EXTENDED STAR CLUSTERS IN THE REMOTE HALO OF THE INTRIGUING DWARF GALAXY NGC 6822*

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ABSTRACT

We present a study on four new star clusters discovered in the halo of the intriguing dwarf irregular galaxy NGC 6822 from a wide-field survey covering 3° × 3° area carried out with MegaCam at the Canada–France–Hawaii Telescope. The star clusters have extended structures with half-light radii \( R_h \approx 7.5–14.0 \) pc, larger than typical Galactic globular clusters and other known globular clusters in NGC 6822. The integrated colors and color–magnitude diagrams of resolved stars suggest that the new star clusters are 2–10 Gyr old and relatively metal poor with \( Z = 0.0001–0.004 \) based on the comparison with theoretical models. The projected distance of each star cluster from the galaxy center ranges from 10.7\(^{\prime}\) (≈1.5 kpc) to 77\(^{\prime}\) (≈11 kpc), far beyond the optical body of the galaxy. Interestingly, the new star clusters are aligned along the elongated old stellar halo of NGC 6822, which is almost perpendicular to the \( \text{H}_1 \) gas distribution where young stellar populations exist. We also find that the colors and half-light radii of the new clusters are correlated with the galactocentric distance: clusters farther from the galaxy center are larger and bluer than those closer to the galaxy center. We discuss the stellar structure and evolution of NGC 6822 implied by these new extended star clusters in the halo. We also discuss the current status of observational and theoretical understandings regarding the origin of extended star clusters in NGC 6822 and other galaxies.

Key words: galaxies: dwarf – galaxies: individual (NGC 6822) – galaxies: star clusters: general – Local Group

Online-only material: color figures

1. INTRODUCTION

Globular clusters (GCs) are a major tracer and a component of stellar populations in galaxies due to their well-defined photometric, chemical, and physical properties. Their color is mostly 0.5 ≤ \( (V - I) \) ≤ 1.0, their metallicity is \( \text{[Fe/H]} \approx -2.0 \) to -1.0, and their half-light radius is usually \( R_h = 2–10 \) pc (Harris 1996). These properties of GCs are known to be universal regardless of the morphological type of galaxies.

Advancement of observational studies, however, has revealed the existence of “unusual” GC populations. Some examples include extremely luminous and large GCs such as α Cen (Lee et al. 1999) and faint fuzzy clusters (Larsen & Brodie 2000) that are relatively faint and red but systematically larger than typical GCs. The existence of these “peculiar” GCs has been suspected to be related with dynamical evolutions of their host galaxies.

Recently, another new population of star clusters was discovered in nearby galaxies. Huxor et al. (2005) reported the discovery of three new GCs in M31 and showed that these star clusters are globular but systematically larger than normal GCs with their half-light radii \( R_h \) of 26–34 pc. Similar star clusters were also discovered in M33 (Stonkutė et al. 2008; Cockcroft et al. 2011). The number of these “extended star clusters (ESCs)” in M31 has increased to 13 through the wide-field survey in the halo of M31 (Huxor et al. 2008, 2011). A recent report of one ESC in the Sculptor Group dwarf spheroidal galaxy

by Da Costa et al. (2009) shows that ESCs are not limited to spiral galaxies but they exist in dwarf galaxies.

NGC 6822 is a small barred dwarf irregular galaxy in the Local Group without any associated neighbors. Stellar populations in NGC 6822 are mostly blue stars younger than ~200 Myr (Gallart et al. 1996a). Many previous studies (e.g., Hodge 1977; Krienke & Hodge 2004) reported that star clusters are concentrated within 6′ from the center of NGC 6822. These include a metal-poor and old GC Hubble VII (H VII) with age >10 Gyr and \( \text{[Fe/H]} = -1.95 \pm 0.15 \) (Cohen & Blakeslee 1998). Another GC in NGC 6822 that is of our interest is an intermediate-age cluster Hubble VIII (H VIII) with diffuse morphology (Wyder et al. 2000). H VIII is known to be about 1.5–4 Gyr old and metal poor with \( \text{[Fe/H]} = -1.58 \pm 0.28 \) (Chandar et al. 2000; Strader et al. 2003).

One more interesting point with NGC 6822 is that the main galaxy body is enveloped with a huge \( \text{H}_1 \) gas cloud (Roberts 1972) and the \( \text{H}_1 \) gas cloud actually constitutes a disk-like rotating structure (de Blok & Walter 2000; Weldrake et al. 2003). It is also found that young blue stars are distributed along the \( \text{H}_1 \) gas structure (Komiyama et al. 2003; de Blok & Walter 2003), suggesting that the \( \text{H}_1 \) gas has been used for the recent star formation. However, Lee & Hwang (2005) show that there is a giant stellar halo composed of red giant branch (RGB) stars older than 1 Gyr around the main body of NGC 6822. The spatial distribution of these RGB stars indicates that the old halo is elongated with its major axis nearly perpendicular to the \( \text{H}_1 \) gas structure. This is consistent with NGC 6822 halo or spheroid composed of intermediate age C stars reported by Demers et al. (2006). These recent developments reveal that NGC 6822 is a rather complex system even though it is a small and isolated dwarf galaxy.

* Based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada–France–Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Science de l'Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii.
In this paper, we present the result of a star cluster survey made over the halo of NGC 6822 and the photometric properties of those new star clusters. Preliminary results of this study were given in Hwang et al. (2005), introducing three ESCs discovered in NGC 6822. We compare various properties of these new clusters with those of two GCs in NGC 6822, H VII and H VIII. We also discuss any correlation between these intriguing ESCs and the large stellar halo of NGC 6822 reported by Lee & Hwang (2005) and Battinelli et al. (2006). In this study, we adopt \((m - M)_0 = 23.35 \pm 0.02\) for NGC 6822, an average of distance moduli measured by using RR Lyrae (Clementini et al. 2003), Cepheids (Pietrzyński et al. 2004), and near-infrared tip of the RGB (TRGB; Cioni & Habing 2005). This translates to 470 kpc in physical distance to NGC 6822 where 1\(^\circ\) corresponds to about 2.2 pc in projected scale.

2. OBSERVATION

Observations of NGC 6822 were made in 2003 August 22 to September 23 (2003B) and in 2005 May 9–17 (2005A) using the MegaCam at the Canada–France–Hawaii Telescope (CFHT) in queue mode operation. The MegaCam is a wide-field mosaic camera composed of 36 2k \( \times \) 4k individual CCDs. It covers about \(1^\circ \times 1^\circ\) area with \(0.187\) arcsec per pixel resolution. Nine fields around the optical main body of NGC 6822 were observed in \(g'\) and \(i'\) bands. That makes our data coverage about 9 deg\(^2\).

The variation of seeing condition between different seasons is negligible. The integrated exposure time is 2100 s (1980 s) in the \(g'\) band and 1300 s (1380 s) in the \(i'\) band for the 2003B (2005A) season. The raw images were processed using the Elixir system by CFHT staff. Elixir is a collection of programs, databases, and other tools specialized in processing and evaluation of the large mosaic data. Detailed information about the Elixir system can be found in Magnier & Cuillandre (2004).

3. DISCOVERY

We have visually inspected all image data and have discovered three new star clusters (C1, C2, and C3) in the 2003B season data and another new star cluster (C4) in the 2005A season data. The locations of the four new star clusters are shown in Figure 1 and the coordinates are listed in Table 1. The first noteworthy point with these new star clusters is their wide spatial distribution. The projected distances from the center of NGC 6822 are 77\(\) for C1, 29\(\) for C2, 11\(\) for C3, and 43\(\) for C4. Only one cluster C3 is located in the outskirts of the ellipse defined by \(15.5 \times 13.5\), which represents the approximate extent of the optical main body of this galaxy. Previously known star clusters including H VII and H VIII (Krienke & Hodge 2004) are inside this ellipse.

The projected galactocentric distance of the most distant cluster C1 reaches about 11 kpc in physical scale, which corresponds to about 10 times the major axis radius of NGC 6822.

Figure 2 displays thumbnail \(i'\)-band images of these new star clusters as well as H VII and H VIII in NGC 6822. It is easily noted that the new star clusters are more extended than H VII and are partially resolved into their member stars, although the size and richness vary among clusters. On the other hand, H VII, is not resolved into individual stars but appears as a single extended source in the same image. This indicates that the new star clusters have different structural properties than typical globular clusters. However, C3, the smallest new cluster, turns out to be similar to H VIII that is another globular cluster with diffuse morphology and intermediate age.

### Table 1

| ID          | R.A. (12000) (h:m:s) | Decl. (12000) (°:′″) | \(g'\) (mag) | \((g' - i')\) (mag) | \(E(g' - i')\) (mag) | \(A_g\) (mag) | \(A_i\) (mag) | \(R_h\) (pc) | \(M_{\odot}\) (mag) | \((V - I)_0\) (mag) |
|-------------|----------------------|----------------------|--------------|---------------------|----------------------|--------------|--------------|-------------|------------------|------------------|
| NGC 6822C1  | 19:40:11.77          | -15:21.47:3          | 16.35 \pm 0.01 | 0.05               | 0.20                | 0.27         | 0.30         | 14.0        | -7.70           | 0.85             |
| NGC 6822C2  | 19:43:04.39          | -14:58:21:5          | 18.25 \pm 0.01 | 1.17               | 0.60                | 0.20         | 0.20         | 11.5        | -6.10           | 0.94             |
| NGC 6822C3  | 19:45:40.15          | -14:49:25:0          | 19.23 \pm 0.01 | 1.67               | 0.51                | 0.28         | 0.28         | 7.5         | -5.22           | 1.31             |
| NGC 6822C4  | 19:47:30.54          | -14:26:49:3          | 18.16 \pm 0.02 | 1.33               | 0.17                | 0.38         | 0.21         | 13.8        | -6.06           | 1.12             |
| Hubble VII  | 19:44:55.77          | -14:48:56:2          | \ldots \quad \ldots | \ldots \quad \ldots | \ldots \quad \ldots | \ldots \quad \ldots | \ldots \quad \ldots | \ldots \quad \ldots | \ldots \quad \ldots | \ldots \quad \ldots |
| Hubble VIII | 19:44:58.21          | -14:43:13:4          | 18.29 \pm 0.03 | 1.24               | 0.36                | 0.80         | 0.44         | 6.1         | -6.24           | 0.93             |

**Notes.**

\(^a\) Not available due to saturation at the cluster center.

\(^b\) Adopted from Wyder et al. (2000).
4. ANALYSIS AND RESULTS

4.1. Resolved Stellar Photometry

Analysis using color–magnitude diagrams (CMDs) based on resolved stellar photometry is one of the best ways to determine the physical parameters of star clusters. Since the new star clusters in NGC 6822 are partially resolved into individual stars in the current image data (see Figure 2), we construct CMDs of the stars to estimate the age and the metallicity of the new ESCs.

We used DAOPHOT/ALLFRAME (Stetson 1994) to carry out the photometry of stars in the field where each star cluster was discovered. Each field is 6.2′ × 14.6′ defined by the size of one CCD chip among the 36 CCDs of MegaCam. Standard procedures required by DAOPHOT/ALLFRAME such as initial source detection, point spread function (PSF) selection, image montage, final source detection, and final ALLFRAME photometry were followed. For further information on this process, please refer to Stetson (1994). We adopted 4σ threshold for the source detection. The photometry data were calibrated using the standard transformation relation provided by CFHT.

The number of detected sources in each field ranges from about 8000 (for C4 field) to 26,000 (for C3 field). We selected stars located within a certain concentric radius from each cluster for the CMD analysis. For C1, C2, and C4 the concentric radius of 15″ was used, while 10″ is adopted for C3. Among the selected stars, however, there are also many foreground stars, which inevitably lead to heavy contamination to the target star clusters. We corrected the field star contamination by using field stars collected from the annulus set between 37″ (200 pixels) and 74″ (400 pixels) from each cluster center. Figure 3 shows the CMD of the new star clusters and their selected fields. First, we calculated the expected number of field stars for each CMD bin with 0.5 × 0.5 mag by normalizing the number of field stars in the corresponding location of the field CMD. Then, the field star correction was made by rejecting stars separated by less than 0.1 mag from the expected field stars in each CMD bin of the cluster CMD. The total number of removed field stars is 34, 25, 30, and 33, leaving about 190, 79, 45, and 60 sources for C1, C2, C3, and C4, respectively. The rate of removed stars to all selected stars for each cluster, ranging from 15% (C1) to 40% (C3), is consistent within the tolerance of ±5% even though we change the field star selection regions. The field star subtracted CMDs of the new star clusters are displayed in the right column of Figure 3.

4.2. Reddening Estimation

One difficulty in the interpretation of photometric results of NGC 6822 clusters is that NGC 6822 field suffers from a relatively heavy and patchy extinction because it is located in low Galactic latitude (b = −18:38926). The foreground reddening estimated by Schlegel et al. (1998) ranges from E(B − V) = 0.16 for the field of C1 to E(B − V) = 0.22 for C2. This requires the correction for the foreground extinction for the analysis of the photometric properties of star clusters that are widely spread in large area.

We utilized the observed colors of foreground stars, mostly Galactic disk dwarf stars, to estimate the reddening for every region in our observed field. The Galactic disk stars are observed as a vertical sequence in (g′ − i′) and i′ CMDs. For a specific region, we select high signal-to-noise ratio (S/N) and non-saturated stars with 0.5 mag < (g′ − i′) < 1.5 mag and 16 mag < i′ < 19 mag that lie within a circular area of radius 3′ and investigate their (g′ − i′) color distribution. The resultant color distribution is fitted by a Gaussian function to determine the peak (g′ − i′) color of the foreground stars and the approximate width of the distribution. However, if the number of high S/N foreground stars is less than 300, the size of the circular area is increased by 0.1 to collect more foreground stars for reliable determination. The peak colors of selected foreground stars range from (g′ − i′) = 0.64 to 1.16 and the (g′ − i′) color distributions are usually very narrow with full width at half maximum (FWHM) ≲ 0.05 mag.

To convert this peak (g′ − i′) color of the foreground stars to the reddening value for the corresponding region, we used the reddening map by Schlegel et al. (1998) as a reference. First, we select about 220 locations evenly spaced over the 3′ × 3′ field. The separation between selected locations is about 12′, which is roughly twice the spatial resolution of reddening map by Schlegel et al. (1998). Then, we compare the peak (g′ − i′) color of the foreground stars and the E(B − V) estimate by Schlegel et al. (1998) for those selected locations to determine the conversion factors that are required to derive the reddening value for every location in the observed field. More details on the reddening map construction around the field of NGC 6822 will be described in our forthcoming paper (N. Hwang et al. 2011, in preparation).

Finally determined and adopted reddening value for each cluster field ranges from E(g′ − i′) = 0.16 for C1 to E(g′ − i′) =
notable differences. The faint end of C2 RGB appears to be at display similar RGB features. However, there are still some (Lee et al. 1993), which corresponds to modulus for NGC 6822, (i)

Since the absolute magnitude of TRGB in

On the other hand, the bright end of C3 RGB is at

We use these adopted reddening values for the analysis of CMD of the new star clusters in NGC 6822.

4.3. Color–Magnitude Diagrams

Figure 4 shows the (g′ – i′)0–i′ CMD of the resolved stars in C1–C4. The adopted reddening for each cluster’s field is listed in Table 1. The RGB is clearly pronounced in each CMD, although the number of detected RGB stars is different from cluster to cluster. C1, the richest cluster among the four new clusters, exhibits a relatively well-populated RGB that runs from i′ ≈ 20.0 mag to ∼24.0 mag. The remaining three clusters also display similar RGB features. However, there are still some notable differences. The faint end of C2 RGB appears to be at i′0 ≈ 23.0, about one magnitude brighter than those of the other clusters. On the other hand, the bright end of C3 RGB is at i′0 ≈ 21.0, about one magnitude fainter than the other clusters.

We use the i′-band magnitude of the TRGB that is known to be constant for the metallicity [Fe/H] < −0.7 (Lee et al. 1993) for the estimation of the distance to each cluster. Even though it is hard to obtain a rigorous measurement of the TRGB magnitude due to the low number of sources, the CMDs in Figure 4 indicate that the TRGBs are located at i′0 ≈ 20.0 for C1, C2, and C4. Since the absolute magnitude of TRGB in I band is ≈−4.0 mag (Lee et al. 1993), which corresponds to i′ ≈ −3.5 mag, the distance modulus for these three clusters is estimated to be (m − M)0 ≈ 23.5. This value is similar to the adopted distance modulus for NGC 6822, (m − M)0 ≈ 23.35 ± 0.02 (Clementini et al. 2003; Pietrzyński et al. 2004; Cioni & Habing 2005). In the case of C3, though the fainter TRGB magnitude may suggest a larger distance than the other clusters, we assume that C3 is a member of NGC 6822 based on the morphological similarity to H VIII as shown in Figure 2. Therefore, we assume that the distance modulus for every cluster is the same as NGC 6822.

We have compared the observed cluster CMDs with the theoretical model isochrones by Marigo et al. (2008) based on the adopted distance and the foreground reddening for each cluster in Figure 4. We selected two ages, log(τ) = 10.0 (10 Gyr) and 9.3 (about 2 Gyr), and four metallicities, Z = 0.0001, 0.0004, 0.001, and 0.004 (−2.3 ≲ [Fe/H] ≲ −0.7). The comparison with theoretical isochrones shows that RGBs of new star clusters are broad so that isochrones with different metallicities and/or ages can be overlaid at the same time. That is, the model isochrones with log(τ) = 10.0 and 0.0001 ≲ Z ≲ 0.001, and log(τ) = 9.3 and 0.001 ≲ Z ≲ 0.004 can be used to represent the majority of RGB stars in C1 and C2. For C3 and C4, many bright RGB stars (i′0 < 22) are traced by the isochrones with 0.0004 ≲ Z ≲ 0.004. This result suggests that the new clusters are as old as log(τ) ≥ 9.3 (about 2 Gyr) and their metallicities range from Z = 0.0001 ([Fe/H] ≈ −2.3) to Z = 0.004 ([Fe/H] ≈ −0.7).

The photometric error in (g′ – i′) is estimated to be no larger than 0.03 mag when i′0 < 23.0 mag, as marked in each panel in Figure 4. Therefore, for i′0 < 23.0 mag, the scatter in RGB may be real, suggesting a metallicity dispersion. However, considering the crowded nature of clusters and the limited spatial resolution of the current image data, these broad RGBs could be the result of random errors involved in the source detection. Similarly, the study by Huxor et al. (2005) show CMDs with broad RGBs for three ESCs in M31 based on the ground-based imaging, overlaid with fiducial lines of different metallicities ranging from [Fe/H] = −2.17 to [Fe/H] = −0.47. However, in the subsequent study by Mackey et al. (2006) based on the
Figure 4. \((g'-i')_0\) and \(i'_0\) CMDs of the new star clusters, C1–C4. Foreground stars were statistically subtracted. Curved lines represent the theoretical isochrones (Marigo et al. 2008), for \(\log(\text{age}) = 9.3\) (dashed lines) and 10.0 (solid lines), and \(Z = 0.0001, 0.0004, 0.001,\) and 0.004. Each combination of \(\log(\text{age})\) and \(Z\) adopted for comparison is given in the lower left panel. See the text for details.

(A color version of this figure is available in the online journal.)

high-resolution Hubble Space Telescope (HST) image data, those M31 ESCs are confirmed to have well-defined RGBs with no discernible metallicity dispersion. Therefore, the future high-resolution observations are crucial for a better determination on the metallicity and age of these new star clusters in NGC 6822.

4.4. Size of Star Clusters

We have used the APPHOT package in IRAF\(^5\) to derive the integrated luminosity profiles in \(g'\) and \(i'\) bands, and then to determine the structural parameters of the new star clusters. For each star cluster, we adopted incremental circular apertures with radii ranging from 4 to 100 pixels. The sky of each cluster was determined as the median of pixel values in the 30 pixel wide annulus set 150 pixel away from the cluster center. We masked bright foreground stars to prevent any contamination to the magnitude profile. The measured flux in each aperture was used to construct the magnitude profile of the cluster as shown in Figure 5.

In the case of an isolated star cluster, the integrated luminosity profile should flatten out at the outer boundary of the cluster. However, due to the field stars in the adjacent field, the integrated luminosity profile may not converge to a fixed value but get brighter again at a certain radius, which is clearly seen in the profiles of C3 and C4. Therefore, we determined the size of a cluster \(R_t\) by finding the radius in the integrated magnitude profile where the magnitude difference between adjacent annuli systematically decreases to a minimum and, at the same time, the magnitude difference between \(R_t\) and the next outer annulus starts to increase again. We repeated this procedure in \(g'\) and \(i'\) bands for each star cluster and determined the radii \(R_t\) in both bands. At \(R_t\), the magnitude difference between the adjacent annuli is usually about 0.01 mag or less. The cluster’s integrated magnitude was measured at the radius \(R_t\). The half-light radius \(R_h\) of a cluster was derived by interpolating along the integrated magnitude profile to find a radius where the luminosity corresponds to half or 0.75 mag fainter than the cluster’s integrated magnitude.

Figure 5 shows the integrated magnitude profiles of the new star clusters and the determined values of \(R_t\) (long arrows) and \(R_h\) (short arrows). The values of \(R_t\) and \(R_h\) in both \(g'\) and \(i'\) bands are usually in agreement with each other, differing by less than the width of an annulus (2 pixels or 0'.37). However, there are a couple of cases that exhibit some differences in \(R_t\) and \(R_h\) depending on the filter bands. In the case of C2, the \(R_t\) is estimated slightly larger in the \(g'\) band by about 1'.85 than in the \(i'\) band, whereas the \(R_h\) values in both bands turn out to be consistent within the tolerance of 0'.37. For C3, even with the same \(R_t\) estimates in \(g'\) and \(i'\) bands, different \(R_h\) values are derived, \(3'.07\) in \(g'\) and \(3'.54\) in \(i'\), which is the largest discrepant measurement depending on the photometric bands. It is regarded as being due to the difference in the observed profiles depending on the filter band. Therefore, we simply adopt the average of the estimates in both bands as final values of \(R_t\) and \(R_h\) for the cluster.

The adopted values of \(R_h\) are 6'.18 ± 0'.07 (14.0 pc) for C1, 5'.09 ± 0'.08 (11.5 pc) for C2, 3'.31 ± 0'.24 (7.5 pc) for C3,

\(^5\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
and 6.08 ± 0.11 (13.8 pc) for C4. We also applied the same method to H VII and H VIII using our image data, and derived $R_h \approx 1'.12 \pm 0.04$ (2.5 pc) for H VII and $R_h \approx 2'.67 \pm 0'.12$ (6.1 pc) for H VIII. This indicates that the new star clusters in NGC 6822 are larger than H VII, an analog of typical GCs by a factor of 2–4 and they are even larger than H VIII, the diffuse GC in NGC 6822. The adopted values of $R_h$ and the associated errors are listed in Table 1.

### 4.5. Integrated Luminosity and Color

We determined the total magnitude in $g'$ and $i'$ bands, and the $(g' - i')$ color of each star cluster based on the aperture photometry made with $R_h$. The $(g' - i')$ colors of new star clusters are relatively red, ranging from 0.93 (for C1) to 1.67 (for C3).\(^6\) The dereddened color $(g' - i')_0$ is derived by correcting the adopted local reddening value $E(g' - i')$ for each star cluster, determined in Section 4.2, which is $(g' - i')_0 = 0.77, 0.90, 1.44,$ and 1.16 for C1, C2, C3, and C4, respectively. For comparison with other studies, we have converted the $g'_0$ and $(g' - i')_0$ of each star cluster into $V_0$ and $(V - I)_0$ using a transformation equation derived by comparing the same Landolt standard stars observed in $g'$ and $i'$ bands (Smith et al. 2002) with those observed in $V$ and $I$ bands (Landolt 1992): $V_0 = g'_0 - 0.370 \times (g' - i')_0 - 0.061$ (rms = 0.015) and $(V - I)_0 = 0.699 \times (g' - i')_0 + 0.312$ (rms = 0.014). The absolute magnitude $M_{V,0}$ of each cluster ranges from $M_{V,0} = -7.70$ for C1 to $-5.22$ for C3. The $(V - I)_0$ colors of the new clusters range from $(V - I)_0 = 0.85$ for C1 to 1.31 for C3. The adopted integrated magnitude and color of new star clusters as well as the reddening values are listed in Table 1.

The luminosity and color of H VII are $M_V = -7.54$ and $(V - I) = 1.31$ (Wyder et al. 2000).\(^7\) Adopting $E(B - V) = 0.19$ that was derived using the color of foreground stars in the H VII field, the reddening-corrected magnitude and color of H VII are $M_{V,0} = -8.16$ and $(V - I)_0 = 1.05$. For H VIII, we have derived the total magnitude $g' = 18.29 \pm 0.03$ and color $(g' - i') = 1.24 \pm 0.03$ using our image data and have determined the reddening $E(g' - i') = 0.36$ or $E(B - V) = 0.21$. Finally, calibrated absolute magnitude and color of H VIII are $M_{V,0} = -6.24$ and $(V - I)_0 = 0.93$. This shows that the magnitudes and colors of these GCs in NGC 6822 are similar to those of the Galactic GCs. The fact that the $(V - I)_0$ colors of the new star clusters are similar to or redder than those of H VII and H VIII in NGC 6822, suggests that the new clusters are as old as these two GCs. We have compared the $(V - I)$ color expected by the theoretical model (Marigo et al. 2008) with the integrated $(V - I)_0$ colors of the new star clusters in NGC 6822. For $Z = 0.0001$

\(^6\) The $(g' - i')$ colors of the four new star clusters were also measured using smaller apertures with $r = 3''$ and the result is $(g' - i') = 0.91 \pm 0.01$ for C1, $1.22 \pm 0.01$ for C2, $1.50 \pm 0.03$ for C3, and $1.51 \pm 0.02$ for C4. These values are consistent with the colors determined using $R_h$ and there appears to be no systematic or significant radial color gradient in the new star clusters. Some differences in $(g' - i')$ colors are due to the selective inclusion or exclusion of resolved bright RGB stars in the small aperture.

\(^7\) Because H VII has its central part saturated, we adopt the photometric data from the study by Wyder et al. (2000).
([Fe/H] ≈ −2.3), similar to the metallicity [Fe/H] ≈ −2.0 of H VII (Cohen & Blakeslee 1998), the model predicts $(V - I) \geq 0.80$ for $\log(t) > 10.0$ so that every new star cluster should be older than $\log(t) = 10.0$. This expects C3 and C4 to be even older than $\log(t) = 10.1$, the maximum age (about 12.5 Gyr) provided by the model, which requires higher metallicity for these two clusters. When we assume $Z = 0.004$ ([Fe/H] ≈ −0.7), the metallicity of H II regions in NGC 6822 (Skillman et al. 1989), the ages of C1 and C2 are consistent with $9.0 < \log (t) < 9.5$, while the estimated age of C3 and C4 is still $\log(t) > 10.0$.

This is basically in agreement with the results obtained in Section 4.3 that the new clusters are older than $\log(t) > 9.3$ and relatively metal poor with $0.0001 < Z < 0.004$. However, the extremely red integrated colors of C3 and C4 may imply higher metallicity compared to the other clusters or the higher reddening for the corresponding field. The CMD of C3 in Figure 4 shows that the bright end of RGB is at about $i_0' = 21.0$, one magnitude fainter than those of the other clusters. If we assume that the faint RGB is due to the intrinsic or the unaccounted reddening and the unreddened TRGB should be around $i_0' = 20.0$, then the extra reddening of $E(g' - i') \approx 0.4-0.5$ has to be introduced, making the total reddening of the C3 field $E(g' - i') \approx 0.63-0.73$. This would make the reddening-corrected color of C3 $(V - I)_0 \approx 0.97-1.04$, similar to the color of H VII and H VIII. However, if the reddening for C3 field is greater than $E(g' - i') \approx 0.44$, the theoretical isochrones cannot be fitted to the CMD of C3 in Figure 4.

If we accept that the red colors are intrinsic properties of the star clusters, then it would be worthwhile to note that the two new clusters C3 and C4 are as red as $(V - I)_0 > 1.0$ and relatively extended with $R_h > 7.0$ pc, which satisfies the criteria for faint fuzzy clusters. This is the first sample of faint fuzzy clusters discovered in the Local Group. We will discuss this in Section 5.3.

5. DISCUSSION

5.1. New Star Clusters and Old Stellar Halo

The wide spatial distribution of newly discovered star clusters is quite surprising considering that the host galaxy NGC 6822 is a small dwarf irregular galaxy. The new star clusters are spread in an area as large as about $120' \times 80'$, while the existing star clusters are concentrated in the optically visible main body of NGC 6822 that is about $15'.5 \times 13.5'$ wide at most. This is much larger than the area spanned by the old and intermediate stellar halo, which extends out to about $40'$ (Lee & Hwang 2005; Battinelli et al. 2006). This is similar to the disks of satellite galaxies in the Milky Way (Metz et al. 2007).

There are a couple of noteworthy points regarding the new star clusters and the old stellar halo of NGC 6822. Figure 1 shows that the four star clusters C1–C4 are distributed along the projected line running from northeast (NE) to southwest (SW). This is consistent with the major axis of the old stellar halo, which is elongated in the same direction (NE-to-SW) as marked in dotted lines in Figure 1. The other point is that the four new star clusters are expected to be older than $\log(t) \approx 9.0$ based on the CMD and integrated color analysis. The RGB stars that are used to trace the old halo of NGC 6822 are also relatively old population with $\log(t) \gtrsim 9.0$. These suggest that the old stellar halo and the new old star clusters may share the common formation history.

Figure 6 displays the distribution of half-light radii $R_h$ and $(V - I)_0$ colors of the four new clusters as well as H VII and H VIII along the projected distance from the NGC 6822 center. Interestingly, as the clusters are located farther from the galaxy center, the clusters tend to be larger in size and bluer in color. The change of the cluster sizes along the distance can be fitted by a log-square function as shown in dashed lines in Figure 6(a). If we consider only the four new clusters, there also seems to be a systematic color change with its gradient about $-0.006 \pm 0.003$ mag arcmin$^{-1}$, marked in dashed lines in Figure 6(b). If the red color of C3, however, is mainly due to the unaccounted intrinsic reddening as discussed in Section 4.5, the color gradient along the projected distance would be not so significant.

A similar kind of size distribution is also pointed out for Milky Way and LMC GCs in the study of van den Bergh & Mackey (2004). In the outer Galactic halo with galactocentric distance $D_{gc} > 40$ kpc, only extended GCs with $R_h > 15$ pc are found, while the inner halo is populated with both compact and extended GCs. Similarly, LMC GCs with $R_h > 10$ pc are only found in the region farther than 8$'$ from the galaxy center. This dependence of star cluster size on the galactocentric distance may be interpreted as the result of high survival rate of extended clusters from the disruption in the outer halo where relatively weak tidal forces are exerted upon the clusters by the galaxy itself. The similar trend observed in the size distribution of star clusters in Figure 6 shows that the old cluster system of NGC 6822 has a common characteristic with Galactic GC as well as LMC GC systems.

Another noteworthy point is that the extended GCs with $R_h > 10$ pc are usually metal poor with [Fe/H] $\lesssim -1.3$, as shown in Figure 5 of van den Bergh & Mackey (2004). The metallicity of the four new clusters is estimated to be $0.0001 < Z \lesssim 0.001$ ($-2.3 \leq [\text{Fe/H}] \leq -1.3$) if we assume the age of clusters $\log(t) = 10.0$. If we interpret the color distribution in Figure 6(b) as metallicity distribution, it leads...
to a strong correlation between the metallicity and the cluster size, that is, the lower metallicity for the larger clusters. This would be consistent with the metallicity distribution of extended Galactic GCs. This may also suggest a metallicity gradient in the halo of NGC 6822, lower metallicity in the outer halo than in the inner halo.

5.2. Complex of Old and Young Stellar Structures

The spatial distribution of old stars combined with old extended clusters makes stark contrast to the central part of NGC 6822 dominated by young stellar populations. This shows that a small dwarf irregular galaxy NGC 6822 is actually a complex of two distinct stellar structures, old stellar halo and young central body. Recent studies also show that the young stellar populations are not restricted to the central body of NGC 6822 but are distributed around the large H1 gas structure (Komiyama et al. 2003; de Blok & Walter 2003) extending northwest-to-southeast (de Blok & Walter 2000). This H1 gas structure with blue stars with ages of \( \sim 10^8 \) yr is almost perpendicular to the alignment of the new star clusters and the elongated old stellar halo (see Figure 1).

NGC 6822 is not the only one dwarf irregular galaxy known to have such a complex stellar structure. The co-existence of underlying old stellar population and the gas-rich young stellar structure is also reported in other dwarf irregular galaxies, including Leo A (Vaneveçiuças et al. 2004), LMC (Minniti et al. 2003), and IC 10 (Demers et al. 2004). The origin of such complex stellar structures in dwarf irregular galaxies is not clearly understood yet. However, it has been recently suggested that the merging between gas-rich dwarf galaxies may induce the formation of the outer old and the inner young stellar structures (Bekki 2008).

Even though it is relatively common to have old underlying stellar structure in dwarf irregular galaxies, ESCs associated with the old stellar halo are not discovered in other dwarf galaxies but only in NGC 6822. If the old stellar structure is the remnant of the merged galaxy as suggested by some theoretical studies, the old ESCs should have survived the merging or accretion process, which is an important clue to the understanding of their origin.

5.3. Nature of Extended Star Clusters

ESCs in small dwarf galaxies are rarely known. NGC 6822 and Scl-dE1, a dwarf spheroidal galaxy in the Sculptor group (Da Costa et al. 2009), are the only cases where ESCs are reported to date. However, if we define the ESCs only by their large size, then such extended clusters may not be totally new. Even in the Milky Way, there are already about 10 GCs with \( R_h > 10.0 \) pc and the largest GC, Palomar 14, is even as large as \( R_h = 24.7 \) pc (van den Bergh 1996), which could be easily classified as ESCs. Nevertheless, even those extended GCs are found to satisfy a certain criterion set between the luminosity and the size of clusters, that is, \( \log R_h = 0.2 M_V + 2.6 \) outlining the upper limit locus in \( R_h \) versus \( M_V \) parameter space (van den Bergh & Mackey 2004). Figure 7 shows that GCs in LMC, as well as the Galactic GCs, also satisfy the same criterion.

On the other hand, the exceptionally bright and large GCs, NGC 2419 and \( \omega \) Cen, are found not to satisfy the above criterion. Instead, these two GCs appear to occupy the similar parameter space with very small dwarf galaxies such as ultracompact dwarf (UCD) galaxies (Mieske et al. 2002), as shown in Figure 7. Moreover, \( \omega \) Cen is known to have multiple stellar populations and is regarded as the core of a disrupted dwarf galaxy (Lee et al. 1999). These results have led to consider that the criterion set by van den Bergh & Mackey (2004) could be used to separate typical GCs from other types of compact objects such as core of dwarf galaxies.

However, recently numerous observational studies have led to discoveries of star clusters that do not satisfy the criterion set by van den Bergh & Mackey (2004). Some examples include GCs in a giant elliptical galaxy NGC 5128. Gómez et al. (2006) show that new GCs in NGC 5128 fall in the gap that used to exist around the GC locus set by van den Bergh & Mackey (2004) in the parameter space of \( R_h \) versus \( M_V \) over a large range of luminosity (\( -11 < M_V < -5 \)). Especially, combined with newly discovered luminous GCs in NGC 1399 (Richtler et al. 2005), UCDs (De Propris et al. 2005; Mieske et al. 2002), and DGTOs (Hásegan et al. 2005), along with the ultrafaint dwarf (UFD) galaxies recently discovered in the Milky Way (Martin et al. 2008; de Jong et al. 2010; Belokurov et al. 2009, 2010). The dashed line is the locus \( \log R_h = 0.2 M_V + 2.6 \) set by van den Bergh & Mackey (2004) as the upper limit for typical GCs. The L-shape indicates the region where faint fuzzy clusters are found as shown by those in NGC 5195 (Hwang & Lee 2006). Note that C1 lies above the GC locus as are the ESCs in M31 and M33, while C2, C3, and C4 are located in the L-shape region, below the GC locus. While traditional Galactic dSphs and M31 dSphs are clearly separated from typical GCs in this diagram, many luminous and compact objects such as UCDs and DGTOs as well as faint objects such as ESCs and UFDs are found to be mixed with GC populations. The dotted line box represents an “avoidance zone” defined by \(-9.4 \lesssim M_V \lesssim -8.0\) and \( 10 \lesssim R_h \lesssim 60\). See the text for details.

(A color version of this figure is available in the online journal.)
be regarded as a remnant or stripped core of dwarf galaxies, such as in the case of ω Cen.

We have added the four ESCs and two GCs (H VII and H VIII) in NGC 5128 as well as 13 ESCs in M31 (Huxor et al. 2005, 2011) and one ESC in M33 (Stonkutė et al. 2008) to the $R_h$ versus $M_V$ plot in Figure 7. It is clear that four M31 ESCs, M33 ESC, and C1 in NGC 6822 lie above the locus that defines the upper limit for typical GCs, while the other new clusters C2, C3, and C4 in NGC 6822 as well as the other ESCs in M31 occupy the same parameter space with typical GCs. With the addition of GCs in NGC 5128, the distribution of star clusters with $−8 < M_V < −5$ over the GC locus set by van den Bergh & Mackey (2004) appear rather smooth, implying that ESCs could be an extension or a family of typical GC population. It is also noted that every sample of ESCs discovered to date usually has almost the same magnitude range covering $−8 < M_V < −4.5$.

However, ESCs in M31, M33, and NGC 6822 are quite different from the luminous GCs in NGC 5128 and NGC 1399 since the ESCs are more than two magnitude fainter in the $V$ band. Between these two classes of clusters, there appears to be a zone defined by $−9.4 < M_V < −8.0$ and $10 < R_{h,pc} < 60$, marked by a dotted box in Figure 7, where few star clusters and/or dwarf galaxies are found. Even NGC 5128 GCs that span the large magnitude range from $M_V = −10$ to $−5$, do not occupy this “avoidance zone.” This leads to a speculation that faint ESCs may be physically different from the luminous extended GCs. We will discuss more about this in Section 5.4. However, further observational investigations are required over other GC systems to confirm whether the “avoidance zone” is physically real.

Another class of star clusters that is worth consideration is the faint fuzzy clusters. Faint fuzzy clusters have large size ($R_h > 7$ pc) and faint luminosity ($M_V > −7.5$) as marked by the L-shape in Figure 7. One more characteristic of faint fuzzy clusters is the red color ($V − I > 1.0$), slightly redder than typical GCs. These clusters were first introduced by Larsen & Brodie (2000) and are known to exist only in some nearby SB0 galaxies including NGC 1023, NGC 3384, and NGC 5195 (Larsen et al. 2001; Hwang & Lee 2006). It has been suggested that faint fuzzy clusters are relatively old ($\geq 7$–8 Gyr), as massive as $10^3$–$10^5 M_\odot$ (Larsen & Brodie 2002; Hwang & Lee 2006), and moderately metal rich with $[\text{Fe/H}] \sim −0.6$ (Larsen & Brodie 2002). From Figure 7, it is noted that faint fuzzy clusters satisfy the criterion set by van den Bergh & Mackey (2004) as shown by the sample of faint fuzzy clusters in NGC 5195 (Hwang & Lee 2006), suggesting that the faint fuzzy clusters could be another population of old GCs.

We have shown that, among the four new star clusters in NGC 6822, two clusters C3 and C4 can be classified as faint fuzzy clusters with $(V − I)_0 \geq 1.0$. The other two clusters C1 and C2 have $(V − I)_0$ colors of typical GCs, which excludes them from the class of faint fuzzy clusters. The comparison with theoretical isochrones as well as model integrated colors implies that the metallicity of C3 and C4 may be $Z \geq 0.004$, i.e., $[\text{Fe/H}] \geq −0.7$. This is consistent with the general picture of faint fuzzy clusters with moderately higher metallicity than that of typical GCs (Brodie & Larsen 2002). These results suggest that the two new extended star clusters, C3 and C4, may be the first sample of faint fuzzy clusters in the Local Group.

The faint fuzzy clusters have been discovered only in three SB0 type galaxies including NGC 1023, NGC 3384, and NGC 5195 and these clusters are regarded as disk populations, following disk rotation confirmed in NGC 1023 (Brodie & Larsen 2002). Therefore, discovery of faint fuzzy clusters in NGC 6822 is very interesting in the following two points: (1) NGC 6822 is not an SB0 type but dwarf irregular galaxy. This makes the first case of faint fuzzy clusters discovered in a galaxy that is not SB0 type. (2) The two extended clusters C3 and C4 are located in the halo, not in the disk-like structure, of NGC 6822.

A noteworthy point regarding the origin of faint fuzzy clusters is that the existing faint fuzzy clusters are found in galaxies that have undergone dynamical interactions with neighboring galaxies. Therefore, the formation of these peculiar clusters is suggested to have correlation with the dynamical interactions of host galaxies (e.g., Fellhauer & Kroupa 2002). As mentioned in Section 5.2, NGC 6822 is a complex of old and young stellar populations superimposed upon a giant H I disk-like structure and such a complex structure is suspected to be the product of merger-like events that may have triggered the very recent increase of star formation rate (e.g., Gallart et al. 1996a). Therefore, the existence of faint fuzzy clusters and ESCs may be consistent with the complex structure of NGC 6822.

5.4. Origin of Extended Star Clusters

As many ESCs are discovered in the very outer part of galaxies, their origin and formation mechanism are of great importance for the understanding of the galaxy halo as well as ESCs themselves. Currently, there are several views on the origin or the formation of ESCs, which can be roughly categorized into the following three scenarios.

1. The remnants or cores of tidally stripped dwarf galaxies form ESCs.
2. Collisions of two or more star clusters in star cluster complexes or a super-star cluster make ESCs.
3. Star clusters are born in various sizes and some ESCs survive the disruption under the weak tidal field.

Without spectroscopic and deeper imaging observations at the current stage, it is difficult to know the origin of ESCs in NGC 6822. However, we briefly discuss the above three scenarios one by one in the context of dwarf irregular galaxy NGC 6822.

5.4.1. Remnant of Dwarf Galaxies

Since many ESCs are similar in size to very small dwarf galaxies such as UCDs, the ESCs have been suspected to be remaining cores of tidally disrupted dwarf galaxies. A representative example is ω Cen in the Milky Way (Lee et al. 1999). If these ESCs are remaining cores or remnants of dwarf galaxies, then one of some important characteristics would be their stellar contents of multiple populations. The study by Mackey et al. (2006) shows that the four ESCs in M31, observed with HST, do not reveal any signature of multiple stellar populations but only display features of typical old GCs in the CMD analysis. The spectroscopic observation of resolved stars in one M31 ESC by Collins et al. (2009) also suggests that the cluster is not a dark-matter-dominated system. These results of observational studies are against the dwarf galaxy core scenario for the origin of ESCs.

However, one important difference between clusters like ω Cen and M31 ESCs is the luminosity. As shown in Figure 7, many luminous GCs with $M_V \lesssim −9.5$ share the same parameter space with ω Cen and UCDs. On the other hand, M31 ESCs are $M_V > −8.0$, fainter than ω Cen-like clusters by more than 2 mag. These two classes of ESCs are separated in $R_h$ and $M_V$.
space by the so-called “avoidance zone” defined in Section 5.3 and marked in Figure 7. Therefore, these two classes may be physically different populations.

Like M31 ESCs, NGC 6822 ESCs are also fainter than $M_V = -8.0$, located on the fainter side of the “avoidance zone” in Figure 7. Therefore, it is likely that NGC 6822 ESCs should be similar to M31 ESCs in many respects, rather than the remnant or the core of defunct dwarf galaxies. However, deep imaging and high-resolution spectroscopic observations are required to test this possibility.

5.4.2. Star Cluster Collisions

The mechanism of star cluster collisions in cluster complexes or super star clusters to form ESCs has been suggested by Fellhauer & Kroupa (2002) to explain the origin of faint fuzzy clusters in NGC 1023. This scenario requires the interaction of galaxies to induce strong star formation and to form super star clusters or stellar complexes within which collisions of individual clusters would lead to form eventually ESCs or faint fuzzy clusters. Actually, some super star clusters or star cluster complexes have been reported in galaxies that are undergoing dynamical interactions, such as the Antennae galaxy (Whitmore et al. 1999, 2010) and M51 (Bastian et al. 2005).

The hierarchical structure of young stellar population has been recently reported in the central part of NGC 6822 (Karampelas et al. 2009; Gouliermis et al. 2010), although the estimated mass of these stellar groupings or associations is relatively small ($10^3$–$10^4 M_\odot$) compared to super star clusters in other galaxies (e.g., $\gtrsim 10^5 M_\odot$ in the Antennae). It may still provide some chance of star cluster collisions within the hierarchical structure at the central part of NGC 6822 due to the high spatial density. Since NGC 6822 ESCs have similar old age and are spread over the wide area where no specific structure is observed other than rather smoothly distributed old stars, formation of these ESCs from several regions of high stellar density would require strong star formation events over a huge volume enveloping the whole stellar halo of NGC 6822. This may not be consistent with the star formation history of NGC 6822 that strong star formation has only been initiated very recently, about $\sim 10^8$ yr ago (Gallart et al. 1996a). Star formations are also expected to begin from the very early stage of stellar evolution of NGC 6822, possibly $\sim 10$ Gyr ago (Gallart et al. 1996b), but it is not clear whether the old star formation was strong enough to form large stellar complexes.

In a very recent study by Assmann et al. (2011), it has been proposed that the merger of two star clusters within low-mass dark matter haloes could produce an ESC. It involves very small mass of dark matter halo so that the velocity dispersion at the cluster center would be $0.7–1.7$ km s$^{-1}$, which is beyond the measurement accuracy of the current facilities. The velocity dispersion of one ESC, EC4, in M31 is estimated to be $2.7^{+2.2}_{-1.7}$ km s$^{-1}$ (Collins et al. 2009). Therefore, according to this theory, the ESC could still have a small-mass dark matter that helps to sustain the extended structure.

5.4.3. Intrinsic ESCs—Survivors of Tidal Disruption

Another recent theoretical study by Hurley & Mackey (2010) argues that star clusters can be born very extended and the clusters could evolve to become old ESCs if the clusters are placed under the weak tidal field, which would be possible only in the outskirts of dwarf galaxies such as NGC 6822. This also suggests that, under the strong tidal field, it would be impossible for star clusters to survive to become old ESCs. This implies that ESCs, even those observed in a large spiral galaxy like M31, are supposed to form in small dwarf galaxies.

Based on a wide-field survey of M31 halo, Mackey et al. (2010) show that many halo GCs of M31 are likely to be found close to stellar streams and that about one-third of the newly discovered halo GCs are of the extended nature. Therefore, it is suggested that M31 ESCs have assembled into M31 halo as a consequence of accretion from the proto-dwarf galaxies that should have disrupted leaving stellar streams behind. This is also consistent with the observational result that the spectroscopically measured velocities of one ESC EC4 in M31 and a nearby stellar stream are in agreement with each other (Collins et al. 2009), indicating that the ESC and the stellar stream are physically associated.

The systematic variation in the sizes of ESCs along the galactocentric distance of NGC 6822, as shown in Figure 6, may be consistent with this scenario in the sense that the smaller clusters (e.g., C3) are located closer to the galaxy center where the tidal interaction would be strong, while the larger clusters (e.g., C1 and C4) are in the outer halo where the tidal force would be weak. Combined with the systematic change of color along the galactocentric distance, it may support the idea that the ESCs have formed as part of the old stellar halo of NGC 6822. This is also consistent with the suggestion that ESCs may be an extension or another family of typical GCs.

However, this poses an intriguing question about why NGC 6822 was more effective to form ESCs over the other dwarf galaxies in the Local Group. There are not many dwarf galaxies that possess an old GC system. Only about four dwarf irregulars including LMC and about five dwarf spheroidals among more than 30 dwarf galaxies in the Local Group are known to have their own GC system (van den Bergh 2000). There are even no known dwarf galaxies in the Local Group that have any ESC other than NGC 6822. Unlike NGC 6822 that is relatively isolated without neighbors, many other dwarf galaxies are found in groups concentrated around two giant spiral galaxies, the Milky Way and M31, in the Local Group. The environmental condition of NGC 6822 might have contributed to create the optimal tidal field to have ESCs. However, further wide and deep observations around other dwarf galaxies are required to find any answer to this question.

5.4.4. ESCs—Mixture of Heterogeneous Populations

If we define ESCs as GCs with large physical size, $R_h \gtrsim 7–10$ pc, then the origin of ESCs observed in many galaxies seems to be diverse depending on the environment and the evolutionary history followed by the host galaxies. At least, there may be two populations of ESCs that have different formation mechanisms.

The first class includes ESCs that are relatively luminous with $M_V < -9.5$ mag and are located in the brighter side of the “avoidance zone” in the $M_V$ and $R_h$ parameter space in Figure 7. Examples include a few Galactic GCs such as $\omega$Cen and NGC 2419, some luminous GCs in NGC 5128 and NGC 1399. Since these ESCs are comparable to UCDs and DGTOs in terms of the luminosity and size, it would be reasonable to assume that these luminous ESCs and compact galaxies should have common origins. The fact that some of these ESCs are known to have signs of multiple stellar populations (e.g., $\omega$Cen) can be supportive of the argument that ESCs are the cores of tidally disrupted dwarf galaxies. It would be also very interesting to test whether some of these luminous ESCs could be remnants of super star clusters or large stellar complexes.
The second class of ESCs is composed of relatively faint clusters including extended clusters in M31 and M33 as well as faint fuzzy clusters. These ESCs are less luminous and are located in the fainter side of the “avoidance zone” in Figure 7. The ESCs discovered in NGC 6822 belong to this class. These ESCs may share the same formation mechanism with typical GCs but have evolved under the specifically optimized tidal field. Faint fuzzy clusters may be a sub-population of this class with slightly enriched metallicity. Dwarf galaxies would be the preferred place for the formation of such ESCs due to the relative weak tidal forces exerted by less massive galaxies, as suggested by Hurley & Mackey (2010). However, dwarf galaxies with ESCs seem to be rare. Only two dwarf galaxies are known to date to have ESCs: NGC 6822 in the Local Group and Scl-dE1 in Sculptor Group (Da Costa et al. 2009). Future observations over the large number of dwarf galaxies would be valuable to test this idea on the origin of ESCs.

These two classes of ESCs, regardless of their luminosities, seem to be intermediary objects between typical compact GCs and large dwarf galaxies. A similar idea has been proposed by Norris & Kannappan (2011) on the study of UCDs arguing that UCDs may be composed of more than two physically distinct populations including stripped nuclei of galaxies, giant GCs or super star clusters, and disrupting GCs based on a tight correlation between mass and size of those objects. Adopting this scheme, the first class ESCs belong to giant GCs or stripped nuclei of galaxies, while the second class ESCs belong to the disrupting GCs. Between these two different classes, there exists a region where neither the first class nor the second class is found (see their Figure 16), which corresponds to the “avoidance zone” in Figure 7.

One more point that might be worth noting is that there is still a possibility that some ESCs found in the outermost halo of galaxies might not be bound to the gravitational potential of the host galaxies. A recent report on the intergalactic GCs in the Virgo cluster by Lee et al. (2010) reveals that there are numerous GCs wandering in the space between galaxies. In NGC 6822, C1 is located well beyond the extent of stellar halo. Considering that NGC 6822 has no distinct close neighbors, C1 could be the first candidate of intergalactic GCs in the Local Group. Future observations to get the velocity of C1 as well as the other ESCs in NGC 6822 would be invaluable to have better idea on their origins.

6. SUMMARY AND CONCLUSIONS

We have discovered four new star clusters in the halo of dwarf irregular galaxy NGC 6822 from a wide-field imaging survey. The star clusters have extended structures with $R_h \approx 7.5–14.0$ pc, larger than typical GCs by a factor of 2–5. The clusters are distributed over a large space with their projected galactocentric distance ranging from 10–70’ (about 1.5 kpc) to 77’ (about 11 kpc), far beyond the optical body of NGC 6822. The spatial distribution of the new star clusters is coincident with the spatial structure of the old stellar halo revealed by recent studies. The analyses of the integrated color as well as CMDs of cluster member stars suggest that the new star clusters are likely to be as old as 2–10 Gyr, and the metallicity is estimated to be between $Z = 0.001$ and $Z = 0.004$ depending on the adopted age. Among the four new clusters, at least two clusters, C3 and C4, can be classified as faint fuzzy clusters based on their very red color with $(V - I)_0 > 1.0$ and large size with $R_h > 7.0$ pc. The red color of these two clusters could be interpreted as the result of moderately enriched metallicity with $Z \approx 0.004$, which is consistent with the metallicity of existing sample of faint fuzzy clusters in the literature.

The colors and the sizes of the new clusters are found to be correlated with the projected distance from the center of NGC 6822 and the clusters located closer to the center are smaller in size and redder in color than the clusters in the outer halo. We suggest that the color gradient may be due to the metallicity gradient existing in the stellar halo and the differences in the cluster size may be correlated with the strength of tidal field of NGC 6822: the stronger the tidal field, the smaller the size of clusters. This is consistent with the recent theoretical study on the formation of ESCs, arguing that ESCs form and survive the disruption only under the weak tidal field condition that would be possible in small dwarf galaxies like NGC 6822. However, deeper imaging and high-resolution spectroscopic observations are required to determine the age and the metallicity with higher confidence, as well as the kinematical properties of these four new ESCs. Future observational data would be invaluable to understand more clearly the origin of these ESCs as well as the evolutionary history of complex dwarf irregular galaxy NGC 6822.

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