Chapter 18
Clusters and the Galactic Halo

I. Neill Reid

18.1 Introduction

Devoting a full chapter to the halo, the oldest stars in the Milky Way, may seem a shade contrarian in a conference that is nominally aimed at discussing young, massive star clusters. But the halo was young once, and the globular clusters that are its most prominent constituents must have rivalled and even exceeded present-day structures like NGC 3603 or 30 Doradus. More to the point, our understanding of the nature of globular clusters has undergone a paradigm shift in the last half-decade with the realisation that many (most?) are not simple, single-starburst entities, but harbour evidence of a complex star-forming history and multiple constituent populations. Equally to the point, 2012 represents an important anniversary for one of the most influential papers of 20th century astrophysics, the first serious attempt 'to reconstruct the galactic past', by Eggen et al. (1962, hereafter ELS). This chapter gives a brief introduction to globular cluster properties and places the ELS paper in its contemporary context. We conclude with discussion of results from more recent investigations of globular clusters, particularly the discovery of multiple stellar populations, and consider the implications for cluster formation and the early life of the Milky Way.

18.2 Globular Clusters and the Galactic Halo

The members of the Galactic halo have been recognised as likely to be the oldest constituents of the Milky Way since Baade's identification of Population I and II in the 1940s. The field halo stars in the Solar Neighbourhood, the 'high velocity stars',

I.N. Reid (✉)
Space Telescope Science Institute, Baltimore, MD, USA
e-mail: inr@stsci.edu

C.P.M. Bell et al. (eds.), *Dynamics of Young Star Clusters and Associations*,
Saas-Fee Advanced Course 42, DOI 10.1007/978-3-662-47290-3_18

had already played a role in the 1920s in Oorts expansion of Lindblad's differential rotation system into a (static) model of the Milky Way (Oort 1928). Globular clusters famously played a key role in the construction of Harlow Shapley's 'Large Galaxy' model for the Milky Way, in large part because of Solon Bailey's discovery of RR Lyrae variables in many such systems.

One hundred and fifty seven globular clusters are currently known (see Fig. 18.1), and the total population is estimated as around 160 systems (Harris 2010). Most are prominent stellar concentrations, easily discernible against the stellar background and, as a result, part and parcel of nebular catalogues since before the Herschels scanned the skies. Twenty-nine of the most prominent northern systems were included in Charles Messier's famous 'not-comets' catalogues published between 1771 and 1787. Other systems are more obscure. In particular, one of the products of the first Palomar Sky Survey was a list of 15 globulars that had previously escaped detection (Abell 1955). Those clusters, identified prosaically as Palomar 1–15, are either highly-obscured systems towards the Galactic Centre or less massive, more diffuse and much more distant than the classical globulars. A further three obscured Galactic Centre systems were identified from plates taken by the ESO Schmidt telescope, while the 2MASS infrared survey has added two additional highly-obscured systems. Those surveys have also been very effective at identifying dwarf galaxy satellites of the Milky Way, with SDSS extending detections to ultra-faint systems (Brown et al. 2012) that are comparable in mass to the larger globulars, an issue we return to towards the end of this chapter.

Parameterising the known systems, clusters range in mass from $\sim 10^6$ to $\sim 10^4$ $M_\odot$, with ω Cen the largest and Palomar 13 the smallest systems currently known. In comparison, ultra-faint dwarf galaxies identified by SDSS have masses of $\sim 10^4$ $M_\odot$, although most of that mass is likely dark matter while there is no evidence for significant dark matter associated with globulars. The majority lie within 5–10 kpc

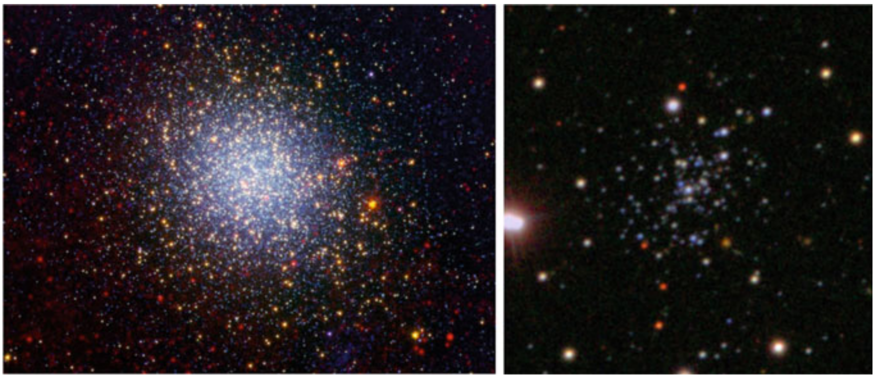

Fig. 18.1 Extreme globular clusters: ω Cen (*left*, figure taken from http://www.spitzer.caltech.edu/images/1908-ssc2008-07a-Globular-Cluster-Omega-Centauri-Looks-Radiant-in-Infrared), the largest Galactic cluster, and Palomar 13 (*right*, figure taken from http://www.galaxyzooforum.org/index.php?topic=272726.0), among the smallest currently known

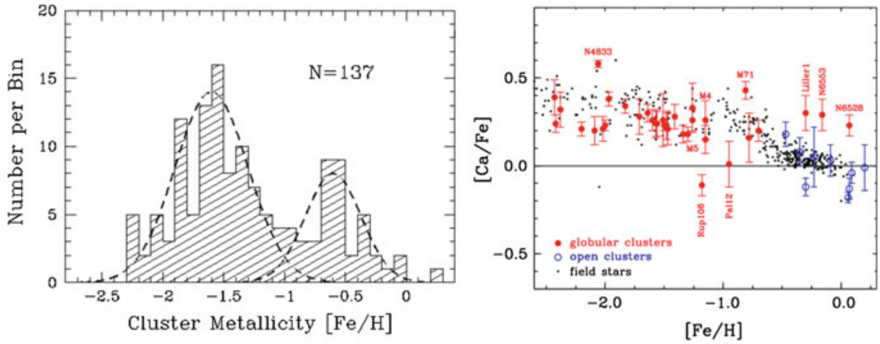

Fig. 18.2 *Left panel*: The metallicity distribution [Fe/H] of globular clusters (from Harris 2001). *Right panel*: The α/Fe abundance ratio as characterised by measurements of calcium abundance in a range of stellar systems (adapted from Gratton et al. 2004)

of the Galactic centre, but the outer clusters lie at galactocentric radii extending beyond 50 kpc, with the most distant system, AM 1, at RGC $\sim$125 kpc. Overall, the radial distribution is consistent with a power-law distribution, $\rho \propto r^{-3.5}$ (Harris 2001). Kinematically, the clusters show substantial velocity dispersion with no evidence for net rotation, indicating a pressure-supported, rather than rotation-supported, system. Determining proper motions (and hence three-dimensional space motions) can be problematic given the distances, and the overall kinematics can still be characterised as consistent with the determination of Frenk and White (1980), $[(U, V, W), (\sigma_U, \sigma_V, \sigma_W) \sim (0, -160, 0), (120, 120, 120)\,\mathrm{km\,s^{-1}}]$. Many clusters are on nearly radial orbits that lead to periodic passages through the inner Galactic disc.

Metallicities for globular clusters can be determined either by matching the colour-magnitude diagram (primarily the red giant branch) against theoretical models or through direct analysis of spectroscopic observations of main-sequence and evolved stars. The results show that they are metal-poor systems, with abundances extending to below [Fe/H] $= -2.5$ dex or less than 1/300th that of the Sun (see Fig. 18.2). There are some hints of a bimodal distribution (see left panel of Fig. 18.2). In addition, detailed analysis of elemental abundances shows that globular cluster stars, and halo stars in general, have enhanced abundances of α elements (Ca, Ti, Mg, etc.) when compared with disc stars. As discussed in the opening chapter, this indicates that those stars formed early in the star formation history of the Milky Way, before Type Ia supernovae could drive up iron production.

Globular clusters have well-defined colour-magnitude diagrams that readily lend themselves to age estimation by matching against theoretical isochrones for the appropriate abundance distribution (see Fig. 18.3). The crucial step is determining reliable cluster distances, since these systems lie well beyond the reach of (current) direct trigonometric parallax measurements. A variety of distance estimators can be used, including horizontal branch stars, RR Lyraes or local main-sequence halo stars (subdwarfs). In each case, the process involves taking nearby stars whose distances

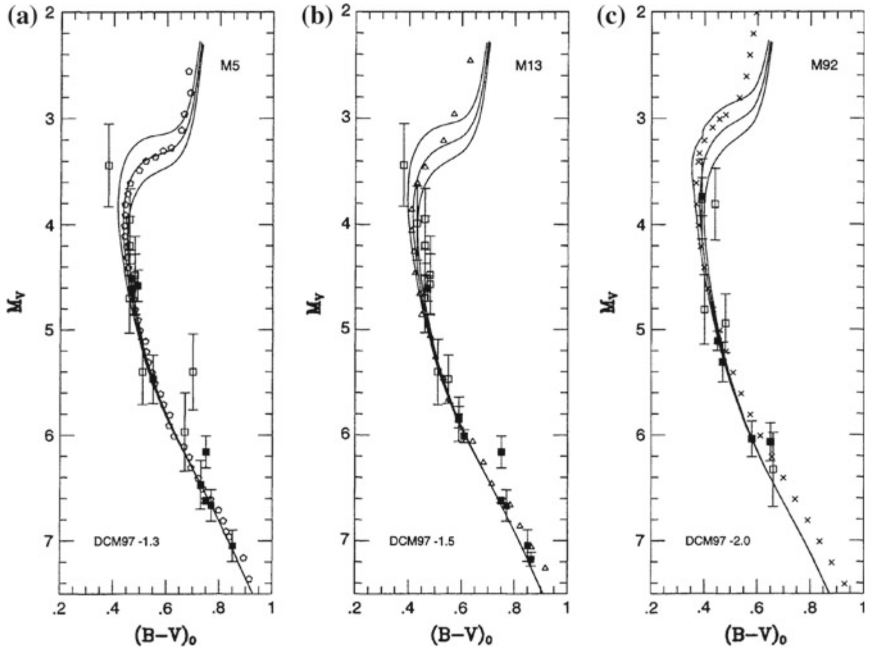

Fig. 18.3 Main-sequence fitting to fiducial colour-magnitude diagrams for globular clusters. The isochrones are drawn from the theoretical models by D'Antona et al. (1997) and are for ages of 10, 12 and 14 Gyr and with abundances of [Fe/H] = −1.3 (M5), −1.5 (M13) and −2.0 dex (M92). Figure from Reid (1997)

can be determined through some method (direct trigonometric parallax, statistical parallax, Baade-Wesselink analysis), and using those stars as templates to match against similar stars in the cluster. Of the local templates, FGK subdwarfs offer the best option since they have sufficiently high space density that reasonable numbers (approximately a dozen) are near enough the Sun for direct parallax measurements.

In main-sequence fitting, the fiducial cluster sequence (apparent magnitude, colour) is corrected for line-of-sight reddening and then matched against the (absolute magnitude, colour) sequence mapped out by the local subdwarfs. The latter stars span a range of abundance, so appropriate corrections need to be applied to the absolute magnitude or colour before matching against a specific cluster. Once the zeropoint is determined, the cluster age follows by matching against theoretical isochrones. Prior to *Hipparcos*, this technique led to ages generally estimated as between 14 and 17 Gyr, which posed something of a problem, given than the age of the Universe was generally pinned at 13–14 Gyr. *Hipparcos* targeted many of the local FGK subdwarfs, determining more accurate parallaxes and expanding the sample with reliable astrometry. The results show a systematic reduction in the average parallax of the calibrators by ∼3 mas. This leads to larger distance estimates to individual clusters, brighter turn-off magnitudes and younger ages (Gratton et al. 1997; Reid 1997).

Typical age estimates for globular clusters now lie in the range 11–13 Gyr, entirely compatible with the age of 13.772 ± 0.059 Gyr derived from analysis of the WMAP measurements of the microwave background (Bennett et al. 2013). There remain a few residual doubts over the new cluster distance scale (e.g. Harris 2001), but *Gaia* will clearly have a big impact here, not only by expanding coverage to many more local subdwarfs, but also by providing direct parallax measurements for the nearest globular clusters.

As the prior discussion suggests, field halo stars are rare. Locally, disc main-sequence stars outnumber halo subdwarfs by ~200 to 1—there are only 4 FGK subdwarfs within 25 pc. Nonetheless, there are sufficient stars to trace the general properties of the population, which are fairly consistent with the cluster system. The radial density distribution is consistent with a power-law, $\rho \propto r^{-3}$. Field halo stars are also α-enhanced, but the metallicity distribution shows a much larger tail extending to significantly lower abundances, [Fe/H] < -4 dex, with the most metal-poor star currently known, HE 1327-2326, having [Fe/H] ~ -5.5 dex. The kinematics indicate a non-rotating, pressure-supported system, like the clusters, with perhaps some indications of triaxiality $[(U, V, W), (\sigma_U, \sigma_V, \sigma_W) \sim (-20, -190, -3), (152, 104, 95)\ \mathrm{km\ s^{-1}}]$ (Carney et al. 1994). There have also been suggestions that there is duality in the field halo star populations, with inner and outer components (Sommer-Larsen and Zhen 1990; Beers et al. 2012).

Local subdwarfs are sparsely distributed, but there are sufficient numbers to set constraints on the mass function for halo stars. The results are broadly consistent with those derived for the mass function derived for solar-metallicity disc stars (Gizis and Reid 1999). Globular clusters provide further insight into the halo mass function, although those analyses are tempered by the fact that those systems undergo significant dynamical evolution. Internal relaxation leads to mass segregation that concentrates higher mass stars (and binary systems) towards the centre, and external interactions, primarily as the cluster passes through the disc, preferentially strip less tightly-bound, lower-mass stars from the system. Nonetheless, analyses of globular cluster show little evidence for significant departures from the disc prescription outlined in Chap. 16, despite the substantial differences in metallicity (Paust et al. 2010).

18.3 Setting the Context

The previous section sketches out much of what we know about the halo now. Much has changed over the last half century. Before discussing the ELS model and how that paper impacted the field, it is useful to spend a little time considering the broader state of astrophysics at that time.

Starting on the largest scales, Hubble had identified the expanding nature of the universe in the late 1920s, but the underlying model still remained a matter of debate. Ralph Alpher and George Gamow laid the basis for the 'hot start' theory in the famous alphabetical article (Alpher et al. 1948), proposing that the universe had an origin at a fixed point of time when all matter was concentrated at extremely high density and high temperature, synthesising the chemical elements. The discovery of the microwave background, the redshifted echo of those high temperatures, still lay several years in the future, so there was on-going debate with the Cambridge-centred steady-state theory favoured by Fred Hoyle, Hermann Bondi and Thomas Gold. Driven partly by the philosophical concept of the Perfect Cosmological Principle (the Universe looks the same at all times and places), steady-state theory envisioned an expanding universe of infinite age and duration, with matter created to maintain uniformity (Hoyle 1948). Competition between the two theories was fairly intense. Indeed, the name 'Big Bang' now widely associated with Alpher and Gamow's work was coined by Fred Hoyle, perhaps as a dismissive label, in one of a series of BBC radio lectures given in March 1949.

Wide-field photographic surveys such as the 10-year program undertaken by C.D. Shane and C.A. Wirtanen, and George Abell's analysis of the Palomar Sky Survey (POSS I) plates revealed that galaxies were clustered. Quasars were on the point of discovery. In the early 1960s, Allan Sandage, Thomas Matthews and collaborators at Carnegie Observatories and Caltech identified several very blue objects that appeared to be the source of very strong radio emission. Cyril Hazard and John Bolton localised the position of the radio source, 3C 273, by timing its occultation by the moon. Maarten Schmidt obtained a spectrum with the Palomar 200-inch telescope in August 1962, and recognised that those features could be explained if the source were at a redshift of $z = 0.157$.

Looking within galaxies, Walter Baade's wartime observations with the Mt. Wilson 100-inch resolved stars in of M32 and the bulge of the Andromeda galaxy, and led to the development of the concept of stellar populations. Baade drew a link between those extragalactic stellar populations and the Galactic globulars, dominated by red giants, and contrasted that with the bright blue stars, and on-going star formation, with the Galactic disc. Allan Sandage and Halton Arp pursued more detailed studies of Galactic clusters, pushing colour-magnitude diagrams to fainter magnitudes to reveal the main-sequence turn-off in globular clusters, and adding observations of extensive numbers of Galactic open clusters. Those observational results, summarised in the composite diagram reproduced in the right panel of Fig. 18.4, provided observational incentive for theoretical work on stellar evolution, particularly the transition onto the red giant branch, pursued by Martin Schwarzschild, Roger Tayler and Fred Hoyle, among others.

The range of stellar chemical abundances was also starting to come into focus. In 1951, Joseph Chamberlain and Lawrence Aller undertook a detailed analysis of the spectrum of two so-called A-type subdwarfs, HD 19445 and HD 140283, comparing their analysis against the main-sequence A star, 95 Leonis, as a reference. The results were surprising, indicating that the subdwarfs had temperatures more consistent with spectral type F and metallicities significantly lower than the solar value (Chamberlain and Aller 1951). Indeed, Aller subsequently admitted that their formally derived metallicity was significantly lower than the $[Fe/H] = -1$ dex quoted in the paper, but they were deliberately cautious because the result was so surprising. Nancy Roman subsequently demonstrated that many high-velocity stars shared these characteristics,

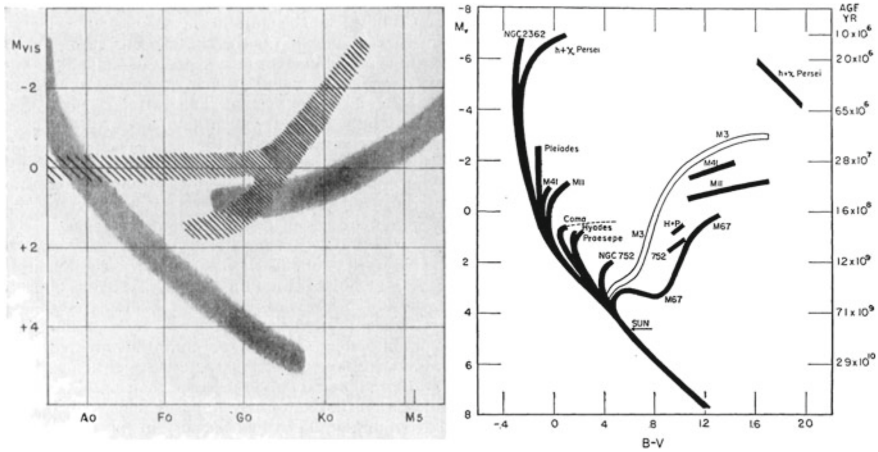

Fig. 18.4 *Left panel*: Schematic representation of Population I (*shaded*) and Population II stars (*hatched*) in M32 (from Baade 1944). *Right panel*: Composite cluster colour-magnitude diagram (from Sandage 1956)

with F-type spectra but a substantial UV-excess due to the reduced line blanketing in the metal-poor atmospheres. The orbits of those stars are highly eccentric, passing through the Galactic bulge, and Roman drew a direct analogy with main-sequence stars in globular clusters (Roman 1954).

At the same time, significant progress was being made on identifying the likely origins of the heavy elements. Gamow had postulated that all elements could be generated by neutron addition to the lightweight elements generated in the Big Bang. However, it became clear that there was no element with a stable isotope of mass 8, setting an insurmountable roadblock to this hypothesis. Partly prompted, no doubt, by his cosmological views, Fred Hoyle had developed the notion of nucleosynthesis, formation of heavy elements by fusion within stars. In the early 1950s, Edwin Salpeter suggested that carbon might be formed by fusing three helium atoms, and Hoyle demonstrated that this process was feasible in red giants. Building on that foundation, Hoyle worked with Geoffrey Burbidge, Margaret Burbidge and Willy Fowler at Caltech to develop a more detailed theory, published in Reviews of Modern Physics in 1957 as the famous B^2FH paper (Burbidge et al. 1957). Their work showed that stars could change the overall composition of the Milky Way (and other galaxies) by transforming hydrogen and helium into increasingly heavier elements. Willy Fowler received the Nobel prize for physics in 1983 '. . . for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe'.

These separate threads were drawn together almost fifty-five years ago, in May 1957 at the Vatican conference on Stellar Populations. Bringing together most of the major astronomers of the time (including Baade, Blaauw, Fowler, Hoyle, Morgan, Oort, Salpeter, and Sandage), that conference took Baade's simple concept of stellar populations, and applied it to observations of stars in the Milky Way. As described by Blaauw (1995), Baade's original separation of the M31 stars into Populations I and II was based on observational properties, specifically the colour-magnitude diagram; stellar evolution was not part of the initial picture. By the Vatican conference, however, the theoretical work by Hoyle, Tayler, Schwarzschild and Fowler, among others, had turned the focus on colour-magnitude diagrams from 'what?' to 'why?'. At the same time, the extensive measurements of stellar motions were being combined with the new radio observations of the gas content of the Milky Way to probe its overall dynamics. In the final presentation of the conference, Oort wove these threads into a complex picture of the Milky Way that included six stellar populations, ranging from Extreme Population I, characterised by OB stars, supergiants and Cepheids within the Galaxy's spiral arms, to the Halo Population, characterised by globular clusters and the high-velocity stars. Crucially, each population had an associated age estimate, heavy element abundance and spatial distribution. The potential for probing the past history of the Galaxy became apparent.

The most important outcome of the Vatican conference was a schematic outline of the current structure of the Milky Way, with clear hints as to the historical progression of star formation within the different sub-systems. Oort's discussion touched on the likely implications for Galactic evolution, and Hoyle discussed how star formation may proceed on smaller scales, but no model emerged providing an overall architecture for the formation of the Milky Way. That important step was first taken by Eggen, Lynden-Bell and Sandage in 1962.

18.4 The ELS Model

The observational foundation of the ELS model lay in Sandage and Eggen's collaborative work on the properties of high-velocity stars. The two astronomers had been close colleagues for some years, but this collaboration developed while Sandage was an invited visitor to the Royal Greenwich Observatory, Herstmonceux Castle, where Eggen was the chief assistant to the Astronomer Royal, Sir Richard Woolley. Eggen had compiled extensive photometric observations of numerous stars in the relatively recently-established Johnson UBV system, including observations of high-velocity stars. A subset of those stars had trigonometric parallaxes, and clearly lay below the main-sequence in the standard M_V, $B-V$ diagram. Indeed, this property led Kuiper (1939) to identify these stars as 'subdwarfs', a term previously applied more broadly to stars with unusual spectral properties.

Spectroscopic observations by Nancy Roman and others had shown that subdwarfs have weak spectral lines, leading to their being assigned earlier spectral types than might be appropriate. The weaker lines also lead to changes in the photometric properties, with lower line blanketing leading to more emission at blue and UV wavelengths. Sandage and Eggen (1959) developed simple models to estimate the effect on the UBV colour indices of reduced line blanketing. Decreasing metal content moves stars to bluer $B-V$ and $U-B$ colours, outlining blanketing lines in the

$U–B$, $B–V$ two-colour diagram. Taking field subdwarfs with trigonometric parallax measurements, they showed that a mean relation could be applied to adjust those stars onto the disc main-sequence. Thus, to first order, the offset of a star from the main-sequence in the M_V, $B–V$ colour-magnitude diagram could be tied to the level of line blanketing, and hence the metallicity.

Sandage and Eggen's 1959 paper defined UV-excess, $\delta U–B$, the vertical offset in $U–B$ between the observed location of a star in the UBV diagram and the location of the Hyades sequence at that $B–V$ colour. The UV-excess not only measures the metallicity of the field subdwarf, but also enables an estimate of its subluminosity, and hence its absolute magnitude. Given that estimate, photometric parallaxes (and distances) could be estimated for high-velocity stars that lacked direct trigonometric parallax measurements, and space motions derived from the radial velocity and proper motions. This was crucial in enabling ELS, since even now, after *Hipparcos*, only a few tens of subdwarfs have reliable trigonometric parallax measurements.

Buoyed by the initial results, Sandage and Eggen acquired further photometric and radial velocity measurements of high-velocity stars. By 1962, Sandage had returned to Mt. Wilson and Eggen had taken up a professorship at Caltech, following a rather public disagreement with Woolley on a policy issue. They were joined by Donald Lynden-Bell, on leave from Clare College, Cambridge, on a postdoctoral appointment with Sandage. Together, the three researchers provided a prime example of the whole exceeding the sum of the parts, combining Eggen's detailed and compendious observations with Lynden-Bell's theoretical knowledge of dynamics and Sandage's broad perspective on large-scale issues.

Observationally, ELS focuses on the analysis of data for only 221 F, G and K stars, comprising 108 nearby stars from Eggen's Solar Neighborhood sample together with 113 high-velocity stars. Besides UBV photometry, all stars had proper motion and radial velocity measurements as well as distance estimates, either from trigonometric parallax or UV-excess-corrected photometric values. As a result, three dimensional (U, V, W) space motions could be derived for each star. Placing those motions in a model potential enabled an estimate of the Galactic orbits.

Lynden-Bell's Galactic potential was derived from an axisymmetric model, set to match the rotation curve derived from radio observations of HI gas clouds in the disc. Stellar orbits were characterised using the angular momentum, h; eccentricity, $e = (R_{\max} - R_{\min}/R_{\max} + R_{\min})$, where $R_{\max}$ and $R_{\max}$ are the apogalacticon and perigalacticon of the orbit; and $|W|$, the velocity perpendicular to the Plane. Integrating the motions over time within a static potential (note that all these calculations were made by hand, not by computer) showed that the orbits were generally unclosed, but maintained the same values of e, h and $|W|$. Similar circumstances hold within a slowly varying potential (a potential that changes on a time-scale that is long relative to the orbital period). However, if the potential varies rapidly, then, on average, the eccentricity increases significantly while conserving angular momentum. The net result in the last case is that test particles will evolve onto highly eccentric, radial orbits.

Working within this theoretical framework, with the knowledge that the sample stars lie within a few hundred parsecs of the Sun, one can calculate the orbital

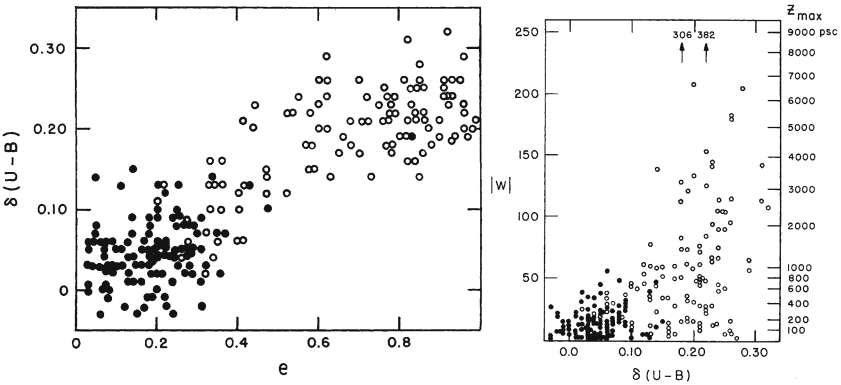

Fig. 18.5 *Left panel*: The correlation between orbital eccentricity and UV-excess (metallicity). *Right panel*: The correlation between the *W* velocity perpendicular to the Galactic plane and UV-excess. The *filled circles* represent stars from the nearby star catalogue, while the *open circles* denote high-velocity stars. Figure adapted from Eggen et al. (1962)

energy and angular momentum, and estimate eccentricities and vertical velocities for each object. The results are shown in Fig. 18.5, which includes the two most influential figures from ELS. The left panel plots orbital eccentricity against UV-excess, showing that the nearby stars tend to have relatively circular orbits while stars with the strongest UV-excess (i.e. the lowest metallicities) have the most eccentric orbits. The right panel maps out the vertical velocities, and the consequent maximum height from the Galactic Plane; it is clear that lower abundance stars have a spatial distribution that extends to significantly larger distances from the Plane.

It is important to note that there is the potential for two systematic selection effects in these figures. Metal-poor stars on circular orbits would not necessarily appear in this sample, since their velocities relative to the Sun would be low, leading to their non-inclusion in the high-velocity star sample, but their local density might preclude inclusion in the nearby star sample. In the same vein, stars with modest UV-excess and intermediate eccentricities might be under-represented in such a relatively small sample.

These concerns aside, ELS highlighted the parallels between the local subdwarf sample and main-sequence stars in globular clusters, known to be amongst the oldest objects in the Milky Way with ages of $\sim 10^{10}$ yr. On that basis, they identified the correlation with UV-excess as a correlation with age, and deduced that the large Z reached by subdwarfs was tied to the likely location of the parent star-forming clouds. Coupled with the theoretical calculations, they concluded that the observations could be explained if the oldest stars in the Galaxy (the subdwarfs) formed during a phase when the galactic potential was undergoing rapid evolution (timescale of a few $\times\, 10^8$ yr) driven by the radial collapse of the protogalactic cloud, whose initial extent was perhaps ten times the size of the present Milky Way. The net angular momentum of the cloud slowed and stopped the collapse in R, but the collapse continued in Z, leading to the formation of a rotating, gas-rich disc, where continuing star formation led to the formation of the present-day disc population. Globular clusters and halo field subdwarfs formed during the collapse, leading to their having strongly radial orbits.

The ELS paper was extremely influential at the time, and continues to play an important role in galaxy formation.

18.5 Searle and Zinn and Galaxy Mergers

ELS established a framework for discussing potential formations scenarios for spiral galaxies like the Milky Way. Conceptually, their model envisages the Milky Way as the product of the monolithic collapse of the gaseous protogalaxy, implying an overall coherence in structure within the Galactic halo. As observations accumulated of larger samples of halo objects more complex circumstances emerged that cast some doubt on that relatively simple model. In particular, more extensive photometry revealed that clusters with the same overall metallicity could have radically different horizontal branch morphologies. For example, both NGC 7006 and M2 have average metal abundances $[M/H] \sim -1.5$ dex, or 1/30th solar; M2 has an extended blue horizontal branch, while NGC 7006 has a relatively short horizontal branch that does not extend far beyond the RR Lyrae instability strip (see Fig. 18.6). This dichotomy has become known as the second-parameter effect. Other examples of second-parameter cluster pairs are M13 and M3, and NGC 288 and NGC 362.

The ELS model envisages rapid, free-fall collapse of the initial protogalactic gas cloud. Under those circumstances, one would not expect significant abundance gradients to develop since the timescale for collapse is short compared with the evolutionary timescale for recycling stellar ejecta in the ISM. Following ELS, alternative models were developed that involved slower, pressure-supported collapse (e.g. Yoshii and Saio 1979); under those circumstances an abundance gradient might develop. The existence of moderately metal-rich globulars in the inner Galaxy was well established by 1978, but the abundance distribution in the outer halo remained uncertain.

Searle and Zinn (1978) were among the first to undertake a major analysis that took advantage of the new information on the halo. They focussed on nineteen globular clusters, the majority of which lay in the outer parts of the Galactic halo. Employing a customised narrowband photometric system, they used red giants to determine the cluster abundances, sampling the CH and CN molecular bands in the giant's spectrum. The results showed no evidence for a systematic radial abundance gradient, arguing strongly against a slow, pressure-supported monolithic initial collapse. However, the clusters in the outer halo also exhibited diverse properties, particularly with regard to the second-parameter effect. This is in contrast to the inner halo clusters, which show little dispersion in morphology at a given metallicity.

There are three factors that drive horizontal branch morphology: metallicity (specifically C, N, O abundances), helium abundance and age (Rood and Iben 1968). Ruling out CNO variations, Searle and Zinn (1978) argued that age differences were more plausible than invoking some unknown additional mechanism for changing helium abundance without changing the overall metallicity. The required age differ-

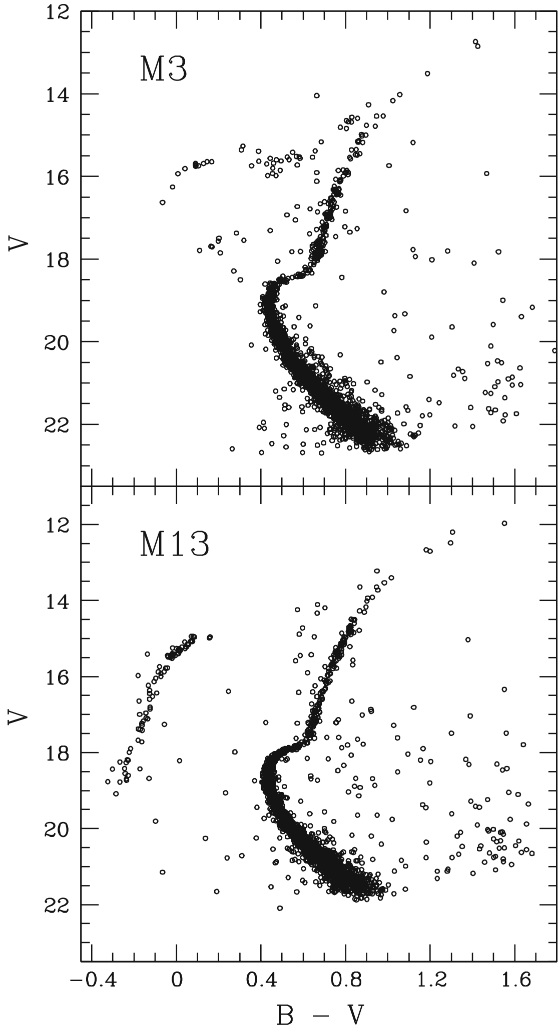

Fig. 18.6 The second-parameter effect in globular clusters. *Upper panel*: V, $B\text{–}V$ colour-magnitude diagram for the intermediate metallicity cluster M3, which has a relatively short horizontal branch. *Lower panel*: V, $B\text{–}V$ colour-magnitude diagram for M13, which has a similar metallicity to M3, however the horizontal branch extends to bluer, hotter stars. Figure from Rey et al. (2001)

ences exceed 10^9 yr, and would therefore be incompatible with formation within an ELS-like initial collapse. Instead, Searle and Zinn (1978) argued for a more chaotic formation scenario, with the outer clusters accreted later in the Galaxys history; specifically, they hypothesised that those clusters '...originated in transient proto-galactic fragments that continued to fall into dynamical equilibrium with the Galaxy for some time after the collapse of its central regions had been completed'.

Following up on this work, Zinn (1980, 1985) extended observations to include 121 clusters, the majority of the Galactic population. Based on those data, he identified two subgroups: halo clusters, with typical Galactocentric distances exceeding 9 kpc, exhibiting a wide range in height above the Plane, predominantly metal-poor, with a high velocity dispersion and negligible net rotation; and disc clusters, confined within 5 kpc of the Plane with metallicities [Fe/H] > -0.8 dex, lower velocity dispersions and moderate rotation. Zinn's suggestion of a two-phase halo has been echoed by subsequent investigations, including analyses of the velocity distribution of nearby subdwarfs by Sommer-Larsen and Zhen (1990) and of the large-scale density distribution and kinematics of metal-poor stars in the SDSS (Beers et al. 2012). He also suggested that the disc clusters may have formed in a 'thick disc' phase of early Galactic evolution, while the halo clusters represent remnants of satellites accreted by the Milky Way after its initial collapse.

Stepping forward thirty years, satellite accretion is a key process in galaxy formation within the ΛCDM (cold dark matter) cosmological paradigm. Direct constraints on the power spectrum of the initial density functions from the cosmic microwave background, galaxy clustering and observations of the Lyman-α forest, suggest that structure formation is hierarchical (Bullock 2010). Dark matter simulations predict that the deep potential wells defined by the dark matter halos, the sites of future large galaxies, should be populated by hundreds of smaller dark-matter concentrations. Some will be accreted by the host galaxy; others may survive as ultra-faint dwarf galaxies (Brown et al. 2012), while still others may have masses that are too low to retain substantial baryonic material.

Satellite accretion and minor galaxy mergers, and their consequences, can be observed in many nearby galaxies. Indeed, the Milky Way itself is undergoing a merger at the present time. The dwarf galaxy in question lies towards the Galactic Bulge, and was only discovered by chance when a survey of the kinematics of the Bulge revealed an unusual feature—a significant number of stars, spanning a wide range of colour, at a specific velocity (Ibata et al. 1994, see Fig. 18.7). The stars were

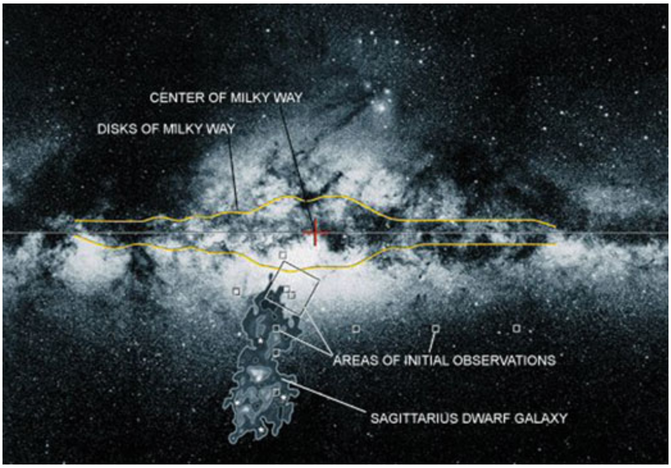

Fig. 18.7 The location of the Sagittarius dwarf galaxy. Figure from http://annesastronomynews.com/annes-picture-of-the-day-the-sagittarius-dwarf-elliptical-galaxy/. Image credit: R. Ibata (UBC), R. Wyse (JHU) and R. Sword (IoA)

identified as members of a dwarf galaxy lying beyond the Bulge, currently being torn apart by the Milky Way. Several globular clusters, including M54 and Terzan 7, are associated with the Sagittarius dwarf galaxy; analysis of data from the 2MASS survey has succeeded in tracing giant star members over more than 270° (Majewski et al. 2003); and theoretical models indicate that the system is likely to be in its third passage through the Milky Way's disc (Johnston et al. 2005).

Following Sagittarius' discovery, extensive searches were undertaken for evidence of past accretion events, and traces of other debris streams have been uncovered in analysis of SDSS data. In particular, several linear features have been uncovered in the so-called 'field of streams' (Belokurov et al. 2006). One such feature is the Monoceros ring (Casetti-Dinescu et al. 2006), which may have originated in the 'Canis Major dwarf', an over-density of stars in that region of the sky; an alternative possibility is that this feature has its origin in a (spatial) flare in the Galactic disc. Whatever the origin, these features are detectable because they lie at Galactocentric distances of $\sim$17 kpc (Li et al. 2012), beyond the steep density decline that marks the edge of the disc.

What are the implications of these results for the origin and formation of the Milky Way? An important point to make is that both the Searle and Zinn model and its successors include an early monolithic collapse in the protogalaxy; that ELS component is responsible for forming the inner halo, and is supplemented by subsequent accretion of dwarf proto-galaxies to form some/most/all of the outer halo, with the accretion phase persisting even to the present day. The crucial question is how significant is the overall contribution to the halo from these accreted satellites?

The observed [α/Fe] ratios of stars in the present-day Milky Way dwarfs may offer some insight on that question. As Fig. 18.8 shows, those values are not consistent with observations of halo stars; the lower ratios imply that those stars formed in an ISM that had been enriched by Type I supernovae in addition to ejecta from short-lived, high-mass stars. Of course, present-day dwarf galaxies may not be representative of satellite galaxies that may have been absorbed earlier in the Galaxy's history; those dwarfs have existed as separate entities for a Hubble time, undergoing sustained periods of star formation. Moreover, while those galaxies appear to have a substantial dark matter component, there is no evidence of dark matter associated with any present-day globular cluster. Thus, if the outer globular clusters are the remnants of accreted dwarf galaxies, either the underlying dark matter was stripped through some mechanism and mixed within the Galactic halo, or the parent systems lacked such a component. In short, there is no question that accretion of satellite galaxies played a role in the formation of the Milky Way, but it may be that Sandage was correct in his characterisation of the Searle and Zinn model as merely ELS plus noise.

18.6 Globular Clusters Revisited

The three decades since Searle and Zinn's analysis have seen extensive observational and theoretical investigations of the properties of globular clusters. Many results from those studies are included in Bill Harris' 2001 Saas-Fee lectures on globulars. Most

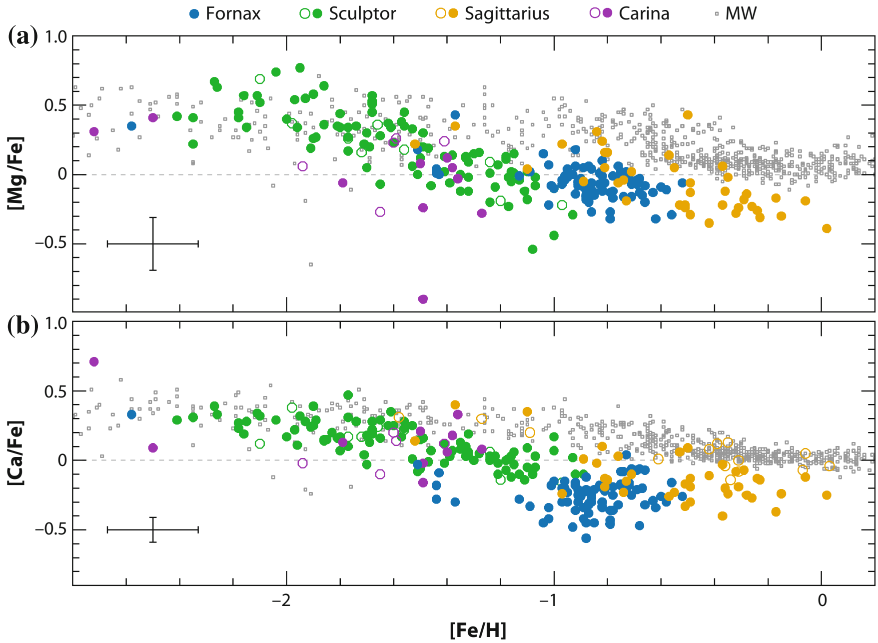

Fig. 18.8 α/Fe abundance ratio as characterised by measurements of magnesium (*upper panel*) and calcium abundance (*lower panel*) in today's dwarf spheroids compared with Milky Way stars. *Open circles* refer to single-slit spectroscopy measurements, while *filled circles* denote multi-object spectroscopy. Figure from Tolstoy et al. (2009)

observations contributing to that review were drawn from ground-based telescopes, but these are high star density systems, which can limit the potential for seeing-limited observations to probe key parameters. Space-based observations offer key advantages in depth and resolution. The initial imaging cameras on *Hubble*, Wide-Field Camera and Wide-Field Camera 2, had relatively small fields-of-view, but with the addition of the Advanced Camera for Surveys (ACS) in servicing Mission 3B (2004) and Wide-Fields Camera 3 (WFC3) in Serving Mission 4 (2009), HST has had the capability of providing observations of extraordinary sensitivity.

One of the most influential HST program for globular cluster studies involves an ACS two-colour (VI) imaging survey of 63 clusters, almost half the known sample (Sarajedini et al. 2007). Data from that program have been used to probe a wide variety of cluster properties, including the stellar mass function (Paust et al. 2010), the binary fraction (Milone et al. 2012), relative cluster ages and the second-parameter problem (Marín-Franch et al. 2009). The mass function results show a strong correlation in slope with cluster mass, underlining the importance of dynamical evolution; none of the results indicate a mass function steeper than that of the local disc stars. The binary fraction is anti-correlated with cluster luminosity, again indicating that mass segregation and tidal stripping have played a role, preferentially stripping single stars in the less massive clusters as the binaries sink towards the cluster centre. Finally, the consensus analysis points towards age as the second-parameter, with the relative age distribution indicating that most clusters formed almost coevally, consistent with an ELS-style monolithic collapse, with a subset that appear to have significantly younger ages, more consistent with the Searle and Zinn formation model (see Fig. 18.9).

Most significantly, HST observations have prompted a radical change in our understanding of the fundamental nature of (many) globular clusters. Classically, globulars were described as simple stellar population, the product of a single, rapid burst of star formation within an isolated gas cloud in the Milky Way's protohalo, with coeval stars of uniform metallicity and helium abundance. Stellar winds generated by either high-mass stars or supernovae explosions overcome the cluster self-gravity and sweep it clear of gas, eliminating the potential for subsequent star forming episodes. That simple picture has cracked in recent years.

ω Centauri, lying towards the Small Magellanic Cloud, represents the thin end of the wedge. The most massive globular cluster, this system has long been known to possess stars spanning a substantial range in metallicity. Red giant cluster members exhibit a significant range in CH and CN bandstrength (Dickens and Bell 1976), RR Lyraes show a mix of pulsational properties (Caputo and Castellani 1975) and main-sequence stars span metallicities spanning almost an order of magnitude, $-1.9 <$ [Fe/H] < -1 dex (Stanford et al. 2007). This diversity is clearly inconsistent with a single starburst, and suggests that the cluster is either the product of a merger, or that the parent entity was sufficiently massive that it could sustain multiple bursts of star formation. Indeed, as early as 1975, there were suggestions that ω Cen might be the remnant core of a dwarf galaxy (Freeman and Rodgers 1975).

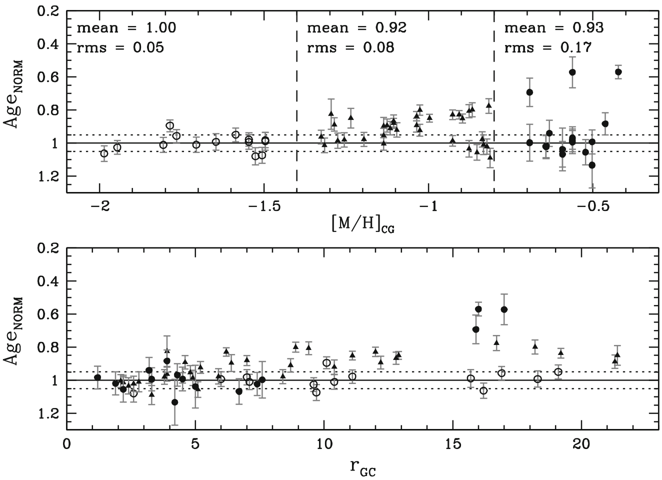

Fig. 18.9 Normalised globular cluster ages as a function of [M/H] (*upper panel*) and galactocentric distance (*lower panel*). *Open circles*, *filled triangles* and *filled circles* represent globular clusters within low-, intermediate- and high-metallicity groups respectively. Figure from Marín-Franch et al. (2009)

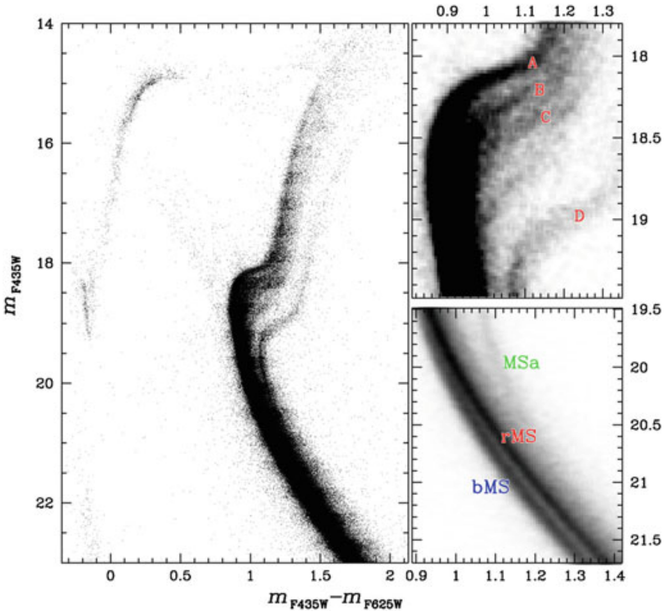

Fig. 18.10 The complex colour-magnitude diagram of ω Cen illustrating the main four sub-giant branches (*upper right panel*) and triple main-sequence (*lower right panel*). Figure from Bellini et al. (2010)

More detailed spectroscopic observations of red giants in other globulars were acquired through the 1970s and early 80s, and it became apparent that there was a dichotomy in CN and CH bandstrengths in a significant number of clusters (see Kraft 1994 for a review). In addition, evidence began to accumulate for an anti-correlation between oxygen and sodium abundances (Cohen 1978; Peterson 1980); Na-rich stars tend to also be CN-strong. These results sparked lively discussion on the origin, with the initial debate focused on either primordial variations in the protocluster gas (nature) or internal mixing of nucleosynthetic products within extended red giant atmospheres (nurture). The identification of carbon and nitrogen abundance variations among main-sequence stars (Suntzeff 1989), which are not expected to undergo extensive internal mixing, argued against the latter option. Similarly, mixing cannot account for the Na-O anti-correlation; that phenomenon can be explained if Na is synthesised from Ne within an environment deep within massive stars where oxygen is being depleted in the ON cycle (Gratton et al. 2004). That, in turn, requires that cluster stars form from material that has been polluted by ejecta from a previous stellar generation or generations.

HST provided the key observations that crystallised this debate. The initial hints came from analyses of WFPC2 observations of ω Cen (Bedin et al. 2004), which revealed that the main-sequence clearly became bimodal 1–2 mag below the turn-off. The full complexity of the cluster only became apparent with the application of refined photometric analysis techniques to the wider-field ACS and WFC3 observations. Figure 18.10 shows the extremely complex nature of this cluster with the high precision WFC3 data revealing as many as 5 distinct stellar sequences (Bellini et al. 2010), more than in many dwarf galaxies. There is a clear variation in age, with separation between the turn-offs, as well as abundance variations. Moreover, the bluer main-sequence has higher metallicity than the red, requiring that the former should have substantially enhance helium abundances, potentially as high as $Y = 0.38$ (Piotto et al. 2005). As with the Na-O anti-correlation, the additional helium can be generated in hot-H burning in massive stars; moreover, helium-rich stars evolve faster, leading to a lower turn-off mass for the same age and lower-mass, hotter (bluer) stars on the horizontal branch. The hypothesis that one could produce this complex morphology through external events, such as mergers of separate protoclusters or external pollution from nearby clusters, requires a sequence of exceedingly improbably events. The simplest explanation is that ω Cen underwent multiple star-forming episodes, and that it was sufficiently massive that it was able to retain a fraction of the original gas content, which was then polluted and enriched by stellar ejecta from the first generation stars before forming a second (and third and fourth) generation population.

Subsequent observations have shown that many globular clusters harbour multiple stellar populations (Piotto 2009). The initial focus was on massive clusters, such as NGC 2808, NGC 1851, NGC 6388 and NGC 6566 (M22), but subsequent observations have shown that anomalies are present in lower-mass clusters. Indeed, even the archetypical metal-poor globular NGC 6397 ([Fe/H] $= -1.9$ dex) shows evidence for main-sequence bimodality (Milone et al. 2012) and, to date, all globulars studied in sufficient detail exhibit the Na-O anticorrelation indicative of early pollution (Carretta et al. 2009).

How does this translate to a model for the origin of globular clusters within the earliest stages of formation of the Milky Way? Gratton et al. (2012) have proposed an interesting scenario. Taking a leaf from cosmological simulations, they envisage the Milky Way's halo forming by accretion of many smaller, gas-rich systems in the early universe. The interactions lead to substantial starbursts within the fragments, with the first stars that form producing a rapid increase in the metallicity of the system. The initial stars trigger a strong burst of star formation in the protoclusters. Massive stars and supernovae from that initial burst removes most of the residual gas, but the protoclusters are sufficiently massive that enough gas is retained to permit the formation of a second (and, for more massive systems, third) generation, whose stars are O-depleted, Na-rich and He-rich, thanks to the ISM pollution from the first stars.

What about the field halo? Approximately 2.5 % of field subdwarfs show evidence for Na-O anticorrelation, suggesting that those stars were formed as second (or later) generation cluster starbursts. Those stars entered the field through standard dynamical evolution processes, such as two-body encounters within the cluster and disc-shocking and encounters with massive objects external to the cluster. Looking at present-day clusters, second generation stars are estimated to contribute approximately two-thirds of the stellar complement, leaving the first generation stars as a minority constituent (Carretta et al. 2009). If we assume similar evaporation rates, the first generation cluster stars that were present when the second generation formed would contribute approximated 1 % of field halo. The cluster system itself contributes approximately 1 % of the mass of the halo ($\sim 10^7\,M_\odot$); thus, ejected and retained globular cluster stars constitute at least 5 % of the mass of the current halo.

However, first generation cluster stars may make a larger contribution to the field. There are strong arguments that those stars must have been substantially more populous if they were to generate sufficient mass-loss to pollute the ISM to match the abundances observed in the second generation stars. Estimates are far from precise, but the case can be made the first generation of cluster stars had to be at least 5 to 10 times more populous than the second generation, with a correspondingly higher evaporation into the field. In that case, the original protoglobulars might well have constituted 25–50 % of the total halo mass. Indeed, given the uncertainties, the original globular clusters might be the parent star-forming sites for all of the stars in the Milky Way's present-day halo (see Gratton et al. 2012 for a more extensive discussion).

A major complication for this scenario is the absence of dark matter in present-day globulars. If one constitutes the initial formation phase as accretion of fragments, à la ΛCDM, one might expect those fragments to mimic current-day dwarf galaxies and have substantial dark matter content. One means of mitigating this issue would be to envisage collisional interactions either between the gas-rich fragments or between the accreted material and gas in the proto-Milky Way. Dark matter would not participate in these dissipational interactions, and would therefore part ways from the gas.

Alternatively, one might imagine protoglobulars as high-density regions within the proto-Galaxy itself, high-mass baryonic concentrations within the overall gravitational potential defined by the Milky Way's dark matter component. The initial star formation and subsequent evolution occurs as the overall system undergoes gravitational collapse, giving a cluster system whose members have very similar ages, consistent with the narrow relative age distribution for the majority of clusters (see Fig. 18.10). Younger clusters would be acquired through subsequent satellite accretion. This scenario thus envisages a lumpy version of ELS as the dominant factor in forming the Milky Way, with a more chaotic initial collapse, with a mild sprinkling of Searle and Zinn in later years. Overall, to echo Sandage, the Milky Way formation process is ELS plus noise.

18.7 Endword

The paper authored by Eggen, Lynden-Bell and Sandage has been extremely influential in shaping discussion over the years, and its results and conclusions continue to play an important role in studies of galaxy formation. As Lynden-Bell (2012) has pointed out, ELS remains the highest-cited paper for each of the three authors, a notable achievement given the competition in each case. As the first serious attempt to reconstruct the overall picture of the formation of the Milky Way, it set the scene for what has become known as galactic archaeology. The concepts of galaxy formation through large-scale collapse and rotational support within a disc still play a key role in the modern view of galaxy formation, albeit supplemented with the additional complexities of subsequent multiple mergers with lower-mass systems.

References

Abell, G. O. 1955, PASP, 67, 258
Alpher, R. A., Bethe, H., & Gamow, G. 1948, Phys. Rev., 73, 803
Baade, W. 1944, ApJ, 100, 137
Bedin, L. R., Piotto, G., Anderson, J., et al. 2004, ApJ, 605, L125
Beers, T. C., Carollo, D., Ivezić, Ž., et al. 2012, ApJ, 746, 34
Bellini, A., Bedin, L. R., Piotto, G., et al. 2010, AJ, 140, 631
Belokurov, V., Zucker, D. B., Evans, N. W., et al. 2006, ApJ, 642, L137
Bennett, C. L., Larson, D., Weiland, J. L., et al. 2013, ApJS, 208, 20
Blaauw, A. 1995, in IAU Symposium, Vol. 164, Stellar Populations, ed. P. C. van der Kruit & G. Gilmore, Kluwer Academic Publishers, 39
Brown, T. M., Tumlinson, J., Geha, M., et al. 2012, ApJ, 753, L21
Bullock, J. S. 2010, in Canary Islands Winter School of Astrophysics on Local Group Cosmology, ed. D. Martínez-Delgado, Cambridge University Press
Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F. 1957, Reviews of Modern Physics, 29, 547
Caputo, F. & Castellani, V. 1975, Ap&SS, 38, 39
Carney, B. W., Latham, D. W., Laird, J. B., & Aguilar, L. A. 1994, AJ, 107, 2240
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2009, A&A, 505, 117
Casetti-Dinescu, D. I., Majewski, S. R., Girard, T. M., et al. 2006, AJ, 132, 2082
Chamberlain, J. W. & Aller, L. H. 1951, ApJ, 114, 52
Cohen, J. G. 1978, ApJ, 223, 487
D'Antona, F., Caloi, V., & Mazzitelli, I. 1997, ApJ, 477, 519
Dickens, R. J. & Bell, R. A. 1976, ApJ, 207, 506
Eggen, O. J., Lynden-Bell, D., & Sandage, A. R. 1962, ApJ, 136, 748
Freeman, K. C. & Rodgers, A. W. 1975, ApJ, 201, L71
Frenk, C. S. & White, S. D. M. 1980, MNRAS, 193, 295
Gizis, J. E. & Reid, I. N. 1999, AJ, 117, 508
Gratton, R., Sneden, C., & Carretta, E. 2004, ARA&A, 42, 385
Gratton, R. G., Carretta, E., & Bragaglia, A. 2012, A&A Rev., 20, 50
Gratton, R. G., Fusi Pecci, F., Carretta, E., et al. 1997, ApJ, 491, 749
Harris, W. E. 2001, Star Clusters: Saas-Fee Advanced Course 28, ed. Labhardt, L. and Bingelli, B., Springer
Harris, W. E. 2010, arXiv:1012.3224. Available at http://physwww.physics.mcmaster.ca/~harris/mwgc.dat
Hoyle, F. 1948, MNRAS, 108, 372
Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 194
Johnston, K. V., Law, D. R., & Majewski, S. R. 2005, ApJ, 619, 800
Kraft, R. P. 1994, PASP, 106, 553
Kuiper, G. P. 1939, ApJ, 89, 548
Li, J., Newberg, H. J., Carlin, J. L., et al. 2012, ApJ, 757, 151
Lynden-Bell, D. 2012, Biogr. Mems Fell. R. Soc., 58, 245
Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., & Ostheimer, J. C. 2003, ApJ, 599, 1082
Marín-Franch, A., Aparicio, A., Piotto, G., et al. 2009, ApJ, 694, 1498
Milone, A. P., Piotto, G., Bedin, L. R., et al. 2012, A&A, 540, 16
Oort, J. H. 1928, Bull. Astron. Inst. Netherlands, 4, 269
Paust, N. E. Q., Reid, I. N., Piotto, G., et al. 2010, AJ, 139, 476
Peterson, R. C. 1980, ApJ, 237, L87
Piotto, G. 2009, in IAU Symposium, Vol. 258, The Ages of Stars, ed. E. E. Mamajek, D. R. Soderblom, & R. F. G. Wyse, Cambridge University Press, 233
Piotto, G., Villanova, S., Bedin, L. R., et al. 2005, ApJ, 621, 777
Reid, I. N. 1997, AJ, 114, 161

Rey, S.-C., Yoon, S.-J., Lee, Y.-W., Chaboyer, B., & Sarajedini, A. 2001, AJ, 122, 3219
Roman, N. G. 1954, AJ, 59, 307
Rood, R. & Iben, Jr., I. 1968, ApJ, 154, 215
Sandage, A. 1956, PASP, 68, 498
Sandage, A. R. & Eggen, O. J. 1959, MNRAS, 119, 278
Sarajedini, A., Bedin, L. R., Chaboyer, B., et al. 2007, AJ, 133, 1658
Searle, L. & Zinn, R. 1978, ApJ, 225, 357
Sommer-Larsen, J. & Zhen, C. 1990, MNRAS, 242, 10
Stanford, L. M., Da Costa, G. S., Norris, J. E., & Cannon, R. D. 2007, ApJ, 667, 911
Suntzeff, N. B. 1989, in The Abundance Spread within Globular Clusters: Spectroscopy of Individual Stars, ed. G. Cayrel de Strobel, 71.
Tolstoy, E., Hill, V., & Tosi, M. 2009, ARA&A, 47, 371
Yoshii, Y. & Saio, H. 1979, PASJ, 31, 339
Zinn, R. 1980, ApJ, 241, 602
Zinn, R. 1985, ApJ, 293, 424