GLOBULAR CLUSTER COLOR-MAGNITUDE DIAGRAMS

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ABSTRACT. This review concentrates on new generalities emerging from this, the second "golden era" of B,V color-magnitude diagrams (CMDs), and remarks about future work in other photometric systems.

1. OVERVIEW

Within the context of this *Symposium*, the interpretation of CMDs of the Galactic globular clusters is central to the development of population synthesis models that will facilitate interpretation of the properties of more distant globulars (observable only by their composite light). As well they *should* serve as key reference points for evaluating the reliability of synthesis techniques in unravelling the integrated light of galaxies. Simultaneous consideration of the spatially resolvable Magellanic Cloud clusters and Dwarf Spheroidal galaxies (reviewed in this volume by Graham, Olszewski and Da Costa) is, of course, also of the utmost importance. As attested to by numerous contributed papers at this *Symposium*, we are embarked upon a new voyage of discovery about the basic constituents of Galactic globular clusters. This review will attempt to illustrate how the CMD fundamentally contributes to understanding star formation and evolution in metal-deficient material by examining: (i) basic morphological properties with emphasis on little-explored phases of stellar evolution; (ii) improving globular cluster ages and, hence, the lower limit to the age of the Universe; and (iii) the nature of globular cluster main-sequence luminosity functions.

The growth in observational material borders on being explosive (Fig. 1).

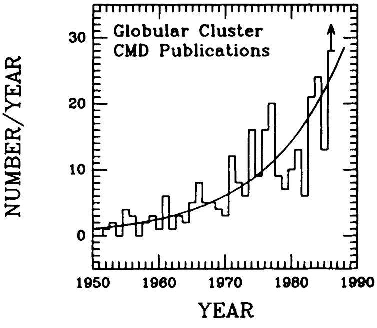

Fig. 1. The annual rate of publication of CMD papers, ignoring unpublished studies, abstracts, etc. (Peterson 1986a). The curved line represents a doubling of the rate on an eight year time scale.

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Although the wealth of material forces me to limit myself primarily to newer, CCD-based CMDs, even then I will be able to mention only a small fraction of the work being done worldwide. More complete references are in Peterson's (1986a) comprehensive CMD bibliography, as well as in the recent reviews of Caputo (1985), Castellani (1985), Sandage (1986), and the proceedings of this, the 1986 Rome and Baltimore conferences.

2. TECHNIQUES AND LIMITATIONS

Despite small sizes, relatively large pixels, occasional random and systematic surface imperfections, charge-transfer problems, etc., CCDs have, since Richer and Fahlman's (1984) first CMD, virtually replaced the use of photoelectrically calibrated photographic plates in determination of globular cluster CMDs. Their linearity, dynamic range, and sensitivity have dramatically reduced the *internal* photometric scatter (Fig. 2). Studies with the modern detectors have also revealed the presence of apparent *systematic* errors in much of the older work, in spite of Herculean efforts in the original studies to avoid them (see, e.g., Harris et al. 1983a; Hesser 1983; Heasley and Christian 1986, as well as Buonanno et al. 1983).

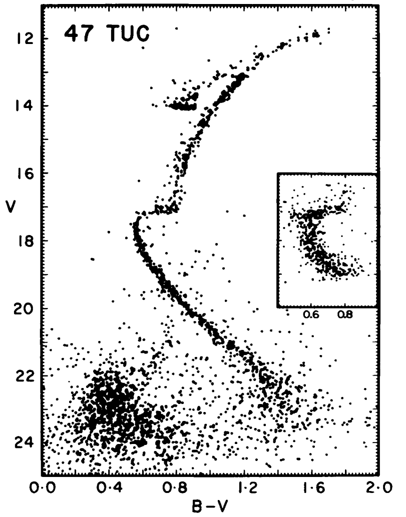

Fig. 2. Comparison of the 47 Tuc main-sequence from CCD photometry (Harris and Hesser 1986) with that (inset) from traditional techniques (Hesser and Hartwick 1977) illustrates a dramatic improvement in internal errors. The giant branch is from the photographic photometry of Lee (1977) and Hesser and Hartwick. Note the turnoff and giant branch of the SMC halo in the lower left-hand portion.

Software techniques share at least equal responsibility for the vastly improved CMDs. Indeed, the fact that CCDs allow us to work to much fainter limits in more crowded fields than before, presents us with fundamentally new, unique problems of data reduction. The key ingredient in the new software is replacement of fixed-aperture techniques with a point spread function empirically defined from uncrowded images in each frame or picture. By so tailoring the measurement aperture, the signal-to-background ratio is maximized and deconvolution of overlapping images becomes feasible. Another significant advance arises from the ease with which "artificial" stars having known magnitudes and positions can be inserted into the original data frames to evaluate errors and completeness factors. Since the appearance of Tody's (1981) "user-friendly" RICHFLD program at Kitt Peak in the late 1970's, many different codes have become available; to mention but a few, Buonanno et al. 1983, DAOPHOT (Stetson 1984, 1987), Walker 1984, Penny and

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Dickens 1986, Lupton and Gunn 1986, and ESO's MIDAS/INVENTORY programs. Relatively few direct comparisons of results from different codes based on similar data have yet appeared, but the ones that have are encouraging (e.g., Gratton and Ortolani 1986a); it will be particularly valuable to have results from Green's (1985) comparison of various codes on *identical* data.

Walker (1986) has given an excellent review of the combined power of the new techniques. To get the best results on fundamental parameters such as ages, my colleagues and I continue to be concerned with the need to pay excruciatingly close attention to possible photometric zero-point errors in broad-band CCD photometry. Although the small internal scatter and high quantum efficiency in CCD photometry makes them seem almost magical, they present the user with all the challenges inherent in first-class photoelectric photometry, with which they share a common enemy: the Earth's atmosphere. Moreover, each chip, camera and filter combination has its own personality. Accordingly it is essential to get many standards each night covering both a wide color and air-mass range, to observe some Pop II tie-in fields, and to make observations of program fields on several nights. Even with these precautions, zero points based on transfers from standard stars outside the cluster CCD frame *may* be randomly in error by amounts up to 0.04 mag (see Table 2 of McClure et al. 1987). The need to reduce many independent frames taken on different nights seems unavoidable if we are to obtain the highest possible *external* precision from the ground with the new techniques.

One of the most exciting aspects of the new techniques is their potential for determining luminosity functions in crowded globular cluster fields. It may not, however, be widely recognized, how enormous is the ratio of reduction to observing time required to perform the deconvolution photometry (100:1 or more on VAX-class machines). For best results, multiple reductions are required with different test stars generated from the empirical point spread function in order to determine completeness factors. In addition, when the goal is to reach either extremely faint magnitudes or to study clusters at lower Galactic latitudes, observations and analysis of comparison star fields are necessary to estimate field star contributions independently of Galactic halo models. Both of these requirements impact substantially upon observing and reduction time.

Finally, the strong effect of distance on the quality of results (Fig. 3) must be born in mind. With 4-m telescopes we are able to get superb data capable, in principle, of age discrimination to ± 1 Gyr at the turnoff to distances of $\lesssim 20$ kpc, beyond which our discriminatory powers decrease rapidly. A similar degradation sets in at lower Galactic latitudes, where crowding and field star contamination dominate our observations. Proper motion studies can, for some clusters, provide a remarkable transformation in the observed CMD (see Fig. 4). For the opportunities and challenges presented by many distant or nuclear bulge objects, however, HST will be essential.

3. ASPECTS, OLD AND NEW, OF CMD MORPHOLOGY

In spite of occasionally valiant efforts, most older CMDs (particularly photographic ones) suffer from often unquantifiable incompleteness, photometric uncertainties, and biases towards larger radii. The potential of a thorough survey, with modern detectors and software, of globular cluster luminosity functions at magnitudes *brighter* than the turnoff deserves emphasis: an order-of-magnitude improvement is now possible for brighter portions of cluster luminosity functions.

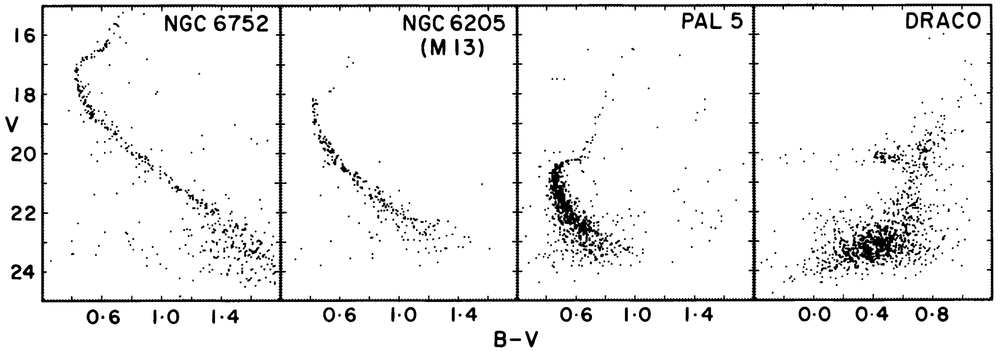

Fig. 3. CMDs from deep CCD exposures illustrate the effect on photometric quality at the turnoffs imposed (primarily) by increasing distance. From left to right: NGC 6752 (Penny and Dickens 1986); M13 (Richer and Fahlman 1986; see also Lupton and Gunn 1986); Pal 5 (Smith et al. 1986), and Draco (Carney and Seitzer 1986; see also Stetson et al. 1985).

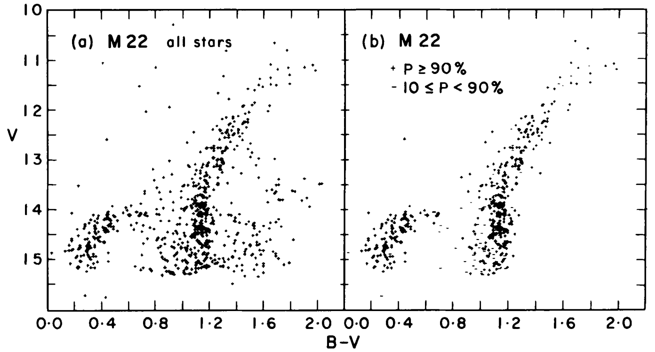

Fig. 4. The beneficial effects of proper motions for clarifying populations within lower-latitude globulars is well illustrated by the case of M22 (Cudworth 1986), at $l = 10°, b = -8°$.

Since brighter stars contribute significantly to the integrated light, a knowledge of their relative numbers and properties is essential for many problems. Some hints of what may result from such work are now described.

3.1 Correlations With Metallicity ([M/H])

The well-known correlation between CMD morphology and metallicity is evident upon comparing Fig. 2 (a cluster with [M/H]~ -0.8) with the much more metal-deficient objects in Figs. 3—5. As metallicity increases, the slopes of the giant and asymptotic branches decrease, the giant-branch and turnoff colors become redder, and there is a tendency for the horizontal branch to become redder. Marked changes arising from [M/H] differences in the shape and position of subgiant and turnoff sequences are predicted by the isochrones and found in the observations (VandenBerg, this conference).

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3.2 The As–Yet Unpredictable Horizontal Branch (HB)

Twenty years after its recognition, a convincing explanation for the "second parameter problem" (Sandage and Wildey 1967, van den Bergh 1965,1967), in which clusters with similar metallicities exhibit dramatically different color distributions of HB stars, remains elusive. One aspect of the observational situation is illustrated in Fig. 5 for three clusters for which the data indicate the same ages, Y and [M/H] values. M92 is thought to be typical of very metal-deficient clusters, while M15 and NGC 5466 show some red HB stars and more variables. The blue gap in the M15 HB (near B−V∼0.05), which sets in where the NGC 5466 HB ends and is not seen in M92, and the long, blue tail are striking features requiring explanation. Buonanno et al. (1985) conclude from their exhaustive analysis of (presently undetectable) differences in age, Y, [O/H], core and envelope masses, rotation, etc., that the solution to the "second parameter problem" may well lie in determining the appropriate weight to be applied to each of many competing parameters within each cluster, possibly as a function of position within the Galaxy. The survey called for in §3 would provide invaluable new constraints on the second parameter problem, to which I'll return in §3.7.

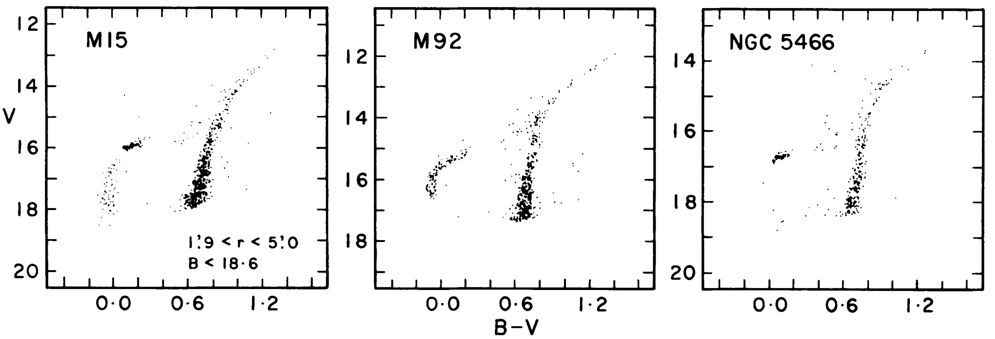

Fig. 5. Three clusters, each having [M/H]= -2.1 ± 0.2, show remarkably different HBs in these *photographic* CMDs from Buonanno et al. (1985).

Clusters having M15-like discontinuous HBs with an extremely blue tail are much more common than once recognized, with attendant importance for integrated light studies of globulars and old stellar populations, ionization of halo gas, etc. (Welch and Code 1980, van Albada et al. 1981, de Boer 1985, Castellani and Cassatella 1986). Such clusters now include (by NGC) 288 (Buonanno et al. 1984), 1851 (Stetson 1981), 1904 (Harris et al. 1983b; see also Heasley et al. 1986, Gratton and Ortolani 1986b), 2419 (Nemec et al. 1986b), 2808 (Harris 1974), 4833 (Nemec et al. 1986a), ω Cen (Da Costa et al. 1986), 6121 (Lee 1977), 6284, 6293 and 6333 (Harris and Harris 1986), and 6752 (Cannon 1981).

As Demarque describes elsewhere in this volume, gaps in luminosity functions are not restricted to globular cluster HBs. Gaps are common on the lower giant branches of metal-poor, but apparently not metal-rich, clusters (King et al. 1985). Such discontinuities provide extremely important constraints on key mixing events at earlier stages of stellar evolution.

3.3 Blue Straggler Stars (BSS)

Until recently the clearest evidence for a BSS sequence lying above and blueward of the main-sequence turnoff in a Galactic globular was M3 (Sandage 1953), with some BSS being suspected in the low-latitude cluster M71 (Arp and Hartwick 1971). Some clusters (47 Tuc—Hartwick and Hesser 1974, NGC 6752—Cannon 1981) definitely seem *not* to have them. Radial velocity membership of BSS is now established in M3 (Chafee and Ables 1983) and ω Cen (Da Costa et al. 1986); while strong sequences are visible in CMDs of NGC 5053 (Nemec and Cohen 1986) and NGC 5466 (Nemec and Harris 1986), and puzzling cooler candidates are identifed in E3 (van den Bergh et al. 1980, McClure et al. 1985). BSS are also known in three dwarf spheroidal galaxies, Sculptor (Da Costa 1984), Ursa Minor (Olszewski and Aaronson 1985) and Draco (Carney and Seitzer 1986). Explanations advanced for BSS include youth, binary mass transfer, main-sequence lifetime extension, etc. ω Cen and NGC 5466 provide much needed new data for this controversial phase of stellar evolution. In the latter cluster, the BSS are more centrally concentrated than the subgiant stars of the same magnitude (Fig. 6), with the inference that their masses are $\sim 1.3 M_{\odot}$. A recent epoch in which single, relatively massive stars were formed in this low density cluster seems unlikely, leading Nemec and Harris to favor scenarios involving mass-transfer binaries or coalesced stars. Clearly, if BSS are generally more centrally concentrated, available CMDs are very incomplete for them.

Another interesting aspect emphasized in the Da Costa et al. and Nemec and Harris work concerns the possible relationship between unusual variable stars, the BSS and extended blue HBs (§3.2). NGC 5466 is the only Galactic globular known to contain an anomalous Cepheid of the type found in dwarf spheroidal galaxies, while the ω Cen BSS, E39, is a dwarf Cepheid (AI Vel) variable. In their study of clusters containing short-period Cepheids, Harris and Harris (1986) have discovered very blue HBs, which they suggest supports the idea that anomalous Cepheids and similar UV bright stars come from the extreme blue end of the HB (whatever produces that!).

3.4 White Dwarf (WD) Stars

Penny and Dicken's (1986) Fig. 13 illustrates the current difficulties in locating this predicted constituent of globulars with ground-based data. Bahcall (1985) and Renzini (1985) have shown the potential of HST for identifying cluster WDs, an opportunity with important ramifications for understanding cluster dynamics and determining distances (Fusi Pecci and Renzini 1979).

3.5 Cluster Cores

Central X-ray sources, possible color gradients and interest in dynamical processes all drive the study of cluster centers reviewed elsewhere herein by Djorgovski and by Grindlay. Spatial resolution limitations from the ground frequently hamper exploration of populations at the centers of globular clusters, but some recent progress has been made and new surveys are being undertaken. The series of photometric studies by Aurière, Cordoni and their colleagues (e.g., Aurière et al. 1986 and Cordoni and Aurière 1984) illustrate the difficulties and potential rewards, one of the latter being the discovery of a strongly variable UV-bright star which seems

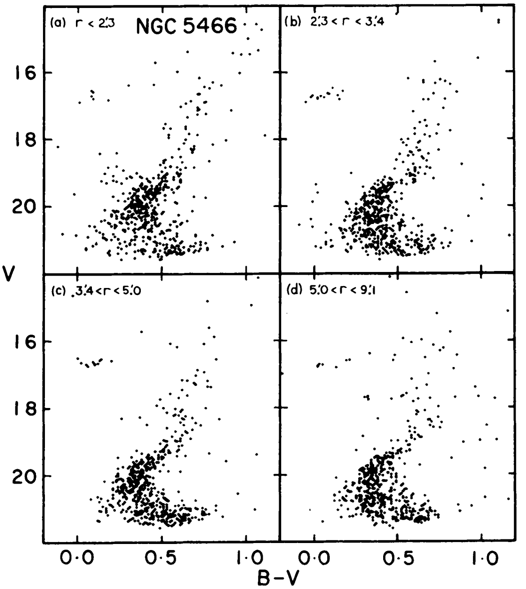

Fig. 6. *Photographic* CMDs as a function of radius for NGC 5466 (Nemec and Harris 1986). Note the large BSS population in the central region, whose area is ~ 1/15th that of the other three regions, and a nearly complete absence of faint blue HB stars.

to be the optical counterpart to the M15 X-ray source (Charles et al. 1986). Preliminary results from a related program of CCD observations from Mauna Kea of metal-poor clusters by Rose and Stetson (1986) may indicate a number of new supra-HB and UV-bright stars in their central regions, which will necesitate a revision of the already-impressive statistics of those stars (last compiled by Harris et al. 1983), and further clarify their, possibly underappreciated, role in the integrated light of galaxies.

3.6 Metal-Rich Clusters

This review has concentrated on metal-poor clusters, largely in reflection of how many fewer metal-rich ones have (or can be!) thoroughly studied from the ground, because of their preferential location in the (crowded) bulge region of the Galaxy. From spectroscopy of the composite light of the central regions of nine globular clusters having [M/H]> −0.8, Rose and Tripicco (1986) find large cluster-to-cluster differences in CN strengths. They also find that clusters having stronger CN strengths invariably show weak Sr II/Fe I ratios normally indicative of a dwarf-star population. To account for this dichotomy among the integrated spectral properties of the metal-rich globulars they speculate on the possibility of a 10 Gyr age spread among the clusters (the dwarf-dominated being younger), or on the presence of Campbell's (1986) coalesced binaries. While I suspect a more conventional explanation will ultimately prove tenable, their surprising results emphasize anew the importance of photometric (and, where appropriate, proper motion—see Fig. 4) studies of the highest possible spatial resolution for Galactic bulge clusters of *all* metallicities.

3.7 Sparse Clusters and Binary Sequences

Most of the Galaxy's lower luminosity clusters lie at substantial distances from the center. An example of their CMDs has already been given (Fig. 3), and in Fig. 7 six more are displayed as a function of distance. At ~120 kpc, AM-1 (Aaronson et al. 1984) is the most distant globular thought to be associated with the Galaxy, while at ~10 kpc the sparse E3 cluster is relatively nearby. The predominance of red HBs among these low [M/H] clusters, i.e., the classical second-parameter effect—§3.2, is evident in Figs. 3 and 7, and led Searle and Zinn (1978) to suggest that the second parameter might be age differences correlated with R_{gc}. With the exception of the much younger stars seen in some (but not all) dwarf spheroidal systems, the best available data for outer halo systems favor the same ~15 Gyr age for them as found for nearer globulars. We probably must await age discrimination at the sub-Gyr (!) level to evaluate age as the second parameter in the outer-halo clusters. However, the discussion under §3.2 has already indicated the complexities of the second-parameter situation. Indeed, as H. Smith and Perkins (1982) have stressed, clusters such as NGC 6171 and 6723, with R_{gc}'s ~3 kpc, provide evidence for the second-parameter effect among *inner* halo clusters (see also G. Smith and Hesser 1986). (Clusters such as AM-4 and E3 avoid the second-parameter problem altogether by having no HBs at all!)

New vistas on physical processes, especially dynamical ones, are opened as a consequence of the lower densities in sparse clusters. For instance, CMD studies reveal that the main sequences of Pal 5 (Fig. 3) and E3 (Fig. 7) are truncated, presumably in part by tidal stripping. The search for binary stars in globulars has been long with modest returns (cf. Trimble 1980, Grindlay–this volume). Evidence for binaries composed of similar-mass stars forming a parallel sequence ~0.75 mag above the main sequence has been seen in E3 (McClure et al. 1986, Gratton and Ortolani 1986a), which raises the suspicion that such pairs might more easily form or, once formed, survive in very sparse clusters. However, no such sequence is seen in Pal 5 (Smith et al. 1986), possibly because of increased observational scatter at the faint magnitude levels involved. Contrary to the suggested association between sparse clusters and binaries, a much more centrally concentrated and massive cluster, M68, shows some indications of main-sequence binaries (McClure et al. 1987). Buonanno (1986) has remarked that he and his colleagues find in their careful CCD photometry main-sequence widths that exceed those explained by photometric errors, which they attribute to binaries, so maybe one doesn't have to be from Victoria to see the effect! Clearly, very high S/N data for large samples extending to faint magnitudes will go far to explore the reality and frequency of main-sequence binaries in Galactic globulars.

4. AGES

Because ages are covered throughly by VandenBerg elsewhere in this *Symposium*, my remarks will concisely reflect a few concerns from my perspective as an observer. It should come as no surprise that the daunting task of setting the lower limit to the age of the Universe from globular cluster CMDs is not amenable to "quick and dirty" solutions: only the most thorough analyses based upon a homogeneous set of the highest S/N-ratio data stand any chance of success. As we newcomers embark on this ambitious quest, we can do no better than to bear in mind the scope and care with which Sandage has approached the necessary observations on this topic throughout his career. With CCD data *relative* age discrimination at the Gyr level is within reach for nearer globulars. However, present estimates are not achieving *absolute* precisions better than a few Gyr for reasons

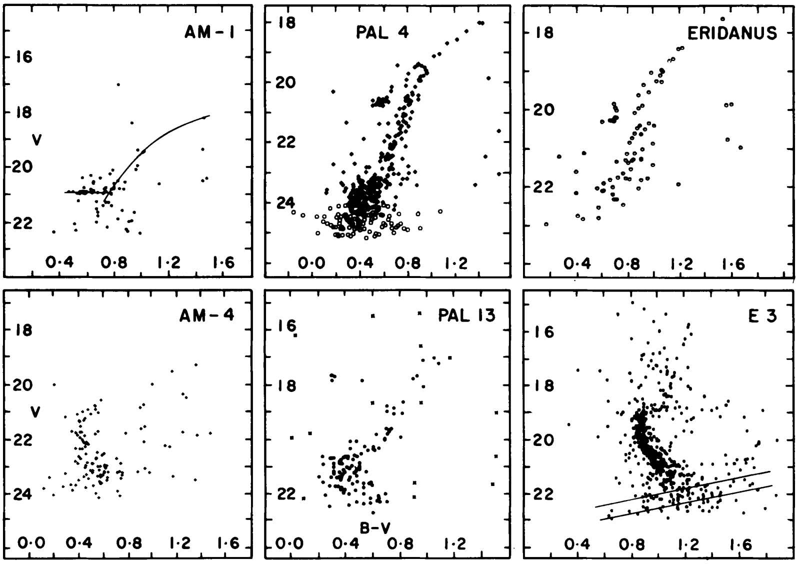

Fig. 7. CMDs for sparse halo clusters, based, except as noted, on CCD data. R_{gc}'s (in kpc) from Webbink (1985) are given following the name. Top row, from left: AM-1, 118 (Aaronson et al. 1984); Pal 4, 96 (Christian and Heasley 1986, see also Reed and Harris 1986); Eridanus, 90 (Da Costa 1985). Bottom row, from left: AM-4, 26, the poorest globular known (Inman and Carney 1986); Pal 13, 26 (*photographic* from Ortolani et al. 1985); E3, 10 (McClure et al. 1985; see also Gratton and Ortolani 1986a). Note the ordinate/abscissa ratios in the Pal 4 and Eridanus diagrams differ from the usual 1:5 value.

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largely—but beware the caveats of §2—not having to do with the CCD photometry itself (e.g., Flannery and Johnson 1982, Heasley and Christian 1986, VandenBerg 1986 and this volume). As a consequence, conflicting results on the systematics of globular cluster ages surface in the latest analyses (Gratton 1985, Sandage 1986, Alcaino and Liller 1986, Peterson 1986b). The latter analysis, based upon the most complete sample consisting of 37 clusters with turnoff-region photometry (much of it photographic), yields 15.1 ± 0.5 Gyr (s.e.m.) with no evidence for differences in age between inner and outer halo clusters or with [M/H].

While there is an enormous amount of work still ahead, I think that there are many reasons for optimism. Once free of the Earth's atmosphere, the quality of the photometry will, with a well-calibrated HST, improve substantially in several regards. As well, the fundamental physical parameters required for interpreting the CMDs are showing steady improvement. Recent observations on the primordial Y value give strong reasons for adopting 0.24 ± 0.01 (Boesgaard and Steigman 1985, Caputo 1985, Kunth 1986, Pagel et al. 1986). Uncertainties in [M/H] and [CNO/H] values are still too large, but can be reduced further, and more distant clusters can come under scrutiny with the next generation of telescopes. New techniques for distance determinations involving the turn-up of the luminosity function at faint magnitudes (VandenBerg 1986) or white dwarfs (Fusi Pecci and Renzini 1985) offer promise for clarification of long-standing debates over HB absolute magnitudes, as will future studies of RR Lyraes and HBs with CCDs. Something that is long overdue, however, is a major attack on reddening determinations *independent* of cluster stars or integrated properties, particularly for those clusters with superbly defined turnoffs. (For instance, application of $uvby-\beta$ photometry to large samples of foreground stars might substantially improve E(B−V)s for many clusters.)

5. MAIN-SEQUENCE LUMINOSITY FUNCTIONS (LF)

As alluded to in §2, the determination of LFs is a very time consuming task much more suited to CCDs than to photographic plates. The initial results are very intriguing and suggest we may be learning something quite new about star formation processes in the early Galaxy. The basic observational results are summarized in Fig. 8, which is based upon work by Lupton and Gunn (1986), Penny and Dickens (1986), Richer and Fahlman (1984, 1986), as well as our own, and is taken from McClure et al. (1986). The figure compares (heavy solid lines) the

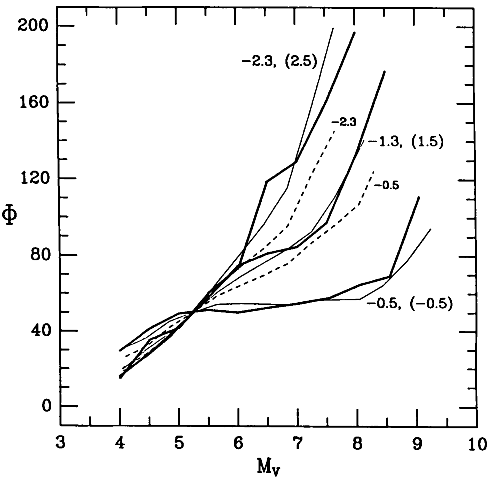

Fig. 8. Mean LFs for globulars of differing [M/H]s are compared with theoretical ones (see text).

average LF from deep CMDs of clusters with [M/H] ~ -2.3 (M15), ~ -1.3 (M5, M13, NGC 6752) and ~ -0.5 (M4, 47 Tuc) with theoretical LFs for the appropriate [M/H] and the usual, power-law, mass-function slope, x (in parentheses). The dashed curves represent additional LFs for $x = 1.5$ and the values of [M/H] shown. Within the small sample, there appears to be a strong metallicity dependence to the present-day mass function for these globulars suggesting that a universal (Salpeter) value is unsuitable for globular clusters. The result is independent of the [M/H] scale adopted. No correlations are evident between the inferred x and concentration class, central relaxation time, or the radius at which the observations were secured. Multi-component King models (Pryor et al. 1987) imply that dynamical corrections, while important, do not significantly alter the slope of the relation between x and [M/H]. Consequently, it appears that relation reflects, at least in part, the properties of the initial mass function in the proto-Galaxy. Observations of M92, M12 and NGC 6362 analyzed recently show a similar correlation of LF slope with [M/H], as described in a contributed paper herein.

In a thought-provoking paper, Smith and McClure (1986) have investigated one side of the "chicken and egg" questions, "does low metallicity favor production of low mass stars (which would run contrary to standard ideas)?" or "does the IMF determine the chemical properties of the halo clusters?". In the latter case, metal-poor clusters might have been formed in proto-clouds with steep mass functions and achieved self-enrichment with little mass loss. On the other hand, proto-clouds with flat mass functions would have produced more than enough heavy elements to enrich themselves to the [M/H]s seen in metal-rich clusters; indeed, a truncation of the mass function for more massive stars would be required to limit the enrichment to the observed levels. McClure (1986) has also noted than a correlation with x might be found in Hartwick's (1986) new description of the Galactic halo, in which case the flat LF clusters would represent the *disk* of the Galaxy, while those with steeper LFs would represent the inner and outer halo components Hartwick identifies from halo RR Lyrae star distributions.

6. OTHER PHOTOMETRIC SYSTEMS AND FUTURE OUTLOOK

The scarcity of CMDs on systems other than UBVRI arises, in large measure, because the necessary network of standards suitable for CCD work is simply *not* available for any system other than UBVRI. Nevertheless, I wish in closing to stress the formidable powers of other systems to provide answers to many of the astrophysical problems we study. An obvious example would be IR photometry, which has been extensively and effectively applied in single-channel mode (Frogel et al. 1983, Lloyd-Evans 1983, and references therein).

Recent observations on the $uvby - \beta$ system by Anthony-Twarog (1986) of NGC 6397 provide a CMD and color-color diagrams (Fig. 9). In the former the turnoff-region is well delineated in the complete sample she has analyzed. When she selects only those stars deemed to have the highest quality (from DAOPHOT's χ statistic), she is also able to identify the turnoff in the the $m_1, b - y$ diagram. If the error of $< m_1 >$ can be reduced to ± 0.01mag, [M/H] can, in principle, be

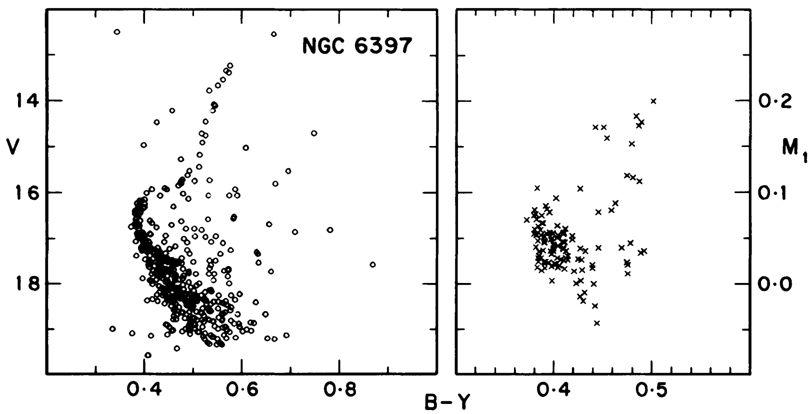

Fig. 9. CMD and color-color plot on the $uvby - \beta$ system from Anthony-Twarog (1986); for the latter, a subset of stars believed to have the most reliable photometry is used to show detection of the turnoff. Note that the zero points are based on only four stars from the photometry of Ardeberg et al. (1983).

determined to ± 0.1dex. However, achieving this goal will require much better zero points than presently possible with the available standards. Encouraging concordance with theoretical isochrones is also obtained in the $c_1, b - y$ diagram.

Cohen (1985) has presented CMDs on the Thuan-Gunn (1976) system for NGCs 5466, 6229 and 7006. While the scatter arising from her short exposures on these distant clusters is large, her data demonstrate the potential of the system. Bell and VandenBerg (1986) have computed synthetic spectra and colors for the T-G system (Fig. 10), demonstrating how the system's CMDs offer the possibility of simultaneously constraining age, [M/H], and T_{eff}.

Another under-explored system that appears to offer considerable opportunities for the study of globulars, particularly in the integrated light from clusters around distant galaxies, is the Washington system (Canterna 1976, Harris and Canterna 1977). Its attractiveness stems, in part, from its broad, yet filter-defined, passbands which yield sensitive abundance information, as Geisler (1986) and Canterna et al. (1986) have convincingly demonstrated. A theoretical color study for the Washington system similar to Bell and VandenBerg's (*op. cit.*) would strongly influence the decision on the part of observers regarding where to put their energies in the laborious development of suitable standards for study of Pop II objects using non-UBV systems. To reiterate: there is no doubt that the lack of networks of faint equatorial standards suitable for calibrating CCD observations on these systems is delaying their wider application to globular cluster photometry.

The time also seems ripe to develop synthetic integrated globular cluster models incorporating the features being defined by the CCD CMDs: such models will be essential for analysis of the most distant globulars. All told, the future of CMD work on Galactic globulars is an exciting one whose impact will be felt on many areas of astrophysical research. HST, the Keck telescope, Tektronix 2048 CCDs, etc. all promise advances not only on the topics mentioned above (and the even more numerous ones not mentioned!), but also on those we do not yet imagine.

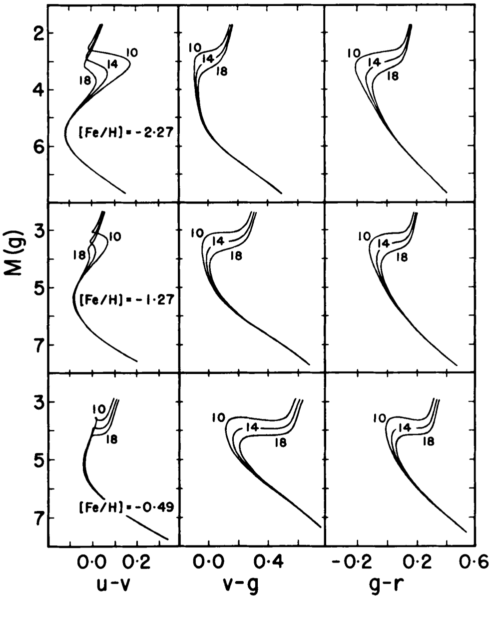

Fig. 10. An adaptation of Bell and VandenBerg's (1986) Fig. 6 depicting the behavior of isochrones for Thuan–Gunn photometry for Y=0.2, ages of 10, 14 and 18 Gyr and the [M/H]'s indicated. Similar calculations for the Washington system would be extremely valuable.

Were Shapley and his contemporaries Hertzsprung and Russell with us today, I'm certain they would be as excited about present and future prospects for research based on CMDs as those of us exploiting the new technology are!

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DISCUSSION

WALLERSTEIN: There is a great similarity between the Thuan-Gunn System and the Washington System. By just adding an I color, the Thuan-Gunn system is almost the same as MT_1T_2.

OSTRIKER: What is the location of blue stragglers?

HESSER: The prominent blue straggler sequence I showed from Nemec and Harris in NGC 5466 consists of stars almost entirely located in the central regions. Nemec and Cohen find a similar result for NGC 5053, another cluster of low central density.

GRINDLAY: I call your attention to the poster paper by Bailyn, et al. which shows that the faint blue horizontal-branch stars appear to be more centrally condensed than the BHB in ω Cen. We have interpreted this as evidence for binary mergers of white dwarfs and main sequence stars in the cluster core. These systems may be easier to recognize than blue stragglers in crowded cluster cores. My question is - when you state faint blue horizontal-branch stars are not observed in 47 Tuc, have you searched into the cluster core?

HESSER: A CCD frame pair (totaling 30 sec of integration and requiring more than 100 hours of VAX 11/780 analysis time) located at 2.5 arcmin. from the center does not show any (or at most only 1 or 2) blue straggler candidates.

ZINN: You said that there is a connection between very blue horizontal-branch stars, blue stragglers, and anomalous Cepheids. There are, however, systems such as the Draco and Sculptor dwarf spheroidal galaxies that contain blue stragglers and anomalous Cepheids and do not contain very blue horizontal-branch stars. This suggests to me that there may be no connection between the very blue horizontal-branch stars and these other types of stars.

HESSER: My statement reflected my understanding of recent results from the galactic globular clusters, particularly the work of DaCosta, Norris and Villmusen, Nemec and H. Harris, and H. Harris and W. Harris, many of whom are here and can better comment than I.

FUSI PECCI: In a poster paper on M 3 we find the blue stragglers to be less centrally concentrated.

HESSER: I warned you there was controversy on this topic!

LILLER: As a footnote to Dr. Hesser's plea for accurate calibration of CCD magnitude determinations, I should like to urge observers to set up photoelectric standards in the same CCD field. This work can be done numerous times - on 6 or 8 or more nights - using relatively small

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telescopes, thereby reducing errors of transfer.

HESSER: You have stated clearly the point I was trying to make and, as I remarked, stands at the heart of Sandage's approach to the fundamental problem of calibration. Each part of the system, camera, chip and filters, has its own "personality" which must be very carefully calibrated.