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THE CCD PHOTOMETRY OF THE GLOBULAR CLUSTER NGC 362*

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ABSTRACT

The wide field ($\sim 20' \times 20'$) CCD photometry has been performed for more than 4,000 stars over a whole region of NGC 362 which is located inside the SMC halo. The Color-Magnitude diagram (CMD) and luminosit function (LF) for red giant branch (RGB) stars are presented, discussing a distinct bump along the RGB and some blue stars appearing in the blue horizontal branch (BHB) and above BHB. The anomalous globular cluster NGC 362 with highly populated red horizontal branch (RHB) stars is compared with the another anomalous globular cluster NGC 288 with highly populated BHB stars. A metal-rich, young blue component and metal-poor, old red component of the SMC halo stars are examined.

Key Words : globular cluster, C-M diagram, luminosity function, theoretical isochrone

I. INTRODUCTION

The globular cluster NGC 362, located in the sky near the Small Magellanic Cloud (SMC) has long been paid attention to the problem of a second parameter: That is NGC 362 has a populated RHB while NGC 288 having the similar metallicity to that of NGC 362 has a populated BHB. The normal globular clusters like M3 which has the same metal abundance as that for NGC 362 show both RHB and BHB in the CMD. Hence, NGC 362 and NGC 288 are called "astrophysical pair" of the second parameter problem. In order to explain the anomalous characteristics of HB morphology of NGC 362 and NGC 288, the age difference has been considered to be a second parameter which controls the morphology of HB stars (Bolte 1989; Sarajedini & Demarque 1990; Green & Norris 1990). However, in recent studies, Catelan & Pacheco (1993, 1994) and Stetson *et al.* (1996) claimed that the age of a cluster is not a unique second parameter. Catelan & Pacheco (1993, 1994) have found from their HB simulations that an age difference $\sim 3Gyr$ (firm lower limit to the difference in age between these two clusters if age is the sole cause of the disparity in their respective HB morphologies) would require that both clusters are $< 10Gyr$.

Harris (1982) has performed photoelectric (89 stars) and photographic ($\sim$ 300 stars) photometry for subgiant branch (SGB) stars, RGB stars, asymptotic giant branch (AGB) stars and HB stars, and Bolte (1987) has performed a CCD photometry for main sequence (MS) stars. Harris (1982) found a distinct peak in the LF along the RGB. The similar bump corresponding to this peak has been identified by Fussi Pecci *et al.* (1990) for 11 globualr clusters and Desidera *et al.* (1997) for 30 globular clusters. And Fussi Pecci *et al.* (1990) showed the correlation of ΔV_{bump}^{HB} (magnitude difference between bump along the RGB and HB lebel) with cluster metallicity.

In the present study, we carried out the CCD photometry of NGC 362 over a whole cluster region. The CMDs for $\sim$ 4,000 stars brigter than $V \approx 19.^{m}0$ are presented in section III, and the LF of SGB and RGB stars is derived in section IV, comparing with a theoretical LF. The conclusion is given in the last section.

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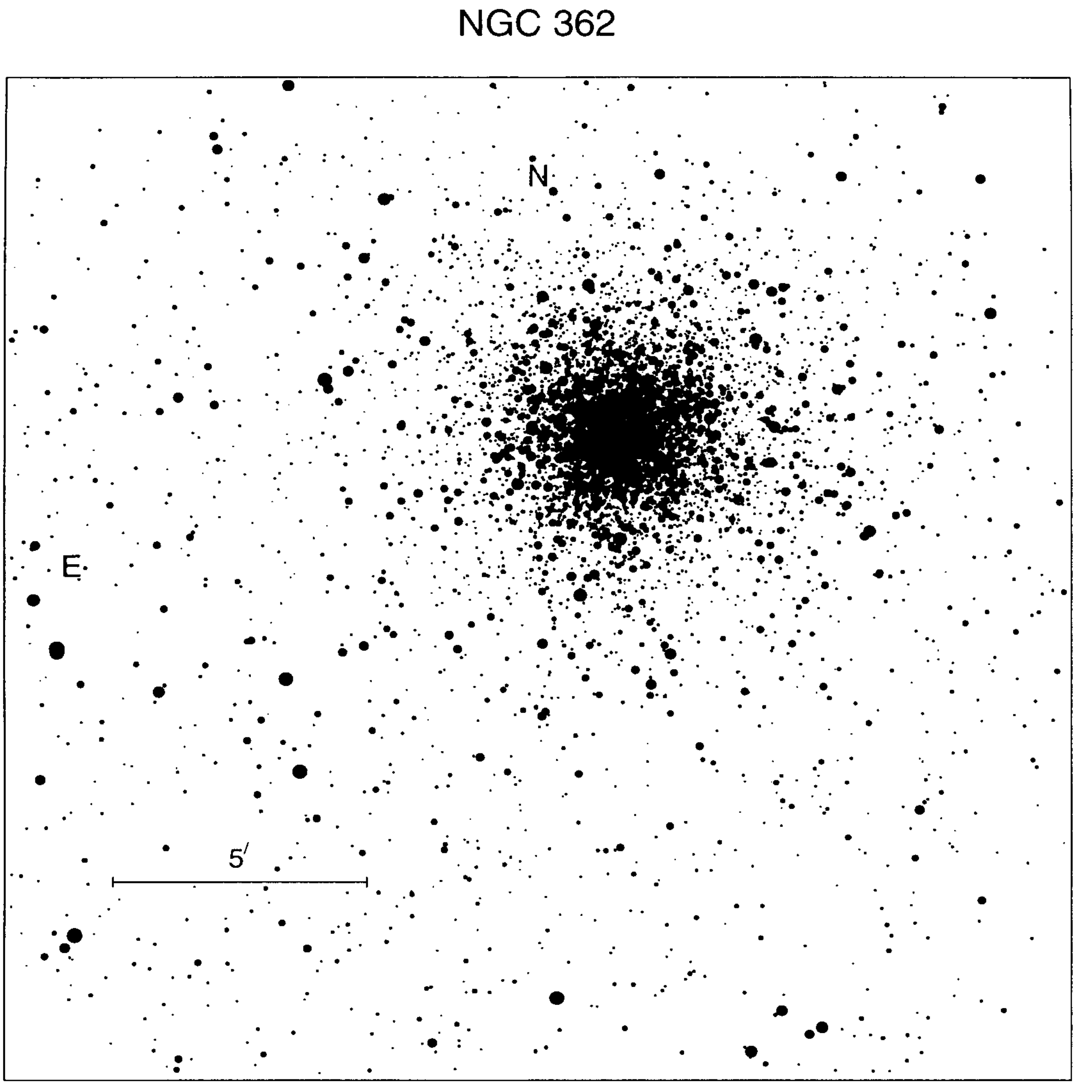

Fig. 1. The map of observed region of NGC 362

II. OBSERVATION AND DATA REDUCTION

The observations were made with the 40″ telescope ($f/8$) at the Siding Spring Observatory on 1995, Aug., 23 by one (H. S.) of us. Tektronix 2048 CCD camera was used as a detector. The gain of the CCD was set to $2e^-/ADU$. The read-out noise was $\sim 43.8e^-$ (Sung *et al.* 1996). The scale is $0.''61/pixel$, covering the field of 20.′8 on a side. The seeing was about $1.''7 \sim 1.''8$ on average. The pre-processing including bias subtraction and flat fielding was performed by using the NOAO/IRAF/CCDRED package. Instrumental magnitudes were obtained using IRAF version DAOPHOTII(Stetson 1994). The map of observed region of NGC 362 is shown in Fig. 1. More than 4,000 stars were measured with V and B filters. To transform the instrumental system to the standard system, we used the combined photoelectric photometry data of Harris(1982). The derived transformation equations are as follows;

$$V_{pe} = v - 0.027(\pm.005)(B-V)_{pe} - 3.134(\pm.004),$$

$$B_{pe} = b + 0.118(\pm.010)(B-V)_{pe} - 3.414(\pm.008).$$

The errors in magnitude and color are shown plotted aginst V magnitude in Fig.2.

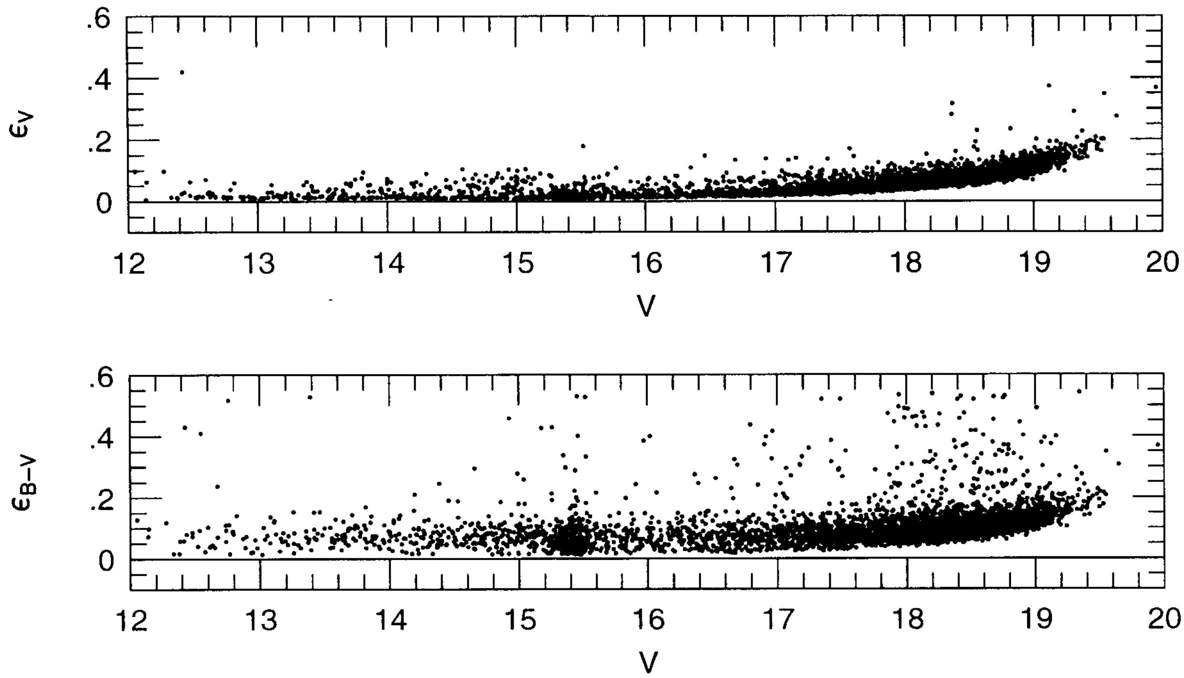

Fig. 2. The errors in V and B-V against V magnitude.

III. COLOR-MAGNITUDE DIAGRAM

The CMD of all measured stars in NGC 362 is shown in Fig. 3 where solid lines denote the fiducial lines by VandenBerg *et al.* (1990) (MS & SGB) and Harris (1982) (RGB, AGB & HB). These lines are fairly well consistent with the mean loci of the present CMD. The CMDs for star in different regions are shown in Fig. 4 and 5. The stars in the inner region($r < 7'$) are mostly cluster members while the stars in the outer region($r > 7'$) are mostly SMC field stars which are seen in both sides of the SGB in Fig. 5.

(a) Giant Branch and Horizontal Branch

The AGB and bright RGB are not very sharply defined in Fig. 3. This seems to be due to photometric uncertainty rather than an intrinsic property. A distinct bump along the RGB is seen at $V = 15.^m45$ which is coincident with the magnitude of the HB.

A highly populated RHB is shown in Fig. 3 and 4, and the color difference between the red edge of RHB and the mean line of the RGB is about $0.^m1$ as shown previously by Harris (1982). It is noted that the similar color difference is shown for 47 Tucanae which has a lager metal abundance than NGC 362. Some stars are seen in and $\sim 0.^m4$ above the region of BHB. If these stars are cluster members, the brighter stars than the BHB level may be evolving stars from the BHB to AGB. Their membership, however, is not able to be clearified in the present photometric study, although some indication for members is suggested from Fig. 4 and 5 where they are not found in the outer region (see Fig. 5).

In the CMD of Harris (1982), a gap of $\Delta(B-V) = 0.^m1$ between the RGB and RHB is shown, but it is not clearly shown in Fig. 3 and 4. This might be attributed to a relatively large dispersion in $(B-V)$ particularly for RGB stars. At the bottom of the AGB ($V \approx 15.^m9, B-V \approx 0.^m8$), a deficient gap is seen in Fig. 3. This might have been caused from the rapid transition of evolved RHB stars to the AGB phase with double-shell sources once the helium core is exhausted (Chiosi 1986; Chiosi *et al.* 1992).

(b) Isochrone Fit

In Fig. 4 a theoretical isochrone of Padova group (Bertelli *et al.* 1994) is superposed on the CMD, taking $[Fe/H] = -1.19, Y = 0.23, age = 13.8Gyr$ and distance modulus, $(m-M) = 14.^m77$. The isochrone fits relatively

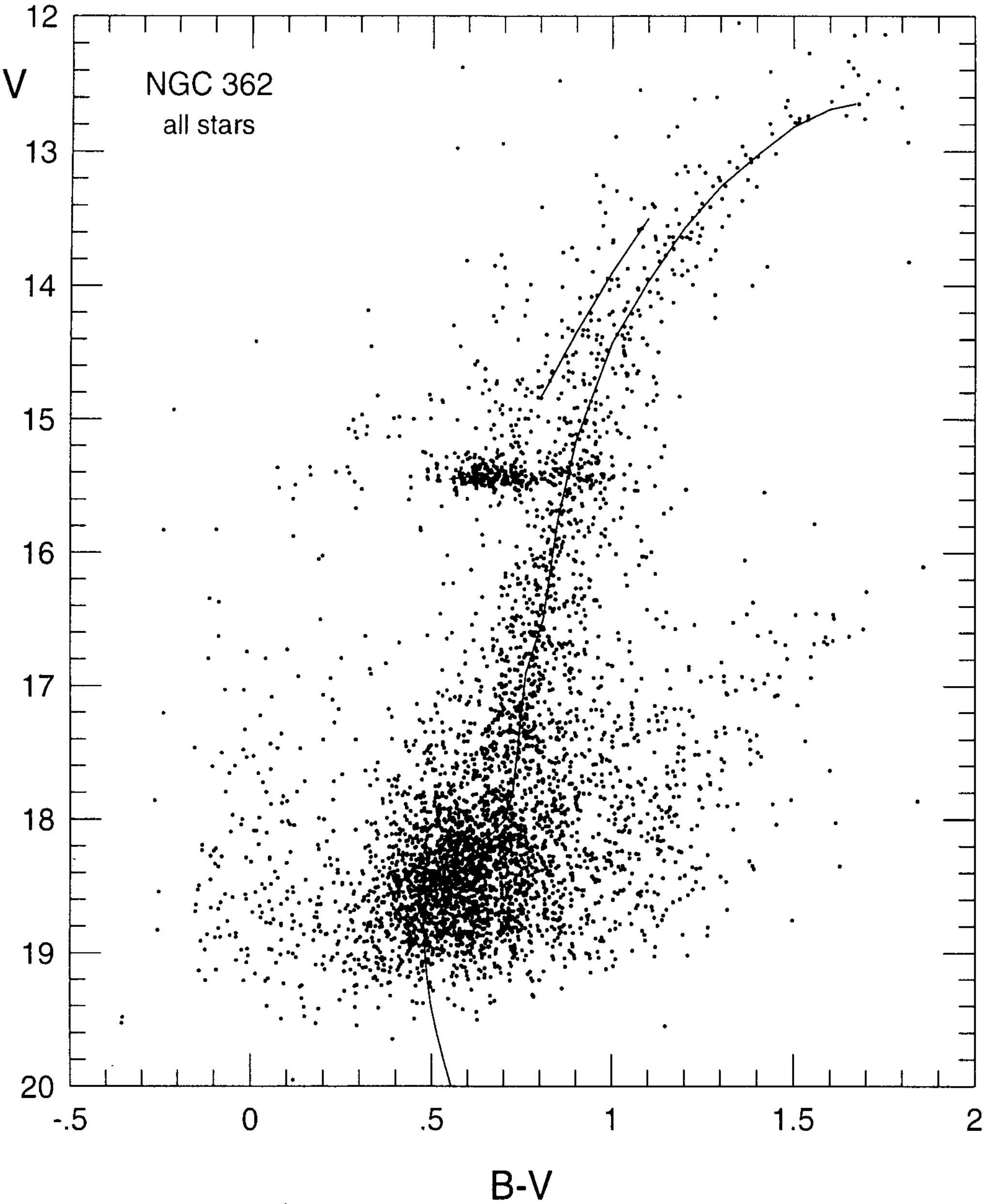

Fig. 3. The CMD for stars in the whole area of NGC 362. The solid lines are the fiducial lines of VandenBerg *et al.* (1990) (MS & SGB), and Harris (1982) (RGB, AGB & HB).

well the observed sequences except for the RHB. The theoretical width of the RHB in color $(B-V)$ is very narrow and shifted toward the bluer color as compared with the observed RHB. According to theoretical calculation of HB stars, the redward shift of RHB can achieved by the increase of metal abundance or by the decrease of q value which is the ratio of core mass to the total mass. If the metal abundance is increased, the theoretical RGB will be less steep in the CMD, deviating from the observed RGB. Hence the increase of metal abundance is not adequate in this case. If the mass loss of RGB stars at the tip of RGB is smaller, the q value will be decreased, causing HB stars to be located more redward along the zero age HB. In the case of NGC 288, more efficient mass loss might be operated, so that it could have only BHB stars although its metallicity and age are the same as that for NGC 362.

NGC 362 is located in the sky $\sim 7°$ northeast from the optical center of SMC. Brück (1978, 1980) has demonstrated from star counts that NGC 362 is well inside the SMC halo. Therefore, in Fig. 5 the faint stars ($V > 16^m$) which

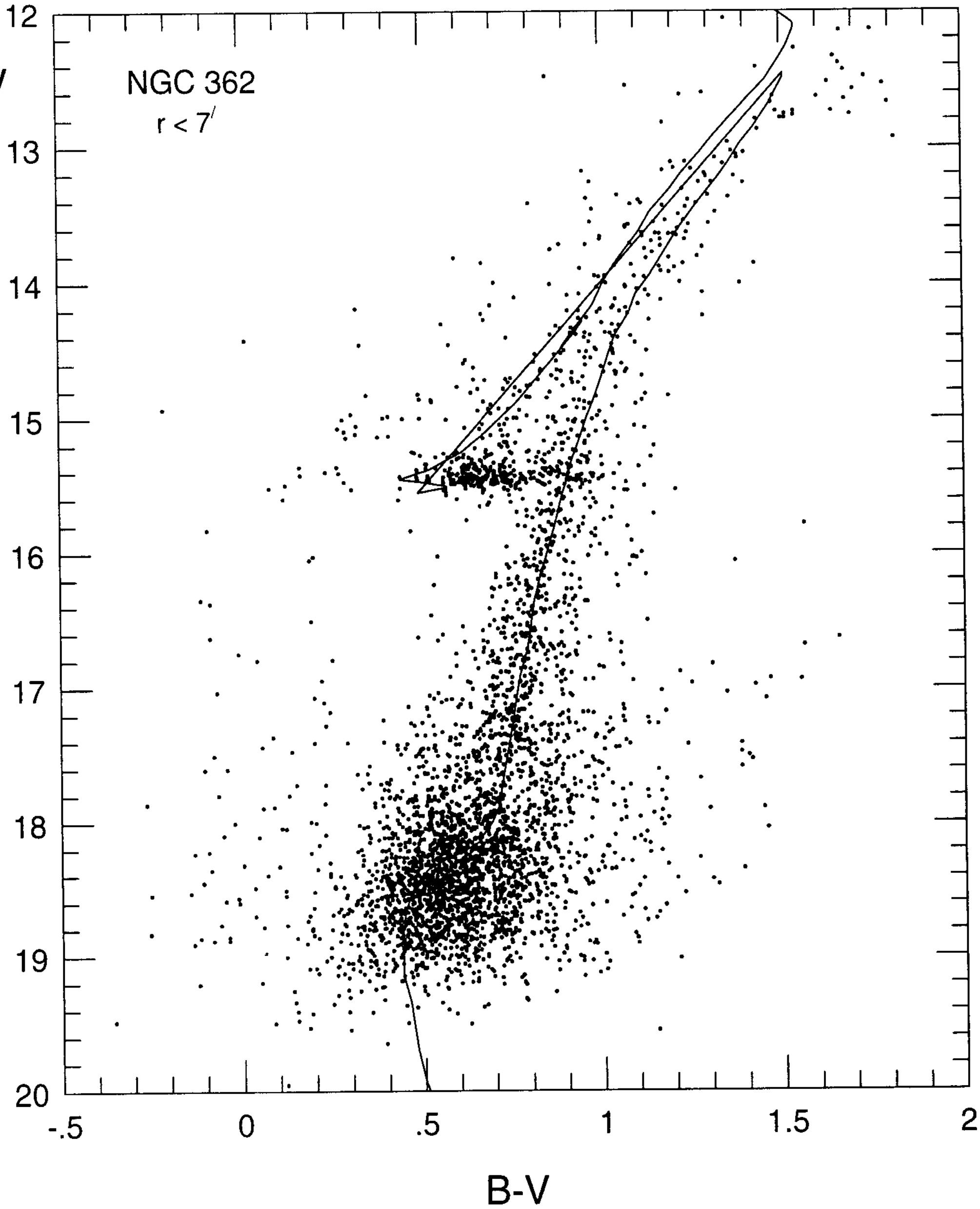

Fig. 4. The CMD for stars in the inner region ($r < 7'$). The solid line is the theoretical isochrone of Padova group (Bertelli *et al.* 1994) with the physical properties of $[Fe/H]$ = -1.19, $Y = 0.23$, age = 13.8 Gyr.

are far away from the mean loci of MS and SGB are probably the field stars of SMC. The blue and red components of these field stars have been discussed by Bolte (1987) who assigned $[Fe/H] = -0.6, Y = 0.25$ and $0.3Gyr$ to the bluer component and $[Fe/H] = -1.27, Y = 0.20$ and $8Gyr$ to the redder component according to Hodge (1983), Bica *et al.* (1986), and Da Costa & Mould (1985). We applied theoretical isochrones given by Padova group (Bertelli *et al.* 1994) to that two components in Fig. 5. Here the blue component which falls into the category of "pop I disk" (Brück 1980) is fitted by isochrone of $[Fe/H] = -0.61, Y = 0.24, age = 0.3Gyr$, and the red component by isochrone of $[Fe/H] = -1.19, Y = 0.23, age = 7.94Gyr$. From this isochrone fitting, it becomes clear that the SMC has at least two components with different chemical abundance and ages. The red component is younger than the metal-rich Galactic globular cluster, 47 Tucanae.

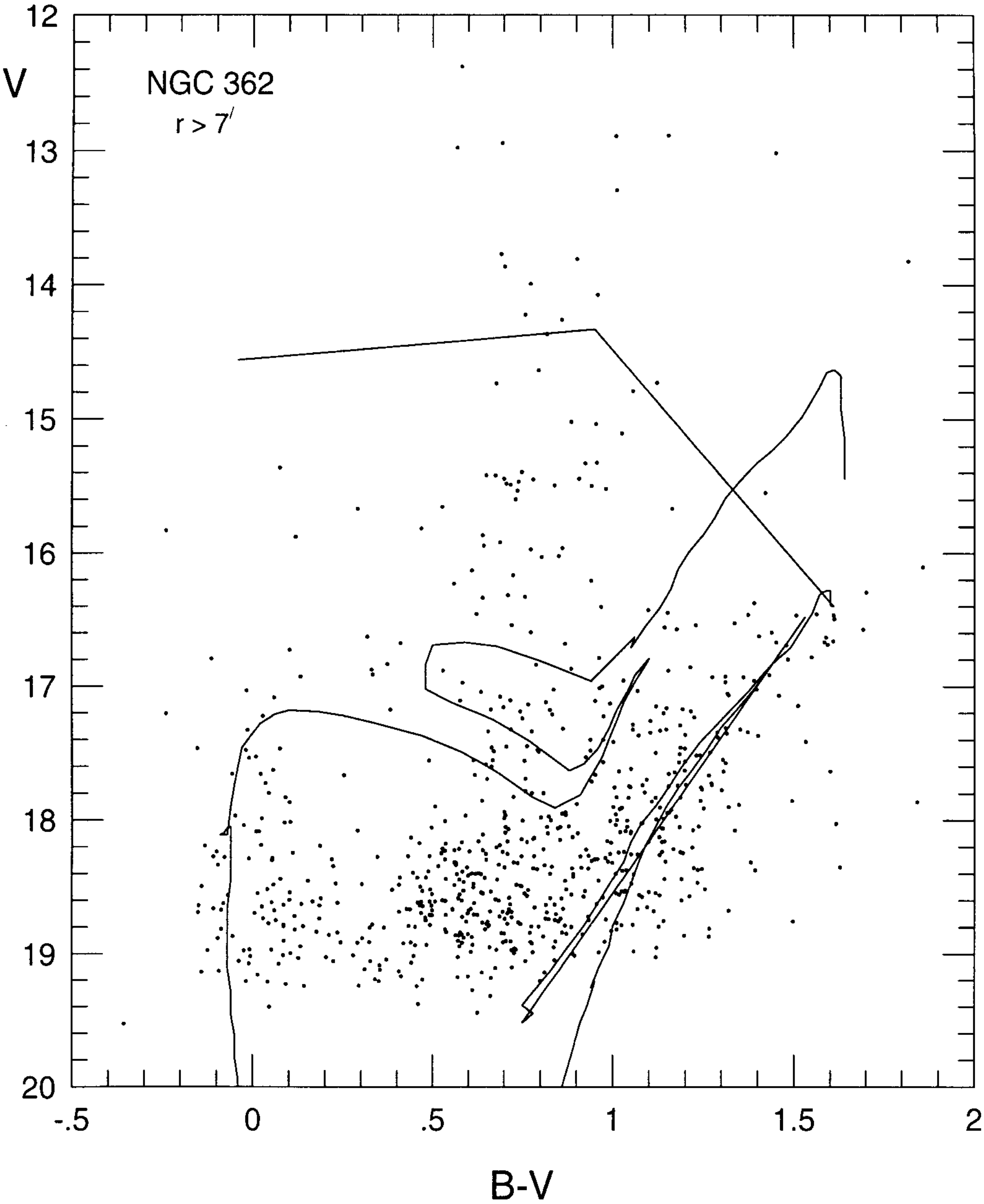

Fig. 5. The CMD for stars in the outer region ($r > 7'$). The solid line is the theoretical isochrone of Padova group (Bertelli *et al.* 1994) with the physical properties of $[Fe/H]$ = -0.61, Y = 0.24, age = 0.3 Gyr(bluer) and $[Fe/H]$ = -1.19, Y = 0.23, age = 7.94 Gyr(redder).

IV. LUMINOSITY FUNCTION OF RED GIANT BRANCH

To estimate ΔV^{HB}_{bump} for NGC 362, the LF for giant stars are needed. The giant stars within the color range of $\pm 2\sigma_{(B-V)}$ along the mean line of SGB and RGB were counted as member stars. To distinguish RGB and AGB stars, the stars redder than the color of the middle line between the mean lines of RGB and AGB were counted as RGB stars. The final LF for SGB and RGB stars is shown in Fig. 6 where the dotted line denotes the theoretical LF which was derived using evolutionary models given by Padova group (Bertelli *et al.* 1994). The predicted LF is well matched to the observed one, showing a distinct bump at $V = 15.^m4$ in both cases. This magnitude is the same as that of the RHB as shown in Fig. 3. Therefore, the magnitude difference ΔV^{HB}_{bump} between the bump position and RHB lebel is zero for NGC 362.

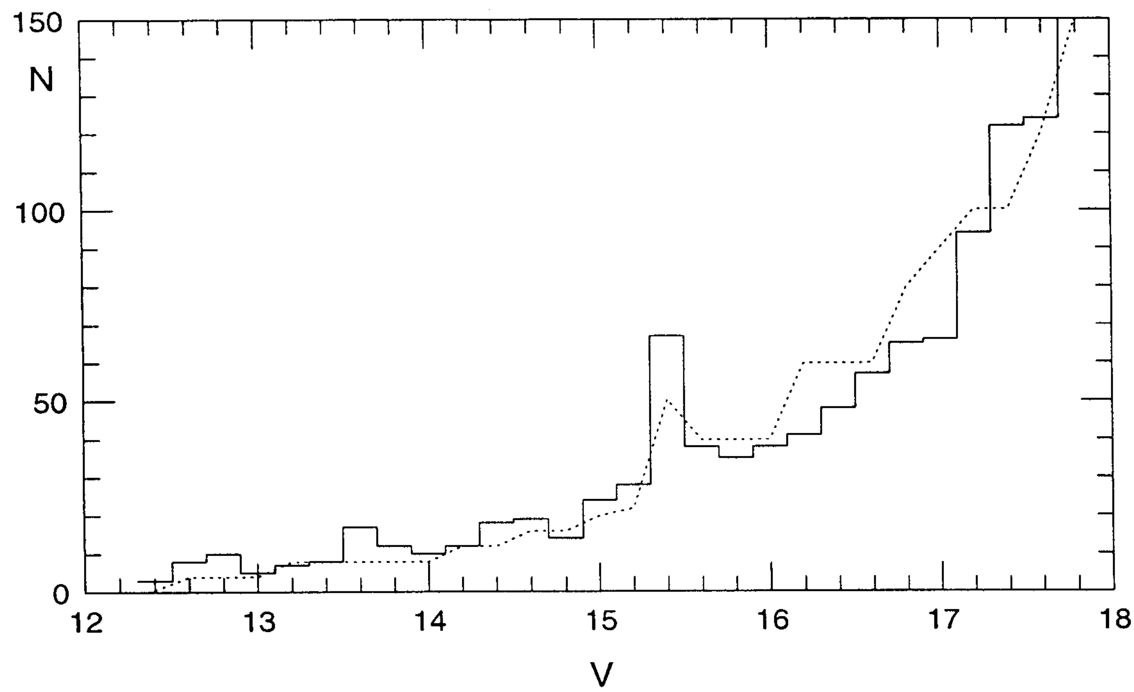

Fig. 6. The LF of RGB of NGC 362. The dotted line is the theoretical LF of Padova group (Bertelli *et al.* 1994).

The metal-rich disk globular cluster, 47 Tucanae (Lee 1976) also has a distinct bump along the RGB, but it appears at $0.^m4$ below the HB lebel. Hence $\Delta V_{bump}^{HB} = -0.^m4$ for 47 Tucane. However, in the metal-poor halo globular clusters like M15 (Sandage *et al.* 1968) and M92 (Sandage & Walker 1966), the distinct bump long the RGB appears above the HB. Recently the correlation of ΔV_{bump}^{HB} with metallicity of globular clusters has been examined for 30 globular clusters by Desidera *et al.*(1997), and showed that ΔV_{bump}^{HB} increases with the decreasing metallicity, confirming the earlier conclusion reached by Fusi Pecci *et al.*(1990) who used 11 globular clusters with $-2.15 < [Fe/H] < -0.71$.

The appearance of bumps and deficient gaps along the RGB has been known from the derivation of CMDs of globular clusters. This phenomenon implies non uniform rate of evolution along the RGB. The physical origin of the bump was first examined by Thomas (1967) and Iben (1968). According to evolution models, at some points on the low part of the RGB, the convective envelope of a RGB star penetrates deeply enough into the inner region of the star to reach the region of varying H-abundance which is established during the core H-burning phase. When the convective envelope retreats from the advancing H-burning shell, a discontinuity in H-profile is left. Eventually the H-burning shell passes through the discontinuity region, producing an observable bump in the LF. According to the above empirical correlation between ΔV_{bump}^{HB} and metallicity, the development of the convective envelope toward the inner region should occur earlier as the metallicity increases if ages of globular clusters are the same within the uncertainty ($\sim 3Gyr$) of age estimate.

V. CONCLUSION

Using the new, wide field ($\sim 20' \times 20'$) CCD data for more than 4,000 stars over the whole cluster region, the CMD for NGC 362 was derived, confirming the results obtained by previous studies. The morphological sequences on the CMD could be well matched by using theoretical isochrone of Padova group (Bertelli *et al.* 1994). Some blue stars appear at the region of BHB and $\sim 0.^m4$ above the BHB. The RR Lyrae gap with a color width of $\Delta(B-V) \approx 0.^m2$ is seen at the left of the blue edge of RHB. Since the most of these blue stars are found in the inner region of $r < 7'$, the possibility of being member stars of NGC 362 cannot be ruled out. Their membership should be examined by the UV observation and/or spectroscopic observation if possible. The faint magnitude limit of the AGB appears at $V \approx 14.^m8$ where a deficient gap is shown. This magnitude is brighter by $\sim 0.^m6$ than the RHB. It is noted that the magnitude difference between the RHB and bottom of AGB is $\sim 0.^m8$ in the disk globular cluster, 47 Tucanae (Lee 1976). In the LF for the RGB stars, a distinct bump appears at $V = 15.^m45$ which is coincident with the visual magnitude of the RHB, and so $\Delta V_{bump}^{HB} = 0$. This case is also seen for NGC 288 which has a highly populated BHB (Bergbusch 1993). This indicates that these two globular clusters have nearly the same metallicity as expected by other direct observations (Caldwell & Dickens 1988). The anomalous distribution of HB stars for NGC 362 and NGC 288 may be explained in terms of mass loss of which the physical mechanism has not been well known yet.

Since NGC 362 is located inside the SMC halo, the faint stars ($V > 16^m$) in the SMC halo appear in the CMD of NGC 362. These stars are separated into metal-rich ($[Fe/H] \approx -0.6$) and young ($\sim 0.3Gyr$) blue component and metal-poor ($[Fe/H] \approx -1.2$) and old ($\sim 8Gyr$) red component, suggesting that the SMC has at least two components of stars with different ages and different metallicity.

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