NEW $g'r'i'z'$ PHOTOMETRY OF THE NGC 5128 GLOBULAR CLUSTER SYSTEM

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Received 2010 May 6; accepted 2010 September 14; published 2010 November 12

ABSTRACT

We present new photometry for 323 of the globular clusters in NGC 5128 (Centaurus A), measured for the first time in the $g'r'i'z'$ filter system. The color indices are calibrated directly to standard stars in the $g'r'i'z'$ system and are used to establish the fiducial mean colors for the blue and red (low and high metallicity) globular cluster sequences. We also use spectroscopically measured abundances to establish the conversion between the most metallicity-sensitive colors ($(g' - r')_0$, $(g' - i')_0$) and metallicity, [Fe/H].

Key words: galaxies: individual (NGC 5128) – globular clusters: general

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

The metallicity distributions of globular clusters (GCs) can provide unique information about the first major episodes of star formation that contribute to the formation of the host galaxy (see Brodie & Strader 2006 and Harris 2010b for reviews). It has now been well established that the observed color distribution of old GCs is bimodal in large galaxies of all types, showing distinct blue and red populations (Gebhardt & Kissler-Patig 1999; Peng et al. 2006; Brodie & Strader 2006; Harris 2009a). The color distribution translates into a bimodal metallicity distribution function (MDF), with the blue clusters corresponding to metal-poor GCs (with peak [Fe/H] $\sim -1.5$) and red clusters corresponding to metal-rich GCs ([Fe/H] $\sim -0.5$), with a second-order dependence on galaxy luminosity (Brodie & Strader 2006). The accurate conversion from color to metallicity is thus an invaluable observational tool for large-scale studies of GC systems. It can provide a way to construct comprehensive first-order MDFs based on very large samples (thousands of clusters) before proceeding with spectroscopic analysis, which requires significantly more telescope time.

Conversions between integrated GC color and metallicity are well known for metallicity-sensitive broadband color indices, such as $(B-I)$ or $(C-T_1)$, that have been frequently used in the past (see, e.g., Geisler et al. 1996; Harris et al. 2004a; Harris 2009a). Much less work of this type has been done in the US Naval Observatory (USNO) $u'g'r'i'z'$ filter system (Smith et al. 2002) or in the similar Sloan Digital Sky Survey (SDSS) $ugriz$ system, but the rapidly growing use of these systems indicates a need to investigate GC color calibrations in their colors that are most sensitive to metallicity. In addition, the potential for a comprehensive photometric data set over many bands within one galaxy, where they can be compared very directly, is appealing.

No single galaxy is an absolutely perfect target for developing the color/metallicity calibrations. The Milky Way GCs have the highest quality set of metallicity measurements, but the total GC population is small and the measurement of their integrated colors requires careful large-aperture work; see Peng et al. (2006) for a published $(g - z)$ calibration based partly on the Milky Way members. M31 has a much larger cluster system and $ugriz$ colors for its GCs have been published (Peacock et al. 2010), but many of these are affected by differing and often-uncertain amounts of reddening. The richest easily accessible and nearly unreddened collections of GCs are in the Virgo giant ellipticals at $d = 16$ Mpc. Jordán et al. (2009) supply $gz$ photometry of GCs in many Virgo members and Harris (2009b) provides $gri$ data for the extremely rich system in M87. These galaxies, however, lie at larger distances from us so their spectroscopic metallicity measurements are far less precise at present than for galaxies in the Local Group.

One of the most attractive individual galaxies for these purposes is NGC 5128, the central giant in the Centaurus group and the nearest giant elliptical galaxy that can be studied in detail. Since its first cluster was identified (Graham & Phillips 1980), it has been the subject of an extended series of GC studies (see Woodley et al. 2010a, 2010b, for citations and a review). At a distance of $3.8 \pm 0.1$ Mpc (Harris et al. 2010) and moderately low and uniform reddening ($E_{V-I} = 0.14$) across its halo, NGC 5128 is an excellent platform for detailed GC studies, permitting the investigation of both individual and global properties of the galaxy’s oldest stellar populations. The total GC population is estimated to be $N_{GC} = 1300 \pm 300$ (Harris 2010a), of which 607 have now been individually identified through a combination of radial velocity measurements (van den Bergh et al. 1981; Harris et al. 1992; Hesser et al. 1984, 1986; Peng et al. 2004b; Woodley et al. 2005; Rejkuba et al. 2007; Beasley et al. 2008; Woodley et al. 2010a, 2010b) and resolution into stars through Hubble Space Telescope (HST) imaging (Harris et al. 2006; Mouchine et al. 2010). In this study, we use an up-to-date catalog of the currently known sample (Woodley et al. 2007, 2010a, 2010b). The purpose of the present paper is to take additional steps towards a calibration of colors and metallicities in the $g'r'i'z'$ photometric system for this nearby, populous GC system.

The NGC 5128 GC system has now been shown to fall into the normal pattern of characteristics established from many other giant galaxies, both elliptical and disk (Harris et al. 2004a; Peng et al. 2004b, 2006). The GCs in this galaxy show the standard bimodal color and metallicity distributions from both photometry (e.g., Harris et al. 2002; Peng et al.

4 The two additional GCs not in the Woodley et al. catalog that were identified by Mouchine et al. (2010) are too faint to appear here.
studies have been carried out in the normal applicable to other galaxies. Previous large-scale photometric studies have been carried out in the normal UBVR system (Peng et al. 2004a) and also in the Washington CMT system (Harris et al. 1992, 2004a, 2004b).

In this paper, we present new measurements for the NGC 5128 clusters in the USNO $g'r'i'z'$ indices, carefully calibrated onto the current standard system. We then use these measurements, along with previously published spectroscopic data for GCs in both NGC 5128 and the Milky Way, to construct transformations from the $g'r'i'z'$ colors to metallicity, [Fe/H]. In Section 2, we discuss our new observations of NGC 5128 and outline our data reduction and photometry procedures, including the creation of our $g'r'i'z'$ catalog of the NGC 5128 GCs. In Section 3, we analyze the color–magnitude and color–color diagrams of both the field stars and GCs around NGC 5128, and in Section 4 we discuss the results of our metal–color calibration. In Section 5, we discuss the use of the $g'r'i'z'$ filter system for future GC studies. We conclude with our results in Section 6.

2. OBSERVATIONS AND REDUCTIONS

Imaging of the NGC 5128 field was taken over five consecutive nights in May 2008 with the Yale/SMARTS 1.0 m telescope at the Cerro Tololo Inter-American Observatory, Chile. Photometry was performed with the $20' \times 20'$ Y4KCam imager in the SDSS $griz \approx g'r'i'z'$ filters$^5$. The scale of the camera is 0.289 pixel$^{-1}$, and at the 3.8 Mpc distance of NGC 5128, 1' corresponds to a linear scale of 1.1 kpc. During the observing run, a malfunctioning amplifier rendered the NE quadrant of the detector unusable. We compensated by using three overlapping pointings, with NGC 5128 positioned on the central, western, and southern regions of the detector. Observations covered a $20' \times 20'$ region centered on NGC 5128 and two 10' × 10' regions east and north of the galaxy. Creating an overlapping grid on the sky, we were able to recover most of our originally planned spatial coverage of the NGC 5128 halo. The total integration time for each pointing was 0.8–1.4 hr in each filter. The seeing ranged from FWHM 1'1 to 1'8 over the course of the run$^6$.

For standardization purposes, 14 $g'r'i'z'$ standard stars from Smith et al. (2002) were also observed every night over the course of the run, typically resulting in 20 independent integrations each night, at intervals of 2–4 hr and over a wide range of colors and airmasses.

2.1. Data Reduction

Master flat fields for each filter were constructed from a combination of twilight flat exposures and dome flats. In addition, on-sky “blank fields” (high-latitude star fields devoid of bright galaxies and with minimal populations of field stars) were observed each night and combined to construct a final illumination correction for the camera. The flat fielding plus illumination correction allowed us to correct for the sensitivity across the detector to within 1%.

All frames were trimmed, overscan-subtracted, bias-corrected, and flat-fielded with the Massey Y4KCam scripts$^7$ written for IRAF$.^8$ Illumination corrections were applied to the $g'$ and $r'$ images. In the $i'$ and $z'$ filters, fringing patterns were also removed by constructing master fringe frames from smoothed medians of the blank-field exposures. These were subtracted from our science frames once normalized to their exposure time.

Large-aperture photometry was performed on the standard stars with a 13 pixel (3'78) radius, determined via a curve-of-growth analysis (IRAF package; Stetson 1990). Nightly photometric calibrations were derived from our observations of the standard stars and the catalog magnitudes in Smith et al. (2002), along with a linear model for the transformations

\[
\begin{align*}
    g'_{\text{inst}} &= g'_{\text{std}} + g' + k_g \Delta g' + a_g (g' - r')_{\text{std}} \\
    r'_{\text{inst}} &= r'_{\text{std}} + r_0 + k_r \Delta r' + a_r (r' - i')_{\text{std}} \\
    i'_{\text{inst}} &= i'_{\text{std}} + i_0 + k_i \Delta i' + a_i (i' - z')_{\text{std}} \\
    z'_{\text{inst}} &= z'_{\text{std}} + z_0 + k_z \Delta z' + a_z (i' - z')_{\text{std}}.
\end{align*}
\]

where $X$ represents the airmass and $g'_{\text{inst}}$ etc. are the large-aperture magnitudes on the internal instrumental scale. The color coefficients, $a_x$, were adopted to be constant over the five consecutive nights of the run; our least-squares solutions gave mean values:

\[
\begin{align*}
    a_g &= 0.003 \pm 0.008 \\
    a_r &= -0.016 \pm 0.009 \\
    a_i &= -0.021 \pm 0.011 \\
    a_z &= 0.015 \pm 0.026.
\end{align*}
\]

These color terms are all nearly zero and verify that the Y4KCam SDSS filters provide a very close match to the standard Sloan system. The airmass coefficients, $X_x$, were solved for each night. Since the airmasses were primarily in the range $X \sim 1.0 - 1.4$, our results are rather insensitive to the precise $k_x$ values.

We then carried out the photometry for all objects in our NGC 5128 program fields using daophot and phot small-aperture photometry within the digiphot.daophot package. Bright isolated stars were used to construct a mean point-spread function (PSF) for each field and each filter. With observations taken in >1.1 seeing conditions, most of the GCs in NGC 5128 appear very nearly star-like (a normal half-light diameter of 5 pc is equivalent to 0'27; see also Harris et al. 2002), enabling us to determine their relative magnitudes and colors from PSF-fitting photometry within digiphot.daophot.allstar. PSF magnitudes were converted to the same large-aperture magnitude scale by a mean offset ($\Delta m = m_{\text{large ap}} - m_{\text{PSF}}$ determined from bright, isolated target objects.

The World Coordinate System (WCS) solutions for the astrometry were derived in two steps. An initial guess to the solution was found with the public-domain astrometric calibration program astrometry.net described in Lang et al. (2010). The first-order WCS solution was fed into WCSSTOOLS (Mink 2002), where a precise solution was found by matching to the USNO UCAC2 catalog. We find that the resulting WCS solutions have mean uncertainties less than 0'25 for all measured objects.

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5 Transformations from Tucker et al. (2006) show the mean differences $\Delta m = m_{\text{USNO}} - m_{\text{SDSS}}$ for GCs observed in this study are $\Delta(g', r, i, z) = (-0.012, -0.005, -0.006, 0.004)$.

6 We note that for the Yale/SMARTS 1.0 m telescope, the observed FWHM is typically ~0'5 higher inside the dome than the outside seeing recorded by the dimm monitor.

7 http://www.lowell.edu/users/massey/obins/y4kcamred.html

8 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of the Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
the first step in the following analysis is to select out the GCs that genuinely belong to NGC 5128. We used the GC database from Woodley et al. (2007, 2010a, 2010b) to match 605 confirmed GCs in NGC 5128 to our catalog of $g'$ $r'$ $i'$ $z'$ measurements. To obtain the most complete set of correlations, we tried matches out to a search radius of 5″, although we found that ~95% of the matches were unique to within 0″8 with an average angular separation of 0″25, consistent with the astrometric accuracy described above. Any remaining duplicates that were clearly false matches were eliminated through their very different colors or magnitudes. Our final list contains 323 confirmed GCs with their internal uncertainties. Any “99.00” values indicate no data.

3. COLOR–MAGNITUDE AND TWO-COLOR DIAGRAMS

Figure 2 shows the color–magnitude diagrams of all measured objects in our NGC 5128 field in the form $r_0$ versus ($g' - r'$)$_0$, ($g' - i'$)$_0$, and ($g' - z'$)$_0$. The GCs are overplotted in red. The photometry is corrected for foreground reddening with $A'_v = 0.879 \cdot A_V = 0.33$, $E_{g' - r'} = 0.10$, $E_{r' - i'} = 0.07$, $E_{i' - z'} = 0.04$ (Fukugita et al. 1996). As noted above, about 95% of the objects in this diagram are field contamination, with most concentrated along ($g' - i'$)$_0$ ~ 1. In Figure 3, we show the color–magnitude diagrams for the GCs only. The characteristic bimodal color distribution is visible in all three plots, although is most obvious in the metallicity-sensitive ($g' - i'$)$_0$ and ($g' - z'$)$_0$ indices.
along with the bimodal solution described above, are shown in samples may reveal it. The color histograms from our data, intermediate mode in our data, but larger and more precise (additional discussion). We find no clear evidence for a third, intermediate-color mode may be due to a small proportion from the spectroscopic line indices for about 70 clusters. The tentative evidence for a trimodal metallicity distribution directly the red. It is worth noting here that Woodley et al. (2010b) found GCs are 0.07 in the blue and 0.02 in the red. The relative fractions of GCs are 0.63 ± 0.07 in the blue and 0.37 ± 0.07 in the red. To estimate the mean colors of each mode, we used the RMIX\(^9\) to fit bimodal Gaussian distributions, yielding \((g' - i')_0 = 0.85 \pm 0.02\) (blue), 1.13 ± 0.02 (red), and also \((g' - z')_0 = 0.98 \pm 0.03\) (blue), 1.35 ± 0.04 (red). The relative colors of typical GCs in these colors, showing that the typical GCs in this galaxy follow the classic pattern of large age and bimodal metallicity distribution like other giant ellipticals, so their range in color is already well restricted, with few genuinely young, blue objects. To specify these intrinsic colors a bit further, we look for their distributions in color–color space, relative to the field stars. Figure 5 shows three of the possible six color–color diagrams, again including all measured NGC 5128 sources, with the GCs over-plotted in red. In each graph, we define regions containing 90% of the GC population. Objects outside these boxes have a high probability of being either contaminants or star clusters that are not classically old. The slopes of the boxes shown in Figure 5 are \(\Delta(g' - r')/\Delta(r' - i') = 1.47\), \(\Delta(g' - i')/\Delta(g' - z') = 0.79\), and \(\Delta(r' - i')/\Delta(i' - z') = 0.74\). The regions of higher GC density highlight the intrinsic colors of typical GCs in these colors, showing that the typical GC population is confined to small regions in color–color space.

\(^9\) RMIX is publicly available at http://www.math.mcmaster.ca/peter/mix/mix.html.

To estimate the mean colors of each mode, we used the magnitude interval 18 < \(r'\) < 20 to avoid excessive random errors at the faint end and any systematic effects of the mass/metallicity relation at the bright end (see Harris 2009a). We used RMIX\(^9\) to fit bimodal Gaussian distributions, yielding \((g' - i')_0 = 0.85 \pm 0.02\) (blue), 1.13 ± 0.02 (red), and also \((g' - z')_0 = 0.98 \pm 0.03\) (blue), 1.35 ± 0.04 (red). The relative fractions of GCs are 0.63 ± 0.07 in the blue and 0.37 ± 0.07 in the red. As above, the dashed lines give the bimodal solution for the color distribution, while the solid line is the sum of both components. Lower panel: histogram of \((g' - z')_0\) colors for the same clusters. As above, the dashed lines give the bimodal solution for the color distribution, while the solid line is the total for the bimodal fit.

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\(^9\) RMIX is publicly available at http://www.math.mcmaster.ca/peter/mix/mix.html.
and that half of the field objects can be rejected this way. Perhaps the most effective single diagrams are $(g' - i')$ versus $(r' - i')$ and $(r' - i')$ versus $(i' - z')$ which define the narrowest zones.

4. CALIBRATION VERSUS METALLICITY

As mentioned above, one of the goals of our study was to define the baseline conversion of the $g'ri'z'$ color indices to metallicity, for “typical” old GCs. Ideally, transformation of a given color index to (say) $[\text{Fe}/\text{H}]$ would be done by having in hand both the photometric indices and the $[\text{Fe}/\text{H}]$ values as determined by high-dispersion spectroscopy. Peng et al. (2006) present a preliminary calibration of this type for $(g - z)$ versus $[\text{Fe}/\text{H}]$, using their unpublished photometry for 40 Milky Way clusters, plus 55 more from the Virgo giants M87 and M49 (see their Figures 11 and 12), along with a variety of literature sources for the spectroscopy.

In our case, high dispersion and high signal-to-noise (S/N) spectroscopy for the clusters in NGC 5128 are as yet available for only a small number of objects (see, e.g., Rejkuba et al. 2007; Taylor et al. 2010). However, Woodley et al. (2010b) present a recent spectroscopic study of a large sample of the NGC 5128 and Milky Way GCs through the use of Lick indices. A significant advantage of their database is that it analyzes the line indices of clusters within both galaxies on an internally homogeneous and self-consistent system, allowing a more reliable comparison. We use the material from their study here, realizing that it may be superseded once a more extensive database of high-dispersion spectroscopic metallicities becomes available.

Here we work with the two most metallicity-sensitive color indices $(g' - i')$, $(g' - z')$ and derive their transformations into $[\text{Fe}/\text{H}]$ in two steps. The first of these is their correlation against the Lick index $[\text{MgFe}]'\!$ defined as

$$[\text{MgFe}]' = \sqrt{\text{Mg}_b \times (0.72\text{Fe}5270 + 0.28\text{Fe}5335)}$$

(Thomas et al. 2003). $[\text{MgFe}]'$ is designed to be a relatively clean heavy-element abundance indicator, highly insensitive to $[\alpha/\text{Fe}]$ variations. In Figure 6, we show the dereddened color indices versus this index for the NGC 5128 clusters in our catalog that are in common with Woodley et al. (2010b). We find in both cases that linear relations match the data well given by

$$(g' - i')_0 = (0.575 \pm 0.039) + (0.203 \pm 0.021)[\text{MgFe}]'\! \quad (n = 61),$$

$$(g' - z')_0 = (0.660 \pm 0.048) + (0.253 \pm 0.025)[\text{MgFe}]'\! \quad (n = 59).$$

In both cases, the rms scatter around these mean lines is ±0.13 mag in color.

The second step is to transform $[\text{MgFe}]'$ to metallicity, $[\text{Fe}/\text{H}]$. Here we use the Milky Way GCs, which have metallicity measurements superior to those of any other galaxy. We adopt $[\text{Fe}/\text{H}]$ values from the catalog of Harris (1996) (2003 edition).
and correlate these against their [MgFe]′ values measured in Woodley et al. (2010b) from Milky Way GC spectra obtained from Puzia et al. (2002) and Schiavon et al. (2005). The results for 40 Milky Way clusters are shown in Figure 7. We note here that the catalog values of [Fe/H] were originally based on the Zinn & West (1984) scale. However, a large number of abundance measurements from high-dispersion spectroscopy have been added, making the current Milky Way catalog list of metallicities close to the Carretta & Gratton (1997) scale.

An interesting question raised by Figure 7 is whether or not the conversion is adequately matched by a linear relation. From Puzia et al. (2002), Woodley et al. (2010b), and Harris (1996), we estimate that the typical uncertainty in each quantity is ±0.1 dex. We find the best-fit linear or quadratic relations to be

\[
[MgFe]′ = (2.987 ± 0.075) + (1.347 ± 0.062) [Fe/H] \quad \text{(linear),} \tag{7}
\]

\[
[MgFe]′ = (3.253 ± 0.120) + (1.966 ± 0.230) [Fe/H] + (0.281 ± 0.104) [Fe/H]^2 \quad \text{(quadratic).} \tag{8}
\]

The rms scatter around these relations is ±0.19 (linear) and ±0.17 (quadratic). Given also that the solution for [Fe/H]^2 term is significant at the 3σ level, we therefore find a slight preference for the quadratic solution and recommend it for future use. We note that Peng et al. (2006) also found that a single linear transformation for (g − z) to [Fe/H] was not suitable. Figure 7 shows, however, that in the range −1.7 ≤ [Fe/H] ≤ −0.3 that contains the great majority of clusters, the difference between the linear and quadratic conversions is small.

Combining the two steps outlined above, our color to metallicity conversions are

\[
(g′ − i′)_0 = 1.235 + 0.399 [Fe/H] + 0.057 [Fe/H]^2, \tag{9}
\]

\[
(g′ − z′)_0 = 1.483 + 0.497 [Fe/H] + 0.071 [Fe/H]^2. \tag{10}
\]

At a mean typical GC metallicity [Fe/H] ≃ −1, we therefore have \(Δ(g′ − i′)/Δ[Fe/H] ≃ 0.29\) and \(Δ(g′ − z′)/Δ[Fe/H] ≃ 0.36\).

With good photometric measurement precisions of ±0.05, the \(g′i′z′\) indices can then be used to predict metallicities to within internal uncertainties of typically ±0.15 dex.

We can compare our recommended conversion of \((g′ − z′)_0\) to [Fe/H] with that of Peng et al. (2006); both curves are shown in Figure 8. For this purpose, the very small differences between the \(g′z′\) and \(g′z′\) systems mentioned earlier are unimportant. Peng et al. adopt a two-section linear curve with the changeover point at [Fe/H] ≃ −1, roughly halfway between the normal metal-poor and metal-rich GC sequences, and compare their data with several population-synthesis models (see their Figure 12). The internal scatter of their [Fe/H] data points around their adopted calibration is not specifically listed but appears to be ±0.2–0.3 dex. The differences between their curve and the one we have derived here are within −0.1 dex over most of the range. While the Milky Way GCs constrain our transformation in the range −2.0 ≤ [Fe/H] ≤ −0.5 (0.7 ≤ \((g′ − z′)_0\) ≤ 1.3), we note our transformation agrees well with Peng et al. for [Fe/H] ≥ −0.5. Close inspection of the data used by Peng et al. (see their Figure 12) indicates that our continuous quadratic transformation falls close to the centroid of their data, and fits the calibration as well as any of the various model curves shown there.

The conversions derived above can be used to determine the mean metallicities of the NGC 5128 GCs. If we adopt the mean colors obtained in Section 3, we find [Fe/H] = −1.19 (blue), −0.27 (red) from a direct average of \((g′ − i′)_0\) and \((g′ − z′)_0\). The two colors give the same metallicities to within ±0.05 dex. In addition, the Peng et al. (2006) calibration for \((g − z)\) gives the same means to within ±0.04 dex. These values are ≃0.1 dex more metal rich than has often been obtained in other giant ellipticals (e.g., Geisler et al. 1996; Brodie & Strader 2006; Harris 2009a), but they fall within the expected range given the combined internal uncertainties in the photometric calibration, reddenings, and transformation coefficients.

Another consistency check of the external accuracy of these transformations can be done by comparing our results with the \(gri\) photometry of the M87 cluster system by Harris (2009b). The data from that study consist of photometry for several thousand GCs throughout the M87 halo, placed accurately on the SDSS standard system by reference to the SDSS-DR5 catalog of sources in the same region. The blue and red GC sequences in M87 are located at mean intrinsic colors \((g − i)_0\) (blue) = 0.80, \((g − i)_0\) (red) = 1.07, obtained using \(E_{g−i} = 0.03\). These translate through the preceding equations into mean metallicities...
of $[\text{Fe/H}] = -1.47$ (blue), $-0.56$ (red), which are both within $\pm 0.1$ dex of the metallicities for the two sequences in giant galaxies obtained through a variety of other methods (e.g., Brodie & Strader 2006).

### 5. COMPARISON OF FILTER SYSTEMS

As noted in the Introduction, broadband photometry with a metallicity-sensitive color index is a fast and effective way to derive first-order MDFs for GC systems, though ultimately not as accurate (or internally precise) as spectroscopic indices. Many different color indices have been used in published studies for this purpose, and it is of interest to gauge how the $u'g'r'i'z'$ filter system compares with others. The well known Johnson/Cousins $(V - I)$ is not an especially sensitive index (see Barmby et al. 2000), but it was adopted particularly in many early HST-based studies that were crucial to defining the bimodality paradigm (e.g., Gebhardt & Kissler-Patig 1999; Larsen et al. 2001, among many others) essentially because the heavily used Wide Field Planetary Camera 2 camera had relatively low blue response. Two other common indices are $(B - I)$ (e.g., Harris 2009a) and $(C - T_1)$ (e.g., Geisler et al. 1996; Harris et al. 2004a). For comparison, the equations linking them to $[\text{Fe/H}]$ are

\begin{align}
(V - I)_0 &= 1.15 + 0.156[\text{Fe/H}] \\
(B - I)_0 &= 2.158 + 0.375[\text{Fe/H}] \\
(C - T_1)_0 &= 1.998 + 0.748[\text{Fe/H}] + 0.138[\text{Fe/H}]^2.
\end{align}

Their slopes near the mid-range $[\text{Fe/H}] \approx -1$ are 0.156 for $(V - I)$, 0.37 for $(B - I)$, and 0.47 for $(C - T_1)$, compared to 0.285 for $(g' - i')$ and 0.355 for $(g' - z')$. Of these five, the Washington index $(C - T_1)_0$ appears to be the most sensitive to metallicity because of its wide baseline and also because the $C$ filter is positioned directly over a large number of heavy-element absorption lines. A more complete comparison of the Johnson/Cousins color indices, including the various pairs that can be constructed from $UBVRIJK$, is given by Barmby et al. (2000).

The use of the near-UV filter in the $u'g'r'i'z'$ system could in principle yield an even more sensitive index such as $(u' - i')$ or $(u' - z')$, but (for most ground-based cameras) at a huge penalty in exposure time. Combinations of optical filters with near-infrared filters have also been explored, such as the combination of $B$ and $R$ with the 3.6 $\mu$ color (Spitler et al. 2008), or $(V - K)$ (Barmby et al. 2000). These have a very wide baseline and can “split” the bimodal GC sequences more clearly, but have the disadvantage that the observations require two sets of instrumentation.

We regard both $(g' - i')_0$ and $(g' - z')_0$ as competitive color indices for GC MDF photometry, though both $(B - I)_0$ and $(C - T_1)_0$ continue to be effective for this purpose as well. These four indices all provide good compromises between intrinsic metallicity sensitivity and the necessary exposure times to obtain precise photometry. For ground-based photometry, an extra factor to consider is the degree of fringing present in the red or near-infrared filters. For example, the fringing was fairly large in the $z'$ filter in this work (as noted above) and this may reduce the internal precision that can be achieved for $(g' - z')$, offsetting the advantage of its wider color baseline.

The data in the Woodley et al. (2010a) catalog also provide a convenient summary of the $(C - T_1)_0$ color indices extracted from the Washington-system survey of the NGC 5128 field (Harris et al. 2004b). The color distribution for 500 clusters in the magnitude range $17 < T_1 < 21$ is shown in Figure 9. Earlier versions of the $(C - T_1)_0$ distribution based on much smaller numbers of individually selected clusters were derived in Harris et al. (1992); Woodley et al. (2005, 2010b). A bimodal-Gaussian fit to this distribution yields mean colors for the two modes of $1.413 \pm 0.038$ (blue), $1.902 \pm 0.038$ (red), with proportions $0.565 \pm 0.074$ (blue), $0.435 \pm 0.074$ (red). There is no significant presence of additional modes.

### 6. CONCLUSIONS

In this study, we have used new ground-based photometry to generate a database of $g'r'i'z'$ indices for the GCs in NGC 5128, the nearest giant elliptical galaxy. Our data have been calibrated against fundamental USNO standard stars and thus provide among the first comprehensive calibrations of intrinsic GC colors in the $g'r'i'z'$ system. Our final data list contains colors and magnitudes for 323 known GCs covering the metallicity range $-2 < [\text{Fe/H}] < 0$.

Adding this material to previously published high-S/N spectroscopic indices for clusters in NGC 5128 and the Milky Way, we derive transformations between $(g' - i')_0$, $(g' - z')_0$, $[\text{MgFe}]^\prime$, and $[\text{Fe/H}]$. These transformations can be used to determine metallicity distributions from the USNO color indices to a typical precision of $\pm 0.15$ dex. Comparison with other widely used photometric indices indicates that the colors constructed from $g'r'i'z'$ are competitive with other broadband optical indices such as $(B - I)$ or $(C - T_1)$.

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ERRATUM: “NEW $g’r’i’z’$ PHOTOMETRY OF THE NGC 5128 GLOBULAR CLUSTER SYSTEM”
(2010, AJ, 140, 2101)

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Received 2011 May 5; published 2011 July 19

Online-only material: machine-readable and VO tables

Due to a conversion error, the right ascension values of all NGC 5128 globular clusters in Table 1 and the online-only photometry catalog were incorrect. No other values in the photometry catalog were affected. A corrected version of Table 1 appears below; and the corrected version of the full machine-readable catalog appears online. We thank Marina Rejkuba for bringing this error to our attention.

Table 1

| ID   | $\alpha$ (J2000) | $\delta$ (J2000) | $V$  | $g’$ | $\sigma_{g’}$ | $r’$ | $\sigma_{r’}$ | $i’$ | $\sigma_{i’}$ | $z’$ | $\sigma_{z’}$ |
|------|-----------------|-----------------|------|------|---------------|------|---------------|------|---------------|------|---------------|
| GC001| 13:25:01.13     | -42:56:51.995   | 18.75| 19.255| 0.033         | 18.477| 0.025         | 18.086| 0.034         | 17.858| 0.031         |
| GC039| 13:24:38.74     | -43:06:26.660   | 19.45| 20.046| 0.059         | 19.129| 0.034         | 18.683| 0.038         | 18.417| 0.037         |
| GC043| 13:24:40.47     | -42:53:35.130   | 99.00| 99.000| 99.00         | 21.718| 0.068         | 21.188| 0.091         | 99.00| 99.00         |
| GC045| 13:24:41.03     | -42:59:48.380   | 20.23| 20.439| 0.086         | 19.891| 0.047         | 19.442| 0.048         | 19.137| 0.046         |
| GC046| 13:24:41.18     | -43:01:45.605   | 19.22| 19.708| 0.054         | 19.017| 0.038         | 18.722| 0.042         | 18.552| 0.039         |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)