Globular Clusters: The View From HST

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Globular clusters represent only a small fraction of the total mass in their parent galaxy, but provide a vast array of tests for stellar physics, dynamics, and galaxy formation. This review discusses the prominent accomplishments of HST-based programs:
(a) The definition of precise fiducial sequences in the HR diagram, extending down to the hydrogen-burning limit
(b) Discovery of the upper white dwarf cooling sequence in several clusters
(c) Discovery of a highly consistent IMF on the lower main sequence
(d) Definitive age measurements for the oldest clusters in the outermost halo of the Milky Way, the Magellanic Clouds, and the dwarf elliptical satellites of the Milky Way
(e) Elucidation of the innermost structure of M15 and other core-collapsed clusters
(f) Discovery of surprisingly large "anomalous" populations of stars within dense cluster cores: extended blue horizontal-branch stars, blue stragglers, and others
(g) The first reliable color-magnitude studies for globular clusters in M31, M33, and other outlying Local Group members
(h) Discovery of massive young clusters in starburst galaxies with ages as small as 1 Myr
(i) Measurement of metallicity distribution functions among globular cluster systems in many giant E galaxies – bimodality is common, but details differ strongly
(j) Deep imaging of cluster luminosity distributions in gE galaxies in Virgo, Fornax, and other Abell clusters as distant as Coma.

The review concludes with brief speculations about future directions in which HST and (later) NGST might contribute to globular cluster studies.

As scientists, we are only as good as our ideas and our tools. There have been few times indeed in the history of astronomy when a single major tool has made the impact of HST. But while this magnificent observatory has helped us to lay out new paths that scarcely existed a decade ago, we have also used it to radically transform more traditional territory.

One of these areas – star clusters and stellar populations – spans the entire 20th century in the astrophysics literature. Few branches of astronomy have such a long history as the study of globular clusters, or have re-invented themselves so many times because of technological advances and innovations. HST is the latest and certainly among the most influential of these revolutions. A flood of observational results from it has generated yet another transformation in our understanding of these dense, populous, and endlessly fascinating stellar systems.

The key advantages conferred by HST – unequalled spatial resolution, photometric depth, access to the ultraviolet, and unique time-series observations – are the same as for any other field, though the first two in the list have been the major players here more than in other areas. For these reasons, almost all of the major contributions of HST to globular cluster studies have entered the literature only after 1995 – that is, starting with Cycle 4 and the installation of COSTAR and WFPC2. This brief overview starts from within the Milky Way and works outward to the current limits of distance to which we can probe globular cluster systems. No claim is made to completeness, but it isolates what I will suggest to be the main directions in which HST has influenced the discipline.

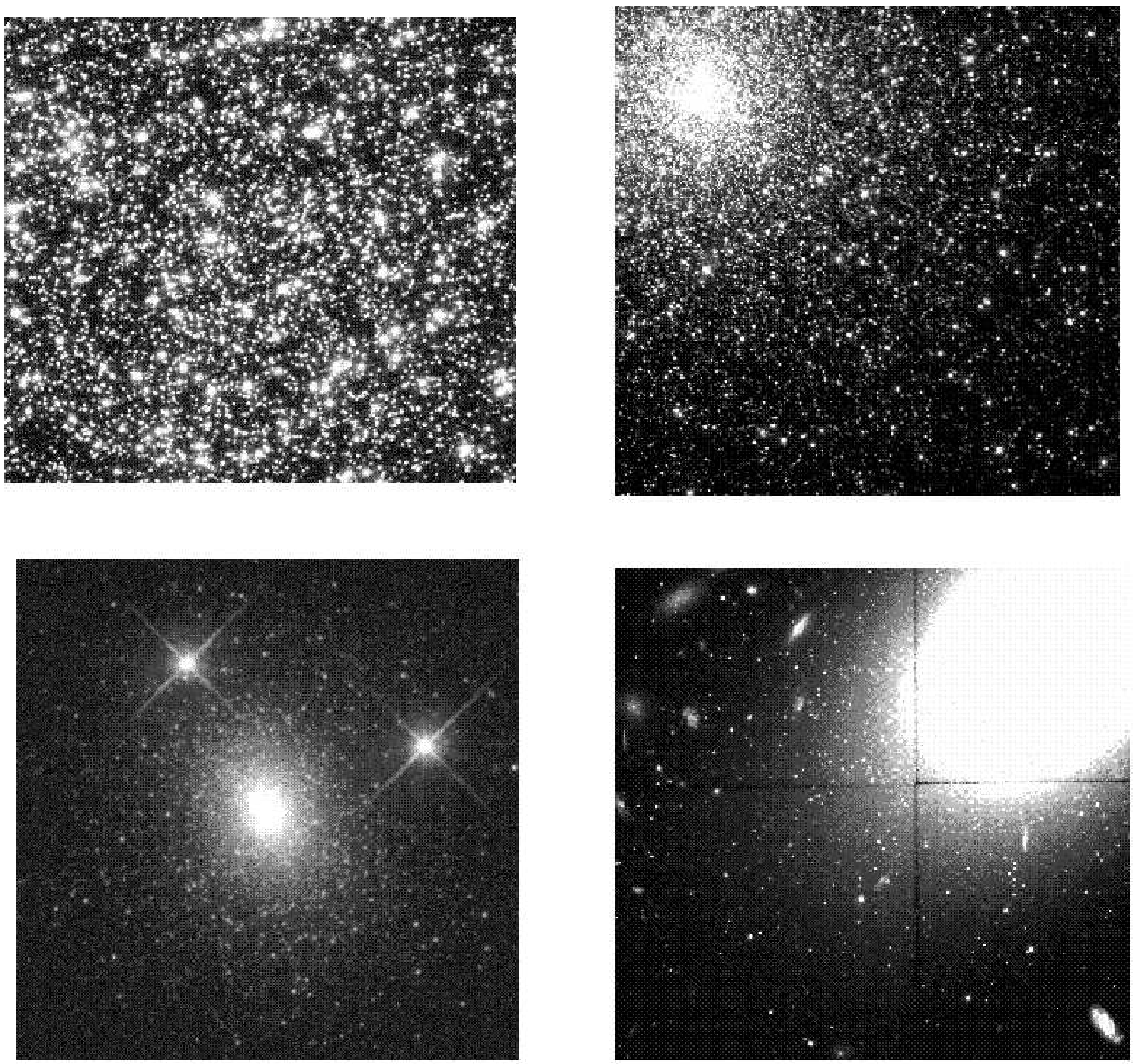

FIGURE 1. Globular clusters, as seen by HST from four distance perspectives: (a) Upper left: the center of 47 Tucanae ($d = 4.5$ kpc), showing the dense population of giants and main sequence stars (R. Saffer and D. Zurek, NASA/StScI Press Release PRC97-35). (b) Upper right: NGC 6093 ($d = 10$ kpc; Hubble Heritage image). (c) Lower left: Cluster G1= Mayall II, the most luminous globular cluster in the halo of M31 at $d = 0.75$ Mpc (M. Rich, K. Mighell, J. Neill, and W. Freedman, NASA/StScI Press Release PRC96-11). (d) Lower right: the Coma giant elliptical IC 4051 ($d = 100$ Mpc), around which the globular clusters show up as a sprinkling of faint starlike images (Baum et al. 1997; Woodworth & Harris 2000).

1. Stellar Populations in Globular Clusters

1.1. *The Limits of the Color-Magnitude Diagram*

The color-magnitude diagram (CMD) for globular clusters forms the classic testbed for studying the evolution and mass distribution of low-mass stars. Before the launch of HST, a whole series of unanswered and quite fundamental questions about such stars were on hand: What does the main sequence look like down to the hydrogen-burning limit? What is the IMF (initial mass function) for stars down to the same limit, and does it depend strongly on metallicity or other factors? Would the position of the white dwarf sequence confirm the expectations of standard stellar structure theory? What trends are exhibited by "anomalous" types of stars such as blue stragglers and extended horizontal-branch stars? Are there distinctive features in the CMD distribution that were previously unknown?

HST programs have provided stimulating responses to all these questions. The present "state of the art" in our definition of the full CMD array for globular clusters can be seen in Figure 2, which is a composite of data from five different clusters of low metallicity ([Fe/H] $\simeq -2$) and is deliberately constructed to show the entire range of globular cluster stars as we now understand them. The precise definition of the principal sequences, as well as the total span in luminosity – covering more than 18 magnitudes from the brightest giants to the faintest dwarfs – far exceeds anything from the pre-HST era.†

The genuine level of progress achieved by the HST-based photometry can be appreciated further by contrasting Fig. 2 with the very earliest CMDs of globular clusters, first measured 90 years ago by Shapley and his collaborators. (For an excellent and representative example, see the diagram for M3 by Shapley & Davis 1920; it was presented in the form of a 'spreadsheet', with numbers of stars labelled in bins of magnitude and 'color class'; the upper red giant branch and most of the horizontal branch can clearly be seen). Another of the two or three truly major turning points in the history of this subject took place just half a century ago, when the long-sought *main sequence turnoff* point (MSTO) was reached for the first time (Arp, Baum, & Sandage 1953; the cluster concerned was the prototypical extreme low-metallicity object M92). This event also represented an extremely rare instance in which both observers and theorists converged on the same target at the same time: it was no accident that stellar models were being constructed specifically to try to understand the puzzles posed by Population II stars and their old, metal-poor red giant branch. The first models which could claim basic success in matching the globular cluster turnoff region and the transition to the convective red giant structure – in other words, the first "isochrone fits" in the sense we use them today – suggested that the age of M92, and thus the halo of the Galaxy, was $3-4$ Gyr (Sandage & Schwarzschild 1952). The biggest error in these fits was a too-bright $M_{bol} \simeq -0.5$ adopted luminosity scale for the RR Lyraes, which set the zeropoint for the main sequence – again, an issue which persists today albeit at a lower level (see, for example, Carretta et al. 2000 for a comprehensive recent discussion of the globular cluster distance scale issues).

Ever since that critical point in history, the mutual stimulation between stellar structure theory and globular cluster photometry has constantly been active, and has taken a new leap in the HST era. The delineation of the faintest sections of the zero-age main sequence (ZAMS) all the way to its lower limit has unquestionably encouraged the development of low-mass stellar models over a range of metallicities (e.g., Cassisi et al. 2000)

† It should be emphasized that Fig. 2, as a composite from several sources, does *not* correctly represent any single cluster, nor does it show the true relative numbers of stars in very different sections of the CMD. For example, the true numbers of HB and red giants relative to the unevolved main sequence stars are far smaller in any real cluster than indicated here. The diagram is intended only to display the locations of the fiducial sequences. Some "anomalous" regions such as the blue stragglers and extreme blue extension of the horizontal branch have been somewhat deliberately overemphasized. Finally, in combining data from the clusters listed, I have taken arbitrary liberties in removing a few stars lying far off any of the sequences which almost certainly represent residual field contamination.

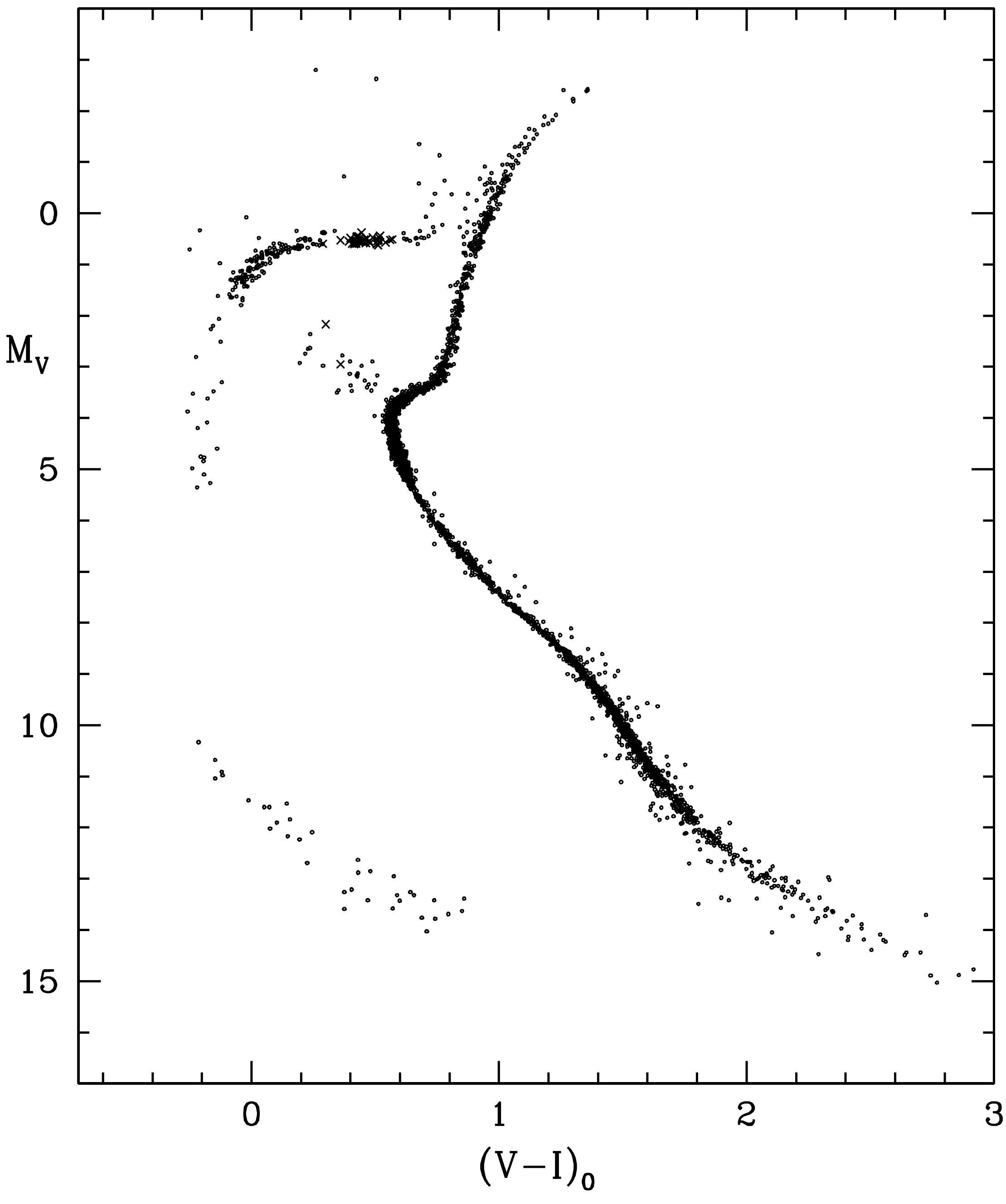

FIGURE 2. Composite color-magnitude diagram for a fiducial "metal-poor" ([Fe/H] $\simeq -2$) globular cluster. Here data are combined from NGC 6397 (King et al. 1997), M55 (Piotto 2000), M68 (Walker 1994), NGC 2419 (Harris et al. 1997), and M3 (Ferraro et al. 1997b). Each point represents a real star taken from one of the above datasets, but they have been deliberately and rather arbitrarily selected to delineate the various evolutionary stages in the CM diagram as clearly as possible. *Small crosses* denote variable stars (RR Lyraes and two SX Phe variables).

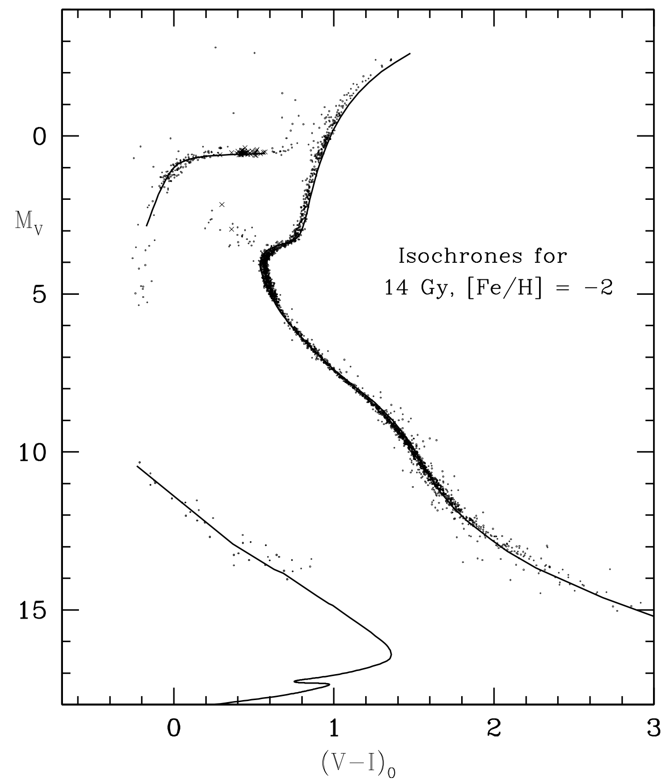

FIGURE 3. Composite isochrone fits to the fiducial CMD of Figure 2. The adopted age (14 Gyr) and metallicity ([Fe/H] = −2) is the same for all parts of the sequences. The ZAMS model line fainter than $M_V \simeq 8$ is from Cassisi et al. (2000), while the upper main sequence region, turnoff, and red giant branch models are from Harris et al. (1997) and the horizontal branch from VandenBerg et al. (2000). The white dwarf evolutionary track is from isochrones provided by Fontaine (2000, private communication).

which follow the observed ZAMS shape in remarkable detail. Similarly, new predictions now exist for the shape of the white dwarf cooling curve as it extends below even the faintest observational limits that we now have (Figure 3).

1.2. *The Quest for the White Dwarf Sequence*

One of the original goals in the scientific case for the launch of HST was to discover the very deepest and faintest parts of the CMD that had never been seen from the ground – the extension of the ZAMS all the way to the hydrogen burning limit, and the cooling sequence of the white dwarfs. But even with HST and WFPC2, these dim stars – some of them barely able to generate a slow trickle of hydrogen fusion, while the others are leaking away their tiny remaining reservoirs of internal heat – can clearly be seen only through long exposures of just the nearest globular clusters (those within a few kiloparsecs of the Sun).

For the white dwarf sequence especially, the challenge was not simply one of limiting magnitude. The WDs are not present in the same numbers as the ubiquitous main-sequence stars, and obtaining many of them within the limited WFPC2 field of view requires selecting target fields uncomfortably close to the cluster center, with the atten-

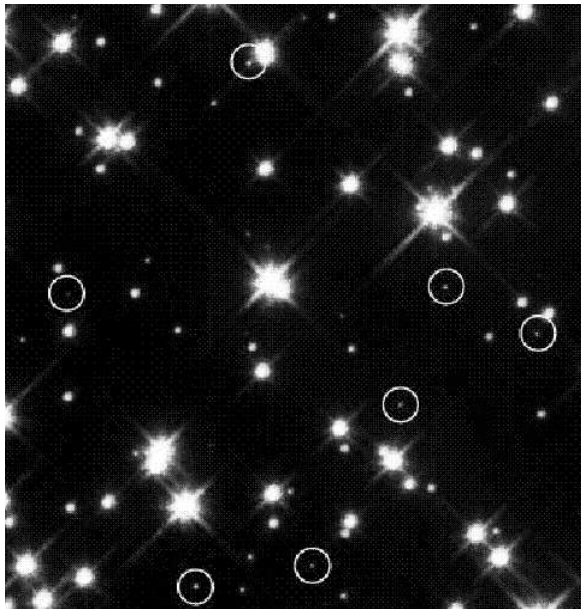

FIGURE 4. A portion of the field within M4 (Richer et al. 1995; from H. Richer and H. Bond, NASA/STScI Press Release PR95-32) in which the white dwarf sequence was first identified. Some of the more than 100 WD's found in this cluster are shown as the faint blue stars in the circles; most of the other objects are main-sequence stars.

dant problems of crowding and scattered light from the other types of cluster stars, all of which are much brighter (Figure 4).

Despite these hurdles, clear successes have been achieved. Unambiguous *sequences* of stars delineating the white dwarf cooling curve were published almost simultaneously for three such clusters: M4 (Richer et al. 1995), NGC 6397 (Cool et al. 1996), and NGC 6752 (Renzini et al. 1996), all as a result of Cycle 4 programs. Several other clusters were soon added to the list (ω Cen, 47 Tuc, M15, and others). It was a significant triumph for both stellar structure modelling and the observational calibration of the ZAMS and ZAHB distance scales that these sequences appeared at the luminosity and color levels at which they were expected for white dwarf masses of $0.5 - 0.6 M_{\odot}$ (Figure 5).

For the lowest-temperature white dwarfs, the stellar atmospheres become cool enough that H_2 opacity dominates, and the flux is redistributed in such a way that the $(V - I)$ color indices become progressively bluer again as the stars become still fainter (Hansen 1999). For the old globular clusters, this *white dwarf turnback point* (WDTB) should appear about three magnitudes fainter than the limits of currently published HST-based CMD's (see Figure 4) and thus presents a formidable challenge for future photometry. Nevertheless, globular clusters are old enough that the first white dwarfs produced in them – 12 Gyr ago or more – should have passed the WDTB point and now lie on the lower branch of the cooling sequence. This final frontier of the CMD will provide an intriguing test of the basic theory for white dwarfs that have evolved nearly to extinction.

1.3. *The Faint Main Sequence and the IMF*

Stars that are just as faint as the white dwarfs, and equally interesting for a different set of reasons, are those at the bottom end of the main sequence. In the pre-HST era, investigations of main sequence luminosity functions (LF) suggested that cluster-to-cluster differences in the LF might exist, possibly correlated with cluster metallicity

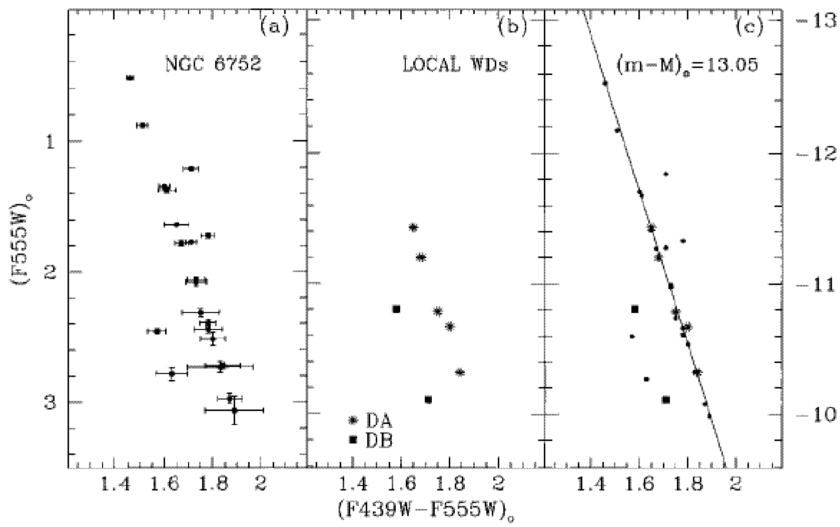

FIGURE 5. The white dwarf sequence in NGC 6752 (from Renzini et al. 1996), superimposed on theoretical cooling curves for 0.5 and $0.6M_\odot$.

or Galactocentric location (e.g., Capaccioli et al. 1991, 1993; Djorgovski et al. 1993). However, these studies were always limited by the inability of ground-based photometry to reach further down the main sequence than $\sim 0.3M_\odot$, or to survey all parts of the clusters including their populous core regions. The conversion of the LF to the more fundamental initial mass function (IMF), through an assumed mass-luminosity relation and modelling of the dynamical history of the cluster, also left important uncertainties in the discussion.

This situation changed dramatically with the advent of HST. A variety of photometric studies reaching absolute limits $M_I = 10$ or more on the main sequence (e.g., von Hippel et al. 1996; Ferraro et al. 1997a; DeMarchi & Paresce 1997, among many others) strongly suggested that the LF in several clusters exhibited a consistent, sharp turndown near $M_I \simeq 9$. Converting the LF into the *mass* function and properly accounting for metallicity meant that this turndown corresponded to a nearly uniform mass of $0.25M_\odot$ in all clusters. Below this point, the IMF was nearly flat in number of stars per unit mass interval. Still deeper data now available for a total of a dozen globular clusters (Paresce & De Marchi 2000) confirm the uniformity of this turnover, and appear to put to rest much of the earlier debate over strong cluster-to-cluster differences. Correlations with extreme differences in Galactocentric distance, however, remain to be explored fully.

The deepest surveys of all – just as for the white dwarf sequence – have been performed on the very nearby NGC 6397 (e.g. King et al. 1998; De Marchi et al. 2000). Using deep WFPC2 images of cluster fields separated by a mere three-year baseline, King et al. (1998) have employed proper motion measurements to separate out cluster members from foreground and background field stars, tremendously reducing the field contamination (Figure 6). With this remarkably clean CMD in hand, we can trace the faint end of the main sequence usefully to a point not far above the hydrogen-burning limit: in the resulting mass function, the IMF stays nearly flat for $0.25M_\odot \gtrsim M \gtrsim 0.10M_\odot$ until at last we see a strong hint of a turndown before the ultimate limits of the data at $\sim 0.09M_\odot$.

For $M \lesssim 0.1M_\odot$, the luminosity and temperature of the star decline so steeply with decreasing mass (compare again Fig. 4) that deeper measurements of the IMF in *any*

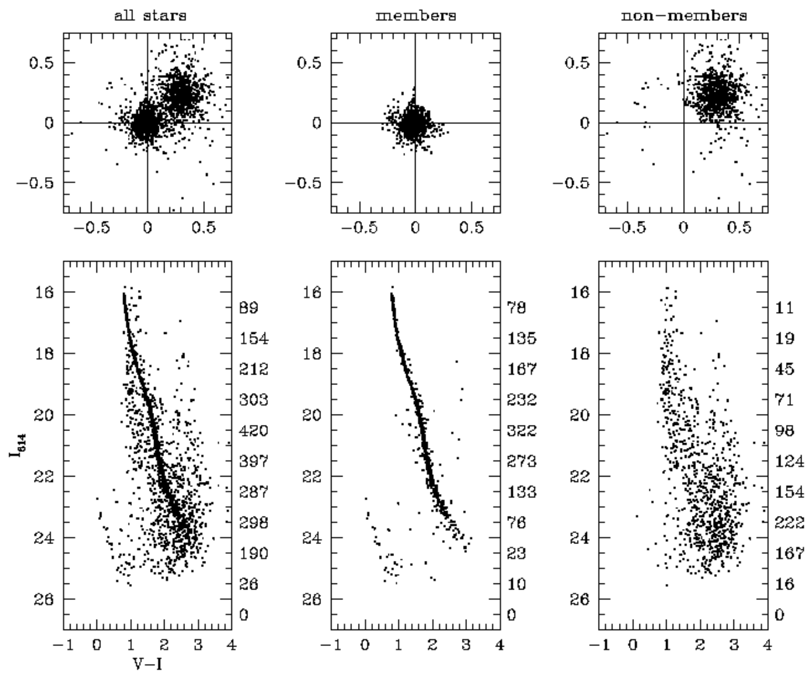

FIGURE 6. WFPC2 photometry of the lower main sequence for NGC 6397, from King et al. (1998). The top panels show the proper motion measurements for all stars in the field (at left), then their division into cluster members (center) and field stars (right). The corresponding color-magnitude arrays in $(I, V-I)$ are shown below each panel, with numbers of stars in each magnitude bin shown on the right border. The use of proper motion provides an extremely effective filter against field contamination.

cluster will be extremely difficult to achieve. Nevertheless, the studies already in hand represent a major accomplishment. They strongly suggest that the IMF for a "generic" globular cluster can be rather simply represented by an approximate Salpeter MF for $M \gtrsim 0.3 M_{\odot}$ and a flat MF over $0.3 - 0.1 M_{\odot}$. Large amounts of mass in a near-invisible substellar (brown-dwarf) component seem unlikely.

2. The Age Profile of the Galactic Halo

A long-standing astrophysical issue has been to determine the ages of the globular clusters and to relate them to the star-forming history of our Galaxy. Since they are found at all galactocentric distances from the Galaxy's inner bulge out to remote satellites at 100 kpc or more, the globular clusters provide the best chance we have to determine the *age distribution function* τ for the Galactic halo.

In principle, τ could vary with Galactocentric location R_{gc}, metallicity [Fe/H], or other factors; in the absence of data, there would be no shortage of theoretical possibilities for the distribution of τ (Figure 7). Perhaps, as in the early picture of Eggen, Lynden-Bell, & Sandage (1962; ELS) the Galactic halo built rather rapidly from the inside out in a single major star-forming epoch (Fig. 7a). In the simplest versions of this model, we would expect to see a narrow range of cluster ages and a tight correlation with R_{gc}. Or, as in the opposite extreme of Searle & Zinn (1978; Fig. 7b), perhaps the entire halo was built piecemeal in a longer and more disconnected series of events involving star formation in dwarf-galaxy-sized protogalactic clouds, which then amalgamated to form

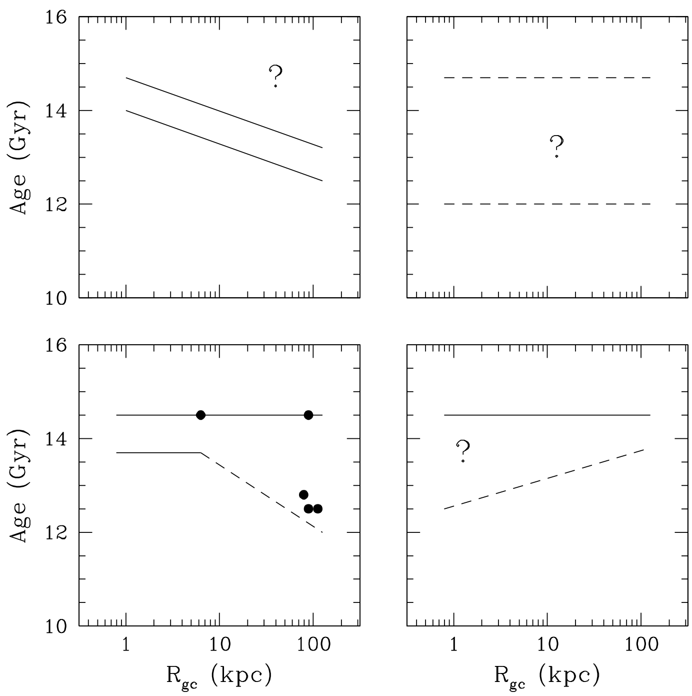

FIGURE 7. Various theoretical scenarios for the age distribution of globular clusters as a function of Galactocentric distance. (The age scale arbitrarily assumes the oldest clusters began at $\tau \simeq 14.5$ Gyr.) See text for explanation. The datapoints in the lower left panel give schematic recent results for some of the outer-halo clusters.

the larger Galaxy; in that case, there might be a much larger range of cluster ages and little correlation with R_{gc}. Tangible evidence that the halo has grown by accretion in this way can be found in the Sagittarius dwarf now being tidally damaged (e.g., Ibata et al. 1995, 1997) and in the moving groups of halo stars that have been isolated in recent surveys (Majewski et al. 1996; Majewski 1999).

Hybrid combinations are, of course, possible: one version mentioned frequently in the recent literature, beginning with Searle & Zinn, postulates that the inner ($R_{gc} \lesssim R_{\odot} \simeq 8$ kpc) halo could have formed rapidly as in ELS but that the outer halo accreted or underwent star formation over progressively longer times (Fig. 7c). Alternately, we could even imagine – based on the many examples of merger events between disk galaxies that are going on today and could have been more frequent in the past – that gas accretion into the Galactic bulge, with attendant star and cluster formation, could have gone on for many Gyr and that the cluster age range in the *inner* halo could be largest (Fig. 7d).

The expectations of these various schematic models are different enough that it should be possible for the actual data to rule out at least some of them. In principle, the observational task is straightforward: (a) obtain a CMD for each cluster which defines the main sequence, turnoff region, giant branch, and horizontal branch precisely. (b) Measure the cluster metallicity [Fe/H] and (if possible) the relative abundances of C,N,O, and other key elements. (c) Decide on the cluster foreground reddening and (somehow) its distance, perhaps through a calibration of the horizontal branch or RR Lyrae luminosity, or through subdwarf parallaxes normalized to the metallicity of the cluster. Then, (d) fit appropriately constructed model isochrones transformed to the observational plane, and find the best-fit age.

Every step in this prescription has generated controversy and a lengthy history in the literature. Furthermore, even the first step (which is where HST observations come in) is fraught with problems of its own. In the distance regime $R_{gc} \lesssim 5$ kpc, most of the target clusters are strongly affected by differential reddening from dust clouds along the line of sight in the Galactic disk, and contamination from Galactic bulge stars. Furthermore, a large fraction of the field stars are at nearly the same metallicity, and nearly the same distance, as the cluster stars. At the opposite extreme ($\sim 40 - 120$ kpc, out to the remote limits of the halo), field contamination or differential reddening are unimportant, but image crowding and sheer distance are important. The most secure zone is still the intermediate halo ($\sim 5-40$ kpc) in which ground-based photometry from large telescopes can provide good results.

The *outermost halo* has only a handful of clusters but can provide critical leverage on the model interpretations. To date, deep main sequence photometry has been obtained for four of these, all at $R_{gc} \sim 100$ kpc (NGC 2419, Pal3, 4, and Eridanus), with two remaining ones (Pal 14, AM1) under study. The prominent results so far are that the biggest and most metal-poor of these (NGC 2419; Harris et al. 1997) has the same age to within ± 0.5 Gyr as the comparison "template" low-metallicity cluster M92; while the three sparse clusters (Pal 3, 4, Eri; Stetson et al. 1999) collectively are about $1.5-2$ Gyr younger than the template clusters M3 or M5 of similar metallicity. (In turn, M3 and M5 might be slightly younger than the more metal-poor M92.)

The eventual goal of this process is of course to establish absolute cluster ages, but the age scale depends on detailed concerns in the stellar models that continue to be debated in the literature (e.g., Carretta et al. 2000; Chaboyer et al. 1996, 1998; VandenBerg 1999; VandenBerg et al. 1996, among many others), with best estimates for the *oldest*, most metal-poor clusters ranging from 12 to 14 Gyr. Instead, to make progress on understanding the shape of the age distribution $\tau(R_{gc}, [\mathrm{Fe/H}])$, attention has turned over the past decade to measuring *relative* ages by matching CMD's of one cluster to another (VandenBerg et al. 1990; Sarajedini & Demarque 1990). Two principal age indicators are used: the magnitude difference $\Delta V(MSTO-HB)$ between the horizontal branch and main sequence turnoff; and the color difference ΔC between the turnoff and the base of the giant branch. Two ways to display these parameters are shown in Figure 8.

The clear indication from these studies, and others now in the literature which cover the intermediate and outer halo, is that the lowest-metallicity clusters ($[\mathrm{Fe/H}] \lesssim -2$) have identical ages (to within the current limits of precision of about 0.5 Gyr) *everywhere in the halo.* Thus, star formation began throughout the Galactic protohalo (or equivalently, throughout all the fragmentary clouds that would eventually amalgamate) at almost the same time. Comparing the metal-rich and metal-poor cluster ages is trickier, since here we must rely on the absolute accuracy of the stellar models rather than differential comparison, but the rather clear signal that has emerged from all the data over the past decade is that the main system of halo clusters took about 2 Gyr to form. In addition, a *few* small clusters (IC 4499, Pal 12, Rup 106, Ter 7, Arp 2) have been found with ages as much as 5 Gyr below than the average of the main system (Stetson et al. 1989; Buonanno et al. 1994; Ferraro et al. 1995; Rosenberg et al. 1998).

It remains to ask what has developed for the Galactic bulge clusters. The most commonly used metal-rich template, 47 Tucanae, has an age $\sim 12-14$ Gyr (depending on the details of the adopted composition and stellar models) which is not obviously different from the outer clusters (e.g., Hesser et al. 1987; Santiago et al. 1996). But many of the

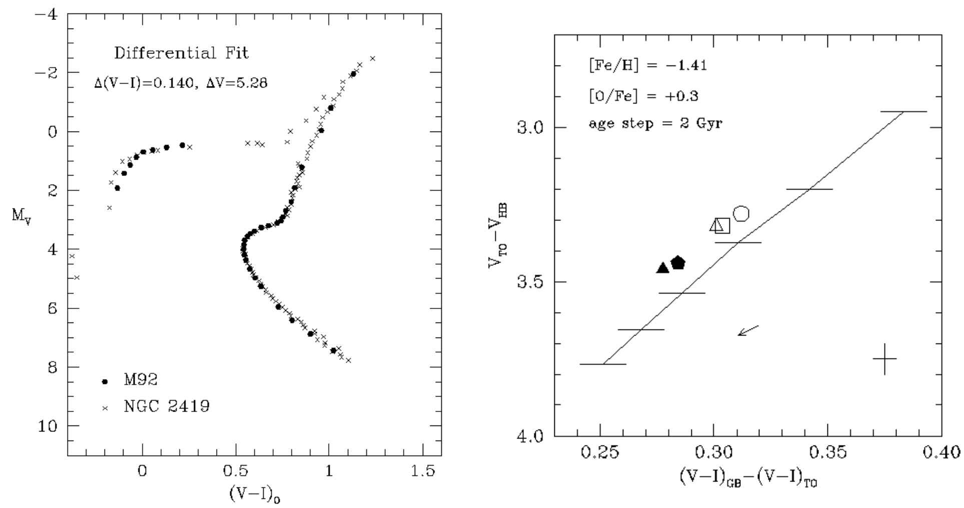

FIGURE 8. *Left panel:* CMD match between the low-metallicity clusters M92 and NGC 2419 (Harris et al. 1997), displayed as mean points in $V, (V-I)$. Both clusters appear to be the same age to within 0.5 Gyr, under the assumption that their chemical compositions are similar. *Right panel:* Parametric match $(\Delta V, \Delta C)$ from Stetson et al. (1999) between M3 and M5 (solid symbols) and Pal 3, 4, Eridanus (open symbols). For smaller ages, the magnitude difference ΔV decreases while the color difference ΔC increases; the theoretical model line is marked in 2-Gyr increments.

clusters much further in to the Galactic center have significantly different metallicities, structures, orbital characteristics, etc. and it is not at all clear that they would necessarily have the same ages too. An analysis of NGC 6352 (a Herculean effort by Fullton et al. 1995 with the original WF/PC camera) yielded a close match to 47 Tuc to within perhaps 1 Gyr. A WPFC2 analysis of NGC 6528 and 6553, both inner bulge clusters, showed that these too were classically "old" and "... strongly support the notion of fast formation and chemical enrichment of the bulge" (Ortolani et al. 1995). More recently, it has been suggested that some other bulge objects (such as Terzan 1; see Ortolani et al. 1999) might indeed be younger by something near 2 Gyr. All of these studies have been severely hampered by the obstacles of differential reddening and field contamination mentioned above, and it is likely that no age comparisons more precise than ± 2 Gyr *at best* have yet been possible there. An alternate approach would be to do the photometry in the near infrared, which would greatly alleviate the crushing handicap of differential reddening and thus enable the definition of precise main sequences. However, a compensating loss is that the isochrones in JHK are not as sensitive to age differences as they are in optical color indices.

These clusters, embedded deep in the starfields of the Galactic bulge and lurking behind the dust clouds scattered through the disk, have stubbornly resisted four decades' worth of attempts to determine precise ages. But without them, the full story for the early star formation history of the Galaxy remains untold in its entirety.

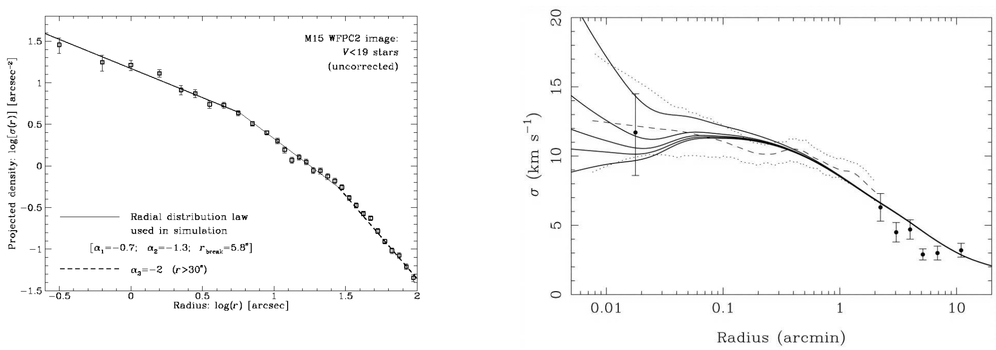

FIGURE 9. *Left panel:* Projected radial density profile for M15, from Guhathakurta et al. (1996). The power-law rise of the core density continues inward to the smallest observed radius, equivalent to $r = 33,000$ AU. *Right panel:* Velocity dispersion profile for M15 from high resolution ground-based measurements, from Gebhardt et al. (2000). The five model curves show the expected trend for isotropic models containing a central black hole of (from lowest curve upward) 0, 500, 1000, 2000, and 6000 $M_{\odot}$.

3. Core Structures and Stellar Populations

Another of the original high expectations for HST was to resolve the stellar populations of globular clusters in their innermost cores, which had been seen in only the sketchiest terms through ground-based imaging. Keen interest accompanied the discovery in the late 1980's of clusters in a wide range of dynamically evolved states, including many that had experienced core collapse and strong mass segregation, and the cameras aboard HST afforded the first clear and comprehensive view of these objects (see again Fig. 1a).

The single cluster which has been subjected to the most intensive scrutiny is unquestionably M15, which is relatively nearby, populous, old, metal-poor, and core-collapsed. A series of HST-based photometric studies following on from pioneering ground-based programs have shown that the power-law rise in surface density that is characteristic of post-core-collapsed (PCC) clusters continues inward in M15 to the smallest radii yet observable (e.g., Yanny et al. 1994; Guhathakurta et al. 1996; and references cited). At the distance of M15, this innermost radial zone at $r \sim 0\farcs3$ is equivalent to about 33,000 AU, or the size of the Oort cloud (Figure 9).

A long-standing question has been whether or not such clusters might contain some central massive object (such as a single black hole, or a cluster of neutron stars). Further information can be obtained through the stellar radial velocities, and any radial trends of the velocity dispersion profile or mean rotation speed. Results obtained with adaptive optics at the CFHT (Gebhardt et al. 2000) show that an isotropic velocity dispersion model with $(M/L)_V = 1.7$ matches the core velocities acceptably, but the effect of a central condensed mass such as a black hole (if any) would only show up definitively at radii $r \lesssim 2''$. Interestingly, the stars in the inner $3\farcs4$ (1.7 pc) show a net rotation $v(\mathrm{rot}) = 10$ km s^{-1}, and all the data combined are consistent with "... a central mass concentration equal to 2500 $M_{\odot}$". A STIS program by van der Marel et al. (2000) now in progress will add more data interior to this radius and should be able to detect any central pointlike mass larger than $\sim 1000 M_{\odot}$.

Although the new data on core *structures* were eagerly, and correctly, anticipated, unexpected results lay in store for the *stellar populations.* One of the first results from a BV

imaging survey of cluster centers showed, to everyone's surprise, that there were metal-rich clusters with strong *blue* horizontal-branch components (NGC 6388, 6441; Rich et al. 1997; also see Buonanno et al. 1997). These high-T_e HB stars are presumably ones in which almost all the surface hydrogen envelope has been removed, leaving only a low-mass surface envelope above the helium-burning core. Such stars are almost completely absent in the outskirts of the same clusters, but are found in large numbers within the dense core-collapsed centers. In other metal-rich clusters with less dense cores (47 Tuc, NGC 5927) they are not to be found. What has happened to drive extra mass loss or envelope stripping from the giants in these unusually dense environments?

The compact cores of many clusters have also turned out to be preferred habitats for other types of unusual stars mixed in with their more normal neighbors. Binary stars should be much more common in the cluster cores, since they are expected to form through dynamical evolution and core contraction (e.g., Hut et al. 1992), and it came as no surprise that HST imaging programs have shown that core binary populations do indeed follow the predicted trends (see, e.g., the results of Edmonds et al. 1996 for 47 Tuc). However, the extreme blue HB (EBHB) stars mentioned above have now been found routinely in many low-metallicity clusters as well (e.g., Sosin et al. 1997; Ferraro et al. 1998; Piotto et al. 1999), with the additional effect of clear 'gaps' at certain places along the BHB sequence (all of them far hotter than the RR Lyrae region). The positions of these features may be quite similar from cluster to cluster (Figure 10). Such gaps were suspected in pre-HST work, but the much larger HB populations accessible from the cluster cores have reinforced their identification. Contemporary BHB stellar models indicate that one of these gaps falls consistently at a mass of $0.535 M_{\odot}$ regardless of metallicity. We still await convincing evolutionary interpretations of this puzzle.

Blue stragglers – which lie nearly along the main sequence above the cluster turnoff point, and can be the result of either stellar collisions or amalgamation of close binaries – were already well known types of cluster stars from ground-based photometry, but have turned up in sometimes-astonishing numbers in the cores (e.g. Guhathakurta et al. 1998; Ferraro et al. 1999). In the extreme case of M80, the number of blue stragglers is similar to the number of HB stars in the core; the sheer size of the population, its lengthy extension up the main sequence, and the high concentration of the M80 core suggest that stellar collisions may be the dominant channel of formation there. When we go on to add the presence of other core phenomena such as millisecond pulsars, novae, dwarf novae, and other peculiar stars (Shara et al. 1996a,b; Edmonds et al. 1997; Gilliland et al. 1998; Lyne 1995; Lyne et al. 1996; Robinson et al. 1995; Phinney 1993; Hut et al. 1992; and references cited), it is clear that we still have much to learn about how stars in crowded and dynamically evolved environments can strongly affect each other in individual detail.

Lastly, the cores of selected nearby clusters can be employed as the basis for surveys and time-series studies of new kinds. In a recent Major Program, Gilliland et al. (2000) are analyzing 636 sequenced exposures of 47 Tuc containing more than 30,000 stars. The primary aim is to search for the eclipse signatures of Jovian planets around the lower main sequence stars, but their database will almost certainly yield a rich harvest of many kinds of variables and eclipsing binaries.

4. Globular Clusters in Local Group Dwarf Galaxies

Old star clusters are to be found in virtually all large galaxies. But exactly how old? Are the ones in other galaxies to be considered near-twins of the classic Milky Way halo clusters, or merely close cousins? The implications for galaxy formation studies are obvious: did the the small galaxies that are still isolated dwarfs *today* (as opposed to

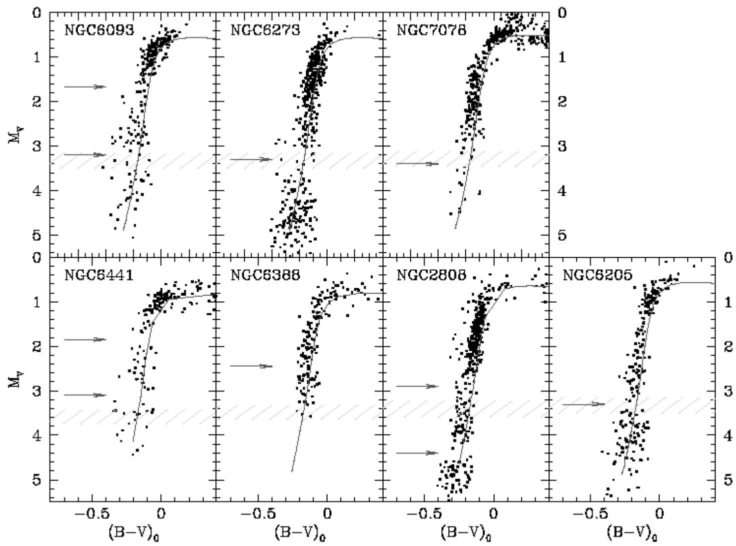

FIGURE 10. Color-magnitude diagrams for the extended blue horizontal branches of seven clusters, from Piotto et al. (1999). Metal-poor clusters are in the top row, while more metal-rich ones are in the bottom row. Arrows mark distinctive gaps in the EBHB sequence. In all seven, a gap appears at a temperature corresponding to $0.535 M_{\odot}$.

ones that might have been absorbed at early times by larger protogalaxies) begin their own star formation at the same epoch as did the larger galaxies?

Once again, HST imaging programs have completely transformed this subject, bringing the stellar content of all Local Group galaxies clearly within reach. There are four satellite galaxies (Sagittarius, Fornax, and the Magellanic Clouds) which have old globular clusters *and* which are within $\lesssim 200$ kpc, close enough that rigorous differential age comparisons can be made with the Milky Way clusters from main-sequence fitting. In both Sagittarius and Fornax, a handful of clusters have each been identified as belonging to the small host galaxy. All are "old" in a generic sense, but only some recent painstaking photometry has been able to circumvent the combined problems of distance, heavy field crowding, and contamination, to produce precise age measurements.

In Fornax, the CMDs (Buonanno et al. 1998, 1999) establish that all but one of its clusters are identical in age with the low-metallicity template M92 to within a Gyr or so. The remaining one (cluster 4) may be up to 3 Gyr younger. The total history of star formation within Fornax is a much more extended one, with identifiable field stars as young as < 0.5 Gyr and the majority of stars belonging to a few-Gyr population (e.g., Buonanno et al. 1999; Saviane et al. 2000). The very old halo which the clusters represent is thus only a small fraction of this tiny galaxy as a whole. A somewhat similar history seems to have happened within Sagittarius (Ibata et al. 1995, 1997). Three clusters (M54, Arp 2, Ter 8) are classically metal-poor and old at $\gtrsim 13$ Gyr, while the fourth (Ter 7, also the most metal-rich) is about 8 Gyr old; meanwhile, the stellar component of Sagittarius is mostly near ~ 10 Gyr but with traces extending down to less than 1 Gyr (see Layden & Sarajedini 2000 for a complete discussion with references). In both Fornax and Sagittarius, it is intriguing that *very* few field-halo stars seem to have remained from the first early burst that created the old clusters, with most of the field-star formation belonging to bursts a few Gyr later – yet it was only the first burst which formed massive clusters.

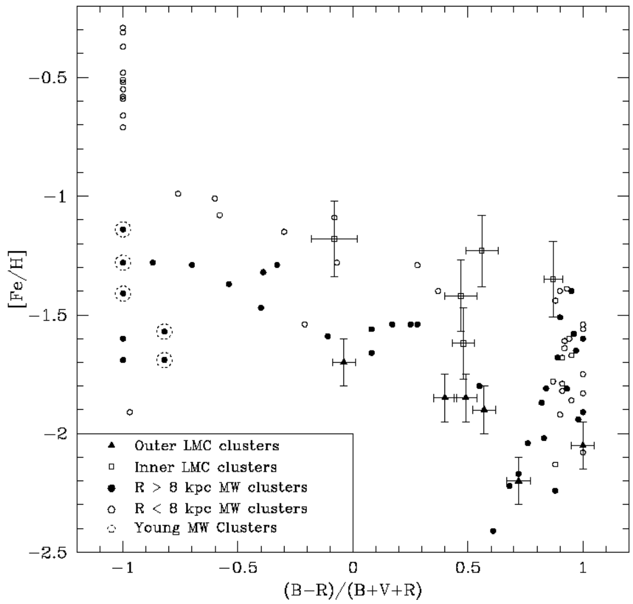

FIGURE 11. Globular cluster metallicity [Fe/H] plotted against horizontal-branch type, from Johnson et al. (1999). Clusters with red HB's are on the left side, blue HB's on the right. Old LMC clusters are the symbols with error bars; the others are Milky Way clusters in the inner halo (solid dots) or outer halo (open dots).

The Large and Small Magellanic Clouds hold a rich variety of star clusters over all ages and sizes, and we can do nothing more here than touch on results for the few oldest ones. Differential CMD fitting of the oldest LMC clusters with the usual Milky Way templates such as M92 and M3 has revealed several with clearly similar CMDs and ages in the standard $12-14$ Gyr range (see particularly Johnson et al. 1999 and Olsen et al. 1998; also Brocato et al. 1996; Mighell et al. 1996; and Bica et al. 1998). The SMC by contrast may have no clusters quite this old; its most prominent candidate, NGC 121, is a rich cluster with RR Lyraes but is probably 2 Gyr younger than Milky Way halo clusters (Shara et al. 1998). Both the SMC and LMC have several massive clusters in the age range of 5 to 10 Gyr, a regime not well represented at all in the Milky Way and thus quite useful for comparisons of moderately metal-poor isochrone models (e.g., Mighell et al. 1998; Sarajedini 1998).

A useful parametric comparison (Johnson et al. 1999; Olsen et al. 1998) in addition to the CMD fitting is the standard graph of horizontal-branch morphology vs. metallicity (Figure 11). Here again, close similarities hold between the LMC and Milky Way halo, and are consistent with an interpretation which has the LMC beginning its first star-forming period within a Gyr of the Milky Way and its other dwarf satellites (cf. the papers cited above for more extensive discussion).

The analyses summarized above point to an evolutionary picture in which most or all of the systems in and around the Milky Way *began cluster formation almost simultaneously* about 13 to 14 Gyr ago. The Milky Way and its satellites now occupy a region of space ~ 300 kpc across, though its comoving volume would have been much smaller at those early times. Were those first star-forming events forcibly "synchronized" by local events perhaps involving gas cloud collisions and shocks? Or is it much more natural to assume that cluster formation within dwarf-sized gas clouds would simply have begun everywhere in the universe not long after the epoch of recombination, so that they would automatically be in step with one another to within a typical ~ 1 Gyr scatter? If the latter view is true, then the maximum age of our local globular clusters should indeed place a very stringent limit on the true age of the universe.

5. M31 and Beyond

More than half the classically old globular clusters in the Local Group reside in the $\sim 750-$kpc distant M31, a significantly bigger galaxy than the Milky Way. From ground-based indicators – luminosities, integrated colors and spectra, and even attempts at color-magnitude diagrams – the M31 halo clusters by and large resemble our own. The definitive tests of their stellar content and evolutionary history, however, lie in obtaining deep CMDs. Even with HST, it has not been possible (yet!) to reach the unevolved main sequences of these clusters, but photometry available so far (Rich et al. 1996; Fusi Pecci et al. 1996; Holland et al. 1997) with limiting magnitudes $M_V \sim +2$ shows that their giant-branch and horizontal-branch morphologies exhibit the "standard" (Milky Way) correlation with metallicity and thus, presumably, age. Deeper and more precise photometry will be possible in the coming Cycles.

The third largest Local Group galaxy, M33, has perhaps two dozen halo clusters which have been classified as conventionally "old" on the basis of integrated colors and spectra. However, a first CMD reconnaisance of some of these with HST (Sarajedini et al. 1998) reveals an intriguing range of RGB and HB morphologies suggestive of an age range as large as 5 Gyr or more. The M33 halo seems to have been remarkably slow to get started, particularly in comparison with the far smaller dwarf ellipticals.

As distance increases, information fades. The most remote cluster for which a direct CMD has been obtained is one in the outer halo of the giant elliptical NGC 5128 (G.Harris et al. 1998; see Figure 12). At its distance of 4 Mpc from the Milky Way, 99.95% of this cluster's stars are hopelessly crowded or too faint for individual measurement even at the best HST camera resolution. However, the few dozen red giants that are measurable roughly delineate an RGB locus with normal characteristics. This study can best be viewed as a trial run for much better things to come, but it gives the first *direct*, star-by-star evidence that the halo clusters in a giant elliptical galaxy are at least roughly similar to those in the very different Local Group members. In coming HST Cycles with newer cameras, it should be possible to explore the NGC 5128 halo stars and clusters down to the horizontal-branch level.

6. Young Globular Clusters: Starbursts and Mergers

Sometimes the things right in front of us are the hardest to recognize for what they are. Our own Galaxy presents such a clear-cut division between star clusters in the halo (old, massive, mostly metal-poor) and the disk (young, small, and near-Solar metallicity) that for decades it was conventional to think of them as fundamentally different objects. The separate subfields that grew up around open clusters and globular clusters rarely communicated with one another, and astronomers studying globular clusters connected even less with those studying gaseous nebulae and star formation. Questions regarding globular cluster formation tended to be addressed only through speculative theoretical models which invoked special, early-universe conditions.

Today, little remains of that artificial and restrictive paradigm. One of the truly major accomplishments of the HST imaging programs has been, at long last, to open up the rich range of star cluster properties in all galaxies, and to expose our Milky-Way-based

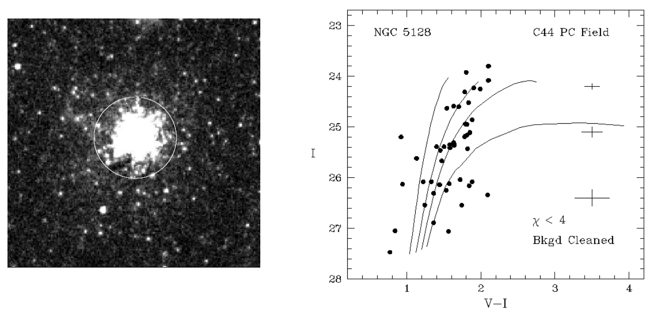

FIGURE 12. *Left panel:* WFPC2 Planetary Camera image of globular cluster C44 in the halo of NGC 5128, from G.Harris et al. (1998). The box shown is $9''$ across. *Right panel:* Observed color-magnitude diagram for N5128-C44. Out of more than 100,000 stars in the cluster, only $\simeq 40$ are uncrowded enough and luminous enough for photometric measurement at HST resolution. The four lines are standard giant-branch sequences for the Milky Way clusters M15, NGC 1851, 47 Tuc, and NGC 6553. C44 appears to be of moderately low metallicity.

prejudices for what they were. In the 3-space of cluster age τ, metallicity [Fe/H], and mass M, it is possible to find clusters from *some* galaxy that occupy every corner of that coordinate space.

Most astronomers in this field would now agree that it has become routinely easy to identify objects which fully qualify as "young globular clusters"; that is, star clusters in the mass range $\sim 10^4 - 10^6 M_\odot$ which differ only in age from the familiar old-halo globulars. The most obvious and best-studied example – in fact, the clear prototype for such objects – is likely to be the central cluster R136 in the 30 Doradus complex. Although this extraordinarily compact and luminous system has long been known, the spatial resolution of HST was needed to demonstrate beyond doubt that it was indeed a young star cluster. Its CMD (Hunter et al. 1995; Massey & Hunter 1998) reveals as many as ~ 60 O3-type stars, the biggest of which may reach 120 $M_\odot$. The cluster as a whole appears to have a normal IMF at least down to $3M_\odot$; accounting for fainter stars, it may have a total mass $\sim 4 \times 10^4 M_\odot$. In structure and size it easily qualifies as a small globular cluster seen at an age of just 4 Myr (Hunter et al. 1996). The vastly larger 30 Doradus gas complex surrounding R136 is highly ionized and stirred up by the outpouring energy from this central engine. We see here a clear suggestion that a *large* reservoir of gas, a tiny fraction of which gets compressed into a small volume a few parsecs across, is needed to form a globular cluster. Only a small part of the total gas in the 30 Dor region has gone into this single massive star cluster, though the whole complex also contains other much smaller clusters (Walborn et al. 1999).

Within the Milky Way, a smaller analog may be found in NGC 3603, a similarly young cluster of a few thousand $M_\odot$ still surrounded by the tangled nebula from which it emerged (Brandner et al. 2000). Objects like R136 and NGC 3603, but even more massive, were tentatively identified long ago from ground-based imaging of starburst galaxies such as NGC 1569, NGC 1705, or M82 (see O'Connell et al. 1994, 1995; De Marchi et al. 1997 for HST data). The term "super star clusters" was coined to refer to these young objects (van den Bergh 1971), though the connection with witnessing the actual process of globular cluster formation (an obvious one, with the usual benefit of hindsight) was not firmly made till much later. It now seems plain that globular clusters and super star clusters are one and the same (Figure 13), and that if we want to

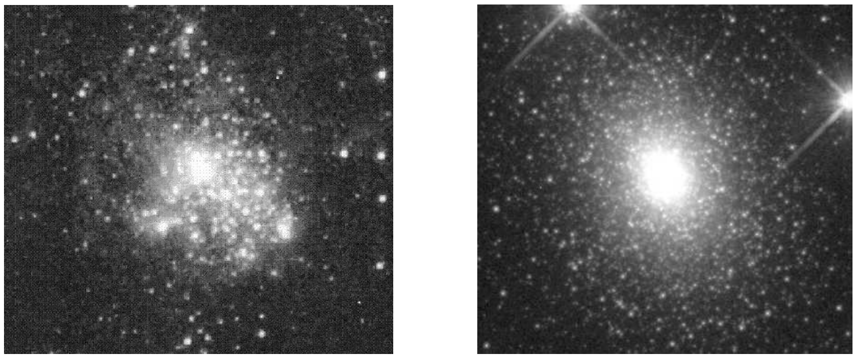

FIGURE 13. *Left panel:* The 4-Myr-old cluster NGC 2403-II (Drissen et al. 1999): a "young globular cluster". *Right panel:* cluster Mayall II = G1, the brightest old-halo star cluster in M31 (from Fig. 1): an "ancient super star cluster".

understand how globular clusters formed, a highly informative approach is to scrutinize the gas clouds within which massive clusters are forming today.

The HST cameras have made it possible to investigate these intriguing objects in considerable detail, and to reveal many more sites where ultra-recent star and cluster formation is happening on large scales. Such events are taking place not only in small starburst irregulars, but in many other circumstances where *large amounts of gas* have been collected together and compressed into $\gtrsim 10^8 M_{\odot}$−sized GMCs. They appear in very gas-rich single disk galaxies such as NGC 2403 (Drissen et al. 1999); disk/disk mergers such as NGC 3256 (Zepf et al. 1999) and the exhaustively studied Antennae (Whitmore et al. 1999; see also Whitmore's review in this volume); or giant ellipticals within which massive HI gas infall is taking place, such as the Perseus cD NGC 1275 (Holtzman et al. 1992; Carlson et al. 1998).

With amazing rapidity, examples have been found which penetrate close to the ultimate age limit $\tau \to 0$. For example, in the starburst dwarf NGC 5253, Calzetti et al. (1997) isolated half a dozen young globulars likely to be all less than 10 Myr old; the youngest, in the centermost starburst region, may be ~ 1 Myr old and is apparently still heavily shrouded in dust and ionized gas (Turner et al. 2000). This object, which the authors claim to hold several *thousand* O stars, may still be in transition from its "protoglobular" gaseous state. A similar situation is found in another starburst dwarf NGC 2366 (Drissen et al. 2000), where at least one cluster (N2363-A) may be $\lesssim 1$ Myr old. It is natural to speculate that active dwarf galaxies like this might closely resemble the protogalactic fragments ($\equiv$ supergiant molecular clouds) out of which larger galaxies are postulated to have assembled (Searle & Zinn 1978; Harris & Pudritz 1994).

This rewarding lode of new data has been directly responsible for stimulating new and more empirically based models for cluster formation (e.g., McLaughlin & Pudritz 1996; Elmegreen & Efremov 1997). Much has been found out about the luminosity distribution of young clusters, which follows a rough power-law form $n(L)dL \sim L^{-\alpha}dL$ strongly resembling the mass spectrum of giant molecular clouds (Harris & Pudritz 1994). The exponent α is near 2 independent of environment, but may progressively steepen from ~ 1.7 at low masses to $\gtrsim 2.3$ at the high-mass end (see Whitmore et al. 1999). Both the mean value of α and its gradual steepening can be understood quantitatively within a model framework whereby protocluster gas clouds build up by collisional accretion (McLaughlin & Pudritz 1996). However, much remains to be understood about the later evolution of the mass distribution function due to progressive dynamical destruction of clusters at various masses, and the effects of mergers and accretion of satellites (see, e.g., Zhang & Fall 1999; Murali & Weinberg 1997; Gnedin & Ostriker 1997; Vesperini 1998; Vesperini & Heggie 1997; Côté et al. 2000 for more extensive discussion of these issues).

7. Giant Ellipticals: Another Direction for Galaxy Archaelogy

Even the most thorough analyses of the Milky Way and other Local Group galaxies do not exhaust what there is to learn about the classic old-halo star clusters. Vastly more populous globular cluster systems reside in giant E galaxies; and their clusters display a surprising range of characteristics far beyond what we see in disk galaxies or dwarfs (for extensive reviews, see Harris 1991, 1999, 2000; Ashman & Zepf 1998). But almost all gE's are at distances which make them a stiff challenge for ground-based photometry or spectroscopy.

While the ground-based 8- and 10-meter-class telescopes have enabled a new round of spectroscopic studies of globular cluster systems (radial velocities, chemical compositions, dynamics), HST has exerted deep influences once again through its imaging capabilities. Any shortlist of highlights would surely include the following:

(a) Two extremely deep photometric studies of the Virgo giant M87 (Whitmore et al. 1995; Kundu et al. 1999) showed definitively that the luminosity function of its globular cluster system (GCLF) has the same log-normal form (number of clusters per unit magnitude) expected from classic studies of the Local Group members. Coupled with considerable previous evidence that the bright end of the GCLF (i.e., above the turnover point at $M_V \simeq -7.5$) is very much the same in all large galaxies, this work added much weight to the view that the GCLF is a near-universal phenomenon.

(b) Many ellipticals in the Virgo/Fornax distance regime and slightly beyond have now been imaged deeply enough to construct populous and nearly contamination-free samples of globular clusters. The metallicity distribution function (MDF), another informative relic of the galaxy's early history, can be assembled from the two-color photometry (to this stage, usually $(V-I)$ from WFPC2). Notably comprehensive and precise studies of M87 and NGC 4472 in Virgo have been published (Puzia et al. 1999; Kundu et al. 1999), while statistical analyses of many more E and S0 galaxies have been carried out by Neilsen & Tsvetanov (1999), Gerhard & Kissler-Patig (1999), and Kundu & Whitmore (1999). These galaxies differ surprisingly in the form of their MDFs, but half or more show distinct bimodality indicative of two major stages of cluster formation (Figure 14). These studies have helped fuel a highly active and progressive debate on the relative merits of *in situ* formation, satellite accretion, or major mergers (e.g., Côté et al. 2000; Forbes et al. 1997; Harris et al. 1998, 2000; Schweizer et al. 1996; Zepf et al. 1999; Sharples et al. 1998, among many others).

(c) For the first time, the globular cluster systems in the 100-Mpc-distant Coma cluster have come within easy reach – an important step since Coma represents a much richer and denser environment of galaxies than anything at closer distances, and thus probably also a different evolutionary history. A series of studies of the Coma giants (Baum et al. 1995, 1997; Woodworth & Harris 2000; Kavelaars et al. 2000; Harris et al. 2000) is beginning to reveal combinations of characteristics that were not seen in any previous cases. The GCLFs in these Coma ellipticals have been studied down to their turnover points, allowing them to be used for distance determination and a new estimate of the Hubble constant (Kavelaars et al. 2000). Under the restricted assumption that the GCLFs in

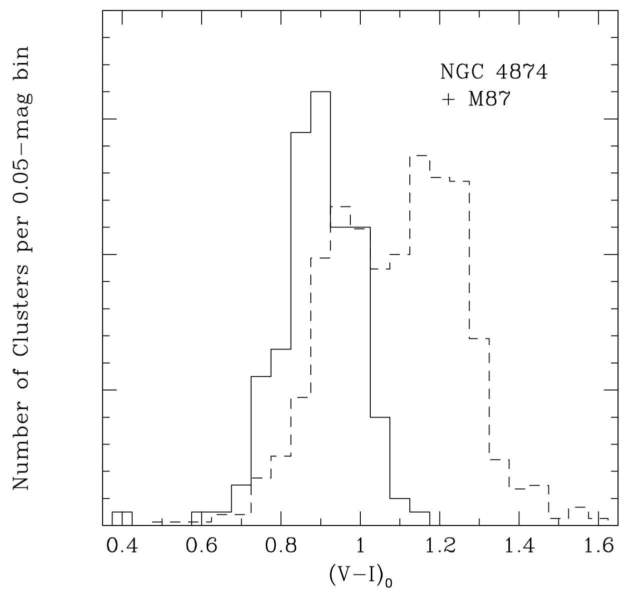

FIGURE 14. The metallicity distribution functions for two cD galaxies, M87 in Virgo (dashed line, from Kundu et al. 1999), and NGC 4874 in Coma (solid line, from Harris et al. 2000). M87 has the classic bimodal form discovered in many large spirals and ellipticals, while puzzlingly NGC 4874 is missing the metal-richer component.

giant ellipticals are similar everywhere (and in particular, between Virgo and Coma), the current results suggest $H_0 = 69 \pm 9$, a result highly consistent with recent determinations through several other standard candles.

8. What Lies Ahead?

From our vantage point well into the HST era, some old questions are still on the table, and many new ones have been put there. Some of these may find answers as soon as the next Cycle of HST programs is underway, or as far downstream as the era of NGST:

- What does the faintest part of the white dwarf cooling sequence look like, and how will it help us constrain both white dwarf physics and cluster ages?

- What are the interactive processes which produce the many anomalous types of stars residing in the central regions of core-collapsed clusters?

- What is the "missing" stellar physics which governs mass loss and the mass distribution for cluster stars in the giant and horizontal-branch stages?

- Do any globular clusters have central black holes? If so, how did they arise? What other types of objects reside in the innermost centers of core-collapsed clusters?

- What kinds of planets reside around globular cluster stars, especially in low-metallicity clusters?

- What are the ages of the Galactic bulge clusters?

- Typically 1% of the gas in a star-forming GMC finds its way into a few condensed star clusters. What governs this mass fraction? Does it differ strongly under different conditions? How does a protocluster cloud make the transition into a bound star cluster over the space of ~ 1 Myr? How does this depend on mass and composition?

- Is the mass distribution function at formation a near-universal phenomenon for globular clusters, regardless of host galaxy type?

- What drives the perplexing range of metallicity distributions and specific frequencies in giant E galaxies? Can we "read" these quantities to deduce what fraction of such a galaxy was assembled from satellite accretions or gas-rich mergers?

It is not hard to predict that globular clusters will continue to provide superb laboratories for stellar physics, as well as testbeds for modelling the early evolution of galaxies.

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