7 Open Clusters and Their Role in the Galaxy

Eileen D. Friel
Department of Astronomy, Indiana University, Bloomington, Indiana, USA

T.D. Oswalt, G. Gilmore (eds.), *Planets, Stars and Stellar Systems. Volume 5: Galactic Structure and Stellar Populations*, DOI 10.1007/978-94-007-5612-0_7,

Abstract: Galactic open star clusters play diverse roles as probes of astrophysical phenomena on many scales. As gravitationally bound stellar systems of from several hundred to tens of thousands of stars they are useful laboratories for the investigation of issues of stellar evolution and nucleosynthesis, stellar interactions and dynamical processes, and star formation. Since open clusters exhibit a wide range of properties and are found at all ages and almost all locations in the galactic disk, when looked at as a system, they are excellent tracers of galactic structure and evolution.

This chapter introduces the properties of open clusters in the Milky Way, discussing their structure, masses, and mass functions. Open clusters are strongly affected both by internal dynamical evolution and by encounters with external forces, such as molecular clouds and the galactic tidal field. N-body simulations provide a mechanism to explore these effects which lead to significant modification of the cluster internal structure and mass and stellar distributions, and control the cluster longevity. Open clusters also provide ideal tests for the confrontation of stellar evolutionary models with observation through their wide range of ages and sampling of stellar masses.

In the context of the Milky Way galaxy, correlations of cluster properties with location provide important constraints to our understanding of both the processes of cluster formation and their dynamical evolution. The dependence of spatial distribution on age within the open cluster system points to a complex interplay between cluster formation and survivability. Abundance gradients, both of overall metallicity and individual elemental abundance ratios, and their evolution over time, point to a complex history of chemical enrichment in the galactic disk. Finally, open clusters are discussed briefly in the context of galaxy formation, mergers, and the development of the outer galactic disk.

Keywords: Galaxy: abundances, Galaxy: disk, Galaxy: open clusters and associations, Galaxy: structure, Stars: abundances, Stars: binaries: general, Stars: C-M diagrams, Stars: kinematics and dynamics, Stars: mass function

1 Introduction and Overview

Star clusters are remarkable tools for studying a vast array of astrophysical phenomena. They serve as laboratories that challenge our understanding of stellar interiors and evolution. Their characteristics as a population elucidate issues ranging from local and global star formation to the structure and evolution of galaxies. The study of star clusters in our own galaxy has provided key information in areas ranging from the details of stellar convection or radiation transport in the cores of intermediate mass stars, to the accuracy of modeling of stellar dynamical systems, to the evidence for galactic mergers and cosmological theories of hierarchical galaxy formation.

Among the populations of star clusters, open clusters play a particularly diverse role. Their range of properties makes them especially attractive as probes of these many facets of astrophysics. Unlike the globular clusters that are thought of as having relatively well-defined properties and limited range of mass, luminosity, structural characteristics and age, open clusters span a wide range of properties.

But what makes an open cluster "open"? The name first denotes the appearance, largely by reference to the much more populous and compact globular clusters. Open clusters are less massive, less centrally concentrated, and in most cases, present a sparse and dispersed looking aggregation above the background field of the sky. A typical open cluster has on the order of 100 or fewer visible members, which leads to its discovery and classification, although its total mass may be many times this amount. Even so, open clusters present a diverse array of appearances, ranging from the quite populous examples of the 100 Myr old M11, to the archetypical M67, to the sparse collections of only a few dozens of stars that make up NGC 3680.

In fact, the characterization of an open cluster usually rests on a collection of observed and deduced properties, including not only its appearance, but its location in the galaxy, its age, its kinematics, and its chemical composition. Like any stellar population, the assignment of the appellation "open cluster" comes after a consideration of the majority of these properties being consistent with membership. As knowledge of open clusters increases, the boundaries of these classifications often become murkier, raising the question of "transition" objects that span the domains of classical globular and open clusters, and posing interesting challenges for theories of cluster formation and evolution.

This evolution of understanding and the increasingly complex picture of cluster populations will be explored in the following sections, but at the outset it is useful to start with a simplified global picture of open clusters and why these characteristics are used to help define the population as a whole.

Open clusters have historically also been called galactic clusters, primarily because of their predominant location in the disk of the Milky Way galaxy. Again, this assignment by location is based on a distinction from the globular clusters, which were considered to populate the spherically distributed halo of the galaxy. Indeed, open clusters are found distributed closely along the galactic plane, with scaleheights consistent with the thin disk stellar populations. Found at almost all galactic radii, barring observational selection effects, this distribution makes them ideal tracers of the galactic disk, probing a large range of distances and locations in the plane of the Galaxy.

The typical open cluster is also young, perhaps a few hundred million years old. But open clusters are found at all ages in the disk. The youngest clusters are being formed now, and their study illuminates the processes of star formation. At the other extreme are open clusters many billions of years old, and whose great ages both frame our understanding of cluster evolution and guide our notions of the early galactic disk. Most importantly, the wide range of ages spanned by the open cluster population affords the opportunity to probe the entire history of the galactic disk, something not provided by other stellar tracers whose populations sample only limited age ranges.

As objects that populate the galactic disk, open clusters are also typically found to have overall chemical compositions that are close to solar, again by contrast to the globular clusters that are typically more metal-poor and show nonsolar abundance patterns. A closer inspection of open clusters shows that their chemical composition across the cluster population varies in useful and interesting ways that reveal both the underlying processes of stellar evolution and nucleosynthesis and the global patterns of chemical enrichment throughout the galaxy. As with many populations, it is the extremes of these distributions that offer special insight.

1.1 Surveys and Catalogs

Of course, the ability to study open clusters as astrophysical laboratories and to use them as tracers of the broader picture of galactic structure and evolution, rests on being able to identify them reliably. In fact, it is the relative ease of detecting and determining the properties of star clusters that has made them useful tools. Although there are challenges in detecting clusters, there are immediate advantages, too. As ensembles of stars with the brightest members revealing the top end of a mass function, clusters can be detected to substantial distances. Determination of fundamental cluster properties, such as distance, reddening, and age, is possible to greater reliability than for individual field stars, through the analysis of color-magnitude diagrams (CMDs), color–color relationships, and comparison to theoretical isochrones. Under the assumption, born out by observations, that the cluster forms from a common natal cloud within a very short period of time, the study of cluster members provides the advantage of understanding their mass, evolutionary state, luminosity, gravity, and those fundamental parameters that enable the study of stellar physics. And because one can build up samples of dozens of stars within a cluster, basic stellar and cluster parameters, such as velocity, chemical composition, and stellar activity, etc, can be determined more precisely, if not accurately, as long as membership is well understood.

There have been and continue to be many efforts to create catalogs of galactic open clusters. The first of these to have widespread use, and the basis for many catalogs and studies that followed, was that by Lynga (1981 – Catalog of open cluster data available through CDS, Strasbourg, updated and published in 1987 as the Lund Catalog of Open Cluster Data, CDS, Strasbourg). The Lynga catalog collected published cluster data on a systematic and unbiased basis and its 1981 version contained 1,180 objects. These objects were identified and collected from a wide variety of visual surveys of photographic plate collections, with an equally wide variety of selection and classification techniques, but the catalog provided the first extensive samples of open clusters and stellar associations for study. Lynga's first analysis based on this catalog (1982) established many of the fundamental cluster properties and their dependence on galactic structure. These correlations were further refined in Janes et al. (1988) who worked from a fundamental dataset of 421 clusters whose parameters had been placed on a uniform system. These two papers established many of the diagnostic trends, such as galactic gradients in metallicity, cluster longevity, cluster size and type, that have continued to be elaborated on with more complete and extensive data sets over the years. Most of the fundamental characteristics have not changed from these initial studies, as will be seen.

The next significant step came with J.-C. Mermilliod's establishment of a web-based database for galactic open clusters (WEBDA), deriving from the Base Donnees Amas which included both derived cluster properties such as age, distance, reddening, and metallicity and measurements for individual stars in the cluster fields. The database includes photometry in most photometric systems in which the cluster stars have been observed, spectral classifications, radial and rotational velocities, astrometric data, with membership probabilities, positions and, most importantly, a complete bibliography of published data and a thorough cross-identification between different studies. The database can also be queried in a variety of ways based on stellar or cluster parameters and available data. The database can be found at http://www.univie.ac.at/webda/webda.html. The WEBDA has been the basis for many studies of overall cluster properties, following the early work by Lynga.

The WEBDA contains only clusters for which there are individual stellar observations and derived cluster parameters; it is not a complete listing of all identified candidate clusters. That is provided by W. Dias, who has compiled and keeps current a catalog of all identified clusters and cluster candidates published in the literature (Dias et al. 2002). Building from the Lynga and Mermilliod catalogs and including more recently published and some unpublished cluster surveys, the Dias catalog includes a total of 1,629 objects as of its 2007 version and an extensive bibliography. The catalog merges available data to present a single table containing summary cluster information including fundamental cluster positional and kinematic information, reddening, distance, and age. It is important to note that the catalog contains any clusters that have been identified as candidates in surveys, and exercises no selection on data quality, nor does it explore or correct for any systematic effects between the wide variety of studies it draws from. While the compilation of data into a single table is a valuable resource, the extreme heterogeneous nature of the data in the Dias catalog must be taken into consideration in the interpretation of any conclusions drawn about the overall properties of the cluster population.

Feeding the cluster catalogs are an increasing number of surveys aimed at uncovering more clusters in obscured areas of the galaxy or in areas that have not yet been systematically explored, such as the inner galaxy, the galactic plane, and regions of star formation where embedded clusters might be found. The release of the 2 Micron All Sky Survey (2MASS, available at www.ipac.caltech.edu/2mass/releases/allsky), in particular, spurred work on identifying cluster candidates that would have been hidden from previous optical surveys. While there have been many efforts in this area, two groups have been particularly active.

Bica, Dutra, Bonatto, and colleagues have published an extensive series of papers in the search for new infrared star clusters and stellar groups (e.g., Bica et al. 2003). These studies have focused on particular galactic regions where cluster surveys are known to be incomplete, where there are known optical and radio nebulae, and where 2MASS was likely to open new windows. These studies, along with detailed follow-up work, have shown that many initially identified cluster candidates were simply blended images.

Froebrich et al. (2007, FSR) carried out a systematic, automated search supplemented by a visual selection for infrared star clusters within 20° of the galactic plane using 2MASS, identifying 1,788 cluster candidates. Of these some 40% were previously known open and globular clusters, and for the remainder of new candidates, they estimated a contamination rate of 50%. This is an important caution for the many studies that are identifying clusters by their local stellar density enhancement. As the authors note, the high star density near the galactic center hampers detection, and variable star density in general introduces significant selection effects that complicate the interpretation of number statistics. Based on fitting models to the cluster density profiles, they distinguish statistically between open and globular cluster candidates and conclude that the vast majority of objects identified are expected to be open clusters.

The thorough FSR survey has spurred a number of follow-up studies (e.g., Bonatto and Bica 2008; Froebrich et al. 2008) to investigate the properties of these candidate clusters, particularly with interest in finding new globular clusters, or massive young and intermediate age clusters. These and other authors note that it is essential to have a robust means for correcting for the strong field star contamination in these cluster fields, and to utilize a variety of techniques for investigating the reality of the cluster beyond the traditional color-magnitude diagram, such as radial density profiles and mass functions. Froebrich et al. (2008) summarize the results of these follow-up studies to date, finding that of the 74 clusters investigated in more detail, approximately half of them had parameters that could be determined. Of these eight were young open clusters with ages less than 100 Myr, and half of them had ages greater than 1 Gyr. They conclude that the FSR catalog contains a large fraction of open clusters, both inside and outside the solar circle. While studies of these cluster candidates are challenging, they clearly offer a means to increase the known cluster sample in important ways and provide insight into processes of star and cluster formation and galactic structure.

This is not the place to list every survey or automated search of 2MASS or the digitized sky surveys that has been undertaken; the literature saw a plethora of them beginning in 2002. While there may be some treasures hidden in these surveys, it is important to recognize that distinguishing between true gravitationally bound, physical associations from chance aggregates on the sky requires in-depth follow-up for individual cluster candidates. This is particularly a concern for the analysis of the increasing number of poorly populated, sparse clusters being uncovered in large scale, automated searches, and as the searches push to find the more interesting, distant, and older clusters in areas of the galaxy that have not been explored before. As several works by Carraro and Janes illustrate (e.g., Carraro et al. 2005), the large and increasing stellar densities in working toward the galactic center, coupled with the patchy and sometimes dense obscuration, result in the appearance of a distinct main sequence in color-magnitude diagrams of the field star population, simply due to geometrical effects. Patchiness in the obscuring material can create the appearance on the sky of groupings of more distant, bright stars that are interpreted as star clusters, which, in fact, have no physical association.

Selection and detection biases in the search algorithms, whether these are automated or traditional visual inspections, must also be carefully considered. Because open clusters are found in the galactic disk, background stellar density can be both high and highly variable, due to dust obscuration and to the overall features of galactic structure. These characteristics of changing background density introduce significant observational selection effects in cluster samples that naturally rely on distinguishing enhancements in cluster stellar density against the background. The ease of identifying a cluster will also depend sensitively on fundamental cluster parameters, such as intrinsic cluster richness, angular size or compactness, apparent brightness of its members, and the state of dynamical evolution of the cluster. For example, poorly populated or sparse clusters will be much more difficult to find, if at all, against a dense stellar background; those poor clusters that one does find can be expected to have systematically smaller sizes relative to clusters measured against more sparsely populated fields. Bonatto et al. (2006) offer a nice discussion of these effects. Similarly, geometrical effects due to obscuration in the galactic plane will lead to the preferential discovery of open clusters at higher galactic latitudes at greater distances; the clusters located within or closer to the galactic plane will be preferentially obscured, particularly at optical wavelengths. Because of the systematically varying stellar density with galactocentric radius and height out of the galactic plane, this introduces strong selection effects with galactic position that must be considered in interpreting the dependence of cluster properties with location.

2 Open Clusters as Stellar Laboratories

From the earliest color-magnitude diagrams of nearby open clusters, it was clear that these ensembles of from tens to hundreds of stars were valuable tools for the study of a wide range of astrophysical phenomena. The basic assumption that stars in a cluster share a common age and common chemical composition, reflecting the environment of the molecular cloud from which they formed, appears to hold from detailed observational studies. As stellar aggregates, they are valuable tools with which to study issues of stellar evolution, stellar interactions and dynamical evolution in gravitationally bound systems, star formation, and stellar nucleosynthesis.

2.1 Color-Magnitude Diagrams

Color-magnitude diagrams of open clusters provide a fundamental tool and diagnostic, more widely used than any other for the determination of cluster properties. Color-magnitude diagrams (CMDs) reveal not only the evolutionary state of the cluster, but its stellar constituents, such as frequency of binaries, the existence of anomalous stars, the nature of its luminosity and mass functions, and its overall properties such as reddening, distance, and metallicity. No wonder the color-magnitude diagrams are the first means with which to study cluster properties. Analysis of cluster CMDs is not without its challenges, however. *Figures 7-1* through *Fig. 7-5* show color-magnitude diagrams for a sample of clusters. The CMD for M67, a nearby, well-studied, 4 Gyr old cluster with solar metallicity, is shown in *Fig. 7-1* (Montgomery et al. 1993). It traces out a clear main-sequence, well-articulated turnoff region, clearly populated subgiant and giant branch, with well-defined concentration of He-core burning "red clump" stars. Even its binary sequence stands out clearly as the stars distributed up to 0.75 magnitudes above the main sequence and in its scattering of blue stragglers brighter and bluer than the main-sequence turnoff.

Not all CMDs are so clean, however, as that for Collinder 261 show in *Fig. 7-2* (Gozzoli et al. 1996). Its main sequence is confused with a populous field population. Only as one limits the field to the most central regions does the cluster main sequence become clearly

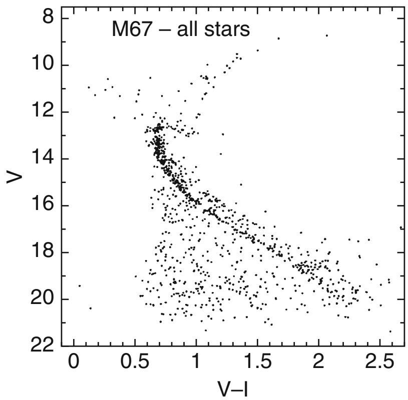

Fig. 7-1
Color-magnitude diagram for stars in the cluster M67, from Montgomery et al. (1993)

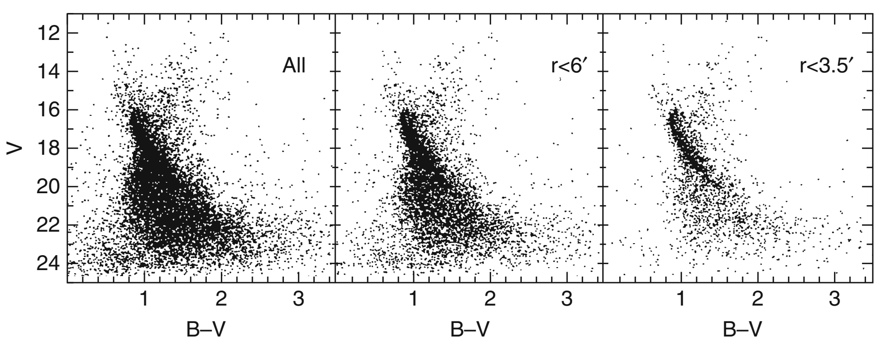

Fig. 7-2
Color-magnitude diagrams of Cr 261 from Gozzoli et al. (1996). Panels show the selection for the full field observed, with increasingly smaller field size centered on the cluster, to show the increasing contrast of cluster to field population

distinguished from the field, which still predominates in number. Deconvolution of the cluster from the field is extremely difficult in a case such as this, although statistical subtraction by sampling a nearby comparison field is possible. That process, too, has its limitations, as the large radii of open clusters can lead to cluster members being located at substantial distances from the cluster center, making the search for a true comparison field in strongly varying background a challenge. The solution taken by Gozzoli et al. (1996) in their analysis of Cr 261 was to add field stars to a simulation of the cluster evolutionary sequence and then compare theoretical isochrones to this synthetic CMD.

The case of NGC 3680 (Nordstrom et al. 1997, *Fig. 7-3*) presents the extreme of a sparse cluster in which the determination of cluster membership is critical to an understanding of its properties. Only with precise radial velocities and proper motions, which allow the determination of membership and binarity, is it possible to identify the cluster members and define the single-star evolutionary sequences of the cluster. Of the 120 stars in the field of this cluster, only 44 are cluster members, and of these, 25 are found to be binaries. Many of the stars that appear to extend the lower main sequence are not cluster members, and this careful study of membership reveals a cluster in the last stages of dissolution, its low mass stars having evaporated, leaving a severely truncated mass function.

Very young clusters present their own challenges in the interpretation of color-magnitude diagrams (e.g., h and χ Persei from Slesnick et al. 2002, *Fig. 7-4*). In color-magnitude diagrams of young clusters, the lower main sequence appears broadened as stars approach the main sequence from the brighter luminosities. With many young clusters embedded in nebulosity, with variable reddening, and with the most massive stars already leaving the main sequence while lower mass stars are still approaching it, the interpretation of cluster membership and CMD morphology is a complex task. Multi-wavelength studies, particularly in the IR, the use of narrow band imaging, such as Hα, and spectroscopy are important tools to use in untangling membership to reveal the true cluster sequences.

Assuming that one is successful in producing a cleaned CMD for a cluster, one has a valuable diagnostic that can be fit with theoretical isochrones to derive fundamental cluster properties,

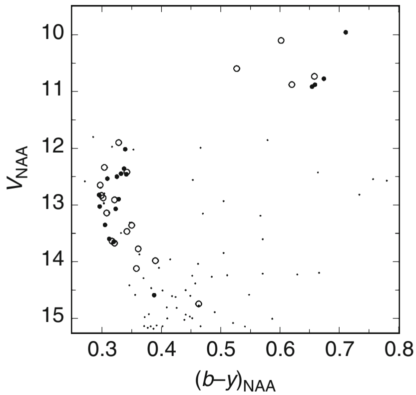

Fig. 7-3

Color-magnitude diagram for NGC 3680 from Nordstrom et al. (1997). ***Small dots*** **denote nonmembers,** ***large dots*** **denote single members, and** ***open circles*** **binary members**

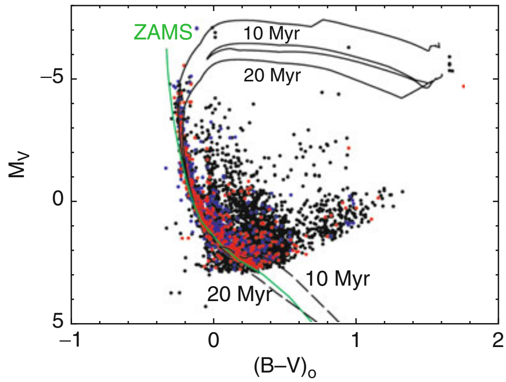

Fig. 7-4
Color-magnitude diagram for stars in the field of h and χ Persei from Slesnick et al. (2002). Also shown are zero-age main sequence and post-main sequence isochrones of 10 and 20 Myr as *solid lines* and corresponding 10 and 20 Myr pre-main-sequence isochrones as *dashed lines*. *Blue* and *red dots* represent stars within 7′ of the centers of h and χ Per, respectively, while *black dots* represent stars in a full 1° × 1° field

such as reddening, distance, metallicity, and age. For many clusters, none of these parameters are independently constrained, so the traditional method of fitting theoretical sequences to the observed CMD becomes an exercise in judgment, trading goodness of fit among a matrix of models parameters, evaluated subjectively. Parameters derived from these fits are also coupled, so that one eventually obtains a self-consistent, but not unique, fit for the combined parameters of cluster age, reddening, distance, and metallicity. There have been some attempts to remove or to quantify the subjective aspect of the analysis of cluster CMDs (e.g., von Hippel et al. 2006), although the traditional approach of fitting isochrones by eye is still the predominant method.

In addition, the choice of theoretical models and their variety of assumptions about input parameters such as opacities, treatment of convection, and most importantly, their transformations from the theoretical to observational plane, result in a range of deduced cluster properties even based on the same set of observational data. The extent of these effects is demonstrated nicely by Grocholski and Sarajedini (2003) who have compared observations of a sample of clusters from the WIYN Open Cluster Survey (WOCS) to a variety of commonly used theoretical isochrones from the literature. They conclude that none of the theoretical models reproduce the observational data in a consistent way over the entire cluster main sequences, and that significant differences in isochrone shape and zero-point exist. Clearly, the deduced cluster parameters will depend on the adopted models.

Uncertainties in the range of parameters resulting from isochrone fits can be appreciable. It is not unusual to see differences of 10–20% in ages and distances, and even larger uncertainties in reddening resulting from independent analyses of a given cluster. As an example, the age of the oldest of the open clusters, Berkeley 17, has ranged from 12 Gyr (Phelps 1997) to 8.5–9.0 Gyr (Bragaglia et al. 2006). Discrepancies between studies on the order of 2–3 Gyr for the older open clusters are not uncommon depending on which models are used, how CMD morphologies are interpreted, and the emphasis placed on various aspects of the fit to evolutionary sequences.

2.2 Structural Properties and Dynamical Evolution

2.2.1 Structural Properties and Masses

Open clusters present a wide array of appearance, from sparse irregular distributions of a few dozens of stars, to rich, populous spherical concentrations. This variety of objects presents challenges in determining their structural properties observationally. Nevertheless, King (1962, 1966) and others (e.g., Mathieu 1984) have shown that modestly populated open clusters have surface brightness profiles expected for isothermal spheres modified by tidal forces. Model fits typically yield core radii of 1–2 pc, and tidal radii of 10–25 pc, although the sparse nature of open clusters, combined with their superposition on often crowded stellar fields and contamination by field stars, makes the determination of tidal radii challenging. Often the tidal radii quoted are computed from the limiting radius in the galactic tidal field assuming circular motion based on the cluster's mass. The resulting concentration ratios, defined as $\log(r_t/r_c)$ are $\lesssim 1$, by contrast to the globular clusters, which typically have concentration ratios of ~1–2, an order of magnitude or more higher. There are exceptions, though, with some of the sparse globular clusters, such as AM4 or Pal 4 with concentration parameters in the range of open clusters.

The velocity distributions in open clusters are typically only a few km s^{-1}, consistent with those predicted from dynamical fits to the spatial distributions. For example, Mathieu finds a velocity dispersion of 1.2 ± 0.35 km s^{-1} for M11 and 0.25 ± 0.18 km s^{-1} for M67 (Mathieu 1985). Because of these low velocity dispersions, it is difficult to detect long period binaries, which can distort the velocity distributions by populating the high velocity tails. But once this effect is corrected for, open clusters offer an opportunity to study directly the velocity distributions as a function of mass over a wide spectrum. A recent extensive radial velocity study by Geller et al. (2008) for NGC 188 derives a global velocity dispersion of 0.64 ± 0.04 km s^{-1}, which they judge may be inflated by up to 0.23 km s^{-1} due to unresolved binaries. When corrected for unresolved binaries, the radial velocity dispersion has a nearly isothermal radial distribution.

Direct determination of masses of open clusters by star counts and observed luminosity functions is challenging for both observational and physical reasons. The typical apparent cluster diameter of about 5 pc refers to a visual impression of the cluster size and, although not strictly defined as a structural property, is most closely related to a half-mass diameter. Because of the low concentration of open clusters, many studies have not sampled the full extent of the cluster. Dynamical models also predict that as clusters evolve, increasing numbers of stars will be found around the much larger tidal radii, well outside the apparent cluster diameters. The numbers of stars often attributed to clusters by simple star counts in the cluster field can then be quite misleading and result in a serious underestimate of the total cluster mass. In addition, open clusters are seen to have substantial numbers of binaries, most often detected as distinct sequences in color-magnitude diagrams, but also identified in long-term radial velocity surveys. Binary fractions may reach 50%, and mass estimates based on star counts and observed luminosity functions must be corrected for this large and often uncertain factor.

Observed luminosity functions for clusters often cover a limited range in mass, and so require a sometimes significant extrapolation of the mass function to lower masses, where much of the mass potentially resides. This effect is counterbalanced by the fact that older clusters have undergone significant dynamical evolution and preferential loss of low mass stars. The mass segregation expected, and seen, in open clusters, also complicates the determination of cluster mass, since most cluster studies concentrate on the central regions, where mass segregation has compounded the depletion of low mass stars.

Determinations of the masses of open clusters attempt to correct for many of these effects. Mathieu (1984), for example, carried out a thorough study of the structural parameters and dynamics of the 200 Myr old cluster M11. With a core radius of 0.72 pc and tidal radius of 15 pc, M11 shows significant mass segregation. After correcting for binaries, scaling counts from the observed region to the entire cluster by using dynamical models, and considering corrections for mass segregation and cluster mass outside the tidal radius, he finds a total cluster mass of 5,200 $M_\odot$. However, this determination reaches only to masses of 0.7 $M_\odot$, and is surely a lower limit; were the cluster mass function to follow that of the field, perhaps as much as 40% of cluster mass may be in stars with masses from 0.1 to 0.7 $M_\odot$.

Similarly large present-day masses have also been determined for the 8–9 Gyr old cluster NGC 6791, for which Kaluzny and Udalski (1992) derive a conservative lower limit to the total cluster mass of 4,070 $M_\odot$ from the observed stars with $V < 21$ (masses of greater than approximately 0.6 $M_\odot$), without correction for binarity or incompleteness in the data. Geller et al. (2008) determined the virial mass for the 7 Gyr old NGC 188 to be 2,300 ± 460 $M_\odot$. A recent very thorough study of the young double cluster h and χ Persei by Currie et al. (2010), identifies as many as 20,000 members in the region, with a total mass of at least 20,000 $M_\odot$. This direct determination reaches down to mid-M dwarfs, includes members in the low density halo region of the clusters, and carefully considers membership to ensure a complete census of the cluster stellar population.

Although open clusters are commonly thought of as groupings of a few dozen to a few hundred stars, it is clear that their total masses cover a wide range in the mass spectrum. There exist quite massive open clusters in the galaxy today, with present-day masses over 10^4 $M_\odot$, and initial masses much larger.

2.2.2 Cluster Dynamical Evolution

Open clusters are strongly affected both by internal dynamical evolution and by encounters with external forces, such as molecular clouds and the galactic tidal field. These effects lead to significant modification of the cluster internal structure and mass distributions, and control the cluster longevity.

Given typical open cluster sizes (radii of ~1–2 pc) and velocity dispersions (~1 km s^{-1}), crossing times for open clusters are only a few Myr. Stellar encounters through these crossings modify the velocities, causing equipartition of energy between stars of different masses. The timescale for this process, or the relaxation timescale, is dependent on the number of cluster stars, as $0.1N^* t(\text{cross})/\ln(N)$. For a typical open cluster, with several hundred to a thousand members, the relaxation timescale is on the order of a few tens of Myr, many times the crossing time. And with typical ages of a few hundred million years, energy equipartition and mass segregation can be expected in mature, bound open clusters. The lower mass stars will have migrated to the outer regions of the cluster, while the more massive stars will have collected in the cluster centers.

This mass segregation is seen in almost all open clusters of sufficient age. Mathieu's (1984) study of M11, a 200 Myr old cluster, shows clear evidence of mass segregation; luminosity functions in the inner regions of the cluster are flatter than those in the outer regions, indicating a deficit of low mass stars. The effects of mass segregation are often most clearly seen when comparing the relative distributions of red giants and main-sequence stars, with the more massive red giants appearing more centrally concentrated than the single main sequence stars. More recent studies, able to reach to lower stellar and even substellar masses, show mass segregation in clusters such as the Pleiades at 120 Myr, (Moraux et al. 2004), Praesepe at ~600 Myr (Kraus and Hillenbrand 2007), and the Hyades at ~700 Myr (Bouvier et al. 2008), with significant depletion of low mass stars.

The movement of low mass stars to the outer regions of the clusters and the low velocity dispersions of clusters result in the gradual evaporation of low mass stars from the cluster over time. These low mass stars collect in an outer halo beyond the tidal radius of the cluster. Independently of any external influences, open clusters will dissolve into the surrounding field. The timescale for evaporation is on the order of ~100 times the relaxation time, setting an upper limit to the lifetime of any bound open cluster (Spitzer 1958). For the typical open cluster of several hundred stars and relaxation times of a few tens of Myr, this results in evaporation timescales on the order of 1 Gyr or larger for more populous clusters.

As Spitzer (1958) pointed out, however, there are more important forces acting on open clusters as they orbit in the galactic potential. Both tidal forces and encounters with giant molecular clouds are extremely effective in disrupting clusters. The efficiency of disruption by clouds is an order of magnitude more important than internal effects for most open clusters, and most clusters are expected to be disrupted on timescales of a few times 10^8 years. The internal mass segregation that brings low mass stars to the outer regions of the cluster aids in the eventual disruption of the cluster, as these stars near the tidal radius are more vulnerable to tidal forces and more likely to gain enough energy to escape the cluster altogether. These internal and external disruptive factors are so effective that one does not expect to see clusters with ages greater than about 1 Gyr.

A number of N-body simulations have demonstrated, in much more detail, the mechanisms and effectiveness of both internal and externally forced cluster dynamical evolution. The relatively small number of stars in open clusters, relative to globular clusters, make them ideal subjects for direct N-body techniques and work over the years has incorporated increasingly realistic physical effects. The first extensive study of open cluster dynamics using N-body calculations was Terlevich's (1987) analysis of an N = 1,000 body simulation that included the effects of mass loss from stellar evolution, binary encounters, tidal perturbation from the smooth galactic field and shocks from encounters with interstellar clouds of different masses, densities, and spatial distributions. Her models show clearly the expected mass segregation, with stars at the tidal radius taking a long time to leave the cluster, where a corona of 50–80 low mass stars form between 1 and 2 tidal radii. The formation and evolution of binaries in the cluster core can have an important effect on the overall evolution of the cluster, more so for the less populous clusters. She finds that mechanisms for the disruption of the cluster depend on the cluster mean radius, and that clusters with radii of 2–3 pc have the largest lifetimes. Encounters with standard interstellar clouds are not effective at disrupting clusters, once other factors such as mass loss, binary interactions, and the smooth tidal field are taken into account. Only encounters with massive giant molecular clouds are capable of disruption of typical open clusters.

In a series of N-body studies that explored successively the impact of different initial mass functions (IMFs), mass loss through stellar evolution, and primordial binary populations, de la Fuente Marcos (1997) found that the interplay of these effects is critical. The initial mass function (IMF) plays an important role in the evolution of binaries, which in turn can strongly influence the cluster evolution. In poorly populated clusters of several hundred members, for example, massive stars in binaries can control the cluster evolution, and in small clusters can accelerate cluster disruption. For models with small N and numbers of binaries, the effects of stellar evolution are dominant in the dynamical evolution of the cluster.

In increasingly more realistic simulations, with larger number of bodies, Portegies Zwart and colleagues studied N-body models that were fully self-consistent in the treatment of stellar evolutionary effects, binary evolution, which included both dynamical and stellar effects, and tidal effects from the general galactic field, in an effort to reproduce in detail the structural and evolutionary characteristics of Hyades-like clusters (Portegies Zwart et al. 2001, 2004). With model clusters of 2,000–3,000 stars, they found that the effects of stellar evolution have more impact in the early stages, resulting in about 20% overall mass loss to the cluster. Yet the total mass loss is larger than the sum of stellar evolution and dynamical effects by some 50%, suggesting that it is the interplay between stellar evolution and dynamics that is important, especially at later times. Their simulations show that the cluster relaxation time evolves through the cluster's lifetime, implying that present-day estimates of the relaxation time may be misleading and not reflect the dynamical age of the cluster. Nevertheless, mass segregation happens early on in their simulations, in agreement with observation. In comparison to well known clusters such as the Hyades, Pleiades, and Praesepe, however, the observations show even flatter luminosity functions than the models. This could be explained if the clusters exhibited primordial mass segregation, or they had higher initial masses than the models assumed, but with shallower density profiles so that the selective evaporation of lower mass stars results in a dynamically older appearance.

Lamers and Gieles (2006) and Gieles et al. (2006) carried out N-body simulations of open clusters including encounters with molecular clouds and shocks from spiral arm passages. They found that the influence of giant molecular clouds is ten times more effective than spiral arm shocking, and accounts for as much effect as all other factors combined. The disruptive timescale for a $10^4\,M_\odot$ cluster in the solar neighborhood is 2 Gyr. A cluster with $M \sim 10^3$ to $10^4\,M_\odot$ is destroyed by just a few encounters with a giant molecular cloud, so individual clusters will have strongly varying lifetimes depending on their particular history of encounters.

The most complete and realistic analysis of the dynamical evolution of a single cluster has been carried out by Hurley et al. (2005) in their modeling of M67. Working from the present-day properties of M67, they use N-body simulations to model the evolution of this 4 Gyr cluster, deducing its original structural parameters and stellar populations. They find that the best fit to the cluster's current total visible mass of $1{,}400\,M_\odot$ and half-mass radius of 4.3 pc is found with a cluster initial mass of $19{,}000\,M_\odot$, composed of 12,000 single stars and 12,000 binaries. After its 4 Gyr of evolution, the total mass has reduced to only $2{,}000\,M_\odot$ as a result of mass loss and evaporation of stars. M67 is dynamically relaxed, having passed through 13 half-mass relaxation times, and is old enough that all information about the initial mass function is lost. Structural parameters change dramatically as the cluster evolves. For example, the cluster initial core density was 150 stars pc^{-3}, increasing to a maximum of 330 stars pc^{-3} at 3.5 Gyr, and only 83 stars pc^{-3} at its present age of 4 Gyr. The simulated cluster luminosity function shows a clear radial dependence with the central region containing many more massive stars than low mass stars, inverting the slope from its initial shape. The slope of the luminosity function becomes flatter as one moves outward in the cluster, as lower mass stars become a more dominant component of the cluster population. *Figure 7-5*, from Hurley et al. (2005), shows the simulated evolution of the luminosity function in radial bins, compared to the original function without dynamical evolution. Only in the outermost regions does the slope of the present-day cluster luminosity function agree with the initial function, but even then, the cluster is depleted in the lowest mass stars.

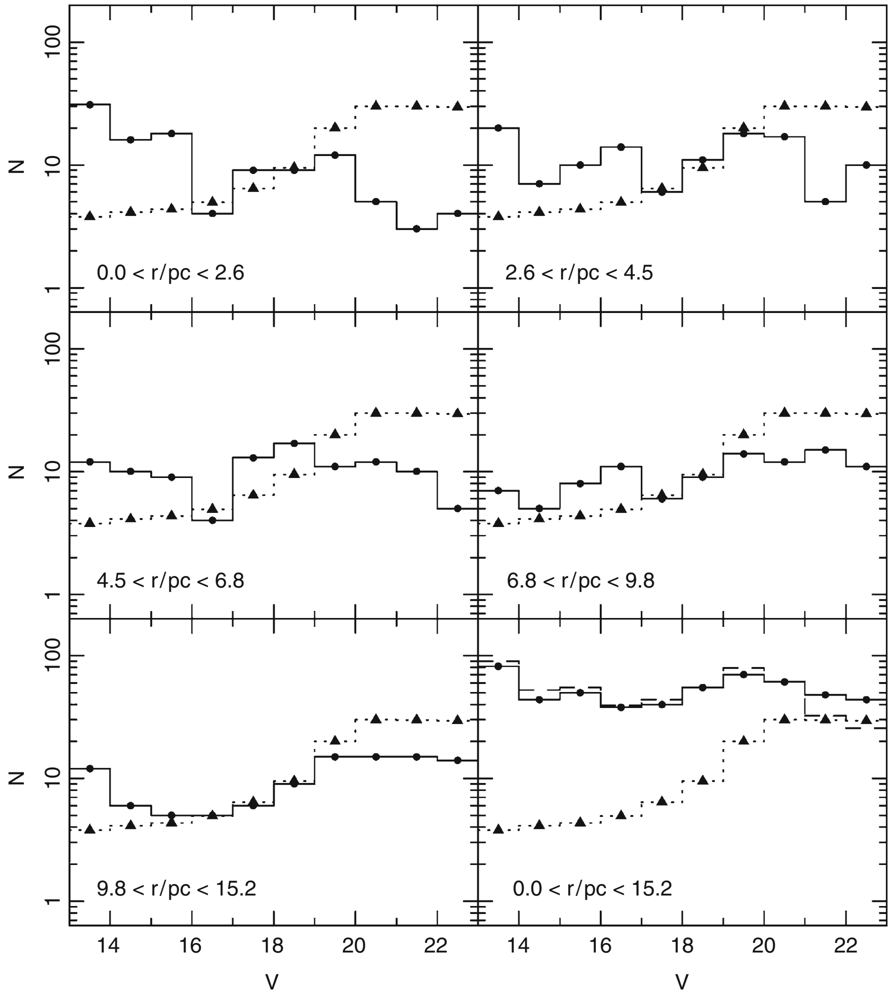

Fig. 7-5

Evolution of the luminosity function of single main sequence stars in M67 from N-body simulations of Hurley et al. (2005). Panels show five radial zones from the center (*upper left*) and the cumulative distribution (*lower right*). *Dotted line* (with triangles) in each panel is the luminosity function expected based on population synthesis of a 4 Gyr cluster with no dynamical evolution. There is a clear radial dependence with the central regions containing many more massive stars. Even in the outer regions, the simulated luminosity function shows a deficit of low mass stars

They also follow the changing nature of the cluster's stellar population mix with time, including the formation and evolution of binary and multiple systems. The mass fraction of white dwarfs is significantly enhanced by the dynamical evolution of the cluster. Their detailed dynamical models allow them to explain the mechanisms of mass transfer or mergers by which stars or binary systems populate unusual regions in the cluster color-magnitude diagram, in very good agreement with the observations.

2.3 Cluster Mass Functions

Both observations and modeling show that open clusters experience significant modification of their mass functions through their lifetimes. As stellar laboratories, young open clusters provide among the best tools with which to study the initial mass function. Particularly compared to studies of field stars, clusters present the advantage of a coeval population at a common distance with common chemical composition, so provide an instantaneous sampling of the IMF at different locations and times in galactic history. Determining the mass function in clusters has its own challenges, however, as one must deal with and correct for incompleteness in samples particularly at the faint, low masses, contamination from cluster nonmembers, and the dynamical evolution that modifies, on a relatively rapid timescale, the mass distribution of the cluster.

As Lada and Lada (2003) point out, the use of young embedded clusters for IMF determinations alleviates many of these issues. They show, for the most well studied of all embedded clusters, the Trapezium in Orion, a present-day mass function that can be traced from ~10 $M_\odot$ OB stars to 0.1 $M_\odot$ brown dwarfs. This mass function features a sharp power law rise from ~10 $M_\odot$ to 0.6 $M_\odot$ with a slope of −1.2 (defined on a logarithmic mass scale where the slope = $\partial \log \xi(\log m / \partial \log m)$, a slope very similar to the value of −1.35 originally derived for field stars by Salpeter (1955). At lower masses it flattens, with a slow rise to a peak at ~0.1 $M_\odot$, followed by a steep decline into the substellar, brown dwarf range. The broad peak of the IMF, which extends roughly from 0.6 to 0.1 $M_\odot$ demonstrates that there is a characteristic mass produced by the star formation process in Orion. The IMF for the Trapezium agrees with that from field stars (Kroupa 2002), suggesting that the IMF and star formation process that produces it is very robust for stellar mass objects. The observed variation in luminosity functions in other clusters can be explained by luminosity evolution in pre-main-sequence stars of clusters of different age, but reflect a similar underlying mass function.

In exploring the question of the universality of the mass function in older clusters, understanding and compensating for the effects of dynamical evolution become important. Recent work that has probed the lowest masses in open clusters in the age range of ~100–700 Myr has provided evidence for remarkably uniform mass functions, across a range of cluster properties and environments. In a series of studies by Moraux and colleagues, comparisons of the Pleiades, Blanco 1, and the Hyades have shown mass functions in the range of 0.03–3 $M_\odot$ that are fit by a common log-normal distribution (Moraux et al. 2007). When consideration is taken of the expected dynamical evolution and preferential loss of low mass stars, they conclude that the present-day mass functions of these clusters are consistent with a common initial mass function that is similar to that of the galactic field. The fact that the initial mass function does not seem to depend on the environment, from clusters of quite different masses, densities, and star-forming environments, places strong constraints on theories of star formation.

However, with the discovery and study of massive young clusters near the galactic center, such as the Arches cluster and NGC 3603, questions arose as to the universality of the initial mass function. Initial work revealed mass functions with slopes that were more shallow and surprisingly strong evidence for mass segregation in the cores of these massive young clusters (Kim et al. 2006; Stolte et al. 2006; Harayama et al. 2008). With ages of only 1–3 Myr, shorter than the cluster relaxation time, such strong mass segregation was not expected. Was the mass segregation primordial, and did it reveal something about the processes of high mass star formation in cloud cores?

The interpretation of the apparent mass segregation in these young clusters is not yet clear, although a variety of explanations can be found. As a number of authors pointed out, although the cluster relaxation time is longer than the cluster age overall, dynamical evolution could have operated on the most massive stars on timescales on the order of the cluster age, resulting in mass segregation. Portegies Zwart et al. (2007), in a study of the Arches cluster, showed that the peculiarities in the mass function can be explained without resorting to primordial mass segregation, and that the Arches mass function is consistent with a Salpeter slope over 1–100 $M_\odot$. The dynamical models can reproduce the observations if the cluster is midway through the process of core collapse. McMillan et al. (2007) have investigated models of star formation that can produce mass segregation in very young clusters that appear not old enough to be dynamically evolved, by assuming that stars form in small clumps that subsequently merge to form larger systems. Mass segregation in these smaller clumps, either initial or a result of dynamical evolution on very short timescales, is then preserved in the larger structures as they merge.

The observational challenges in the analysis of these data are severe, however, and others have noted that, even with these massive clusters, sample incompleteness, the difficulty of correcting for field star contamination, differential reddening, and crowding in these galactic fields, complicate the interpretation of luminosity and mass functions. Ascenso et al. (2009), for example, conclude that there is currently no robust way to differentiate between true mass segregation and observational effects.

Nevertheless, in a comparison of observational results for the Arches, R136, NGC 3603, and Orion, Stolte et al. (2006) conclude that the slopes of the present-day mass functions for these clusters from very different star-forming environments are in remarkable agreement, in accordance with a universal IMF slope. While all of the clusters show observational evidence for mass segregation in their cores, the present-day mass functions rapidly approach a normal IMF outside the core, and they suggest that a mass-segregated core with an extended stellar halo may be a common cluster structure in a variety of environments.

2.4 Stellar Evolution and Star Clusters

Star clusters have long been recognized and used as the optimum test cases for the confrontation of stellar evolutionary models with observation. Open clusters, through their wide range of ages and sampling of the full range of stellar masses, serve as probes of a multitude of stellar phenomena. Here is a sample of only a few of the areas they touch.

2.4.1 Convective Overshooting

Stars with masses in the range of ~1–2.2 $M_\odot$ develop a small convective core, from which convective elements overshoot the boundary between the convective inner zone and the relatively stable outer radiative zone. Overshooting effectively increases the mass of the core, extending the stellar lifetime, and is reflected in the detailed morphology of the HR diagram, particularly in the region of the main sequence turnoff. A variety of formalisms for treating convective overshooting have been developed, leading to a variety of theoretical predictions (e.g., Bertelli et al. 1985; Maeder and Meynet 1991). Open clusters with ages from roughly 700 Myr to several Gyr offer the ideal tests to constrain the appropriateness of particular models, the extent of convective overshooting, its dependence on stellar mass and other parameters, and its impact on the determination of stellar ages. A large number of observational studies from the 1990s to the present have offered these detailed comparisons (e.g., Daniel et al. 1994; Andersen et al. 1990;

VandenBerg and Stetson 2004). Although after the initial flurry of studies, it became clear that the magnitude of the effect of convective overshooting was not as dramatic as first identified, it is nevertheless clearly a factor that must be taken into account both in stellar modeling and in deriving accurate cluster ages and parameters.

2.4.2 White Dwarfs and the Initial–Final Mass Function

The availability of deep, precise color-magnitude diagrams of nearby open clusters has allowed the study of stellar populations that probe the final stages of stellar evolution for intermediate and low mass stars. Deep photometry over large areal extents in open clusters now reveals the faint white dwarf sequences in a number of open clusters of a range of ages, metallicities, and structural parameters (e.g., Kalirai et al. 2003). The resulting samples provide constraints on a variety of physical phenomena, from the cooling ages of white dwarfs, to the upper mass limit for white dwarf production, the relationship between the initial and final mass of a star, and the total amount of mass loss through stellar evolution, which in turn is a critical parameter for models of galactic chemical evolution and enrichment of the interstellar medium. Recent work by Kalirai et al. (2008), for example, shows a clear correlation between initial and final stellar mass, with more massive main sequence stars producing more massive white dwarfs, and total mass loss scaling with initial mass. The most massive stars that will form white dwarfs lose about 85% of their mass, while solar mass stars will lose only ~55% of their total mass.

2.4.3 Binary Stars and Blue Stragglers

Open clusters are excellent laboratories for the study of binary systems and their manifestation through dynamical evolution. The color-magnitude diagrams of open clusters frequently show distinct binary sequences, particularly in those nearby or relatively high latitude clusters with minimal field star contamination. Equal mass binary systems will appear 0.75 magnitudes brighter than single stars on the main sequence, while unequal mass systems will distribute in brightness between the two sequences. Studies of individual clusters indicate binary fractions of 20–50% are common, suggesting that the fraction of binaries in clusters is not very different from that of the field. The long-term monitoring program of radial velocities in open clusters carried out by Mermilliod and Mayor for the study of cluster membership, binarity, and rotational velocities, shows an overall frequency of spectroscopic binaries of 30% (Mermilliod et al. 2008).

Interestingly, older open clusters often show a population of blue stragglers, stars more luminous and bluer than the main sequence turnoff. These stars are thought to derive from normal main sequence stars that have increased in mass above a single star mass typical of the turnoff through mass transfer, mergers, or collisions in binary systems. The exact mechanism for the formation of blue stragglers is still not understood, but the open cluster systems provide excellent laboratories for confronting models of their formation and dynamical evolution with the properties of observed systems (Hurley et al. 2005). A recent study of the old open cluster NGC 188 by Mathieu and Geller (2009), for example, identifies 76% of the 21 blue stragglers in the cluster to be in binary systems, and their rotational and orbital properties suggest that most, and possibly all blue stragglers derive from multiple star systems, likely following several formation scenarios simultaneously.

2.4.4 Stellar Nucleosynthesis and Evolution

It is commonly assumed that members of open clusters share the chemical composition of the gas cloud from which they formed and so reflect the environment of their birthplace. How valid is this assumption? Is there any sign of self-enrichment in the clusters? Spectroscopic studies have shown that to high precision, derived stellar abundances among cluster members are highly uniform, with internal dispersions entirely consistent with expected measurement errors. De Silva et al.'s (2006) study of the Hyades, for example, found little or no intrinsic scatter among Hyades F–K dwarfs in a study of the heavy neutron-capture elements that are not thought to be modified during normal stellar evolution. Similar uniformity of abundance has been found in many studies of samples of brighter evolved stars in clusters. Yet relatively few studies have studied both cluster dwarfs and giants simultaneously with a common data set and analysis to investigate the extent of variations in abundance that might be due to expected evolutionary effects or unexpected systematic variations.

Samples that included both giants and dwarfs have been studied in the clusters IC 4651 (Pasquini et al. 2004), M67 (Randich et al. 2006), and the Hyades (Schuler et al. 2006, 2009). Taking into account the intricacies of stellar abundance analyses, these works find heavy elements (Fe, Ni, Cr) to be identical within the uncertainties for the evolved and unevolved stars, indicating, as expected, that the derived stellar abundances reflect the primordial composition.

For the light elements, there is mixed evidence for abundance variations due to evolutionary effects that bring nucleosynthetically processed material to the stellar surface. Unlike the case of the globular clusters, however, where stellar evolutionary effects on light elements such as C, N, O, Na, Mg, and Al are pronounced and strongly correlated, for the younger and more metal-rich open cluster stars, the effects are both more modest and, in some cases, ambiguous. For the CNO cycle, theoretical models for stars of the ages and compositions of open clusters predict some modification of surface C and N abundances in evolved stars, with depletion of C and enhancement of N, with O unchanged, and reduction in the $^{12}C/^{13}C$ isotopic ratio. Smiljanic et al. (2009) find the behavior of N, C, and $^{12}C/^{13}C$ in general agreement with predictions of first dredge up in a set of giants from ten open clusters. Schuler et al. (2009) find for the Hyades that the N and O abundances are in excellent agreement with prediction of the first dredge up, as is the isotopic ratio of $^{12}C/^{13}C$. However, the ^{12}C abundances are depleted in the giants much more than predicted by models. The cause of this additional depletion is unknown, although they suggest that it must lie outside of the CNO bi-cycle.

The situation with regard to the other light elements Na and Al is unclear. Sodium is commonly found to be enhanced in red giants in open clusters by values of + 0.2 to 0.3 dex, compared both to field dwarf stars (Friel 2006; Sestito et al. 2008) and to unevolved stars in the same cluster (Pasquini et al. 2004; Schuler et al. 2009). Enhancement in Na and Al may be seen if the Ne-Na and Mg-Al nucleosynthetic cycles are active in the core regions and if the convective zone extends deep enough during the first dredge up to bring the processed material to the stellar surface. Standard models predict only slight enhancement, if any, in Na abundances, and no enhancement in Al. Schuler et al. (2009) find abundances for Na, Mg, and Al in Hyades giants to be much larger than those found in dwarfs, by amounts that exceed those predicted. Complicating the picture for Na and Al abundances are the poorly understood effects of corrections for non local thermodynamic equilibrium (non-LTE) for stars of these metallicities, masses, and evolutionary state. It is currently thought that much of this discrepancy for Na, in particular, is due to issues in the abundance analyses and the impact of unaccounted for non-LTE effects. But there is much work to be done in this area.

Open clusters have been primary tools in the effort to understand the abundances of the light element lithium, which is also produced in the Big Bang and whose presence in stellar atmospheres is a sensitive indicator of a myriad of stellar internal and evolutionary processes. The observed patterns of lithium abundance are a complex function of mass, composition, stellar rotation, and age, and continue to challenge theoretical understanding of stellar interiors and mixing processes. The subject of lithium abundances in open clusters would fill a review article itself, and the reader is referred to Pinsonneault (1997) for a recent review.

3 Open Clusters as Galactic Tracers

Open clusters can also be looked at as a system whose properties and distribution can tell us much about the processes of their formation and evolution in the context of the galaxy. Early on, even with small samples of clusters, certain characteristics were clear: The open clusters were strongly concentrated to the plane of the galaxy and many properties were correlated with cluster age and with galactic location, indicating that significant environmental processes have shaped the cluster population of today. van den Bergh (1958) noted that the four oldest open clusters were located at higher distances out of the plane than was typical for open clusters, and from a larger sample of 20 clusters, van den Bergh and McClure (1980) pointed out that clusters with ages greater than 1 Gyr were located preferentially toward the galactic anticenter compared to their younger counterparts. Oort (1958) noted that old clusters were 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. The disruptive effect of encounters with massive clouds could explain a paucity of old clusters (Spitzer 1958), but, in fact, these processes were too efficient to explain the many ancient clusters seen. The population of clusters seen today is the result of the relationships and complex interplay between processes of formation, intrinsic cluster properties, internal dynamics, and the galactic environment.

3.1 Spatial Distribution of Clusters

The first large-scale study of general cluster properties was based on the Lynga catalog (1982), as analyzed by Janes et al. (1988). A weighting scheme that considered the varying quality of catalog data, as well as a uniform and systematic approach to the determination of cluster parameters yielded a sample of 421 clusters which revealed many overall properties of the open cluster system. The first of these was the general spatial distribution of open clusters, showing clearly that its characteristics were a function of cluster age. This distinction was manifest clearly in the radial distribution, which showed that older clusters are not found in the inner part of the galaxy. From about the solar circle outward, although clusters of all ages could be found, the average cluster age increased, and older clusters predominated in the outer disk, even after considering the incompleteness effects expected at larger distances (see *Fig. 7-6*).

The vertical distribution of open clusters also showed a clear dependence on age. For clusters with ages less than about 300 Myr, the exponential scaleheight from the plane was constant, at 55 pc, but increased gradually for older clusters. The distribution of these young clusters also showed a clear displacement of the sun of 21 pc with respect to the galactic mid-plane, similar to what is seen relative to field stars. However, for clusters of all ages, the disk becomes

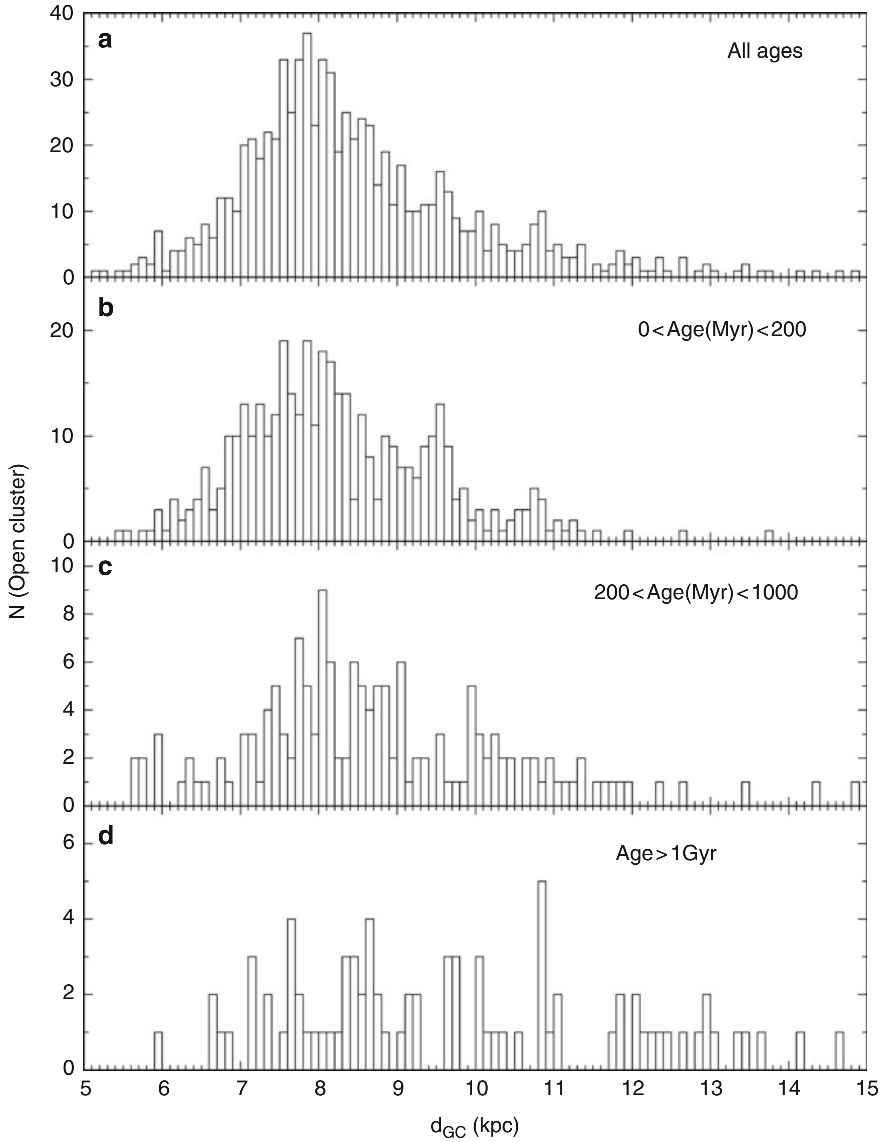

Fig. 7-6
Distribution of open clusters with distance from the galactic center from Bonatto et al. (2006). Clusters distributions are grouped by age, as shown (Cluster parameters are adopted from the WEBDA database)

thicker with increasing galactocentric distance, a trend which is much more pronounced for the older clusters. Later studies quantified this dependence, when larger samples of clusters were available, particularly at the larger ages. Janes and Phelps (1994) found that the vertical distribution of clusters with ages greater than about the Hyades was well fit by an exponential with a scaleheight of 375 pc.

Twenty years later, with a cluster sample increased by 50%, and improved parameters for many clusters, Bonatto et al. (2006), carried out a similar analysis. Using a sample of 654 clusters with known distance, drawn almost exclusively from the WEBDA, they looked in detail at the dependences of scaleheight on age. Their results reinforce the general trends seen in the earlier papers. The entire cluster population shows an exponential scaleheight of 57 pc, but this value increases with increasing cluster age: Clusters with ages younger than 200 Myr show an exponential scaleheight of 48 pc, for those with ages from 200 Myr to 1 Gyr it increases to 150 pc, while clusters with ages greater than 1 Gyr are nearly uniformly distributed within 400 pc of the plane (their ➋ *Fig. 7-10*). For the younger clusters their determinations agree well with other work, but for the oldest clusters, the lack of exponential falloff with height contrasts with that found by Janes and Phelps (1994). This difference may be due to the somewhat different age range considered, as the Janes and Phelps sample included clusters as young as 700 Myr, and the additional old clusters in the later work. Nevertheless, the oldest clusters are clearly found in a more spatially extended vertical distribution than the younger clusters.

The more recent, larger cluster sample used by Bonatto et al. (2006) also illustrates the thickening of the disk with increased galactocentric distance. The galactic disk as traced by the clusters with ages less than 1 Gyr shows a thickening by a factor of 2 in moving from inside to outside the solar circle. For $R_{gc} < 8$ kpc, the exponential scaleheight is $z(h) = 39.3 \pm 3.3$ pc, while outside this distance, $z(h) = 78.1 \pm 5.9$ pc. Both the values of the scaleheight and the thickening with distance are consistent with the disk as defined by H I and reflect the association of star formation with the parent gas (J. M. Dickey, this volume).

In all of these studies which rely on samples of clusters ranging over the full extent of the galactic disk, one must be aware of observational selection effects and incompleteness which can severely affect the conclusions based on observed distributions. Clearly incompleteness is a function of cluster distance. But the varying stellar density in different galactic directions will also affect the ability to distinguish clusters, with greatest impact for the discovery of sparse clusters against the dense stellar fields toward the galactic center. Bonatto et al. (2006) attempt to quantify and correct for incompleteness in their sample by using the variation in the background density from 2MASS to define the detectability of clusters projected toward different regions of the sky. Based on this model, they correct the observed radial and vertical distributions of clusters. When corrected for incompleteness, the observed cluster scaleheights increased by factors of roughly 50%.

More important is the effect the corrections have on the radial distribution of clusters and the interpretation of its general characteristics. As mentioned above, the general observation that old clusters are not found much inside the solar circle has been known for some time. This observation is clearly revealing cluster and galactic dynamics at work, but how much is observational selection? Janes and Phelps (1994), with the first substantial sample of old clusters, noted that their galactic distribution is highly asymmetric, with none found inside a galactocentric distance of 7.5 kpc (assuming a solar galactocentric distance of 8.5 kpc). Considering that the younger clusters show a distribution centered on the sun, with appreciable numbers in the inner galaxy, they argue that the distribution for old clusters cannot be entirely observational selection effects, although those must certainly come into play to some degree.

Bonatto et al. (2006) look at the radial profile of the full cluster population, which, as expected due to observational selection effects, shows a maximum at the solar position, and then decreases in number both interior and exterior to the solar circle. How much of this fall off is due to incompleteness in the sample and how much reflects the underlying number distribution of open clusters in the galactic disk? Limiting to the region within 1.3 kpc of the sun, to minimize the effect of incompleteness, but still correcting for it, they find a disk scale length of 1.4 ± 0.2 kpc. Considering the full extent of the cluster sample, again corrected for incompleteness, the distribution is fit with a scale length of from 1.5 to 1.9 kpc. Both of these determinations reveal a disk scale length that is shorter by a factor of 2 than that derived from stellar populations (see Churchwell and Benjamin, this volume). It is not clear whether this reflects an intrinsic difference with respect to the field star population, or uncertainties in determination.

The observed lack of older clusters in the inner parts of the galaxy remains in the Bonatto et al. (2006) analysis, even after the correction for incompleteness and selection effects.

3.2 Cluster Physical Parameters

Cluster structural parameters and size, and any correlations of structural parameters with location in the Galaxy, provide important constraints to our understanding of both the processes of cluster formation and their dynamical evolution. Cluster sizes may reflect a primordial dependence on gas densities or thresholds for star formation, which vary with location in the galaxy. Alternatively, at the most basic level, the dynamical evolution of an open cluster of a given mass is determined by its linear size. A massive but small cluster will dissolve due to internal interactions, while a large cluster of the same mass will be more affected by external tidal interactions with the galactic field or molecular clouds. The distribution of cluster diameters thus sheds light on these processes.

Janes et al. (1988), and more recently van den Bergh (2006) have looked into the distribution of cluster diameters based on the catalogs of Lynga (1982) and Dias et al. (2002), respectively. From samples on the order of 400 and 600 clusters, respectively, there are clear correlations of cluster size with both location in the galaxy and with age. The largest clusters are found at the youngest ages. The majority of these extremely large clusters are unbound systems, and radial velocity studies have indicated that these associations will dissolve in a few million years. Van den Bergh estimates that approximately 20% of the "clusters" in these catalogs with ages less than 15 Myr are expanding stellar associations, rather than bound, stable clusters. In their review on embedded young clusters, Lada and Lada (2003) note that when emerging from their natal clouds young embedded clusters expand significantly and for long periods before they reach a final equilibrium. For clusters with ages less than 10 Myr, bound and unbound emerging clusters are indistinguishable.

Janes et al. (1988) found that for clusters between ~50 Myr and 1 Gyr, there is no correlation of cluster size with age, and conclude that there is no preferred mass scale for survivability. Looking at a somewhat finer resolution in age, and with a larger sample, van den Bergh observes that there is evidence for a slight increase in cluster size with age. Clusters with ages between 150 Myr and 1.5 Gyr are systematically larger than clusters with ages from 15 to 150 Myr. The typical cluster diameter increases from 2 pc to 3 pc in this age range. He suggests that this effect may be due to the loss of gas by the evolving stars in the cluster.

In all studies, the oldest clusters, those with ages greater than 1–1.5 Gyr, are systematically larger than the younger bound clusters. This fact may initially seem surprising; one might expect the oldest clusters to be more tightly bound to have survived to such great ages. However, these clusters have other properties that distinguish them from the majority of the open cluster population. They are also located preferentially at larger distances from the galactic plane and at large galactocentric distances in the outer disk, clearly a feature that allows them to survive.

There is also some indication that cluster diameters increase with increasing distance from the galactic center. These large samples show evidence that the proportion of clusters with small diameters is smaller at larger distances, or that larger clusters predominate at larger galactocentric distances. One might be tempted to interpret this correlation as indicating that large clusters are preferentially destroyed at small galactocentric radii or that they can survive at larger galactocentric radii because of the less frequent interactions with molecular clouds. However, this apparent correlation is strongly influenced by a variety of observational selection effects that complicate its interpretation. Small clusters will not be discovered at the same rate as larger clusters at great distances. As discussed earlier, the changing stellar background density affects the likelihood of finding sparser clusters. Most importantly, these measures are of apparent cluster diameter, not a physical parameter such as half-light or half-mass radius, so the determinations themselves are affected by the cluster mass. More populous clusters, or those seen against a less dense stellar background, will be traced to larger radii simply because there are more stars to measure or they are easier to distinguish against the low density background.

The discovery of open clusters from IR surveys, particularly 2MASS, has both increased the number of clusters over these earlier samples and allowed us to probe regions of the galaxy that may help understand the impact of dynamical effects. In a series of papers following up on the survey by Froebrich et al. (2007), Bonatto and Bica have shown that these newly discovered clusters have radii that are systematically smaller than previously known open clusters of similar age (e.g., Bonatto and Bica 2007, 2008). For clusters located inside the solar circle, the systematically smaller core and limiting radii relative to clusters outside the solar circle point to the influence of tidal effects that may have accelerated dynamical evolution.

They also find, as in earlier studies, that sizes of open clusters appear to increase with galactocentric distance, but that the newly discovered clusters tend to be smaller than previously known open clusters at the same galactocentric distance, particularly in the region from 8 to 10 kpc. As they note, part of this relation of increasing size with galactocentric distance may be primordial, and reflect the fact that the higher density of molecular gas in the inner galactic regions may have produced clusters with smaller initial radii.

Among the FSR clusters, they find a rough trend of increasing size with height from the galactic plane. This is not unexpected from dynamical effects, as clusters closer to the galactic plane suffer more frequent encounters with molecular clouds, and will survive only if they are more compact. Again, though, one must caution that observational selection effects will naturally lead to the measurement of larger cluster diameters against the lower stellar background density of the higher latitude fields.

These global correlations suggest that dynamical effects play an important role in influencing cluster intrinsic properties, as would be expected. Larger, sparser clusters are able to survive to greater ages in the areas of the galaxy less populated by large molecular clouds or other strong gravitational forces, that is in the outer disk and farther from the galactic plane. It is difficult to go beyond these general observations however, to investigate the details of the impact that overall galactic properties have on cluster evolution and longevity, because of the importance of basic observational selection effects on both the detectability of the clusters and their measured properties. Obtaining measurements of physically based structural parameters, such as the half-light or half-mass radius, rather than an apparent linear diameter, derived from a uniform data set and for a large number of clusters would undoubtedly allow progress to be made in this area. In the meantime, as discussed earlier, a great deal of insight into the overall effects of dynamical evolution on cluster structure and longevity can be obtained from the detailed modeling of n-body simulations in a realistic galactic potential.

3.3 Spiral Arms

The positions of galactic clusters and stellar associations have been used to attempt to trace out regions of star formation and spiral arms in the galactic disk. The first large samples of clusters, however, showed no clear association with the larger structure of spiral arms. Instead, young clusters (less than 20 Myr) clumped in several large complexes, not aligned with spiral structure, while older clusters showed no distinguishing distribution (Lynga 1982).

The larger optical samples recently analyzed by Bonatto and Bica (2006) and van den Bergh (2006), show stronger evidence of the longitudinal distribution of young clusters reflecting areas of active star formation and the presence of spiral structure. Enhancements in the number of clusters are seen at $l \sim 285^{\circ}$, coinciding with the Carina arm, particularly in the youngest clusters with ages less than ~10 Myr, and at $l \sim 125^{\circ}$ coinciding with Cassiopeia. When projected onto the galactic plane, clusters with ages less than 60 Myr show a distribution coincident with the Orion spiral arm, and a lack of clusters in the interarm region between the Orion and Sagittarius arms, just inside the solar position. Beyond this immediate solar region, the detailed distribution of young clusters shows no particular pattern suggestive of association with spiral structure.

New infrared surveys, however, with their ability to probe areas of high extinction and active star formation provide an opportunity to uncover clusters either in the process of formation or emerging from their natal clouds, whose galactic distribution may indicate spiral structures.

The Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) project has mapped out the inner galaxy at mid-IR wavelengths (3.6, 4.5, 5.8, and 8.0 mμ) and produced a database from which candidate star clusters have been detected by Mercer et al. (2005). GLIMPSE data are very effective at discovering heavily embedded young clusters and their galactic distribution shows interesting asymmetries. Within their survey area they detect more than twice as many new clusters in the southern half of the Galaxy as the northern half, and more below the galactic mid-plane than above. Both of these asymmetries are seen in the optical and 2MASS cluster samples, although not as pronounced. The longitudinal distribution of GLIMPSE clusters shows distinct peaks at $l = 330^{\circ}$and 313°, which may trace the location of spiral arm tangencies; the enhancement at $l = 330^{\circ}$ is also seen in 2MASS. The use of these surveys to explore the galactic distribution of newly discovered clusters is just beginning, as the detailed properties of these cluster candidates are still to be explored. They promise, however, to yield particular insight into questions of star and cluster formation in the inner galactic disk.

3.4 Longevity of Open Clusters

The dependence of spatial distribution on age that is apparent in the open cluster system points to a complex interplay between cluster formation and survivability. The distribution of cluster ages sheds further light on this balance. If the cluster population seen today were a result of a uniform rate of cluster formation combined with an exponentially declining dissolution rate, one would expect to see a simple exponential distribution with a characteristic single lifetime. What is seen is much different. The age distribution of clusters shows three distinct populations with different timescales of longevity.

The youngest population of clusters identified is one with lifetimes of only a few tens of millions of years. This group of clusters is apparent in any large sample, and their numbers rapidly decrease with age beyond a few tens of millions of years. These are stellar associations

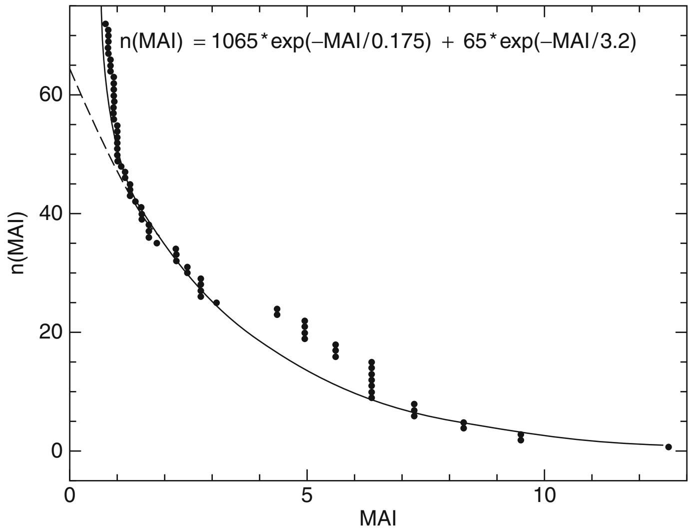

Fig. 7-7

Cumulative distribution of numbers of clusters with ages greater than the morphological age indicator, MAI, from Janes and Phelps (1994). The *solid line* shows the function with exponential timescales of 175 Myr and 3.2 Gyr. The *dashed line* shows only the second, longer decay timescale appropriate for the older clusters in the distribution

that are not gravitationally bound, and are in the process of dissolving and dispersing into the general field population.

The majority cluster population has a characteristic lifetime of a few hundred million years and presents a rather homogeneous group. These clusters dominate the galactic system of open clusters and largely define the properties of the "typical" open cluster. Janes and Phelps (1994) find an exponential decay time for these clusters of 175–230 Myr (➲ *Fig. 7-7*). Bonatto et al. (2006) derive an exponential of 123 Myr for the majority population.

As was first apparent in Janes et al. (1988) and reinforced with larger samples in Janes and Phelps (1994), the age distribution shows a long tail to larger ages, in a distribution that cannot be fit with a single exponential with a decay time of a few hundred million years (➲ *Fig. 7-7*). This group, only a few percent of the total cluster population, can be characterized with lifetimes of 3–4 Gyrs, and includes members with ages approaching the age of the galactic disk and the youngest of the globular clusters. Janes and Phelps (1994) fit this older population in the cluster age distribution with an exponential of 3–5 Gyrs. Bonatto et al. (2006) derive an exponential timescale of 2.4 ± 1 Gyr for this old population. In either case, there is a substantial population of old clusters not explained by the simple picture of uniform formation combined with dissolution.

The mix and relative numbers of these populations vary with location in the Galaxy, leading to the spatial distributions correlating with age. The outer disk clusters are systematically longer lived; the typical open cluster in the outer disk will survive about twice as long as one in the inner disk. The characteristic lifetime of open clusters of all types is a distinct function of galactocentric radius.

3.5 The Oldest Open Clusters

The oldest of the open clusters are clearly a special population whose detailed properties relate to a number of issues in galactic structure and formation, the dynamical evolution of clusters, and the balance between the mechanisms of cluster formation and dissolution. It is observed that clusters with ages greater than about 1 Gyr are located preferentially in the outer galaxy, almost exclusively outside about 6 kpc from the galactic center. They are also preferentially located at greater heights from the galactic plane. They are, in general, slightly larger in apparent linear diameter than their younger siblings.

Is there anything about the details of the distribution of their properties that would provide insight into what allows these clusters to survive so long?

The value of old open clusters in exploring the development and evolution of the galactic disk led, over the past several decades, to special efforts to discover old clusters through systematic searches and to determine their properties through follow-up photometry and spectroscopy. The first substantial increase in the sample of old clusters came with a survey by Phelps et al. (1994) and Janes and Phelps (1994), who identified a sample of 72 clusters with ages greater than the Hyades, or about 700 Myr. In the years following, continued effort to expand the number of old clusters known through studies of promising individual clusters, as well as the automated searches from IR surveys, have revealed increasing numbers of old cluster candidates. The follow-up studies of cluster candidates from the FSR survey, for example, have, to date, identified 16 more confirmed open clusters with ages greater than 1 Gyr (Froebrich et al. 2008).

The current Dias catalog, the WEBDA, and earlier lists of old clusters (Friel 1995) combined with follow-up of the FSR survey, reveals over 160 clusters with ages greater than 1 Gyr. This can be contrasted with the 86 clusters in the Bonatto et al. (2006) sample drawn from the WEBDA. While these numbers suggest a rapid increase in sample size, it is important to recognize that some fraction of these old ages may be incorrect estimates and that some of the "clusters" identified are simply asterisms detected in automated searches and not true bound clusters. Most importantly, the age estimates come from a variety of techniques and individual determinations, so are not on a uniform and consistent scale. Even given these caveats, with likely contamination at the level of 10–20%, the increase in numbers indicates that there are many more old clusters available from which to probe the early galactic disk.

These larger samples confirm the initial conclusions of Janes and Phelps (1994), that among these old clusters there is no correlation of age with location. *Figure 7-8* shows the distribution of cluster location with age from these heterogeneous samples, for clusters with age greater than 1 Gyr. While relative to the majority of the open cluster population with ages of several hundred million years, the old clusters are found preferentially in the outer disk and at larger heights from the galactic plane, when just the old clusters are considered, there appear to be no strong trends of age with location. As *Fig. 7-8* shows, the oldest clusters in the group, those with ages greater than ~4 Gyr, are located at all galactocentric radii. Similarly, the oldest clusters are found at all heights from the plane; they are not at preferentially larger distances than clusters with ages of only 1–2 Gyr. This observation is somewhat surprising; one might have expected the very oldest of the clusters to be the most distant or farthest from the plane in positions that have allowed them to survive the disruptive tidal forces in the plane. Yet two of the oldest clusters known, Be 17 and Cr 261, at 10 and 8 Gyr, respectively, are found only about 200 pc from the plane. Cr 261 and NGC 6791 are found just inside the solar circle, at galactocentric radii of

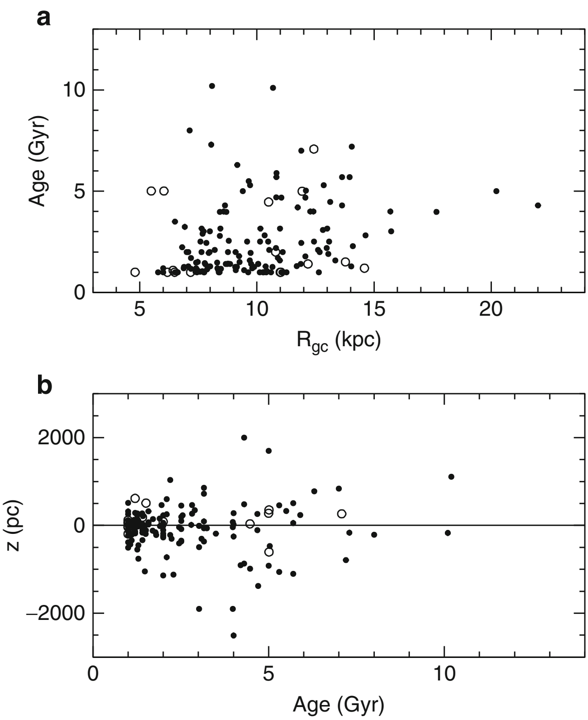

Fig. 7-8
Distribution of cluster location with age for open clusters older than 1 Gyr. Filled circles are clusters with data drawn primarily from the WEBDA, with ages from Salaris et al. (2004) when available; open circles are confirmed open clusters identified in FSR and characterized in follow-up studies (Froebrich et al. 2008). (a) Age as a function of galactocentric radius where the sun is at 8 kpc. (b) Distance from the galactic plane as a function of cluster age

7 and 8 kpc, respectively. And, the most distant open clusters known, Be 29 and Saurer 1, are only 3–5 Gyr old. All of these examples illustrate the large scatter seen among cluster properties with age.

Among these old clusters, there is a tendency for the most distant objects to be farthest from the galactic plane. This is not surprising and is expected purely from observational selection effects. Clusters at the very large distances in the outer disk are likely to be found only if they are far from the plane; those in the plane are heavily obscured.

There is much less information about the kinematics or orbital characteristics of these old clusters that might reveal more detail about their origins or reasons for longevity. However, what information there is suggests no strong correlations of kinematic behavior with age or location. Based on a sample of 35 clusters with ages greater than 1 Gyr, Scott et al. (1995) showed that the radial velocities of the old clusters are consistent with those expected from the disk rotation curve defined by the younger clusters, but with a larger dispersion of 29 km s^{-1} versus 10 km s^{-1} typical of younger clusters. Alternatively, assuming the clusters rotate about the galactic center with constant rotation velocity, the old cluster system reflected in this sample rotates with a velocity of $211 \pm 7\,\mathrm{km\,s^{-1}}$ with a line-of-sight dispersion of $28\,\mathrm{km\,s^{-1}}$, lagging only slightly the solar rotation. These kinematics are consistent with those of the old, mixed-age, thin disk field population.

For the limited number of clusters for which one has full space motions and can compute orbits, one finds generally the same result. Orbits for five classic old clusters were modeled by Carraro and Chiosi (1994) who found eccentricities of 0.15 or less, consistent with their association with the old, thin disk population. However, the clusters are also found to be close currently to their maximum excursion from the galactic plane, where they spend most of their time away from the disk and its disruptive influences. On the other hand, there are several clusters with clearly anomalous orbits, even judged solely by their radial velocities. The cluster Be 17, the oldest open cluster known in the galaxy, which is located almost directly in the anticenter, at $l = 176^{\circ}$, has a radial velocity of $-84\,\mathrm{km\,s^{-1}}$ (Scott et al. 1995), indicating a significantly noncircular orbit.

The old cluster NGC 6791, for which proper motions exist, has the most eccentric and unusual orbit known for an open cluster (Bedin et al. 2006). With an eccentricity of ~0.5, its orbit takes it to a perigalacticon of ~3 kpc, into a region of the galaxy where no old open clusters are currently seen, while its apogalacticon is not far beyond the solar radius. The cluster, however, has suffered strong dynamical effects due to its numerous passages through the galactic plane: In each orbital period of ~130 Myr, it passes three times through the galactic plane, once at $R_{gc} \sim 9$ kpc, and twice at $R_{gc} \sim 5$ kpc, where the disk is much denser. NGC 6791 is also one of the most massive and dense open clusters, properties which are clearly responsible for its longevity.

One can ask if there is structure in the age distribution of these oldest clusters that could point to preferred periods for star formation or provide insight into the nature of the formation or disruption processes that have allowed these clusters to survive for so much longer than the typical open cluster. In looking at the subtleties of the age distribution, it is extremely important to have ages on a uniform scale, determined in similar fashion and accurate in a relative sense even if the zero-point may be uncertain. Two studies have paid particular attention to this issue.

Janes and Phelps (1994) used an age indicator based on the morphology of the cluster color-magnitude diagram, using the relative locations of the main sequence turnoff and the red giant branch and He-core burning red clump stars, to determine a "morphological age indicator" (MAI) which is well correlated with the logarithm of cluster ages. Using this measure of cluster age, they obtained a sample of 72 clusters with ages greater than the Hyades, which at the time was several times larger than had been known previously. Within this sample, they noted the possibility of an excess of clusters in the age range of 5–7 Gyr (see ➋ *Fig. 7-7*), suggesting either large bursts of star formation at this period or perhaps that a larger proportion of clusters forming at that time had orbits that allowed them to survive. They argue that these old clusters cannot be just the long-lived tail of the general open cluster population because there are far too many to be explained if extrapolated from the current numbers of younger clusters. Similarly the old clusters cannot have diffused away from the galactic plane through encounters with giant molecular clouds or other massive objects, because these encounters would tend to disrupt the clusters on shorter timescales than their ages. They conclude that these old clusters must have formed from a distinct process of disturbances to the galactic disk, through infalling material or tidal interaction.

Salaris et al. (2004) further calibrated these morphological indicators in terms of absolute ages, based on a consistent set of updated stellar models, and tied to a similar set used to date a large sample of globular clusters. They also find that the distribution of these ages deviates from the simplest case of a uniform formation rate and exponentially declining dissolution rate. They also find an excess of clusters in the 4–6 Gyr range at the 2 sigma level. This distribution is independent of galactocentric distance, which suggests that the cluster formation and destruction processes are not correlated with R_{gc} for these old clusters. The same is not the case for the z-distribution. Clusters closer to the plane follow more closely the scaling relationship corresponding to a dissolution timescale of 2.5 Gyr. The clusters more distant from the plane ($|z| > 300$ pc) show a clear excess of clusters in the range of 3–6 Gyr with a difference that is significant at more than the 3 sigma level. They suggest this points to a more homogeneous or uniform "creation–destruction process" for the clusters closer to the galactic plane. While this result reinforces the idea that the clusters survive most readily at higher distances from the galactic plane, the impact of incompleteness in the sample and selection effects at the lowest z-distances needs to be considered.

The very oldest of the open clusters can be used to set limits to the age of the galactic disk and the relative timescale of disk and halo formation. Although there are still debates on the exact ages of particular clusters, there is general agreement that Be 17, NGC 6791, and Cr 261 are the oldest open clusters currently known, with ages of 8–10 Gyrs (e.g., Phelps 1997; Bragaglia and Tosi 2006; Krusberg and Chaboyer 2006). These ages are consistent with the age of the galactic disk as probed by the white dwarfs. Salaris et al. (2004) who have determined the ages of open and globular clusters in a similar homogenous fashion determine a delay of 2.0 $\pm$ 1.5 Gyr between the start of the formation of the halo, as indicated by the oldest metal-poor globular clusters, and the thin disk formation, indicated by the age of the oldest open clusters. They also find no age difference between the thin and thick disk formation as reflected in the cluster populations. In contrast, probing the time delay between the formation of the thin and thick disks from a sample of clusters with self-consistently determined relative ages, Krusberg and Chaboyer (2006) find an age difference of 2.8 $\pm$ 0.8 Gyr between the metal-rich thick disk globular clusters and the oldest open clusters.

With many new candidate clusters with ages greater than 1 Gyr being identified in automated IR searches, it would be interesting to place them on a uniform age scale to explore further both the details of structure in the age distribution of open clusters and its relation to the globular cluster systems.

4 Galactic Chemical Evolution

Open clusters, found at all ages and throughout the galactic disk, serve as excellent tracers of the overall chemical enrichment of the disk. As they preserve the abundances of the gas from which they formed, studying the chemical profiles of clusters of different ages and locations provides a history of star formation and nucleosynthesis throughout the galaxy and across its lifetime. Recent high precision analyses indicate that stellar abundances among cluster members are highly uniform, consistent with no intrinsic scatter within the cluster (De Silva et al. 2006), so one can be assured that the abundances determined reflect the initial composition in a well-mixed gas cloud. As noted earlier, stellar evolutionary effects and mixing of processed material to the stellar surface may alter abundances of some light elements (e.g., Li, C, N) in the atmospheres of giant stars. While observations of some elements present challenges to theoretical models, they do not alter the usefulness of stellar and cluster abundances as tracers of overall galactic chemical evolutionary patterns.

Stellar abundances and overall metallicities in clusters have been derived by a wide variety of photometric and spectroscopic methods. Early work relied on photometric abundance indicators using UBV, DDO, Washington, and Stromgren photometric systems, which were able to provide overall metallicities for substantial numbers of stars in a cluster field. While photometric studies have the advantage of reaching large samples and faint, distant objects, they suffer from potential contamination by nonmembers and reddening. Significant numbers of spectroscopic studies began to appear in the 1980s, but samples were initially limited, and high-resolution spectroscopy was rare. Photometric and low-resolution spectroscopic abundances generally yield overall metallicities that are internally accurate to 0.1–0.15 dex in [M/H],[1] but with the possibility of significant systematic differences between studies. Photometric and spectroscopic indices measure the blanketing in either narrow or broad bands due primarily to blends of Fe and Fe-peak elements, or common molecular species, such as CN or MgH, which are then calibrated to [Fe/H] or, in the case of some photometric indices, interpreted through the analysis of color-magnitude diagrams with the help of theoretical isochrones. The Lynga, Dias, and Mermilliod catalogs of cluster parameters include metallicity determinations drawn from a wide variety of sources, and care must be taken to assess the systematic differences inherent in these collections. Systematic differences of 0.1–0.2 dex are common and can either obscure or create and certainly confuse correlations and general trends that have the potential to reveal much about galactic structure and evolution.

The availability of stellar abundances based on a uniform treatment and analysis for large samples of clusters is critical for an accurate and thorough understanding of abundance patterns both within the cluster population and on galactic scales. A plethora of differences in how measurements are made and analyzed, such as continuum tracing, equivalent widths, or spectral synthesis, or methods of analysis, such as choice of model atmospheres, adopted atomic parameters, temperature scales, or treatment of convection or assumptions of local thermodynamic equilibrium (LTE), all have a bearing on final results, and can introduce substantial systematic differences between studies. Fortunately, a growing number of studies are providing both the sample sizes, and the means to intercompare studies to understand the nature and magnitude of systematic differences that can impact the interpretation of observational results. The increasing number of high-resolution spectroscopic studies, in addition, are providing not only overall metallicity, but individual elemental profiles that shed light on detailed nucleosynthetic and star formation histories among the diverse cluster population.

4.1 Disk Abundance Gradients

The variation of abundance with position in the galactic disk provides essential constraints to models of chemical evolution, and open clusters, with their range of ages and distances are among the best indicators of trends in overall metallicity as well as abundance patterns. From the first studies it was clear that the cluster population shows a significant decrease in metallicity with increasing galactocentric distance; clusters in the outer disk are distinctly more metal-poor than those in the solar neighborhood. The exact shape of this distribution and the magnitude of the trend and whether or not it varies with age, however, are still subjects of debate.

[1]Stellar abundances are defined on a logarithmic scale relative to the solar abundance, with $[X/H] = \log (X/H)_{star} - \log (X/H)_{\odot}$, where X is the number density of the element. Here M refers to an overall metallicity of heavy elements rather than an individual element.

Janes (1979) offered the first quantitative description of the abundance gradient from open clusters, using a sample of 41 clusters with overall metallicities derived from a combination of DDO and UBV photometry of cluster giants. He found a gradient of d[Fe/H]/dR = −0.05 dex kpc^{-1} over a range of 8–14 kpc from the galactic center (assuming a solar distance of 10 kpc), by combining the cluster data with field red giant stars. The clusters alone indicated gradients of −0.039 ± 0.031 for clusters younger than 800 Myr, and a steeper value of −0.076 ± 0.028 for those older. Janes et al. (1988) expanded this work using the much larger sample of clusters in the Lynga catalog to derive a gradient of −0.07 for clusters younger than 200 Myr. Older clusters yielded a steeper gradient of −0.14 dex kpc^{-1}, but this result was dominated by a handful of clusters in the outer part of the galaxy with metallicities [Fe/H] of −0.5 to −0.6 dex. In all cases, while the overall trend of decreasing metallicity with distance was clear, the dispersion in abundance at any distance was appreciable. In neither case was there evidence for a gradient in abundance vertically from the galactic plane.

Piatti et al. (1995) derived a very similar gradient of −0.07 dex kpc^{-1} from a large and homogeneous sample of abundances from DDO photometry for 63 clusters, primarily younger than 1 Gyr. Unlike previous studies, however, they found clusters to exhibit a steep abundance gradient perpendicular to the galactic plane, of −0.34 dex kpc^{-1}. Based on the calculation of orbits for 19 clusters with proper motion as well as radial velocity data, they concluded that the present-day gradients have not been modified significantly by cluster orbital motion.

The first appreciable sample of abundances based on spectroscopy came with Friel and Janes (1993), who used low-resolution spectroscopy of cluster red giants, concentrating on the oldest and most distant objects known at the time, and supplemented by several well-studied clusters from the literature, to derive a gradient of −0.09 ± 0.02 dex kpc^{-1}. A later paper (Friel et al. 2002) expanded this sample to 39 clusters with a new abundance calibration to find a gradient of −0.06 ± 0.01 dex kpc^{-1} over the range of 7–16 kpc in galactocentric distance (assuming a solar distance of 8.5 kpc). They found no vertical gradient in abundance, once correcting for the selection effect that makes more distant clusters in the outer disk (which are also more metal-poor) more likely to be found at large distances from the plane.

It was common in these, and many other studies of the disk abundance gradient, to fit linear relations to characterize the dependence of abundance with distance as the simplest assumed form, although a number of authors (Friel 1995) commented on the possibility of more complex distributions. Twarog et al. (1997) came to a very different conclusion, using a sample of 76 clusters spanning a wide range of ages, and placed on a common metallicity scale by combining DDO photometry and spectroscopic results from Friel and Janes (1993). They found that the metallicity distribution was best described by two distinct zones in galactocentric radius, separated at 10 kpc, on a scale where the sun is at 8.5 kpc. Between 6.5 and 10 kpc, the cluster metallicity is roughly solar, with a dispersion of only 0.1 dex. Outside 10 kpc, the mean metallicity drops by a factor of 2, to [Fe/H] = −0.3, and remains constant to the most distant cluster, at ~16 kpc. They suggested that the discontinuity is a reflection of the edge of the initial galactic disk, and that the initial offset in [Fe/H] created by different histories of chemical evolution on either side of the break has been preserved to the present day in the cluster population.

Since then, the discovery and study of several extremely distant clusters has allowed the gradient to be traced beyond galactocentric distances of 20 kpc and provides insight on the behavior in the very outermost disk. The most distant of these clusters, Berkeley 29, at R_{gc} = 22 kpc, has a metallicity [Fe/H] of only −0.3 to −0.5 (Yong et al. 2005; Carraro et al. 2004), far more metal-rich than expected if the radial gradient slope of −0.06 dex kpc^{-1} continued to

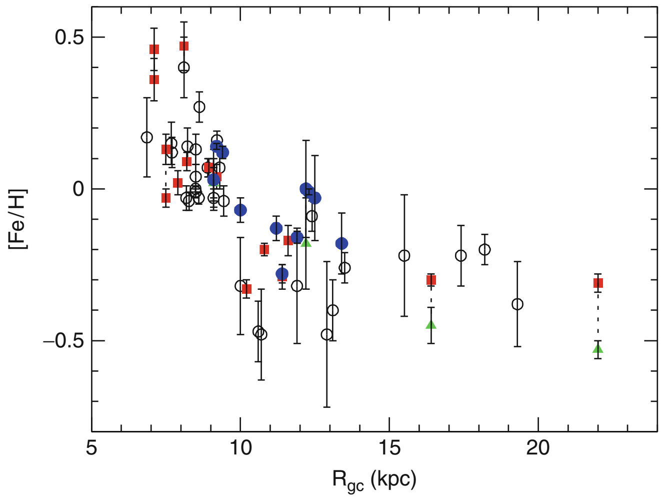

Fig. 7-9

Radial abundance gradient from high-resolution spectroscopic studies. Open circles from a variety of sources in the literature, with values as collected by Magrini et al. (2009) supplemented by Friel (2006), *filled squares* from Sestito et al. (2008), *filled circles* from Friel et al. (2010), *filled triangles* from Yong et al. (2005). Clusters in common to samples are connected by *dotted lines*. Error bars indicate uncertainties in mean cluster abundances as cited by the authors

these distances. As more clusters were added, data showed clearly that the disk radial abundance gradient appears to flatten out beyond about ~10–12 kpc, reaching a plateau of [Fe/H] ~ −0.3 to −0.5 (Yong et al. 2005; Carraro et al. 2007).

Although one must be cautious in merging results from different studies, in the past few years, several of the larger programs aimed at obtaining samples observed and analyzed in a homogeneous and uniform fashion are beginning to yield results. *Figure 7-9* combines determinations from a variety of high-resolution studies now available, with the larger samples identified (filled squares from Sestito et al. (2008), filled circles are Friel et al. (2010), and filled triangles are Yong et al. (2005)). Error bars give the error in the mean cluster abundance as cited in the literature; these usually reflect only internal errors. Abundances for clusters in common to more than one study are joined by dotted lines, indicating the magnitude of possible systematic effects between analyses. Although the scatter at any galactocentric radius is appreciable, if one concentrates on the filled points as representative of the more homogeneous samples, there appears to be a fairly steep gradient up to R_{gc} ~ 10–13 kpc, while beyond this distance and out to the most distant cluster at 22 kpc, the slope is consistent with zero. The average metallicity beyond ~13 kpc is ~ −0.3 dex.

The nature of the break in behavior of the abundance distribution, and its exact location, is neither well characterized nor understood. Again, emphasizing the importance of large, homogeneous samples, Jacobson and collaborators (e.g., Jacobson et al. 2009) have investigated cluster abundances in the transition region of ~10–13 kpc. Their results show substantial scatter in [Fe/H] values for clusters in this region, with values ranging from 0.0 to −0.3, well in excess of observational errors, indicating that the transition is not abrupt as suggested by Twarog et al. (1997).

It is worth noting that the value of the gradient in the inner disk is highly dependent on the presence of two very metal-rich clusters NGC 6791 and NGC 6253 at 8 kpc and 7 kpc, respectively. Although the high metallicities of these clusters have been confirmed in numerous studies, and agree within 0.1 dex, it is not clear how representative these clusters are of the inner disk. The sample of clusters shown in ➋ *Fig. 7-9* is far from being a complete sample or one whose observational selection biases are well understood.

Notable in all of these portrayals of the abundance gradient, however, is the large dispersion in cluster abundances at a given galactocentric radius. The distribution of these samples average azimuthally over large regions in the galactic disk and perhaps it is not unexpected to find large variation in abundance. Are the open clusters telling us about the magnitude of the variation? There is, in fact, evidence for localized and substantial azimuthal variation in abundance in the outer disk. Luck et al. (2006) find, from a sample of almost 200 Cepheids, enhancements of 0.2 dex in [Fe/H] over the overall radial gradient, at longitudes of $l \sim 120^\circ$, several kpc exterior to the solar circle. Using young clusters in the inner galaxy, Davies et al. (2009) also find azimuthal variations in abundance that suggest effects due, in this case, to the patchy star formation driven by the central bar of the Milky Way. As the number of confirmed open clusters both in the inner and outer disk continue to increase, they offer the potential to trace the two-dimensional abundance structure of the galactic disk.

4.2 Evolution of the Abundance Gradient with Age

The fact that open clusters can be dated with more certainty than field stars, and that they span all ages in the galactic disk, make them among the best tools with which to study the time evolution of the abundance gradient, a critical constraint to models of galactic chemical evolution.

The earliest studies of the abundance gradient from clusters indicated that the oldest clusters showed the steepest gradients (Janes 1979; Janes et al. 1988). Among their sample of clusters with ages ranging from ~700 Myr to 10 Gyr, Friel et al. (2002) found a slight suggestion of a steepening of the gradient with increasing cluster age, but the significance of the result was limited by the restricted distance range for the youngest clusters. The very different distance distributions of clusters of different ages, coupled with the possibility of the gradient changing slope in different parts of the disk complicate the interpretation. The fact that older clusters are found preferentially in the outer disk, and not found at all inside about 6–7 kpc, means that only younger clusters can probe the inner regions of the disk. The discovery and study of clusters to distances of ~20 kpc in the disk, however, extends the range over which comparisons can be made.

Magrini et al. (2009) use a compilation of the most recent high-resolution abundance studies of open clusters to investigate the time evolution of the gradient over galactocentric distances of 7–22 kpc. Although by combining disparate samples, systematic differences between studies become a factor, they estimate that these amount to only 0.12 dex in [Fe/H]. Their sample of 45 clusters span ages of 25 Myr to 11 Gyr when placed on a uniform age scale. With this sample, they find no strong evidence for evolution in the abundance gradient over this period (➋ *Fig. 7-10*). In the regions from 7 to 12 kpc, where the gradient is steepest before flattening out in the outer regions, there is slight evidence for the gradient of the youngest clusters (ages <0.8 Gyr) to be flatter than that determined from the older clusters. In the outer disk, beyond ~12 kpc, the cluster abundances are consistent with a zero slope, which does not change over the lifetime of the galaxy.

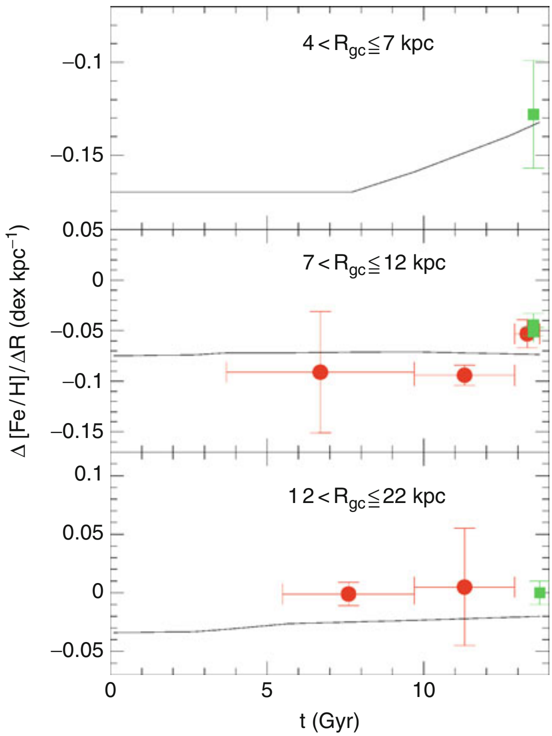

Fig. 7-10
Time evolution of the slope of the abundance gradient, d[Fe/H]/dR, for three regions of galactocentric distance, from Magrini et al. (2009). ***Continuous lines*** **in each panel are slopes of the gradients predicted by models of galactic chemical evolution.** ***Filled circles*** **represent the slopes from open cluster gradients calculated in three age bins: ages <0.8 Gyr, ages between 0.8 and 4 Gyr, and ages >4 Gyr.** ***Filled squares*** **represent slopes of gradients from Cepheids calculated for each radial region**

4.3 Elemental Abundance Ratios

While overall metallicity and Fe abundances are useful in tracing the general trends of chemical enrichment, they do not provide much information on the details of star formation and nucleosynthesis. Those are revealed in the behavior of elements such as oxygen, the α-elements, r- and s-process elements, and their specific abundance patterns. Although there were a few pioneering efforts to obtain high-resolution spectroscopy from which elemental abundances could be determined, it was not until the mid-1990s and especially the 2000s when studies began to yield appreciable numbers of clusters for which elements other than Fe or the lightest elements (such as Li or C) were determined. Several groups have led in these efforts: the Bologna Open Cluster Chemical Evolution project (Bragaglia and Tosi 2006), Randich and collaborators (e.g., Sestito et al. 2008), Carraro and collaborators (e.g., Carraro et al. 2007), Jacobson, Friel, and collaborators (Jacobson et al. 2009; Friel et al. 2010), and Yong, Carney, and collaborators (Yong et al. 2005).

Of particular interest is the behavior of oxygen and the α-elements Mg, Si, Ca, and Ti, which are formed through stellar nucleosynthetic processes in massive stars, and, as a result, are quickly recycled to the interstellar medium through mass loss and Type II supernovae explosions. Elevated abundances of these elements, relative to the solar ratios, point to episodes of rapid star formation and distinctive star formation histories.

Initial studies of the abundances of the outermost disk clusters indicated just this possibility. Yong et al. (2005) and Carraro et al. (2004) found that the clusters that defined the plateau of [Fe/H] ~ −0.3 in the outer disk also showed elevated values of those elements formed in massive stars, indicating genesis associated with a period of rapid star formation. The pattern of elemental abundances found in these most distant clusters did not match those of either the thin or thick disk, nor the halo. Based on their peculiar abundances, and in particular the enhanced oxygen, α-elements, and the r-process element europium, Yong et al. (2005) suggested that these outer disk open cluster abundance ratios are consistent with the outer disk being formed via a merger event or series of events.

However, further work on these and additional open clusters in the outer disk now suggests abundance ratios that are consistent with scaled solar values, similar to those found in clusters in the solar neighborhood (Carraro et al. 2007; Sestito et al. 2008). The nature of the most distant disk clusters is still a puzzle, but it seems less likely now that they have a distinctly different formation history, at least as revealed in the signature of their abundances. *Figure 7-11* collects results for α-elements from high-resolution studies in the literature, plotting the radial distribution of [X/Fe] for Mg, Si, Ca, and Ti. Elemental ratios show no strong dependence on radius, although there are indications that not all α-elements scale in the same way. Mg and Si are often higher than Ca and Ti, but the differences are small and consistent with observational uncertainties. In *Fig. 7-11*, clusters in common to different samples are connected by dotted lines and demonstrate the importance of understanding and taking into consideration systematic differences between studies, particularly for those outer disk clusters that indicated enhanced abundances. Overall, the cluster abundances follow the trends of [Fe/H] that are seen in field star studies, and fall within the dispersions of the thin disk field star population (see P. E. Nissen, this volume).

There also appear to be no pronounced trends of abundance ratio with age. The oldest clusters, Be 17, NGC 6791, and Cr 261, at ages of 8–10 Gyr, for example, have solar abundance ratios. In particular, their abundances of oxygen and the α-elements, which might have shown some enhancement due to rapid star formation in the early disk, are, instead, consistent with solar values. Over the full range of cluster ages, the α-elements generally show solar ratios as well.

Several elements do show slight enhancements over solar. Na and Al, for example, are often found to be enhanced in open clusters. These elements are produced in burning cycles in intermediate mass stars, in particular the Ne-Na and Mg-Al cycles that operate at high temperatures in shell burning in evolved stars. Enhanced abundances of these elements may point to contributions from winds of intermediate mass stars polluting the interstellar medium with the products of these advanced burning stages. It is also possible that these elements are enhanced through mixing to the stellar surfaces of products of internal processes in evolved stars, since many of the abundance determinations rest on analysis of the brighter cluster giants. As discussed earlier, the limited observations of stars of differing evolutionary state within a cluster do not yet provide a clear picture of whether internal processes are operating. A more prosaic explanation is that the Na enhancement, in particular, may be due to difficulties in analysis, and the lack of correction for non-LTE effects in the abundance analysis of evolved giant stars, which form the basis for most cluster abundance studies. Until these analysis issues are understood fully, the interpretation of the enhanced Na abundances remains unclear.

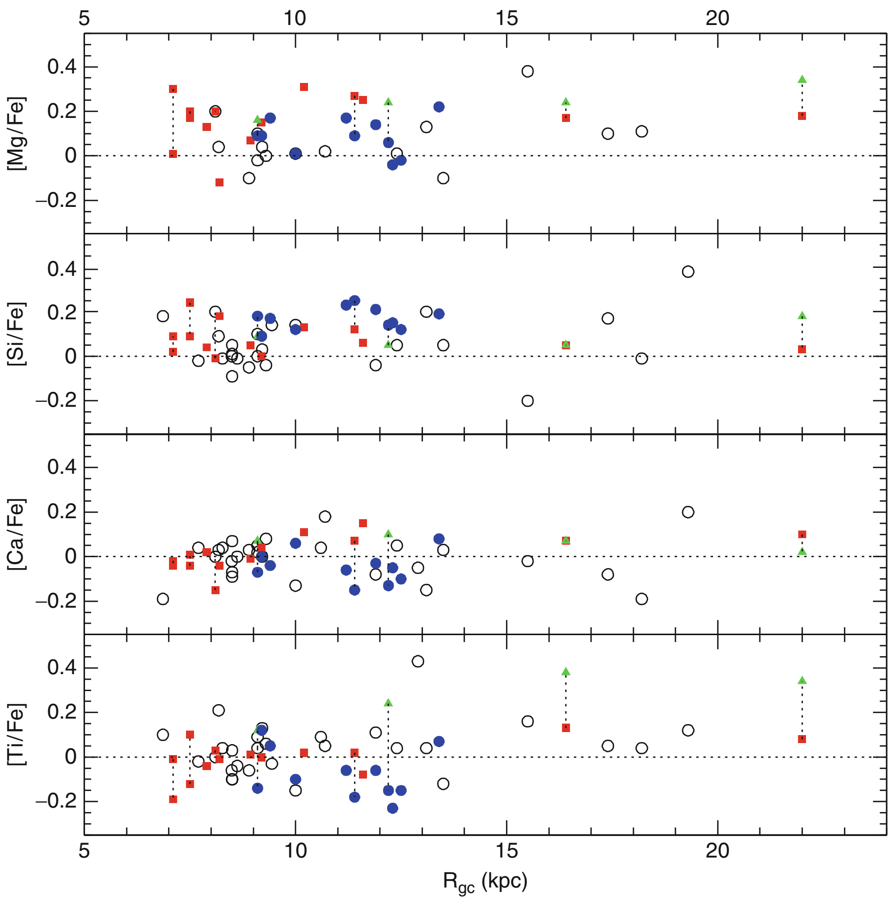

Fig. 7-11

Distribution of [X/Fe] for α-elements Mg, Si, Ca, and Ti with galactocentric radius. Open circles are from a variety of sources in the literature, with values as collected by Magrini et al. (2009) supplemented by Friel (2006), *filled squares* are from Sestito et al. (2008), *filled circles* are from Friel et al. (2010), *filled triangles* from Yong et al. (2005). Clusters in common to samples are connected by *dotted lines*

4.4 Age–Metallicity Relationship

The evolution of the metallicity of the disk is a fundamental observational constraint for theories of galactic chemical evolution. From the first small and local samples, open clusters have posed a challenge to the idea that the galactic disk is gradually enriched over time by the products of successive generations of star formation. The existence of old, solar metallicity clusters such as NGC 188 indicated that the disk had to have been enriched early. As samples have increased, the conclusion has not changed.

The homogeneous samples of cluster metallicities from Friel and Janes (1993) and Friel et al. (2002) showed no dependence of metallicity on cluster age ranging from Hyades-age to the

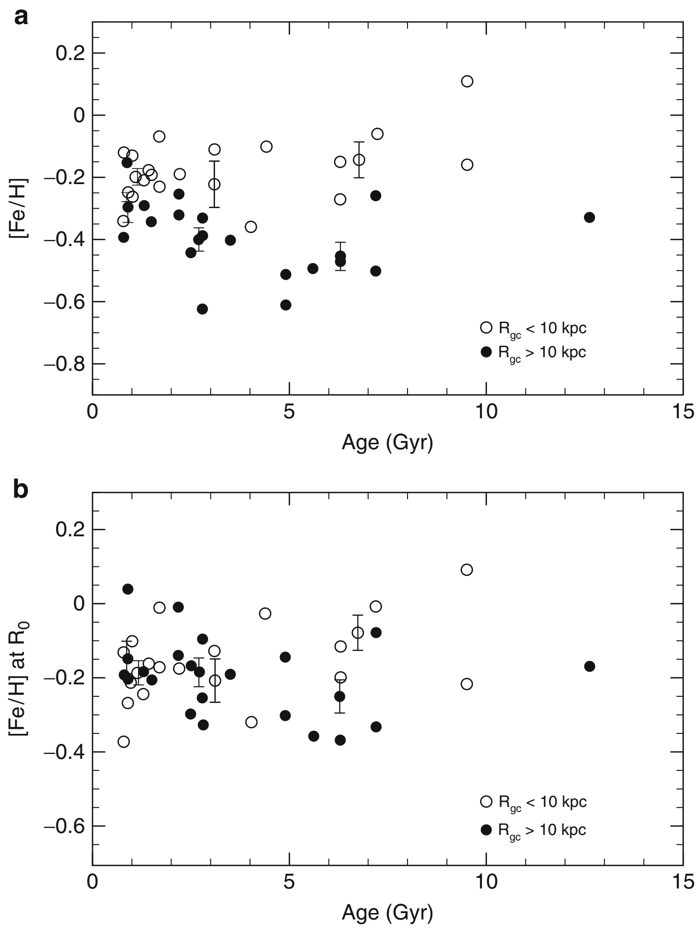

Fig. 7-12
Open cluster metallicities versus age, from Friel et al. (2002). Clusters are on a uniform relative age scale established in Janes and Phelps (1994). Clusters are distinguished by their position in galactocentric radius; those with R_{gc} < 10 kpc are shown as *open circles*; clusters with R_{gc} > 10 kpc are shown as *filled circles*. Points with error bars indicate the mean metallicity of clusters in three age ranges: less than 2 Gyr, between 2 and 4 Gyr, and greater than 4 Gyr. Panel (a) **shows metallicities as measured. Panel** (b) **plots metallicities that have been corrected for a radial abundance gradient, assuming a uniform slope of −0.06 dex kpc^{-1}**

10 Gyr cluster Be 17 (*Fig. 7-12*). Similar results were derived by Carraro and Chiosi (1994) and Salaris et al. (2004), who were careful to place both the cluster metallicities and ages on common scales. Most recently, the compilation of high-resolution results by Magrini et al. (2009), shows that abundances of clusters of different age groups vary very little, if at all, compared to the expectation for enrichment predicted by the chemical evolution models (*Fig. 7-13*). While models are able to predict abundances of younger clusters, they fail by a significant margin to predict the elevated abundances of clusters older than a few Gyr, as the lower panel in *Fig. 7-13* demonstrates.

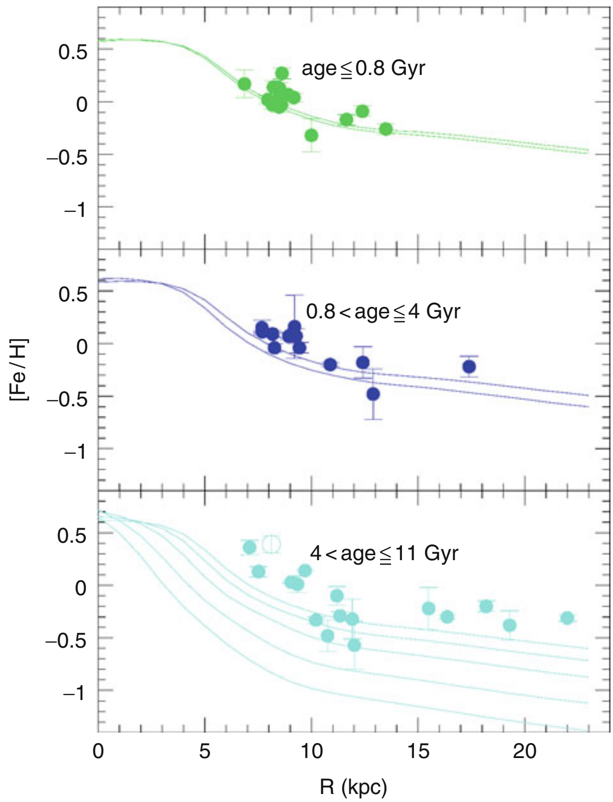

Fig. 7-13

Abundance gradient for open clusters compared to theoretical models from Magrini et al. (2009). Panels show abundances for different age ranges. *Solid lines* show the predictions for models in each age range: *top panel* for the present day and 1 Gyr ago, *middle panel* for 1 and 4 Gyr ago, and *lower panel* for 4, 6, 8, 10, and 11 Gyr ago

The lack of correlation between cluster age and metallicity is observed at all positions in the disk that are sampled by open clusters, once the overall effect of the radial abundance gradient is taken into account (*Fig. 7-12*). 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 case of NGC 6791 stands as a prime example, with an age of ~8 Gyr and a metallicity from high-resolution analyses of [Fe/H] = +0.4 dex, or twice that of the 700 Myr old Hyades. NGC 6791 may be anomalous in that its orbit indicates a perigalacticon of only 3 kpc (Bedin et al. 2006), so it may have formed in a region of the galaxy much more enriched than its present-day position at a galactocentric distance of 8 kpc. But even discounting NGC 6791 as highly unusual, the roughly solar metallicity of NGC 188, at 6–7 Gyr, and the relatively high metallicity of Be 17, with [Fe/H] = −0.15 at an age of 10 Gyr, provide other examples that run counter to expectation. It is clear that where a cluster is formed is much more of a factor in determining its metallicity than when it formed.

The distribution of cluster abundances both with respect to age and galactic location offers another important constraint for models of chemical evolution. As Figs. 7-9 and 7-12 demonstrate, the open clusters show a rather large dispersion in abundance at a given galactocentric position or at a given age, reflecting a range of abundance of a factor of 2 or more.

4.5 Comparison to the Disk Field Populations

The chemical history of the disk as reflected in the open clusters is, in its general characteristics, very similar to that found in other disk populations. Studies of the radial abundance gradient based on other tracers such as OB stars, H II regions, planetary nebulae, or Cepheids, show dependencies that are consistent with open clusters, recognizing that they track populations in general much younger than the open clusters. Recent work on Cepheids has shown abundances in the outer disk that follow the same flattening in the gradient as revealed in the older open clusters (Yong et al. 2005; Andrievsky et al. 2004). Extensive studies of field stars by Edvardsson et al. (1993) and Nordstrom et al. (2004) show radial gradients in the solar neighborhood that are consistent with those of the open clusters of comparable age.

Considering the age–metallicity relationship, comparison to the field star results is less straightforward to make. While there are many efforts at establishing the relationship between age and metallicity for field stars in the solar neighborhood, debate continues over the shape of the mean relationship, and in particular, the impact of selection effects, biases, or uncertainties that would distort or exclude classes of stars at the extremes of the distributions (see Feltzing et al. 2001 for a review). Although studies agree that there is a large dispersion about any mean relationship, debate continues on whether the mean metallicity shows very little variation with age (as demonstrated in the Nordstrom et al. 2004 sample), or continues to decrease with increasing age (Reddy et al. 2003). Given the large and real scatter in metallicity at all ages in the field star distribution, the lack of dependence of open cluster metallicities with age can be accommodated within any of the extant large field star studies, but is in better overall agreement with the results from Nordstrom's Geneva–Copenhagen survey.

4.6 Comparison to Theoretical Models

There is now an abundance of models of the chemical evolution of the Milky Way, all of which have had success at reproducing many of the observational constraints provided by the present-day distribution of gas and star density, the star formation rate, the overall run of abundance gradients from early type stars and young disk objects, and the present-day mass function. Although models are increasingly complete, they are not uniquely constrained by the available observational data, and the basic observed relationships most frequently adopted can be reproduced by quite different combinations of model parameters. In all of these models, the primary free parameters are the star formation rate and its dependence on gas and total density, the form of the initial mass function, and the extent, rate, and composition of the gas flows into and out of the galaxy. While the radial abundance gradient, for example, is predicted by any models with a star formation rate that varies with the gas or total mass, its slope is strongly modified by infall.

The open clusters present basic observational behavior that confronts any model of galactic chemical evolution: The decrease in metallicity with increasing Galactocentric radius through the solar neighborhood to a plateau in the very outer disk, with no strong evidence of any evolution in time, the lack of any correlation between cluster age and metallicity, an appreciable scatter in metallicity at any age and position in the disk, and abundance ratios that are roughly solar and constant with age and location in the disk. While some of these observations add to the evidence from field star studies or other stellar populations, the open clusters provide several constraints that are unique.

Because of their capability to probe a range of ages, particularly the early stages of disk evolution, the open clusters provide the best candidates to understand the time evolution of abundance gradients. Current models of chemical evolution can produce a wide array of predictions of the time evolution of the gradient, depending on the relative importance of the efficiency of star formation and enrichment processes and the nature and amount of infalling material at various locations in the galactic disk (Tosi 1988). For models that predict gradients that steepen with time (e.g., Chiappini et al. 2001), the outer disk is pre-enriched by the previous evolution of the halo, and because of the relatively low star formation, remains relatively little enriched, while the inner disk undergoes more star formation and enrichment over time, resulting in a steeper gradient at later times. For models that show a flattening of the gradient with time (e.g., Hou et al. 2000), the inner disk undergoes rapid star formation which elevates its metallicity initially, while the outer disk undergoes slower enrichment, gradually building up the metallicity in the outer regions relative to the inner, and flattening the gradient. Varying rates of infall of material and levels of pre-enrichment result in different forms and rates of time evolution of the gradient.

The fact that the open clusters show only very slight evidence for the present-day gradient to be slightly flatter than at earlier times, with no strong evolution, coupled with the apparent flattening of the gradient in the outer regions of the galactic disk, favors models that utilize an inside-out formation of the disk. The infall of gas, which is radially dependent, produces a rapid collapse in the inner regions ($R_{gc} < 12$ kpc), with a uniform accretion in the outer regions. Coupled with more efficient star formation in the inner regions, a steeper gradient is established early, while in the outer disk, the low metallicity of the infalling gas and the low star formation rate contribute to maintain a flat and slowly evolving gradient. However, as Magrini et al. (2009) find, to reproduce the completely flat gradient in the outer disk, additional uniform accretion of material is needed, which would result in more star formation and enrichment than is observed. They suggest that the outer plateau could be the result of a past merger which provided pre-enriched material without strongly affecting the star formation rate.

A recent complication to the interpretation of all of these models, however, comes with consideration of the potential effect of radial migration of stars and stellar systems within the disk. Simulations by Roskar et al. (2008) show that stars migrate across significant galactocentric distances due to resonant scattering with transient spiral arms, while preserving their initial circular orbits. Although the models are interpreted in terms of individual stars, the simulations suggest that radial migration mechanisms are capable of affecting stellar clusters as well. As they note, this effect may explain the large scatter and weak correlation seen in the field star and open cluster age–metallicity relationship, and has implications for the shape and evolution of the radial abundance gradient. Radial migration causes more mixing in older populations, resulting in the appearance of flatter gradients at earlier times, but would also dilute the effect of initial gradients. Most importantly, the phenomenon decouples the currently observed properties of stellar populations from their place and conditions of birth and would have a significant impact on the interpretation of cluster properties in a galactic context.

5 Clusters in the Context of Galaxy Formation and Evolution

Our picture of galaxy formation and evolution has matured enormously in the past few decades. Two alternative views continue to offer the principal frameworks in which to consider observational constraints: that of overall halo collapse with subsequent disk formation and continued collapse under self gravity and that of hierarchical accretion and ongoing merger of satellite galaxies within a cold dark matter dominated cosmology (Eggen et al. 1962; Majewski 1993; Freeman and Bland-Hawthorn 2002). There is now ample direct observational evidence of mergers within the Milky Way galaxy, and the fact that they leave distinct dynamical and chemical traces of past events has become a primary tool for investigating and even reconstructing the detailed history of galaxy formation and evolution.

In the framework of the gradual collapse, followed by the self-regulated chemical and dynamical evolution of the gaseous galactic disk, the open clusters are formed from the very earliest stages, as evidenced by the existence of clusters such as NGC 6791 and Be 17. As clusters continue to form within the process of overall star formation, they reflect gradients in disk structural or chemical properties. Clusters are also disrupted by external influences within the disk, such as interactions with molecular clouds, transient spiral arms, and the general tidal field. This interplay between cluster formation and destruction shapes the population now seen, potentially obscuring much of the original distributions that could have preserved the processes of disk formation and evolution.

Nevertheless, there are clues. The trend of decreasing abundance with galactocentric distance, but lack of vertical abundance gradient among the clusters, and the lack of dependence on cluster age tells us about the relative importance of star formation and infall in the disk. The lack of any correlation of cluster age with metallicity and the fact that, at any position in the disk, the oldest clusters are forming with compositions as enriched as those of much younger clusters suggests substantial inhomogeneity in the overall composition of the interstellar material.

If the inside-out model of galaxy formation applies, the open clusters should serve as valuable indicators of the growth of the galactic disk, particularly in the outer regions of the galaxy. One might expect to see the median age of clusters decrease as one moves outward in the galactic disk, pointing to more recent star formation, with young clusters at the very edge of the disk. Indeed, the very oldest clusters known are found inside about 10–11 kpc from the galactic center. However, the open clusters do not show a strong age dependence with R_{gc} and instead the outer disk clusters are generally older than average (➋ *Fig. 7-8*). This fact is usually interpreted as being due to their ability to survive in these regions and not due to the lack of young clusters. How much of this effect is due to incompleteness in the cluster sample, however, remains to be seen.

In fact, there is evidence for molecular gas and stellar clusters being formed in the far outer regions of the Galaxy. A number of embedded clusters have been found at $R_{gc} \geqslant 13$ kpc out to 20 kpc. The molecular clouds containing clusters in these regions of low gas density resemble molecular clouds in the inner galaxy, suggesting that processes that lead to the formation of stellar clusters are very similar throughout the galactic disk (Yun et al. 2009). The existence of ongoing cluster formation in the very outer reaches of the disk supports the notion of the gradually growing disk.

The discovery of several open clusters at galactocentric distances of ~20 kpc (Be 29 and Saurer 1), along with the observations on the abundance patterns in the outer disk, has led to the idea that distant open clusters may be tracing merger events (Yong et al. 2005). This is not an unreasonable line of reasoning to pursue. Dwarf galaxies contain star clusters of a variety of ages and the Sagittarius dwarf spheroidal, currently merging with the Milky Way, has at least seven globular clusters associated with it. These clusters are now distributed along the orbital path of the galaxy as it wraps itself around the Milky Way.

If there have been merger events in the galactic disk, might it not be reasonable to expect open clusters to be associated with these mergers, either acquired from the merging galaxies, or formed as a result of the merger event itself? Can any open clusters be associated with known mergers or are there subpopulations of clusters that might reveal past mergers? The current picture is ambiguous.

The discovery in the Sloan Digital Sky Survey of a large overdensity of stars in the region of Canis Major in the outer galactic disk offers the potential to identify star clusters associated with the structure (Yanny et al. 2003; Crane et al. 2003; Conn et al. 2005; Bellazzini et al. 2006). This large stellar structure, known also as the Monoceros Ring, spans almost 100° in galactic longitude, is nearly coplanar with the outer disk, and appears elongated along the tangential direction, with a mean galactocentric radius of ~13–16 kpc. The overdensity appears superimposed on the galactic warp, complicating the interpretation. A variety of explanations exist for the structure – simply a manifestation of the galactic warp, an outer spiral arm, a resonance induced by an asymmetric galactic component, a response of the galactic disk to the close passage of a satellite galaxy, or the remnants of a tidally disrupted satellite galaxy. In any case, identifying stellar clusters associated with the stellar structure could help in choosing among these alternatives.

Frinchaboy et al. (2004) identified a number of open and globular clusters, based on both position and limited available radial velocities, that could be associated with the Monoceros Ring and outer disk structure. The cluster planar distribution, argued to be highly significant, suggested to them evidence of an origin related to the interaction of a satellite galaxy with the Milky Way. Later work, along with determination and improvement in radial velocity and distance determinations for the outer disk clusters, suggests that at most only one cluster, Tombaugh 2, has both position and radial velocity that is consistent with an association with the core Canis Major system. However, its properties are also entirely in keeping with those of open clusters at its general galactocentric radius; its metallicity and its elemental abundance pattern do not distinguish it in any way from the overall cluster population (Villanova et al. 2010). Whether other clusters may be associated with the extended stellar stream of a disrupting satellite galaxy remains to be seen.

The two most distant open clusters in the galaxy, Be 29 and Saurer 1, have recently been claimed to be associated with the Sgr dwarf (Carraro and Bensby 2009), based on a combination of their locations and velocities being consistent with models of the trailing stream of the disrupting galaxy. The cluster abundances present a confused picture, however, and do not distinguish the clusters in terms of star formation history that might associate them uniquely with a stellar population other than the general outer disk.

At present, while intriguing, there appears to be no strong evidence that would associate any open clusters with specific merging events in the galactic disk.

Even if no open clusters have yet been definitively associated with the remnants of an accretion event, some of the properties of old clusters are naturally explained in the context of merger scenarios. Evidence for infall to the disk comes in the form of not only accretion events, but high velocity clouds and the energetic recycling of processed material from the disk. Theoretical modeling indicates that these events can initiate star formation at appreciable distances from the plane, and should clusters form, they would preserve the large z motions and possibly eccentric orbits introduced by the colliding or accreting material. This scenario provides an explanation for the existence of old open clusters at substantial distances from the galactic plane and a mechanism for them to have acquired the orbits that allow them to survive to such substantial ages. Very few open clusters have proper motion and radial velocity measurements that allow the determination of their orbits to test this idea. The handful of clusters with radial velocities that are suggestive of eccentric or unusual orbits would be particularly interesting to investigate.

Cross-References

- Dynamics of Disks and Warps
- Galactic Distance Scales
- Globular Cluster Dynamical Evolution
- Interstellar PAHs and Dust
- Mass Distribution and Rotation Curve in the Galaxy
- Star Counts and the Nature of the Galactic Thick Disk

References

Andersen, J., Nordstrom, B., & Clausen, J. V. 1990, ApJL, 363, 33

Andrievsky, S. M., Luck, R. E., Martin, P., & Lepine, J. R. D. 2004, A&A, 413, 159

Ascenso, J., Alves, J., & Lago, M. T. V. T. 2009, A&A, 495, 147

Bedin, L. R., Piotto, G., Carraro, G., King, I. R., & Anderson, J. 2006 A&A, 460, 27

Bellazzini, M., Ibata, R., Martin, N., Lewis, G. F., Conn, B., & Irwin, M. J. 2006, MNRAS, 366, 865

Bertelli, G., Bressan, A., & Chiosi, C. 1985, A&A, 150, 33

Bica, E., Dutra, C. M., & Barbuy, B. 2003, A&A, 397, 177

Bonatto, C., & Bica, E. 2007, MNRAS, 377, 1301

Bonatto, C., & Bica, E. 2008, A&A, 485, 81

Bonatto, C., Kerber, L. O., Bica, E., & Santiago, B. X. 2006, A&A, 446, 121

Bouvier J., Kendall, T., Meeus, G., Testi, L., Moraux, E., Stauffer, J. R., James, D., Cuillandre, J.-C., Irwin, J., McCaughrean, M. J., Baraffe, I., & Bertin, E. 2008, A&A, 481, 661

Bragaglia, A., & Tosi, M. 2006, AJ, 131, 1544

Bragaglia, A., Tosi, M., Andreuzzi, G., & Marconi, G. 2006, MNRAS, 368, 1971

Carraro, G., & Bensby, T. 2009, MNRAS, 397, L106

Carraro, G., Bresolin, G., Villanova, S., Matteucci, F., Patat, F., & Romaniello, M. 2004, AJ, 128, 1676

Carraro, G., & Chiosi, C. 1994, A&A, 288, 751

Carraro, G., Geisler, D., Villanova, S., Frinchaboy, P. M., & Majewski, S. R. 2007, A&A, 476, 217

Carraro, G., Janes, K. A., & Eastman, J. D. 2005, MNRAS, 364, 179

Carraro, G., Ng, Y. K., & Portinari, L. 1998, MNRAS, 296, 1045

Chiappini, C., Matteucci, F., & Romano, D. 2001, ApJ, 554, 1044

Conn, B. C., Lewis, G. F., Irwin, M. J., Ibata, R. A., Ferguson, A. M. N., Tanvir, N., & Irwin J. M. 2005, MNRAS, 362, 475

Crane, J. D., Majewski, S. R., Rocha-Pinto, H. J., Frinchaboy, P. M., Skrutskie, M. F., & Law, D. R. 2003, ApJ, 594, L119

Currie, T., Hernandez, J., Irwin, J., Kenyon, S. J., Tokarz, S., Balog, Z., Bragg, A., Berlind, P., & Calkins, M. 2010, ApJ Supp, 186, 191

Daniel, S. A., Latham, D. W., Mathieu, R. D., & Twarog, B. A. 1994, PASP, 106, 281

Davies, B., Origlia, L., Kudritzki, R.-P., Figer, D. F., Rich, R. M., Najarro, F., Negueruela, I., & Clark, J. S. 2009, ApJ, 696, 2014

de la Fuente Marcos, R. 1997, A&A, 322, 764

De Silva, G. M., Sneden, C., Paulson, D. B., Asplund, M., Bland-Hawthorn, J., Bessell, M. S., & Freeman, K. C. 2006, AJ, 131, 455

Dias, W. S., Alessi, B. S., Moitinho, A., & Lepine, J. R. D. 2002, A&A, 389, 871

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101

Eggen, O. J., Lynden-Bell, D., & Sandage, A. R. 1962, ApJ, 136, 748

Feltzing, S., Holmberg, J., & Hurley, J. R. 2001, A&A, 377, 911

Freeman, K., & Bland-Hawthorn, J. 2002, ARAA, 40, 487

Friel, E. D. 1995, ARAA, 33, 381

Friel, E. D. 2006, in Chemical Abundances and Mixing in the Milky Way and its Satellites, Castiglione della Pescaia, Italy. ESO Astrophysics Symposia (Springer-Verlag), 3

Friel, E. D., Jacobson, H. R., & Pilachowski, C. A. 2010, AJ, 139, 1942

Friel, E. D., & Janes, K. A. 1993, A&A, 267, 75

Friel, E. D., Janes, K. A., Tavarez, M., Scott, J., Katsanis, R., Lotz, J., Hong, L., & Miller, N. 2002, AJ, 124, 2693

Frinchaboy, P. M., Majewski, S. R., Crane, J. D., Reid, I. N., Rocha-Pinto, H. J., Phelps, R. L., Patterson, R. J., & Munoz, R. R. 2004, ApJL, 602, 21

Froebrich, D., Meusinger, H., & Scholz, A. 2008, MNRAS, 390, 1598

Froebrich, D., Scholz, A., & Raftery, C. L. 2007, MNRAS, 374, 399 (FSR)

Geller, A. M., Mathieu, R. D., Harris, H. C., & McClure, R. D. 2008, AJ, 135, 2264

Gieles, M., Portegies Zwart, S. F., Baumgardt, H., Athanassoula, E., Lamers, H. J. G. L. M., Sipior, M., & Leenaarts, J. 2006, MNRAS, 371, 793

Gozzoli, E., Tosi, M., Marconi, G., & Bragaglia, A. 1996, MNRAS, 283, 66

Grocholski, A. J., & Sarajedini, A. 2003, MNRAS, 345, 1016

Harayama, Y., Eisenhauer, F., & Martins, F. 2008, ApJ, 675, 1319

Hou, J. L., Prantzos, N., & Boissier, S. 2000, A&A, 362, 921

Hurley, J. R., Pols, O. R., Aarseth, S. J., & Tout, C. A. 2005, MNRAS, 363, 293

Jacobson, H. R., Friel, E. D., & Pilachowski, C. A. 2009, AJ, 137, 4753

Janes, K. A. 1979, ApJ Suppl, 39, 135

Janes, K. A., & Phelps, R. L. 1994, AJ, 108, 1773

Janes, K. A., Tilley, C., & Lynga, G. 1988, AJ, 95, 771

Kalirai, J. S., Fahlman, G. G., Richer, H. B., & Ventura, P. 2003, AJ, 126, 1402

Kalirai, J. S., Hansen, B. M. S., Kelson, D. D., Reitzel, D. B., Rich. R. M., & Richer, H. B. 2008, ApJ, 676, 594

Kaluzny, J., & Udalski, A. 1992, Acta Astron, 42, 29

Kim, S. S., Figer, D. F., Kudritzki, R. P., & Najarro, F. 2006, ApJ, 653, 113

King, I. 1962, AJ, 67, 471

King, I. R. 1966, AJ, 71, 64

Kraus, A. L., & Hillenbrand, L. A. 2007, AJ, 134, 2340

Kroupa, P. 2002, Science, 295, 82

Krusberg, Z. A. C., & Chaboyer, B. 2006, AJ, 131, 1565

Lada, C. J., & Lada, E. A. 2003, ARAA, 41, 57

Lamers, H. J. G. L. M., & Gieles, M. 2006, A&A, 455, L17

Luck, R. E., Kovyukh, V. V., & Andrievsky, S. M. 2006, AJ, 132, 902

Lynga, G. 1982, A&A, 109, 213

Maeder, A., & Meynet, G. 1991, A&A Suppl, 89, 451

Magrini, L., Sestito, P., Randich, S., & Galli, D. 2009, A&A, 494, 95

Majewski, S. R. 1993, ARAA, 31, 575

Mathieu, R. D. 1984, ApJ, 284, 643

Mathieu, R. D. 1985, in IAU Colloq. 88, Stellar Radial Velocities, ed. A.G. Davis Philip, & D. W. Latham (Schenectady, NY: L. Davis Press), 249

Mathieu, R. D., & Geller, A. M. 2009, Nature, 462, 1032

McMillan, S. L. W., Vesperini, E., & Portegies Zwart, S. F. 2007, ApJL, 655, 45

Mercer, E. P., Clemens, D. P., Meade, M. R., et al. 2005, ApJ, 635, 560

Mermilliod, J.-C., Mayor, M., & Udry, S. 2008, A&A, 498, 949

Montgomery, K. A., Marschall, L. A., & Janes, K. A. 1993, AJ, 106, 181

Moraux, E., Bouvier, J., Stauffer, J. R., Barrado y Navascues, D., & Cuillandre, J.-C. 2007, A&A, 471, 499

Moraux, E., Kroupa, P., & Bouvier, J. 2004, A&A, 426, 75

Nordstrom, B., Andersen, J., & Andersen, M. I. 1997, A&A, 322, 460

Nordstrom, B., Mayor, M., Andersen, J., Holmberg, J., Pont, F., Jorgensen, B. R., Olsen, E. H., Udry, S., & Mowlavi, N. 2004, A&A, 418, 989

Oort, J. H. 1958, in Stellar Populations, Richerche Astronomiche, Specola Vaticana, ed. D. J. K. O'Connell, (Amsterdam: North Holland), 63

Pasquini, L., Randich, S., Zoccali, M., Hill, V., Charbonnel, C., & Nordstrom, B. 2004, A&A, 424, 951

Phelps, R. L. 1997, ApJ, 483, 826

Phelps, R. L., Janes, K. A., & Montgomery, K. A. 1994, AJ, 107, 1079

Piatti, A. E., Claria, J. J., & Abadi, M. G. 1995, AJ, 110, 2813

Pinsonneault, M. 1997, ARAA, 35, 557

Portegies Zwart, S., Gaburov, E., Chen, H.-C., & Gurkan, M. Atakan 2007, MNRAS, 378, 29

Portegies Zwart, S. F., Hut, P., McMillan, S. L. W., & Makino, J. 2004, MNRAS, 351, 473

Portegies Zwart, S. F., McMillan, S. L. W., Hut, P., & Makino, J. 2001, MNRAS, 321, 199

Randich, S., Sestito, P., Primas, F., Pallavicini, R., & Pasquini, L. 2006, A&A, 450, 557

Reddy, B. E., Tomkin, J., Lambert, D. L., & Allende Prieto, C. 2003, MNRAS, 340, 304

Roskar, R., Debattista, V. P., Quinn, T. R., Stinson, G. S., & Wadsley, J. 2008, ApJL, 684, 79
Salaris, M., Weiss, A., & Percival, S. M. 2004, A&A, 414, 163
Salpeter, E. 1955, ApJ, 121, 161
Schuler, S. C., King, J. R., & The, L.-S. 2009, ApJ, 701, 837
Schuler, S. C., Hatzes, A. P., King, J. R., Kurster, M., & The, L.-S. 2006, AJ, 131, 1057
Scott, J. E., Friel, E. D., & Janes, K. A. 1995, AJ, 109, 1706
Sestito, P., Bragaglia, A., Randich, S., Pallavicini, R., Andrievsky, S. M., & Korotin, S. A. 2008, A&A, 488, 943
Slesnick, C. L., Hillenbrand, L. A., & Massey, P. 2002, ApJ, 576, 880
Smiljanic, R., Gauderon, R., North, P., Barbuy, B., Charbonnel, C., & Mowlavi, N. 2009, A&A, 502, 267
Spitzer, L. 1958, ApJ, 127, 17
Spitzer, L., & Harm, R. 1958, ApJ, 127, 544
Stolte, A., Brandner, W., Brandl, B., & Zinnecker, H. 2006, ApJ, 132, 253
Terlevich, E. 1987, MNRAS, 224, 193
Tosi, M. 1988, A&A, 197, 33
Twarog, B. A., Ashman, K. M., & Anthony-Twarog, B. J. 1997, AJ, 114, 2556
VandenBerg, D. A., & Stetson, P. B. 2004, PASP, 116, 997
van den Bergh, S. 1958, Z. Astrophys, 46, 176
van den Bergh, S. 2006, AJ, 131, 1559
van den Bergh, S., & McClure, R. D. 1980, A&A, 80, 360
Villanova, S., Randich, S., Geisler, D., Carraro, G., & Costa, E. 2010, A&A, 509, 102
von Hippel, T., Jefferys, W. H., Scott, J., Stein, N., Winget, D. E., DeGennaro, S., Dam, A., & Jeffery, E. 2006, ApJ, 645, 1436
Yanny, B., Newberg, H. J., Grebel, E. K., Kent, S., Odenkirchen, M., Rockosi, C. M., Schlegel, D., Subbarao, M., Brinkmann, J., Fukugita, M., Ivezic, Z., Lamb, D. Q., Schneider, D. P., & York, D. G. 2003, ApJ, 588, 824
Yong, D., Carney, B. W., & De Almeida, M. L. T. 2005, AJ, 130, 597
Yong, D., Carney, B. W., De Almeida, M. L. T., & Pohl, B. L. 2006, AJ, 131, 2256
Yun, J. L., Davide, E., Palmeirim, P. M., Gomes, J. I., & Martins, A. M. 2009, A&A, 500, 833