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METALLICITY OF GLOBULAR CLUSTER M13 FROM *VI* CCD PHOTOMETRY

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ABSTRACT

From the VI images of M13, obtained by using 2K CCD camera and the BOAO 1.8m telescope, we derive the $(V - I) - V$ CMD of M13. From the shapes of red giant branch, the magnitude of horizontal branch, and the giant branch bump on the constructed CMD, we determined the metallicity of the globular cluster to be $1.74 \lesssim$[Fe/H]$\lesssim -1.41$. The good agreement between our determination of [Fe/H] and those determined by using other methods implies that the morphology of red giant and horizontal branches on $(V - I) - V$ CMD's can be good indirect metallicity indicators of Galactic globular clusters.

Key words: spectroscopy, absorption-line, galactic bulge

1. INTRODUCTION

Metal abundances of the Galactic globular clusters, measured by the ratio [Fe/H], have been used as tracers of the early chemical evolutionary phases of Galactic environment, since total metal abundances and their variations among clusters can be considered as fossils record of the chemical enrichment history occurred in the Galaxy. Abundance analysis using high resolution spectra is the best way for the precise measurements of metal abundance of cluster stars. The most widely used metallicity scale for Galactic globular clusters has been the one obtained by Zinn & West (1984) from a calibration of integrated parameter Q_{39}. Recently, Carretta & Gratton (1997) derived a new metallicity scale using a homogeneous data set of high-dispersion and high-S/N spectra of more than 160 red giants in 24 clusters, coupled with the Kurucz (1992) model atmospheres, and showed that the Zinn & West (1984)'s scale is clearly non-linear in comparison to their improved scale. We note, however, that this result is based on only $\sim$ 16% of the known Galactic globular clusters. However, high resolution spectroscopy of stars in a globular cluster is very time consuming, and can be obtained mostly only for the brightest giants because of their large distances. Therefore, several indirect metallicity indicators, which require a relatively accurate calibration to provide the true content in [Fe/H] have been devised.

This is the second in a series of papers studying morphologies of red giant branch (RGB) and horizontal branch (HB) on the $(V - I) - V$ color magnitude diagrams (CMDs) and their use of indirect metallicity indicators of Galactic globular clusters. In the paper of Sohn & Lee (2000), they derived metallicities and reddenings and other physical parameters such as the HB magnitudes of

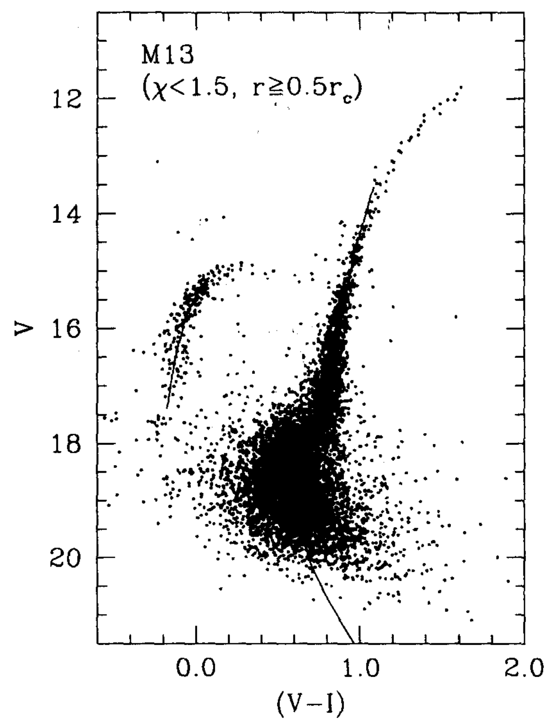

Figure 1. $(V-I)-V$ CMD of stars in M13 having $\chi < 1.5$. Fiducial sequence of Johnson & Bolte (1998) is plotted as a solid line.

M3 and M5 applying Sarajedini (1994)'s method on the $(V-I)-V$ CMDs, and suggested that the morphologies of RGB and HB on the $(V-I)-V$ CMDs can be good indirect metallicity indicators of Galactic globular clusters.

Sarajedini (1994) devised a method that can simultaneously determine the metallicity and reddening (SMR method) for globular clusters in the $(V-I)-V$ CMD plane by using the $(V-I)_o$ value of RGB measured at the level of HB and the difference in V between the HB and RGB at $(V-I)_o = 1.2$. His calibration was based on the scale of Zinn & West (1984) and high precision CCD photometry obtained by Da Costa & Armandroff (1990). Recently, Carretta & Bragaglia (1998) provided new accurate relations to employ the method of Sarajedini (1994) combined with the Carretta & Gratton (1997) abundance scale.

In this paper, we applied the SMR method on the $(V-I)-V$ CMD for M13 in order to derive metallicitiy, reddening, and other physical parameters such as the HB magnitudes. M13 (NGC 6205) is one of the closest and best studied globluar clusters with $(m-M)_o = 14.35$ (Peterson 1993) and a target of early photometric studies (e.g., Arp 1955). After emergence of the second-parameter problem (e.g., Sandage & Wildey 1967, Rood 1973), M13 and M3 (NGC 5322) have been commonly considered as a classic prototype of second parameter pair. While they have almost identical total masses, densities and overall metal abundances, their CMDs have HB morphologies widely different each other. On the $(B-V)-V$ CMD, Paltrinieri et al. (1998) showed the long

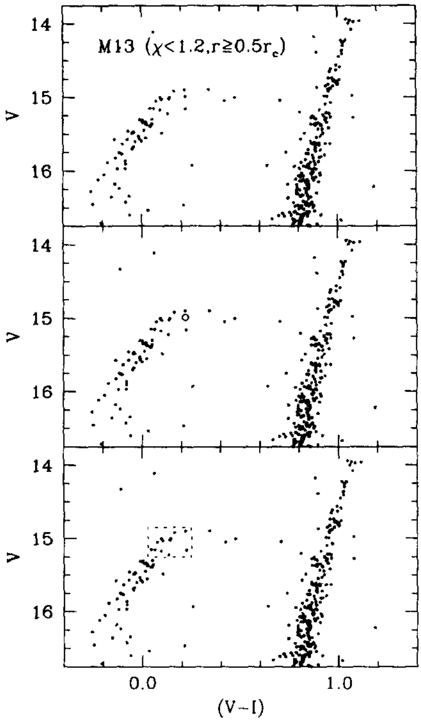

Figure 2. (Top) HB stars of M13 having $\chi < 1.2$ and radius larger than half core radius. (Middle) HB stars of M13 with the previously known RR Lyrae variable star plotted as open circle. (Bottom) HB stars of M13 with variable stars removed. Dashed boxes are used to determine the mean magnitude of HB.

extension of the blue tail of the HB down to $V \sim 19$ and the presence of two gaps. From the *HST*/WFPC2 observation of the central region of M13, Ferraro et al. (1997) also found a long HB blue tail extending 4.5 mag in V and two gaps similar to those seen in the clusters of NGC 6752 and NGC 2808. Spectroscopically, M13 has become the target of several investigations on the nature of the chemical anomalies that are present among RGB stars (Kraft et al. 1992, Peterson et al. 1995, Smith et al. 1996, Carreta & Gratton 1996).

The observation and data reduction are described in §2. In §3, we show the $(V-I)-V$ CMD of M13, and derive the mean V magnitude of HB. We also determine the metallicity of M13 and compare them with the previously determined ones in §3.

2. OBSERVATION AND DATA REDUCTION

VI images of M13 and a number of standard stars on the Landolt (1992) were obtained over the night in UT 1999 March 23 by using the 1.8m telescope at BOAO. The detector was SITe CCD chip with a 2048 × 2048 format. At the f/8 Cassegrain focus, the image scale is 0.34 arcsec pixel^{-1}, which gives the sky coverage of 11.8×11.8 arcmin^2. A single exposure centered on the cluster center was taken in V and I filters with the exposure times of 40 and 15 seconds, respectively.

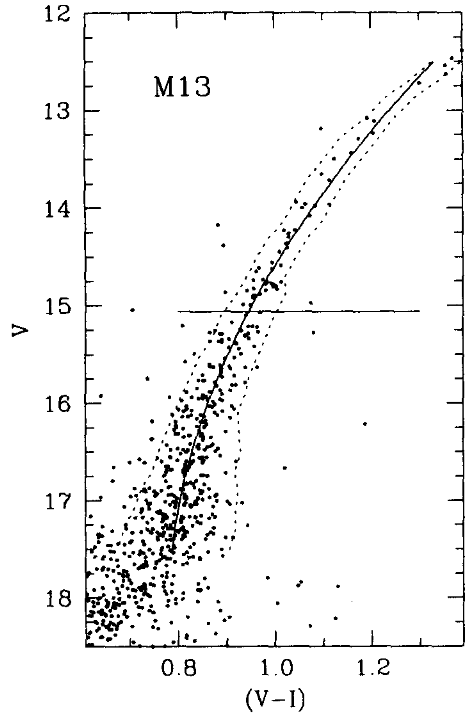

Figure 3. RGB stars of M13. Quadratic formula of RGB shape and the level of V(HB) are also plotted.

The data were reduced following standard processing lines. The bias level and pattern were removed by subtracting both a fit to the overscan region and a master zero-level frame. The results were then divided by twilight flat images to remove additional pixel-to-pixel variations through the frame. Details of the photometric calibrations using standard stars are given in the Paper I. The final photometric transformations for V magnitude and $(V-I)$ color are $V - v_o = -0.044(\pm 0.014)(v - i)_o - 2.528(\pm 0.011)$ and $(V - I) = 0.962(\pm 0.022)(v - i)_o + 0.244(\pm 0.017)$, respectively. The night of the run was fully photometric, and the average seeing measured from the reduced images was $\sim$ 0.9 arcsec FWHM.

The PSF-fitting photometry package DAOPHOTII/ALLSTAR (Stetson 1987, Stetson & Harris 1988) was used to measure the V and I magnitudes of the individual stars in M13. We used $\sim$ 90 − 100 isolated bright stars located away from the cluster center to calculate the accurate point spread function (PSF) on the image to avoid the crowding effect. An iterative method was applied to remove neighboring stars of selected PSF stars, so that we were able to achieve appropriate PSFs for each frame. We undertook two additional passes after the first ALLSTAR pass to find more faint stars on the subtracted frames. Using the growth-curve method DAOGROW, the mean difference between the PSF-based magnitude and the total magnitude of selected PSF stars was calculated in each frame. This aperture correction was applied to PSF-based magnitudes of all resolved stars in the frame. Photometric transformations were then applied to derive the standard magnitudes of stars appeared in both frames. The positional transformation solution for the VI pairs was derived by

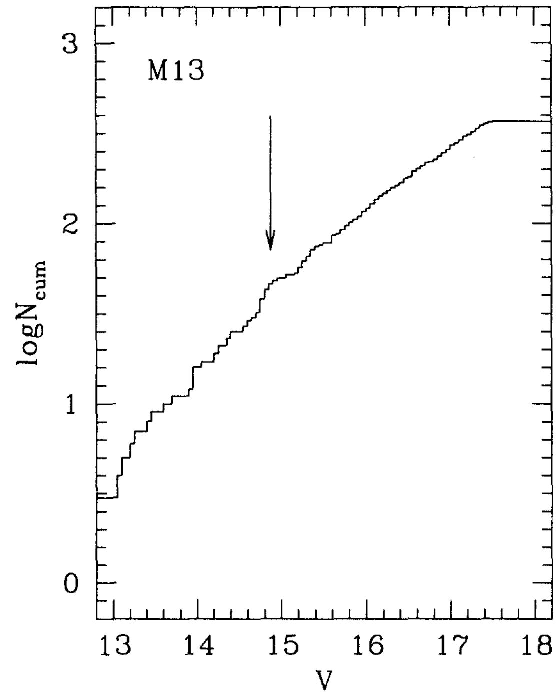

Figure 4. Cumulative luminosity function of RGB stars in M13. Arrow indicates the RGB bump.

applying DAOMATCH and DAOMASTER (Stetson 1992) packages. The size of match-up radius on DAOMASTER procedure has been reduced until the rms residuals of $x-$ and $y-$ positions for each frame were less than 0.1 pixels. From these procedures, we detect 19,219 stars.

3. COLOR-MAGNITUDE DIAGRAM AND METALLICITY

Figure 1 shows the $(V - I) - V$ CMD of stars in M13 field having $\chi \leq 1.5$, which quantifies how well the empirically derived PSF for a frame matches with the profile of actual stars. To avoid the crowding effect, the CMD is based on stars with locations of $r > 0.5r_c$, where $r_c = 52.5$ arcsec is the core radius of the cluster (Trager et al. 1993). Fiducial sequences of Johnson & Bolte (1998) are plotted on Figure 1 as solid line, showing a good agreement with our result.

The CMD of M13 reveals a long blue tail of HBs extending from the hotter edge of the RR Lyrae instability strip down to the level of main-sequence turn-off (MSTO). Similar tail was detected in the ground based $(B-V)-V$ CMD (Paltrinieri et al. 1998) and $(U-V)-V$ CMD from HST/WFPC2 observations (Ferraro et al. 1997). The giant branch can be traced up to the tip, which is located at $V \sim 12.0$ and $(V - I) \sim 1.60$. Because of its blue HB morphology, M13 just has a few RR Lyrae variables. Note that among 16 vaiable stars in M13 listed in Sawyer-Hogg (1973), Preston et al. (1991) confirmed only 3 RR Lyraes in the whole cluster. A check of the coordinates has shown

Table 1. Photometric parameters and the estimated metallicities of the M13.

cluster	V(HB)	$(V-I)_g$	$\Delta V_{1.2}$	E$(V-I)$	[Fe/H]$_{S94}$	[Fe/H]$^1_{CB98}$	[Fe/H]$^2_{CB98}$
M13	15.06 ±0.11	0.947 ±0.012	1.83 ±0.10	0.00	-1.46 ±0.11	-1.74	-1.41

[Fe/H]$_{S94}$: based on Sarajedini (1994)
[Fe/H]$^1_{CB98}$: based on the relation between [Fe/H] and $\Delta V_{1.2}$ of Carretta & Bragaglia (1998)
[Fe/H]$^2_{CB98}$: based on the relation between [Fe/H] and $(V-I)_{o.g}$ of Carretta & Bragaglia (1998)

that only one RR Lyrae star falls within the region considered in the present study. Figure 2 shows HB stars of M13 having $\chi \leq 1.2$ and $r > 0.5r_c$. The middle panel of Figure 2 shows the identified RR Lyrae variable star (plotted as open circle) and HB stars (filled circles). The mean magnitude of the HB is estimated by computing the mean V of the non-variable stars in the dashed box on the lower panel of Figure 2. This yields V(HB)$= 15.06 \pm 0.11$, which is in an excellent agreement with V(HB)$= 15.05 \pm 0.10$ determined by Paltrinieri et al. (1998). The quoted error is composed of standard errors of the means and estimated uncertainty in the photometric zero point.

Sarajedini (1994) suggested a technique by which the metal abundance and reddening of a globular cluster can be derived simultaneously using the shape of the RGB and observed value of the HB magnitude [i.e., V(HB)] and the $V-I$ color of the RGB at the level of the HB [i.e., $(V-I)_g$]. Here, we apply this method to derive the metallicity and reddening of M13 with the V(HB) derived above. For this, we first determine the RGB shape on the CMD of M13 by using a quadratic relation of the form $V-I = a_0 + a_1V + a_2V^2$. The coefficients are derived by fitting the relation on the RGB area plotted as dashed lines in Figure 3. RGB regions are defined from the eye-fitting of RGB fiducial line and its widths on $V-I$ color. The derived values of the individual coefficients are $a_0 = 6.429043$, $a_1 = -0.621279$, and $a_2 = 0.017081$, and the derived relation is plotted in Figure 3 (solid line). The horizontal line indicates the level of V(HB).

Applying eq. (1) of Paper I to the eq. (6) and eq. (7) of Sarajedini (1994), we simultaneously estimate E$(V-I)$ and [Fe/H] of M13 with $\Delta V_{1.2}$ and $(V-I)_g$ as input parameters. Here, $\Delta V_{1.2}$ is the difference in V between the HB and the RGB at $V-I = 1.2$, and $(V-I)_g$ is the $V-I$ color of the RGB measured at the level of HB. At V(HB)$= 15.06 \pm 0.11$ of M13, quadratic fit to the RGB stars give $(V-I)_g = 0.947 \pm 0.012$. The determined reddening and metal abundance are E$(V-I) = 0.00$ and [Fe/H]$= -1.46 \pm 0.11$. Sarajedini (1994)'s calibration was based on Zinn & West (1984) metallicity scale. Therefore, we also applied Carretta & Bragaglia (1998)'s new relations, tied to the Carretta & Gratton (1997) abundance scale, to estimate metallicity of M13. From the relation between [Fe/H] and $\Delta V_{1.2}$, we derived [Fe/H]$= -1.74$. Also, metallicities are derived to be [Fe/H]$= -1.41$ from the relation between [Fe/H] and $(V-I)_{o.g}$. Table 1 gives the photometric parameters and metallicities of the M13 derived by applying the SMR method.

The luminosity of the RGB bump, an evolutionary pause on the first-ascent RGB (e.g., Iben 1968), is primarily dependent on the cluster metal abundance. Sarajedini & Forrester (1995) derived the relation between metallicity and the RGB bump luminosity, i.e., [Fe/H] $= -1.33 + 1.43\Delta V^{\rm HB}_{\rm Bump}$. We also use this equation to derive the metal abundance of M13. In Figure 4, we present the cumulative LF for M13 RGB stars located at radius larger than the cluster's half core radius with a binning size of 0.05 mag. It is apparent that there is RGB bump at the magnitude of $V_{\rm Bump} = 14.88 \pm 0.05$. Here, the quoted error is just the binning size of the LF. Using V(HB)$= 15.06$, we obtaine $\Delta V^{\rm HB}_{\rm Bump} = -0.18 \pm 0.12$, which yield [Fe/H] $= -1.59 \pm 0.09$. Since M13 lies at a fairly

Table 2. Metallicity estimates for M13.

[Fe/H]	Reference
-1.60	Hesser et al. (1977)
-1.60	Searl & Zinn (1978)
-1.47	Cohen & Frogel (1982)
-1.60	Friel et al. (1982)
-1.60	Frogel et al. (1983)
-1.65	Zinn & West (1984)
-1.60	Buonanno et al. (1991)
-1.76	Claria et al. (1994)
-1.58	Kraft et al. (1997)
-1.51	Carretta & Gratton (1997)
-1.60	Grundahl et al. (1998)

high Galactic latitude ($b = 41^o$), the field star contamination on RGB stars in this study is almost negligible.

The derived [Fe/H] values in this paper range $-1.74 \sim -1.41$ for M13. In Table 2, we list the previous determination of [Fe/H] obtained by using various low-resolution spectroscopic and photometric techniques. Some of these values are interdependent and range $-1.76 \sim -1.51$, which are in a good agreement with the metalicity range of M13 derived in this paper. This result leads to the conclusion that the morphologies of RGB and HB on the $(V - I) - V$ CMD can be good indirect metallicity indicators. A large and homogeneous CCD photometry data set based in V and I band is needed to take advantage of it.

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