Near Infrared Photometry of Galactic Globular Clusters M56 and M15. Extending the Red Giant Branch vs. Metallicity Calibration Towards Metal Poor Systems.

Valentin D. Ivanov
Steward Observatory, The University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721; vdivanov@as.arizona.edu

Jordanka Borissova
Institute of Astronomy, Bulgarian Academy of Sciences, 72 Tsarigradsko chaussée, BG – 1784 Sofia, Bulgaria, jura@haemimont.bg

Almudena Alonso-Herrero
Steward Observatory, The University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721; aalonso@as.arizona.edu

and

Tatiana Russeva
Institute of Astronomy, Bulgarian Academy of Sciences, 72 Tsarigradsko chaussée, BG – 1784 Sofia, Bulgaria

ABSTRACT

Infrared JK_s-band photometry of the Galactic globular clusters M15 and, for the first time, M56 is presented. We estimated the reddening \( E(B−V) = 0.18 \pm 0.08 \text{ mag} \) and distance modulus \( ([m−M]_V = 15.43 \pm 0.30 \text{ mag}) \) towards the poorly studied globular cluster M56. We combined our data with observations of other clusters from the literature (12 in total) to extend the \([\text{Fe}/\text{H}]\) vs. Red Giant Branch (RGB) slope relation towards metal-poor clusters. Our best fit yields to \([\text{Fe}/\text{H}] = −3.40(±0.22) − 27.74(±2.35) \times (\text{RGB Slope}), \) with an r.m.s. = 0.20. The broader metallicity baseline greatly reduced the uncertainties compared to other existing calibrations. We confirmed a previously obtained calibration of the relation between the RGB color \((J−K_s)_0(\text{RGB})\) at \( M_{K_s} = −5.5 \) vs.

\(^1\)Based on data taken at the Steward Observatory 2.3m Bok Telescope equipped with the 256x256 near IR camera.
[Fe/H]: $[\text{Fe/H}] = -6.90(\pm 0.99) + 6.63(\pm 1.05) \times (J - K_s)_0(RGB)$ with an r.m.s. = 0.33. Finally, using the new RGB slope calibration we estimated the abundance of the super metal-rich cluster Liller 1 $[\text{Fe/H}] = 0.34 \pm 0.22$.

Subject headings: Stars: Population II – Stars: Hertzsprung-Russell (HR) diagram – Galaxy: globular clusters: individual: M15 – Galaxy: globular clusters: individual: M56 – Galaxy: globular clusters: individual: NGC7099 – Galaxy: globular clusters: individual: NGC6553 – Galaxy: globular clusters: individual: Liller 1

1. Introduction

Globular clusters are a fundamental laboratory for the study and understanding of stars and their evolution. They offer a unique opportunity to study samples of stars with a single age and metallicity, and provide a sequence of parameters which describe the stellar populations as ensembles of stars. Those parameters include the position of the red giant branch (RGB), the relative populations of the blue and red horizontal branches, and the relative number of RR Lyr variables.

Davidge et al. (1992) considered for the first time the slope of the RGB on a combined optical-infrared color-magnitude diagram (CMD) as a metallicity indicator. This technique is particularly promising (Kuchinski, Frogel & Trendrup 1995; Kuchinski & Frogel 1995; Ferraro et al., 2000), because it is not affected by the reddening towards the cluster. Bypassing the reddening correction can help to improve significantly the photometric determination of the metallicity of more distant and highly obscured systems.

The stars on the RGB radiate most of their energy in the infrared, with the added advantage that the reddening is greatly diminished in this part of the spectrum. Although both those arguments are not relevant for observations of Galactic globular clusters, they become critical in the studies of distant systems, where the patchy internal extinction is added to the foreground extinction in the Milky Way, which makes the interpretation of the data more difficult. Also, many potential targets of interest (such as nearby dwarf galaxies) are expected to have a low metal content. Until recently, the available calibrations did not span all the necessary range of [Fe/H]. Indeed, Kuchinski & Frogel (1995) based their calibration on a set of Galactic globular clusters with metallicities from [Fe/H] = 1.01 to -0.25. Ferraro et al. (2000) presented for the first time high quality near infrared CMDs of 10 Galactic globular clusters, and a detailed analysis of the RGB behavior as a function of metallicity.
The goal of this work is to increase the statistical basis of the RGB slope vs. [Fe/H] calibration, and to test the existing calibrations (Kuchinski, Frogel & Trendrup 1995; Kuchinski & Frogel 1995; Ferraro et al., 2000). Clusters with low metallicities are of particular interest, because they will allow to make this tool applicable to metal-poor stellar systems. We will also increase the statistical basis of the RGB slope vs. [Fe/H] calibration.

We present here JK$_s$ photometry of the central area of M 15 and, for the first time, M 56. The basic data for the clusters are given in Table [Harris 1996; June 22, 1999 version]. They are both extremely metal-poor clusters. The table contains data on two more clusters (M 30 and NGC 6553) which we collected from the literature.

M 15 is a well studied Galactic globular cluster. It possesses one of the highest known central densities (Yanny et al. 1994). King (1975) and Bahcall & Ostriker (1975) speculated that the cluster might have undergone a core collapse or might contain a central black hole. Sandage (1970) obtained ground-based photometry of the outer region of M 51 and detected an extended blue horizontal branch (hereafter HB) but no significant population of blue stragglers. Subsequent photometric works were presented by Aurière & Cordoni (1981), Buonano et al. (1985), Bailyn et al. (1988), and Cederblom et al. (1992). More recently, the cluster was observed in the optical with the HST by Ferraro & Parsce (1993) and Yanny et al. (1994). Frogel, Persson & Cohen (1983) published JHK measurements of five bright red giants in M 15. The most recent variability study of M 15 (Buter et al., 1998) reported light curves of 30 confirmed variable stars, mostly RR Lyr.

In contrast, M 56 is surprisingly poorly studied, probably because is lays close to the Galactic plane ($l = 62.66^\circ, b = +8.34^\circ$). Rosino (1951) obtained the first photographic CMD of this cluster. Barbon (1965) built the first CMD in the standard BV colors. Smriglio, Dasgupta & Boyle (1995) used the Vilnius photometric system to estimate the extinction towards M 56, and pointed to a possible reddening variation across the cluster area. A number of observations of variable stars in M 56 have been undertaken throughout the years (Sawyer 1940; Sawyer 1949; Rosino 1961; Wehlau & Sawyer Hogg 1985). The latest CMD for this cluster (Grundahl et al. 1999) is in the Strömgren $(u, u - y)$ system and shows very well defined blue and red HBs.

2. Observations and Data Reduction

We obtained JK$_s$ imaging of M 56 and M 15 using a 256 × 256 NICMOS3 array at the 2.3-m Bok Telescope of the University of Arizona on Kitt Peak, with a plate scale of 0.6 arcsec pixel$^{-1}$, under photometric conditions on Nov 5, 1998. The average seeing during
the observations was 1.0-1.2 arcsec. The observational strategy consisted of taking cluster images interleaved with sky images 6′ – 7′ away from the targets. We dithered both object and sky images to improve the bad pixel and cosmic ray corrections.

The data reduction included subtraction of dark current frames, flat-fielding with median combined empty sky frames, and sky subtraction using IRAF. The images were shifted to a common position with cubic spline interpolation, and averaged together to produce the final image. The photometric calibration was performed using observations of standard stars from the list of Elias et al. (1982). Although we used the $K_s$ filter which has shorter longer wavelength transmission limit than the $K$ standard filter, the two photometric system are nearly identical (Persson et al. 1998) within the observational errors. The photometric calibration errors associated with the standard stars scatter are 0.05, and 0.06 mag in $J$, and $K_s$ respectively.

The stellar photometry of the final combined frames was carried out using DAOPHOT II (Stetson 1993). We found some small variations in the FWHM of the PSF ($\approx 0.08$ arcsec) between the inner and outer frame regions. A variable PSF was constructed using a large number of moderately bright, isolated stars. We assumed that the PSF varied linearly with the position in the frame. A subset of the photometric data is presented in Table 2 where the coordinates are given in pixels relative to the cluster centers, and the last two columns contain the formal DAOPHOT errors.

The formal DAOPHOT errors shown in Figure 1 demonstrate the internal accuracy of the photometry. The typical errors down to $J \leq 16$ and $K_s \leq 16$ are smaller than 0.1 mag. The larger spread of errors in M15 is due to the denser central core of this cluster. To account for the uncertainty of the sky subtraction we added in quadrature 0.01 mag in $J$, and 0.02 mag $K_s$ to these errors. To estimate independently the internal accuracy of our photometry we carried out an artificial star simulation. This is the most complete technique for error determination because it includes the sky background variations, crowding errors, and the PSF variations across the field. We added 100 artificial stars with known brightnesses at random places on the $J$ and $K_s$ images of each cluster. We measured then their magnitudes in the same manner as for the program stars. We repeated this simulation ten times and calculated the mean standard deviations for given magnitude bins (Table 3). We successfully recovered the formal DAOPHOT errors (Figure 1). The former errors are small compared with the photometric calibration errors, and thus we used the

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DAOPHOT errors throughout the paper taking advantage of the individual error estimates for each star.

We have one star in common with Frogel, Cohen & Persson (1983) - I-12 in their notation. It is at the edge of our field. They estimated $K = 9.42$, and $J = 10.19$. Our measurements are $K_s = 9.37 \pm 0.06$, and $J = 10.29 \pm 0.06$ where the formal DAOPHOT errors and the photometric calibration errors are added in quadrature. The corresponding differences are 0.05 mag and 0.10 mag, acceptable if compared with the errors. Undoubtedly some of the problem in $K_s$ may arise from the different photometric systems. Persson et al. (1998; see their Table 3) showed that for red stars $K_s$ and $K$ are rarely further apart than 0.02 mag.

3. Color-Magnitude Diagrams

The $K_s$, $J - K_s$ CMD for M 15 and M 56 datasets are presented in Figure 2. Only stars with DAOPHOT errors of less than 0.06 for $K_s \leq 14.0$ mag, (filled circles) and stars with errors less than 0.10 for $K_s \geq 14.0$ (open circles) were included. To minimize the field star contamination in M 56 for stars with $K_s$ brighter than 14.0, only stars within the radius $r = 1.16'$ (Harris 1996) were included. The stars from within 7 times the core radius of M 15 ($r_{core} = 0.07'$, Harris 1996) were excised.

3.1. M 15

The giant branch of M 15 is very well defined up to $K_s = 9.5$ mag. The position of the brightest non-variable star suggests that the RGB tip lies at $(J - K_s) = 0.92$ mag and $K_s = 9.37$ mag. None of the red variables listed in Clement (1999) lies in our field.

The HB can be identified at $K_s = 14.35 \pm 0.3$ mag, derived as an average of 25 RR Lyr stars (represented by diamonds in Figure 2; Clement 1999). Unfortunately our observations do not span long enough time interval to calculate the average K-band magnitude of each RR Lyr star. Instead, the plotted RR Lyr magnitudes represent their snapshot brightnesses at the moment of the observation. The typical amplitude of RR Lyr in the infrared is 0.2-0.3 mag (Carney et al., 1995). Combined with the average photometric error (0.17 mag for $K=14-16$), it accounts for the HB uncertainty.

The red HB spans a range from $(J - K_s) = 0.46$ to 0.35 mag. On the $(V, B - V)$ CMD, M 15 shows the typical HB morphology of metal-poor clusters, with a high blue-to-red HB star ratio, and large number of RR Lyr variables (Durrell & Harris 1993). Our data are not
deep enough to detect the blue HB stars.

3.2. M 56

The giant branch is well defined up to $K_s \approx 10$ mag. The RGB tip lies at $(J - K_s) = 0.94$ mag and $K_s = 9.72$ mag. The horizontal branch can be identified at $K_s = 14.45 \pm 0.02$ mag. The clump at $(J - K_s) = 0.45$ mag constitutes the red HB, and the stars with $(J - K_s)$ between 0.10 and 0.20 mag and $K_s$ between 14.45 and 15.60 mag are the blue HB. Unfortunately our photometry is not complete at this level to determine the blue-to-red HB star ratio. Since the cluster is close to the Galactic plane, some background contamination would be present. The stars with $(J - K_s) \approx 0.2$ and $K_s \leq 14.5$ mag are a clear example. Among the fainter stars we have a mixture of field and member stars, and we do not include those in our considerations.

Clement (1999) lists twelve variables in M 56. Our imaging includes only V2 and V6 (marked in Figure 2). Their membership is confirmed by relative proper motion measurements (Rishel, Sanders, & Schroder 1981). Wehlau & Sawyer Hogg (1985) classified V2 as an irregular red variable with small V amplitude. Its position in our CMD confirms it. V6 has a well determined 90 day period, and was classified as an RV Tau type (Sawyer 1940; Sawyer 1949; Wehlau & Sawyer Hogg 1985). Russeva (2000) tentatively identified 7 additional red variable stars, marked in Figure 2 as open diamonds. They all belong to the RGB, and are among the brightest and reddest stars in our sample. There are no known RR Lyr stars in our field.

3.3. Reddening and Distance of M 56

Our photometry allows to carry out a new determination of the distance and reddening to M 56. Since M 15 has a similar metal content to M 56, M 15 can be used as a template for the intrinsic RGB color. In addition, Kuchinski & Frogel (1995) demonstrated that the color of RGB at the level of the HB shows little or no change with metallicity.

For M 15 we measured a reddening corrected color at the HB level of $(J - K_s)_{GB,HB,0} = 0.58 \pm 0.04$ mag. The observed RGB color of M 56 at the level of HB is $(J - K_s)_{GB,HB} = 0.62 \pm 0.02$ mag. Assuming that the color difference is only due to the reddening, we obtained a relative color excess of $E(J - K_s)_{M 56,M 15} = 0.04 \pm 0.04$ mag. Using Rieke & Lebofsky (1985) extinction law we found $E(B - V)_{M 56,M 15} = 0.08 \pm 0.08$ mag, and finally a color excess of of M 56 is $E(B - V)_{M 56} = 0.18 \pm 0.08$ mag. The error
includes the internal photometric error, errors of fiducial lines fits of both globular clusters, and the uncertainty of the HB levels. Note, that even though the HB level in M15 has a large uncertainty (0.30 mag), this does not affect seriously our reddening estimate because of the steep RGB. The calculated reddening of M56 is very close to the value of E(B−V) = 0.20 mag given by Harris (1996).

The comparison of the reddening corrected HB levels of M56 and M15 can be used to determine the differential distance to M56 with respect to M15. We obtained K_{s,HB,0} = 14.32 ± 0.30 mag, and K_{s,HB,0} = 14.38 ± 0.04 mag for M15 and M56 respectively, using the reddening law from Rieke & Lebofsky (1985). We adopted for M15 a color excess of E(B−V) = 0.10 mag and a distance modulus of (m − M)_V = 15.37 mag from Harris (1996). The distance scale was established by adding to his horizontal branch vs. metallicity calibration an empirical evolutionary correction to the zero age horizontal branch as determined by Carney et al. (1992). The typical distance modulus uncertainty was ±0.1 mag. Thus, we find a distance modulus to M56 of (m − M)_V = 15.43 ± 0.30 mag. Unfortunately the large uncertainty in the HB level prevents us from making a better estimate. Harris (1996) gives (m − M)_V = 15.65 mag. If corrected for the reddening, it becomes (m − M)_0 = 15.03 mag. This estimate is based on RR Lyr observations by Wehlau & Sawyer Hogg (1985) who obtained (m − M)_0 = 14.81 mag with a different extinction value. Previously Harris & Racine (1979) determined 9.7 kpc or (m − M)_0 = 14.81. Our distance estimate is larger than those. We attribute the difference to the uncertain HB position in M15.

According to Guarnieri et al. (1998), the K_s-band absolute magnitude of the HB depends on the cluster metallicity: M_K(HB) = −0.2 * [Fe/H] − 1.53. This relation predicts a 0.06 mag difference in the HB level of the two clusters, which is smaller than the uncertainties in our observed HB positions. It also predicts an absolute K_s-band magnitude for the HB of M15 of M_K(HB) = −1.08 mag, very close to the average < M_K(HB) > = −1.15 ± 0.10 mag value measured by Kuchinski & Frogel (1995b) for their sample of globular clusters. Our data yield M_K(HB) = −0.95 ± 0.30, where the error is dominated by the spread of the RR Lyr apparent brightnesses.

4. The Red Giant Branch as a Metallicity Indicator

4.1. The Red Giant Branch Slope vs. [Fe/H]

It is well known that both intrinsic colors (J − K_s)_0 and (V − K_s)_0 are sensitive to metallicity (e.g. Frogel; Cohen & Persson 1983, Braun et al. 1998). Kuchinski et al. (1995)
and Kuchinski & Frogel (1995) demonstrated empirically and theoretically that the slope of the upper RGB in the $K_s$ vs. $(J - K_s)$ diagram is sensitive to the metallicity for a sample of metal-rich Galactic globular clusters. Tiede, Martini & Frogel (1997) extended this relation to a sample of open clusters and bulge stars. Possible extragalactic applications prompted us to extend this calibration towards lower metallicity clusters.

We added to Kuchinski & Frogel (1995) sample our two globular clusters M15, M56, and two more clusters from the literature (NGC 7099 and NGC 6553). NGC 7099 is the most metal-poor among the clusters observed in infrared by Cohen & Sleepers (1995), and their photometry includes a sufficiently large number of RGB stars. NGC 6553 was studied by Guarnieri et al. (1998). Although it is not a particularly metal-poor cluster, it will improve the statistical weight of our calibration. Gathering data from different sources observed with different photometric systems always involves some danger of incompatibility. For red stars the average difference between $K$ and $K_s$ measurements of Persson et al. (1998) is 0.01 mag with a standard deviation of 0.02 mag. We increased correspondingly the uncertainties of the photometry.

First, we had to separate the giants belonging to the upper RGB. Following Tiede, Martini & Frogel (1997), these are stars with absolute $K$ magnitudes spanning the range from $-2$ to $-6.5$ mag. However, Frogel & Elias (1988) and Montegriffo et al. (1995) determined that most (if not all) of the brightest RGB stars are in fact AGB long-period variables. Hence, we excluded from our analysis all the known red variable stars. Further, we excluded stars within the central 50 arcsec in both M15 and M56 to minimize the errors due to field crowding.

As in Kuchinski et al. (1995) we carried out a least-squares fit to the giants from 0.6 mag to 5.2 mag above the HB level in $K_s$, taking into account errors along both axes. This effectively increased the weight of the most accurate measurements, which are usually the brightest cluster stars. To exclude possible random errors we rejected stars which deviated more than three times the r.m.s. of the first fit. This resulted in a loss of only 5, 1, 2 and 4 stars for M15, M56, NGC 7077 and NGC 6553, respectively, confirming the good quality of the photometry. The best fits for the slopes of the RGB of these clusters are shown in Table 4. The errors in this table are purely statistical. The fits and the RGB stars used are plotted in Figure 3. Varying the HB level within the errors, produced an additional 0.002 error in the RGB slope, and was added in quadrature to the statistical errors. To verify our fitting technique we carried out simulations by creating 100 artificial RGBs analogous to the M15 RGB. We started from the $K_s$-band magnitudes of each star, calculated the corresponding $J - K_s$, and added random Gaussian errors with the appropriate $\sigma$ for each star, along both axes. We were able to recover the original RGB slope to within less than
The relation of the RGB slope vs. the \([\text{Fe/}H]\) is shown in Figure 4. Fitting a straight line to the data taking into account the errors along both axes yields to:

\[
\text{[Fe/H]} = -3.40(\pm 0.22) - 27.74(\pm 2.35) \times (\text{RGB Slope})
\]  

with the r.m.s. = 0.20. To test for the compatibility of the data collected from various sources, we carried the same fit using only the data from Kuchinski & Frogel (1995), and our two clusters. We obtained a fit statistically indistinguishable from Equation (1).

There are three recent determinations of this relation in the literature. Kuchinski & Frogel (1995) derived for their sample of ten metal-rich clusters:

\[
\text{[Fe/H]} = -2.98(\pm 0.70) - 23.84(\pm 6.83) \times (\text{RGB Slope})
\]  

Later Tiede, Martini & Frogel (1997) re-derived it. For the sample of twelve globular clusters they obtained:

\[
\text{[Fe/H]} = -2.78(\pm 0.61) - 21.96(\pm 5.92) \times (\text{GB slope})
\]  

and if the most metal-poor cluster is rejected:

\[
\text{[Fe/H]} = -2.44(\pm 0.67) - 18.84(\pm 6.41) \times (\text{GB slope})
\]  

Most recently Ferraro et al. (2000) obtained with much higher quality data of 10 clusters:

\[
\text{[Fe/H]} = -2.99(\pm 0.15) - 23.56(\pm 1.84) \times (\text{GB slope})
\]  

They used the metallicity scale of Caretta & Gratton (1997).

Our large range of metallicity improves the fit significantly, although the 1\(\sigma\) errors are slightly larger than those of Ferraro et al. (2000). All these derivations are statistically indistinguishable from our calibrations. This is particularly important when one has to extrapolate the RGB slope vs. \([\text{Fe/H}]\) relation outside of the explored metallicity range.

We can now apply our relation to estimate the metallicity of the most metal-rich Galactic globular cluster Liller 1. For this cluster Armandroff & Zinn (1988) estimated \([\text{Fe/H}] = +0.20 \pm 0.3\) based on integrated light spectroscopy. Frogel, Kuchinski & Tiede (1995) obtained an RGB slope of \(-0.135 \pm 0.009\), and derived \([\text{Fe/H}] = +0.25 \pm 0.3\). Using the same RGB slope, our fit and that of Ferraro et al. (2000) yield metallicities of \([\text{Fe/H}] = +0.34 \pm 0.22\) and \([\text{Fe/H}] = +0.19 \pm 0.15\), respectively. These estimates have to be taken with caution until more data allow to test whether the RGB slope vs. \([\text{Fe/H}]\) relation is indeed linear for super metal-rich stellar populations.
4.2. The Red Giant Branch Color vs. [Fe/H]

The slope of the RGB as described here is difficult to measure in distant stellar systems because it requires deep photometry, reaching the HB level. As somewhat observationally less challenging alternative we considered the RGB color at a given absolute magnitude as a metallicity indicator. Following Frogel, Cohen & Persson (1983), we chose to calibrate \((J - K_s)_0(\text{RGB})\) at \(M_{K_s} = -5.5\) mag.

A drawback of this method is that unlike the RGB slope, the RGB color is reddening sensitive and requires a correction prior to the calibration. We used the reddening and distance estimates from Harris (1996). We also assumed that the HB level is always at \(M_{K_s} = -1.15\) mag neglecting the HB luminosity dependence on [Fe/H] (Kuchinski & Frogel 1995).

We calculated the RGB colors from the linear fits to the RGBs (Table 4). A test with M 15 and M 56 showed that it is identical to averaging the colors across the RGB within the observational uncertainties. The small number of stars on the RGB tip actually makes the averaging less reliable. In addition, most of the RGBs show a high degree of linearity (Kuchinski et al., 1995; Kuchinski & Frogel, 1995). The errors associated with the RGB colors were calculated as a quadrature sum of the r.m.s. of the fit, the errors from the E(B-V) \((\approx 0.02\) mag) and the errors from the uncertain distance moduli \((\approx 0.10\) mag).

Our best fit of \((J - K_s)_0(\text{RGB})\) at \(M_{K_s} = -5.5\) vs. metallicity (Figure 5) was derived with errors along both axes:

\[
[\text{Fe/H}] = -6.90(\pm0.99) + 6.63(\pm1.05) \times (J - K_s)_0(\text{RGB})
\]

with r.m.s. = 0.33. We attribute the large r.m.s. to the reddening uncertainties.

Frogel, Cohen & Persson (1983) found:

\[
[\text{Fe/H}] = -6.905 + 6.329 \times (J - K_s)_0(\text{RGB})
\]

with r.m.s. = 0.16. This calibration is identical to ours within the uncertainties. It was important to confirm their result, because although it was based on photometry of a large number of clusters (33), it only included 10-20 stars per cluster.

Minitti, Olszewski & Rieke (1995) also calibrated the intrinsic RBG color at \(M_{K_s} = -5.5\) mag and obtained:

\[
[\text{Fe/H}] = -5.0 + 5.60 \times (J - K_s)_0(\text{RGB}).
\]

Their fit is close to ours but shows a slightly different slope. It is based on twenty clusters. Unfortunately the severe field star contamination towards the Galactic bulge prevented them from a reliable estimate of the cluster colors in many cases.
Ferraro et al. (2000) also performed a similar calibration:

\[
[\text{Fe/H}] = -4.76(\pm 0.23) + 5.38(\pm 0.27) \times (J - K_s)_0(\text{RGB})
\]

where the fit coefficients are within 3\(\sigma\) of ours. Obtaining better reddening estimates would be crucial for resolving this discrepancy.

5. Summary

We showed that the position of the infrared RGB can be used to reliably determine the abundance of metal-poor stellar systems with an accuracy of \(\approx 0.2\) (in [Fe/H]). Our main results include:

(1) We presented infrared photometry of the Galactic globular clusters M 15 and, for the first time, M 56, and studied the morphology of their CMDs.

(2) We estimated the reddening towards M 56 by comparing the RGB color at the level of HB to that of M 15, and obtained \(E(B - V) = 0.18 \pm 0.08\) mag. We used the relative HB levels of the same two clusters to derive a distance modulus to M 56 of \((m - M)_V = 15.43 \pm 0.30\) mag if \((m - M)_V = 15.37\) mag is assumed for M 15.

(3) We compiled a sample of 12 Galactic globular clusters with high quality infrared photometry. We recalibrated and extended the RGB slope vs. [Fe/H] relation towards low metallicity globular clusters. We also reevaluated the RGB color \((J - K_s)_0(\text{RGB})\) at \(M_{K_s} = -5.5\) mag vs. [Fe/H] relation. These are potentially useful tools to study extragalactic metal-poor stellar systems, particularly with high obscuration. Our results independently confirm the previously obtained calibrations.

(3) As an application, we used our newly determined RGB slope vs. [Fe/H] relation to estimate the abundance of the super metal-rich Galactic globular cluster Liller 1, and obtained \([\text{Fe/H}] = 0.34 \pm 0.22\).

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Table 1. Cluster data.

| Name       | RGC | R⊙ | (m – M)\_V | E(B – V) | S\_RR | HBR  | [Fe/H] | r\_c | r\_h |
|------------|-----|-----|------------|----------|-------|------|--------|------|------|
| M 15/NGC 7078 | 10.4 | 10.3 | 15.37      | 0.10     | 24.1  | 0.67 | -2.25  | 0.07 | 1.06 |
| M 56/NGC 6779  | 9.7  | 10.1 | 15.65      | 0.20     | 2.2   | 0.98 | -1.94  | 0.37 | 1.16 |
| M 30/NGC 7099  | 7.1  | 8.0  | 14.62      | 0.03     | 10.7  | 0.89 | -2.12  | 0.06 | 1.15 |
| NGC 6553      | 2.5  | 5.6  | 16.05      | 0.75     | 0.6   | -    | -0.34  | 0.55 | 1.55 |

Note. — Columns: (1) name, (2) galactocentric distance in kpc, assuming \(R_0 = 8.0\) kpc, (3) distance from the Sun in kpc, (4) visual distance modulus, not corrected for extinction, (5) Galactic reddening, (6) specific frequency of RR Lyr, (7) HB ratio \(HBR = (B-R)/(B+V+R)\), (8) \([Fe/H]\), (9) core radius in arcmin, (10) half-mass radius in arcmin

References. — Harris (1996)
Table 2. Photometry of the Galactic globular clusters M 15 and M 56.

| ID  | X    | Y    | Ks  | J - Ks | σ(Ks) | σ(J)  |
|-----|------|------|-----|--------|-------|-------|
| M 15|      |      |     |        |       |       |
| 1   | 11.64| 2.21 | 17.32| 0.45   | 0.37  | 0.36  |
| 2   | 186.90| 2.34 | 14.38| 0.48   | 0.08  | 0.06  |
| 3   | 42.45| 2.72 | 9.37 | 0.92   | 0.03  | 0.01  |
| 4   | 117.50| 3.15 | 16.80| 0.39   | 0.17  | 0.15  |
| 5   | 140.80| 3.31 | 15.99| 0.23   | 0.10  | 0.10  |
| 6   | 56.02| 3.50 | 14.53| 0.60   | 0.05  | 0.04  |
| 7   | 228.20| 3.60 | 13.63| 0.53   | 0.04  | 0.02  |
|     |      |      |     |        |       |       |
| M 56|      |      |     |        |       |       |
| 1   | 241.90| 47.89| 16.28| 0.81   | 0.08  | 0.12  |
| 2   | 254.00| 47.90| 18.00| 0.12   | 0.23  | 0.22  |
| 3   | 42.37| 47.90| 17.65| 0.23   | 0.13  | 0.15  |
| 4   | 64.44| 48.20| 17.33| 1.10   | 0.23  | 0.26  |
| 5   | 233.90| 48.31| 11.57| 0.93   | 0.03  | 0.04  |
| 6   | 158.10| 48.32| 12.51| 0.77   | 0.02  | 0.04  |
| 7   | 94.04| 48.67| 14.70| 0.59   | 0.01  | 0.04  |

\*Numbers larger than 10,000 are composed of the numbers from Clement (1999) plus 10,000 for cross-identification purposes.

Note. — The complete data set is available in the electronic form of the Journal.
Table 3. Mean standard deviations from the artificial star simulations (see Section 2 for details).

| Magnitude Bin | M 56 J | Ks | M 15 J | Ks |
|---------------|-------|----|-------|----|
| 10.0-12.0     | 0.04  | 0.05 | 0.04  | 0.05 |
| 12.0-14.0     | 0.05  | 0.07 | 0.06  | 0.08 |
| 14.0-16.0     | 0.10  | 0.15 | 0.13  | 0.17 |

Table 4. Fits to the RGBs of our clusters. The slopes determined by Ferraro et al. (2000) are given in the last column for comparison.

| Cluster        | r.m.s. | b       | a       | a(Ferraro et al., 2000) |
|----------------|--------|---------|---------|------------------------|
| M 15           | ±0.04  | 1.34 ± 0.08 | −0.053 ± 0.007 | −0.047 ± 0.001 |
| M 56           | ±0.05  | 1.32 ± 0.06 | −0.052 ± 0.005 | -                     |
| NGC 7099       | ±0.07  | 1.07 ± 0.06 | −0.035 ± 0.004 | −0.043 ± 0.003 |
| NGC 6553       | ±0.06  | 2.34 ± 0.09 | −0.108 ± 0.008 | −0.095 ± 0.002 |

Note. — Solutions to \( J - K_s = a \times K_s + b \)
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Fig. 1.— Formal DAOPHOT errors of the M 15 and M 56 photometry in J (upper panels) and $K_s$ (lower panels).

Fig. 2.— Color-magnitude diagrams $K_s$ vs. $J - K_s$ for M 15 (left) and M 56 (right). Only stars with DAOPHOT errors less than 0.06 mag for $K_s \leq 14.0$ mag, (filled circles) and stars with errors less than 0.10 mag for $K_s \geq 14.0$ (open circles) were included. See Section 3 for details. Open diamonds are variable stars. The typical 1σ errors are indicated on the left hand side, for different magnitudes. Also the effect of visible extinction of $A_V = 1.0$ mag is shown with an arrow.

Fig. 3.— Color-magnitude diagrams $K_s$ vs. $J - K_s$ for M 15, M 56, NGC 6553 and NGC 7099 with the RGB linear fits. See Section 4.1 for details.

Fig. 4.— RGB slope vs. $[\text{Fe}/\text{H}]$ relation. The filled circles are M 15 and M 56, the triangles are the data from Kuchinski & Frogel (1995), and the open circles are data added from other sources (see Section 4.1 for details). The error bars represent ±1σ errors. The thick solid line shows our best fit and the thick dashed lines show ±1σ error for the slope. The thin solid line shows the best fit and the thin dashed lines show ±1σ error of Ferraro et al., (2000).

Fig. 5.— Relation of $(J - K_s)_0$(RGB) vs. $[\text{Fe}/\text{H}]$. The cluster symbols are the same as in Figure 4. The thick solid line shows our best fit and the thick dashed lines show ±1σ error for the slope. The thin solid line shows the best fit and the thin dashed lines show 1σ error of Frogel, Cohen & Persson (1983). The dotted line is the fit of Minitti, Olszewski & Rieke (1995).
