JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
29: 269~278, 1996

UBV CCD PHOTOMETRY OF INTERMEDIATE AGE OPEN CLUSTER M11 I. STATISTICAL ANALYSIS *

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(Received September 25, 1996; Accepted October 14, 1996)

ABSTRACT

We present the color-magnitude diagrams (CMD) of more than 24,000 stars in the field of an intermediate age open cluster M11, based on wide field CCD imaging. The morphology of the CMDs varies strikingly as the distance from the center of the cluster increases. From the surface number density analysis, we confirm the mass segregation effect in this cluster: the bright, massive stars are centrally more concetrated than the faint, low mass stars. The slope of the field-corrected surface density with respect to magnitude progressively increases as the radius increases, up to $r = 5'$. Most of the field stars in or near the cluster main sequence band and in the bright part of the red stars in the CMDs appear to be nearly at the same distance as M11, and they are considered to be the major component of disk stars in the Sagittarius-Carina arm.

Key Words : cluster: open, surface density: luminosity function, mass segregation

I. INTRODUCTION

Open clusters are important targets for the test of stellar evolution theory and for the study of mass segregation effects of stellar system. Many open clusters are not adequate for the study of the above mentioned problems due to the paucity of the member stars or due to the irregular shape of the clusters. M11(NGC6705,$\alpha_{2000} = 18^h51^m4^s, \delta_{2000} = -6°16.'5$) is one of the most adequate clusters for the study of these problems. It contains a very large number of member stars including a few dozens of red giant stars within a relatively circular distribution of stars. M11 is one of the well-known open clusters, but it has not been fully observed. Johnson *etal.* (1956;hereafter JSW) performed *UBV* photoelectric and photographic photometry for about 400 stars in the cluster field, deriving the cluster distance($d = 1.66$ kpc),reddening($E(B-V)$=0.42), and color excesses ratio. Also they concluded that the age of the cluster is intermediate between the Pleiades and Praesepe, and they presumed that M11 is closer to the sun than is the Scutum cloud. On the other hand, McNamara *at al.*(1977;hereafter MPS) carried out an accurate proper motion survey in the cluster field of $\sim 20' \times 20'$ down to $V = 16.^m5$. MPS obtained the cluster proper motion dispersion of 0.″093/*century* for the highest weight group. McNamara & Sanders(1977) also studied the internal motion of stars in M11 using the proper motion data of MPS. They found the velocity dispersion of $2.9kms^{-1}$ independent of stellar mass and the existence of extensive cluster halo. Based on the proper motion study of MPS, Solomon & McNamara(1980) performed photographic photometry and confirmed the effect of mass segregation from the spatial distribution of red giants and upper main sequence(MS) stars. Matieu(1984) performed deep photographic photometry and star count using the KPNO 4*m* plates. He found a thin strip of stars in the red part of the main sequence of M11 and concluded from the spatial distribution of these stars that they are field

* This work was supported by the grant KOSEF(95-0702-01-01-3) and in part by the Basic Science Research Institute Program, Ministry of Education, BSRI-95-5411.

stars. He estimated the tidal radius of M11 to be $10 \sim 20pc$ from the critical evaluation of membership criteria and its surface density profile. He also suggested that the deficiency of lower mass stars($M \leq 1.6\,M_\odot$) in the luminosity function (LF) of M11 relative to the field initial LF.

Mathieu *et al.*(1986) measured the radial velocity of 39 stars in M11, deriving their mean radial velocity of$v_r = 34.5 \pm 1.4 km/sec$. On the other hand, Lee *et al.*(1989) studied the radial velocities of two spectroscopic binaries found by Mathieu *et al.* and derived the lower limit of the cluster distance modulus of $m - M = 12.7$ from their colors and best-fit Yale isochrone. Recently Brocato *et al.*(1993) performed deep BV CCD photometry of $5' \times 5'$ field located at the $\sim 7'$ west from the cluster center using the ESO 3.6m telescope. The CMD they obtained illustrates a well-populated MS up to $V \sim 20.^m5$, showing 2.5 times enhancement of lower($V \geq 15^m$) MS stars(steeper LF) which is contradictory to the result of Mathieu(1984). In this paper, we evaluate the magnitude of mass segregation and radial variation of cluster LF using the new, wide-field CCD photometric data of M11. We describe the observation and data reduction in Section II. The overall characteristics of color-magnitude diagram(CMD), the size of the cluster derived from star count, and radial variation of the CMD morphology are presented in Section III. In Section IV, the total surface density of blue and red components, field-corrected cluster surface density and its variation with increasing radius are examined. Section V discusses our results and Section VI gives the summary and conclusions.

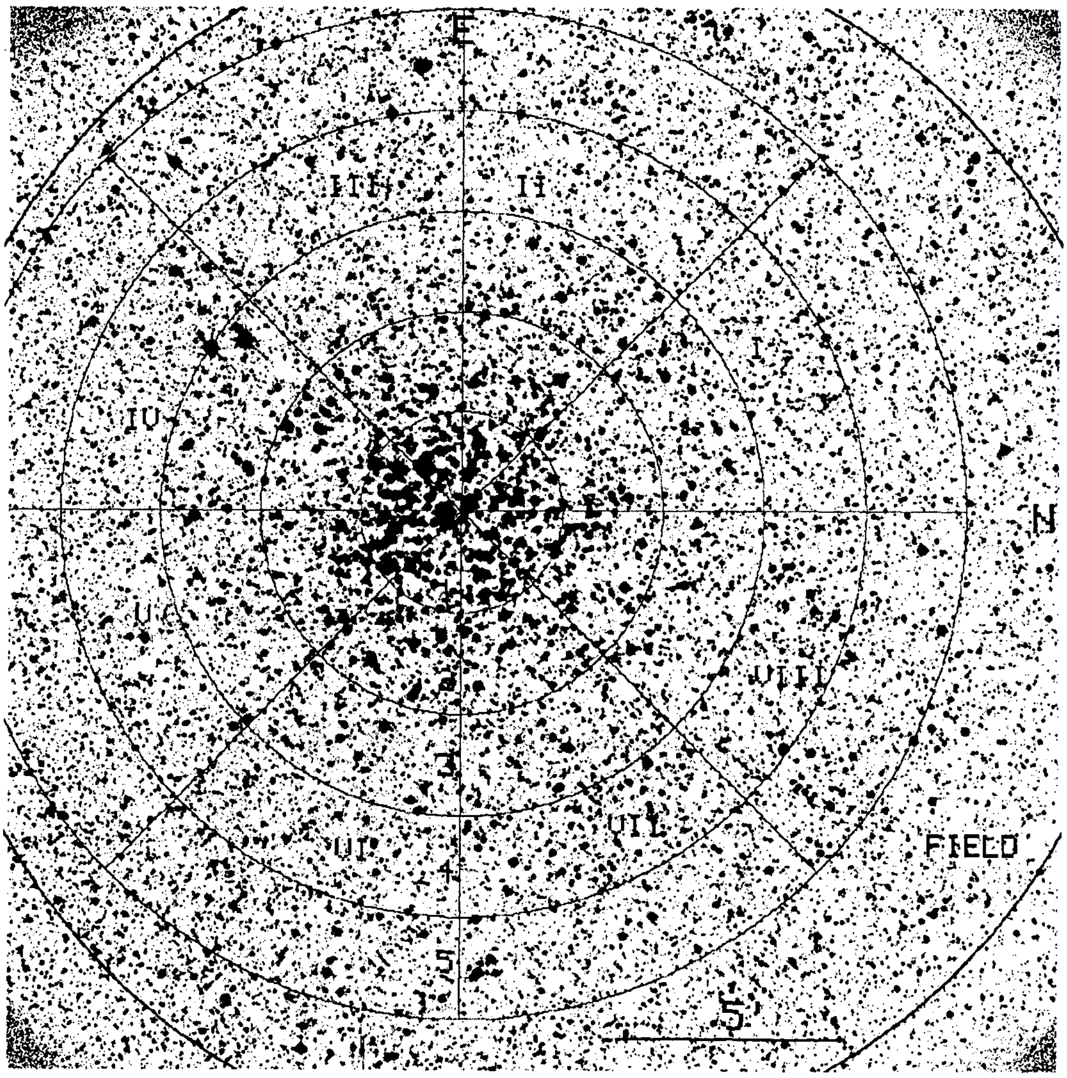

Fig. 1. A CCD image of M11 taken with V filter. The thick line represents the boundary of our photometry. The image was divided into 5 rings and 8 sectors. North is right, and east is up.

II. OBSERVATION AND DATA REDUCTION

The observation for the cluster were made with the 40″ telescope($f/8$) at the Siding Spring Observatory on Aug. 23, 1995. The Tektronix 2048 CCD camera was used as a detector. The gain of the CCD was set to $2e^-/ADU$. The read-out noise was $\sim 43.8e^-$ which was estimated from the standard deviation of bias frames. The scale is 0.″61/*pixel*, covering a field of 20.′8 on a side. The seeing was about 2″ 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 the IRAF version of DAOPHOT II(Stetson 1991). The CCD image of M11 obtained with V filter is shown in Figure 1. The area close to the edges of the CCD image are inadequate for the reliable photometry due to the vegnetting effect. Therefore we limited our photometry to the area inside the radius=12′ from the image center, as marked in Figure 1. More than 24,000 stars were measured both in V and B filter images. The instrumental magnitudes were transformed to the standard UBV system using the combined photoelectric photometric data of JSW and Eggen(1974). The photometric data given by Eggen were transformed to those of JSW by correcting a small amount of zero-point differences using 4 common stars($\Delta V = 0.103 \pm 0.026, \Delta(B-V) = 0.000 \pm 0.008, \Delta(U-B) = 0.020 \pm 0.024, \Delta = Eggen - JSW$, respectively). All the quoted errors represent the weighted transformation errors. The short exposed images were used only for securing the photometry of the very bright stars most of which were saturated in the long exposure images. The transformation equations we obtained are as follows;

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

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

$$U_{pe} = u + 0.045(\pm.007)(U-B)_{pe} - 6.305(\pm.006).$$

Table 1. Observation Log

Filter	V		B		U
Exposure Time	5^s	$50^s \times 2$	10^s	$100^s \times 2$	$200^s \times 2$
$FWHM('')$	1.6	1.9	2.1	2.1	2.2

III. COLOR-MAGNITUDE DIAGRAM

(a) Color-Magnitude Diagram

The CMD of all the measured stars in M11 is shown in Figure 2, where three components of stars are clearly seen. The first component is a well populated MS in the Blue part of CMD, which is extending from $V \sim 11^m$ to the observational limit. A slight deficiency of MS stars is seen at $V \sim 13.^m5$ as pointed out by Kjeldsen & Frandsen(1991). The second component is a red population in the CMD. The upper part of this component has been known as the red giants of the cluster, but the fainter part of this component has not been discussed yet. The third which is less distinctive component compared with the first two components s a thin strip of stars($V = 14^m \sim 16^m, (B-V) = 1$) which are located at just the red side of the cluster MS band. These stars have been discussed as field stars by Mathieu(1984). This component is more clearly seen prominently in the CMD of stars in the outer rings(see Figure 3). For the purpose of statistical analysis, we divided the cluster into 5 rings(the width of ring=2′) over the region of $r = 0' \sim 10'$ as shown in Figure 1, and the CMDs of each ring are displayed in Figure 3. Figure 3 shows that there are dramatic chages of CMD morphology as the radii from the center of the cluster increase. The solid lines in Figure 3 represent the lower envelope of MS stars of M11. This was determined in the CMD of the ring 2($r = 2' \sim 4'$).

In the inner most ring, MS stars and red giants of M11 are clearly distinguished from field stars. The number of stars in the ring 1 decreases drastically in the faint magnitude. This incompleteness for the faint stars is caused from the concentration of bright stars in the central region of M11. Such an incompleteness in photometry is not seen in the CMDs of the outer rings. The number of the MS stars shows a decreasing tendency with radius up to $r \sim 10'$. As mentioned above, there is a upturned strip of stars from $V \sim 16$ to $V \sim 14$ near $B - V \simeq 1.0$ at $r \geq 4'$. Brocato *et al.*(1993) thought this feature as artifacts of statistics. The photometric errors of these stars are small

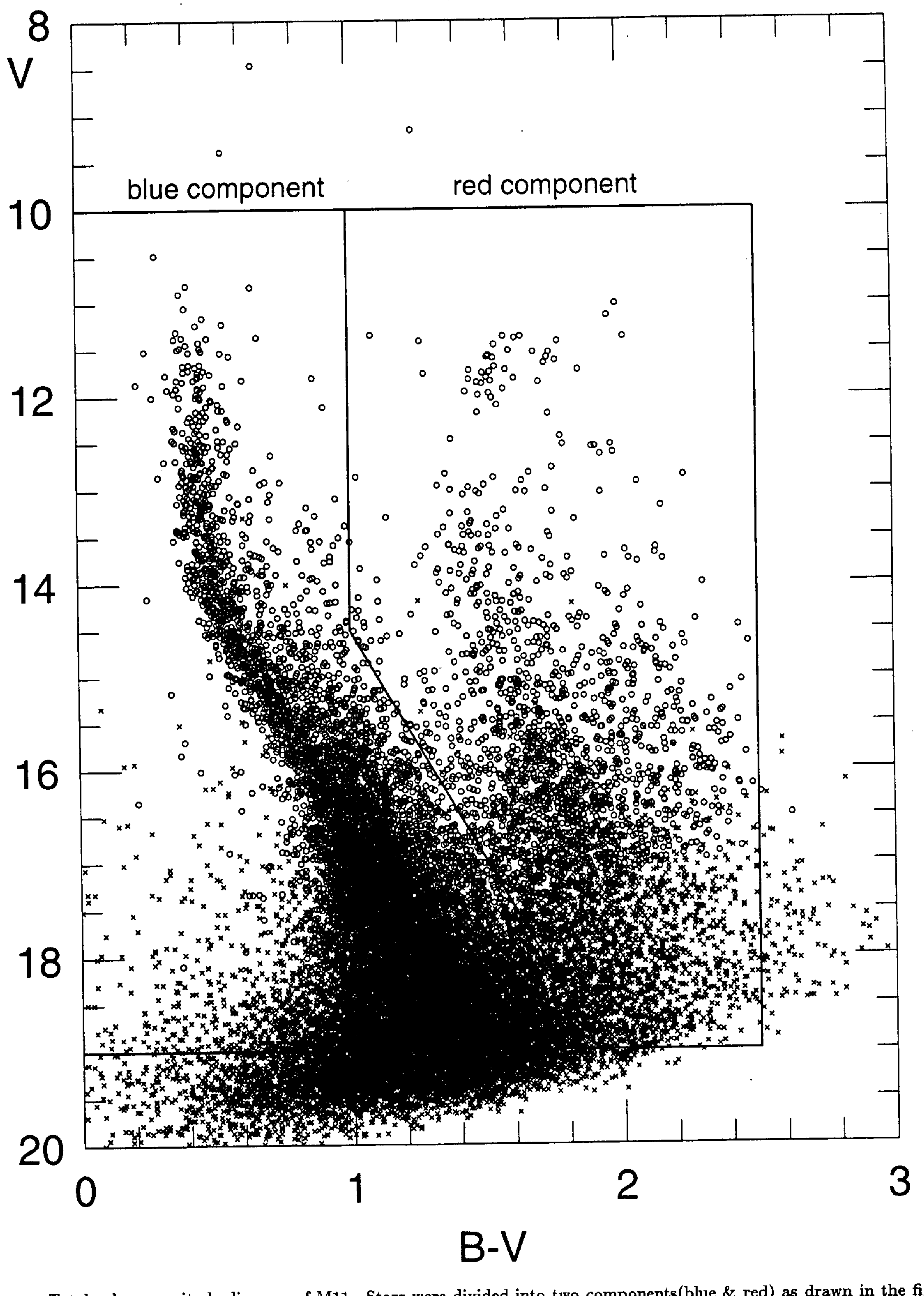

Fig. 2. Total color-magnitude diagram of M11. Stars were divided into two components(blue & red) as drawn in the figure for the statistical analysis. Open circles and crosses represent stars with smaller($\epsilon \leq 0.^m1$) and larger($\epsilon > 0.^m1$) photometric error, respectively.

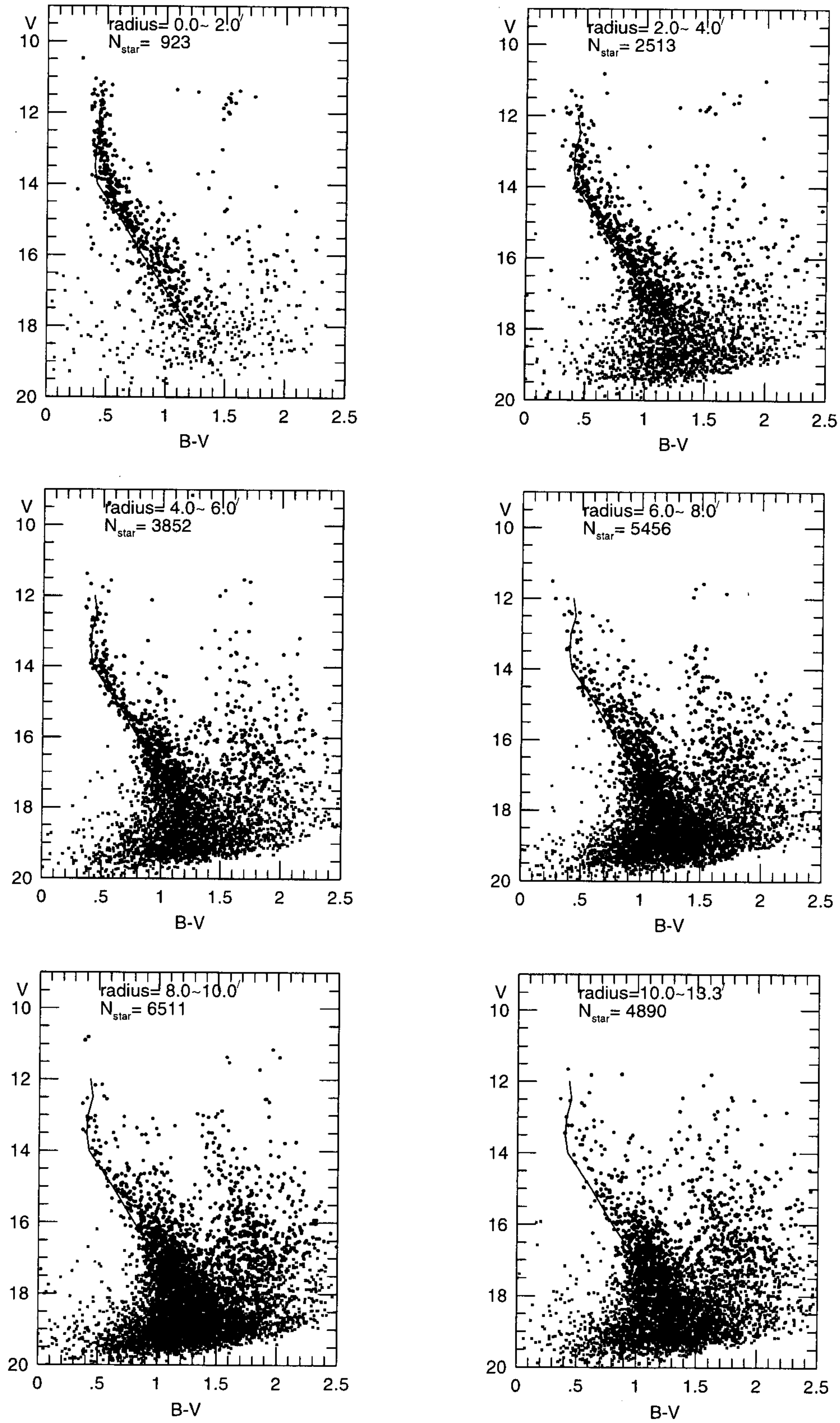

Fig. 3. Color-Magnitude diagrams of the measured stars in various regions in M11. The solid line represents the lower envelope of MS stars in the ring 2.

enough and the number of stars belonging to this strip is not so small. Hence we conclude that this is real feature.

(b) The Size of M11

From the model calculation, Mathieu(1984) obtained the tidal radius of M11 as $10 \sim 20pc$(equivalently $20.'2 \sim 40.'4$ at $d = 1.7kpc$). The most direct method of obtaining the size of a cluster is to examine the radial variation of surface density as shown for bright blue stars($V \sim 16^m, B-V \leq 1.^m2$) in Figure 4. The surface density of these stars decreases up to $r = 10'$ as the radius increases, and beyond this, the surface density becomes equal to that of field stars. Accordingly we adopt approximately $r = 10'$ as the radius of M11. This value is much smaller than that derived from model calculations of Mathieu whose model is strongly dependent on the mass of the cluster and the degree of mass concentration. From now we take the outer region of $r > 10'$ as a field region(i.e. "control field") of the cluster.

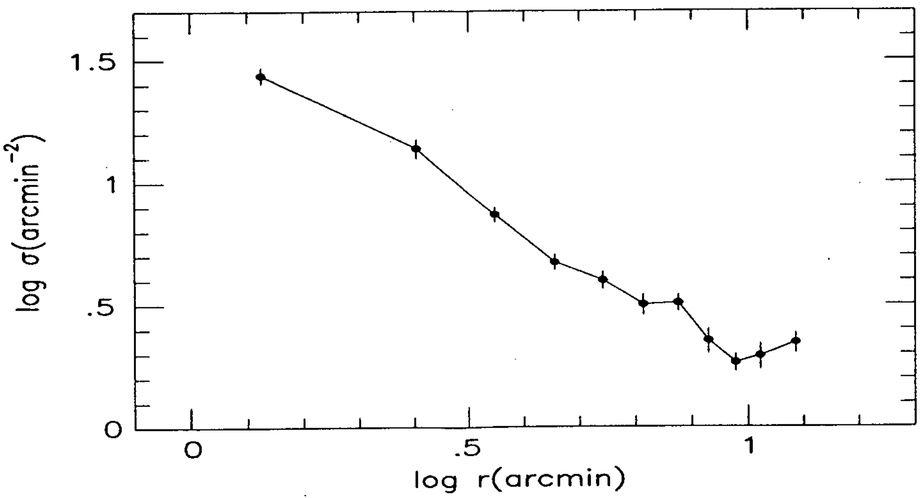

Fig. 4. Surface density profile of stars with $V \leq 16$ and $(B-V) \leq 1.^m2$.

IV. SURFACE NUMBER DENSITY VARIATION

The surface number density is defined by the number of stars per magnitude interval in unit area. The surface density $\sigma(r, m)$ is a function of magnitude and radius from the cluster center. For convenience, we set the magnitude interval as $\Delta m = 1^m$ and the width of annulus as $\Delta r = 2'$. The radial variation of total surface density of the blue component stars in Figure 2 are shown in Figure 5. The total surface density increases as magnitude increases except for the rinng 1. This reveals the completeness of photometry up to $V = 17.^m5$ at $r \geq 2'$. The $\sigma_{tot}(r, m)$ at ring 1 is much great than those ofr the other regions. The difference in $\sigma_{tot}(r, m)$ from that of the field region becomes smaller as the radius increases. At the ring $5(r = 8' \sim 10')$ there appears no difference in surface density from the field region. And the slope of surface density becomes steeper for the outer rings. This is due to the decreasing number of bright, blue stars as the radius increases. On the other hand, the variation of the surface density of red component stars is very different from that of blue component stars as shown in Figure 6. The excess in surface density relative to that of field region can be

found only in the brightest magnitude bin($V = 11^m \sim 12^m$). In the next magnitude bin, the surface density of field region dominates those of cluster regions. The surface density of red component reaches peak at $V \sim 17.^m5$. For the stars fainter than $V \sim 13$ the surface density is nearly independent of radius. This indicates that the faint red star of $V > 13$ seen in the cluster field are actually field red stars. In a small region of sky, we may assume that the distribution of the field stars is uniform. Then the cluster surface number density is obtained by subtracting the surface number density of field stars from the observed total surface density. For the blue component stars, the distribution of the field-corrected cluster surface density σ_{cl} with respect to the magnitude were derived by excluding the stars in ring 4 and 5, because of significant statistical fluctuation in surface density. And their slopes $\eta(r)$ were

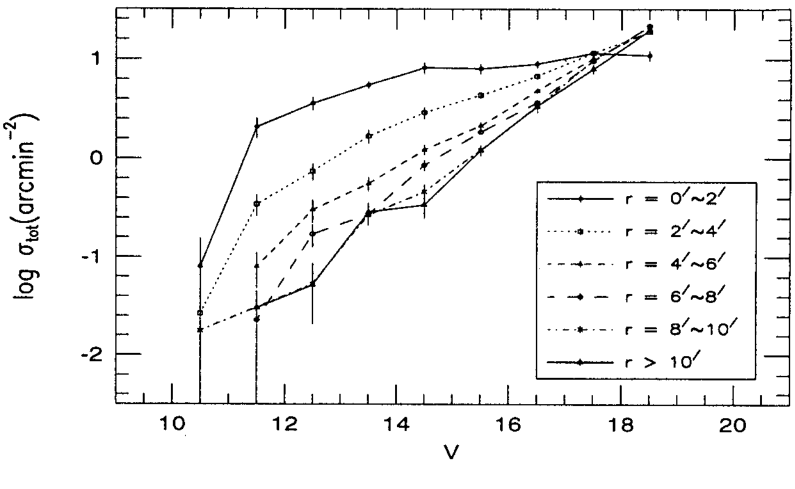

Fig. 5. Radial variation of surface density distributions of blue stars.

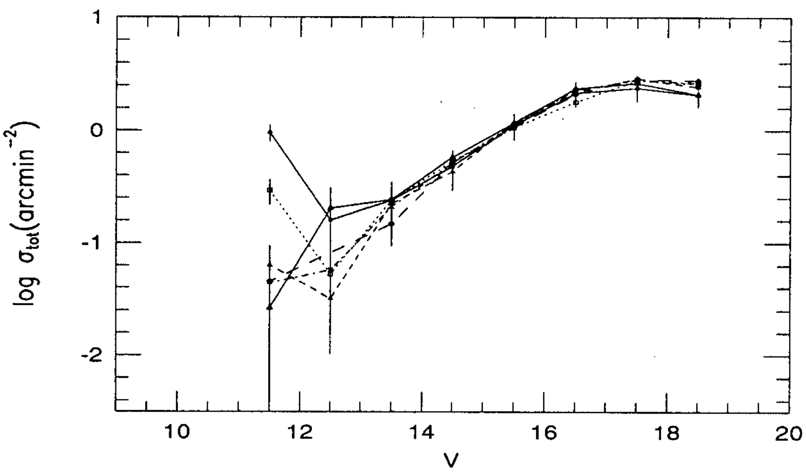

Fig. 6. Radial variations of surface number density distributions of red stars. Symbols are the same as Fig. 5.

evaluated using the following relation:

$$\eta(r) \equiv \frac{dlog\sigma(r,m)}{dM_V\ or\ m}.$$

Here $\eta(r)$ is equivalent to the slope of luminosity function(LF) at radius r. The results for the range of $V = 11^m \sim 15^m$ are shown for stars in rings 1~3 in Figure 7. The cases for the field stars near the cluster in the magnitude range of $V = 11.^m \sim 18.^m5$(equivalently $M_V = -1^m \sim 6^m$ at $V - M_V = 12.^m5$: Brocato *et al.* 1993) and for the solar neighborhood stars(Table 2 in Lee & Sung 1995) are also included for a comparison. The value of $\eta(r)$ seem to be nearly consistent with the maximum value of the cluster when the distribution of $\eta(r)$ is extended outward from $r = 5'$ in the cluster. The distribution of $\eta(r)$ with respect to radius and the radial distribution of surface density in Figure 6 indicate that brighter, massive stars in M11 are located at the inner region while fainter, low mass stars are dominant in the outer region of the cluster. This means that the mass segregation has been achieved in M11. The central concentration of massive stars is clearly evident even for brightest stars of $V = 11^m \sim 12^m$ as shown in Figure 8, where filled and closed circles denote the surface density of massive stars of blue component and red component, respectively. Here we used 28 red giant stars whose memberships are known from proper motion and radial velocity survey. This number of red giants is consistent with the number estimated from the cluster surface density of red component stars and the relevant area. The massive blue stars show slightly more central concentration than red giant stars as noted by Mathieu(1984).

V. DISCUSSION

(a) The Size of M11

The observed region of M11 is limited by $r = 13.'3$ from the cluster center, and the radius of $r = 10'$ is adopted. This radius is much smaller than the tidal radius($r = 20.'2 \sim 40.'4$) derived from the dynamical model calculation by Mathieu(1984). The most important parameter in the calculation of dynamical evolution model is the total mass of a cluster and its degree of concentration. In the estimation of the cluster total mass, Mathieu(1984) included all the stars in the MS band if their proper motion membership probabilities are greater than 0.1. The CMD of stars whose proper motion were measured are shown in Figure 9. The most of faint stars have low membership probability as noted by Mathieu, suggesting that the proper membership probability is a function of magnitude. In the CMD of proper motion member stars, a large number of photometric non-member stars are included. The most of them have the color of reddened giants stars. These stars are actually field stars whose proper motions are identical to those of the cluster members. The CMD morphology of proper motion non-member stars in Figure 9 is nearly the same as that for field stars as in Figure 3. For the proper motion non-member stars there exist three components in the CMD as mentioned in section III.a. Considering the accuracy of proper motion measurement, Mathieu(19840 included all the stars as members if their position in the CMD coincide with the MS band of M11. However, there are significant number of non-member stars in the MS band of M11. Some of these stars are very bright.The non-member stars in the MS band have nearly the same lower envelope of the MS band of M11. This indicates that there exist many field stars at nearly the same distance to M11 as seen in Figure 9. The blue components in Figures 2, 3 or 9, therefore, seems to have nearly the same distance moduli. This implies that there are non-negligible number of non-member stars in the cluster MS band. These two components contributed to the LF of MS stars. The excess in the number of MS stars fainter than $V = 15^m$ in the study of Brocato *et al.*(1993) may be caused by the inclusion of the second component in the blue region of CMD. A simple count of stars in the cluster MS band, therefore, may overestimate the mass of M11. The large tidal radius of M11 calculated by Mathieu(1984) may be caused by the inclusion of non-member stars in or near the MS band of M11.

(b) Non-Member Stars in the Red Part

In the C MD of proper motion non-member stars in Figure 9, a large number of red stars are seen in the right part($(B-V) \geq 1.^m3$). JSW simply noted that these stars are the brightest stars of the background Scutum cloud. Some of these stars, however, seem to be related to the second component of the ield stars existing just in the right part of the MS band of M11. If we take these stars as red giants of the age $\sim 5Gyr$(Brocato *et al.* 1993: equivalent to the red giant clump stars in M67), then their absolute mean magnitude and intrinsic color are given by $M_V \sim 0.^m9$ and $(B-V)_\circ \sim 1.0$. The stars in the range of ($V = 13^m \sim 15^m$ are reddened by $E(B-V) = 0.^m4 \sim 0.^m5$. Then the distance moduli of these stars range from $(V-M)_\circ = 11^m \sim 13^m(d = 1.7 \sim 4kpc)$. This result suggests that some of these red stars are at the same distance as M11. These stars may be disk giant stars in the Sagittarius-Carina arm ($d \sim 2kpc$ in the direction of M11: see Figure 1 of Feinstein 1994)

There is a slight gap in the red star population near $V \sim 15^m$ in Figure 2. The stars fainter than $V = 15^m$ have redder colors than those of brighter stars. The colors of these stars are redder as the magnitudes are fainter. These may imply that these stars are more reddened distant red giant stars. Recently their spectroscopic study on the giant stars in the Baade Window, Sadler *et al.*(1996) reported that the red giants with $V < 15.^m5$ are foreground disk stars, but with $V > 16^m$ belong to the buldge. The distance distribution of red giants in Baade Window (Fig. 8 in Sadler *et al.*) shows two peaks. The one is at $d \sim 2kpc$, and the other is $d \sim 7kpc$. Scutum star cloud($l^{II} \sim 27°$) exists far from the galactic center(Baade Window), but the population of red stars seems to have similar characteristics.

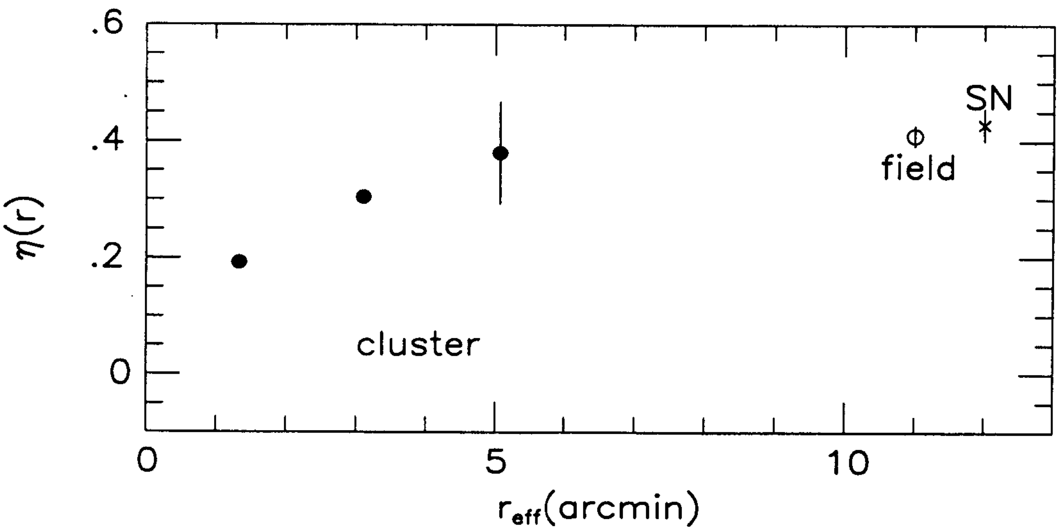

Fig. 7. Radial Variation of the LF slopes. Filled circles represent the LF slopes of the cluster regions, while open circle represents that of field region. Cross mark indicates the LF slope of solar neighborhood MS stars.

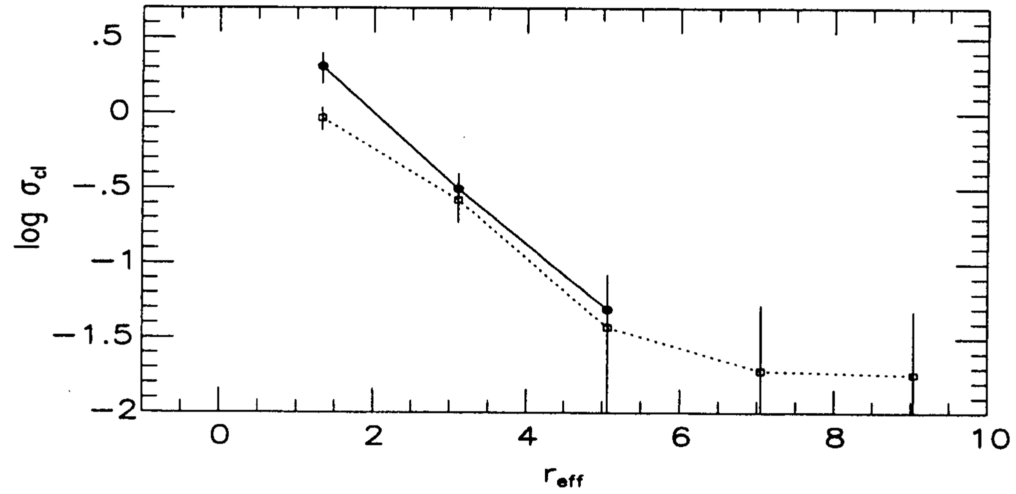

Fig. 8. Radial Variation of the surface density of brightest stars. Filled circle represents the surface density of massive blue stars, while square represents that of red giants.

VI. SUMMARY AND CONCLUSION

Using a new, wide field($\sim 20' \times 20'$) CCD data, we have presented a new CMD of an intermediate age open cluster M11. The field covered by this study is much wider than the other photometric studies, and is comparable to that of proper motion study of MPS. The results obtained in the present study are summarized as follows: (1) The morphology of the CMD varies strikingly with increasing the radius. (2) The slopes of field-corrected LF of M11 also vary. The slopes of the LFof the inner rings are flatter than that of the outer rings, and at $r \sim 5'$ it reaches that of a field region which is similar that of the solar neighborhood. From the variation of the LF with increasing the radius, we have confirmed that the mass segregation is achieved in M11. (3) From the surface density analysis, we have determined the cluster radius as $r \sim 10'$. This value is much smaller than the tidal radius obtained by Mathieu(1984) from the dynamical evolution model calculation. (4) There are a large number of non-member stars in or near the MS band of M11. These stars seem to be at the same distance as M11. (5) The enhancement of the MS stars($V \geq 15^m$) found by Brocato *et al.*(1993) may be attributed to the field stars as mentioned in (4).

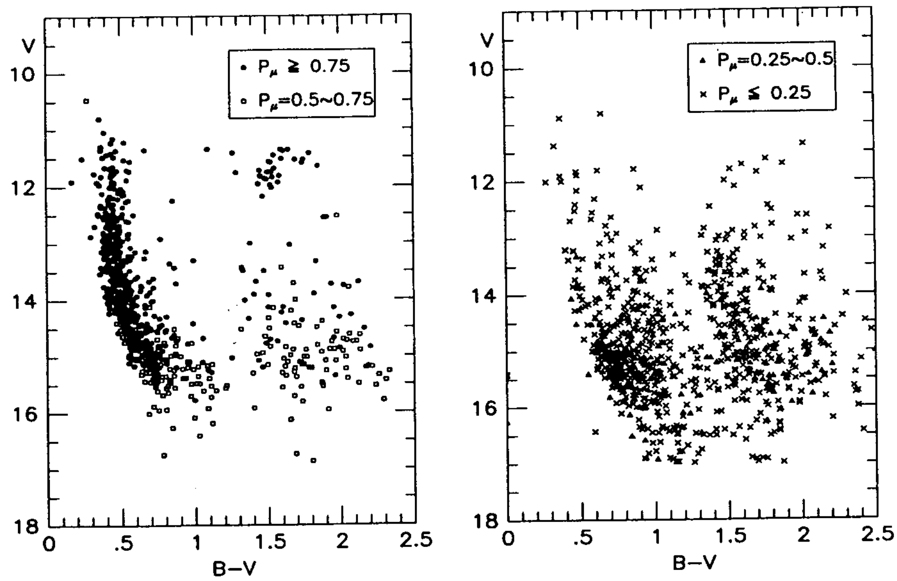

Fig. 9. CMD of proper motion stars. The CMD in the left represents the proper motion member stars($P^{\mu} \geq 0.5$), while the CMD in the right represents the proper motion non-member($P^{\mu} < 0.5$).

ACKNOWLEDGEMENTS

The authors wish to thank the director of the Mount Stromlo and Siding Spring Observatories, professor J. Mould, for allowing us to use the 40″ telescope and facilities at the Siding Spring Observatory. One of the authors(H.S.) would like to express his deep thanks to the staff at the Siding Spring Observatory, for their help during the observing run.

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