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THE BVR CCD PHOTOMETRY OF GLOBULAR CLUSTER M13

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ABSTRACT

The BVR CCD photometry was performed for the globular cluster M13 down to V = 19^m over the region from the center to the west 13 arcmin and the CMD of M13 is investigated. The major photometric error in the crowded field which is due to the variation in the sky background was corrected by the median filtering method and the direct sky method. Some characteristics of the CMD of M13 obtained in the present study are as follows: Firstly, the distribution of stars on the CMD is well consistent with the mean lines of Sandage(1970) along the red giant branch(RGB), horizontal branch(HB) and asymtotic giant branch(AGB). Secondly, some gaps exists along the RGB and blue horizontal branch(BHB). Thirdly, the UV-bright stars are more concentrated at the inner region of the cluster.

Key Words : globular cluster, CMD, CCD photometry

I. INTRODUCTION

It is well known that the characteristics of the CMDs of globular clusters are related with their evolutionary physical properties. For example, as the metallicity of a cluster increases, the RGB in the CMD becomes redder and less steep and the HB stars are more populated in the RHB(Sandage, 1982).

It has been known that the morphology of each branch in the CMD varies with radial distance from the center. In NGC 5466, Namec & Harris(1988) found that 42 of the 48 blue stragglers($M = 1.3 \pm 0.3\ M_\odot$) are located within r = 2.5 arcmin. They claimed that this result is caused from the mass segregation effect. In the CMD of M30, Rose *et al.*(1987) found the difference in the ratio R of the number N(HB) of HB stars to the number N(RGB) of RGB stars with radial distance from the center ; that is R = 6 in $r < 10''$ and R = 1.6 in $10'' < r < 30''$. Recently, from the HST observation of M15, Stetson(1994) reported that the number of bright red giants is small in the central region and the RGB shifts systematically toward the blue color as decreasing radial distance, and a large number of blue and yellow stragglers exist within $r = 12''$.

M13(NGC 6205 ; $\alpha_{50} = 16^h39^m54^s$, $\delta_{50} = +36°33.'2$) is a bright and close globular cluster(integrated magnitude $V_m = 5.7$, $R_\odot = 7.1kpc$; Webbink, 1985), and so this cluster has been well studied by various investigators(Arp & Johnson, 1955; Savedoff, 1956; Baum *et al.*, 1959; Sandage, 1970; Simoda & Tanikawa, 1972; Cathey, 1974). Rich & Fahlman(1985) reported from the UBV CCD photometry that M13 has the uniform metal abundance of main sequence stars and no binary sequence. Also Folgheraiter *et al.*(1993) reached the same conclusion as that of Rich & Fahlman(1985) from VR CCD photometry of subgiant stars. The abundances of red giant stars in M13 have been investigated by various authors(Cohen, 1978; Bell & Dickens, 1980; Lehnert, Bell, & Cohen, 1991 etc.). de Bour & Code(1981) reported from the integrated far UV energy distribution that M13 has about 200 blue horizontal branch(BHB) stars. Leget *et al.*(1992) studied the projected radial distribution of BHB stars using UV-(2000 Å). They also reported that the radial distribution of BHB stars is slightly steeper than that expected by the King's law in the visual region. Recently Guarnieri *et al.*(1993) presented from the UBV CCD photometry of M13, the various CMDs different with radial distance. However, they did not proceed more detailed analysis for these CMDs. In the present study, we carried out the BVR CCD photometry of M13, and it is attempted to examine the morphology and variation of CMDs with radial distance from the cluster center.

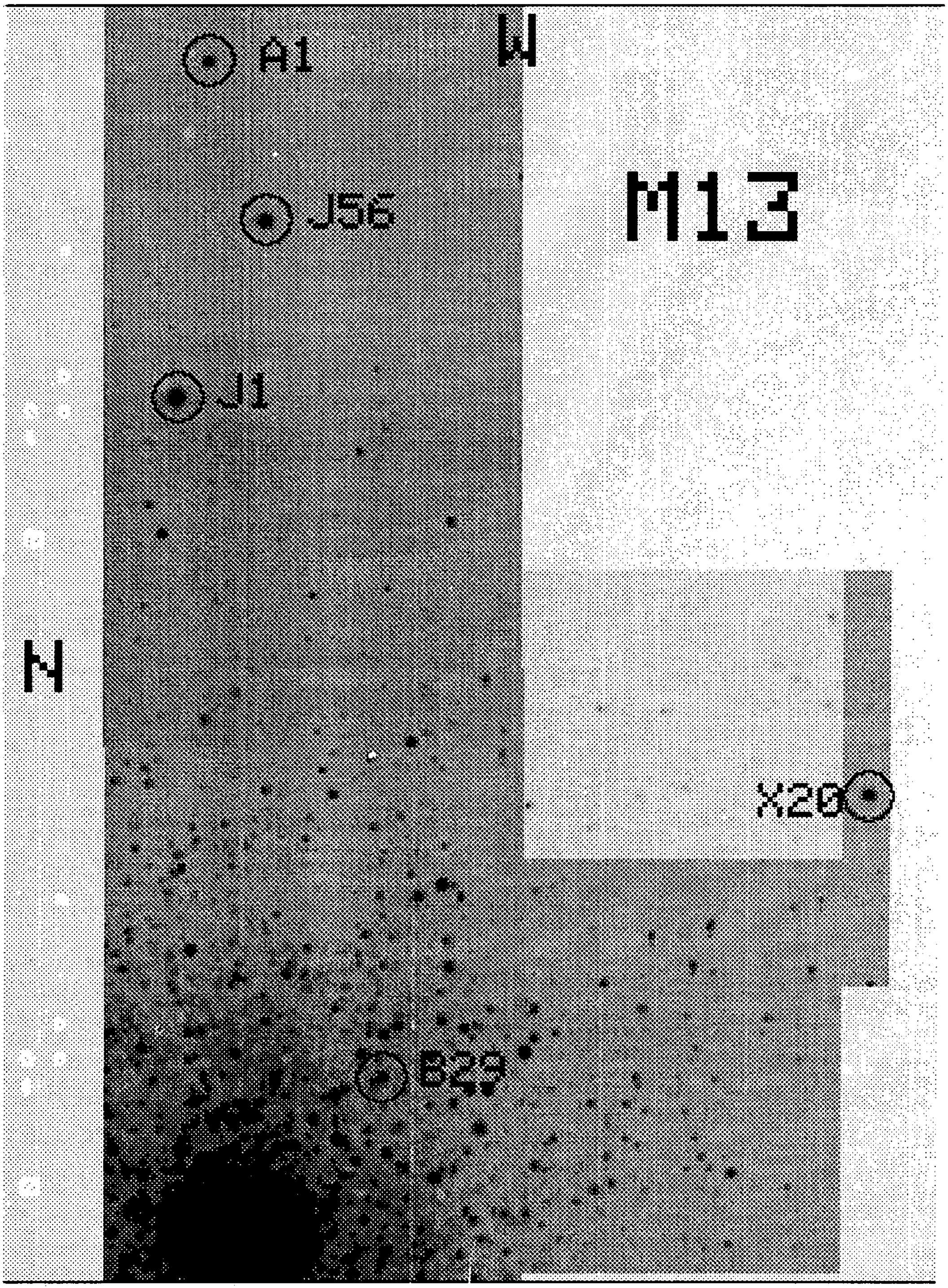

Fig. 1. The map of observed region of M13. Some bright stars in Sandage's(1970) paper are marked by circle. B29(Barnard 29) is a UV-bright star, VZ1128 type.

II. OBSERVATION AND DATA REDUCTION

The observation of M13 was performed on April 4, 1994 using the 60 cm Richey-Chrétien Reflector with Photometrics Series 200 CCD camera system (PM512 CCD chip, pixel size = $20\mu m \times 20\mu m$, equivalent to 0.5xx ″/pixel), and standard BVR filters(Bessell, 1993) at the Sobaeksan Astronomy Observatory. The observed regions are total six areas allowing a slight overlap between neighboring regions from the center to the west 13 arcmin(Fig. 1). Exposure times are 100 sec × 2 frames and 80 sec × 1 frame per each filter in each region. The seeing(FWHM) is about 2.4″(about 5 pixels).

Bias frames were taken occasionally during observations and flat frames were taken 8 times per each filter using the twilight sky and dawn sky. The bias subtraction and flat fielding for each frame were performed by following the standard CCD reduction procedure(Massey, 1992). After that, each two 100 sec frames were combined to obtain a single frame, and then all images were reduced to 2 x 2 binning images in order to save the reduction time. Cosmic rays and bad pixels were removed before combining two 100 sec frames. The IRAF/IMRED package was used for all the pre-processing procedure(Massey, 1992; Massey & Davis, 1992; Wells, 1994; Stetson, 1992a).

The IRAF/DAOPHOT II(Stetson, 1992b; Davis, 1994) package was used in the point spread function(PSF) photometry. The major photometric problem in a crowded field photometry is the correct estimate of the variable sky background. For solving this problem we used the median filtering method(Stetson & Harris, 1988) and direct sky method(Parker, 1991) for which we set allstar parameters(sannulus = 2, wsannulus = 7). After then we iterated allstar task eight times taking the previous allstar output file as an input data file for the next iteration. The final stars are selected on the base of ($\sigma < 0.1$) or ($\chi < 2$, $\sigma < 0.25$). The mean values of 100 sec and 80 sec data were weighted by σ^{-2} . In Fig 2, the uncertainty of stars with V < 16 in the inner regions is nearly twice that of the outer region, and this result is mainly due to a crowding effect in the inner region. All the data were transformed to the standard system using the photoelectric data of Sandage(1970), Arp & Johnson(1955) and Cathey(1974). All six regions were transformed individually using the pe standard stars in each frame, and (V-R) and (B-R) colors in the outer regions in high quality stars with the least photometric error in the overlap region were used as secondary standards.

Our instrumental magnitudes were transformed to the BVR system via the following equations;

$$V = v - 0.023(\pm0.011)(B - V) + const$$
$$(B - V) = (b - v) + 0.124(\pm0.027)(B - V) + const$$
$$(V - R) = (v - r) + 0.273(\pm0.026)(V - R) + const$$
$$(B - R) = (b - r) + 0.184(\pm0.016)(B - R) + const$$

The residuals of our transformed data of standard stars from their published standard values are shown in Fig 3. The mean values of ΔV, $\Delta(B-V)$, $\Delta(V-R)$, and $\Delta(B-R)$ are $0^m.00 \pm 0^m.036$, $0^m.00 \pm 0^m.051$, $0^m.00 \pm 0^m.039$, and $0^m.00 \pm 0^m.042$.

III. Color-Magnitude Diagram and Lumininosity Function

(a) Morphology of the CMD and Luminosity Function

M13 has very few RHB stars and RR Lyrae variable stars but a highly developed BHB up to $V = 18^m$ as seen in Fig. 4. In the V-(B-R) plane which has the largest color difference between red giansts and BHB stars, the two distinct gaps along the BHB are clearly seen.

We divided the observed total region into the inner($r < 100$ arcsec) and the outer($r > 100$ arcsec) regions. In Figs. 5 and 6 it is clearly seen that the inner region stars are more dispersed in the CMDs as compared with the outer region stars. This large dispersion is clearly expected as seen in Fig 2.

In the CMDs of the inner region stars in Fig. 5, two distinct gaps near V = 13.5 and V = 14.5 are shown along the RGB, and several supra-HB(SHB: Strom *et al.*, 1970) stars are also seen above the BHB(V < 14.5). In the V-(B-V) plane in Fig. 6, the mean lines for the outer region stars are exactly following the mean lines(solid line) given by Sandage(1970). Along the RGB and HB, a few gaps and bumps are shown, and only one supra-HB star is seen above the red edge of BHB(V < 14.5), and Barnard 29(VZ1128 type) is located at the position of V = 13.14, (B-V) = -0.20, (V-R) = -0.035, and (B-R) = -0.272. Along the RGB, four narrow gaps appear : The first one, at $V \approx 13.2$, the second, at $V \approx 13.8$, about 1 magnitude brighter than HB, the third, at $V \approx 14.6$, the level similar to the HB magnitude, and the fourth, at $V \approx 15.5$, about 1 magnitude fainter than HB. Along the BHB, two distinct gaps also appear: at $V \approx 15.5$, and $V = 16.4 \sim 17.1$. These gaps are more clearly seen in the luminosity functions of each branch stars in Fig. 7 where Fig. 7(a), Fig. 7(b) and Fig. 7(c) are respectively for the total stars in Fig. 4, for the stars in the outer region in Fig. 5 and for the stars in the inner region in Fig. 6. The thin solid lines in Fig. 7 are represent cumulative luminosity functions. Along the RGB, a distinct bump is seen near V = 14.7 as indicated by Simoda & Tanikawa(1972).

(b) Gaps

i) Horizontal branch

A gap near V = 15.5 on the BHB has been shown in the CMD of Arp & Johnson(1955) for M13 and also seen in other clusters such as M15(NGC 7089: Arp, 1955; Buonanno *et al.*, 1985; Stetson, 1994), NGC 288(Buonanno *et al.*, 1984), NGC1851(Stetson, 1981; Walker, 1992), M2(Alcaino & Liller, 1980), and M68(Walker, 1994). A wide gap at V = 16.4 $\sim$ 17.1 on the EBHB(extended BHB; Stetson, 1994) is equivalent to that seen in NGC 6752(Lee & Cannon, 1980; Buonanno *et al.*, 1986). However, these gaps are not clearly seen in the CMD given by Leget *et al.*(1992) and Guarnieri *et al.*(1993). Simode & Tanikawa(1972) showed the uniform sparse distribution of EBHB stars in the luminosity function. In the observational aspect, the existence of gaps is affected by various factors such as observed area, the number of observed stars and photometric uncertainty. Therefore, this problem should be checked by more accurate, extensive observation of all stars in the cluster.

The morphology of HB is generally dependent on metal abundance, mass loss, mass of hydrogen envelope, and core rotation, etc.(Chiosi *et al.*,1992; Buonanno *et al.*, 1985). The importance of these properties is related to "the second parameter" problem as well as the early evolutionary history of our Galaxy. Many investigators have tried to explain the existence of gap, bimodal HB distribution and EBHB. Norris(1981) and Norris & Smith(1983) showed that CN distribution of RGB stars and the number distribution of HB stars have a bimodal distribution, explaining these by the core rotation. Renzini(1983) noticed that the gap on the BHB appears in some highly concentrated clusters. However, the less concentrated cluster NGC 288 also has the the gap on the BHB. Lee *et al.*(1990) reported that EBHB and bimodal HB distributions can be formed by a large HB mass dispersion, but they failed to reproduce the gap in M15. Recently, Fusi Pecci *et al.*(1993) concluded that more concentrated clusters tend to have a bluer and more extended HB, but van den Bergh & Morris(1993) cautioned that the results are dependent of cluster sample.

ii) Red Giant Branch

The gaps along the RGB are seen in the CMDs of many globular clusters (Lee & Cannon, 1980; Lee, 1977b; Sandage *et al.*, 1968). Hence these observations suggest that some gaps are real. Dermarque *et al.*(1972) explained the formation of gap by the fast rotating core model.

Generally the gaps and bumps are known to be related to the nonuniform evolution along RGB, but Bahcall & Yahil(1972) have reproduced the gaps on the RGB in M15 using simulated luminosity function with random statistical fluctuation. The gaps may be filled as by increasing the number of stars. In the CMDs of 10,297 stars in M15 given by Stetson(1994), no distinct gaps along the RGB are seen. And in the CMD of NGC 6752(Buonanno *et al.*, 1986), the distinct gap between RGB and SGB(Lee & Cannon, 1980) is not seen. Lee(1977a, 1977b) showed that the gap position and width are related to observational regions and photometric error, and these effects also are shown to be dependent of radial distance(Walker,1992). In Fig. 5 and 6 we found that the gap position for the inner region stars is systematically slightly brighter than for the outer region stars, but the relative position betwen gaps is nearly identical. If we shift the CMD for stars of the inner region toward the faint and blue region by about 0.1 magnitude, the positions of gaps in the two CMDs are exactly overlapped each other. The similar effect seems to be included in figure 12 of Stetson(1994). Therefore, the width and position of gaps are strongly related to the number of observed stars, observed area and photometric error, and so accurate and deep CCD photometry over the whole area of cluster is needed.

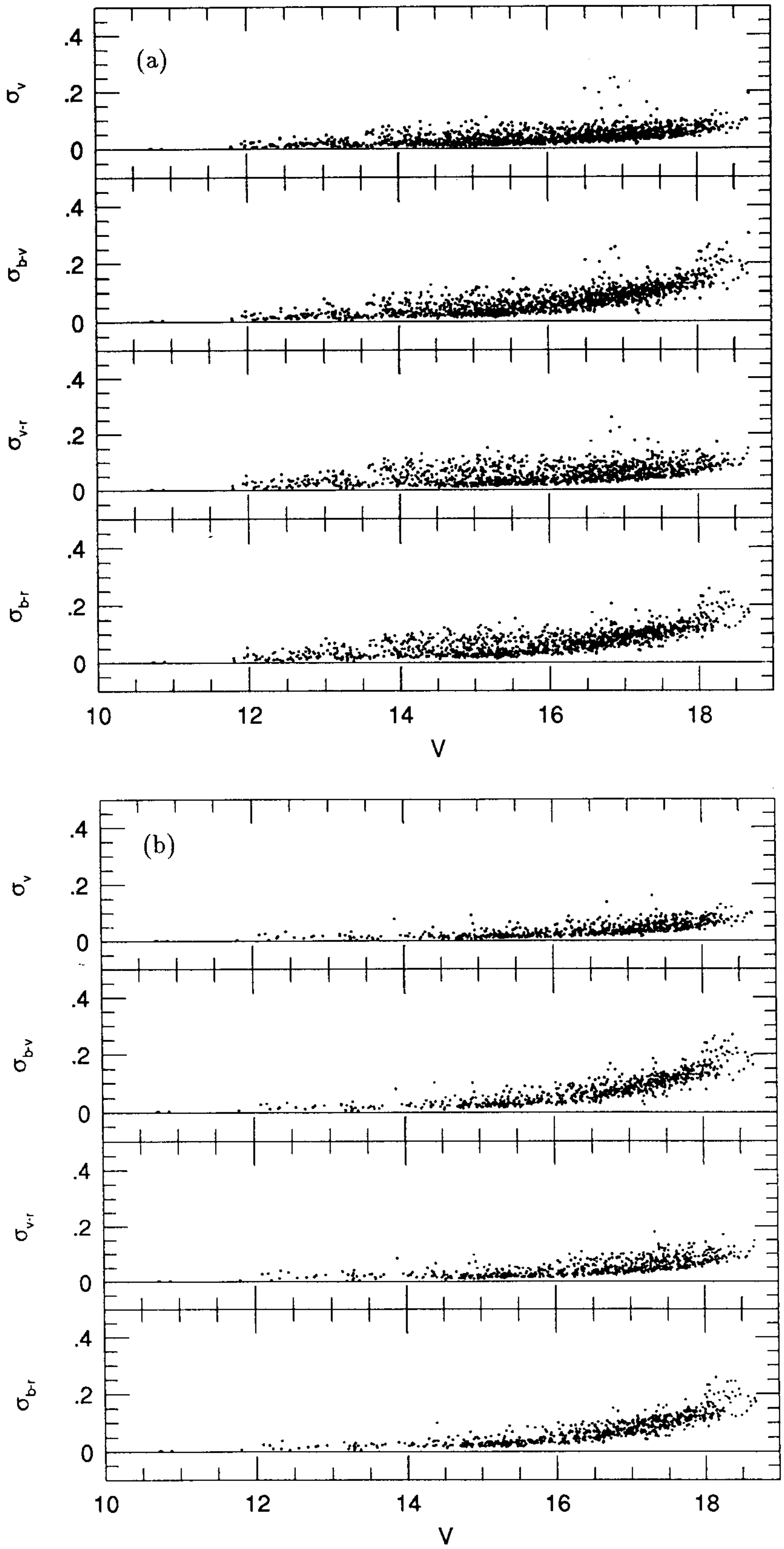

Fig. 2. The errors in magintude and color against the present magnitude V_o; (a) for all stars in the observed region, and (b) for stars in the regions except the center frame. We can see that the error in the central region is nearly twice that of the outer region because of a crowding effect.

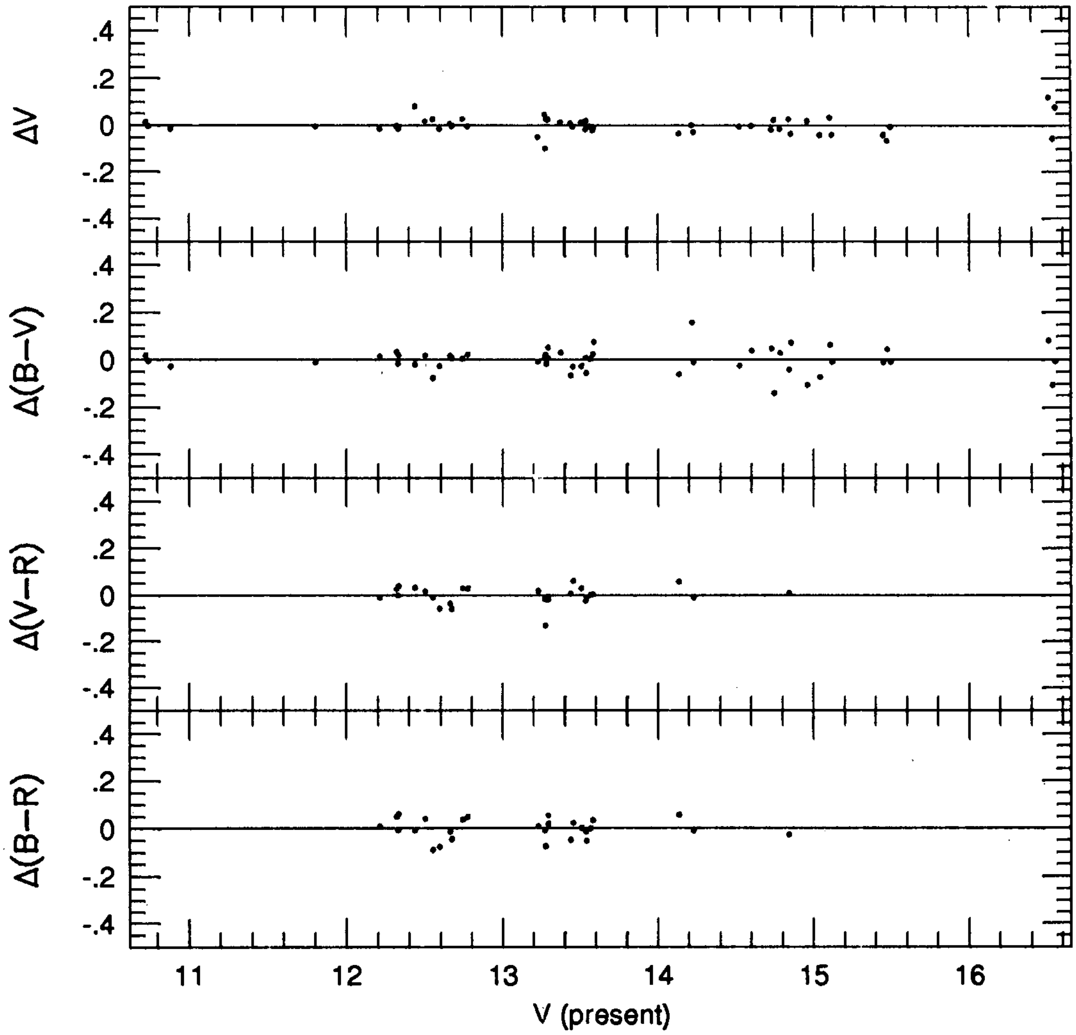

Fig. 3. The differences of the standard minus the present in magnitude and color present against the magnitude V of the present. For (V-R) and (B-R), only Cathey(1974)'s values are plotted.

(c) UV-bright star

The UV-bright stars are less massive than HB stars because they are in the post-HB stage after a significant mass loss(Zinn *et al.*, 1972; Strom *et al.*, 1970; Norris, 1974). The comparison of Fig. 5 with Fig. 6 shows that the UV-bright stars are more concentrated in the inner region. This tendency of the central concentration could be explained as follows : Firstly, the evolution time scale of UV-bright stars(SHB: $\sim 10^7$ yr, VZ1128 type: $\sim 3 \times 10^5$ yr : Norris, 1974) is shorter than a relaxation time scale($T_r \sim 10^{8.67}$ yr: Webbink, 1985) of M13. Secondly, the finding probability of them is higher in the inner region where more stars are concentrated.

Buonanno *et al.*(1985) showed that M15 with EBHB has typical SHB stars but NGC 5466 without EBHB has no SHB stars. Lee(1974) also found a SHB star in the instability region in NGC 6752 with a large EBHB. Therefore it coule be suggested that the EBHB stars are the feeder of SHB stars. Also in figure 3. of Leget *et al.*(1992), M13 has more UV-bright stars than M5. This result may be an evidence for the above suggestion.

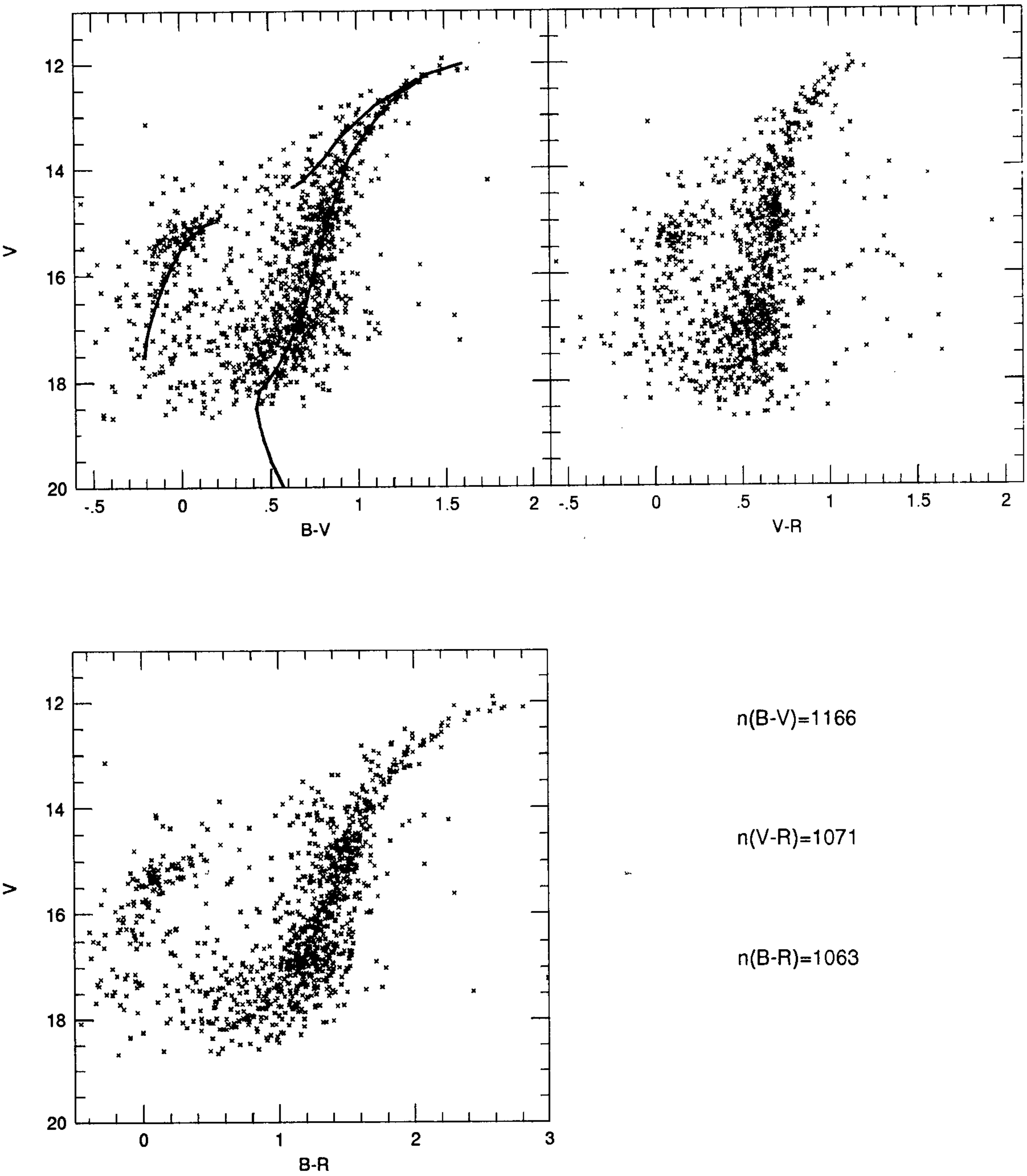

Fig. 4. The CMDs for stars in the whole observed area of M13. In the V-(B-V) plane, the solid line are the mean line of Sandage(1970). The total numbers of measured stars in each color are given in the lower, right corner.

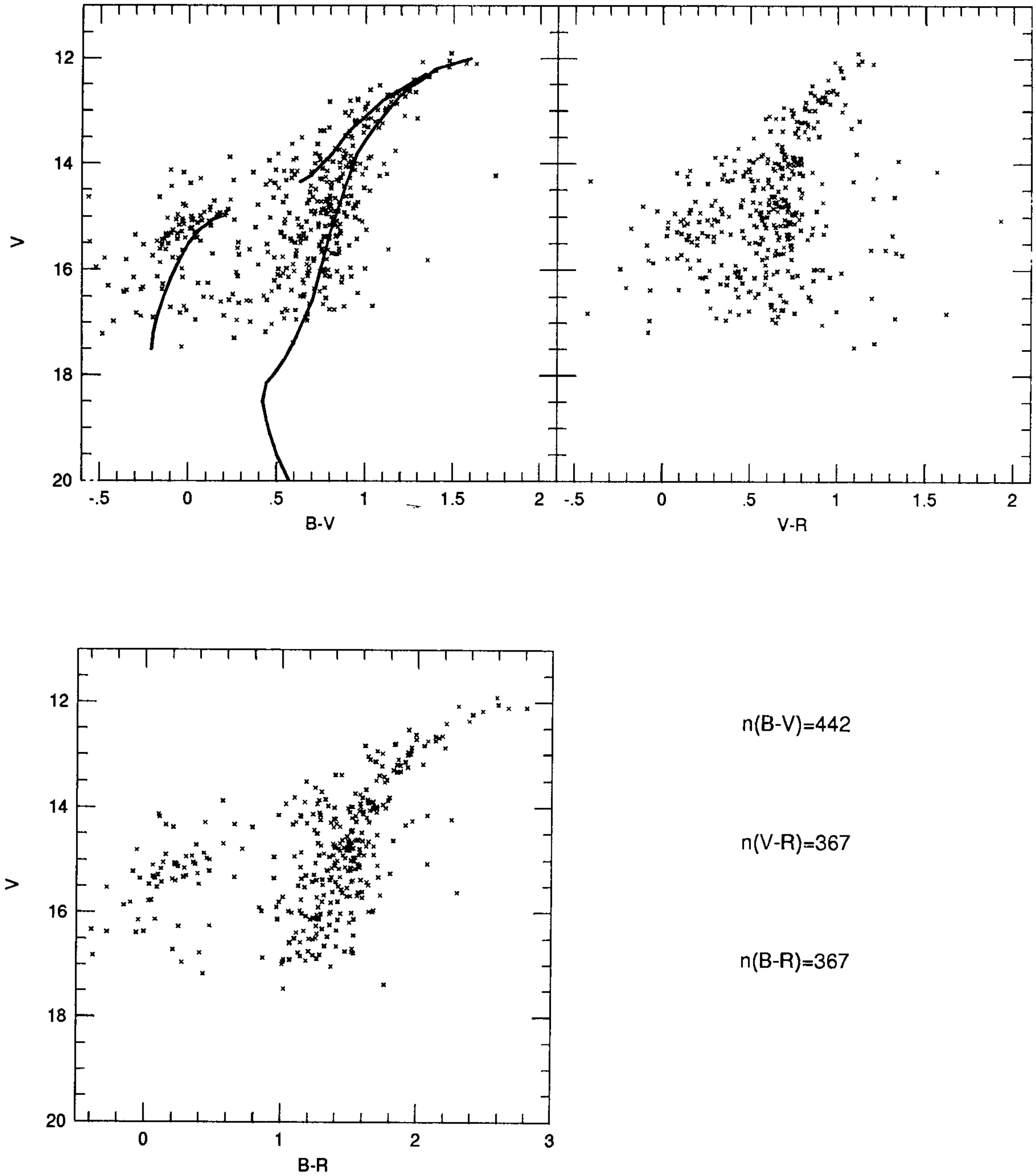

Fig. 5. The CMDs for stars in the inner region($r < 100''$) of M13. The numbers of measured stars in each color in the inner region are given in the lower, right corner.

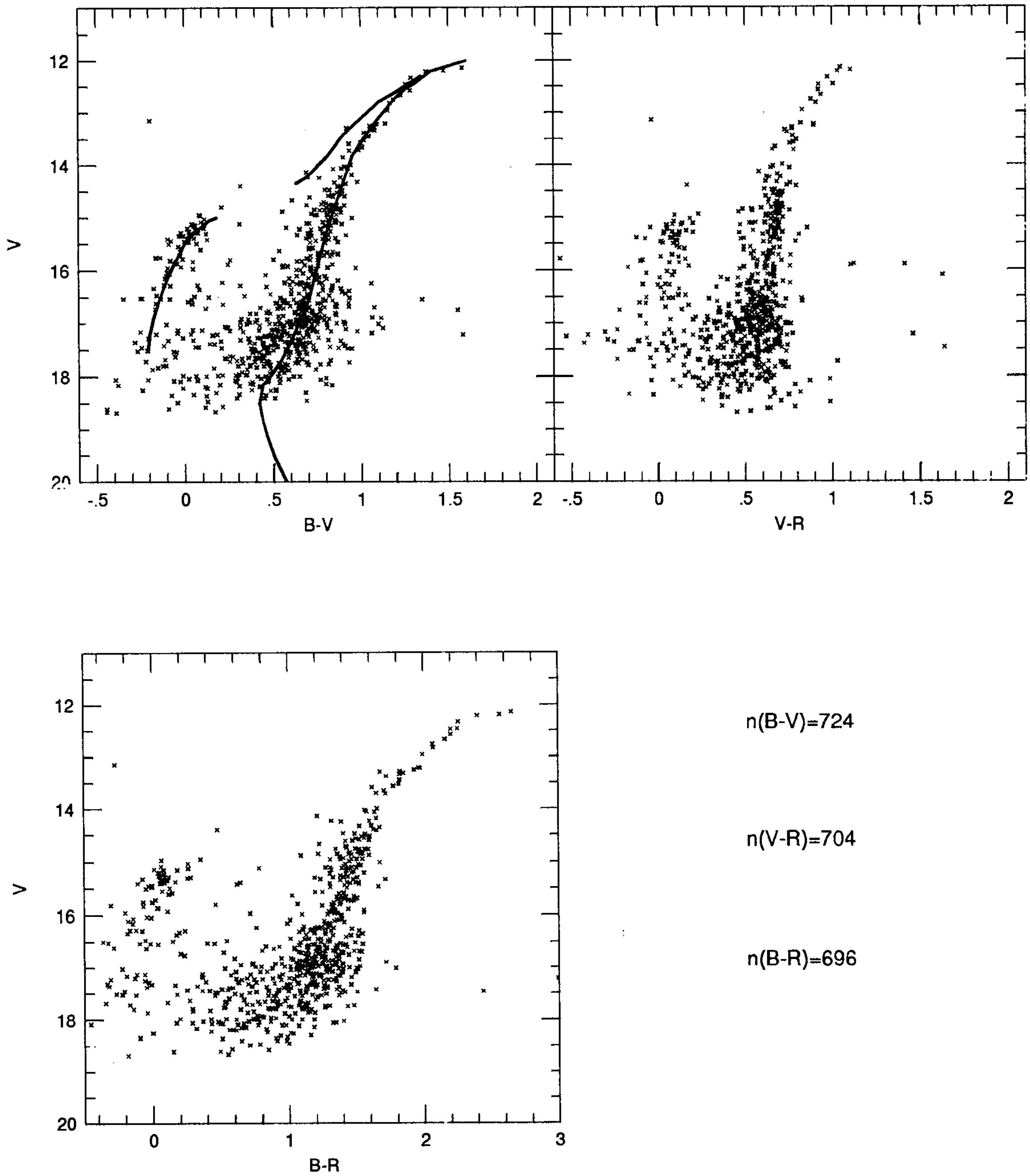

Fig. 6. The CMDs for stars in the outer region($r > 100''$) of M13. The numbers of measured stars in each color in the outer region are given in the lower, right corner.

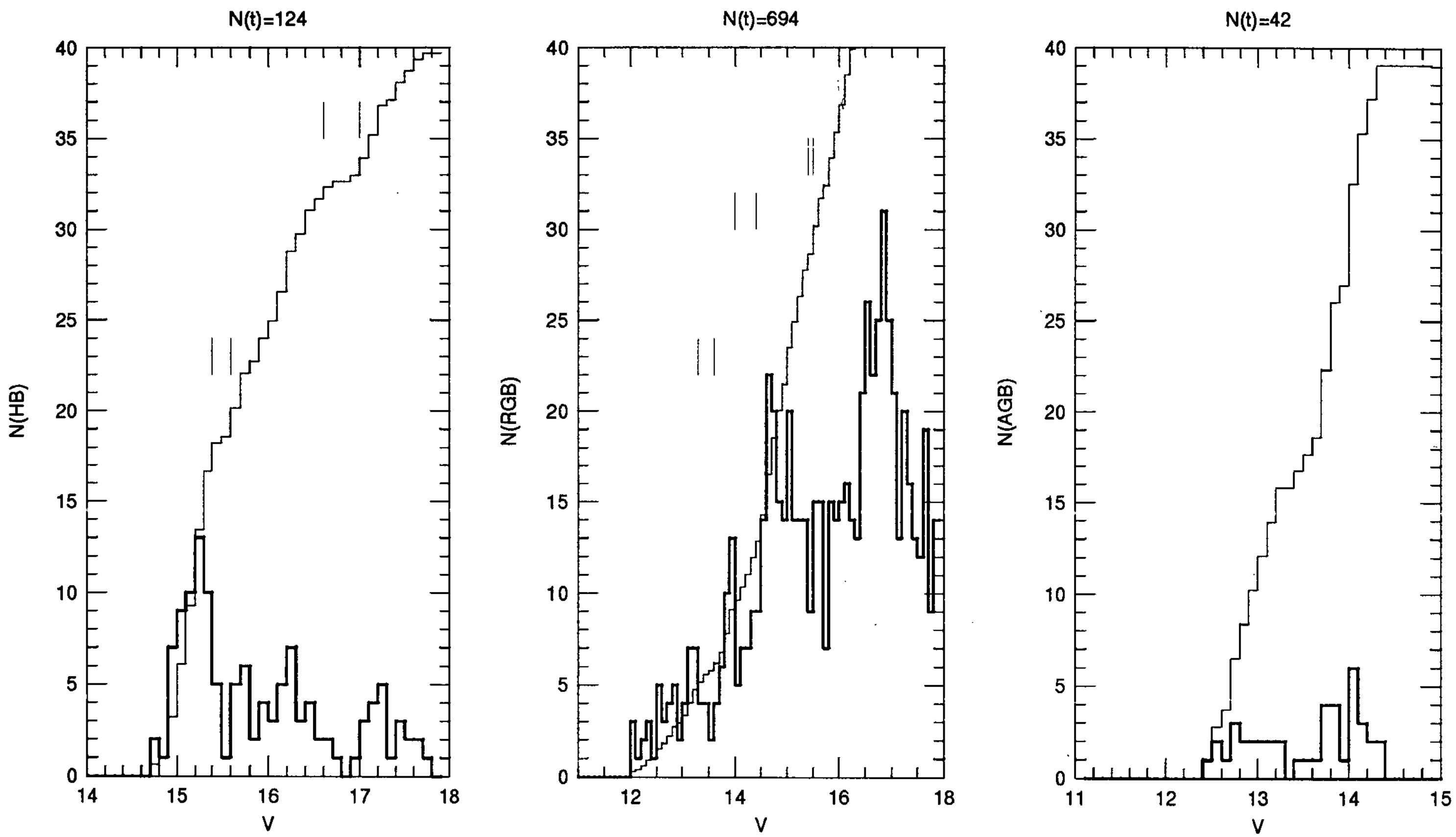

Fig. 7. The luminosity function(thick line) and cumulative luminosity function(thin line) of each branch stars in the V-(B-R) plane. The positions of gaps are marked by double short lines; (a) for all stars in the observed total region of M13. (b) for stars $r < 100''$ (c) for stars $r > 100''$

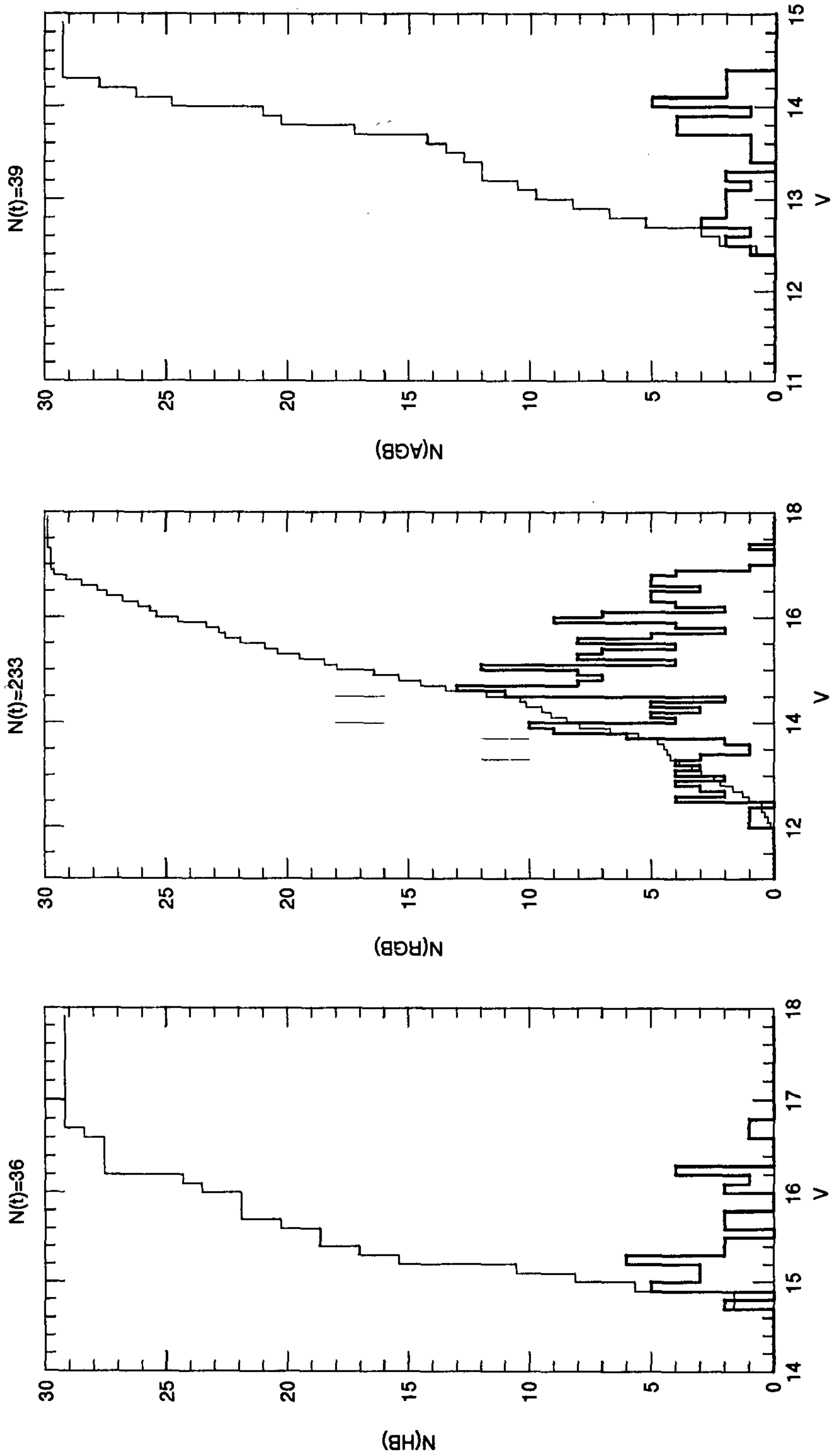

Fig. 7(b).

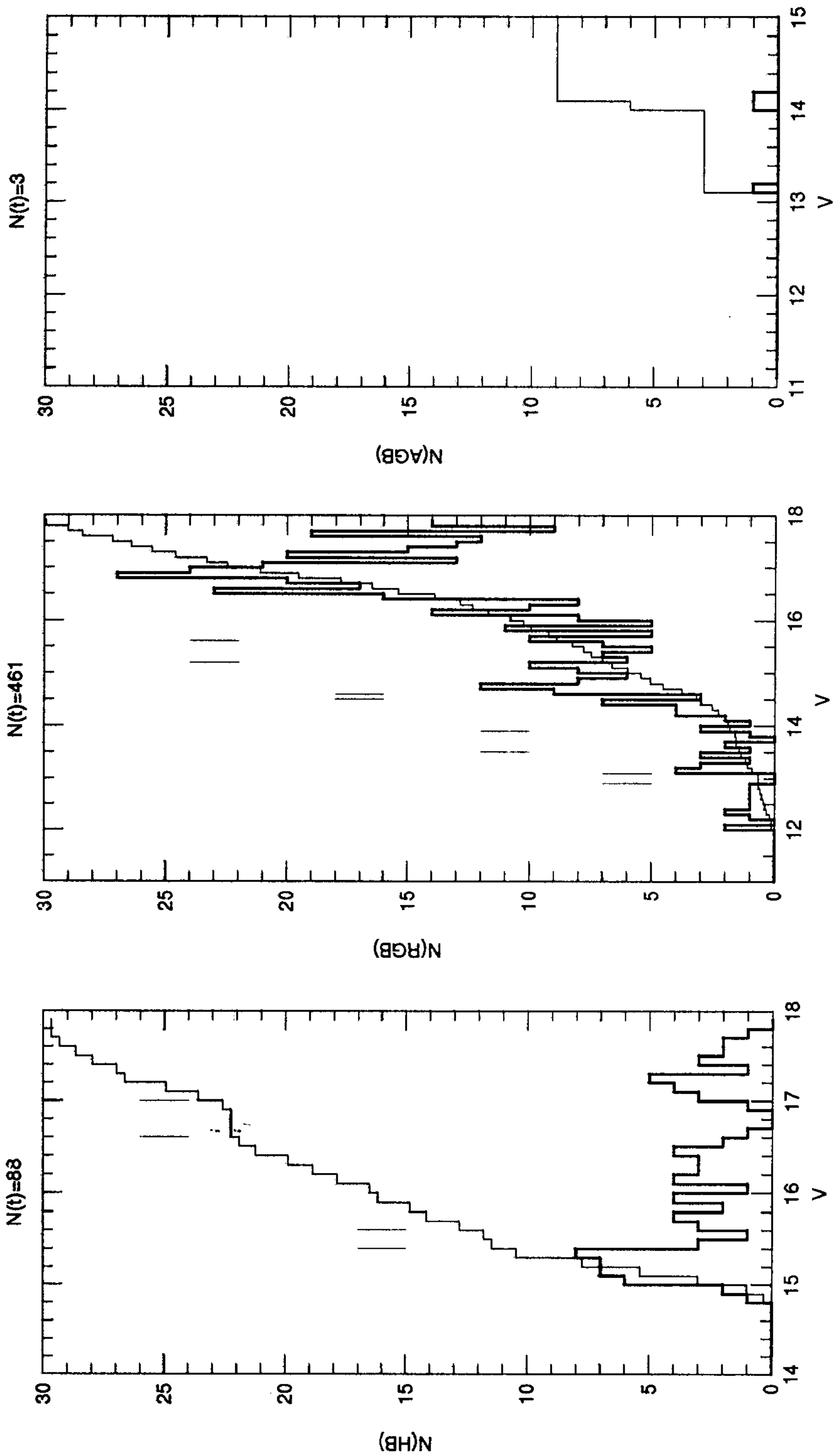

Fig. 7(c).

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