AN EXTENDED STAR CLUSTER AT THE OUTTER EDGE OF THE SPIRAL GALAXY M 33

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Received 2007 August 23; accepted 2008 February 1; published 2008 March 12

ABSTRACT

We report the discovery of an extended globular-like star cluster, M 33-EC1, at the outer edge of the spiral galaxy M 33. The distance to the cluster is 890 kpc, and it lies at a projected distance of 12.5 kpc from the center of M 33. Old age (≳ 7 Gyr) and low metallicity ([M/H] ≲ −1.4) are estimated on the basis of isochrone fits. Color–magnitude diagrams of stars, located in the cluster’s area, and photometric and structural parameters of the cluster are presented. The cluster’s luminosity (M_V = −6.6) and half-light radius (r_h = 20.3 pc) are comparable to those of the extended globular clusters, discovered in more luminous Local Group galaxies, the Milky Way and M 31. Extended globular clusters are suspected to be remnants of accreted dwarf galaxies, and the finding of such a cluster in the late-type dwarf spiral galaxy M 33 would imply a complex merging history in the past.

Key words: galaxies: individual (M 33) – galaxies: star clusters

1. INTRODUCTION

Resolved stellar diagnostics has been extensively applied for the investigation of the merging history of galaxies. In this context, extended stellar systems have been recently known to be informative. Firstly, some of the extended stellar systems in the Milky Way (MW), e.g., M 54 and ω Cen, are suggested to be remnants of accreted dwarf galaxies, which might be responsible for the thick disk and halo formation. Such systems have produced large-scale stellar streams in the MW; thus they are useful for highlighting various substructures of the host galaxies and for revealing their merging history. Secondly, while the key physical processes that discriminate extended star clusters and low surface brightness dwarf spheroidals (dSphs) are poorly understood, their distinction is rather ambiguous.

Searches for extended stellar systems discovered at least a dozen low surface brightness dSphs in the vicinity of the MW (Sakamoto & Hasegawa 2006; Belokurov et al. 2007; Irwin et al. 2007) and M 31 (Martin et al. 2006). Recently Huxor et al. (2005) and Mackey et al. (2006) discovered four extended luminous star clusters in the vicinity of M 31. Star clusters of this type are also found in the spirals M 51 and M 81 (Chandar et al. 2002). Single shot Suprime-Cam mosaic (5 × 2 CCD chips; pixel size of 0.2′′) covers a field of 34′ × 27′, and a magnitude of V ∼ 25 is reached in 60 s. Broadband images—V band (exposures 5 × 90 s; seeing ~1″.0), R band (5 × 90 s; ~0″.6), and I band (5 × 200 s; ~0″.8)—were acquired during photometric nights. For standard reduction procedures we used the attributed to the thick-disk/halo component. A warp of the M 33 gaseous disk was already known from H I observation (Corbelli et al. 1989), and a stellar stream was suggested recently from spectroscopy of individual stars (McConnachie et al. 2006). Any further evidence on the M 33 perturbation and accretion events is indispensable in disclosing the real formation history of the galaxy.

We report a discovery of an extended star cluster, M 33-EC1, in the M 33 photometric survey (P. N. Arimoto) frames obtained with the Subaru Telescope (Figure 1). The cluster is located at R.A. = 01h32m58.5s, decl. = 29°52′03″ (J2000.0), lying far south from the M 33 center at a projected galactocentric distance of 48′.4. Previous M 33 cluster studies did not reveal any clusters of a comparably large size (Chandar et al. 1999, 2001). An extensive catalogue of M 33 star clusters recently compiled by Sarajedini & Mancone (2007) does not include this new object.

In Section 2 we present details of observations and data reduction. In Section 3 the derived cluster parameters and resolved stellar photometry results are given. In Section 4 we briefly discuss the impact of our finding in the context of galaxy formation.

2. OBSERVATIONS AND DATA REDUCTIONS

Photometric data of the discovered star cluster, M 33-EC1, were obtained during the course of the M 33 wide-field photometric survey performed with the Subaru Telescope, equipped with the Prime Focus Camera (Suprime-Cam; Miyazaki et al. 2002). Single shot Suprime-Cam mosaic (5 × 2 CCD chips; pixel size of 0.2′′) covers a field of 34′ × 27′, and a magnitude of V ∼ 25 is reached in 60 s.Broadband images—V band (exposures 5 × 90 s; seeing ~1″.0), R band (5 × 90 s; ~0″.6), and I band (5 × 200 s; ~0″.8)—were acquired during photometric nights. For standard reduction procedures we used the
software package (Yagi et al. 2002) dedicated to the Suprime-Cam data. We employed the DAOPHOT (Stetson 1987) program set implemented in the IRAF software package (Tody 1993) for crowded-field stellar PSF (point-spread function) photometry and integrated aperture photometry of the cluster. The PSF stellar photometry on five individual exposures in each passband was performed.

Instrumental magnitudes were transformed to the standard photometric system by referring to the published M 33 photometric catalogue (Massey et al. 2006). In total 220 stars spanning the I-band magnitude range from 19 to 21 and wide color ranges \((R - I)\) from \(-0.15\) to \(1.3\); \((V - I)\) from \(-0.25\) to \(2.5\) were selected as local standards. The rms errors of the transformation equations for \((V - I)\) and \((R - I)\) colors, and the I-band magnitude are less than \(0.035\) which, taking into account the number of employed stars, assures accurate calibration. Considering the intrinsic calibration accuracy of the standard stars (Massey et al. 2006), we estimate the accuracy of our photometric data to be of \(\sim 0.015\) at \(I = 22^m\). We used a bilinear \((R - I)\) color transformation equation due to a significant difference between the transmission curve of the Suprime-Cam \(R\)-band interference filter and that of the standard Cousins \(R\)-band filter.

The star cluster M 33-EC1 is located far beyond the M 33 galaxy’s disk; therefore, it is reasonable to assume that its colors are contaminated only by the MW’s foreground extinction. Photometric data were de-reddened using the \(E(B - V) = 0.06\) value, derived at the cluster’s position from the extinction maps (Schlegel et al. 1998), as follows

\[
A_V = 3.1 \cdot E(B - V), \quad A_I = 0.11, \quad E(R - I) = 0.045.
\]

3. RESULTS

3.1. Color–magnitude Diagram

The color–magnitude diagram (CMD) of a region of \(20''\) radius, centered on the star cluster M 33-EC1, is dominated by red giant branch (RGB) stars; see Figure 2. Reduction and photometry procedures enable us to recognize and remove obvious bright non-stellar objects (star/galaxy separation was performed by eye referring to PSF fitting parameters—sharpness and \(\chi^2\)); however, faint unresolved background galaxies can still be present in this diagram.

In order to resolve the well-known age–metallicity degeneracy of the RGB position in the CMD, inherent to old populations, it is helpful to introduce faint RGB and horizontal branch stars into the isochrone fitting procedure; see, e.g., Martin et al. (2006). The global shape of our CMD resembles the CMD plotted in Figure 7 from Martin et al. (2006), implying the presence of a very old population with a prominent horizontal branch. However, the limiting magnitude of our observations is too shallow for a reliable morphology study of the lower part of the CMD. Therefore, to estimate the intrinsic RGB width over the entire magnitude range, and to derive radial and magnitude dependence of data completeness, we performed an artificial star test (AST) on \(R\)- and \(I\)-band images. The AST results quantify in detail the photometry errors, confusion limits and data completeness, making the isochrone fitting procedure more robust and better constrained.

Six reference points on the observed RGB \((I, R - I = 20.90, 0.72; 21.90, 0.65; 22.90, 0.57; 23.40, 0.53; 23.90, 0.49; 24.40, 0.46)\) were selected to represent the entire magnitude range of the cluster’s stellar population. DAOPHOT’s \textit{addstar} procedure was employed to add artificial stars to the images. To avoid self-crowding we generated individual AST images at every reference point. Each AST image contains 400 artificial stars of the same magnitude distributed on a regular grid (step \(3''\)) over the region of \(60'' \times 60''\) centered on the cluster. However, only 140 artificial stars fall within the actual cluster radius of \(20''\). In order to increase the number of artificial stars and derive radial data completeness distributions more reliably, we generated 21 individual images for each passband and every reference point by shifting the grid around the initial position to 8 and 12 symmetrically distributed locations around the initial position at radial distances of \(\sim 0'6\) and \(\sim 1'2\), respectively. Therefore, within a radius of \(20''\) we used 2940 artificial stars in total at each reference point on the RGB. The photometry procedure of the AST images was exactly the same as the one employed for the real-star photometry.
To understand the morphology of star distribution in the lower part of the CMD, we constructed an artificial-star CMD. The radial distribution of the artificial stars at every reference AST point on the RGB was chosen to represent the observed radial density distribution of the cluster stars. However, to increase the robustness of the artificial star CMD, we used a number of artificial stars five times greater than the number of real stars. The observed cluster stars overplotted on the artificial star CMD are shown in Figure 2 (panel (b)).

The “Christmas tree-like” artificial star CMD (Figure 2, panel (b)) implies that the CMD of the star cluster M 33-EC1 is composed solely of RGB stars, experiencing very low contamination by foreground stars and background galaxies. Note, however, the enhanced (with respect to the artificial stars) density of the faint blue ($R - I < 0.25$) objects, which could be attributed to the horizontal branch stars of the cluster or faint blue galaxies. Therefore, the straightforward isochrone fit to the observed stars can be applied down to $I = 23^{m}$, using only the RGB part of the isochrones.

We constructed a radial data completeness plot (Figure 3) by counting the recovered artificial stars in $2^{\circ}$ wide annulus zones centered on the cluster. Stars down to $I = 23^{m}$ are well recovered even at the very center of the cluster. At this magnitude level we are able to find and measure more than 70% of the stars at the cluster’s center and more than 95% at larger radii (Figure 3).

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A magnitude of the brightest RGB star (it is located within the cluster’s core, however, in an uncrowded area, and thus measured accurately) is of $I = 20.81 \pm 0.01$. Taking into account the MW foreground extinction ($A_I = 0.11$), this converts to a distance modulus of $(m - M)_0 = 24.75 \pm 0.20$ and places the star cluster M 33-EC1 at a distance of $890 \pm 30$ kpc. The distance modulus error is dominated by the systematic error of the TRGB calibration ($\pm 0.10$) and by an additional increase of the distance modulus, arising due to a probability, that the brightest observed star is below the very tip of the theoretical RGB, because of a small total number of RGB stars in the cluster.

It is worthwhile to stress that we determine the RGB tip of the M 33 galaxy’s outer disk at $I = 20.68 \pm 0.02$, which converts, by applying the MW foreground extinction, $A_I = 0.08$, and assuming the validity of the TRGB method for the case of the M 33 outer disk’s metallicity, to $\sim 850$ kpc. The derived distance of M 33 is in agreement with recent M 33 galaxy distance determinations, based on the TRGB method, by Galleti et al. (2004) and Tiede et al. (2004)—855 kpc and 867 kpc, respectively. However, the detached eclipsing binary method gives a significantly longer distance of 964 kpc (Bonanos et al. 2006), while a cepheid based distance is shorter—802 kpc (Lee et al. 2002). Therefore, in the remainder of this paper we will use the distance modulus of 24.75, which places M 33-EC1 at a projected distance of 12.5 kpc from the M 33 center.

To estimate the cluster’s age and metallicity we compared the shape and slope of the observed RGB with the isochrones of Girardi et al. (2002) and VandenBerg et al. (2006). In the case of Girardi et al. (2002) isochrones, we achieved the best fit for the interpolated isochrone of the age of 13 Gyr and metallicity of $[M/H] = -1.2$ (Figure 2, panel (a); isochrone of the age of 14 Gyr and metallicity of $[M/H] = -1.3$ is overplotted). However, the isochrone of lower metallicity, $[M/H] = -1.4$, and age of $\sim 18$ Gyr, as well as the isochrone of higher metallicity, $[M/H] = -1.0$, and age of $\sim 2.5$ Gyr, can also be fitted reasonably well. Therefore, additional information is needed in order to break the age (2.5–18 Gyr) and metallicity ($[M/H] = -1.4 - 1.0$) degeneracy.

We obtained more constrained fits by employing VandenBerg et al. (2006) isochrones (2–18 Gyr), which are available on the finer metallicity grid for three alpha element abundance ratios ($\alpha$/Fe) = 0.0, 0.3, 0.6. We achieved good, although degenerate, fits for ages of $\sim 7$ Gyr and metallicity of $[M/H] < -1.4$ independent on alpha element abundance, see Figure 4. The isochrones spanning a narrow age and metallicity range are overplotted on CMDs for illustrative purposes. Assuming a reasonably old cluster age of 13 Gyr, we derived a metallicity of $[M/H] = -1.6$. Note that for the same age (13 Gyr) metallicity derived from the Girardi et al. (2002) isochrones is higher by 0.4 dex. The derived metallicity $[M/H] \lesssim -1.4$ is in good agreement with the recent spectroscopic metallicity determination of the M33 halo stars in a nearby field to the M 33-EC1 location (McConnachie et al. 2006).

3.2. Integrated Photometry and Structural Parameters

The M 33-EC1 age of $\sim 7$ Gyr, estimated from the isochrone fitting, implies that it should possess a globular cluster-like surface number density profile, which is traditionally fitted by the King model (King 1962):

$$\rho(r) = \rho_0 \cdot [(1 + (r/r_c)^2)^{-1/2} - (1 + (r/r_c)^2)^{-1/2}]^{-1},$$

where $\rho_0$ (central surface number density), $r_c$ (core radius), and $r_t$ (tidal radius) are profile fitting parameters. However, due to a small number of bright stars and an incompleteness of the stellar photometry catalogue at fainter magnitudes (see Figure 3), we decided to fit the King model to the surface brightness rather than to the surface number density profile. This assumption is reasonable for the surface brightness profiles, constructed from aperture photometry, which even at large radial distances sample the cluster’s stellar population satisfactorily well.
On the other hand, large M33-EC1 extent and relatively low luminosity (mass), as well as long (∼12.5 kpc) projected distance from the host galaxy’s center, can lead to the assumption that the cluster is dynamically young and possesses a surface brightness profile, which could be reproduced by the empirical EFF model derived for young (<300 Myr) Large Magellanic Cloud clusters. We employed the EFF model in differential form representing surface brightness profile

\[ \mu(r) = \mu_0 \cdot (1 + (r/r_c)^2)^{-n}, \]

and in integral form representing integrated luminosity profile

\[ \Sigma(r) = \Sigma_0 \cdot r_c^n \cdot (n - 1) \cdot [1 - (1 + (r/r_c)^2)^{1-n}]. \]

where \( \mu_0 \) is the central surface brightness, \( \Sigma_0 \) is the central luminosity, \( r_c \) is the scale-length, and \( n \) is the power-law index.

The determination of an accurate center of the well resolved cluster is a sensitive procedure in constructing the surface brightness profile. In the central part of M 33-EC1 luminous stars are distributed slightly asymmetrically (see Figure 1); therefore, systematic sky-background variation by rms of the sky-background value with oversubtracted and undersubtracted sky background. The subtraction errors were evaluated by constructing the profiles derived parameters were computed based on transformation Equations (6), (7), (9) and (10) presented by Larsen (2006) for the EFF profile

\[ \text{FWHM} = 2 \cdot r_c \cdot \sqrt{2^{1/n} - 1}, \]

and the King profile

\[ \text{FWHM} = 2 \cdot r_c \cdot \sqrt{((1 - \sqrt{0.5})/\sqrt{1 + (r/r_c)^2} + \sqrt{0.5})^{-2} - 1}, \]

\( r_h = 0.547 \cdot r_c \cdot (r/r_c)^{0.486}. \)

For further discussion we choose the conservative lower limit of the cluster’s half-light radius of \( r_h = 4'7, \) which, at the estimated distance of 890 kpc, converts to \( \sim 20.3 \) pc, revealing the extended M33-EC1 nature. It is also important to note that

\[ r_h = r_c \cdot \sqrt{0.5^{(1/(1-n))} - 1}, \]

\[ r_h = 0.547 \cdot r_c \cdot (r/r_c)^{0.486}. \]
the differences between $V$, $R$, $I$-band profile fit parameters are smaller than their standard deviations. Therefore, in Table 1 we give averaged parameters for the three passbands. It is worth noting that a change of the fitting radius from $12''$ to $19''$ does not influence the derived cluster parameters significantly. Integrated magnitudes and colors derived at the cluster’s center and radii of $(1-4) \cdot r_{h}$ are listed in Table 2. We find no significant color gradient over the entire radial cluster’s extent. The $V-I$ color of M 33-EC1, taking into account that only foreground extinction is present at this galactocentric distance, is in the color range of the intermediate- and old-age ($\lesssim 5 \, \text{Gyr}$) M 33 clusters (Sarajedini & Mancone 2007).

4. DISCUSSION

We report the discovery of an extended globular-like star cluster (eGC) at the outer edge of the M 33 galaxy, M 33-EC1. All the previously known clusters in M 33 are compact ones with core radii of $r_{c} \lesssim 2 \, \text{pc}$ (Chandar et al. 1999, 2001). Therefore, M 33-EC1 with $r_{c} \sim 25 \, \text{pc}$ is of a very rare type, and the only such object found in the Subaru Suprime-Cam wide-field survey frames ($\sim 1:1 \times 1:7$) of the M 33 galaxy.

The $r_{h}-M_{V}$ diagram proved to be a very informative and suggestive tool for a star-cluster study (van den Bergh & Mackey 2004). In Figure 6 we plot this diagram, taking representative objects from various studies published recently, and mark M 33-EC1. The MW galaxy has ten exceptionally large ($r_{h} \gtrsim 15 \, \text{pc}$) globular clusters (Harris 1996). However, only two of them (NGC 5053 and NGC 2419) are of comparable luminosity or brighter ($M_{V} < -6.5$) than M 33-EC1. Recently, four clusters of such an extreme type have also been found in the vicinity of M 31 (Huxor et al. 2005; Mackey et al. 2006). Huxor et al. (2005) pointed out that eGCs in the MW are fainter than those in the M 31 galaxy, due to differing formation and evolution scenarios of the host galaxies.

Owing to its luminosity, structural parameters, and metal-poor nature, M 33-EC1 is very similar to NGC 5053 (MW eGC) and to four M 31 eGCs. Therefore, regardless of the difference in morphological type, size, and luminosity, in the vicinity of three different galaxies eGCs of the same type reside. Similar eGCs discovered in the spirals M 51 and M 81 (Chandar et al. 2004), and in the giant elliptical galaxy NGC 5128 (Gómez et al. 2006) expand further the variety of eGC’s host galaxies (Figure 6). To our knowledge, M 33 is the smallest spiral galaxy hosting eGCs.

We note that recent studies (Sakamoto & Hasegawa 2006; Belokurov et al. 2007; Irwin et al. 2007) do not warrant a simple classification of stellar systems by using their structural parameters; therefore, the structural parameters of M 33-EC1 may also be shared with low surface brightness dwarf galaxies. In this context, the extended nature and very low concentration

| $r_{h}$ | $V$ | $V-R$ | $R-I$ | $M_{V}$ | $\Sigma_{V}$ | $\mu_{V}$ |
|--------|-----|-------|-------|--------|------------|--------|
| 0      | 0.47| 0.44  | 22.6  | 23.03  | 23.52      | 24.42  |
| 1      | 19.11| 0.47  | -5.83 | 14.4   | 23.52      | 24.42  |
| 2      | 18.50| 0.47  | -6.44 | 6.3    | 24.42      |        |
| 3      | 18.39| 0.46  | -6.55 | 3.1    | 25.19      |        |
| 4      | 18.33| 0.49  | -6.61 | 1.8    | 25.75      |        |

Note: Distance from the cluster’s center, $r_{h}$, is given in the cluster’s half-light radius, $r_{h} = 4.7$, units.

Figure 6. Plot of $r_{h}$ versus $M_{V}$ for the eGC M 33-EC1 (filled star). The extended M 31 clusters (Mackey et al. 2006) (open stars), the MW globular clusters (Harris 1996; catalogue revision: Feb. 2003) (filled circles), and clusters in M 51 (crosses), M 81 (asterisks), M 83 (open circles), M 101 (pluses) galaxies (Chandar et al. 2004) are shown. The star clusters of M 33 are not indicated because of their small sizes, $r_{c} \lesssim 2 \, \text{pc}$ (Chandar et al. 1999, 2001). Dashed ($\log(r_{h}) = 0.2 \cdot M_{V} + 2.6$; van den Bergh & Mackey 2004) and dotted (average surface luminosity of $15 \cdot L_{\odot} \cdot \text{pc}^{-2}$ within $r_{h}$ lines are drawn for reference. The solid L-shape line marks a location of faint fuzzy clusters (Brodie & Larsen 2002). The MW globular clusters of Cen, NGC 2419, and NGC 5053 are labeled. $r_{h} < 2.5$; Table 1) of M 33-EC1 suggests that this stellar system could be a low surface brightness dwarf galaxy. The central surface brightness of $\mu_{0,V} \sim 23 \, \text{mag arcsec}^{-2}$ is both consistent with lower end of surface brightness of the MW globular clusters (Harris 1996) and with local dwarf galaxies (Mateo 1998). At present, we have no clear diagnostics to discriminate between these possibilities. The best way to constrain the origin of M 33-EC1 would be to conduct a study of cluster dynamics. The velocity dispersion data, in particular, would make it possible to determine whether this cluster contains dark matter or not (Bender et al. 1992), since low surface brightness dSphs are found to exhibit a very large mass-to-light ratio; see, e.g., Kleyne et al. (2005) and Martin et al. (2007).

The extended nature of M 33-EC1 becomes very important when it is considered in light of the merging history of M 33. Based on the assumption that M 33 has no (prominent) thick disk and/or halo (Ferguson et al. 2007), it has long been postulated that very few, if any, massive accretion events have taken place. It is still controversial, however, whether M 33 is a pure stellar disk system or has a thick disk and/or a halo component. It is interesting to note, however, that accumulating evidence suggests a complex merging history of M 33. Chandar et al. (2002) reported that there is a wide spread in the age of star clusters and some old clusters have velocities consistent with the halo component dynamics. McConnachie et al. (2006) suggested a halo component and a possible stream by means of a spectroscopic study of individual RGB stars. The discovered M 33-EC1 cluster may also give support for the merging history scenario—it could be a stripped dwarf galaxy that has accreted and merged onto M 33—a scenario suggested for eGCs in M 31 (Huxor et al. 2005). We note that the proximity of M 33-EC1 relative to the stream (McConnachie et al. 2006) could suggest a physical connection; however, the preliminary metallicity estimates for both parties differ significantly. We here just mention that the metallicity of globular clusters in the Sagittarius dwarf spheroidal do not necessarily agree with that of the parent galaxy (Bellazzini et al. 2003).
Vansevičius et al. (2004) discovered an extended halo in the dwarf irregular galaxy Leo A and suggested that even such a small dwarf galaxy was formed in a much more complex way than previously believed, implying hierarchical galaxy formation on all scales. Recent findings indicate that small late-type disk galaxies, such as M 33, could have experienced merging events. Therefore, the eGC presented in this paper, M 33-EC1, together with various objects, which are suggested to associate with the M 33 halo, are all important targets for detailed study in order to understand the merging history of not only M 33, but of galaxies on all scales.

We are indebted to Chisato Ikuta for her invaluable help with observations on Subaru telescope. We are grateful to the anonymous referee for constructive suggestions and proposed corrections. This work was financially supported in part by a Grant of the Lithuanian State Science and Studies Foundation, and by a Grant-in-Aid for Scientific Research by the Japanese Ministry of Education, Culture, Sports, Science and Technology (No. 19540245).

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