A SURVEY OF STAR CLUSTERS IN THE M31 SOUTHWEST FIELD: 
UBVRI PHOTOMETRY AND MULTIBAND MAPS

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ABSTRACT

A new survey of star clusters in the southwest field of the M31 disk based on the high-resolution Subaru Suprime-Cam observations is presented. The UBVRI aperture CCD photometry catalog of 285 objects (V < 20.5 mag; 169 of them identified for the first time) is provided. Each object is supplemented with multiband color maps presented in the electronic edition of the Astrophysical Journal Supplement. Seventy-seven star cluster candidates from the catalog are located in the Hubble Space Telescope archive frames.

Subject headings: galaxies: individual (M31) — galaxies: star clusters

Online material: color figure, extended figure set, machine-readable table

1. INTRODUCTION

Detailed studies of the star clusters in M31 are essential to understanding the evolution mechanisms of disk galaxies and of the cluster population itself. Many observational surveys of this galaxy have been devoted to globular clusters; see, e.g., Kim et al. (2007) and references therein. Due to crowding, plausible detection and analysis of star clusters projected on the disk of M31 became feasible only with high-resolution imaging; see Krienke & Hodge (2007) for an extensive discussion of the problem. However, Hubble Space Telescope (HST) observations cover only a small part of the M31 disk, and up-to-date cluster population studies (e.g., Krienke & Hodge 2007) are based on HST fields scattered over the area of M31.

A homogeneous (in object detection and photometry) survey of star clusters in the southwest field of the M31 disk was conducted by Kodaira et al. (2004, hereafter Paper I) over an area of ~500 arcmin², making use of the high-resolution imaging capability of the Subaru Suprime-Cam (Miyazaki et al. 2002). In Paper I we presented a catalog of 49 prominent compact objects and a catalog of 52 emission objects. Structural parameters of 49 compact and 2 emission objects brighter than V ~ 19.0 mag were derived from the V-band Suprime-Cam image by Šablevičiūtė et al. (2006, 2007), showing that they are fainter and span a slightly wider half-light radius range than the M31 clusters studied by Barmby et al. (2002, 2007). The UBVRI (R and I bands are in Cousins system) photometry of these clusters was performed on the Local Group Galaxy Survey (LGGS; Massey et al. 2006) images by Narbutis et al. (2006b), resulting in a smaller scatter in color-color diagrams than photometry data of the same objects taken from the Revised Bologna Catalogue of M31 globular clusters and candidates compiled by Galleti et al. (2004).

Promising results from these studies motivated us to extend a sample of star clusters up to V ~ 20.5 mag. Here we present the results of UBVRI aperture CCD photometry for 285 star cluster candidates located in the same Suprime-Cam field of the M31 disk (see Fig. 1). The multiband color maps, combined from GALEX, LGGS, 2MASS, Spitzer (24 μm), and H i (21 cm) images, are provided in the electronic edition of the Supplement. We describe the object selection procedure in § 2, photometry and calibration in § 3, and present the catalog in § 4.

2. OBJECT SELECTION

The Suprime-Cam survey of star cluster-like objects was conducted in the southwest (SW) field of the M31 disk (~17.′5 × 28.′5 in size), centered at α2000 = 0h40.9m and δ2000 = +40°45′ (Fig. 1). Visual inspection of the high-resolution Suprime-Cam mosaic images, with characteristic full width at half-maximum (FWHM) of the point-spread function (PSF) of ~0.7″, enabled us to select the initial sample of ~600 star cluster candidates up to V ~ 21 mag.

In addition, several objects that were not recognized as cluster candidates in our survey were appended to the initial cluster candidate sample from the Revised Bologna Catalogue of M31 globular clusters and candidates v.3.2, July 2007 (Galleti et al. 2007) and from the recent HST survey of the M31 disk cluster population conducted by Krienke & Hodge (2007). About 40 objects included in Galleti et al. (2007) and overlapping with our survey field originally come from the recent survey by Kim et al. (2007); however, ~50% of these objects were omitted from our catalog because their surface brightness profiles closely resemble that of stars.

To study selection effects inherent to the initial cluster candidate sample, archival HST frames (see Appendix A) were employed. A completeness of ~70% in the visual selection of star cluster candidates at the limiting magnitude of the catalog (V ~ 20.5 mag) was estimated by comparing our initial sample of ~600 objects with an overlapping sample studied by Krienke & Hodge (2007). We also checked our objects against available archival HST images, and some of our cluster candidates were classified as asterisms. Moreover, few new star cluster candidates, overlooked during a visual inspection of the Suprime-Cam images, were found on HST frames. Summing up results of these tests, we find the completeness of our cluster candidate sample to be higher than ~50% at V = 20.5 mag. This is a conservative magnitude limit for objects that can be identified as star clusters on the Suprime-Cam...
images. However, it is difficult to estimate the completeness of the present cluster candidate sample more accurately, since it depends on a strongly varying background object density across the surveyed area, and the clusters’ luminosities, colors, and concentrations.

A strong contamination of young star cluster samples selected in M31 by asterisms has been demonstrated recently by Cohen et al. (2005). Therefore, in order to clean our cluster candidate sample (\(V \leq 20.5\) mag), we determined cluster structural parameters by employing the BAOLAB/ISHAPE program package (Larsen 1999) and using the analysis technique described in Šablevičiūtė (2005). Therefore, in order to clean our cluster candidate sample more accurately, since it depends on a strongly varying background object density across the surveyed area, and the clusters’ luminosities, colors, and concentrations.

For the star cluster aperture photometry, we used LGGS\(^4\) \(U, B, V, R, I, H\alpha\) and \(I\) band mosaic images of four M31 fields (F6, F7, F8, and F9) overlapping with the field studied in Paper I. The mosaic camera used for LGGS consists of eight CCDs. Each CCD chip covers a \(9' \times 18'\) field and has an individual set of color equations. The observations and data reductions are described in detail by Massey et al. (2006).

We considered mosaic images, cleaned of cosmic rays and cosmetic defects, to be preferable to individual exposure images for star cluster aperture photometry. The dithering pattern of five individual exposures is the same for each field (maximum shifts up to \(1'\) from the first exposure), with an exception of the \(U\)-band mosaic of the F9 field, which is combined from six individual exposures. Massey et al. (2006) do not recommend a straightforward use of their mosaic images for accurate photometry; therefore, we treated each CCD chip area in the mosaic image separately, taking special care of objects residing in different CCDs of the combined individual exposures.

### 3. PHOTOMETRY

#### 3.1. PSF Homogenization

PSFs of the LGGS mosaic images used for aperture photometry differ significantly (see Table 1). Moreover, four of them have a coordinate-dependent PSF, with a FWHM varying by more than 0.2\(''\) across the field. That would lead to a variable aperture correction and, if not properly corrected, to a cluster color bias for the small apertures (diameter of \(\sim 3''\)) used in this study. Since the intrinsic surface brightness distribution profiles of star cluster candidates are unknown, we homogenized mosaic image PSF shapes, instead of using variable aperture corrections. This also ensures a consistency in aperture selection, photometric error, and photometric background estimates.

We applied the DAOPHOT package (Stetson 1987) from the IRAF program system (Tody 1993) to compute original PSFs for all mosaic images. By convolving the widest PSF (FWHM = 1.3\(''\)) with the Gaussian kernel, a reference PSF of FWHM = 1.5\(''\) was produced. The IRAF’s psf\_match procedure was employed to compute the required convolution kernels for individual mosaic images with respect to the reference PSF. These kernels were symmetrized by replacing their cores with the best-fitting Gaussian profiles, and their wings with the best-fitting exponential profiles, truncated at 3.5\(''\). The IRAF’s convolve procedure was employed to produce mosaic images possessing unique and coordinate-independent PSFs of FWHM = 1.5\(''\). The homogenized images were photometrically calibrated and used for star cluster photometry. The maximum difference of the aperture corrections in

### Table 1

| Source Images | Parameter | FWHM (arcsec) | Scale (arcsec pixel\(^{-1}\)) |
|---------------|-----------|---------------|-------------------------------|
| Suprime-Cam   | B, V, R, H\(\alpha\) | 0.6–0.7       | 0.20                          |
| LGGS\(^a\)   | U, B, V, R, I, H\(\alpha\) | 0.7–1.3       | 0.27                          |
| GALEX\(^b\)  | FUV, NUV  | \(\sim 4.5, \sim 5.5\) | 1.50                          |
| 2MASS         | J, H, K\(\alpha\) | \(\sim 3.5\)   | 1.00                          |
| Spitzer       | 24 \(\mu\)m | \(\sim 6.0\)   | 2.45                          |
| H\(^i\)       | 21 cm     |                | 10.3                          |

\(^a\) Mosaic images of the F6–F9 fields.

\(^b\) Strongly variable asymmetric PSF.

\(^c\) TIFF format image.
different passbands is less than 0.02 mag. A test of photometric accuracy of the entire PSF homogenization procedure suggests that errors do not exceed 0.01 mag.

3.2. Calibrations

For the \textit{UBVRI} cluster photometry calibration, we selected well-isolated stars of high photometric accuracy (<0.03 mag), measured in each passband more than 3 times, from Table 4 of Massey et al. (2006). The calibration stars were measured on the homogenized mosaic images through the circular aperture of 3.0″ diameter by employing the IRAF’s \texttt{phot} procedure. The aperture correction (aperture magnitude minus total magnitude) of 0.27 mag was determined for all homogenized mosaic images.

Massey et al. (2006) provide color equations for individual CCD chips of the mosaic camera (see their Table 2). We solved those equations by fitting photometric zero points of all passbands for every individual field and CCD chip. Typically, 80 (ranging from 20 to 140) calibration stars per chip were used. The final errors of derived zero points are less than 0.01 mag, with typical fitting rms < 0.03 mag for the \textit{J} band and < 0.02 mag for other passbands. Color equations given by Massey et al. (2006), supplemented with the derived zero points, were used to transform instrumental magnitudes to the standard system. For objects located in the mosaic image areas combined from different CCDs, we used color equations of corresponding CCDs and performed independent transformations to the standard system.

A comparison of three published stellar photometry data sets in the SW field of the M31 disk (Narbutis et al. 2006a) suggests caution when using tertiary standards as local photometric standards. However, a careful reduction, calibration, and internal consistency check performed by Massey et al. (2006) resulted in millimagnitude differences between the photometry results of overlapping fields. To our knowledge, this is the most accurately calibrated photometry data set in the M31 galaxy to date.

3.3. Results

The aperture \textit{UBVRI} photometry was carried out by employing the IRAF’s \texttt{XPHOT} package. The images of all objects, except for five saturated in the \textit{I} band, are free of visible defects. Apertures were centered on clusters’ luminosity distribution peaks in the Suprime-Cam \textit{V}-band mosaic image and transformed to individual LGGS image coordinate systems with the IRAF’s \texttt{geokoxytran} procedure. In order to minimize cluster photometry contamination by background objects in crowded fields, we decided to use individual small circular (elliptical for the two bright objects KW102 and KW141 to avoid obvious nearby background stars) apertures; their sizes are provided in Table 2. The photometric background was determined in individually selected and object-centered circular annuli with typical inner and outer radii of 3″ and 8″, respectively. For some clusters, located on a largely variable background, circular background determination zones were selected individually in representative areas.

The catalog of 285 star cluster candidates consists of 138 and 141 objects measured in two and three different LGGS fields, respectively, while six objects have been measured in one field. Two main types of error sources determine the final accuracy of the photometry: the photon noise, \textit{\sigma}_{\text{\textit{\eta}}} (estimated by \texttt{XPHOT}), and the calibration procedure, \textit{\sigma}_{\text{c}}. The \textit{V}-band magnitude and colors, derived in different LGGS fields for each object, were examined interactively. Weighted averages were calculated taking into account individual \textit{\sigma}_{\text{\textit{\eta}}} and down-weighting data derived in the mosaic image areas combined from different CCDs. The rms of averaged magnitudes and colors characterize calibration errors in general, so they were assigned to \textit{\sigma}_{\text{c}}. The lowest possible calibration errors of 0.010, 0.015, and 0.020 mag were set for objects having 3, 2, and 1 independent measurements, respectively. The final photometric errors, provided in the catalog (Table 2), are calculated as \textit{\sigma} = (\textit{\sigma}_{\text{\textit{\eta}}}^2 + \textit{\sigma}_{\text{c}}^2)^{1/2}. The photometric error values, \textit{\sigma}_{\text{\textit{\eta}}}, for corresponding \textit{V}-band magnitudes are plotted in Figure 2.

In order to check the aperture size effect on the color accuracy and possible bias due to a contamination by background stars, all objects were measured through four additional apertures, changing the adopted size by ±0.6″ and ±1.2″. The results of the aperture size test, published by Narbutis et al. (2007), show that contaminating background stars have the strongest influence in the \textit{I} band. The \textit{U} – \textit{B} color of red objects tends to be systematically bluer, and an opposite effect is observed for the \textit{V} – \textit{I} of blue objects. However, in most cases the final photometric errors provided in the catalog (Table 2) represent the accuracy of...
cluster colors well. A comparison of our photometry data with HST observations of the same objects by Krienke & Hodge (2007) shows a reasonably good agreement (Narbutis et al. 2007).

4. THE CATALOG

The photometric catalog of 285 star cluster candidates in the M31 SW field is presented in Table 2, the full content of which is available in the electronic edition of the Supplement. Object coordinates, V-band aperture magnitudes, U/B, B/V, V/R, and R/I colors with their photometric errors, a flag for 77 objects located in HST frames, and cross-identifications with Galleti et al. (2007), Krienke & Hodge (2007), and Paper I (69, 24, and 58 clusters, respectively) are provided.

All catalog objects, overlaid on the Spitzer 24 μm image, are shown in Figure 1. Elliptical ring segments, indicating distances (6–18 kpc) from the M31 center in the galaxy’s disk plane, were drawn assuming the following M31 parameters: a distance modulus of m – M = 24.47 (McConnachie et al. 2005), center coordinates α2000 = 10h42m44.3s, δ2000 = 41°16′09″ (NASA Extragalactic Database), a major axis position angle of 38° (de Vaucouleurs 1958), and a disk inclination angle to the line of sight of 75° (Gordon et al. 2006).

V-band magnitude and B – V color histograms of the catalog objects are shown in Figure 2. Shaded histograms show a subsample of 77 objects identified in the HST frames.

Observed color-color diagrams of star cluster candidates, overplotted with simple stellar population (SSP) models of metallicity Z = 0.008 and ages ranging from 1 Myr to 15 Gyr, are presented in Figure 3. Default PEGASE parameters and a universal initial mass function (Kroupa 2002) were applied. Reddening vectors are depicted by applying the standard extinction law: a V-band extinction to color excess ratio AV/E(B – V) = 3.1 and color excess ratios E(U – B)/E(B – V) = 0.72, E(R – I)/E(B – V) = 0.69. The Milky Way interstellar extinction in the direction of the M31 SW field is E(B – V) = 0.062 (Schlegel et al. 1998).

Figure 3, together with multiband color maps, suggests that the present sample covers a wide range of stellar populations, from old globular clusters through young massive clusters. Some objects, suspected to be young and heavily reddened in the U – B vs. B – V diagram, are displaced in opposite R – I directions from the bulk of objects in the R – I vs. B – V diagram, making a large scatter. A detailed color analysis of these cases, taking into account multiband color maps, reveals two main reasons: R – I is increased due to an additional flux from red background
stars in the $I$ band, and $R - I$ is decreased by an additional contribution from the H$\alpha$ emission in the $R$ band.

Combined multiband color maps (Fig. Set 4; see Appendix B for description) of 285 objects are provided in the electronic edition of the Supplement. They serve as an illustrative material showing the objects' structure, the location of the aperture used for photometry, individual background conditions, and position in the survey field. These maps are also a valuable tool for revealing cluster interrelations with a global framework of various M31 galaxy components.

5. SUMMARY

We have performed the Suprime-Cam survey of star clusters in the southwest field of the M31 disk up to $V \sim 20.5$ mag, providing the $UBVRI$ CCD aperture photometry catalog of 285 cluster candidates. The catalog includes 77 objects located in the $HST$ frames. Photometry was performed through individually selected small apertures. Object cross-identifications with Galleti et al. (2007) and Krienke & Hodge (2007) are provided for 69 and 24 objects, respectively. Multiband color maps combined from LGGS ($U$, $B$, $V$, $I$, and $H\alpha$ bands), $GALEX$ (NUV, FUV), 2MASS ($J$, $H$, and $K_s$ bands), Spitzer ($24 \mu m$), and H $\alpha$ (21 cm) images, are available in the electronic edition of the Supplement.

This catalog contains an almost complete homogeneous sample of target objects in the surveyed area and will serve as a basis for follow-up imaging or spectroscopic studies. The presented materials suggest that the sample in the catalog covers a wide range of stellar populations, from old globular clusters through young massive clusters. An analysis of the catalog will be forthcoming (V. Vansevičius et al. 2008, in preparation).

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APPENDIX A

HST FRAMES

The Multimission Archive at the Space Telescope Science Institute (MAST) was searched for HST frames overlapping with the Suprime-Cam survey field and publicly available to the date of 2007 August 7. Flat-fielded frames were cleaned of cosmic rays and corrected for distortions by employing procedures of the IRAF’s STSDAS package. The World Coordinate System information was extracted from the TIFF to the FITS format.

The LGGS mosaic images (Massey et al. 2006) in the $U$, $B$, $V$, $I$, and $H\alpha$ bands of the F7 or F8 fields were used for a multiband map construction. For objects located to the south of the F7 field, images of lower resolution from field F8 were substituted. The 2MASS $J$, $H$, and $K_s$ band “$1\times$” and “$6\times$” survey images were retrieved from the NASA/IPAC Infrared Science Archive and co-added to increase their signal-to-noise ratio. In general, the $6\times$ co-added image was used, except for the gap region in the north of the surveyed field, where the $1\times$ image was substituted. The $GALEX$ NUV and FUV images by Gil de Paz et al. (2007) were retrieved from the $GALEX$ Atlas of Nearby Galaxies and co-added to increase a signal-to-noise ratio. The $Spitzer$ MIPS ($24 \mu m$) post-BCD (basic calibrated data) images of M31 (Program ID 99; PI: G. Rieke) were retrieved from the $Spitzer$ Space Telescope Science Center Data Archive, and mosaicised using the Swarp package (author E. Bertin).

The H $\alpha$ (21 cm) image was retrieved from the National Radio Astronomy Observatory image gallery (image courtesy of NRAO/AUI and David Thilker [JHU], Robert Braun [ASTRON], WSRT). It was converted from the TIFF to the FITS format using ImageTools. The sky coordinate grid indicated by Westmeier et al. (2005) in their Figure 1 on the same H $\alpha$ image, was used for the initial registration. Fine adjustments were made assuming a global correlation between the $Spitzer$ ($24 \mu m$) and H $\alpha$ (21 cm) source distributions, noted by Gordon et al. (2006).

The Suprime-Cam $V$-band mosaic image coordinate system was used as a reference to register and transform all images to the homogeneous pixel scale of 0.2$''$ pixel$^{-1}$. The IRAF geotran procedure was used for the LGGS, $GALEX$, and 2MASS image.
transformations; the register procedure was used for the Spitzer (24 μm) and H i (21 cm) images. Most defects were masked prior to transformations. Since the LGGS images cover a wide wavelength range, they served as a reference for registering other images. A visual inspection was carried out to ensure an accurate coordinate match of the images prepared for a multiband map production. The FWHM and original pixel scale values of those images are provided in Table 1.

The sub-images of 80″ × 80″, centered on the objects’ position, were cut out from the transformed images. SAOImage DS9 was employed to combine them into multiband color maps. The LGGS, 2MASS, and GALEX sub-images are displayed in a linear intensity scale, and the Spitzer sub-images are displayed in a square root scale. The minimal shown data level is individual for each sub-image, depending on the background intensity; however, the range of displayed intensities was kept constant for all objects. The constant displayed intensity limits across the surveyed area were applied only for H i (21 cm) sub-images and are overplotted with contour lines. A gray-shaded inset shows a global H i emission intensity, with black standing for the highest and white for the lowest signal level over the entire surveyed area. The size of panel b is 15′′ × 15′′, and the size of panels c–f is 80″ × 80″. The aperture used for the photometry is overlaid in panel b. The object in panels c–f is marked with a circle of 10″ in diameter. North is up, east is left. [See the electronic edition of the Supplement for figures 4.1–4.285.]

**Fig. Set 4.** — An example of multiband maps (top) and a corresponding layout template (bottom), indicating panel notations, is shown here as a guide to the individual multiband color maps, constructed for all objects, available in the electronic edition of the Supplement. The object’s ID, the I-band magnitude, and the B − V color are provided in the top left corner. Panel a shows positions of 285 objects in the M31 SW field (circles); elliptical ring segments indicating distances from the M31 center (6−18 kpc) are marked with dashed lines overlaid on the Spitzer (24 μm) image; the object under consideration is indicated by a red square of a size equivalent to the size of panels c–f. In panels b–f of the layout template, passbands of images displayed in red, green, and blue color channels are indicated by corresponding colors. The LGGS images were used in panels as follows: (b–d) U, B, V, I, Hα bands of the original resolution; (e) the V-band of a homogenized PSF (FWHM = 1.5″); (f) the I and J bands of a homogenized PSF (FWHM = 3.5″) matching the PSF of 2MASS images. Contour lines in panel e emphasize the H i distribution; the gray-shaded inset shows a global 21 cm emission intensity, black standing for the highest and white for the lowest signal level over the entire surveyed area. The size of panel b is 15′′ × 15′′, and the size of panels c–f is 80″ × 80″. The aperture used for the photometry is overlaid in panel b. The object in panels c–f is marked with a circle of 10″ in diameter. North is up, east is left. [See the electronic edition of the Supplement for figures 4.1–4.285.]

An example of the online multiband color maps and a layout template are shown here in Figure 4. Since the displayed intensity range is kept constant for all objects, colors of individual objects are roughly preserved. However, the real emission level at 24 μm should be estimated by referencing the object’s position in the global Spitzer image of the survey field. Multiband maps for all 285 objects are provided in Figure Set 4, available in full in the electronic edition of the Supplement.

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