FIDUCIAL STELLAR POPULATION SEQUENCES FOR THE $u'g'r'i'z'$ SYSTEM

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ABSTRACT

We describe an extensive observational project that has obtained high-quality and homogeneous photometry for a number of different Galactic star clusters (including M 92, M 13, M 3, M 71, and NGC 6791) spanning a wide range in metallicity ($-2.3 \lesssim [\text{Fe/H}] \lesssim 0.4$), as observed in the $u'g'r'i'z'$ passbands with the MegaCam wide-field imager on the Canada–France–Hawaii Telescope. By employing these purest of stellar populations, fiducial sequences have been defined from color–magnitude diagrams that extend from the tip of the red-giant branch down to approximately four magnitudes below the turnoff: these sequences have been accurately calibrated to the standard $u'g'r'i'z'$ system via a set of secondary photometric standards located within these same clusters. Consequently, they can serve as a valuable set of empirical fiducials for the interpretation of stellar populations data in the $u'g'r'i'z'$ system.

Key words: globular clusters: general – globular clusters: individual (M 92, M 13, M 3, M 71) – Hertzsprung–Russell diagram – open clusters and associations: individual (NGC 6791)

1. INTRODUCTION

Recently, the Sloan Digital Sky Survey (SDSS) officially ended its planned five years of sky-scanning operations to obtain an unprecedented amount of imaging and spectroscopic data for approximately one-quarter of the sky. The SDSS was carried out on a dedicated 2.5 m telescope equipped with a large-format mosaic CCD to image the entire northern Galactic cap (i.e., $b > 30\degree$) in five photometric bands and two digital spectrographs to provide spectra for $\sim$1 million stars, galaxies, and quasars scattered throughout the imaging area. Although designed to primarily investigate the large-scale structure of the universe, the imaging component of the SDSS has obtained high-quality multicolor photometry for about $10^8$ stellar objects in the Milky Way, which represents the largest and most homogeneous database on Galactic stellar populations ever obtained. A notable feature of this database is that it was compiled in a new photometric system consisting of five unique passbands ($u', g', r', i'$, and $z'$) that were specifically designed for the SDSS to provide continuous coverage over the entire optical wavelength range (Fukugita et al. 1996).

While the SDSS was the first to implement the standard $u'g'r'i'z'$ photometric system, analogous versions of these same filters are also currently in use with CCD imagers installed on the Gemini Telescopes, the Canada–France–Hawaii Telescope, and the Hubble Space Telescope. In addition, the very fact that the SDSS has already provided such a large database of photometry of stars and galaxies implies that this photometric system is also becoming widely accepted as the filter set of choice for many planned ground-based observational projects and large-scale sky surveys (e.g., LSST, OmegaCam, Pan-STARRS, VST). Despite this, much of our current observational and theoretical knowledge of resolved stellar populations is based largely on the conventional Johnson–Kron–Cousins $UBVRI_C$ photometric system, with a few other studies relying on niche systems such as the Stromgren, DDO, Vilnius, and Geneva systems. Consequently, the empirical and theoretical tools that would tie such as the standard $u'g'r'i'z'$ system to the fundamental properties of observed stellar populations have yet to be defined. Specifically, neither well-calibrated fiducial stellar population sequences nor reliable color–$T_{\text{eff}}$ relations are currently available, and yet, without them, it is impossible to fully exploit the capabilities of the SDSS data set as well as complementary studies employing these same filters.

In order to remedy these deficiencies, there is good reason to rely on $u'g'r'i'z'$ observations of star clusters within our own Galaxy. Clusters are the ideal stellar population templates because, despite a handful of exceptions (e.g., ω Cen and M 22), their constituents are believed to be effectively coeval, equidistant, and nearly identical in terms of their heavy elemental abundances. As a result, their color–magnitude diagrams (CMDs) generally exhibit extremely tight and well-populated sequences of stars that span several orders of magnitude in brightness. Their wide distribution in metallicity is also suitable for characterizing how the photometric properties of stellar populations vary as a function of $[\text{Fe/H}]$. Consequently, cluster observations offer the perfect data sets to define fiducial stellar population sequences that cover a broad range of stellar parameter space. These sequences serve as a set of empirical “isochrones” that not only facilitate the analysis of other stellar population data, but also provide calibrators for stellar evolutionary models that are transformed to the observed CMDs via theoretically derived color–$T_{\text{eff}}$ relations (e.g., see Brown et al. 2005). Given the fact that the standard $u'g'r'i'z'$ system was introduced only a short time ago, however, the photometric database for star clusters remains too small to accomplish the tasks mentioned above.

Unfortunately, the SDSS alone cannot provide a sufficient database since (1) the main Sloan survey with the 2.5 m telescope is based on instrumental $ugriz$ passbands that are very similar, but not quite identical, to the $u'g'r'i'z'$ passbands with which the standard Sloan photometric system was

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Figure 1. Schematic showing the layout of the 36 individual CCD chips in the MegaCam mosaic camera. Each chip measures $2048 \times 4612$ pixels and projects to $6.4 \times 11.4$ at the CFHT f/4 prime focus resulting in a full field of $\sim0.96 \times 0.94$ degrees for the entire mosaic. The cross near the center of the mosaic (located $\sim14''$ below the top of ccd22) corresponds to the location of the optical axis of the telescope in the focal plane. The boxes denoted by dotted lines indicate the approximate locations of the six fields containing the secondary $u'g'r'i'z'$ standards (c.f. Figure 2 in Paper I).

defined on the 1.0 m telescope of the USNO Flagstaff Station (Smith et al. 2002). In addition, (2) the brightest stars lying on the red-giant branches (RGBs) of the nearest clusters saturate during $\sim60$ s drift-scan exposure times, (3) the SDSS imaging data do not extend deep enough to provide good photometric precision for some of the fainter stars lying on the main sequences in the more distant metal-poor globular clusters, (4) the survey footprint does not reach down to the Galactic plane where the majority of metal-rich open clusters reside. These reasons imply that the SDSS may not be the most ideal source of star cluster photometry for the derivation of fiducial stellar population sequences.

Hence, we recently began an extensive observational project aimed at thoroughly exploring the nature of stellar populations in the $u'g'r'i'z'$ photometric system via observations of Galactic star clusters. Our first paper (Clem et al. 2007, hereafter Paper I) presented a network of fainter secondary standard stars for the $u'g'r'i'z'$ system in selected star cluster fields to better aid observers on large-aperture telescopes in calibrating their photometry. In fact, the current investigation relies on these standards to calibrate a sample of high-quality and homogeneous $u'g'r'i'z'$ photometry obtained on the 3.6 m Canada–France–Hawaii Telescope (CFHT). This photometry is subsequently employed here to derive a set of accurate stellar population fiducial sequences that span a broad range in both magnitude and metallicity. In our third and final paper (Clem et al. 2008, in preparation) we will utilize these fiducials to test a new grid of theoretical color–$T_{\text{eff}}$ relations and bolometric corrections for the $u'g'r'i'z'$ system that have been calculated from synthetic spectra.

The following sections present the details related to the observation, reduction, and compilation of the photometry collected at the CFHT that will be used to derive a set of fiducial stellar population sequences for the $u'g'r'i'z'$ system. In Section 2 we describe the observational setup employed at the CFHT to collect the cluster photometry as well as the data reduction procedure, including the important step of calibrating the observed cluster photometry to the standard $u'g'r'i'z'$ system. Section 3 presents the details of the fiducial sequence derivation process. Finally, a short summary of our results, as well as a discussion of the usefulness of these fiducials for stellar populations research, is given in Section 4.

2. THE CFHT STAR CLUSTER SURVEY

To address the need for fiducial sequences in the $u'g'r'i'z'$ system, an observational program aimed at obtaining high-quality photometry for a number of Galactic star clusters was conducted on the CFHT in early 2004. One of the most notable features of these cluster observations is the fact that they were obtained using the CFHT’s wide-field mosaic imager known as “MegaCam.” As shown in Figure 1, MegaCam contains 36 individual CCDs that combine to offer nearly a full $1 \times 1$ degree field of view with high angular resolution ($\sim0.187''$ pixel$^{-1}$ at

4 Tucker et al. (2006) have published simple linear transformation equations that relate the instrumental $ugriz$ magnitudes to standard $u'g'r'i'z'$ with reasonable precision (2–3%). At some time in the future more sophisticated transformations may be derived that will enable users to predict standard-system indices from the main-survey observations with a high level of accuracy, at least for normal stellar spectral-energy distributions. Our own instrumental observations from the CFHT have been similarly transformed to the standard $u'g'r'i'z'$ system rather than to the $ugriz$ main-survey system; see below, and Clem et al. (2007).
the f/4 prime focus). Moreover, MegaCam operates with a set of $g'r'i'z'$ filters whose effective wavelengths and bandwidths are very similar to those of the USNO/SDSS. For observations in the UV, however, a slightly different filter than $u'$ is employed; this so-called $u^*$ filter was designed to take advantage of the superb sensitivity of the MegaCam CCDs at short wavelengths along with the reduced atmospheric extinction in the UV at high altitudes.

In order to graphically compare the USNO and MegaCam photometric systems, we present in Figure 2 the spectral coverages of both filter sets. Note that both sets of response functions presented in the figure are a result of convolving the raw filter profiles with the reflection/transmission characteristics of the telescope optics and the quantum efficiency of the detectors employed at both the USNO and CFHT telescopes. The differences between $u^*$ and $u'$ mentioned above are clearly evident in the plot with the central wavelength of the $u^*$ filter positioned about 200 Å redder than that of the standard $u'$ filter employed at the USNO. As discussed later in this investigation, this fact poses a particular problem in transforming photometry observed in MegaCam's $u^*$ filter to $u'$ on the standard system. Apart from the differences between $u'$ and $u^*$, however, the agreement between the remaining four filters seems quite good. The only exceptions are the two $z'$ filters where the USNO version appears to have more response towards longer wavelengths. This difference can be explained by the fact that both the MegaCam and USNO $z'$ filters are manufactured to have no long-wavelength cutoff (see Fukugita et al. 1996). Instead, their redward edges are defined by the long-wavelength quantum efficiency characteristics of the detector employed.

2.1. Observations and Data Reduction

Table 1 presents a list of the dates when data for the program clusters were collected on the CFHT during the 2004A observing semester. The observing run identifications provided in the second column denote blocks of several consecutive nights when the same instrumental setup was in place on the telescope, and all raw science images collected during these blocks were preprocessed using the same run-averaged master bias and flat-field frames. It is important to note that, due to the nature of the "queue-scheduled" mode of observing operations at the CFHT, the cluster data were collected on nights when actual sky conditions at the telescope closely matched the tolerances specified in the initial project proposal (i.e., near photometric conditions during dark or gray time with moderately good seeing). As a result, the observations were generally conducted on non-consecutive nights, and a complete set of cluster observations in all five filters may not have been collected on the same night or even during the same observing run (for example, the M 3 data were collected over four separate nights spanning three different observing runs).

Our goals for this project were to obtain a series of five short- and five long-exposure images in each filter for each cluster in our target list. This not only ensured a good signal-to-noise ratio for stars extending from the tip of the RGB down to a few magnitudes below the turnoff in each filter, but also allowed a star to be detected multiple times to help improve the precision of its final photometry. Furthermore, the telescope was dithered by a few tens of arcseconds between exposures to allow detection of stars that may have fallen on gaps in the MegaCam

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Table 1

| UT dates       | Run ID | $u^*$ | $g'$ | $r'$ | $i'$ | $z'$ | Clusters observed | Photometric? |
|----------------|--------|-------|------|------|------|------|-------------------|-------------|
| 2004 May 13    | 04AM04 | 7     | 0    | 0    | 0    | 0    | M 92              | Y           |
| 2004 May 23    | 04AM05 | 20    | 0    | 0    | 0    | 10   | M 3, M 92         | Y           |
| 2004 June 10   | 04AM06 | 0     | 10   | 10   | 10   | 0    | M 92              | Y           |
| 2004 June 11   | 04AM07 | 5     | 10   | 10   | 10   | 0    | M 3               | Y           |
| 2004 June 14   | 0     | 0     | 0    | 8    | 0    | 0    | M 3               | N           |
| 2004 June 19   |       | 0     | 10   | 10   | 10   | 0    | NGC 6791          | Y           |
| 2004 July 7    | 04AM07 | 8     | 6    | 0    | 0    | 0    | M 13, NGC 6791    | Y           |
| 2004 July 8    |       | 0     | 10   | 10   | 10   | 0    | M 71              | Y           |
| 2004 July 10   |       | 10    | 0    | 0    | 0    | 12   | NGC 6791          | Y           |
| 2004 July 13   |       | 10    | 0    | 0    | 0    | 10   | M 71              | Y           |
| 2004 July 16   |       | 10    | 10   | 10   | 10   | 0    | M 13              | Y           |
| 2004 July 17   |       | 3     | 8    | 0    | 0    | 0    | M 3, M 5          | Y           |

**Totals**: 73 64 50 58 42

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5 Electronic versions of tables containing this information for the USNO are available at [http://www-star.fnal.gov/ugriz/Filters/response.html](http://www-star.fnal.gov/ugriz/Filters/response.html), while analogous data for the CFHT’s MegaCam can be found at [http://www.cfht.hawaii.edu/Instruments/Imaging/Megacam/specsinformation.html](http://www.cfht.hawaii.edu/Instruments/Imaging/Megacam/specsinformation.html).
mosaic in previous frames. In total, 287 separate MegaCam images in the $u'g'r'i'z'$ filters was collected over the 12 separate nights listed in Table 1. All but one of these nights were deemed photometric on the basis of the observing logs, observer’s notes, and weather conditions at the Mauna Kea site with atmospheric seeing conditions ranging between 0.54′′ and 1.45′′ (FWHM; median of ~0.93′′) over all nights. Table 2 lists the number of short and long exposure images obtained per filter on a cluster-by-cluster basis. It is worthwhile to note that, in addition to the clusters listed in Table 2, the globular cluster M 5 and the open cluster M 67 were included as targets in the observing proposal. However, M 67 was not observed during this period, while only 8 $g'$ frames were taken for M 5. As a result, these two clusters are excluded from consideration for the remainder of the analysis. In addition, the 8 $i'$ images for M 3 obtained during non-photometric conditions were also excluded from the data reductions. This left 271 MegaCam images remaining to be processed in the analysis below.

It is important to note that all of the raw science images acquired for this investigation were preprocessed by the CFHT’s Elixir project (Magnier & Cuillandre 2004) prior to their distribution to the principal investigators. This involved the standard steps of overscan correction, bias subtraction, flatfielding (using run-averaged twilight sky flats), masking of standard steps of overscan correction, bias subtraction, flat-distribution to the principal investigators. This involved the acquired for this investigation were preprocessed by the CFHT’s data reductions. This left 271 MegaCam images remaining to be processed in the analysis below.

| Cluster | $u'$ | $g'$ | $r'$ | $i'$ | $z'$ |
|---------|-----|-----|-----|-----|-----|
| M 92   | 17  | 10  | 10  | 10  | 10  |
| M 13   | 16  | 10  | 10  | 10  | 10  |
| M 5    | 18  | 10  | 10  | 18  | 0   |
| M 71   | 10  | 10  | 10  | 10  | 10  |
| NGC 6791 | 18 | 10  | 10  | 10  | 12  |
| Totals | 73  | 64  | 50  | 58  | 42  |

Table 2
Number of $u'g'r'i'z'$ Observations per Cluster

2.2. Photometric Calibrations

As a result of the efforts described in Paper I, most star clusters in the CFHT survey contain a sizable number of local standard stars whose magnitudes have been referred to the $u'g'r'i'z'$ system with an accuracy of 1% or better in each filter. Therefore, calibrating the cluster photometry relies solely on comparing the observed instrumental magnitudes for these stars to their counterparts on the standard system in order to solve for the transformation coefficients using least-squares analysis. In the beginning stages of the calibration process, each CCD exposure from the mosaic was treated separately. That is, the transformation constants were allowed to be determined freely and independently on the basis of the local standard stars contained in the image. Unfortunately, since the range in air mass spanned by the cluster observations on any given night was typically quite small ($\Delta (\sec z) \lesssim 0.2$), it was soon discovered that the derived extinction coefficients often took on negative values and/or were wildly inconsistent between the different CCD images. Due to these findings, the canonical atmospheric extinction coefficients for Mauna Kea (as determined by the Elixir project) were employed for the calibrations rather than having them computed from the data. That is, all chips are assigned $K_u = 0.35$, $K_g = 0.15$, $K_r = 0.10$, $K_i = 0.04$, and $K_z = 0.03$ mag per air mass for all photometric nights.

With the extinction coefficients set to constant values for all chips, secondary runs through the calibrations were performed with one less unknown in the transformation equations. Upon completion, a weighted average of the linear color terms was then calculated and imposed as an additional known constant common to all chips for a final calibration run that left only the photometric zero points to be recomputed on a chip-by-chip basis. Given the fact that the spectral response of a telescope/detector system is largely determined by the combined effects of the transmission of the atmosphere, the reflectivity and transmissivity of the telescope components, and throughput of the filters, it can be expected that chip-to-chip differences in the computed color terms vary by only a few percent (provided that the CCDs are similar in design and the filter is spatially uniform). Indeed, from our own derivation of separate color terms for different chips, we found that the largest variations in the color coefficients between the different chips from any single photometric night amounted to $\sim 4\%$ in the $u'$ filter.

Once the transformation constants from all nights were derived, the best estimates of the calibrated magnitudes for each secondary standard star observed over all 11 photometric nights were then determined. Figures 3 and 4 illustrate the extent to which the cluster data have been placed on the standard system by comparing the $u'g'r'i'z'$ photometry to the mean calibrated photometry for the secondary standards stars. The
with respect to indicate that a sizable fraction of the secondary standards towards positive values in each panel of Figure 3; this seems to exhibit more scatter towards positive residual values as well as larger means and standard deviations when compared to plots that considered only less crowded stars. Hence, we strongly feel that our derived photometric transformations are sufficient to transform the observed MegaCam photometry to the standard system based on the fact that the median magnitude differences tend to lie within 0.01 mag of zero difference over the entire ranges in $g'$, $r'$, and $i'$, and the lines corresponding to zero difference tend to pass through the densest parts of the point distributions.

Secondly, the situation with the $u'$ magnitude differences plotted as a function of color in the top panel of Figure 4 appears quite troublesome. In particular, there is considerable disagreement in the residuals towards bluer and redder colors which would seem to suggest that the use of a single linear color term in the transformation equations is inadequate to account for the bandpass mismatch between the $u'$ and $u^*$ filters. As mentioned above, the CFHT’s $u^*$ filter was constructed to be substantially different than the $u'$ filter in order to take advantage of the good UV sensitivity of MegaCam and reduced atmospheric extinction at short wavelengths atop Mauna Kea. The effective wavelength of the $u^*$ filter is about 200 Å redder than that of $u'$, and, as shown in Figure 2, this places most of the $u^*$ response redward of the Balmer discontinuity at 3700 Å; this has profound implications for transforming the observed $u^*$ magnitudes for B- and A-type stars (i.e., those with the largest Balmer jumps) to the standard system.

2.3. Transforming $u^*$ to $u'$

The deviations shown in the top panel of Figure 4 for $\Delta u'$ appear to indicate that the transformation of MegaCam’s $u^*$ to $u'$ is more complex than can be accounted for using a simple linear color term. As a result, we have endeavored to derive a more realistic higher-order polynomial transformation that would better convert MegaCam’s $u^*$ photometry to $u'$ on the standard system. To keep this derivation as empirically-
and spectral class in order to better investigate the difference...catalog that cover a wide range in luminosity opted to use the SEDs presented in the Gunn & Stryker (1983) derived to transform the MegaCam photometry to the standard hand panel employs the linear color terms that were initially synthetic spectra presented by Castelli et al. (1997). The left-hand panel computes by convolving the respective filter transmission functions shown in Figure 2 with the stellar spectral energy distributions as presented by Gunn & Stryker (1983). Giant and dwarf stars in the Gunn & Stryker sample are denoted by open and solid circles, respectively. The median differences in the observed residuals from the top panel of Figure 4 are also plotted as solid gray squares to illustrate the agreement between our own data and the computed magnitudes. The solid line provides the third-order polynomial that was fit to the data to help transform $u^*$ to $u$. based as possible, we employed our own photometric data as well as the colors and magnitudes computed by convolving the filter transmission functions for both the standard $u'g'r'i'z'$ and MegaCam’s $u'g'r'i'z'$ systems (c.f. Figure 2) with the spectral energy distributions for real stars. For the latter, we opted to use the SEDs presented in the Gunn & Stryker (1983) spectrophotometric catalog that cover a wide range in luminosity and spectral class in order to better investigate the difference between $u^*$ and $u'$ photometry for different stellar types. When the differences between the “computed” $u^*$ and $u'$ magnitudes are compared against $(g' − i')$, as shown in Figure 5, we see that indeed there is a rather complex behavior in the residuals that appears to coincide quite well with the residuals shown in the top panel of Figure 4 (the gray squares with error bars denote the same median points plotted in Figure 4). While it would appear that the dwarfs and giants follow a slightly different trend towards redder colors (i.e., $(g' − i') ≳ 1.0$), we have decided to find a single, multi-order function that would best correct the $u^*$ photometry for most stellar types. Consequently, the solid line plotted in the figure indicates the third-order polynomial we have fitted to both sets of data to better define the transformation between $u^*$ and $u'$. Note that this fit is only valid over the range $−0.5 < (g' − i') < 3.5$ and is not intended to correct the $u^*$ photometry for extremely blue or red stars.

To test the quality of this new non-linear transformation between $u^*$ and $u'$, Figure 6 presents a comparison between various VandenBerg et al. (2006) isochrones with the denoted ages and metallicities (as plotted left to right in the figure) that have been transformed to the $[(u^* − g'), M_{r*}]$ plane using color–temperature relations computed from the ATLAS9 synthetic spectra presented by Castelli et al. (1997). The left-hand panel employs the linear color terms that were initially derived to transform the MegaCam photometry to the standard system, and it shows that the two sets of isochrones are in considerable disagreement in a number of different locations due to the mismatch between the $u^*$ and $u'$ filters, most notably in the turnoff region for metal-poor stars, and the RGB and main sequence regions for more metal-rich stars. The right-hand panel, on the other hand, plots isochrones where $u^*$ has been corrected using the third-order function shown in Figure 5. Reassuringly, the new nonlinear transformation seems to provide theoretical loci in the region $0.0 < (u^* − g') < 3.0$ that are in quite good agreement with those on the standard system, and, with a few exceptions discussed below, both sets of isochrones overlap each other to within 0.01 mag over the entire range in magnitude. This fact bodes well for our derivation of the fiducial cluster sequences in $u^*$ since the stars that define RGB, SGB, turnoff, and upper-MS loci for all clusters in the survey fall within this color range.

In regards to the few remaining obvious differences between the two theoretical loci in the right-hand panel for the upper-RGB for the most metal-poor isochrone and the lower-MS for the most metal-rich, they would appear to indicate that our polynomial relation is unable to correct the $u^*$ magnitudes for all types of stars (in particular, those stars that lie at the extremes of luminosity, color, and/or metallicity). Unfortunately, as far as we are aware, there does not exist a sufficient database of stars with varying metallicities, temperatures, and/or luminosities that have been observed in both the $u^*$ and $u'$ filters to conduct a more rigorous investigation into the differences between these two filters for a wide-variety of stellar types. Also, it is important to stress that the transformations between $u^*$ and $u'$ that we have derived here are invalid for blue horizontal branch stars or other hot stars, such as blue post-AGB stars, sdB stars, white dwarfs, or some blue stragglers. Although we are quite confident that...
the fiducials we derive below are accurately calibrated to the standard system for the $g'$, $r'$, $i'$, and $z'$ filters, we strongly advise the reader to use caution when employing the sequences that include $u'$ filter for the interpretation of stellar photometry, especially for metal-poor giants or metal-rich dwarfs, due to the simple fact that the fiducials may not be adequately transformed to $u'$ on the standard system for these types of stars.

3. THE CLUSTER PHOTOMETRY

The transformation terms computed during the calibration to the standard $u'g'r'i'z'$ system described in the previous section were subsequently applied to the instrumental magnitudes that were derived for all detected objects in every CCD image for each cluster field. Simultaneously, the zero points between the relative profile-fitting magnitude system and the standard one were reetermined by direct comparison to the local secondary standards within each cluster field on a frame-by-frame basis. This final step in the reduction process compensates for uncertainties caused by short-term fluctuations in the extinction or errors in the aperture corrections. While this does nothing to improve the absolute calibration of the photometry to the standard system in the mean, it does improve the frame-to-frame repeatability of the measurements by ensuring that the photometry from each image is now referred to a common magnitude zero point defined by the local secondary standards. In addition, the transformation of the natural ($x$, $y$) coordinates of the stars in each image to an astrometrically meaningful system based on the USNOB-1.0 catalog facilitates the matching of stars from different chips and different exposures and results in a single master star list for the entire field surrounding each cluster.

3.1. Refining the Sample

Given that we have on hand approximately 16.9 million individual magnitude and position measurements derived for some 650,000 distinct objects in five different clusters, it is inevitable that a sizable number of these detections will be non-stellar objects (e.g., background galaxies, cosmic rays, satellite or meteor trails) or image blemishes (e.g., defective pixels, diffraction spikes). Moreover, when dealing with crowded cluster fields such as these, the photometry for a significant fraction of the legitimate stars will undoubtedly be contaminated by light from neighboring objects even under the most ideal seeing conditions. As a result, when the cluster photometry is plotted on color–magnitute or color–color diagrams for the purpose of analysis, these spurious objects and crowded stars may contribute increased scatter or broadening of the primary cluster sequences, and it is better to exclude them from consideration when deriving the fiducials. While it is obviously not feasible to censor problematic measurements by hand, the various programs that have been used to extract the PSF instrumental photometry from the CCD images output certain image-quality and data-reliability indices that can be used to reject spurious detections or non-stellar objects from consideration. In addition to these indices, the discussion below describes the mechanics of the so-called “separation index” (sep; see Stetson et al. 2003) that is quite effective in culling severely crowded stars from the cluster data sets.

In brief, the definition of the separation index is based on the fact that the typical seeing profile for each star in a particular image is well approximated by the Moffat function (Moffat 1969):

$$ S(r) \propto \frac{F}{[1 + (r/r_o)^2]^\beta}, $$

(1)

where $r$ is the distance from the star’s centroid, $r_o$ is some characteristic radius that can be related to the FWHM of the stellar brightness profile, $F$ is just the stellar flux determined from $F \propto 10^{-0.4m}$, where $m$ is the apparent magnitude, $S(r)$ is the surface brightness of the stellar profile at radius $r$, and $\beta$ is a parameter that governs the shape of the stellar profile. Based on this definition, if one assumes a reasonable value for $\beta$ (typically 1.5–2.5 for stellar profiles in digital images) and FWHM for the seeing value, it is a simple matter to compute the surface brightness produced by a particular star with both an apparent magnitude $m$ and a centroid position at any point in the field. Based on this definition, the sep index for any given star can be mathematically expressed as

$$ sep_i = \frac{S_i(0)}{\Sigma_j S_j(r_j)}. $$

(2)

Here $S_i(0)$ is the surface brightness at the centroid of the star in question and $S_j(r_j)$ is the surface brightness contribution from the $j$th neighboring star situated at a distance $r_j$ away.

The computation of the sep index for the five different cluster data sets assumes the typical values of FWHM = 1.0′′ and $\beta = 2$ and uses the apparent $r'$ magnitude to define the fluxes for the individual stars. In order to save computational time, the determination of sep for any particular star in the field considers contributions only from those stars lying within 10 times the assumed FWHM. The top panel of Figure 7 shows the plot of the derived sep index versus apparent $r'$ magnitude for stars in M 13. As evidenced by the higher concentration of points at increasing magnitudes, fainter stars are more susceptible to contamination by light from neighboring stars in the field than bright ones. Since the M 13 turnoff corresponds to $r' \sim 18.6$, the scattering of points to brighter magnitudes and higher sep values primarily correspond to stars lying on the RGB and HB of this cluster. Based on examinations of the cluster CMDs using

![Figure 7. Plots of the image-isolation and image-quality indices sep, $\chi$, and sharp versus apparent $r'$ magnitude for stars in the globular cluster M 13. Only those stars with sep > 3.5 are plotted in the bottom two panels. Stars lying below the solid curve in the middle panel together with those having $-1 < \text{sharp} < 1$ in the bottom panel are retained in the sample for the derivation of the cluster fiducial sequences.](image-url)
Figure 8. Two \((g' - r', r')\) CMDs for stars in the field surrounding the globular cluster M 13. The left-hand panel plots those stars judged to have the highest quality photometry on the basis of their \(sep\), \(\chi\), and \(sharp\) values as described in the text. The right-hand panel presents stars that are excluded from the deviation of the fiducial sequences due to their poorer photometry. Note the more diffuse nature of the primary cluster sequences in the right-hand panel.

Figure 9. Various \(u'g'r'i'z'\) CMDs and associated derived fiducial sequences for the globular cluster M 92. Each panel includes only those stars judged to have the highest quality photometry based on their values of \(\chi\), \(sharp\), and \(sep\).

During the process of deriving PSF magnitudes the DAOPHOT/ALLSTAR software computes two image-quality indices known as \(\chi\) and \(sharp\) for every detected object in a CCD image. In the final reduction of all the data for a particular cluster, the individual \(\chi\) and \(sharp\) measurements for each star are then averaged and reported in the data tables. Briefly, \(\chi\) is simply a measure of the agreement between the object’s observed brightness profile and the derived PSF model (i.e., the quality of the fit between the model PSF and the object). As shown in the middle panel of Figure 7, the \(\chi\) values for the vast majority of objects with \(sep > 3.5\) in M 13 tend to cluster around \(\chi \approx 1\) over the entire magnitude range which would indicate that they are legitimate stars. Those at larger \(\chi\) values, on the other hand, are most likely either non-stellar objects or stars whose brightness profiles are corrupted by image defects or diffraction spikes. Stars lying above the solid curve shown in the same panel are excluded on the basis of the \(\chi\) values.
Figure 12. Same as Figure 9, but for the globular cluster M 71. Each panel plots only those stars that lie within a radius of 2.5′ from the cluster center in order to reduce field star contamination in the CMDs.

Figure 13. Same as Figure 9, but for the open cluster NGC 6791. u′ photometry is not available for this cluster. Each panel plots only those stars that lie within a radius of 5′ from the cluster center in order to reduce field star contamination in the CMDs. Finally, a plot of the sharp index versus apparent r′ magnitude in the bottom panel of Figure 7 shows that real stars have a propensity to hover in a narrow range centered on zero. This is due to the fact that the sharp index measures the degree to which an object’s intrinsic angular radius differs from that of the model PSF. Therefore, detections with large positive sharp values have larger characteristic radii compared to the PSF model and are most likely resolved galaxies, while those with significantly negative sharp values have apparent radii smaller than the seeing profile, and thus are unlikely to be astronomical objects viewed through the atmosphere and telescope optics; they probably correspond to an image blemishes or cosmic rays. As a result, one can safely assume that objects with |sharp| < 1 have a high degree of probability of being real stars.

To demonstrate the effectiveness of the χ, sharp, and sep indices in culling crowded stars and spurious objects from the photometry lists and producing extremely well-defined cluster sequences, Figure 8 shows two CMDs for M 13 with those stars that survived the cuts plotted in the left-hand panel and those that did not in the right. Note the well-defined and very tight cluster sequences extending from the RGB to the lower main sequence in the left-hand panel. In contrast, stars that were excluded in the right-hand panel result in a quite diffuse and noisy main sequence, turnoff, and lower-RGB regions due largely to the effects of crowding. It is important to mention that while the stars plotted in the left panel do not represent a complete sample of all the cluster members, they do provide a suitable representative sample for the derivation of the fiducial sequences.

3.2. Defining the Fiducials

With objects from each of the cluster data files rejected or accepted according to the cuts in χ, sharp, and sep mentioned above, the definition of the fiducial sequences from the cluster photometry proceeds by defining the ridge lines of the stellar locus in color–magnitude space. Due to the various possible combinations of different colors and magnitudes that are available to plot a cluster’s CMD, the r′ magnitude was adopted as the primary ordinate against which the median colors were...
defined since the cluster loci are rarely double valued in \( r' \), and the level of completeness at faint magnitudes is the best for \( r' \). Therefore, each ridge line is created by determining the median color of stars that lie within different \( r' \) magnitude bins. The size of these bins is arbitrarily adjusted along the cluster locus to include a sufficient number of stars to define a median color. For example, larger magnitude bins are defined in parts of the CMD where the photometric scatter is larger at the faint end and where the number of stars is scarce at the bright end. Smaller bins are employed for areas of the cluster loci with large curvature and numerous stars (e.g., between the turnoff and base of the RGB). Outlying stars are iteratively clipped during the determination of the median color to ensure that the ridge line is not significantly skewed. While this technique seemed to work quite well, it is just too small, the scatter in the sequences is too large, or there were some regions of the CMD where the number of stars is too small, the scatter in the sequences is too large, or the cluster locus is double valued (i.e., the subgiant branch of NGC 6791) for an accurate median color to be defined; in these cases the location of the points defining the ridge lines are determined by eye estimation.

Figures 9–13 present the various CMDs of each cluster in the sample along with their associated ridge lines spanning the MS, SGB, and RGB (tabulated in Tables 3–7). It is important to note that the photometry for each cluster has been censored according to the same \( \chi \), \( sharp \), and \( sep \) cuts mentioned above before plotting. In addition, only those stars that lie within a radius of 2.5\( \arcmin \) and 5.0\( \arcmin \) of the centers of M 71 and NGC 6791, respectively, have been plotted to help reduce field star contamination in their CMDs. These imposed cuts appear to have been quite successful in yielding extremely well-defined and tight loci of stars extending from the upper-RGBs down to approximately 4 magnitudes below the turnoff points.

### 4. SUMMARY

Using high-quality, homogeneous observations obtained with the wide-field MegaCam imager on the 3.6 m Canada–France–Hawaii Telescope, we have derived fiducial stellar population sequences for the Galactic star clusters M 92, M 13, M 3, M 71, and NGC 6791 in the \( u'g'r'i'z' \) photometric system. These sequences, which span a wide range in both metallicity and magnitude, have been accurately calibrated to within 1% of the standard \( u'g'r'i'z' \) system using a set of secondary standard stars derived in Paper I. As a result of our efforts, we anticipate that these fiducial sequences will serve as valuable tools for the interpretation of other stellar population investigations involving the \( u'g'r'i'z' \) bandpasses by virtue of the fact that they represent a set of empirical isochrones for both metal-poor and metal-rich stars having wide-ranging physical parameters. Indeed, a preliminary set of the fiducials presented in this work has already been employed in the interpretation of CMDs for a number of newly discovered Milky Way satellites (see, for example, Belokurov et al. 2006, 2007a, 2007b).

In addition to the usefulness of these fiducial sequences for the interpretation of observed data, they also provide an excellent test of the accuracy of color–temperature relations and bolometric corrections that have been derived from
model atmospheres and synthetic spectra. In a future paper (J. L. Clem et al. 2008, in preparation) we intend to perform tests of such synthetic color and magnitude transformations by comparing isochrones models to the fiducials derived here. Our aim is to assess the quality of the color–magnitude relations and bolometric corrections in providing isochrones that can reproduce the observed cluster photometry when reasonable estimates of the cluster reddening, metallicity, and distance are assumed, as well as test their consistency when isochrone fits to the \( u' g' r' i' z' \) photometry are compared to those in other photometric systems (e.g., BVR\( _{IC} \) and uvby).

It is important for the reader to note, however, that the fiducials derived in this investigation are presented on the \( u' g' r' i' z' \) system and not on the natural photometric system of the 2.5 m SDSS survey telescope (i.e., the \( ugriz \) system). Subtle differences exist between the two systems such that photometry reported on both systems for an identical stellar sample can differ systematically by as much as a few hundredths of a magnitude in some filters. Therefore, we caution against using these fiducials to interpret and/or analyze \( ugriz \) photometry from the SDSS without first applying appropriate transformation relations (see Tucker et al. 2006). Although these transformations may not be appropriate for stars with strong emission features in their spectra or stars with extreme colors (i.e., later than M0 spectral class), we expect they are good enough to transform the fiducials presented here on the \( u' g' r' i' z' \) system to the SDSS 2.5 m \( ugriz \) system, while keeping the uncertainties in the photometric zero points on the AB system (see Oke & Gunn 1983) to within a few percent.

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