**LETTER TO THE EDITOR**

**Globular clusters of NGC 3115 in the near-infrared**

**Demonstrating the correctness of two opposing scenarios**

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**ABSTRACT**

We combined new near-infrared VLT/HAWK-I data of the globular clusters (GCs) in the isolated edge-on S0 galaxy NGC 3115 with optical and spectroscopic ones taken from the literature, with the aim of analyzing the multiband GC color distributions. A recent study from the SLUGGS survey has shown that the GCs in this galaxy follow a bimodal distribution of Ca II triplet indices. Thus, NGC 3115 presents a critical example of a GC system with multiple, distinct, metallicity subpopulations, and this may argue against the “projection” scenario, which posits that the ubiquitous color bimodality mainly results from nonlinearities in the color-metallicity relations. Using optical, NIR, and spectroscopic data, we found strong and consistent evidence of index bimodality, which independently confirms the metallicity bimodality in NGC 3115 GCs. At the same time, we also found evidence for some color–color nonlinearity. Taken in the broader context of previous studies, the multicolor consistency of the GC bimodality in NGC 3115 suggests that in cases where GC systems exhibit clear differences between their optical and optical-NIR color distributions (as in some giant ellipticals), the apparent inconsistencies most likely result from nonlinearities in the color-metallicity relations.

**Key words.** galaxies: elliptical and lenticular, cD – galaxies: individual: NGC 3115 – galaxies: star clusters: general

1. Introduction

The study of globular cluster (GC) systems in galaxies is one of the keystones for understanding the processes at the base of the formation and evolution of galaxies (Ashman & Zepf 1992; Brodie & Strader 2006). Recently, the interpretation of one of the most intriguing properties of GC systems in early-type galaxies, the nearly universal presence of two distinct peaks in the optical-color distribution, has inspired a vigorous and prolific debate (Yoon et al. 2006, 2011; Kundu & Zepf 2007; Chies-Santos et al. 2012; Blakeslee et al. 2012; Usher et al. 2012; Vanderbeke et al. 2014).

The importance of GC bimodality was recognized before it was a commonly observed property in early-type galaxies (Ashman & Zepf 1992). The apparent inconsistencies most likely result from nonlinearities in the color-metallicity relations of GCs (Peng et al. 2006; Richtler 2006; Yoon et al. 2006). In particular, Yoon and colleagues and Richtler demonstrated that these nonlinearities naturally produce bimodal color distributions derived from different colors. These authors

There are various proposed explanations for the GC color bimodality in ETGs: *dissipational* merging of spirals, in which a merger-formed population of red, metal-rich GCs is assumed to appear distinct from the blue, metal-poor GCs of the progenitor spirals (Ashman & Zepf 1992); the dry hierarchical assembly, which begins with a massive “seed” ETG that has a unimodal metal-rich GC distribution, and in which it is possible to produce a bimodal metallicity distribution through dissipationless accretion of many early-type dwarfs (Côté et al. 1998); and the *in situ* formation scenario (Forbes et al. 1997). Most of these proposed mechanisms, though, have assumed a simple linear conversion between [Fe/H] and color, which seemed justified from the small fractional age variations among the GCs (Cohen et al. 1998; Kuntschner et al. 2002; Puzia et al. 2005). However, this assumption became the subject of debate when three independent works, using observations and stellar population models, pointed out non-negligible nonlinearities in the color-metallicity relations of GCs (Peng et al. 2006; Richtler 2006; Yoon et al. 2006). In particular, Yoon and colleagues and Richtler demonstrated that these nonlinearities naturally produce bimodal color histograms from nonbimodal [Fe/H] distributions. This interpretation, dubbed the projection effect, provided an alternative explanation based on stellar evolution for the ubiquity of bimodal GC color distributions.

In this regard, Cantiello & Blakeslee (2007) suggested the use of multicolor GC histograms to verify the consistency of [Fe/H] distributions derived from different colors. These authors
highlighted the role of optical to near-infrared (NIR) colors to distinguish between genuine bimodality in [Fe/H] and projected bimodality in color. If the nonlinear projection is at work, then the [Fe/H] distributions inferred from linear inversion of different color indices for the same GC sample will show some degree of inconsistency (discordant [Fe/H] peaks and/or fractions of GCs in each [Fe/H] component). The analysis of optical-to-NIR GC colors in various ETGs, as well as $u$ to $z$ photometry in some Virgo cluster members, indicates that the nonlinear projection effect is present at some level in these galaxies (Blakeslee et al. 2012; Chies-Santos et al. 2012; Yoon et al. 2011, 2013).

At the same time, the results of the SLUGGS survey, which collected spectra of ~1000 GCs in 11 galaxies and derived [Fe/H] from the calcium II triplet index, CaT, support true [Fe/H] bimodality in at least some galaxies in addition to the Milky Way. Usher et al. (2012) found evidence for bimodal CaT distributions in six of eight galaxies with sufficient numbers of GC spectra. Nevertheless, the spectroscopically and photometrically derived [Fe/H] distributions show non-negligible differences in several galaxies of the SLUGGS sample, thus lacking the aforementioned multi-index coherence. However, the case of NGC 3115, an isolated lenticular galaxy at a distance of ~10 Mpc (Tonry et al. 2001), revealed highly consistent [Fe/H] and color distributions, leading the authors to present this galaxy as a critical test of [Fe/H] bimodality (Brodie et al. 2012). Previous optical VLT FORS2 spectroscopy for 17 GCs in NGC 3115 showed hints of both a bimodal metallicity distribution and color or spectral index nonlinearity (Kuntschner et al. 2002), but it was limited by sample size.

In this Letter, we combine new NIR photometry with literature data to investigate the consistency of the bimodality in the optical, NIR, optical-NIR colors, and CaT, of the GCs in NGC 3115.

2. Observations

To analyze the properties of the GC system in NGC 3115, we took advantage of NIR observations with VLT/HAWK-I, HST/ACS optical photometry from Jennings et al. (2013) and spectroscopy from the SLUGGS survey (Usher et al. 2012).

All photometry is corrected for Galactic foreground-reddening using the Schlegel et al. (1998) maps, with recalibration from Schlafly & Finkbeiner (2011). To compare all data in the same photometric system, magnitudes were converted to AB mag using the zero points derived using the SYNPHOT task of IRAF/STSDAS and the spectrum of Vega from the Kurucz (1993) atlas of stellar atmosphere models.

2.1. VLT/HAWK-I near-infrared data

We used HAWK-I science verification data. The observations were carried out in very good seeing conditions, with $FWHM \leq 0.7$ in all three bands. The science observations centered on NGC 3115 were interleaved with sky exposures of equal exposure time. The total on-source exposure times were 480 s in $I$, 960 s in $H$, and 1620 s in $K_s$.

A series of custom IDL scripts was used to carry out the data reduction. Briefly, this consisted of subtracting dark exposures, producing super-sky flats from the stacked, unregistered sky exposures, and applying the derived flats to the individual science and sky exposures. Finally, individual exposures were registered and coadded.

Because it is difficult to model the disk component of the galaxy, we adopted the approach described in Jordán et al. (2004). After taking the logarithm of the galaxy image, we fitted two-dimensional bicubic splines to the brightness distribution using SExtractor (Bertin & Arnouts 1996). We then took the inverse logarithm of this model and subtracted it from the original image.

The photometry was then obtained from a second run of SExtractor on the residual image. Because of the very strong SBF signal (Tonry et al. 1990), we added the galaxy model times a filter-dependent constant to the SExtractor input rms map to avoid detecting surface brightness fluctuations as sources (see Jordán et al. 2004). To derive the absolute calibration, we compared our photometry catalogs with the 2MASS point source catalog. A total of 15 point sources in the JH frames, and 11 in $K_s$ were used to derive the zero points, providing $zp_J = 25.75 \pm 0.06$ mag, $zp_H = 26.03 \pm 0.06$ mag, and $zp_K = 25.03 \pm 0.09$ mag. The list of matched sources is reported in Table 2.

2.2. Optical photometry and spectroscopy

We compared the NIR data with ACS optical photometry and with the SLUGGS data. The literature catalogs were selected on the basis of either the radial velocity or the spatial extent of the source or for both quantities. This allowed us to obtain GC catalogs with negligible contamination from foreground or background sources.

The SLUGGS survey is based on Subaru Suprime-Cam $g i$ photometry and Keck/Deimos Ca II triplet spectroscopy. The final sample of matched sources includes $N_{GC} = 88$ GCs (HS sample hereafter).

The ACS catalog consists of deep $g_{F475W}$ and $z_{F850LP}$ photometry. We paired our NIR catalog with the ACS one, which produced a sample of $N_{GC} = 264$ GC candidates (HA sample).

Finally, we also considered the sample of objects obtained by matching all three of the catalogs, which includes 74 GCs (HSA sample).

We analyzed the color and CaT distributions for the above three samples using the Gaussian mixture modeling code (GMM, Muratov & Gnedin 2010). This uses the likelihood-ratio test to compare the goodness of fit for double Gaussians versus a single Gaussian. For the best-fit double model, it estimates the means and widths of the two components, their separation $DD$, and the degree of inconsistency (discordant [Fe/H] peaks and/or fractions of GCs in each [Fe/H] component) for the same GC sample will show some degree of inconsistency (discordant [Fe/H] peaks and/or fractions of GCs in each [Fe/H] component).

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we selected only GCs within the magnitude range $20.5 \leq m_R \leq 22.5$, and photometric uncertainty on color $\Delta m < 0.07$ mag (sel#2).

The results of the GMM tests on the three GC samples with the two different selection criteria are reported in Tables 3–4 and can be summarized as follows:

i) **HS sample (sel#1)** – The color–color and color–CaT diagrams for this sample and selection are shown in Fig. 1. In general, the GMM results agree well for the various indices. However, for the purely NIR colors, the likelihood ratio test, $p(x^2)$, is consistent with a bimodal distribution in $J-Ks$ and $H-Ks$, while the $p$-values for the peak separation and kurtosis do not significantly favor bimodality.

ii) **HA sample (sel#1)** – Although the sample is nearly twice as large as the HS sample, the relevance of color bimodality in optical and optical-to-NIR data, and the lack of a strong evidence of bimodality in NIR colors is nearly identical to the previous case.

iii) **HSA sample** – The sample, contains 58 GC candidates in the case of sel#1 and returns GMM values consistent with the two previous samples (Fig. 2).

iv) **sel#1 versus sel#2** – As expected, the results of GMM obtained using sel#1 or sel#2 are very similar for the HS and HSA samples. This is mostly a consequence of the small difference between the catalogs obtained when adopting one selection or the other. However, the similarity between selections #1 and #2 is also true for the HA sample, which is twice as large as sel#2, meaning that it reaches $N_{GC}$ up to four times higher than some other samples or selections.

v) **Red GCs** – Although the values for the fraction of red GCs $f_{red}$ derived from different samples, or selection, or colors are largely consistent, closer inspection shows the systematic nature of $f_{red}$ with respect to galactocentric distance $R_{GC}$, that is, the radial gradient in mean GC color. In particular, for sel#1 we find ($f_{red}^{HA}$) = 0.67 ± 0.04, while ($f_{red}^{HS}$) = 0.55 ± 0.04$^4$.

Because the mean $R_{GC}$ of the HA sample is smaller than that of the HS ($R_{GC}^{HA}$ = 16% smaller), the difference in $f_{red}$ for the two samples reflects the known tendency of red GCs to be more centrally concentrated than blue ones (Kissler-Patig 1997; Larsen & Brodie 2003).

A summary of Tables 3, 4 is reported in Table 1. The table gives the averaged $p$-values from the different samples, obtained from coupling all the optical colors (e.g. $g-i$; the column $N_{col}$ gives the number of colors used for the average), all the optical-to-NIR (e.g. $g-H$), and all the NIR colors (e.g. $J-K$). The most profound result here, again, is the coherence between optical and optical-to-NIR colors, and the already mentioned lack of bimodality in NIR colors based on peak separation and kurtosis statistics.

Before moving on, we note that in some cases the GMM analysis indicates that three Gaussians are preferred to

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**Table 1. Average results of GMM tests.**

| Col. range | $p(x^2)$($z$) | $p(DD)$($z$) | $p(kurt)$($z$) | $f_{red}$ ($z$) | $N_{col}$ |
|-----------|---------------|---------------|----------------|----------------|----------|
| **GC selection #1** | | | | | |
| Optical | 0.00(0.02) | 0.03(0.04) | 0.06(0.01) | 0.55(0.02) | 5 |
| Opt.+NIR | 0.00(0.02) | 0.15(0.04) | 0.03(0.01) | 0.56(0.02) | 24 |
| NIR | 0.20(0.09) | 0.67(0.11) | 0.92(0.06) | 0.44(0.12) | 9 |
| **GC selection #2** | | | | | |
| Optical | 0.00(0.01) | 0.02(0.05) | 0.06(0.01) | 0.56(0.02) | 5 |
| Opt.+NIR | 0.00(0.03) | 0.17(0.03) | 0.03(0.01) | 0.52(0.02) | 24 |
| NIR | 0.07(0.11) | 0.82(0.04) | 0.94(0.07) | 0.36(0.08) | 9 |

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$^4$ For the selection #2 we find ($f_{red}^{HA}$) = 0.56 ± 0.09, and ($f_{red}^{HS}$) = 0.52 ± 0.06.
range of the models. It is evident that the GC system covers almost the full metallicity from the full set of color–color diagrams (Georgiev et al. 2012).

Optical-to-NIR colors compared with purely optical colors allow a more consistent interpretation of integrated colors is hindered by the age-metallicity degeneracy (Raimondo et al. 2005). The model grid ranges from 2 to 14 Gyr in SSP age, and from −2.3 to +0.3 dex in [Fe/H]. Interpretation of integrated colors is hindered by the age-metallicity degeneracy (Worthey 1994). In this case, though, the broad wavelength coverage of the data and the higher sensitivity to [Fe/H] of optical-to-NIR colors compared with purely optical colors allows one to set more robust constraints on the stellar populations from the full set of color–color diagrams (Georgiev et al. 2012). Overall, the SSP models and the data agree well in general, and it is evident that the GC system covers almost the full metallicity range of the models.

In Fig. 2 we show a color–color diagram for the HSA sample (sel#1). The sample from matching the three catalogs is smaller than the others considered above. However, the features observed in other samples are preserved, with lower scatter. Among these we highlight first, the absence of a GC component with $i$−$H$ ≤ 3 dex, or even the complete lack of clusters with this or a lower metallicity. Second, on the high-metallicity regime, some GC candidates ($g_{F475W} − 2\times\text{sSFO}P ≥ 1.5$ and $i−H ≥ 0.9$ mag) are consistent with [Fe/H] ≥ +0.3 dex. The fraction of high-metallicity GC candidates is ∼5–10%. Other color–color diagrams also show a similar fraction of GCs above the [Fe/H] = 0.3 dex limit.

Furthermore, while the bluer GCs appear to match the locus of SSP models for ages $t > 10$ Gyr, the red clusters are more consistent with $t < 10$ Gyr. However, the age sensitivity of the models is weak, and uncertainties in evolutionary and atmospheric models of AGB stars—such as low temperature opacity, the prescriptions for mass loss and dust—as well as the presence of extreme horizontal branch stars, might lead to artificial age differences. Nonetheless, the suggested trend agrees with other studies that found the metal-poor GCs to be 1–2 Gyr older than metal-rich ones (Puzia et al. 2005; Woodley et al. 2010).

An additional interesting feature of Fig. 2 is the nonlinear shape of the color–color relation: at blue colors, $i − H$ increases steeply with $g_{F475W} − 2\times\text{sSFO}P$; the dependence flattens at intermediate colors before becoming steep again. This is similar to the behavior found by Blakeslee et al. (2012) and resembles the quasi-inflection point present in color-metallicity relations, possibly indicating the shift in HB morphology around $i−H ∼ 0.5$ mag (Yoon et al. 2006; Cantiello & Blakeslee 2007).

Finally, with regard to the dip in the color distributions, there is general agreement among the various color indices for a deficit of GCs in the $−1.2 ≤ [\text{Fe/H}] ≤ −0.4$ dex range. This confirms the results from the CaT index (Brodie et al. 2012) and indicates that CaT provides metallicity estimates consistent with integrated colors (when interpreted with the above models), at least at this intermediate [Fe/H] regime.

### 5. Discussion and conclusions

Our analysis of the GC system in NGC 3115 provides additional definitive proof of GC [Fe/H] bimodality in this S0 galaxy, the first to be firmly established beyond the Milky Way. Various studies have noted that to rule out the possibility that nonlinearities project a nonbimodal [Fe/H] distribution into a bimodal color distribution, one must recover consistent [Fe/H] distributions from multiple different photometric indices. In particular, Cantiello & Blakeslee (2007) showed that optical-to-NIR colors are the most useful in constraining the underlying metallicities. This is in part because the broad color baselines imply a lower sensitivity to the detailed shape of the index–metallicity relation; for the converse reason, bimodal [Fe/H] distributions may not be evident in the purely NIR colors. The present study confirms these expectations: i) the optical and optical-to-NIR colors are clearly bimodal and consistent with each other in terms of proportions of red and blue GCs; and ii) the pure NIR distributions give ambiguous results, in the sense that different colors and/or statistical indicators show the presence or lack of bimodality.

The comparison of GC colors with SSP models confirms earlier results (Brodie et al. 2012), using CaT as a proxy for metallicity, which derived a bimodal [Fe/H] distribution with a dip at $−1.3 ≤ [\text{Fe/H}] ≤ −0.3$ dex. The model comparison also suggests that the metal-rich GCs have slightly younger ages than (or as good as) the double Gaussians model. The results of GMM fits with three components are reported in Table 5. Only cases where the least populated peak contains at least ∼10% of the total population are considered. Although some colors for some samples are well fit with three Gaussians, we stress the lack of coherence in these tri-modal models for different colors.

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**Table 2.** Matched HAWK–JHK photometry for all detected sources.

| ID (J2000) | RA (J2000) | Dec (J2000) | $m_J$ (mag) | $m_H$ (mag) | $m_K$ (mag) | (CS) |
|---|---|---|---|---|---|---|
| 1 | 151.261846 | −7.778326 | 14.532 ± 0.001 | 14.560 ± 0.001 | 14.832 ± 0.001 | 0.997 |
| 2 | 151.339249 | −7.779547 | 15.262 ± 0.002 | 15.290 ± 0.001 | 15.713 ± 0.001 | 0.990 |
| 3 | 151.328988 | −7.815540 | 13.407 ± 0.001 | 13.335 ± 0.001 | 13.949 ± 0.001 | 1.000 |
| 4 | 151.246152 | −7.782556 | 20.196 ± 0.013 | 20.526 ± 0.018 | 21.869 ± 0.061 | 0.020 |
| 5 | 151.280919 | −7.782237 | 19.050 ± 0.007 | 19.092 ± 0.006 | 19.317 ± 0.008 | 0.983 |

**Notes.** Columns list: (1) ID number; (2) right ascension; (3) declination; (4) $J$-band magnitude; (5) $H$-band magnitude; (6) $K_s$-band magnitude; (7) sExtractor mean JHK’s CLASS_STAR parameter.

5 [http://www.oa-teramo.inaf.it/spot](http://www.oa-teramo.inaf.it/spot)

6 Larger fractions, up to ∼15%, are implied by the $z − J$ or $z − H$ colors. The data-to-model mismatch might in part results from the uncertainty in high-[Fe/H] SSP models for these colors that is caused by the partial overlap or proximity of the passbands and uncertainties in stellar atmosphere models in this wavelength regime. However, a similar fraction of GCs with [Fe/H] ≥ 0.3 dex was also found by Brodie et al. (2012) – we transformed their $[\text{Fe/H}]$ assuming the results of Tantalo et al. (1998), with $[\text{Fe}/\text{Fe}] = 0.35$ (Pietrinferni et al. 2006). Moreover, these higher-metal-rich fractions are for the HA sample, which is the most centrally concentrated of the considered samples (item (iv), Sect. 3), and would therefore have the highest proportion of metal-rich GCs.
Indirectly, when taken in the broader context of previous work, the bimodality of [Fe/H] systems and, more specifically, the existence or lack of a universal color nonlinearity, most clearly in the case of consistency of the color distributions, we also observe color–metallicity relations playing an important role for some previously studied giant ellipticals. Finally, our study shows the effectiveness of optical-to-NIR colors as an unambiguous test for underlying metallicity bimodality.

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| Color | \( z_{\text{red}} \) | \( \chi^2 \) | Peak Separation (p) | Width Ratio \( \rho \) | Degree of Preference (p-value) |
|-------|-----------------|--------------|-------------------|----------------|-----------------------------|
|       |                 |              |                   |                |                            |
| g-H   | 0.944 ± 0.010  | 1.381 ± 0.016| 0.70 ± 0.011     | 0.25 ± 0.011  | 0.49 ± 0.012                |
| g-Ks  | 0.942 ± 0.010  | 1.381 ± 0.016| 0.70 ± 0.011     | 0.25 ± 0.011  | 0.49 ± 0.012                |
| J-H   | 1.381 ± 0.016  | 0.70 ± 0.011 | 0.25 ± 0.011     | 0.38 ± 0.014  | 0.44 ± 0.012                |
| J-Ks  | 1.381 ± 0.016  | 0.70 ± 0.011 | 0.25 ± 0.011     | 0.38 ± 0.014  | 0.44 ± 0.012                |
| H-Ks  | 0.49 ± 0.012   | 0.49 ± 0.012 | 0.49 ± 0.012     | 0.49 ± 0.012  | 0.49 ± 0.012                |
| \( \Delta \chi^2 \) | 0.63 ± 0.010   | 0.63 ± 0.010  | 0.63 ± 0.010     | 0.63 ± 0.010  | 0.63 ± 0.010                |

Notes: Columns list: (1) color; (2) mean uncertainty of the first and second peaks in the double-Gaussian model; (3) mean uncertainty of the first and second peaks in the single-Gaussian model; (4) width ratio \( \rho \); (5) peak separation \( p \); (6) kurtosis \( \kappa \) indicating the significance of the preference for a double-Gaussian over a single-Gaussian model (lower \( p \)-values are more significant); (7) (11) separation of the peaks in units of the two Gaussian widths; (12) kurtosis of the distribution \( \xi \).
Table 4. Results of GMM runs on GCs selected using criterion \#2 (based on Δ color and magnitude, see text).

| Color (1) | p1 (2) | p2 (3) | \(σ_1\) (4) | \(σ_2\) (5) | \(N_{GC}\) (6) | Frac (7) | \(p(x^2)\) (8) | \(p(DD)\) (9) | \(p(kar)\) (10) | DD (11) | Kurtosis (12) |
|----------|--------|--------|-------------|-------------|-------------|--------|-------------|-------------|-------------|---------|-------------|
| g – i    | 0.785 ± 0.011 | 1.106 ± 0.133 | 0.060 ± 0.007 | 0.076 ± 0.011 | 68 | 0.523 ± 0.064 | 0.001 | 0.023 | 0.001 | 4.74 ± 0.54 | -1.467 |
| g – J    | 1.032 ± 0.083 | 1.672 ± 0.110 | 0.112 ± 0.057 | 0.251 ± 0.066 | 68 | 0.566 ± 0.144 | 0.001 | 0.167 | 0.001 | 3.30 ± 0.59 | -1.292 |
| g – Ks   | 0.867 ± 0.083 | 1.710 ± 0.084 | 0.221 ± 0.058 | 0.261 ± 0.068 | 65 | 0.536 ± 0.112 | 0.003 | 0.134 | 0.003 | 3.49 ± 0.54 | -1.210 |
| i – J    | 0.308 ± 0.040 | 0.671 ± 0.072 | 0.101 ± 0.025 | 0.120 ± 0.034 | 69 | 0.375 ± 0.146 | 0.002 | 0.190 | 0.008 | 3.28 ± 0.66 | -0.994 |
| i – H    | 0.219 ± 0.034 | 0.697 ± 0.047 | 0.103 ± 0.022 | 0.155 ± 0.029 | 69 | 0.510 ± 0.084 | 0.001 | 0.114 | 0.001 | 3.63 ± 0.49 | -1.309 |
| i – Ks   | 0.068 ± 0.008 | 0.608 ± 0.085 | 0.189 ± 0.051 | 0.191 ± 0.055 | 69 | 0.502 ± 0.155 | 0.114 | 0.322 | 0.008 | 2.84 ± 0.43 | -0.997 |
| J – Ks   | -0.324 ± 0.141 | -0.028 ± 0.051 | 0.173 ± 0.059 | 0.104 ± 0.029 | 60 | 0.686 ± 0.240 | 0.100 | 0.798 | 0.977 | 1.45 ± 1.26 | 1.063 |
| H – Ks   | -0.147 ± 0.107 | -0.074 ± 0.025 | 0.124 ± 0.046 | 0.031 ± 0.023 | 61 | 0.368 ± 0.210 | 0.013 | 0.845 | 0.988 | 0.82 ± 1.57 | 1.381 |
| J – H    | -0.128 ± 0.054 | 0.037 ± 0.095 | 0.027 ± 0.023 | 0.092 ± 0.028 | 67 | 0.191 ± 0.294 | 0.781 | 0.474 | 0.729 | 2.43 ± 1.01 | 0.019 |
| G/T      | 5.26 ± 0.256 | 7.70 ± 0.257 | 0.828 ± 0.205 | 0.741 ± 0.129 | 69 | 0.523 ± 0.106 | 0.022 | 0.217 | 0.015 | 3.18 ± 0.51 | -0.426 |

HA (HAWK-1-ACS) Sample:

| \(\theta_{FESP} – \theta_{VESP}\) | 0.931 ± 0.009 | 1.325 ± 0.018 | 0.060 ± 0.006 | 0.149 ± 0.010 | 252 | 0.596 ± 0.037 | 0.001 | 0.118 | 0.001 | 3.47 ± 0.29 | -1.307 |
| \(\theta_{FESP} – H\) | 1.089 ± 0.048 | 1.699 ± 0.061 | 0.173 ± 0.056 | 0.214 ± 0.036 | 207 | 0.500 ± 0.097 | 0.001 | 0.127 | 0.002 | 3.14 ± 0.38 | -0.711 |
| \(\theta_{FESP} – Ks\) | 1.034 ± 0.028 | 1.760 ± 0.032 | 0.170 ± 0.020 | 0.231 ± 0.021 | 215 | 0.563 ± 0.045 | 0.001 | 0.102 | 0.001 | 3.58 ± 0.24 | -1.188 |
| \(\theta_{FESP} – Ks\) | 0.837 ± 0.025 | 1.670 ± 0.039 | 0.168 ± 0.028 | 0.300 ± 0.045 | 165 | 0.674 ± 0.050 | 0.001 | 0.118 | 0.038 | 3.43 ± 0.43 | -0.573 |

HSA (HAWK-1-GLUGGS-ACS) Sample:

| \(\theta_{FESP} – \theta_{VESP}\) | 0.917 ± 0.016 | 1.367 ± 0.025 | 0.065 ± 0.001 | 0.120 ± 0.022 | 56 | 0.573 ± 0.073 | 0.001 | 0.021 | 0.001 | 4.65 ± 0.68 | -1.453 |
| \(\theta_{FESP} – \theta_{VESP}\) | 0.140 ± 0.017 | 0.274 ± 0.018 | 0.030 ± 0.010 | 0.054 ± 0.011 | 56 | 0.630 ± 0.127 | 0.032 | 0.277 | 0.005 | 1.06 ± 0.59 | -1.129 |
| \(\theta_{FESP} – J\) | 0.789 ± 0.027 | 1.116 ± 0.014 | 0.057 ± 0.025 | 0.071 ± 0.014 | 56 | 0.554 ± 0.082 | 0.001 | 0.008 | 0.001 | 5.07 ± 0.91 | -1.477 |
| \(\theta_{FESP} – H\) | 1.052 ± 0.037 | 1.705 ± 0.069 | 0.124 ± 0.023 | 0.248 ± 0.042 | 56 | 0.554 ± 0.093 | 0.001 | 0.202 | 0.002 | 3.32 ± 0.63 | -1.226 |
| \(\theta_{FESP} – Ks\) | 0.858 ± 0.009 | 1.178 ± 0.014 | 0.245 ± 0.029 | 0.285 ± 0.077 | 56 | 0.542 ± 0.124 | 0.027 | 0.208 | 0.005 | 3.28 ± 0.50 | -1.132 |
| \(\theta_{FESP} – Ks\) | 0.182 ± 0.026 | 0.491 ± 0.061 | 0.105 ± 0.022 | 0.048 ± 0.034 | 168 | 0.185 ± 0.127 | 0.011 | 0.998 | 0.106 | 3.78 ± 0.84 | -0.756 |

Notes. Columns list: same as in Table 3.
Table 5. Results of GMM runs for the three Gaussian model with GCs selected using criterion #1.

| Color | $p_1$ ($N_{GC}$, $\sigma$) | $p_2$ ($N_{GC}$, $\sigma$) | $p_3$ ($N_{GC}$, $\sigma$) | $p_4$ ($\chi^2$) | $p_5$ (DD) | $p_6$ (kurt) | DD | Kurtosis |
|-------|-----------------------------|-----------------------------|-----------------------------|-----------------|-------------|--------------|-----|----------|
| HS (HAWK-I+SLUGGS) sample ($N_{GC}^{tot}$ = 73) |
| $g - J$ | 1.063 (34.5, 0.114) | 1.472 (6.5, 0.049) | 1.746 (32.0, 0.197) | 0.001 | 0.033 | 0.001 | 4.67 | -1.241 |
| $i - J$ | 0.251 (25.9, 0.058) | 0.428 (25.5, 0.112) | 0.685 (21.5, 0.111) | 0.003 | 0.718 | 0.012 | 1.99 | -0.944 |
| $i - H$ | 0.221 (32.4, 0.078) | 0.475 (7.1, 0.033) | 0.713 (33.5, 0.120) | 0.001 | 0.098 | 0.001 | 4.23 | -1.364 |
| GaT |
| $g - J$ | 5.064 (13.1, 0.285) | 6.162 (29.8, 1.141) | 7.881 (30.1, 0.681) | 0.019 | 0.89 | 0.005 | 1.32 | -1.062 |
| $g - z$ | 0.951 (44.6, 0.073) | 1.177 (8.5, 0.027) | 1.388 (74.8, 0.107) | 0.001 | 0.118 | 0.001 | 4.11 | -1.254 |
| $g - J$ | 1.078 (43.1, 0.102) | 1.412 (8.1, 0.060) | 1.718 (76.8, 0.206) | 0.001 | 0.136 | 0.001 | 4.00 | -1.145 |
| $g - K_s$ | 0.878 (42.6, 0.159) | 1.636 (73.1, 0.215) | 2.023 (12.2, 0.185) | 0.001 | 0.11 | 0.001 | 4.01 | -1.063 |
| $z - J$ | 0.123 (45.7, 0.068) | 0.313 (72.5, 0.094) | 0.521 (9.8, 0.024) | 0.036 | 0.444 | 0.012 | 2.32 | -0.805 |
| $z - H$ | 0.110 (44.2, 0.081) | 0.264 (8.9, 0.025) | 0.435 (74.9, 0.099) | 0.01 | 0.449 | 0.003 | 2.58 | -0.947 |
| HA (HAWK-I+ACS) sample ($N_{GC}^{tot}$ = 128) |
| $g - J$ | 1.063 (34.5, 0.114) | 1.472 (6.5, 0.049) | 1.746 (32.0, 0.197) | 0.001 | 0.033 | 0.001 | 4.67 | -1.241 |
| $g - z$ | 0.951 (44.6, 0.073) | 1.177 (8.5, 0.027) | 1.388 (74.8, 0.107) | 0.001 | 0.118 | 0.001 | 4.11 | -1.254 |
| $g - J$ | 1.078 (43.1, 0.102) | 1.412 (8.1, 0.060) | 1.718 (76.8, 0.206) | 0.001 | 0.136 | 0.001 | 4.00 | -1.145 |
| $g - K_s$ | 0.878 (42.6, 0.159) | 1.636 (73.1, 0.215) | 2.023 (12.2, 0.185) | 0.001 | 0.11 | 0.001 | 4.01 | -1.063 |
| $z - J$ | 0.123 (45.7, 0.068) | 0.313 (72.5, 0.094) | 0.521 (9.8, 0.024) | 0.036 | 0.444 | 0.012 | 2.32 | -0.805 |
| $z - H$ | 0.110 (44.2, 0.081) | 0.264 (8.9, 0.025) | 0.435 (74.9, 0.099) | 0.01 | 0.449 | 0.003 | 2.58 | -0.947 |
| HSA (HAWK-I+SLUGGS+ACS) sample ($N_{GC}^{tot}$ = 58) |
| $g - J$ | 1.099 (26.6, 0.114) | 1.629 (25.6, 0.191) | 2.035 (5.8, 0.112) | 0.007 | 0.173 | 0.002 | 3.56 | -1.139 |
| $g - z$ | 1.042 (25.4, 0.144) | 1.801 (6.7, 0.071) | 1.779 (25.9, 0.278) | 0.005 | 0.009 | 0.001 | 6.69 | -1.256 |
| $g - J$ | 0.956 (33.2, 0.278) | 1.707 (6.6, 0.158) | 1.705 (8.1, 0.116) | 0.006 | 0.042 | 0.008 | 5.09 | -1.059 |
| $g - K_s$ | -0.026 (3.7, 0.035) | 0.148 (27.1, 0.084) | 0.452 (27.3, 0.108) | 0.237 | 0.437 | 0.01 | 2.70 | -1.048 |
| $z - J$ | 0.126 (33.2, 0.059) | 0.290 (13.7, 0.038) | 0.479 (11.3, 0.054) | 0.015 | 0.177 | 0.173 | 3.33 | -0.658 |
| $z - H$ | -0.162 (17.2, 0.152) | 0.058 (9.9, 0.044) | 0.340 (30.9, 0.175) | 0.745 | 0.754 | 0.252 | 1.97 | -0.577 |
| Notes. | Columns list: (1) color; (2–4) first, second and third peaks in the three Gaussian model, numbers within parentheses are the number of GCs associated with each peak, and the width of the distribution; (5–7) GMM $p$-values, as in Table 3; (8) separation of the peaks in units of the three Gaussian widths; (9) kurtosis of the distribution.