Issues in the Formation of Globular Cluster Systems

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1. Cluster Ages in the Milky Way Halo

Globular clusters make up less than 1% of the visible halo stars. These, in turn, form only a few percent of all the mass present in the potential well of a large galaxy. However, these ancient star systems contain information about the history of halo formation out of all proportion to their fraction of the total mass. The literature on globular cluster systems in the Milky Way and other galaxies is now far too large to summarize in one short review, so I will concentrate only on a few recent issues that have taken on particular importance.

Within our own Milky Way, globular cluster ages have once again taken center stage in the debate over halo formation. With continuing in stellar physics and evolution codes, the best estimates of absolute ages for the oldest globular clusters have undergone modest downward revisions. A very considerable factor helping to drive them in this direction has been the appearance of the Hipparcos parallaxes, with much new information on field-star subdwarfs used to calibrate globular cluster distances (e.g., Reid 1997; Gratton et al. 1997; Pont et al. 1997). This new material, though important, has not yet settled the distance calibration issue; early reports of resulting cluster ages as low as 10 Gyr are not being borne out by subsequent studies, and it may not be too early to suggest an emerging new consensus of theory and observation around $\tau \simeq (13 \pm 1)$ Gyr for the oldest, most metal-poor halo clusters.

Independently of absolute age calibrations, we can estimate the duration of the halo formation era by finding relative cluster ages from widely different parts of the halo and over the full range of cluster metallicities. With present-day high precision main sequence photometry, these relative ages can be gauged to within $\pm 0.5$ Gyr for clusters of similar compositions. Various recent discussions (Richer et al. 1996; Chaboyer et al. 1996; Bruzual et al. 1997) suggest that there is an overall age-metallicity relation, with the more metal-rich clusters (47 Tuc and the others like it) being $\sim 2$ Gyr younger on average than the most metal-poor (and presumably oldest) ones like M92 and M15. But perhaps surprisingly, we are discovering that the ages of the lowest-metallicity clusters are identical to within measurement precision everywhere in the halo from Galactocentric distances of $\sim 5$ kpc out to $\sim 100$ kpc (see Figure [1]). The most recent and telling comparisons of this type are by Harris et al. (1997a, for the remote-halo cluster NGC 2419 versus the inner-halo clusters of similar metallicity).

The implications is that, all over the protogalaxy which would eventually evolve into the Milky Way, globular cluster and halo-star formation began at virtually the same time. This volume is now almost 200 kpc in diameter. How can we fit this in to the overwhelming evidence for a lumpy formation history
Figure 1. Ages of low-metallicity ([Fe/H] \(\lesssim -1.8\)) globular clusters in the Milky Way; data from Harris et al. (1997a) and Richer et al. (1996). The zeropoint of the age scale is adopted as 13 Gyr (see text). The circled cross denotes M54, the largest and most metal-poor globular cluster in the Sgr dwarf (Layden & Sarajedini 1997). Relative age uncertainties average \(\pm 1\) Gyr per cluster (cf. Harris et al. 1997a).

and the buildup of the halo from many pieces (see below)? This upper end to the cluster age distribution may simply be telling us that any of the pregalactic ‘pieces’ (dwarf-sized \(10^8 - 10^9\) \(M_\odot\) gas clouds) could have begun building stars at about the same time after they emerged from the recombination era and began collecting into the protogalactic potential wells. These protodwarfs (or SGMC’s; see Harris & Pudritz 1994; McLaughlin & Pudritz 1996) are exactly the right environments for the buildup of protoglobular clusters, a process which should take a few \(\times 10^8\) years, regardless of location within the halo.

High precision new calibrations of the relative ages of clusters, based firmly on deep main-sequence photometry, are continuing to accumulate. Within a few years the long-sought goal of a complete age profile for the Galactic halo may be within our grasp. With it may come the first unequivocal solution to the famous ‘second-parameter’ problem affecting the color-magnitude distributions of stars in the diagrams of the metal-poor clusters, which have long been suspected to be due primarily to age differences (e.g. Lee et al. 1994).

2. The Deconstructionist Halo

Kinman (1959) first demonstrated that the Milky Way globular cluster system contained at least two kinematically distinct subgroups which also differed in mean metallicity. The landmark paper of Zinn (1985) strongly reinforced this conclusion with considerable new data, and related it in modern terms to the probable formation histories of the different metallicity groups. The case for two major subpopulations builds from what is now seen to be a remarkably common
phenomenon of halo cluster systems in other galaxies: a bimodal metallicity distribution (Figure 2). In the Milky Way, the clusters more metal-poor than $[\text{Fe/H}] \sim -1.0$ define what we traditionally think of as the “normal halo”, with a Gaussian-like metallicity distribution centered at $[\text{Fe/H}] = -1.6$ and little or no systemic rotation, closely resembling the field halo stars. By contrast, the metal-richer subpopulation ($[\text{Fe/H}] > -1.0$) carries a significant overall rotation, and (if the best current age estimates are correct) may be younger on average by up to 2 Gyr than the metal-poor halo. Zinn (1985) and Armandroff (1989) favored interpreting these clusters as a disk system, possibly identified with the stellar thick disk, and most workers have referred to them collectively as “disk clusters” since. However, this identification is very much open to debate. Minniti (1995) has pointed out that the kinematics of the metal-richer clusters, coupled with their rather restricted space distribution in the innermost few kpc, may be more consistent with a bulge-like population rather than the thick disk.

Figure 3 shows the kinematical distribution. The small number of objects, the internal scatter, and the effects of distance errors for these highly reddened clusters (which make the actual positions of many points in the graph highly uncertain and thus of low weight) would allow any $v_{\text{rot}}$ within the range of $\sim 100$ to 200 km/s, which could be either bulge-like or disk-like. To cloud the issue further, Burkert & Smith (1997) claim that some of these inner clusters (those with the most positive radial velocities and smallest longitudes) may form a bar-like system embedded in the bulge. Unfortunately these same objects tend to be among the ones with the worst known distances and reddenings.
Figure 3. Radial velocities for metal-rich globular clusters in the Milky Way, with data from Harris (1996). Here $v_r$ is the velocity relative to a stationary point at the Sun; in this graph, a constant $v_{rot}$ appears as a straight line (see Zinn 1985 for definition of the angle $\psi$). The solid line is $v_{rot} = 160$ km/s. Higher-weight points are plotted with larger symbols; the open circles are those clusters claimed by Burkert & Smith (1997) to be in a barlike configuration.

Whether or not the clusters truly represent any subpopulation of the field stars is, once again, closely connected with ages. Holtzman et al. (1993) estimate that the bulge stars have a mean age near 10 Gyr on a scale where the inner globular clusters are 13 Gyr. A very similar $\sim 3–4$ Gyr difference between field stars and clusters is found by Layden & Sarajedini (1997) for the Sagittarius dwarf elliptical. If the Milky Way halo was built from the amalgamation of many such pieces, the evidence suggests that the clusters had a considerable head start, and were present for a long time while most of the Galaxy’s raw material was still gaseous. Earlier arguments (see Harris 1991) based on space distributions, free-fall times, and metallicity enrichment timescales, had suggested that globular clusters might be generically older by perhaps $\sim 1$ Gyr than the bulk of the halo in most large galaxies – quite a bit less than the direct age differences now emerging from the new color-magnitude studies.

Attempts have also been made to deconstruct the metal-poor cluster population into distinct subgroups. Morphological differences in the color-magnitude diagrams certainly correlate with galactocentric distance (the second-parameter problem; e.g. Lee et al. 1994), and may correlate with age and kinematics. One suggested subgroup may even have a retrograde net rotation, and it is at least possible that it may represent a particularly large satellite accretion event (Rodgers & Paltoglou 1984; Zinn 1993; van den Bergh 1993). Better and more direct age information should help to evaluate the range of possibilities.

The importance of the cluster/field-star age offset is considerable. There appears to have been plenty of time after the initial burst of globular cluster
formation for the leftover and newly enriched gas – which in fact was most of the Galaxy's raw material – to mix, dissipate, recollect into new clouds, and recollapse before beginning new and more substantial bursts of star formation that gave rise to the bulge, the thick disk, and eventually the thin disk. By that time, much of its memory of the initial state from the cluster-forming epoch would have been thoroughly erased as it evolved into different subpopulations. Thus the long-standing question whether or not the globular clusters can be taken as ‘representative’ of some major stellar population in the bulge or halo seems to me to be moot – essentially unanswerable. At present, they represent only themselves. To be sure, some fraction of the field-star component must consist of stars tidally stripped from existing clusters, or from small clusters that were entirely dissolved; but current observations, simulations, and theoretical constraints suggest that this fraction is not likely to exceed $\sim 10\%$ (e.g., Harris & Pudritz 1994; Capriotti & Hawley 1996; Murali & Weinberg 1997).

3. Giant E Galaxies: Stormy Beginnings

Observations for globular cluster systems in other galaxies have been advancing by leaps and bounds in the last few years. Accurate metallicity distributions for huge samples of clusters are starting to become available for key objects such as NGC 4472, NGC 1399, M87, and the other gE's in Virgo and Fornax (e.g., Whitmore et al. 1995; Geisler et al. 1996; Forbes et al. 1997a,b). With these come more comprehensive luminosity functions (GCLFs) and space distributions, and eventually (with the 8-meter class of telescopes; cf. Cohen & Ryzhov 1997) spectra and dynamical analyses. From these studies, two common themes have emerged so strongly that they must take precedence in any respectable scenario of cluster formation:

1. The near-universality of the mass distribution function (GCLF): in galaxies of all types and sizes, the clusters follow $dN/dM \sim M^{-1.8\pm0.3}$, except for the lowest $\sim 10\%$ of the mass range which is most strongly affected by dynamical erosion. The GCLF is to first order independent of metallicity and age. Thus, globular cluster formation seems to require only a large input supply of gas clumped together into the SGMC-sized clouds inferred (see above) for the Milky Way. If this approach is basically correct, then it is highly encouraging of the view that the sites of massive star cluster formation happening now in (e.g.) NGC 1275 (Holtzman et al. 1992) or the Antennae (Whitmore & Schweizer 1995) do resemble what must have been happening wholesale at much earlier epochs.

2. The metallicity distribution function, which repeatedly shows a bimodal form in giant ellipticals and spirals alike. The metal-richer subpopulation is, invariably, the more centrally concentrated. The interpretation that these are the signatures of two major, distinct epochs of cluster formation is now compelling. But what drove these bursts, and why just two? Answers are still not clear, and the choice of mechanisms is now apparently larger than we had thought a few years ago. These mechanisms can be thought of roughly in two categories: “external” (environmental effects from outside the galaxy in question), or “internal” (processes strictly within the galaxy and largely immune to environment).
Figure 4. Specific frequencies $S_N$ (number of globular clusters per unit galaxy luminosity) for cD-type galaxies (brightest cluster members). Solid dots are from Blakeslee et al. (1997), and open circles are other cD’s from Harris et al. (1997b). More luminous cD’s are preferentially in richer clusters, and have higher specific frequencies. The line at $S_N = 3.5$ represents the average for normal (non-cD) ellipticals.

The most well known external mechanism is mergers, invoked as an important source of globular cluster formation by Schweizer (1987) and Ashman & Zepf (1992) and frequently mentioned since. We now have clear-cut evidence that massive star clusters can and do form out of the shocked gas during mergers (e.g. Whitmore & Schweizer 1995; Schweizer et al. 1996; Holtzman et al. 1992, 1996). Lee et al. (1997) and Geisler et al. (1996) favor the interpretation that the metal-richer cluster population in typical gE’s was formed in a merger-stimulated burst. This approach may explain E galaxies with low specific frequencies; but the gE’s and cD galaxies with very high specific frequencies still appear to need a qualitatively different approach. Unless the cluster formation efficiency is phenomenally high during the merger, the colliding pre-cD ‘galaxies’ must be so gas-rich to yield the requisite number of globular clusters that they must essentially be protogalactic clouds (Harris 1995). Other, more detailed, difficulties are discussed by Forbes et al. (1997a) and Geisler et al. (1996).

The cD/BCG galaxies make up a subclass of special interest. The new data of Blakeslee et al. (1997) add considerably to what we know of these centrally dominant systems (Figure 4). It is now clear that $S_N \sim N_{cl}/L_{gal}$ varies closely with the depth of the surrounding potential well (as measured by the velocity dispersion of the surrounding galaxies, or the X-ray gas temperature). The bigger cD’s sit in deeper potentials and have more clusters per unit light. West et al. (1995) propose that such galaxies sit amidst an extended halo of intragalactic clusters belonging to the potential well of the surrounding galaxy cluster. Grillmair et al. (1994) and Kissler-Patig et al. (this conference) present tentative evidence that such a population has been found around NGC 1399.
Furthermore, Côté et al. (1997) show that the shape of the GCS metallicity distribution in giant ellipticals can be matched if it is assumed that the metal-poor clusters were acquired from tidally stripped smaller neighbors (galaxy harassment) (though the high specific frequency and total cluster population present much larger problems in this scenario).

Of the “internal” mechanisms, Forbes et al. (1997a) favor the more traditional (in some sense) view that the globular clusters in normal E galaxies formed in situ in two or more major epochs of local gaseous collapse and star formation, regardless of outside influences. They suggest that the high-$S_N$ cD-type ellipticals may then have acquired large extra cluster populations by tidal stripping from other neighboring galaxies. The traces of these events are left in the GCS metallicity distribution and space distribution. Later on, dynamical erosion – tidal shocking, dynamical friction, stellar evaporation – will gradually remove clusters and reduce their masses; it is intriguing to note that these effects may act in such a way as to preserve the basic shape of the GCLF that is built in at birth (McLaughlin & Pudritz 1996; Vesperini 1997; Elmegreen & Efremov 1997). Finally, Harris et al. (1997b) have noted the potential importance of galactic winds, particularly for the massive ellipticals in which the first star formation burst is expected to be rapid. That is, if indeed the halo globular clusters form during the first Gyr, then they are likely to have been affected strongly by the first SNII-driven galactic wind, which must have been going on at very much the same time. If the wind is capable of driving out a large amount of the initial gas, then it is conceivable that the very high specific frequencies in the cD galaxies are the visible result: that is, many clusters formed in the first burst, but before the remaining gas could continue well into its subsequent normal star formation, it was expelled, eventually leaving behind a large galaxy with an artificially high ratio of clusters to field stars.

For each of the individual mechanisms mentioned above, we can point to a galaxy in which that particular process seems to be the dominant one in the evolution. But it appears that no single approach is the answer to every situation, and of the impressive list of processes capable of globally influencing the characteristics of GCSs, we are going to have to understand them all.

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