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Star clusters in late-type galaxies

Myung Gyoon Lee*
Astronomy Program, SEES, Seoul National University, Seoul 151-742, Korea

Abstract. I present an overview of recent progress in the study of star clusters in nearby late-type galaxies. Colour-magnitude diagrams of star clusters in several nearby spiral galaxies show some differences in the mean colour of the globular clusters and in the magnitude of the brightest clusters. Recent wide field CCD survey of star clusters in M33 found that the star cluster system of M33 is dominated by blue clusters, and that the red clusters are more dispersed in a wider region than bluer clusters. Age distribution of the clusters in the interacting system M51 shows that a significant number of clusters in M51 were probably formed during the interaction of NGC 5194 and NGC 5195. About 50 faint fuzzy clusters are found in NGC 5195, SB0. Recent wide field CCD survey of star clusters in NGC 6822 discovered a new kind of extended clusters in the remote halo of NGC 6822. These new clusters in NGC 6822 share several common features with the faint fuzzy clusters found in the interacting SB0 galaxies, providing an important clue to understanding the origin of extended clusters.

Keywords : star clusters: general — galaxies: dwarf, spiral — galaxies:individual (M31, M33, M51, M81, M101, NGC 6822, NGC 6946)

1. Introduction

Nearby late-type galaxies provide a rich zoo of star clusters. Star clusters are an ideal tool for understanding the formation and evolution of their host galaxies as well as themselves.

Historically NGC 6822 is the first extragalactic system, beyond the Magellanic Clouds, where star clusters were discovered. In 1925 Hubble published a paper with a title,

*e-mail:mglee@astrog.snu.ac.kr

"N.G.C. 6822, A Remote Stellar System", where he described about 10 nebulae he found in NGC 6822, as follows:

"Several other minute nebulous images lie within the limits of the cluster[meaning NGC 6822], which may be small, unresolved globular clusters belonging to the system, or, more probably, non-galactic nebulae whose images are superposed on N.G.C. 6822.".

These objects are called today as Hubble IV ("5$''$ diam. Round" in Hubble 1925), Hubble VI ("8$''$ diam. Round"), Hubble VII ("8$''$ diam. Round"), Hubble VIII ("6$''$ diam. Round") and Hubble IX ("5$''$ diam. Round"), respectively. It is interesting that Hubble gave more weight on the possibility that they may be foreground objects, although he mentioned also the possibility that they may be globular clusters of NGC 6822. Later it turned out that all of them are indeed star clusters belonging to NGC 6822 and that Hubble VII is a genuine old globular cluster (Chandar, Bianchi, and Ford 2000). Since then there were numerous studies on the star clusters in late-type galaxies.

Recently with the advent of wide field CCD imaging facilities and the high resolution CCD imaging cameras on board the Hubble Space Telescope, it became possible to find and study star clusters not only in the remote halo of nearby large galaxies, but also in relatively more distant galaxies. There are several new findings in recent studies of these clusters, some of which, based on our work, are briefly described in the following.

2. Star clusters in nearby spiral galaxies

There are three spiral galaxies in the Local Group: the Milky Way Galaxy, M31 and M33. M31 and M33 are close enough to find star clusters in the ground-based images. On the other hand, star clusters in late-type galaxies beyond the Local Group are challenging to find in the ground-based images, requiring the space telescopes.

Figure 1 displays the $M_V - (B-V)_0$ colour-magnitude diagrams (CMDs) of the star clusters in three Local Group spiral galaxies and four nearby spiral galaxies at the distance 3–10 Mpc derived from recent studies. In the case of the Milky Way Galaxy (Sbc), we plotted 140 open clusters (Lata et al. 2002) and 151 globular clusters (Harris 1996). The source of the photometry of the star clusters in M31 (Sb, $M_V = -21.2$) is Barmby et al. (2000) who compiled all the previous photometry of the M31 clusters.

M33 is a well-known Sc galaxy ($M_V = -18.87$), and there were several surveys of star clusters in this galaxy (see Chandar, Bianchi and Ford 1999, 2001). Recently Park et al. (2006) presented a new survey of star clusters in M33 based on the wide field CCD images obtained using the CFH12K camera at the CFHT and on the HST WFPC2 archive images. There are about 200 clusters confirmed in the HST WFPC2 images (including known clusters and new clusters), and about 1500 probable clusters, which are included in Figure 1. Ten red clusters ($(B-V) > 0.6$) in the halo of M33 which were confirmed to be genuine old globular clusters from the HST WFPC2 photometry (Sarajedini et al. 1998) are also marked in Figure 1.

Taking advantage of the high resolution of the HST WFPC2 camera, Chandar, Whitmore and Lee (2004) presented a new survey of globular clusters in five spiral galaxies at 3–10 Mpc: M81 (Sab, $M_V = -21.63$), M83 (Sc, $M_V = -21.01$), NGC 6946 (Scd, $M_V = -21.46$), M101 (Scd, $M_V = -21.42$) and M51(Sbc, $M_V = -21.68$), based on the HST WFPC2 images. Star clusters in these galaxies except for M83 are included in Figure 1 (there is no available BV photometry of star clusters in M83).

We corrected for only foreground reddening to derive the intrinsic colours and magnitudes of the clusters in all galaxies except for the Milky Way Galaxy in Figure 1. Note that compact clusters are selected in the typical surveys of star clusters (mostly aiming at selecting globular cluster-like clusters) in nearby galaxies so that the counterparts of Galactic open clusters are rarely included in the cluster sample.

Several important features are seen in Figure 1.

1. The intrinsic $(B - V)$ colours of the Galactic globular clusters are redder than $(B - V)_0 \approx 0.5$, and mostly bluer than $(B - V)_0 \approx 1.0$. Most of this red bright clusters in other galaxies may be similar globular clusters, while some of them may be highly reddened clusters. We consider the bright red clusters with $M_V < -6$ mag and $(B - V)_0 > 0.5$ to be bright globular clusters for now.

2. The brightest globular clusters in M33 is about one magnitude fainter than those of other galaxies which are about two magnitude brighter than M33. The bright cluster system of M33 is dominated by blue young clusters, which is similar to that of the LMC (Bica et al 1996). The brightest blue clusters are as bright as the brightest globular clusters. However, the brightest blue clusters in M33 is about two magnitude fainter than those of the LMC. Figure 2 displays the spatial distribution of blue clusters with $(B - V) < 0.3$, intermediate-colour clusters with $0.3 < (B - V) < 0.6$, red clusters with $(B - V) > 0.6$ and all clusters located in the HII regions (which are mostly young clusters). It is seen that red clusters are more dispersed in a wider region than blue or intermediate-colour clusters, indicating that most of the red clusters belong to the halo, while the bluer clusters belong to the disk of M33.

3. The colour of the globular clusters in M31 is, on average, redder than those of the Milky Way Galaxy and M33. The colour dispersion of the globular clusters in M31 is larger than those of the Milky Way Galaxy and M33.

4. The mean colour of the globular clusters in M51 is bluer, indicating more metal-poor, than that of M81 and NGC 6946. The mean colour of the globular clusters in M81 is similar to that of M31. The colour difference indicates that the origin of the globular clusters in M51 may be different from those in M31 or M81.

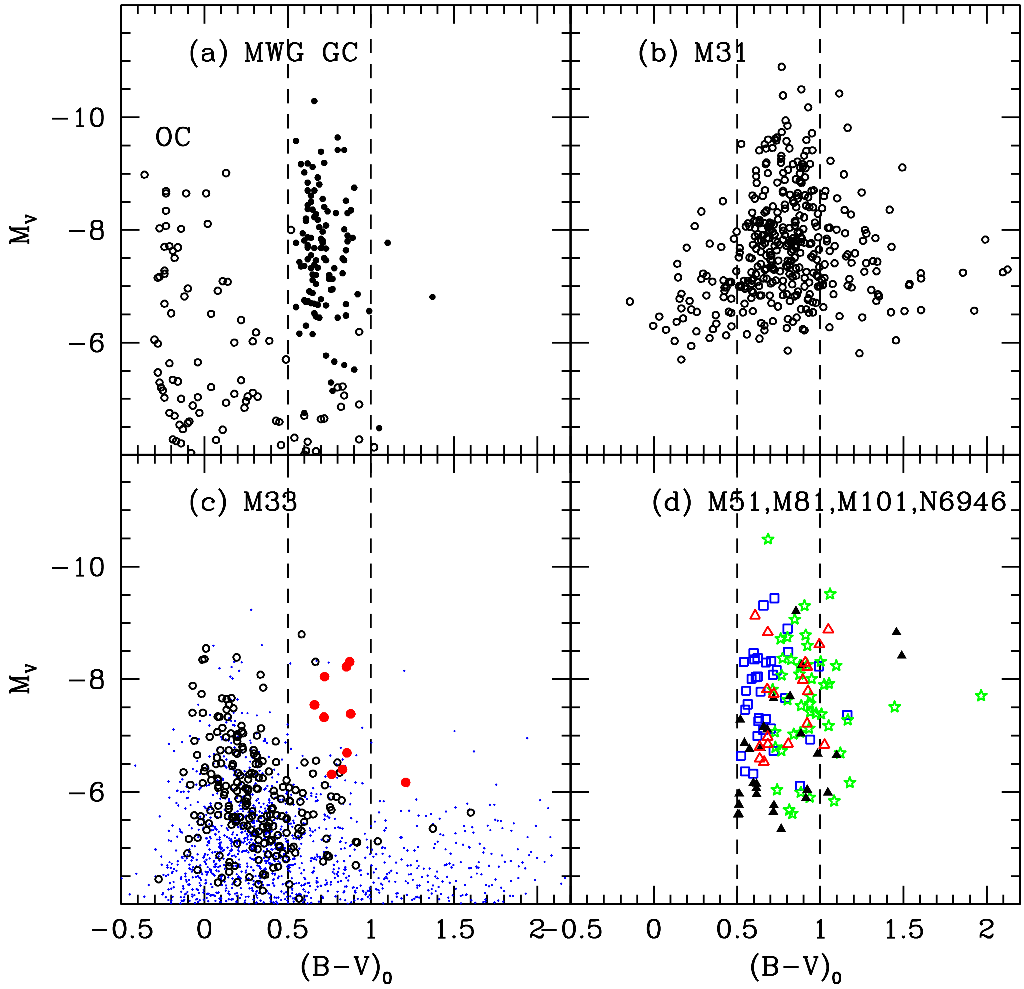

Figure 1. Colour-magnitude diagrams of star clusters in spiral galaxies. (a) The Milky Way Galaxy: open clusters (Lata et al. 2002) (open circles) and globular clusters (Harris 1996) (filled circles). (b) M31 star clusters (Barmby et al. 2000); (c) M33: Genuine clusters (open circles), probable clusters (dots) and genuine old globular clusters (filled circles) (Park et al. 2006); (d) Globular clusters in M51 (open squares), M81 (starlets), M101 (filled triangles), NGC 6946 (open triangles) (Chandar, Whitmore, and Lee 2004). The dashed lines represent approximate boundary for the Galactic globular clusters.

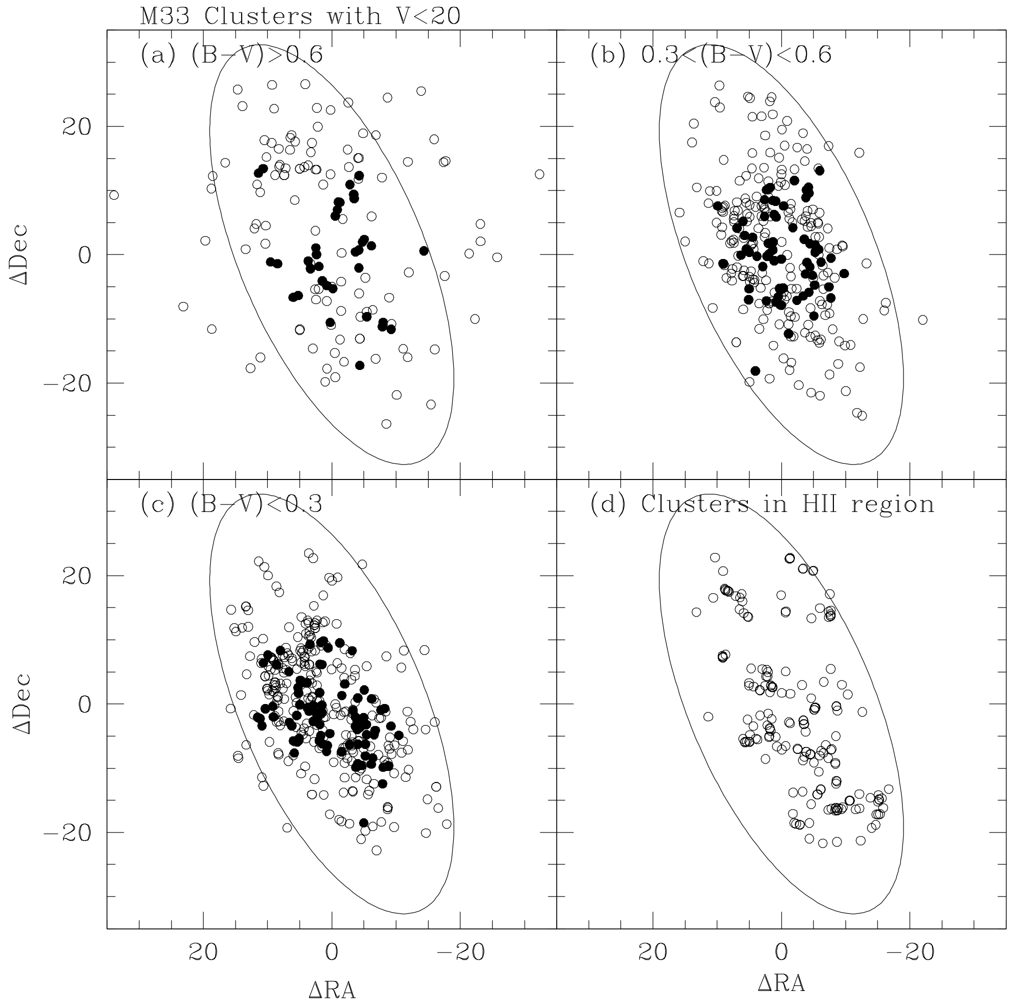

Figure 2. Spatial distribution of stars clusters in M33. (a) Red clusters with $(B-V) > 0.6$. (b) Intermediate-colour clusters with $0.3 < (B-V) < 0.6$. (c) Blue clusters with with $(B-V) < 0.3$. (d) Clusters located in the HII region. The large ellipse represents roughly the optical boundary of M33 (Park et al. 2006).

3. Star Clusters in the interacting galaxy system M51

M51 is an interacting system of two spiral galaxies NGC 5194 and NGC 5195. Lee, Chandar and Whitmore (2005) presented a photometric study of about 400 isolated star clusters resolved in the HST WFPC2 images of M51. Since they selected only resolved clusters, many unresolved young clusters are missing in their sample. Figure 3 displays the colour-magnitude diagrams of the star clusters they found. It is seen that the bright cluster system of M51 is dominated by the blue clusters. This feature is similar to those of M33 and the LMC, but the brightest blue clusters in M51 is much brighter than those in M33 and LMC.

Figure 4 displays an age distribution of these clusters in M51 and they are derived using the spectral energy distribution fitting method. Several notable features are seen in Figure 4.

1. Ages of the clusters range from a few Myr to about 10 Gyr, mostly smaller than 1 Gyr.
2. Age distribution of the clusters shows two distinguishable peaks: one strong peak at 4 Myr and another broad peak at 100 – 400 Myr. The broad peak may contain two peaks at 100 and 400 Myr, which need to be confirmed with better data. These peaks are consistent with the crossing times of the companion galaxy NGC 5195 through the NGC 5194 disk which were estimated both in the single and multiple-passage dynamical models. This provides strong evidence supporting the hypothesis that star clusters form during the interaction of galaxies.
3. The broad peak is mostly due to the massive clusters ($logM/M_{\odot} > 4.5$) in the outer region, while the strong peak is mainly due to the low-mass clusters ($logM/M_{\odot} < 4.5$) in the central region.
4. Very young clusters are seen mostly in the central region and on spiral arms, some along the tip of one spiral arm passing the central region of NGC 5195, extending from NGC 5194).

Lee, Chandar, and Whitmore (2005) also found about dozen faint red clusters, so-called faint fuzzy clusters in the companion galaxy NGC 5195. Faint fuzzy clusters are faint ($M_V > -8$), large (half-light radii larger than 7 pc) red ($(V-I) > 1.0$) clusters introduced by Larsen and Brodie (2000) in their study of star clusters in the lenticular galaxy NGC 1023. They are known to be old (ages larger than a few Gyrs old) (Brodie and Larsen 2002). Figure 3 (right panel) displays the colour-magnitude diagram of the star clusters detected in the public HST ACS images of NGC 5195 (Hwang and Lee 2006), including the faint fuzzy clusters discovered by Lee, Chandar and Whitmore (2005). The HST ACS images of NGC 5195 Hwang and Lee used cover much larger field of view and have higher spatial resolution than the HST WFPC2 images used by Lee, Chandar, and Whitmore (2005). The blue clusters are mostly located on the spiral arm extending north from NGC 5194. The cluster system of NGC 5195 is dominated by red clusters, and there are about 50 faint fuzzy clusters (marked by the filled circles) among them.

NGC 5195 is the third galaxy which is known to have faint fuzzy clusters following

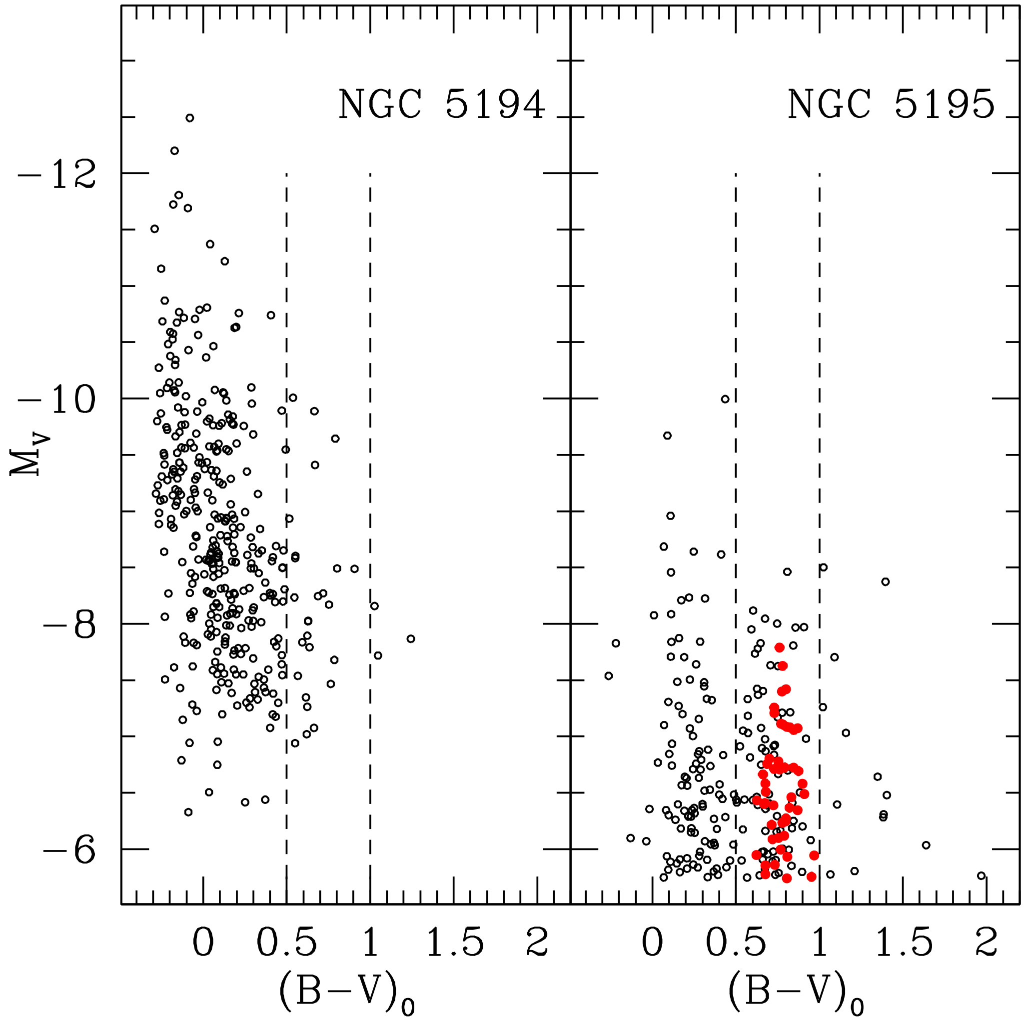

Figure 3. Colour-magnitude diagrams of star clusters found in the HST WFPC2 images of NGC 5194 (Lee, Chandar and Whitmore 2005) and in the HST ACS images of NGC 5195 (Hwang and Lee 2006). The large circles represent the faint fuzzy clusters in NGC 5195. The dashed lines represent approximate boundary for globular clusters.

NGC 1023 and NGC 3384. Interestingly all these three galaxies are SB galaxies interacting with either dwarf galaxies or larger galaxies. This indicates that the origin of faint fuzzy clusters may be related not only with the formation of the SB0 galaxies but also with the galaxy interaction.

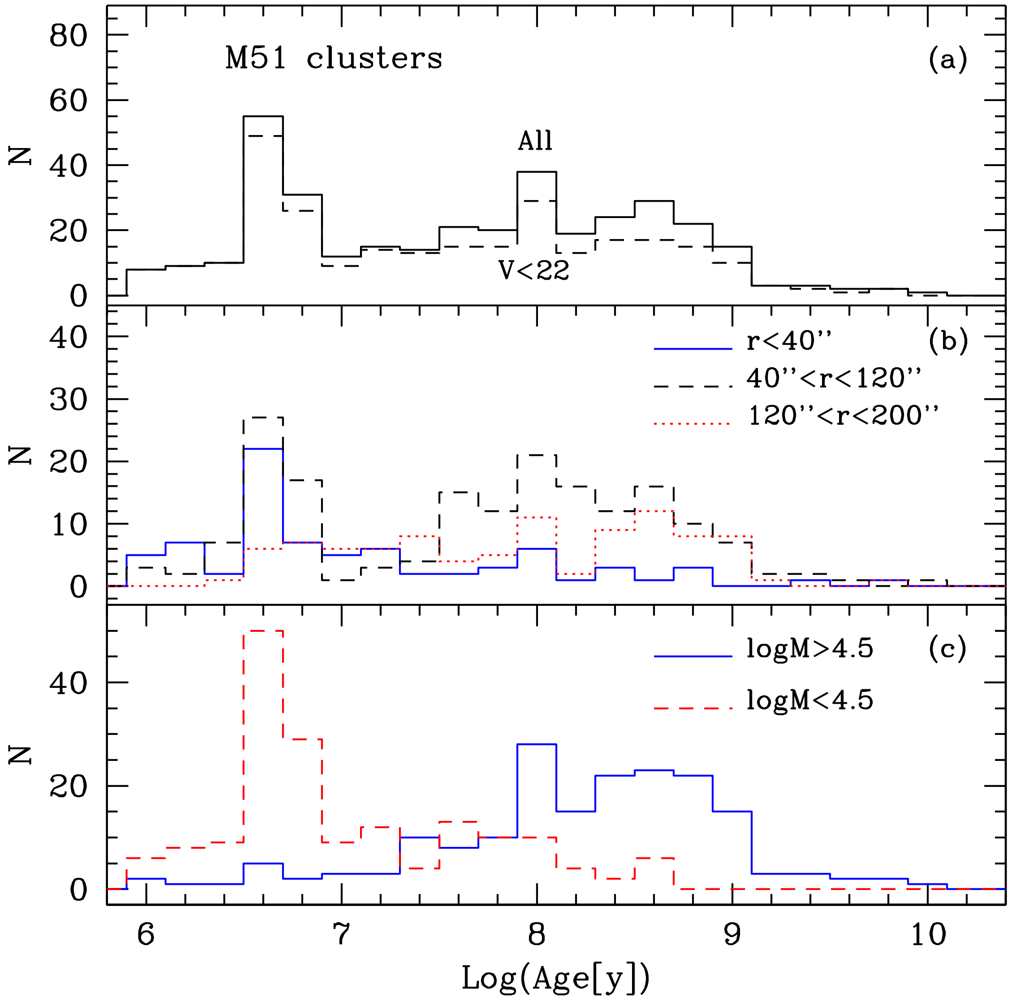

Figure 4. Age distribution of star clusters in NGC 5194. (a) All clusters (solid line) and bright clusters with $V < 22$ mag (dashed line). (b) Radial variation. $r < 40$ arcsec (solid line), $40 < r < 120$ arcsec (dashed line), and $120 < r < 200$ arcsec (dotted line). (c) High mass clusters with $\log M > 4.5 M_\odot$ (solid line) and low mass clusters with $\log M < 4.5 M_\odot$ (dashed line).

4. New star clusters in the dwarf irregular galaxy NGC 6822

NGC 6822 is a dwarf irregular galaxy ($M_V = -16.0$) without any nearby companion galaxies. It is much fainter than the LMC ($M_V = -18.5$), but slightly brighter than another Local Group dwarf irregular galaxy IC 1613 ($M_V = -15.3$). Since the first discovery of five star clusters by Hubble (1925), about 17 clusters in total are found in NGC 6822 (Hodge 1977; Krienke and Hodge 2004). Only one cluster, Hubble VII, among these is known to be a genuine old globular cluster.

Recently Hwang et al. (2005) presented a survey of star clusters in the deep and wide field CCD images taken using the Megacam at the CFHT, covering a total field of 2 deg $\times$ 2 deg. Surprisingly they found three new clusters in the remote halo of NGC 6822. Figure 5 shows the greyscale maps of the i-band images of the new clusters in comparison with the known globular cluster Hubble VII. The new clusters look extended and partially resolved into stars, while Hubble VII looks compact and unresolved in Figure 5. The half-light radii of these clusters are derived to be 10-23 pc, much larger than those of typical globular clusters. They are fainter than $M_V \approx -8.0$. Interestingly the magnitude, colour and size of these clusters are in the range of those for the faint fuzzy clusters found in NGC 5195 and other SB0 galaxies. These extended clusters are also similar to those recently found in the halo of M31 (Huxor et al. 2005). The origin of these extended star clusters is not clearly understood yet, requiring further studies.

The location of these clusters are illustrated in Figure 6. All previously known clusters are located in the main body of NGC 6822, while new clusters are far from the center of NGC 6822. The most remote cluster among the new clusters is found to be located as far as 79 arcmin away from the center of NGC 6822 (the projected distance is about 12 kpc). This distance is several times larger than the size of the region in NGC 6822 where star clusters were previously found. This case is similar to NGC 1841, the outermost star cluster in the LMC, located at about 13 kpc from the LMC centre. However, NGC 6822 is 2.5 magnitude fainter than the LMC. Color-magnitude diagrams of the resolved stars in the clusters indicates that at least two of these clusters are probably old globular clusters. The existence of the newly discovered star clusters suggests that the underlying halo may have a different structure from previously known structure of NGC 6822: a bar-like optical body or a giant HI disk-like cloud which is extended along NW-SE direction (de Block and Walter 2000).

5. Summary

It has been long since the first study of extragalactic clusters beyond the Magellanic Clouds was published by Hubble (1925). Although there were many studies of the clusters in late-type galaxies, new aspects of star clusters and new kinds of star clusters are continuing to be discovered today. Especially we are enjoying the introduction of a new family of extended clusters which may link the previously known compact star clusters and the small compact dwarf galaxies. It is challenging but important to understand the origin of these extended clusters. Today is the golden age for star clusters.

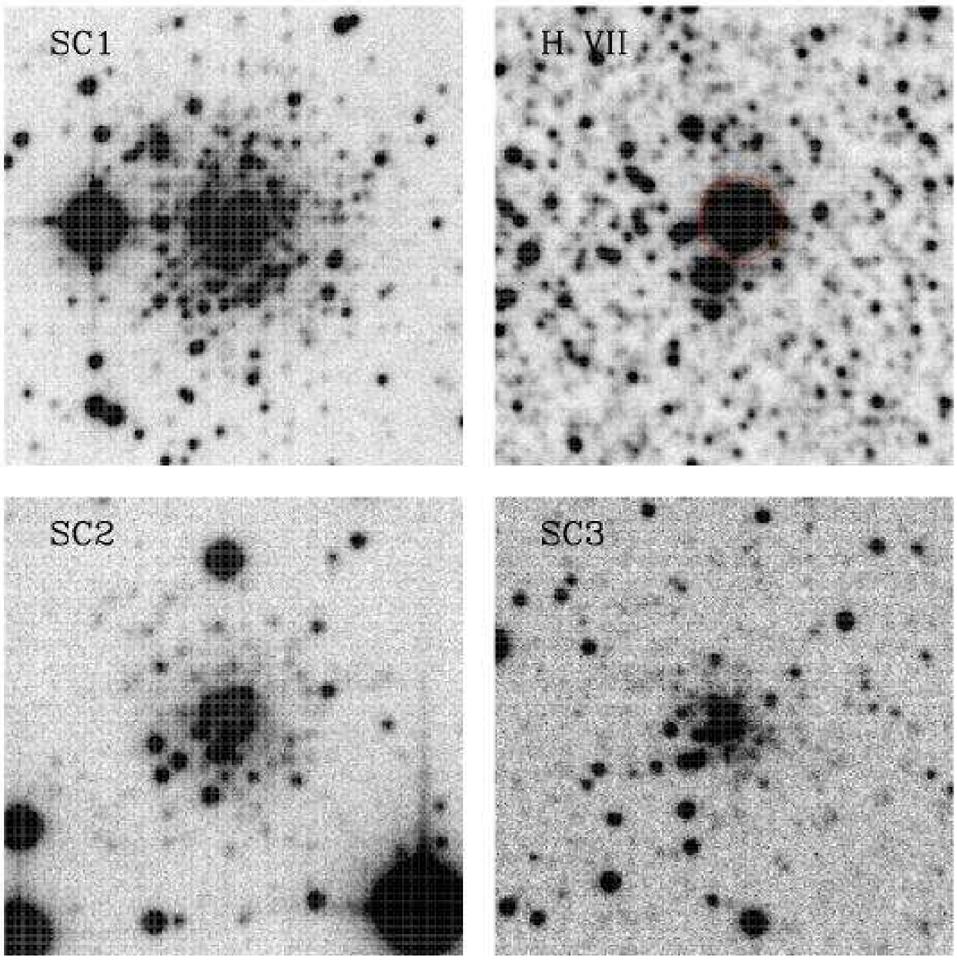

Figure 5. Greyscale maps of the i-band images of new star clusters in comparison with the well-known globular cluster HVII in NGC6822 (Hwang et al. 2005). Note that the new clusters are extended and partially resolved, while the globular cluster H VII is more compact and not resolved.

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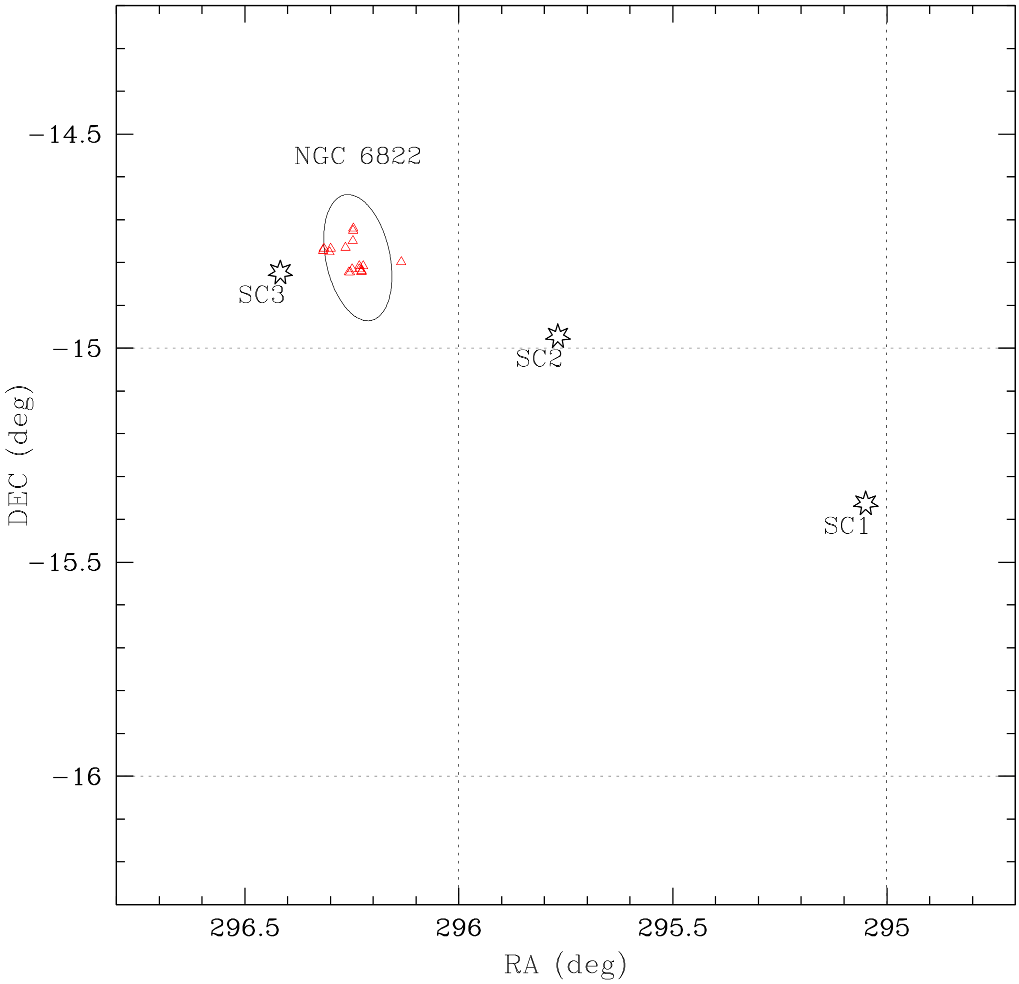

Figure 6. Spatial distribution of new star clusters in NGC 6822 (starlets) in comparison with known clusters (open triangles). The large ellipse represents the main optical body of NGC 6822 (Hwang et al. 2005). Note the large distance of the new star clusters from the centre of NGC 6822.

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