989, Caputo et al 1990, Aparicio et al 1990, Montgomery et al 1993). While luminosity functions for young open clusters continue to increase to fainter magnitudes and lower masses, in old clusters there is strong evidence for luminosity functions that either flatten, or reach a maximum, turn over, and decrease toward fainter magnitudes. Although field contamination and incompleteness complicate the interpretation of these results, the data point to strongly decreasing mass functions for the lower main sequence in the clusters.

The most unusual case studied thus far is NGC 3680, where a thorough and complete radial velocity survey has identified only 13 single main-sequence cluster members from a sample of approximately 120 stars in the field of the cluster (Nordstrom et al 1995). The cluster has apparently no low mass members remaining. The cluster NGC 3680 may be an extreme example of a cluster caught in its last years, but similar indications are found in NGC 752 (Daniel et al 1994) and IC 4651 (Anthony-Twarog et al 1988) and suggest that, rather than beginning with anomalous mass functions, these open clusters are sufficiently old dynamically that many of their low mass members have evaporated.

In addition to the dynamical evolution expected for isolated systems, we expect these open clusters to be particularly vulnerable to disruptive effects of Galactic tidal forces and encounters with interstellar clouds. The effects of these disruptive forces on Galactic clusters have been discussed and modeled by Spitzer (1958), Spitzer & Harm (1958), Wielen (1977, 1985), and Terlevich (1987) among others. These models indicate that most open clusters will be completely disrupted by successive tidal encounters with interstellar clouds on time scales of 10^8 to 10^9 years. However, these disruption time scales depend strongly on both cluster mass and core radius. The N-body simulations of Wielen (1985) and Terlevich (1987) predict that only encounters with the most massive, rare giant molecular clouds will be capable of disrupting open clusters with the larger number of members typical for the old open clusters.

Apparently, the open clusters we see today with ages of over a billion years have survived because of their larger than average mass, higher central concentration, and orbits that allow them to avoid the disruptive influence of the giant molecular clouds.

2.2 *Old Clusters as Tests of Stellar Evolution*

Traditionally, star clusters have been recognized as the optimum test cases for judging the applicability of stellar evolutionary models and the validity of their physical parameters and prescriptions. Most recently, however, the intermediate age open clusters have received special attention because of their potential to test the importance and efficiency of the phenomenon of convective overshooting in stars with masses from 1.0 to $2.2 M_\odot$.

There are many treatments of the physics of convective overshooting in the literature and the reader is referred to the excellent discussions of Maeder & Meynet (1989, 1991), Bertelli et al (1986), and Chiosi et al (1992) for more detail. The basic physical effect in the overshooting models, by comparison to conventional models, is the development of a small convective core in stars with masses $>1 M_\odot$, from which convective elements overshoot the boundary between the convective inner zone and the radiatively stable outer zone. If overshooting occurs, it effectively increases the core mass of the star during its main-sequence lifetime, thereby providing more fuel to live longer and causing the star to act like a much more massive star compared to evolutionary results from conventional models. The observational implications are seen most clearly in the morphology in the main-sequence turnoff region of the HR diagram and in the relative numbers of stars in various advanced stages of evolution (cf Mazzei & Pigatto 1988; Maeder & Meynet 1989, 1991).

A variety of treatments of overshooting have appeared in the literature over the past 10 years (Maeder & Meynet 1989, 1991; Meynet et al 1993; Bertelli et al 1985, 1986, 1992) for comparison with nonovershooting, conventional models of stellar evolution (VandenBerg 1985, Castellani et al 1992). The availability of alternative models and the recognition that intermediate age open clusters provide the best observational tests of the theory have spurred a large number of photometric studies of clusters in the age range of 700 million to several billion years in an effort to provide observational constraints. Among those working to obtain modern CCD photometry of clusters in this crucial age range are most notably Anthony-Twarog, Twarog, and collaborators (Anthony-Twarog et al 1988, 1989, 1990, 1991); Aparicio and colleagues (Aparicio et al 1990, 1991, 1993; Alfaro et al 1992); and Carraro and colleagues (Carraro & Ortolani 1994a, 1994b; Carraro & Patat 1994).

In spite of the plethora of observational studies to provide tests, the differing input physics and, more importantly, the differing prescriptions for the transformation from the theoretical to the observational plane make it a challenge to compare directly the results from the many available models. In addition, many of these investigations and their comparisons to theoretical models suffer from very poorly constrained observational parameters of reddening and metallicity or from disregard of existing data on these parameters, which limit the usefulness and the validity of these comparisons and their conclusions. As stressed by Twarog et al (1993) and Nordstrom et al (1995), a truly significant confrontation with alternative stellar evolutionary scenarios can be made only when all the observational parameters are used in conjunction to constrain the range of theoretical models used to interpret the observational color-magnitude diagrams.

Nevertheless, when limited to only the most well-studied and well-parameterized open clusters, the evidence is mounting in favor of models that include the effects of overshooting from convective cores in the mass range above $1.2M_{\odot}$. The very thorough recent studies by Anthony-Twarog et al (1991), Twarog et al (1993), Daniel et al (1994), and Demarque et al (1994), for example, lend clear support for the use of overshooting models. Using well-studied clusters, one can even begin to place limits on the efficiency of overshooting by matching the detailed morphology of the turnoff region. Although early papers indicated that the use of overshooting models would result in ages up to a factor of two larger than determined by conventional models, recent changes in the methodology of the overshooting models and more realistic estimates of the efficiency of overshooting suggest that the changes in the age scale for the intermediate age open clusters will be modest (Daniel et al 1994, Demarque et al 1994).

In spite of the evidence in support of overshooting models, it is important to note that the evolutionary models do not provide a perfect fit to all aspects of the color-magnitude diagram morphology in many of these clusters. Among the best-studied examples, the cases of M67 (Montgomery et al 1993), NGC 752 (Daniel et al 1994), NGC 188 (Twarog & Anthony-Twarog 1989), and NGC 3680 (Nordstrom et al 1995) all suggest that improvements can be made to the models and, in particular, to the accuracy of the transformation of the theoretical parameters to the observational plane.

2.3 *Binaries and Blue Stragglers*

Binary and composite systems are a frequent occurrence in open clusters. Attempts have been made to determine the proportion of binary systems and the distribution of their mass ratios in several open clusters, both by direct measurements of radial velocities and by inference from the observed width of the cluster main sequence. Many old open clusters show evidence for significant binary populations, and current estimates of the binary fraction in clusters range from 20 to 50% (Mermilliod & Mayor 1989, 1990; Anthony-Twarog et al 1990; Montgomery et al 1993; Aparicio et al 1990).

In addition, many old open clusters, like the globular clusters, show pronounced populations in the blue straggler region of the color-magnitude diagram (CMD) above and the blue of the main-sequence turnoff. A recent review on the nature and our understanding of the blue straggler population in star clusters can be found in Stryker (1993). Radial velocity and membership information exists for only a small number of old clusters, but these data indicate that a significant number of stars in the blue straggler region are radial velocity members, and among members the frequency of spectroscopic binaries exceeds 40% (Milone et al 1991, Milone 1992). In addition, the blue stragglers in the well-studied cluster M67 show clear segregation to the cluster center, consistent with their being more massive objects in a dynamically relaxed cluster (Mathieu & Latham 1986). However, a coherent picture of what drives the blue straggler phenomenon in open clusters remains elusive, and the lack of data available on both blue straggler members and structural parameters of open clusters prevents any investigation of the frequency of blue straggler populations with cluster type.

In addition to their intrinsic importance, the extent and nature of the binary stars and blue stragglers in the field of old open clusters have important consequences for the interpretation of CMDs and their comparison to theoretical models. As was first stressed by Andersen et al (1990), and recently well illustrated by Daniel et al (1994) for NGC 752, Demarque et al (1994) for NGC 2420, Anthony-Twarog et al (1991) for NGC 3680, and Aparicio et al (1990) for King 2, the turnoff region morphology is very strongly affected by the presence of compound systems. A cluster population of equal mass binaries will define an evolutionary sequence parallel to the single star main sequence but displaced by 0.75 toward brighter magnitudes. When these binary systems evolve through the single star turnoff region, they yield a wider color distribution at the luminosity of the turnoff and continue to luminosities brighter than the single star turnoff region, before they themselves evolve across the Hertzsprung gap and into the red giant region. The crossing of the single star and binary star evolutionary sequences creates a very complex color and luminosity distribution, just in the region where one wants to make detailed comparison to subtle features predicted by alternative theoretical isochrones, and to make age determinations based on turnoff color and morphology. Without full information on the binary nature and the membership probability of stars in these regions of the CMD, conclusive comparison to isochrones is compromised. Fortunately, the long-term efforts of many groups (e.g. Latham 1985, Mayor 1985) are providing high-precision velocities for stars in many open clusters, which permit both membership determinations and dynamical studies (Mermilliod 1990).

3. SPATIAL PROPERTIES

3.1 *Correlations with Galactic Position*

Even with the initial small samples, it was apparent that the oldest members of the open cluster population were distributed in the Galaxy differently from the majority population of younger open clusters. As early as 1958, van den Bergh had noted that the four oldest open clusters were located at higher distances out of the Galactic plane than were typical for open clusters. van den Bergh & McClure (1980), working with a sample of 20 clusters, substantiated this trend and were the first to point out that the clusters with ages greater than about 1 Gyr were located preferentially toward the Galactic anticenter relative to their younger counterparts. With increasingly larger samples of clusters available from the literature and the catalogs of Lynga (1981, 1987) and Mermilliod (1992), the properties of the open cluster population and, in particular, the distribution of the oldest open clusters in the Galaxy became more clearly delineated in a series of studies by Lynga (1982), Janes & Adler (1982), and Janes et al (1988). Since then, working from a list of potential old clusters given in Janes & Adler (1982), Kaluzny and colleagues obtained CCD photometry that revealed that many of these candidates were, indeed, very old (e.g. Kaluzny 1988, 1989; Kaluzny & Mazur 1991).

The most recent analysis of the overall properties of the old open clusters has been made by Phelps et al (1994) and Janes & Phelps (1994). As a result of an extensive photometric survey to identify candidate old clusters and obtain relative age ranking through color-magnitude diagram morphology, combined with a thorough literature search, the Phelps et al survey has yielded 72 clusters that are the age of the Hyades or older. Since that publication, three additional old clusters have been found (RL Phelps, private communication; Patat & Carraro 1994; Carraro & Ortolani 1994a) and one in the original list was found to be younger than the Hyades (Carraro & Ortolani 1994b). Table 1 gives a summary of properties for these 74 clusters. For most clusters the basic data on distances and original sources of photometry can be found in Janes & Phelps (1994), but where possible, their list has been supplemented with more recent results. With a sample almost quadrupled over that of van den Bergh & McClure's, the spatial distribution of the old clusters has become particularly well defined.

Figure 1 shows the distribution of these clusters projected onto the Galactic plane. Old clusters are completely absent inside a radius of 7.5 kpc, where their distribution drops off rapidly. Janes & Phelps argue that this abrupt edge to the distribution is indeed real, and point out that their searches would have revealed

Table 1 The oldest open clusters: summary of properties[a]

Cluster	l	b	D (kpc)	R_{gc}(kpc)	z (pc)	MAI	[Fe/H]	Ref 1[b]	Ref 2[c]
NGC 188	122.78	22.46	1.52	9.35	580	7.2	−0.05	1	3
King 2	122.88	−4.67	6.24	12.98	−510	5.6	–	1	–
IC 166	130.08	−0.19	3.08	10.74	−10	1.5	−0.32	1	1
NGC 752	137.17	−23.36	0.36	8.75	−145	1.4	−0.16	1	1
Be 66	139.42	0.23	4.85	12.59	20	4.4	–	2	–
NGC 1193	146.81	−12.18	4.01	12.00	−845	4.9	−0.50	1	1
King 5	143.75	−4.27	2.19	10.34	−163	0.9	−0.38	1	3
NGC 1245	146.64	−8.93	2.98	11.09	−465	1.0	0.14	3	4
Hyades	180.05	−22.40	0.05	8.55	−20	0.9	0.12	1	4
NGC 1798	160.76	4.85	3.44	11.79	290	1.5	–	1	–
NGC 1817	186.13	−13.13	1.81	10.26	−410	1.3	−0.39	1	1
Be 17	175.65	−3.65	2.40	10.89	−155	12.6	−0.29	4	3
Be 18	163.63	5.01	3.70	12.09	325	5.6:	–	5	–
Be 20	203.50	−17.28	8.14	16.12	−2420	4.9	−0.75	1	3
King 8	176.40	3.12	3.35	11.84	180	0.8	−0.40	1	1
Be 21	186.83	−2.50	5.80	14.27	−255	2.8	−0.97	1	1
Be 22	199.80	−8.50	3.60	11.92	−530	3.5	–	6	–
NGC 2141	198.07	−5.79	4.25	12.60	−430	2.8	−0.39	1	1
NGC 2158	186.64	1.76	3.88	12.36	120	2.2	−0.23	1	3
NGC 2194	197.26	−2.33	2.65	11.06	−110	1.0	–	1	–
NGC 2192	173.41	10.64	3.44	11.88	635	1.1	–	1	–
NGC 2204	226.01	−16.07	4.33	11.84	−1200	2.2	−0.58	1	4
NGC 2236	204.37	−1.69	3.32	11.61	−100	0.9	–	1	–
NGC 2243	239.50	−17.97	3.66	10.76	−1130	5.6	−0.56	1	1
Tr 5	202.86	1.05	2.80	11.13	50	4.9	–	5	–
NGC 2266	187.78	10.28	3.36	11.80	600	1.0	–	1	–
Be 29	197.98	8.03	10.50	18.72	1465	5.6	–	6	–
Be 31	206.26	5.12	3.80	12.02	340	3.5	−0.50	5	3
Be 30	210.80	2.89	2.34	10.58	120	0.9	–	1	–
Be 32	207.95	4.40	3.07	11.30	235	7.2	−0.58	1	3
To 2	232.90	−6.84	6.08	13.08	−725	2.5	−0.35	1	3
NGC 2324	213.45	3.31	3.18	11.29	185	0.9	−0.31	1	3
NGC 2354	238.42	−6.80	1.80	9.56	−215	1.3	–	1	–
NGC 2355	203.36	11.80	2.20	10.52	450	0.9	–	1	–
NGC 2360	229.80	−1.42	1.14	9.28	−30	1.0	−0.28	1	1
Haf 6	227.85	0.25	3.20	10.91	15	0.9	–	7	–
Mel 66	259.61	−14.29	2.88	9.44	−710	6.3	−0.51	1	1
NGC 2423	230.47	3.55	0.75	9.00	45	0.8	−0.04	1	4
Mel 71	228.96	4.45	2.69	10.46	210	1.0	−0.29	1	4
NGC 2420	198.11	19.65	2.28	10.59	765	2.8	−0.42	1	1

Table 1 (*cont.*)

Cluster	l	b	D (kpc)	R_{gc}(kpc)	z (pc)	MAI	[Fe/H]	Ref 1[b]	Ref 2[c]
AM2	246.89	−5.09	8.35	14.06	−740	8.3	–	1	–
Be 39	223.47	10.09	4.01	11.71	700	7.2	−0.31	1	1
NGC 2477	253.58	−5.83	1.15	8.89	−115	1.0	−0.05	1	1
NGC 2506	230.57	9.91	3.22	10.81	555	2.5	−0.52	1	1
Pi 2	258.83	−3.29	2.84	9.47	−165	1.7	–	1	–
Pi 3	257.83	0.43	1.19	8.83	10	3.1	–	8	–
NGC 2627	251.58	6.65	1.91	9.28	220	2.8	–	1	–
Praesepe	205.54	32.52	0.16	8.62	85	0.9	0.07	1	4
NGC 2660	265.86	−3.03	2.89	9.18	−155	0.9	0.06	1	4
M 67	215.58	31.72	0.77	9.05	405	6.3	−0.09	1	1
NGC 2849	265.27	6.33	5.73	10.64	630	1.0	–	1	–
092-SC18	287.10	−6.70	6.32	9.00	−740	5.6	–	1	–
NGC 3680	286.77	16.93	1.07	8.27	310	1.5	−0.16	1	1
NGC 3960	294.41	6.18	1.68	7.96	180	0.8	−0.34	1	1
Cr 261	301.69	−5.64	2.56	7.49	−250	9.5	−0.14	1	3
096-SC04	305.35	−3.17	7.57	7.44	−420	0.8	–	1	–
NGC 5822	321.71	3.58	0.73	7.94	45	1.3	−0.21	1	1
IC 4651	340.07	−7.88	0.92	7.65	−125	1.8	−0.16	1	4
IC 4756	36.37	5.26	0.39	8.19	35	0.9	−0.22	1	2
Be 42	36.17	−2.19	1.15	7.60	−45	0.9	–	1	–
NGC 6791	70.01	10.96	4.20	8.12	800	9.5	0.15	1	1,3
NGC 6802	55.34	0.93	1.02	7.96	15	0.9	–	1	–
NGC 6819	73.98	8.47	2.05	8.18	300	3.1	0.05	1	1,2
NGC 6827	58.24	−2.35	8.60	8.32	−355	1.0	–	1	–
IC 1311	77.70	4.25	4.71	8.80	350	0.8	–	1	–
NGC 6939	95.88	12.30	1.20	8.70	255	2.2	−0.14	1	2
NGC 6940	69.90	−7.16	0.81	8.26	−100	0.8	−0.06	1	2
Be 54	83.13	−4.14	2.30	8.54	−165	7.2	–	6	–
NGC 7044	85.87	−4.13	3.86	9.08	−280	1.2	–	1	–
Be 56	86.04	−5.18	5.73	9.92	−515	6.3	–	1	–
NGC 7142	105.42	9.45	2.95	9.70	485	4.4	0.00	1	1
King 9	101.45	−1.84	4.56	10.41	−145	4.4	–	1	–
King 11	117.16	6.47	2.19	9.69	245	6.3	−0.36	1	3
NGC 7789	115.49	−5.36	1.84	9.44	−170	1.7	−0.24	1	1,3

[a]For each cluster, the properties listed are: cluster name, l—Galactic longitude in degrees, b—Galactic latitude in degrees, D—distance to cluster in kiloparsecs, R_{gc}—cluster Galactocentric radius in kiloparsecs, z—cluster height from the Galactic plane in parsecs, MAI—Morphological Age Index in Gyr from Janes & Phelps (1994) or from K Janes (private communication) based on photometry (Ref 1), and [Fe/H]—metallicity from source given in Ref 2.
[b]Sources for distances and photometry: 1. Janes & Phelps 1994; 2. Phelps 1994, private communication; 3. Carraro & Patat 1994; 4. Phelps et al 1995; 5. Kaluzny 1995; 6. Kaluzny 1994; 7. Patat & Carraro 1994; 8. Carraro & Ortolani 1994a.
[c]Sources for metallicities: 1. Friel & Janes 1993, 2. Thogersen et al 1993, 3. Friel et al 1995, 4. Lynga 1987.

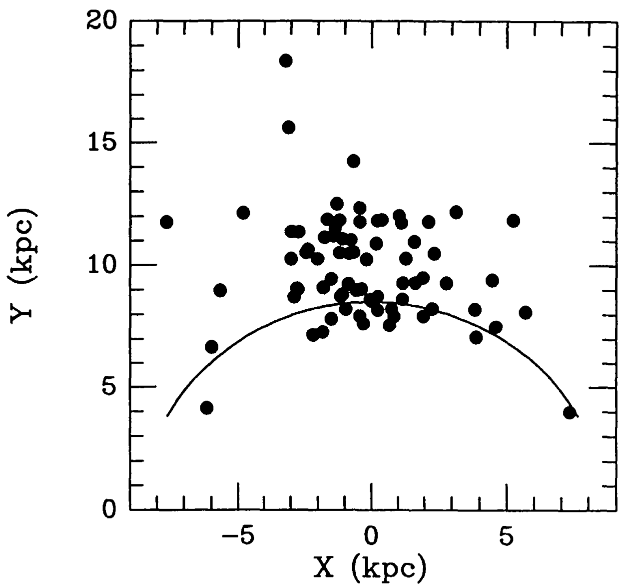

Figure 1 Positions of open clusters that are the age of the Hyades and older, taken from Table 1, shown projected onto the Galactic plane. The solar position is at (x, y) = (0,8.5 kpc) and the Galactic center is at (0,0). The solid line shows a circle with a radius of 8.5 kpc.

old clusters well inside this radius, if they existed, since younger clusters are found in these regions.

Obviously, location in the outer disk strongly favors cluster longevity. It has long been recognized that frequent encounters with giant molecular clouds, which are found primarily in the inner Galaxy, are very effective at destroying typical open clusters (Spitzer 1958, Wielen 1985, Terlevich 1987). An additional explanation is revealed by looking at the cluster distribution with height above the plane.

Figure 2 shows the distribution of open clusters with height above the plane as a function of Galactocentric distance. Clusters with ages less than that of the Hyades, taken from the Catalog of Open Cluster Data (COCD) (Lynga 1987) are shown in the first panel and older clusters from Table 1 are shown in the second panel. The older clusters fill a much thicker distribution, in addition to being located exclusively in the outer disk. Janes & Phelps (1994) find that the old cluster population is fit by a 375-pc scale-height exponential, an appreciably thicker distribution than that of the 55-pc scale-height young cluster population.

The old clusters not only spend their time in the outer disk away from the disruptive effects of giant molecular clouds, they spend their time at large distances from the Galactic plane, further enhancing their survivability.

3.2 *Kinematics*

In most cases, we have only cluster radial velocities, not complete space motions, through which to investigate cluster kinematics, though radial velocities have been determined for more than half the old clusters known. The most recent analysis of the kinematic properties of the old open cluster system has been made by Scott et al (1994), who present results for some of the most recently discovered very old clusters. They find that the radial velocities of the old clusters are consistent with those expected from the disk rotation curve defined by the young clusters (e.g. Hron 1987), but with a larger dispersion about the mean rotation curve of 29 km s^{-1}, in contrast to the 10 km s^{-1} typical of younger clusters (Lynga & Palous 1987, Liu et al 1989). Alternatively, assuming the old clusters move in a constant velocity of rotation, by analogy to analyses of the globular cluster system (Frenk & White 1980, Armandroff & Zinn 1988), the old open cluster system rotates with a velocity of 211 ± 7 km s^{-1} and a line-of-sight velocity dispersion of 28 km s^{-1}.

These kinematics are consistent with those expected if the old clusters share the general kinematic properties of the old, mixed-age, field disk population (Delhaye 1965). Because these clusters lie very close to the Galactic plane, their observed radial velocities are primarily combinations of their velocity components with respect to a local standard of rest in the directions of Galactic radial (Π) and rotational (Θ) motion. Indeed, the cluster line-of-sight velocity dispersions reflect the combined Π and Θ velocity dispersions with respect to

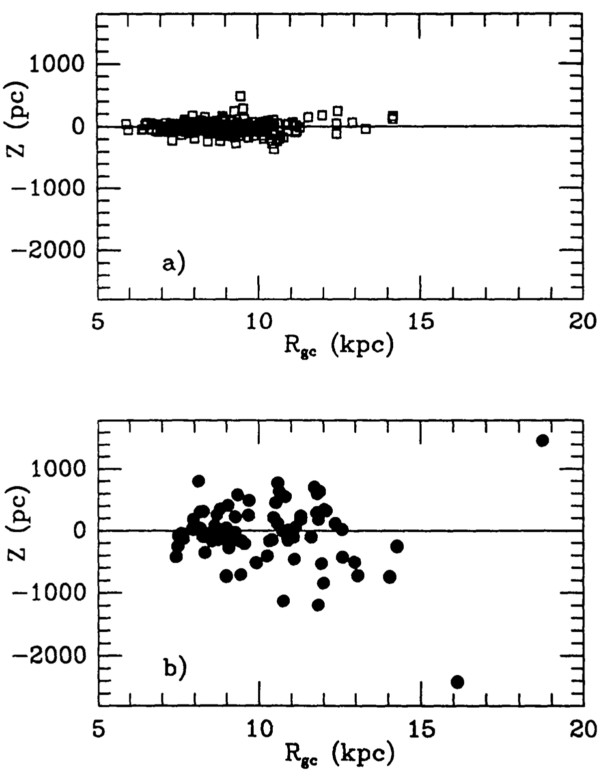

Figure 2 Distribution of open clusters with height from the plane as a function of Galactocentric distance, R_{gc}. The Sun is at 8.5 kpc. (*a*) Distribution for clusters with ages less than the Hyades, from Lynga (1987). (*b*) Distribution for clusters with ages equal to or greater than the Hyades from Table 1.

the Local Standard of Rest of 31 and 21 km s^{-1} typical of old disk, late-type stars.

Although the observed radial velocities tell us very little about the velocities perpendicular to the plane, the cluster scale height of 375 pc (Janes & Phelps 1994) is generally consistent with that found for other old disk populations (Yoshii et al 1987, Sandage & Fouts 1987, Norris & Ryan 1991), suggesting similarities in kinematics.

With increasing samples of clusters, we can begin to look at the details of the velocity distributions and investigate correlations with other cluster properties. Although we see a few clusters whose velocities deviate significantly from the mean rotation curve, their numbers are not unusual from a statistical perspective. Residuals from simple galactic rotation are not correlated with any other cluster properties, such as position in the Galaxy, distance from the plane, age, or composition.

The few old open clusters for which we have proper motions to permit a determination of their space motions indicate that they follow orbits that keep them far from the plane and in the outer disk. Early work on M67 and NGC 188 by Keenan et al (1973) and more recent calculations by Carraro & Chiosi (1994a) for these and three additional old clusters show that the clusters are on fairly low eccentricity orbits that take them not more than a few kpc from their current Galactocentric radii. They are also found to be currently quite close to the maximum distance their orbits take them from the plane. On the other hand, in a few cases, the observed velocities indicate significantly noncircular motions. A recent solution of velocities for the very old cluster NGC 6791 based on proper motions (Cudworth & Anthony-Twarog 1993 and private communication) shows it to be lagging circular rotation by about 65 km s^{-1} and moving outward from its current Galactocentric radius of 8.1 kpc with a substantial velocity of approximately 100 km s^{-1}. The clusters Be 17 and NGC 1817, located almost directly in the anticenter, have line-of-sight velocities that indicate deviations from the mean rotation curve of -88 and 52 km s^{-1}, respectively (Scott et al 1994, Friel et al 1989).

It is important to keep in mind that the clusters we now see are remnants of an originally much larger population of clusters, as is discussed below. By investigating the systemic properties of the old clusters, we will gain insight as much into the processes that create or destroy clusters as those that enable the clusters to survive to great ages. The fact that the spatial distributions and kinematics of the cluster system are generally consistent with normal disk rotation properties is an important key, but these distributions are molded by the efficiency of disruptive processes. In particular, the cluster velocities out of the plane, if we could determine them, would offer a way of distinguishing between the alternative pictures of cluster formation: whether clusters are formed in special events with the orbits that allow them to survive, or whether we are seeing simply the tail of a distribution from which the lower velocity (lower scale height) members have been destroyed.

4. AGE DISTRIBUTION OF THE CLUSTER POPULATION

4.1 *Cluster Age Determinations*

The open clusters offer an important advantage in studies of the evolution of the Galaxy because they provide a direct time line for investigating change. In spite of uncertainties in dating them, and the intricacies and subtleties of fitting theoretical isochrones to their CMDs, the clusters still provide a fairly accurate, at least relative, age relationship with which to study changes in the structure and chemistry of the Galaxy.

Ideally, one would have ages carefully and consistently determined by fitting of a uniform set of theoretical isochrones constrained by well-determined observational cluster parameters such as reddening and metallicity. Unfortunately, such precise and detailed age determinations do not exist for most old open clusters. Often the photometric data do not reach faint enough and the cluster sequences are complicated by strong field star contamination, making accurate isochrone fitting difficult. Although as discussed below, abundances have been determined for roughly half the old clusters, the cluster reddenings are still, in many cases, very poorly constrained; this uncertainty has significant impact on age determinations. The use of a wide variety of theoretical models to derive ages and differing methodologies in transforming the theoretical parameters to the observed color-magnitude plane has made it difficult to arrive at a consistent age ranking by simply collecting cluster ages as quoted in the literature.

Recent efforts to place many of the well-studied clusters on a uniform age system using a consistent set of theoretical isochrones (Carraro & Chiosi 1994b) have taken an important step toward presenting a homogeneous set of cluster ages. Unfortunately, studies of this kind are still limited by small sample sizes, the lack of deep photometry of excellent quality, and the lack of determinations and failure to use known cluster reddenings and metallicities.

To look at trends in properties with age in sufficiently large samples, one must turn to more general morphological age classifications that can be applied to large numbers of clusters and yield relative age indicators. Though these age estimates are only approximate, they allow us to examine the properties at the extremes of the cluster population by including the recently discovered very old and distant open clusters, for which we have only preliminary photometry and lack determinations of metallicity and reddening.

The morphological age classification schemes rely on the presence and parameterization of the evolved stars in a cluster, so are well suited to the old open cluster system. The color-magnitude diagrams of old open clusters are typically characterized by the presence of stars in the later stages of stellar evolution, both along the red giant branch and in the red giant "clumps," or the population of stars in the He-core burning phase of stellar evolution, analogous to the red Horizontal Branch stars in globular clusters (Cannon 1970). As with the globular clusters, the absolute magnitude and color of the clump stars are roughly constant, while the luminosity of the turnoff becomes fainter and the color redder, as the cluster ages.

Anthony-Twarog & Twarog (1985) first developed a calibration for a "morphological age ratio" or MAR, which related the change in CMD turnoff and evolved star luminosity and color to cluster age. Recently, Janes & Phelps (1994) defined a variant of this quantity, a morphological age index, or MAI, which can be determined even for clusters lacking a well-developed horizontal branch clump. Their age calibration was based on representative ages from isochrone fitting for well-studied open and globular clusters, and resulted in an approximately linear relationship between MAI and cluster age, on a scale where a typical globular cluster age is 15 Gyr. They caution against taking the MAI too literally as a true cluster age, stressing that the purpose is to derive a robust relative age indicator. Table 1 lists the MAI values for all open clusters known to be the age of the Hyades or older, calculated from the morphological parameter δV measured from the CMD (Phelps et al 1994 and K Janes, private communication) and the calibration to MAI given in Janes & Phelps (1994). With a sample of 74 cluster we can begin to clarify the relation of cluster properties with relative age, and to show, for the first time, some detail in the age distribution of the oldest open clusters that still exist.

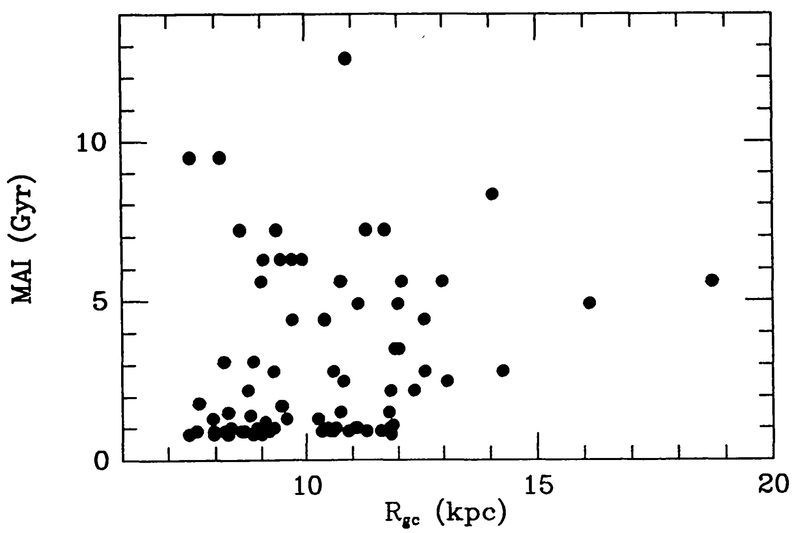

Figure 3 Relationship between Galactocentric distance and morphological age index MAI for clusters from Table 1.

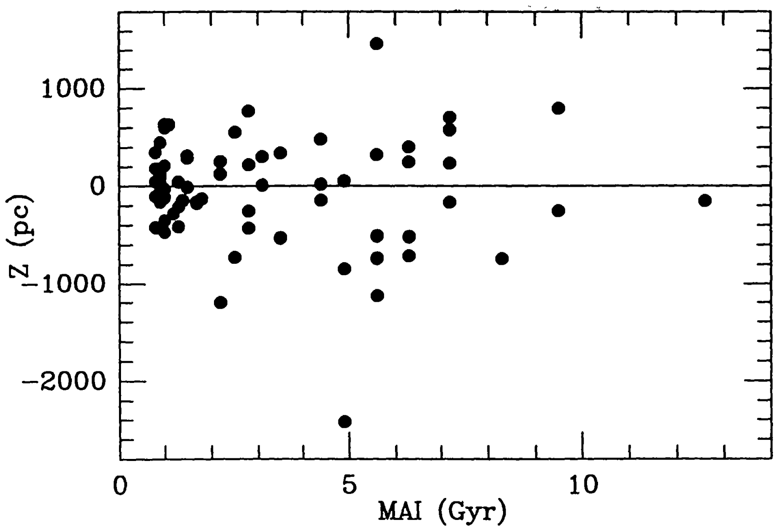

Figure 4 Relationship between morphological age index MAI and distance from the Galactic plane Z for clusters from Table 1.

4.2 *Correlation of Cluster Properties with Age and the Cluster Age Distribution*

In the first small samples of old open clusters there were hints that the very oldest clusters were located close to the solar Galactocentric radius, lending support to the idea that the disk had formed from the center outward, and that among the old clusters, the most distant clusters would tend to be younger than those at the solar position. On the other hand, one might expect the oldest clusters to be located at the largest Galactocentric radii, because there they are more likely to avoid the disruptive influences of the Galactic disk (Janes et al 1988). Figure 3, a plot of MAI index as a function of Galactocentric radius, indicates that neither of these descriptions is adequate. Among the very oldest clusters—those with MAI values of 3 or greater (approximately older than 3 Gyr), there is no apparent change in mean cluster age with increasing distance from the Galactic center. Similarly, if we omit the much smaller scale height population of young clusters, the old clusters do not show a dependence of cluster age with height above the plane (Figure 4).

The larger sample of clusters also sheds light on aspects of the formation and survivability of open clusters and early star formation in the Galactic disk. Figure 5, adapted from Janes & Phelps (1994), with the incorporation of results from new photometry noted in Table 1, is a histogram of open clusters and globular clusters on the scale of the MAI index. Janes & Phelps draw attention to several aspects of this distribution. First, the Galactic disk is at least 10 Gyr old and the oldest open clusters approach the ages of the youngest globular clusters. Second, the observed cumulative distribution can be fit with a combination of two exponentials in cluster age: one with an exponential lifetime of 200 Myr and a second with a lifetime of approximately 4 Gyr.

The distribution of open cluster ages depends on both the cluster birthrate and the destruction rate, neither of which is known. In fact, we can hope to use this distribution to constrain destruction processes. However, modeling of cluster dynamics and destruction mechanisms (e.g. Spitzer 1958; Wielen 1971, 1977, 1985; Terlevich 1987) can quite successfully explain the shorter lifetime component, which is well represented also in the population of all open clusters (Lynga 1982, Janes et al 1988) and is, in fact, the majority population. On the other hand, our understanding of cluster dynamics predicts that we should see very few, if any, clusters with lifetimes on the scale of 4–5 Gyr. Relative to these models, the observed number of long-lived clusters is unexpectedly large. Although the old-age tail to this distribution had been seen in the smaller samples, previously it was represented by only the clusters NGC 188 and NGC 6791. Now, these two "oldest open clusters" are joined by six more, apparently of equal or greater age.

4.3 *How Old are the Oldest Clusters?*

For many years, the two clusters NGC 188 and NGC 6791 were thought to be the oldest open clusters. Their existence was used to shed light on the time scale of disk formation, and their ages relative to those of the globular cluster ages provided constraints on the length of the time interval between halo and disk formation. Not surprisingly, the ages of these clusters have been the subject of some controversy. Age estimates for NGC 188 have ranged

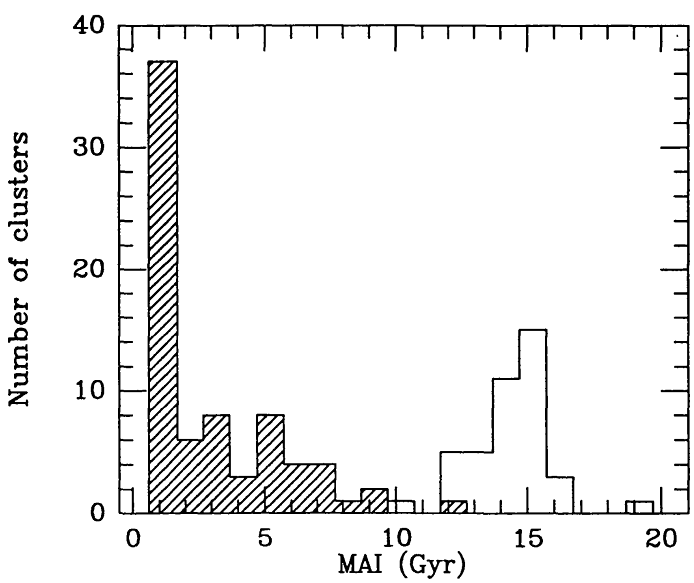

Figure 5 Histogram of number of clusters as a function of morphological age index MAI, after Janes & Phelps (1994), but with the additional data of Table 1. Open clusters are shown by the cross-hatched regions. Globular clusters are shown by the unfilled histogram.

from 10 Gyr, using conventional evolutionary models and generally accepted parameters for reddening and metallicity (VandenBerg 1985), to 6.5 Gyr, based on more recent work that invokes changes in the cluster reddening and distance modulus and compares NGC 188 to other open and globular clusters and to theoretical isochrones (Twarog & Anthony-Twarog 1989). Using evolutionary tracks calibrated to solar values, Demarque et al (1992) also calculate an age of $6.5^{+1.5}_{-0.5}$ Gyr. An entirely new method, essentially independent of reddening and distance estimates, relies on spectroscopic determinations of the temperature of turnoff stars, which are translated into ages by comparison to theoretical isochrones, and yields an age of 7.7 ± 1.4 Gyr for NGC 188 (Hobbs et al 1990). Ages for NGC 6791 have been similarly controversial, with determinations ranging from 12 Gyr, when judged by relation to the CMD of NGC 188 at 10 Gyr (Janes 1988), to only 7 Gyr (Demarque et al 1992); most recently, Garnavich et al (1993) find an age of 9 Gyr.

As illustrated by the alternating papers of VandenBerg (1985), VandenBerg & Poll (1989), Twarog & Anthony-Twarog (1989), and Demarque et al (1992), the fundamental uncertainties leading to these differences in age are in the transformations from the theoretical to the observed plane and in the adopted observational parameters of reddening and metallicity. In spite of the debate over the ages of NGC 188 and NGC 6791, there now appear to be several more clusters as old as or older than these prototypical open clusters. The cluster Berkeley 17 now stands as the oldest of the open clusters, with an MAI of 12.6 Gyr. This approximate age is substantiated by recent deep photometry of this cluster, shown in Figure 6. With the reddening well-constrained, and at least preliminary results available on its metallicity (Friel et al 1995), isochrone fits to conventional models yield an age of 12 ± 2 Gyr (Phelps et al 1995). As Figure 6 indicates, the cluster is sparse, reddening is high, and there are still deficiencies in the details of the fit to models, but every indication leads us to think that we have found an open cluster in the outer Galactic disk that has an age similar to that of the younger of the globular clusters in the halo of the Galaxy. Apart from the higher field contamination, the quality of the color-magnitude diagram of Be 17 is not too different from those of the sparse halo clusters E3 (McClure et al 1985) or some of the poorer Palomar clusters (Hesser 1988). Although the CMD of Be 17 is shown because of its significance as the oldest open cluster currently known and because it illustrates well the difficulty of deriving ages for these sparse clusters, note that not all old clusters look like this. The CMD of the populous NGC 6791 presents a very different impression (Kaluzny & Udalski 1992, Montgomery et al 1994) with its well-defined evolutionary sequences.

It is important to verify the ages of these oldest half-dozen open clusters with improved deep photometry and determinations of their compositions and reddenings, and to put the open and globular clusters on the same age scale. If

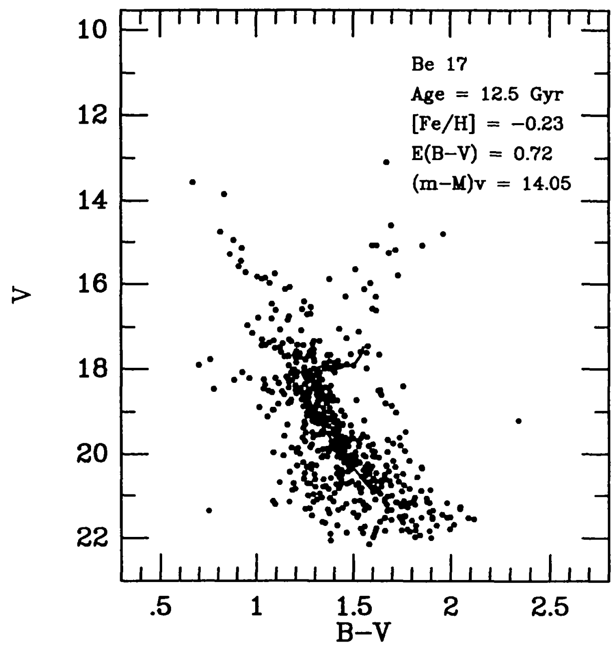

Figure 6 Color-magnitude diagram of Berkeley 17, the oldest known open cluster, after Phelps et al (1995). Isochrone for [Fe/H] = −0.23 at 12.5 Gyr is taken from VandenBerg (1985) and is fit assuming $E(B-V) = 0.72$ and an apparent distance modulus $(m-M)_v = 14.05$.

the very old age of Be 17 remains, and the 9–10 Gyr ages of the other candidate clusters are confirmed, we will have identified our oldest reliably dated tracers of the disk. Their presence, number, kinematics, and chemical composition will provide valuable clues on the progression from halo to disk formation.

5. CHEMICAL EVOLUTION OF THE GALACTIC DISK

The open clusters have long been used to trace the chemical structure and evolution of the disk. Because they can be relatively accurately dated and we can see them to large distances, they form an excellent time line along which to study the progress of overall enrichment in the disk.

Cluster metallicities have been derived by a wide variety of methods. Photometric abundance indicators in the systems of DDO, UBV (cf Janes 1979, Cameron 1985), Washington (Canterna et al 1986, Geisler 1987, Geisler et al 1992), or Stromgren (cf Nissen et al 1987) photometry have been used extensively. Spectroscopic determinations have been far fewer, and large samples have been achieved only with moderate to low resolution (Friel & Janes 1993). There have been relatively few abundance determinations from high-resolution spectroscopy because of the faintness of the clusters (Smith & Suntzeff 1987, Hobbs et al 1990, Hobbs & Thorburn 1991, Friel & Boesgaard 1992, Brown et al 1993). Most of these methods, apart from the high-resolution spectroscopic studies, yield overall metallicities that are accurate to 0.1 to 0.15 dex in [Fe/H].

Determinations prior to 1987 have been brought together and placed on a common system in the COCD (Lynga 1987). In comparing these and more recent studies, there remains, as always, the possibility of systematic differences between various abundance systems at the level of 0.1 dex (cf Wheeler et al 1989).

Many studies over the years have used the open cluster population to trace abundance gradients and to investigate the relation between age and metallicity. These studies rested on much smaller samples than we now have at our disposal, and their results are reevaluated here in the light of new data, particularly for the very old open clusters previously unknown. The most recent values of [Fe/H] on a uniform spectroscopic abundance scale are given in Table 1.

5.1 *Disk Abundance Gradients*

The shape and magnitude of the radial abundance gradients in the disk provide essential constraints to models of chemical evolution. The open clusters, which cover a large range in distances and ages, are among the best indicators of the trends of overall metallicity [Fe/H].

Although sample sizes have increased and the quality of the observational parameters has improved, the conclusion that the old cluster population shows a significant decrease of overall metallicity with increasing Galactocentric radius remains unchanged since the first studies. Although the metal-poor nature of a few outer disk clusters was noted by Arp in 1962, Janes (1979) was the first to determine the disk abundance gradient based on the old open clusters, finding $\Delta[\mathrm{Fe/H}]/R_{gc} = -0.075 \pm 0.034$ dex/kpc for a sample of 15 clusters with ages greater than 800 Myr. Taking advantage of the larger sample available in the COCD (Lynga 1987), Janes et al (1988) found a gradient of −0.14 dex/kpc for clusters with ages greater than 200 Myr.

The most recent and extensive sample of old clusters with metallicity determinations on a uniform abundance scale is that of Friel & Janes (1993). Their sample covers a much larger range in distances than previous work and includes clusters not known previously. With a sample supplemented by additional clusters with metallicities given in the Lynga catalog, they derived a radial abundance gradient of -0.095 ± 0.017 dex/kpc for 33 clusters older than the Hyades that spanned Galactocentric distances from 7 to 16 kpc. Similar results on the slope of the abundance gradient were found by Geisler et al (1992) using abundances determined from Washington photometry.

The sample continues to increase, as more attention is paid to determining parameters for the oldest and most distant clusters. Figure 7 shows the most recent version of the abundance gradient, now including preliminary values from Friel et al (1995), and recent revisions in the reddenings and distances to several clusters. The value of the gradient, -0.091 ± 0.014 dex/kpc, is essentially unchanged from previous values but now rests on a sample of 44 clusters that span the age of the old disk. The clusters continue to show no gradient in abundance with height out of the plane (Friel & Janes 1993).

Although Figure 7 indicates that the disk is clearly more metal-poor in the outer regions, the dispersion of cluster metallicities about the mean at any distance is significant. The observed scatter about the linear fit, 0.17 dex, is significantly larger than the expected observational uncertainty. In interpreting this relationship, and in particular in comparing it to theoretical predictions, it is important to recognize that in spite of our best efforts, the distances and reddenings to a number of these clusters are still quite uncertain. For example, the cluster To 2, once thought to have a Galactocentric distance of 18.5 kpc has moved successively to a Galactocentric distance of 16 kpc, and, most recently, to only 13 kpc (Adler & Janes 1982, Janes 1991, Kubiak et al 1992). As a result of concomitant changes in its estimated reddening, from $E(B-V) = 0.08$ to 0.20 to 0.40, values for its metallicity have varied from −0.7 to −0.4 (Friel & Janes 1993, Friel et al 1995, Brown et al 1993). Fortunately, it is now only one of many clusters, and changes in its position in Figure 7 do not significantly affect the mean relation.

Similarly, the sometimes large differences in cluster metallicities found between spectroscopic methods and earlier Washington photometry (Geisler et al 1992) are being resolved to bring consensus on the slope and the dispersion in radial abundance profiles. Revisions to reddening, improved knowledge of membership, and most importantly, high-resolution abundance analyses lead to much improved, and usually much larger, abundance determinations than

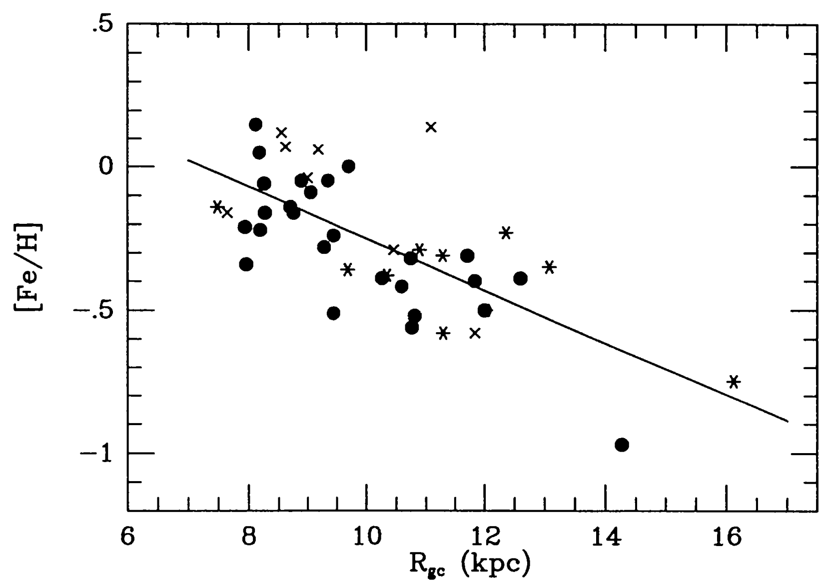

Figure 7 Radial abundance gradient for the old open clusters, with metallicities from Table 1. Filled circles are points from Friel & Janes (1993) or Thogersen et al (1994). Starred symbols are preliminary metallicities from Friel et al (1995). Crosses are data taken from Lynga (1987). The solid line is a least-squares fit to the data that yields an abundance gradient of Δ[Fe/H]/R_{gc} = −0.091 ± 0.014.

some earlier, puzzlingly low estimates from Washington photometry (Brown et al 1993; D Geisler, private communication). Nevertheless, caution should be exercised when comparing small samples isolated by age and/or distance to theoretical predictions or to results for other disk populations.

In spite of these caveats, it is particularly interesting to compare this gradient to those found for other cluster populations that differ in age or in position in the Galactic disk. Has the abundance gradient changed over the lifetime of the disk, as expected theoretically (Matteucci & François 1989, Tosi 1995)? Is it a function of Galactocentric radius, being shallower in the outer disk as predicted by some evolutionary models?

Evidence from the open cluster population alone indicates that the gradient is unchanged over the lifetime of the disk. Among the sample of old clusters of Friel & Janes (1993) or Friel et al (1995), there is no dependence of gradient with age. A sample of 20 clusters with ages less than 1 Gyr analyzed by Panagia & Tosi (1981) yielded a gradient of -0.095 ± 0.034 dex/kpc, exactly the value found for older clusters. Clusters from the COCD with ages less than 200 Myr follow a somewhat shallower gradient of -0.07 dex/kpc (Janes et al 1988), but the uncertainty is large.

Investigating possible changes in the slope of the abundance gradient with Galactocentric distance is complicated by the fact that the older clusters are found exclusively in the outer disk, while the inner disk samples are exclusively younger clusters. However, if we believe that there is no dependence on the disk gradient with age, we may directly compare inner and outer disk samples for insight into positional dependence. Cameron (1985), from a sample of clusters of all ages, found a gradient of -0.11 ± 0.02 dex/kpc, and a suggestion that the gradient steepened in the outer disk. Similarly, Panagia & Tosi (1981) found marginal evidence for a steepening of the gradient among their sample of 20 clusters, when divided at the solar radius. However, both the samples cover a very limited range in distance, rest on small numbers of clusters, and show a very large scatter in the data. Among the old clusters presented in Figure 7, there is no strong evidence for a change in the slope of the relationship with distance, if one formally computes slopes based on different age ranges. However, much rests on the positions of the two most distant clusters, and one can imagine other, nonlinear relations of the change in cluster metallicity with distance, including, for example, two fairly uniform distributions on either side of a "break" in the abundance profile at 1–2 kpc outside the solar circle at 8.5 kpc. One must exercise caution when combining samples that were obtained with different techniques and have no objects in common to ensure that they are on a uniform scale, but the cumulative evidence of young and old samples is suggestive of a flatter gradient in the inner disk in contrast to model predictions (Matteucci & François 1984). Larger samples that cover a wider range of distances in the inner Galaxy will help resolve this issue.

5.2 *Age-Metallicity Relationships*

The evolution of the metallicity of the disk over its lifetime is a fundamental observational constraint to any theory of the chemical evolution of the Galactic disk. As a result, the determination of the age-metallicity relationship for the Galaxy has been the subject of numerous studies over the past decades.

It has long been appreciated that clusters provide an excellent timeline for study of the evolution of the disk. From the first small samples, open clusters have pointed to the same picture—that there is no evidence for a variation of abundance with age in the Galactic disk. The existence of the old, solar metallicity clusters M67 and NGC 188 indicated that the disk had to have been enriched early. Arp (1962) showed the flat distribution of [Fe/H] with age among seven open clusters ranging in age from NGC 188 to the Hyades. He also pointed out a significant variation in metallicity at a given age among the disk clusters. Hirshfeld et al (1978) almost doubled this sample with more intermediate age clusters to substantiate both of Arp's conclusions.

However, the old clusters were always a small population and concerns about the small sample sizes, the lack of clusters with ages greater than M67 ($\sim$5 Gyr) and the influences of variations in abundance as a function of position in the disk, led many to prefer the results on the age-metallicity relationship to come from field star studies (McClure & Tinsley 1976, Twarog 1980).

Now, with increased samples of old clusters and with improved abundance and age determinations, we can examine the form of the age-metallicity relationship with more confidence. The sample of 33 clusters from Friel & Janes (1993) showed no trend of metallicity with cluster age—a lack of correlation that persisted to ages of 8 Gyr and held true regardless of position in the disk. The results for the large sample of clusters with Washington photometry by Geisler et al (1992) showed a similar lack of dependence. The preliminary abundance results of Friel et al (1995), which now include twice as many clusters with ages greater than about 5 Gyr, are shown in Figure 8. The cluster abundances have been corrected for the radial abundance gradient to reflect the metallicities that clusters would have at the solar position; they are plotted as a function of morphological age index MAI from Table 1 rather than cluster age, since for many of these very oldest clusters, ages are not yet available from main-sequence isochrone fitting.

Figure 8 shows that the cluster metallicity is not a function of cluster age. Combined with the abundance gradient shown in Figure 7, this indicates that the cluster abundance is controlled primarily by where and not when the cluster formed. Suggestions that this was the case were made as early as 1962 by Arp based on a sample of only seven clusters, but now can be more clearly defined. Similar conclusions are also reached from a smaller sample of clusters that have been placed on a homogeneous age system (Carraro & Chiosi 1994b), so the uncertainty in the MAI scale used in Figure 8 is not a factor. In addition, similar

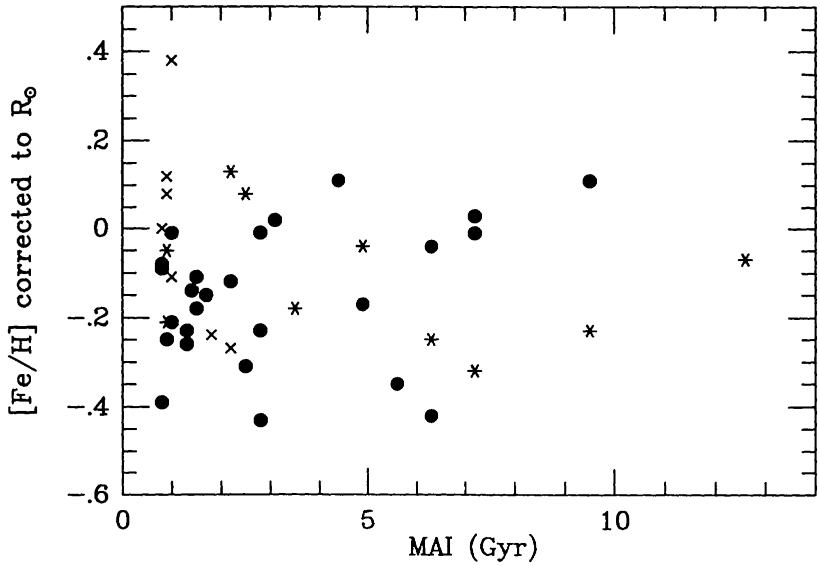

Figure 8 Relationship of metallicity [Fe/H] as a function of age, as measured by the morphological age indicator MAI for clusters with metallicities in Table 1. The [Fe/H] values have been corrected for the radial abundance gradient and normalized to the abundance they would have if located at the solar Galactocentric distance of 8.5 kpc. Symbols as in Figure 7.

conclusions were drawn by Friel & Boesgaard (1992) from analysis of high-resolution abundance determinations for younger clusters in the neighborhood of the Sun.

The lack of correlation between cluster age and metallicity is observed at all positions of the disk that are sampled by the open clusters. If we divide the cluster sample by position and plot age vs metallicity separately for clusters at the solar position and those in the outer disk, we would find a difference in the mean level of enrichment but still a perfectly flat lack of correlation between cluster age and metallicity (cf Figure 4 in Friel & Janes 1993). Revisions in the metallicity for clusters observed by Geisler et al (1992) lead to identical conclusions from abundances in the Washington system (D Geisler, private communication). Apparently, over the entire age of the disk, at any position in the disk, the oldest clusters form with compositions as enriched as those of much younger objects.

The open clusters provide one other piece of information in the overall picture of disk chemical enrichment. In Figures 7 or 8, one sees that at a given position, or a given age, there is a significant spread in abundances about the mean value. The same kind of dispersion is seen among the young clusters (Boesgaard & Friel 1990, Friel & Boesgaard 1992) and is exemplified by comparison of the Hyades to the Coma cluster. These two clusters have almost the same age, 700 and 400 Myr, respectively, yet their Fe abundances of $+0.13 \pm 0.02$ and -0.05 ± 0.03 differ by a factor of 1.5, at a high level of significance. It is difficult to judge the exact magnitude of the intrinsic dispersion from these studies but a value of 0.1 to 0.15 dex is indicated.

5.3 *Comparison to Field Disk Populations*

One might ask whether the old open clusters are indeed good tracers of the disk evolution, since they are clearly a remnant population, many of whose members have been selectively destroyed over the history of the disk. Although the destruction processes may well have altered the kinematic profile of the cluster population, it is more difficult to see how such processes could have dramatically modified the chemical properties, since we have found no correlation between kinematics and any other cluster properties.

In fact, the chemical history of the disk as painted by the open clusters is very similar to that found in other disk populations. Previous studies of the radial abundance gradient based on a wide assortment of objects and a careful, consistent analysis (Grenon 1987) yielded values quite consistent with the most recent determinations from clusters. The recent, extensive study by Edvardsson et al (1993) concentrates on old disk field stars and shows an overall radial gradient that is independent of age—in good agreement with that from the clusters.

Other surveys of field stars have not revealed such pronounced gradients among old disk giants (Neese & Yoss 1988, Lewis & Freeman 1989). However, results from these studies are strongly affected by selection effects and rely on techniques for determining individual stellar distances that are much less reliable than those used to obtain cluster distances.

Gradients are found, of course, among younger tracers of the disk. Shaver et al (1983) provide a review of the results from the youngest population, the HII regions. Although these regions furnish abundance determinations of N, O, S, and other elements, whereas the clusters monitor primarily the [Fe/H] abundance, the slopes of the gradients are generally consistent when the different abundance ratios are taken into account (Sommer-Larsen & Yoshii 1990). Results for the slightly older population represented by the planetary nebulae also show radial gradients, in general agreement with those from other objects (Pasquali & Perinotto 1993). Taken together, these results from objects of all ages indicate that the abundance gradient in the disk has not changed appreciably over its lifetime.

On the other hand, there have been many studies of the age-metallicity relationship in the field disk population that have indicated a modest increase in the average metallicity of the disk over the past 10 Gyr (Pagel & Pachett 1975, Twarog 1980, Carlberg et al 1985, Meusinger et al 1991). Virtually all models of chemical evolution have taken the age-metallicity relationship determined by Twarog (1980) as a basic observational constraint.

More recently, however, the thorough study by Edvardsson et al (1993) reveals a flat age-metallicity relationship for field stars over the age of the disk, with appreciable intrinsic scatter in overall abundance at any position and age, in complete agreement with the results from clusters. The apparent gradual enrichment found by Twarog (1980) and others is explained as largely a result of selection effects that bias the sample against old, metal-rich stars (McClure & Tinsley 1976, Knude 1990). There is no such bias against finding old, metal-rich clusters in the disk.

5.4 *Comparison to Theoretical Models*

These three basic facts—the decrease in metallicity with increasing Galactocentric distance, the lack of any correlation between cluster age and metallicity, and the appreciable dispersion in metallicity at any age and position in the disk—present a challenge to theories of Galactic chemical evolution. A review of models of galactic chemical evolution is outside the scope of this article, but several previous reviews and recent discussions can be found in Tinsley & Larson (1978), Lacey & Fall (1985), Tosi (1988a, 1988b), Matteucci & François (1989), and Ferrini et al (1992).

Although details and approaches vary among authors, common to all models of chemical enrichment are the basic parameters of star formation rate and its dependence on gas and total density; the form of the initial mass function; the extent, rate, and mean abundance of infall to the disk and radial flows; and the details of nucleosynthesis and recycling of processed material in the disk. Although models are increasingly complete in their incorporation of the wide variety of physical parameters and phenomena, as emphasized by Tosi (1988a), they are not uniquely constrained by the available observational data. The basic observed relationships most frequently adopted can be reproduced by very different combinations of model parameters. What do the open cluster data, coupled with the evidence from other disk populations, add?

The existence of metal-rich clusters with ages of approximately 10 Gyr suggests that the disk had to undergo very rapid enrichment, much more rapid than is usually modeled by adopting the Twarog (1980) age-metallicity relationship. In addition, enrichment had to be fairly inhomogeneous, with infall playing a very important role, to produce the substantial dispersion we see at all ages and locations in the Galaxy. The radial abundance gradient is predicted by any model with a star formation rate that varies with the gas or total mass, though its slope is strongly modified by infall and radial flows in the disk. Infall is required to steepen the predicted gradients and bring them into agreement with observation (Tosi 1988a,b).

However, all models predict the gradient to evolve with time, becoming steeper as the disk evolves. The rather large slope of the gradient seen in the old clusters and its apparent lack of change over the lifetime of the disk are difficult to explain with current models (Tosi 1995). It may be that the form of the gradient is more complicated than a simple linear dependence over the entire disk or that the stars and the gas may show different behavior. The models adequately predict the steady-state behavior of the interstellar medium, which mixes rapidly, while the stars preserve the inhomogeneities of their place of formation.

The old stars and clusters of the disk require more sophisticated models of chemical enrichment that can follow the perturbations on the disk by infalling matter and the noninstantaneous recycling of processed material. As probes of the disk's chemical evolution, they continue to challenge our understanding and provide valuable insights.

6. CLUSTERS IN THE CONTEXT OF GALAXY FORMATION AND EVOLUTION

Because they serve as excellent tracers, star clusters in our own and other galaxies have been important tools in the development and refinement of scenarios of galaxy formation. The study of globular clusters in the Milky Way, for example, has led to the consideration of a model of halo formation from the accretion of fragments of smaller masses containing clusters (Searle & Zinn 1978); the properties of the globulars as a function of Galactocentric distance, their kinematics, and their age and abundance distributions have provided among the most stringent constraints to models of halo collapse (Sandage 1990, Carney et al 1992, Lee 1992). Similarly, the study of younger cluster populations in nearby galaxies, like the Magellanic Clouds, M31, and M33, has helped define the history of star formation in these systems (Christian & Schommer 1988, Elson & Fall 1985, Olszewski 1993).

What do the properties of the old open clusters tell us about the formation and early evolution of the Galactic disk? Can we use them to illuminate the detailed history of star formation? What do they tell us about conditions under which they formed?

One might start, simply, with the age distribution of the old clusters shown in Figure 5. Without attending too much to the details of bumps and wiggles in this distribution—which may result from ages based on rough estimates of cluster parameters and will change as more accurate age determinations are available—two important observations can be made.

The first is the fact that there are significant numbers of open clusters surviving on timescales of 4–5 Gyr. The second is that the oldest of these clusters are among the oldest objects known in the disk and approach the ages of the youngest clusters found in the Galactic halo. This distribution is a complex function of not only the star formation in the disk, but the selective processes of internal cluster dynamical evolution and destruction by interaction with the Galactic disk. We can hope to use the cluster age distribution, coupled with the spatial distribution of the clusters, to tell us about the formation processes that would leave these clusters in a position to survive.

Old open clusters are located preferentially in the outer Galactic disk and at larger than typical distances from the Galactic plane, so that they are relatively undisturbed by the massive concentrations in the disk that would lead to their rapid destruction. The clusters survive because their orbits keep them in special locations. Theoretical considerations indicate that they can not have formed in the plane of the disk and been accelerated to their current positions—they would not survive the encounters necessary to move them (Spitzer 1958, Wielen 1977). We must then look to processes that lead to cluster formation at substantial distances from the plane over the lifetime of the disk, with perhaps episodes of cluster formation that lead to clusters with special orbits.

The many alternative views of galaxy formation and the complex observational picture have recently been reviewed by Majewski (1993). As he points out, theories of galaxy formation and evolution have developed in two general categories—1. those of overall halo collapse with subsequent disk formation and continued collapse under self-gravity and 2. those in which accretion plays an important role. It is likely that the Galaxy formed by processes that combine both of these phenomena but their different detailed predictions provide a convenient framework in which to consider the place of the oldest open clusters.

The fundamental model of halo collapse and subsequent disk formation was proposed by Eggen et al (1962) and has been vigorously debated since (see Majewski 1993 for the numerous original references). In our evolving view of the details of the process, a key point has been the time lag between the formation of the halo, represented by the globular clusters, and the disk, represented by, among other objects, the oldest open clusters. We now know of open clusters (e.g. Be 17) with ages approaching the ages of the youngest globular clusters (VandenBerg et al 1990, Sarajedini & Demarque 1990, Chaboyer et al 1992), which suggests that star formation in the disk was occurring at an epoch that overlapped globular cluster formation. If the age of Be 17 is truly 12 Gyr (Phelps et al 1995), then it formed at roughly the same time as both young outer halo clusters (Rup 106, Pal 12) and the youngest disk globular cluster, NGC 5927 (Fullton & Carney 1995), and has an age in general agreement with the disk age indicated by the luminosity function of the white dwarfs (Wood 1992, Hernanz et al 1994). Are the oldest of the open clusters part of a continuous process of cluster formation, leading from the more massive, typically older globulars to the less massive, typically younger open clusters? Are the 8–12 Gyr open clusters "transition" objects that fall between our traditional perceptions of classic globular and young open clusters?

The scenario of globular cluster formation is not at all agreed upon, and particularly unclear is the relation of the disk and inner halo clusters to the remainder of the cluster population (Lee 1992, Carney et al 1992, Zinn 1993). In this confusing context, the oldest open clusters may be looked upon from two basic perspectives:

1. In the context of models that explain galaxy formation in terms of general halo collapse followed by the self-regulated chemical and dynamical

evolution of a gaseous protodisk (Burkert et al 1992), the old open clusters may be formed as part of the extended phase of star formation that lasts for some 5 Gyr after the rapid phase of thick disk formation. This model predicts that star formation occurs over an extended period at intermediate scale heights of 600 to 300 pc until the disk settles into its thin distribution where star formation occurs today. Overall characteristics of the cluster z distribution are consistent with this picture, though the model, or destructive mechanisms that later go into effect, would require fine tuning to match details of the cluster age distribution. In this picture, the old open clusters may be the natural extension of the disk globular cluster population to smaller masses and younger ages (Larson 1988, 1992).

2. Alternatively, turning to a picture of galaxy formation that includes the influence of accretion and infall onto the galactic disk, one finds also a natural mechanism for open cluster formation, as an extension of the processes that have led to the younger outer halo globular clusters. There is ample observational evidence for past and present infall to the disk from high velocity clouds (Danly 1992), accretion of satellite galaxies (Ibata et al 1994), and energetic recycling of processed material from the disk (Tenorio-Tagle & Bodenheimer 1988). Theoretical modeling of these events indicates that they can initiate star formation at appreciable distances from the plane and thicker stellar distributions (Comeron & Torres 1992, Quinn et al 1993), and one can anticipate that bound clusters formed in such events would preserve the large z motions and possibly eccentric orbits introduced by the colliding material. Such a formation scenario would explain the location of old open clusters at high distances from the Galactic plane and the fact that they remain on orbits that are beneficial to survival. The age and metallicity distributions of the old open clusters may require a scenario that involves more prolonged and gentle infall of material onto the disk, rather than a model of lumpy collapse or early accretion by substantial satellites (Sandage 1990, Quinn et al 1993).

Most likely the Galaxy formed by processes that combine both of these phenomena (Majewski 1993), and the open clusters that remain today have formed by a variety of mechanisms. We do not have answers to the questions posed earlier. We are just beginning to unravel the clues that the oldest disk clusters provide. As we continue to do so, however, it is important to seek a formation process that can explain the full spectrum of cluster properties, both open and globular, along with the ensemble of field populations. Essential to furthering this understanding will be the improvement and verification of cluster age determinations with excellent, deep main-sequence photometry, coupled with independent determinations of cluster reddening and metallicity, to refine the details of the cluster age distribution. Determination of cluster proper motions, within reach for many of these clusters, combined with precision radial velocity measurements, which allow the calculation of the orbits of these unusual clusters, will provide important tests for formation scenarios and constraints on the efficiency of disruptive forces by external agents and internal dynamical evolution. Detailed abundance profiles as well as mean metallicities of individual stars in these clusters offer probes of their nucleosynthetic history, which, by comparison to similar signatures for globular clusters and old disk field stars, may point to differences in enrichment histories and sites and mechanisms for formation.

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