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Studying Globular Clusters in the Dwarf Galaxy NGC 247 Using Subaru Hyper Suprime-Cam Imaging

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STUDYING GLOBULAR CLUSTERS IN THE DWARF GALAXY NGC 247
USING SUBARU HYPER SUPRIME-CAM IMAGING

A Thesis

Presented to

The Faculty of the Department of Physics and Astronomy

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Vakini Santhanakrishnan

December 2016

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The Designated Thesis Committee Approves the Thesis Titled

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by

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APPROVED FOR THE DEPARTMENT OF PHYSICS AND ASTRONOMY

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ABSTRACT

STUDYING GLOBULAR CLUSTERS IN THE DWARF GALAXY NGC 247 USING SUBARU HYPER SUPRIME-CAM IMAGING

by Vakini Santhanakrishnan

While globular clusters (GCs) are among the most ancient stellar systems in the universe, there are still lingering questions about how and where they formed. There is relatively little known about GCs in spiral galaxies beyond the Milky Way. We analyzed confirmed GCs, examined putative GC candidates, and looked for new GCs around the nearby dwarf spiral galaxy NGC 247 at about 3.5 Mpc away in the Sculptor group, based on wide-field imaging data from the Subaru Hyper Suprime-Cam (HSC), with a 1.5 degree field of view. The extremely wide-area coverage, depth, and image quality of HSC provide great potential for studying GCs around nearby galaxies. Using colors, magnitudes, and sizes of spectroscopically-confirmed objects, we defined criteria for selecting GC candidates in NGC 247. We examined candidates visually and were able to eliminate objects that were previously classified to be GC candidates, as well as find new GC candidates. Spectroscopic follow-up is planned to confirm some of the new GC candidates.

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This research was a rewarding experience in learning about one of the oldest astronomical objects (GCs) and being a small part of a more extensive research in understanding the evolution of GCs.

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CHAPTER 1

INTRODUCTION AND MOTIVATION

1.1 Globular Clusters

Globular star clusters (GCs) are among the oldest ($\tau \sim 10\text{--}13$ Gyr) radiant objects in the universe (Harris 1991). They are densely packed ensembles of stars (half-light radii of a few parsecs; Brodie & Strader 2006). Roughly spherical in shape, they are found in the bulge and halo regions of galaxies (Harris 1991). However, there are still lingering questions about how and where they were formed. There is relatively little known about GCs in spiral galaxies beyond the Milky Way owing in part to the low numbers of GCs per galaxy in spiral galaxies relative to ellipticals. Another complication is that the spiral disks (particularly when face-on) pose difficulty in detecting GCs against the backdrop of clumpy spiral arms.

GCs contain information about the star formation history and assembly of their host galaxies. The Milky Way and most other massive galaxies exhibit GC bimodality: two distinct GC subpopulations that show color differences thought to reflect differences in their heavy metal content (Brodie & Strader 2006). Since the GCs of spiral galaxies are generally fewer in total number and in number per unit galaxy luminosity (specific frequency), and due to spiral contamination, the bimodality is less obvious compared to the ellipticals.

There are three broad, long-standing scenarios suggested for GC origins: disk–disk major mergers, dissipational galaxy collapse (*in situ* model), and the dissipationless accretion of much smaller galaxies (Brodie & Strader 2006). In both the major merger and accretion models, it is believed that metal-rich GCs were formed in massive galaxies and that the metal-poor GCs were acquired by the accretion of neighboring lower-mass galaxies to produce bimodality. Therefore, it is

important that we study these dwarf galaxies that are still intact to see if their GC system properties are consistent with the accretion/merger scenario to explain bimodality.

GC systems of typical elliptical galaxies can be accounted for by the merger of two or more spiral galaxies, but for more luminous, high elliptical galaxies, the greater number of GC population is unaccounted by the simple spiral-spiral mergers (Rhode & Zepf 2003). By studying the accretion history of GCs, galactic stellar halo accretion can also be probed. Simulations of accreted stellar components seem to be consistent with the GC distribution in the Milky Way and the nearest giant spiral galaxy M31, implying that many of the GCs were brought in by accretion events (Abadi et al. 2006). On the other hand, there is a surprising observation that the GC systems in the Sculptor group (including NGC 247) galaxies are in rotating disks rather than in the non-rotating halos (as in the case of Milky Way), suggest that GCs were formed *in situ*, rather than accreted (Olsen et al. 2004). However, the number of confirmed GCs in these galaxies make the observation uncertain. Furthermore, GCs could potentially hold clues to understanding dark matter. There is an empirical correlation between total halo mass of a galaxy (including all visible and dark matter in its potential well), and the total mass in its GC system (Harris et al. 2015). However, more data are needed from dwarf galaxies such as NGC 247 to test the correlation.

CHAPTER 2

NGC 247 - DWARF SPIRAL GALAXY

2.1 Introduction

The dwarf spiral galaxy NGC 247, classified as SAB(s)d (Brodie & Strader 2006), is one of the nearest galaxies in the southern sky. It is located about 3.5 Mpc (Tully et al. 2013) away in the constellation of Cetus (The Whale). NGC 247 is gravitationally bound to the Sculptor group, a group of 13 known galaxies, which is just beyond our Local Group (Cote et al. 1997). NGC 247 resembles our Milky Way Galaxy in the sense that both are spiral galaxies. However, NGC 247 is a factor of ~ 10 times less massive than the Milky Way. The stellar mass for NGC 247 was measured to be $\sim 3 \times 10^9 M_{\odot}$ (J. Carlin et al., in preparation). Edge-on spirals, as seen from the side with a visible bulge, are preferred for GC detection. We choose to search for GCs in edge-on galaxies such as NGC 247 to minimize the effects of dust and background inhomogeneities on GC detection from the clumpy spiral arms in more face-on spiral galaxies (Brodie & Strader 2006). There are currently only 3 confirmed GCs in this galaxy from Olsen et al. (2004), but we have obtained new imaging data that can help us in identifying more GCs.

2.2 Subaru/Hyper Suprime-Cam

In this research, we have aimed to identify additional GCs in NGC 247 through new deep, wide-field Hyper Suprime-Cam (HSC) imaging. HSC is a powerful mosaic CCD prime-focus camera on the 8.2-m Subaru telescope located on the peak of Mauna Kea, Hawaii. Its focal plane is covered with 104 red-sensitive CCDs (Goto et al. 2015). The HSC has a circular field-of-view (FOV) of 1.5 deg in

diameter with a pixel scale of $0.17''$, and the FOV is ten times larger in area than the FOV of Suprime-Cam (Miyazaki et al. 2012).

2.3 Previous work on NGC 247

Work was previously done by Olsen et al. (2004) in identifying the GC systems of six major Sculptor group galaxies including NGC 247. Here we summarize the results from their analysis and observations. The data used were from the Cerro Tololo Inter-American Observatory (CTIO) 4m telescope, Mosaic II camera with a pixel scale of $0.27''$, using Washington CM filters, and Harris R filter. The camera had a FOV of 36×36 arcmin and the central wavelengths of the Washington C and M filters are $3850 \text{ \AA}$ and $5115 \text{ \AA}$ respectively. The central wavelength of the Harris R filter is $6440 \text{ \AA}$. The Washington C passband is between the U (ultraviolet) and B (blue) bands, and the Washington M passband is close to the commonly used V (visual) band.

Olsen et al. (2004) selected the GCs based on photometry and object morphology. In order to limit the number of candidates for spectroscopic follow-up, and to simplify the photometric analysis, they avoided the crowded galaxy disks in their survey. GC selection regions for each of the galaxies were derived by comparing the Milky Way GCs color–magnitude range to their color–magnitude diagrams. Next, they used the shapes and areas of the isophotes. Isophotes usually define two things: the shape of an object and the amount of light it gives off. Though the GCs appear point-like (stellar), they are slightly extended. The area of the isophotes was used to find extended objects such as GCs. They established a loose criterion that the GC candidates should have isophotal ellipticities $e < 0.4$, where $e = 0$ represents a circular isophote. In order to quantify the amount of light received, they

calculated the flux from pixels contained within the isophote lying 5σ above the background. The objects that obeyed their color, magnitude, and ellipticity limits and that passed visual inspection (to eliminate image artifacts and obvious background galaxies) were selected as viable spectrograph targets. They were able to narrow their search to ~ 100 GC candidates per galaxy, to follow up with multiobject spectrographs. There were 123 GC candidates selected from NGC 247.

Olsen et al. (2004) performed spectroscopy of some of their probable GC candidates. Eighty-one GC candidates in NGC 247 were observed with the Hydra-CTIO multifiber spectrograph to measure their radial velocities. Out of these 81 candidates, 30 GC candidates returned only a weak spectrum. Spectroscopy helped them in removing the background galaxies from their GC candidates list. To further remove the foreground stars, they used the measured velocities, along with the full width half maximum (FWHM) of their objects compared with the FWHM of point-like sources. Thus, they discovered and confirmed the existence of the first known GCs in NGC 247. One of them will be shown in Figure 3.11: an image from HSC. They were able to confirm only 3 GCs in NGC 247 out of the 51 GC candidates that had good spectra, which is a $\sim 6\%$ success rate. The GC candidates' spectra were consistent with the previous confirmed GCs in the Milky Way.

Our research builds upon this paper in identifying more GC candidates from the wide field, deep images from HSC for one of the Sculptor group galaxies NGC 247. The existing estimate of number of GCs in NGC 247 according to Olsen et al. (2004) is 60 ± 30 . Figure 2.1 shows the spatial positions of the spectroscopic targets marked on our HSC image.

Figure 2.1: NGC 247 - spiral dwarf galaxy (FOV: 45×23 arcmin $\sim 46 \times 25$ kpc), with the spectroscopically targeted objects marked on the HSC image. Yellow, blue, red, magenta, and green symbols mark GCs, foreground stars, background galaxies, probable galaxies, and unclassified objects (low signal-to-noise spectra). This image is only a subsection of the overall image available from HSC.

2.4 Goals of the research

By taking advantage of wide-field and 0.6 arcsec seeing of HSC images, we are searching for new GC candidates and also vetting previous GC candidates not subjected to spectroscopy by Olsen et al. (2004). We combine the magnitudes obtained with the 3 filters (Washington CM and Harris R filters) from Olsen et al. (2004), and magnitudes from the SDSS g and i filters from HSC, plus magnitudes from a *Spitzer Space Telescope* image (effective wavelength of $3.6 \mu\text{m}$ - infrared). A total of 6 filters provide different combinations of color-color and color-magnitude diagrams that are used to define selection regions for GCs in NGC 247. We are hoping that half or more of our GC candidates in NGC 247 can be confirmed as GCs (through spectroscopy in the near future).

CHAPTER 3

DATA SOURCES, PHOTOMETRY, AND CATALOGS

Here we discuss data extraction from the HSC images using Source Extractor (SExtractor). SExtractor is a software package that optimally detects, de-blends, measures, and classifies sources from astronomical images (Bertin & Arnouts 1996).

3.1 General Concepts and Definitions

Before discussing data extraction, we present some of the parameters used in order to do GC selection.

3.1.1 Astrometry

Astrometry is the calibration of an image or set of positional measurements to a standard reference frame. Astrometric parameters give the position of the object in the image, be it in pixels or other coordinates. The parameters used in this research are Right Ascension (RA) and Declination (DEC) measured in degrees (J2000) and X and Y positions of the objects in pixels.

3.1.2 Photometry

Magnitude is a logarithmic measure of the brightness of an object measured in a specific wavelength or passband. *Apparent magnitude* (m) of an object tells how bright that object appears at its great distance from Earth. *Absolute magnitude* (M) is the apparent magnitude of an object if it were placed 10 parsec from Earth. Bright objects have negative magnitudes compared to the faint ones. SExtractor performs photometry (how bright objects are) based on five different approaches to

compute the magnitudes: isophotal (**MAG_ISO**), corrected-isophotal (**MAG_ISOCORR**), automatic (**MAG_AUTO**), best estimate (**MAG_BEST**), and fixed-aperture (**MAG_APER**).

Isophotal magnitudes are computed using the detection threshold as the limiting isophote. The best estimate magnitudes and the fixed-aperture magnitudes were used in this research. The best photometry combines the isophot-corrected magnitude (ISOCOR) and the automatic aperture magnitudes (AUTO- SExtractor uses a flexible elliptical aperture around every detected object and measures all the flux inside that). Aperture photometry is a technique that simply collects and sums up the observed counts within a specified aperture (circular in this case) centered on the source. The diameter of the aperture in pixels **PHOTOM_APERTURES** is supplied by the user.

3.1.3 Geometric parameters

Geometric parameters describe the shape and size of the object (Holwerda 2005) and are required to perform the GC selection. The important parameter used in this research was FWHM measured in degrees or pixels. FWHM measures the spatial concentration of the image of an object, when that object does not have sharp edges, as shown in Figure 3.1.

Figure 3.1: Graphical representation of how FWHM is measured. For example, a star has a profile that closely resembles the Gaussian “seeing” disk – from Earth atmosphere turbulence.

3.2 HSC Imaging data

NGC 247 was observed using Subaru/HSC on 2015 Oct 15 with long exposure times of 16×300 s in the g filter and 10×300 s in the i filter, and with seeing of ~ 0.6 arcsec. The g and i filters’ central wavelengths are 4680 Å and 7480 Å respectively. The short exposure time for the g and i filters was 1×30 s. The short exposure images were not dithered, so there are chip-gaps remaining. The observations were a part of the Magellanic Analog Dwarf Companions And Stellar Halos (MADCASH) survey (Carlin et al. 2016), whose primary aim is to study the satellites and resolved stellar halos of dwarf galaxies. Our study of GCs in NGC 247 will ultimately connect with the stellar halo science that is being conducted by the MADCASH survey, by looking at possible links between GCs and stellar halos in dwarf galaxies. The data from HSC for NGC 247 were pipeline reduced at Princeton and broken up into about 80 subsections. Our work for this project then began with a mosaic of 8 central subsections, corresponding to a similar field of view

to CTIO/MOSAIC. There were long exposure images, and short exposure images for the saturated objects, for both the g and i filters.

Figure 3.2: Overview of the HSC field centered on the galaxy NGC 247, with the box showing the CTIO 4m / MOSAIC-II field of view for comparison.

Figure 3.3: Comparison of CTIO Harris R filter image (left) to HSC i band image (right) (FOV is 50×43 arcsec).

Figure 3.2 shows the extremely wide coverage by HSC compared to the CTIO 4m FOV. The wide coverage and the depth that HSC provide (as shown in Figure

3.3) increase the possibility of finding GCs in NGC 247. The median seeing with HSC was 0.6 arcsec compared to ≤ 1 arcsec seeing conditions with the CTIO 4 m telescope, MOSAIC II camera (Olsen et al. 2004).

3.2.1 Data extraction using SExtractor in FITS images

A catalog of objects was generated using SExtractor V2.4.3 and cross-identification was performed by the ASSOC process. Shorter and longer exposure images were analyzed separately because of saturated bright sources in the long exposures. The steps for data extraction and catalog cross-identification are presented in detail in the following sections, because the original documentation for SExtractor is incomplete.

3.2.2 Object Catalogs

The steps followed in order to extract the catalogs of the objects are:

- SExtractor V2.4.3 was downloaded and installed. Along with it comes important files namely **default.sex** (configuration file - SExtractor default input parameters used), **basic.param** (requested output parameters file), and **.conv** (conversion file) which are required to produce the catalogs.
- The **default.sex** file was renamed to **N247g.sex** and modified, and a name for the output catalog was specified. See Figure 3.4.

```

1 # SExtractor configuration file for N247_ctr_g.fits.
2 #
3
4 #----- Catalog -----
5
6 CATALOG_NAME      N247_ctr_g.cat  # name of the output catalog
7 #CATALOG_NAME      STDOUT          # name of the output catalog
8 CATALOG_TYPE      ASCII_HEAD      # NONE,ASCII,ASCII_HEAD, ASCII_SKYCAT,
9                                     # ASCII_VOTABLE, FITS_1.0 or FITS_LDAC
10 PARAMETERS_NAME   basic.param     # name of the file containing catalog contents
11
12 #----- Extraction -----
13
14 DETECT_TYPE        CCD             # CCD (linear) or PHOTO (with gamma correction)
15 DETECT_MINAREA     3               # min. # of pixels above threshold
16 DETECT_THRESH      3               # <sigmas> or <threshold>,<ZP> in mag.arcsec-2
17 ANALYSIS_THRESH    3               # <sigmas> or <threshold>,<ZP> in mag.arcsec-2
18
19 FILTER             Y               # apply filter for detection (Y or N)?
20 FILTER_NAME        gauss_4.0_7x7.conv # name of the file containing the filter
21

```

Figure 3.4: A screenshot of the N247g.sex file which includes the output catalog name and the parameter file name.

- The basic.param file was modified to print out the output parameters
NUMBER, X_IMAGE, Y_IMAGE, ALPHA_J2000, DELTA_J2000, EXT_NUMBER,
MAG_AUTO, and FWHM_WORLD as shown in Figure 3.5.

1	NUMBER	Running object number	
2	X_IMAGE	Object position along x	[pixel]
3	Y_IMAGE	Object position along y	[pixel]
4	ALPHA_J2000	Right ascension of barycenter (J2000)	[deg]
5	DELTA_J2000	Declination of barycenter (J2000)	[deg]
6	EXT_NUMBER	FITS extension number	
7	#FLUX_ISO	Isophotal flux	[count]
8	#FLUXERR_ISO	RMS error for isophotal flux	[count]
9	#MAG_ISO	Isophotal magnitude	[mag]
10	#MAGERR_ISO	RMS error for isophotal magnitude	[mag]
11	#FLUX_ISOCOR	Corrected isophotal flux	[count]
12	#FLUXERR_ISOCOR	RMS error for corrected isophotal flux	[count]
13	#MAG_ISOCOR	Corrected isophotal magnitude	[mag]
14	#MAGERR_ISOCOR	RMS error for corrected isophotal magnitude	[mag]
15	#FLUX_APER	Flux vector within fixed circular aperture(s)	[count]
16	#FLUXERR_APER	RMS error vector for aperture flux(es)	[count]
17	#MAG_APER[4]	# Fixed aperture magnitude vector	[mag]
18	#MAGERR_APER	RMS error vector for fixed aperture mag.	[mag]
19	#FLUX_AUTO	Flux within a Kron-like elliptical aperture	[count]
20	#FLUXERR_AUTO	RMS error for AUTO flux	[count]
21	MAG_AUTO	Kron-like elliptical aperture magnitude	[mag]
22	#MAGERR_AUTO	RMS error for AUTO magnitude	[mag]
23	#FLUX_PETRO	Flux within a Petrosian-like elliptical aperture	[count]
24	#FLUXERR_PETRO	RMS error for PETROsian flux	[count]
25	#MAG_PETRO	Petrosian-like elliptical aperture magnitude	[mag]
26	#MAGERR_PETRO	RMS error for PETROsian magnitude	[mag]
27	#FLUX_BEST	Best of FLUX_AUTO and FLUX_ISOCOR	[count]
28	#FLUXERR_BEST	RMS error for BEST flux	[count]

Figure 3.5: A screenshot of the `basic.param` file with the required output parameters uncommented. At times, it requires that you comment the description, as seen in line 17 of the screenshot.

- The catalogs for g and i filter images are generated using the command
`sex -c N247g.sex N247g.fits '[1]'` and
`sex -c N247i.sex N247i.fits '[1]'` respectively. [1] implies the file extension number.
- The respective g and i filter catalogs are created as given by `CATALOG_NAME` in Figure 3.4. `N247_ctr_g.cat` contains the extracted objects' specified parameters of the g filter image as shown in Figure 3.6. The number of objects extracted from g and i filter long exposure images were 120,000 and 92,000 respectively and 12,000 for the g and i band short exposure images.

1 #	1 NUMBER	Running object number								
2 #	2 X_IMAGE	Object position along x								[pixel]
3 #	3 Y_IMAGE	Object position along y								[pixel]
4 #	4 ALPHA_J2000	Right ascension of barycenter (J2000)								[deg]
5 #	5 DELTA_J2000	Declination of barycenter (J2000)								[deg]
6 #	6 EXT_NUMBER	FITS extension number								
7 #	7 MAG_BEST	Best of MAG_AUTO and MAG_ISOCOR								[mag]
8 #	8 FWHM_WORLD	FWHM assuming a gaussian core								[deg]
9	1	2605.4888	2.5062	11.8739288	-21.1566705	1	29.7369	0.0001515749		
10	2	178.2211	1.9864	11.9953847	-21.1565981	1	29.3845	0.0002641971		
11	3	1178.9602	1.9897	11.9453098	-21.1566483	1	28.0910	0.0004187014		
12	4	1726.0133	2.2889	11.9179362	-21.1566556	1	29.5217	0.000220702		
13	5	7984.0225	1.9760	11.6047964	-21.1566007	1	29.0664	0.0002468969		
14	6	6010.4019	3.2011	11.7035526	-21.1566277	1	29.5224	0.0001787341		
15	7	6398.5444	2.8848	11.6841306	-21.1566304	1	29.1560	0.0002524694		
16	8	1067.9962	4.0130	11.9508621	-21.1565490	1	29.2441	0.0002150423		
17	9	7230.0029	6.5070	11.6425262	-21.1564282	1	29.2719	0.00019469		
18	10	5032.7622	2.1225	11.7524720	-21.1566984	1	28.9799	0.0002922033		
19	11	5077.8706	2.3857	11.7502148	-21.1566855	1	29.2747	0.0001862571		
20	12	7924.0205	4.7148	11.6077989	-21.1564763	1	29.5842	0.0001786746		
21	13	2276.5222	3.2652	11.8903897	-21.1566271	1	29.1807	0.0001927932		
22	14	2963.4990	3.4332	11.8560146	-21.1566342	1	28.7993	0.0002066599		
23	15	3635.0984	3.3436	11.8224088	-21.1566463	1	29.4293	0.000250155		
24	16	609.5075	4.2764	11.9738039	-21.1565147	1	29.1844	0.0002021439		
25	17	5779.1597	6.8370	11.7151236	-21.1564641	1	29.3081	0.0001476642		
26	18	7564.4961	7.0213	11.6257889	-21.1563880	1	29.3975	0.0001860857		
27	19	1829.7231	2.5497	11.9127468	-21.1566470	1	28.2264	0.0002959725		
28	20	2634.0200	3.0298	11.8725011	-21.1566467	1	29.1158	0.0001772306		

Figure 3.6: A screenshot of the N247_ctr_g.cat with the values for the requested output parameters.

3.2.3 Cross-identification within SExtractor

SExtractor performs automated cross-identification of each detection with an ASCII list. It works in pixel coordinates only. Configuration parameters related to cross-identification are prefixed with ASSOC. After deriving the catalogs of objects for the *g* and *i* band images separately, the objects in the catalogs are cross identified using the ASSOC process. In order to do that, the `.sex` file was modified to reflect the association parameters.

```

52 #----- Background -----
53
54 BACK_SIZE      50,50      # Background mesh: <size> or <width>,<height>
55 BACK_FILTERSIZE 3,3      # Background filter: <size> or <width>,<height>
56
57 BACKPHOTO_TYPE GLOBAL    # can be GLOBAL or LOCAL
58
59 #----- Check Image -----
60
61 #CHECKIMAGE_TYPE OBJECTS      # can be NONE, BACKGROUND, BACKGROUND_RMS,
62                                # MINIBACKGROUND, MINIBACK_RMS, -BACKGROUND,
63                                # FILTERED, OBJECTS, -OBJECTS, SEGMENTATION,
64                                # or APERTURES
65 #CHECKIMAGE_NAME VCC1287_i_mask.fits # Filename for the check-image
66
67 #----- Memory (change with caution!) -----
68
69 MEMORY_OBJSTACK 3000      # number of objects in stack
70 MEMORY_PIXSTACK 300000    # number of pixels in stack
71 MEMORY_BUFSIZE  1024      # number of lines in buffer
72
73 #----- ASSOCiation -----
74
75 ASSOC_NAME      N247_ctr_i.cat # name of the ASCII file to ASSOCIate
76 ASSOC_DATA      0             # columns of the data to replicate (0=all)
77 ASSOC_PARAMS     2,3,7        # columns of xpos,ypos[,mag]
78 ASSOC_RADIUS     2.0          # cross-matching radius (pixels)
79 ASSOC_TYPE       MAG_MEAN     # ASSOCIation method: FIRST, NEAREST, MEAN,
80                                # MAG_MEAN, SUM, MAG_SUM, MIN or MAX
81 ASSOCSELEC_TYPE  MATCHED      # ASSOC selection type: ALL, MATCHED or -MATCHED
82
83
84 #----- Miscellaneous -----
85
86 VERBOSE_TYPE     NORMAL      # can be QUIET, NORMAL or FULL
87 #HEADER_SUFFIX   .head       # Filename extension for additional headers
88 WRITE_XML        N           # Write XML file (Y/N)?
89 XML_NAME         sex.xml      # Filename for XML output
90

```

Figure 3.7: A screenshot of the `assoc .sex` file with the ASSOCIation portion modified.

The various parameters needed for the cross-identification process are shown in Figure 3.7. Since cross-identification works in pixel coordinates, it required that we specify the columns that contain the X and Y coordinates in the ASSOC list (in this example, it was the catalog generated with the *i*-filter image, if we use the *g*-band image to run it) in the ASSOC_PARAMS. The name of the catalog generated using the *i* filter image is given in ASSOC_NAME. With the matching done, the information from the matching are propagated to the output catalog specified in

.sex file. The .param or the parameter file was modified to extract information about all the parameters of the matched catalog. The output of ASSOC data in the SExtractor was done through the VECTOR_ASSOC() parameter as shown in Figure 3.8. The number within the brackets indicates the total number of columns from the *g* and *i* band catalogs that were being matched.

185 #FLAGS	Extraction flags	
186 #FLAGS_WEIGHT	Weighted extraction flags	
187 #FLAGS_WIN	Flags for WINDOWed parameters	
188 #IMAFLAGS_ISO	FLAG-image flags OR'ed over the iso. profile	
189 #NIMAFLAGS_ISO	Number of flagged pixels entering IMAFLAGS_ISO	
190 #NLOWWEIGHT_ISO	Nb of pixels with low weight over the iso. profile	
191 #NLOWDWEIGHT_ISO	Nb of pixels with low det. weight over the iso. profile	
192 #FWHM_IMAGE	FWHM assuming a gaussian core	[pixel]
193 FWHM_WORLD	FWHM assuming a gaussian core	[deg]
194 #ELONGATION	A_IMAGE/B_IMAGE	
195 #ELLIPICITY	1 - B_IMAGE/A_IMAGE	
196 #POLAR_IMAGE	$(A_IMAGE^2 - B_IMAGE^2)/(A_IMAGE^2 + B_IMAGE^2)$	
197 #POLAR_WORLD	$(A_WORLD^2 - B_WORLD^2)/(A_WORLD^2 + B_WORLD^2)$	
198 #POLARWIN_IMAGE	$(AWIN^2 - BWIN^2)/(AWIN^2 + BWIN^2)$	
199 #POLARWIN_WORLD	$(AWIN^2 - BWIN^2)/(AWIN^2 + BWIN^2)$	
200 #CLASS_STAR	S/G classifier output	
201 #VIGNET	Pixel data around detection	[count]
202 #VIGNET_SHIFT	Pixel data around detection, corrected for shift	[count]
203 VECTOR_ASSOC(17)	#ASSOCIated parameter vector	
204 NUMBER_ASSOC	Number of ASSOCIated IDs	
205 #THRESHOLDMAX	Maximum threshold possible for detection	[count]
206 #FLUX_GROWTH	Cumulated growth-curve	[count]
207 #FLUX_GROWTHSTEP	Step for growth-curves	[pixel]
208 #MAG_GROWTH	Cumulated magnitude growth-curve	[mag]
209 #MAG_GROWTHSTEP	Step for growth-curves	[pixel]
210 #FLUX_RADIUS	Fraction-of-light radii	[pixel]
211 #XPSF_IMAGE	X coordinate from PSF-fitting	[pixel]
212 #YPSF_IMAGE	Y coordinate from PSF-fitting	[pixel]
213 #XPSF_WORLD	PSF position along world x axis	[deg]
214 #YPSF_WORLD	PSF position along world y axis	[deg]

Figure 3.8: A screenshot of the assoc .param with the modified VECTOR_ASSOC in line 203.

The output ASSOC catalog was generated as shown in Figure 3.9 using the command

```
sex -c assoc_N247g.sex N247g.fits'[1]'
```

The output catalog has 17 columns as specified by the VECTOR_ASSOC(). From the cross-identification process, the number of objects decreased from 120,000 objects to 60,000 objects for the long exposure images, and from 12,000 objects to 6,000 objects for the short exposure images. The reduction in the number of sources from the long exposure image catalogs was primarily caused by fewer sources in the *i*

seeing of 0.6 arcsec with HSC also increased the photometric depth.

Index	X	Y	Area	Ell	Flux_T1	Flux_M	Flux_C	merr_T1	merr_M	merr_C	Flag	SI	C	M	T1	sigC	sigM	sigT1
1	95	3159.751	13.645	70.0	0.138	6.31495E+03	1.37448E+03	5.80139E+02	0.0381	0.0561	0.0665	0	0.06	24.1972	24.1546	22.8242	0.0665	0.0561
2	100	4282.312	11.373	99.0	0.175	1.32169E+04	5.24124E+03	6.09247E+02	0.0174	0.0233	0.0628	0	0.04	24.3532	22.8937	22.0413	0.0628	0.0233
3	132	2458.440	19.781	42.0	0.483	2.86311E+03	1.07433E+03	2.31107E+02	0.0509	0.0643	0.1048	0	0.03	25.3058	24.5226	23.6880	0.1048	0.0643
4	133	1891.287	26.513	37.0	0.110	3.89154E+03	1.84880E+03	3.39911E+02	0.0368	0.0465	0.0901	0	0.40	24.9124	23.9556	23.3536	0.0901	0.0465
5	134	4760.977	27.649	36.0	0.163	2.18990E+03	3.06085E+02	2.32337E+02	0.0607	0.1463	0.1114	0	0.27	25.0955	25.6980	23.9591	0.1114	0.1463
6	148	2146.951	34.989	24.0	0.163	1.44716E+03	1.86526E+03	6.64783E+02	0.0750	0.0491	0.0692	0	0.92	24.0768	23.8483	24.3897	0.0692	0.0491
7	160	4735.795	29.995	39.0	0.108	3.85482E+03	5.91498E+02	1.51103E+02	0.0371	0.0926	0.1416	0	0.93	25.7393	25.1449	23.3801	0.1416	0.0926
8	172	4116.556	12.464	205.0	0.195	3.96971E+04	8.45988E+03	2.01732E+03	0.0090	0.0183	0.0330	0	0.03	22.9367	22.2667	20.8428	0.0330	0.0183
9	178	4375.840	32.882	28.0	0.327	2.01742E+03	3.94527E+02	2.41676E+02	0.0604	0.1102	0.1139	0	0.92	25.0875	25.4541	24.0562	0.1139	0.1102
10	185	1856.430	30.815	30.0	0.202	1.95147E+03	8.75753E+02	1.75389E+02	0.0679	0.0780	0.1342	0	0.54	25.6170	24.7552	24.1021	0.1342	0.0780
11	188	5931.809	36.218	27.0	0.234	2.18538E+03	9.33533E+02	6.76587E+01	0.0542	0.0680	0.2499	0	0.87	26.8160	24.8374	24.0054	0.2499	0.0680
12	206	5127.966	47.139	19.0	0.300	1.41732E+03	9.76080E+02	3.56447E+02	0.0687	0.0740	0.0918	2	0.94	24.7495	24.5478	24.4252	0.0918	0.0740
13	210	4024.487	40.660	39.0	0.123	2.95988E+03	7.80321E+02	3.36148E+02	0.0472	0.0821	0.0910	0	0.20	24.7864	24.7662	23.6423	0.0910	0.0821
14	258	5803.279	40.647	41.0	0.305	3.88094E+03	1.03572E+03	5.72719E+02	0.0408	0.0722	0.0752	0	0.18	24.1674	24.4215	23.3417	0.0752	0.0722
15	286	6133.832	36.781	103.0	0.126	1.79361E+04	4.86842E+03	2.56801E+03	0.0135	0.0231	0.0259	0	0.16	22.5459	22.7482	21.6805	0.0259	0.0231
16	287	1233.846	43.992	40.0	0.209	3.20470E+03	2.57140E+02	1.30005E+02	0.0467	0.1495	0.1467	0	0.18	25.7919	25.9475	23.5777	0.1467	0.1495
17	290	4283.185	48.956	19.0	0.558	1.13198E+03	4.25337E+02	2.09516E+02	0.0893	0.1027	0.1184	2	0.55	25.2773	25.4049	24.6749	0.1184	0.1027
18	299	4285.230	51.976	15.0	0.250	1.03645E+03	4.25337E+02	2.09516E+02	0.0857	0.1027	0.1184	2	0.78	25.2773	25.4049	24.7688	0.1184	0.1027
19	310	657.921	47.174	36.0	0.501	2.16502E+03	3.43737E+02	1.38496E+02	0.0660	0.1255	0.1533	0	0.01	25.7600	25.6662	23.9944	0.1533	0.1255
20	345	2330.293	29.587	221.0	0.236	4.17270E+04	1.15922E+04	1.75222E+03	0.0090	0.0150	0.0368	0	0.03	23.1636	21.9927	20.7943	0.0368	0.0150
21	346	5378.296	44.996	64.0	0.131	6.04054E+03	2.00274E+03	7.31173E+02	0.0321	0.0473	0.0652	0	0.03	23.9695	23.7675	22.8670	0.0652	0.0473
22	377	3243.921	39.578	55.0	0.301	3.64182E+03	4.20105E+02	2.94085E+02	0.0493	0.1083	0.1003	2	0.01	24.8528	25.3608	23.4230	0.1003	0.1083
23	378	6118.454	60.940	26.0	0.146	1.67885E+03	3.52164E+02	1.58928E+02	0.0675	0.1112	0.1292	0	0.26	25.5922	25.6238	24.2618	0.1292	0.1112
24	380	865.337	66.142	22.0	0.337	1.41628E+03	6.38651E+02	5.05748E+02	0.0736	0.0930	0.0783	2	0.94	24.2441	24.8928	24.4161	0.0783	0.0930
25	397	5810.902	63.113	19.0	0.413	1.45065E+03	3.77982E+02	2.78161E+02	0.0669	0.1095	0.1055	0	0.71	24.9051	25.4733	24.3977	0.1055	0.1095
26	407	5169.207	67.265	19.0	0.150	1.29231E+03	7.23400E+02	5.36550E+02	0.0769	0.0788	0.0723	0	0.80	24.1906	24.7673	24.5124	0.0723	0.0788
27	425	1928.152	39.826	124.0	0.415	1.16930E+04	5.41608E+03	7.70037E+02	0.0216	0.0282	0.0617	0	0.02	24.0663	22.8208	22.1660	0.0617	0.0282
28	426	4373.895	44.651	102.0	0.426	1.09092E+04	1.77625E+03	2.97682E+02	0.0213	0.0504	0.1015	0	0.03	25.0715	24.0139	22.2598	0.1015	0.0504
29	427	3095.304	55.651	60.0	0.206	5.35819E+03	1.70506E+03	2.52213E+02	0.0331	0.0490	0.1066	0	0.16	25.2717	24.0770	23.0204	0.1066	0.0490
30	428	5079.980	52.563	79.0	0.186	1.03662E+04	4.12151E+03	1.79648E+03	0.0200	0.0293	0.0347	0	0.12	22.9648	22.9574	22.2723	0.0347	0.0293
31	429	4630.603	56.870	63.0	0.276	5.53677E+03	1.68209E+03	3.18549E+02	0.0347	0.0508	0.0934	0	0.55	24.9781	24.0548	22.9797	0.0934	0.0508
32	434	5337.468	72.433	15.0	0.316	7.68640E+02	1.24611E+03	2.11591E+02	0.1110	0.0606	0.1174	0	0.40	25.4400	24.3968	25.0901	0.1174	0.0606
33	440	1926.182	66.371	38.0	0.278	2.97649E+03	1.00861E+03	6.16481E+02	0.0464	0.0683	0.0647	0	0.46	24.0712	24.4353	23.6222	0.0647	0.0683
34	444	727.739	66.617	29.0	0.118	1.71627E+03	7.54224E+02	2.63525E+02	0.0717	0.0738	0.0965	0	0.13	25.0846	24.8343	24.2282	0.0965	0.0738
35	451	4452.950	34.815	244.0	0.171	5.24794E+04	1.91816E+04	5.42601E+03	0.0073	0.0106	0.0177	0	0.03	21.8348	21.3524	20.5239	0.0177	0.0106
36	465	2215.645	73.310	10.0	0.505	1.06500E+03	6.78148E+02	6.05221E+02	0.0904	0.0858	0.0723	2	0.56	24.0298	24.8099	24.7151	0.0723	0.0858
37	470	2953.950	47.680	84.0	0.151	7.23717E+03	2.58064E+03	8.51516E+02	0.0301	0.0364	0.0574	0	0.03	23.8205	23.5073	22.6717	0.0574	0.0364

Figure 3.10: A screenshot of the CTIO catalog with magnitudes from the Washington C , M and Harris R filters.

3.4 Catalog from *Spitzer* imaging

In addition to the five filters (Washington CM , Harris R and SDSS g,i), we extracted the catalog for a *Spitzer Space Telescope* image in the $3.6 \mu\text{m}$ band using SExtractor.

A total of 6 filters were combined to produce various color–magnitude, color–size, and color–color plots to hunt for new GCs.

Figure 3.11: Subsection of the HSC field, showing part of the resolved outer disk of the galaxy NGC 247 (6×3 arcmin $\sim 6 \times 3.5$ kpc in size). One spectroscopically confirmed GC is marked at lower left and a new candidate at upper right.

3.5 Methods used to correct and match catalogs

In this section, we present various methods used for correcting and matching the catalogs before GC selection using color, magnitude, and size of the objects was made.

3.5.1 Coordinate calibration between the HSC and CTIO images

In order to construct a good GC selection region, we needed to combine the HSC data (SDSS g,i filters) with the CTIO (Washington C and M , Harris R filters) data from (Olsen et al. 2004). However, to start combining data from Olsen et al. (2004), we had to first take out the large offset in the coordinates (World Coordinate System (WCS)) between the two images. The Olsen et al. (2004) catalog contained only the objects' pixel coordinates along with the corresponding magnitudes from the 3 filters (C, M , and R).

The software Image Reduction and Analysis Facility (IRAF) was used to do the coordinate matching between the images. IRAF is a software system for reduction and analysis of astronomical data and is supported by National Optical Astronomy Observatories (NOAO). SAOImage DS9, an image display tool, is a package that is included with IRAF.

The steps followed for matching the coordinates of the HSC and CTIO images were:

- (1) We selected point sources/stars that were not saturated from one of the CTIO filter images (for example the Harris R filter image) through DS9, and created a regions file. From IRAF, the R filter image was again opened through DS9 and the regions file was uploaded. Using the command `imexamine` or `imexam`, the point sources were verified by looking at their radial and surface plots. An example of one of the confirmed stars' (Olsen et al. 2004) radial and surface plots are shown in Figures 3.12 and 3.13 respectively. Once the radial and surface plots are verified using `imexam`, the unsaturated stars' pixel coordinates X and Y (in pixels) were added into a file. The stars selected in the R filter image were identified in one of the g or i band HSC images, and their RA and DEC (in dd:mm:ss) were noted. A text/data file, for example `stars.dat`, was created having lines with pixel coordinates (X and Y from R filter image) and matching celestial coordinates (RA and DEC from HSC image).

Figure 3.12: The radial intensity profile of a spectroscopically confirmed star (*STAR_38*), showing a good fit to a Gaussian curve.

Figure 3.13: The surface plot of *STAR_38* shows a pointy peak against the background noise, indicative of no saturation.

- (2) Next, we used the tool `ccmap` from IRAF to see how good our star selection or solution was. The command was run from the IRAF command line as follows:

```
ccmap input='stars.dat' database='output.db'
solution='ngc247R.fits'
```

The Harris *R* filter image from which unsaturated stars were selected was used to run the above command. An interactive map opened up as shown in Figure 3.14, and the solution was verified to be good by looking at the residuals in the two directions of the map. The points can even be rejected to attain a better solution. The result of this process was a database file

named `output.db` containing the mathematical coordinate transformation, which will be used later.

Figure 3.14: The interactive map containing the astrometric solutions to the `stars.dat` file we created. The residuals are 0.0039 arcsec and 0.00288 arcsec in the two directions.

- (3) To apply the coordinate transformation to the CTIO *R* filter image, the following command in IRAF was run:

```
ccsetwcs ngc247R.fits output.db ngc247R_new.fits
```

`output.db` is the database created in the above step. To check that the transformation was done successfully, we opened both the images (CTIO *R* filter, and HSC *g* or *i*) in 2 frames in DS9 and looked at various objects to see if the coordinates matched using the *match frames* option of DS9. The

above processes were repeated for the Washington C and M filter images to match them up to the HSC g and i images.

- (4) Now that the coordinates of the CTIO and HSC images are matched, we moved on to the next step of converting the pixel coordinates of the objects in the Olsen et al. (2004) catalog to celestial coordinates (in degrees) using the computed plate solution in step (2) (`output.db`). This step was essential, as the catalogs created by SExtractor for the HSC images contained RA and DEC in degrees. A data file with only the pixel coordinates extracted from the Olsen et al. (2004) catalog was created (`olsen_pixel.dat`). This transformation was done by using the IRAF command `cctran`. The `cctran` was used by using the `epar` (edit parameters) approach this time. The snapshot of the parameters of `cctran` is shown in Figure 3.15.

I R A F

Image Reduction and Analysis Facility

```

PACKAGE = imcoords
TASK = cctran

input = 1 olsen_pixel.dat The input coordinate files
output = olsen_deg.dat The output coordinate files
database= output.db The input database file
solution= ngc247R.fits The input plate solutions
(geometr= geometric) Transformation type (linear,geometric)
(forward= yes) Transform x / y to ra / dec (yes) or vice versa (no) ?
(xref = INDEF) The X reference pixel
(yref = INDEF) The Y reference pixel
(xmag = INDEF) The X axis scale in arcsec per pixel
(ymag = INDEF) The Y axis scale in arcsec per pixel
(xrotati= INDEF) The X axis rotation angle in degrees
(yrotati= INDEF) The Y axis rotation angle in degrees
(lngref = INDEF) The ra / longitude reference coordinate in lngunits
(latref = INDEF) The dec / latitude reference coordinate in latunits
(lngunit= degrees) The input / output ra / longitude reference coordinate units
(latunit= degrees) The input / output dec / latitude reference coordinate units
(project= tan) The sky projection geometry
(xcolumn= 1) Input column containing the x / ra / longitude coordinate
(ycolumn= 2) Input column containing the y / dec / latitude coordinate
(lngform= %.6f) Output format of the ra / longitude / x coordinate
(latform= %.6f) Output format of the dec / latitude / y coordinate
(min_sig= 7) Minimum precision of the output coordinates
(mode = ql)

```

ESC-? for HELP

Figure 3.15: The parameters of `cctran` are shown in this snapshot. The input file contains the data file we created of Olsen’s objects’ coordinates in pixels (`olsen_pixel.dat`). The output file was generated with the coordinates converted to degrees `olsen_deg.dat`, and the `lngform` and `latform` were modified to display the converted decimal coordinates up to six decimal places.

- (5) The `olsen_deg.dat` data file contains RA and DEC (in degrees) for the corresponding pixel coordinates of the Olsen et al. (2004) catalog. The two catalogs were merged to a final catalog `olsen_cmt.dat`. The final catalog contains RA and DEC (in degrees) and magnitudes using the Washington *C* and *M* and Harris *R* filters. This catalog will be used for matching and further analysis.

3.5.2 Catalog Matching

The ASSOC process for cross-identification of objects could only be used within catalogs generated by SExtractor. Hence, a different approach was

implemented to combine the new catalog `olsen_cmt.dat` created in the above section with the HSC catalog. The ASSOC catalog (containing g and i magnitudes) created by SExtractor for the HSC images were matched with the new catalog (`olsen_cmt.dat` - containing C , M , R magnitudes) by a package named `astropy` in python. `astropy.coordinates` contains commonly used tools for comparing or matching coordinate objects. Of particular importance were those for determining separations between coordinates and those for matching a coordinate (or coordinates) to a catalog. These were mainly implemented as methods on the coordinate objects.

Now that the HSC catalogs and the new catalog (`olsen_cmt.dat`) have RA and DEC in degrees, the RA and DEC of the 2 catalogs were matched using a matching radius of 0.5 arcsec. The number of objects after matching ASSOC catalogs of HSC and the new catalog were reduced to ~ 8000 objects. The reduction was due to fewer objects in the Olsen et al. (2004) catalog. A sample python code to do the matching is shown below.

```
from astropy.coordinates import match_coordinates_sky
from astropy.coordinates import SkyCoord
from pylab import *

#Read ASSOC catalog created from HSC images (g and i bands)
#Read Olsen catalog (C,M,T bands)

##### Matching Catalogs #####

## Function by Aaron Deich, SJSU/UCSC 2015

def match_coordinates(ra_hsc,dec_hsc,ra_olsen,dec_olsen):
    matchcoord = SkyCoord(ra=ra_hsc*u.degree,dec=dec_hsc*u.degree)
    catalogcoord = SkyCoord(ra=ra_olsen*u.degree,dec=dec_olsen*u.degree)
```

```

idx, sep2d, dist3d = match_coordinates_sky(matchcoord, catalogcoord)
return idx, sep2d

idx_2, sep2d_12 = match_coordinates(ra_hsc, dec_hsc, ra_olsen, dec_olsen)
sep2d_12 = sep2d_12.to(u.arcsec)
idx_hsc_good = where(sep2d_12 < 0.5 * u.arcsec)

```

3.5.3 Zero-point corrections

We needed the g and i bands' zero-point adjustments to perform analysis using color, magnitude, and size plots. Zero-point correction was computed by comparing the instrumental magnitudes of point source objects such as stars extracted through the SExtractor to the calibrated magnitudes published in MADCASH survey. There were different methods employed to get the zero-point corrections. The calibrated magnitudes used the aperture photometry. So, the **MAG_APER** photometry of the SExtractor was used to get the instrumental aperture magnitudes. The aperture sizes were mentioned in **PHOT_APERTURES** in the corresponding photometry section of the **.sex** file. The aperture diameters used were from 4 pixels to 20 pixels. We looked at the thin horizontal stretch shown in Figure 3.16 where point sources (stars) belong. As aperture size was increased, the offset stabilized to a more constant value. The zero-points were derived for both the g and i long exposure images.

Figure 3.16: Plot of g -calibrated magnitude ($m_g(\text{cali})$), and the difference between the g -instrumental (aperture size 20 pixels - ($m_{g20}(\text{instr})$)) and g -calibrated magnitude done for objects in the HSC long-exposure image.

From the Figure 3.16, the offset for the g and i magnitudes' long exposure images was determined to be 3.0 [mag]. This offset was then subtracted from the instrumental magnitudes generated in the ASSOC catalog produced by SExtractor for further analysis.

3.5.4 Short-exposure images

Since some objects are saturated in the long exposure image, the short exposure images were analyzed for those objects. There was an additional

magnitude correction that was done other than the zero-point corrections. Catalog of objects in the short exposure g and i bands were made using the SExtractor, as mentioned in Chapter 3. Then, the short-exposure catalogs were matched to the long exposure g and i band catalogs using the match coordinates of the astropy package, as mentioned in Section 4.2. The difference in the magnitudes between the matched long and short exposure catalogs was computed and the median was found. The g -magnitude and i -magnitude medians were found to be 3.60 and 3.49 respectively. These corrections were added to the g and i magnitudes in the short-exposure catalogs, in addition to the zero-point offset that was previously calculated.

CHAPTER 4

GLOBAL CLUSTER SELECTION METHODS

Here, various methods are developed to select GC candidates by constructing color–magnitude, color–color, and magnitude–FWHM plots. The GC selection was defined by using the magnitudes, colors, and sizes of the spectroscopically-confirmed GCs in NGC 247 from Olsen et al. (2004). During the course of the research, there was an ultra-compact dwarf (UCD) discovered by Romanowsky et.al., which will be marked in all of our plots. UCDs are recently discovered compact stellar systems that are typically more luminous and larger in spatial extent than GCs (Brodie et al. 2011).

4.1 Size – Magnitude plot

In nearly all cases, the GCs have a more extended spatial distribution than the galaxy field stars (Brodie & Strader 2006). A plot of the FWHM (apparent size of an object) in the g band versus g band magnitude (m_g) for all the sources in the long exposure was made. Therefore, it was important to find parameters that can be used in plots to differentiate the stars from the GCs.

Figure 4.1: Full-width half maximum in g band ($FWHM_g$) vs g -band magnitude (m_g) diagnostic plot from the long-exposure image, with colored symbols marking spectroscopically-confirmed objects.

From Figure 4.1, we can see that with the 0.6-arcsec seeing of HSC, most stars, GCs, and galaxies can be differentiated based on their apparent sizes. The stellar sequence is visible at around ~ 0.6 arcsec. The GCs seem to fall close to the star sequence, and it is hard to make a clear differentiation between the stars and GCs from this plot. However, there is a better distinction of galaxies which can be eliminated from the analysis. Since all of the confirmed GCs have a $FWHM < 1.0$, only objects with $FWHM < 1.0$ were used for further analysis. The cut-off for m_g was ~ 19 , below which the objects are saturated. The saturated objects in the long exposure images are examined in the short exposure images separately.

4.2 Color–Magnitude Diagrams

The Hertzsprung–Russell (HR) diagram which is commonly used to study the temperatures and magnitudes of individual stars is a variant of the color–magnitude

diagram (CMD). The magnitude of a star is related to the log of flux. Color is the difference between the magnitudes for a given source in two different filter bands. Hence, color is related to the ratio of the fluxes. Searches for GCs using broadband colors are necessarily statistical in nature due to the significant interloping Milky Way stars and distant galaxies (Durrell et al. 2014). The color in our research was obtained by subtracting the long exposure objects' magnitudes in g band (4680 Å) and i band (7480 Å). We chose the optical $g - i$, because it is well measured for these relatively bright objects and has a long wavelength baseline (di Tullio Zinn & Zinn 2015). The plot with g -magnitude on the vertical axis and color on the horizontal axis is shown in Figure 4.2 and was made with the Durrell et al. (2014) paper as a reference. Only objects with $FWHM_g > 1.0$ were plotted.

Figure 4.2: CMD diagram of sources from the central region around NGC 247 with colored symbols marking spectroscopically-confirmed objects.

In Figure 4.2, the boxed regions are the locations of the (from top left to bottom right) bright MW halo turnoff stars (BTO), faint turn off stars (FTO), the blue globular cluster region (bGC), the adjoining red globular cluster region (rGC), and the red halo star populations (RED). The horizontal dashed line marks the expected location of peak of the GC luminosity function. To select candidate GCs, we made use of specific regions within the g and $g - i$ CMD. Most GCs have $0.55 < (g - i) < 1.15$ (Durrell et al. 2014) and $m_g > 20.6$, which we adopted as our color and magnitude criteria for GC selection. As the range of $(g - i)$ colors is indicative of the range of metallicities of the (assumed old) GCs, the color criterion

is further divided into a blue metal-poor GC population (bGC) and a red metal-rich GC population (rGC) with the dividing color at $m_g = 0.80$ (Durrell et al. 2014). Sections were defined in the $m_g, (g - i)$ CMD as shown in Figure 4.2 to make a clear distinction between the many different populations in the CMD.

- (1) Bright turn off (BTO): $18.5 < m_g < 20$, $0.2 < (g - i) < 0.5$; largely contains BTO stars from the inner Milky Way (MW) halo populations.
- (2) Faint turnoff (FTO): $20 < m_g < 23$, $0.2 < (g - i) < 0.5$; largely contains FTO stars.
- (3) Blue GC (bGC): $20.6 < m_g < 23$, $0.55 < (g - i) < 0.80$; samples the NGC 247 bGC population.
- (4) Red GC: $20.6 < m_g < 23$, $0.80 < (g - i) < 1.15$; samples the NGC 247 rGC population.
- (5) RED: $20 < m_g < 23$, $1.3 < (g - i) < 1.5$; samples both inner halo main-sequence stars and faint MW disk stars.

There are about 83 GC probable candidates within the bGC and rGC, with the $m_g > 20.6$ GC luminosity function cut off. For $m_g \leq 20.6$, we looked at the data of the short exposure image. The short exposure objects overlaid on the long exposure objects for $m_g \leq 20.6$ is shown in Figure 4.3. Only objects with $FWHM_g < 1$ were selected in the short exposure images too. There were probable GC candidates in the short exposure image with $m_g < 20.6$. The combined probable GC candidates from the short and long exposure images that obeyed the CMD ($g - i$ color) selection region were 133.

There was one spectroscopically-confirmed GC (NGC_247_73) that was not within our selection region. This was an interesting candidate, as it was much more

extended than the other 2 confirmed GCs. Since there have been only 3 GCs confirmed in NGC 247, it is unclear where GCs like NGC_247.73 fit in.

Figure 4.3: CMD diagram of sources from the long and short exposure central regions around NGC 247 with colored symbols marking spectroscopically-confirmed objects. The objects marked in gray are from the long exposure image, while the ones marked in purple are from the short exposure image

4.3 Color-Color Diagrams

Investigating astronomical objects by adding more filters provide diagnostic power for classifying objects (Muñoz et al. 2014). Many of the GCs in dwarf galaxies have been found to be blue, consistent with very old ages and low metal abundances (di Tullio Zinn & Zinn 2015). With six different filter bands (g, i from HSC, C, M, T from CTIO, and $3.6 \mu\text{m}$ - infra red from *Spitzer*), many combinations

of color-color plots were made to see if the GC region could be differentiated from the stellar sequence.

Figure 4.4: Color-color diagram using the matched catalog from HSC and CTIO magnitudes.

Figure 4.5: Color-color diagram using only the magnitudes from the CTIO catalog.

Figure 4.6: Color-color diagram using the matched catalog from HSC and *Spitzer* magnitudes.

From the above plots, it is quite hard to differentiate decisively between the GC and the stellar regions. The last plot between HSC and *Spitzer* catalog seems to be doing a better job in differentiating, but still the differentiation is inconclusive.

4.4 Concentration Index

Concentration Index (CI) is the difference in magnitudes from two different aperture sized photometry. This helped in point source selection.

Figure 4.7: Plot of g -band concentration index $\Delta g = g_4 - g_8$ vs the g magnitudes (`MAG_BEST`) for sources in the long exposure. Also included are the confirmed objects.

The Figure 4.7 shows the CI plot for the long exposure image. Aperture photometry (`MAG_APER`) was used in SExtractor to calculate the CI. The aperture sizes chosen were 4 and 8 pixel diameters. Point sources were examined based on the concentration index $\Delta g = g_4 - g_8$ (the difference between the four-pixel and 8-pixel diameter g aperture magnitudes). The stellar sequence at $\Delta g \sim 0.6$ is visible as shown in Figure 4.7. We also made this plot with the short exposure g and i band image data to examine the saturated objects.

Figure 4.8: Plot of g -band CI $\Delta g = g_4 - g_8$ using aperture magnitudes vs the g *BEST* magnitudes (m_g) for sources in the short exposure with the spectroscopically-confirmed objects marked.

The Figures 4.8 and 4.9 show the g and i bands' CI indices using aperture magnitudes (`MAG_APER`) of the short exposure images.

CI for g magnitude was computed by $\Delta g = g_4 - g_8$ and CI for i magnitude was computed by $\Delta i = i_4 - i_8$ (difference between the four-pixel and 8-pixel diameter i aperture magnitudes).

Figure 4.9: Plot of i-band CI using aperture magnitudes $\Delta i = i_4 - i_8$ vs the i magnitudes (m_i) for sources in the short exposure with the spectroscopically-confirmed objects marked.

From the plots above, the GCs seem to be closely following the stellar sequence. It is hard to make a differentiation between the point sources and GCs. However, we could see that at least two of the GCs on the stellar sequence look extended compared to the stars. One of the confirmed GCs is more extended with the $g_4 - g_8$ close to 1 and is closer to the galaxies.

In the next chapter, we analyze few probable GC candidates that fall within the CMD and CI criteria.

CHAPTER 5

ANALYSIS AND RESULTS

To facilitate spectroscopy in the near future and to narrow down our search of GCs visually, some GC candidates were chosen that followed the criteria of both the CMD and CI diagrams.

5.1 GC candidates

GCs have a slightly extended spatial distribution compared to stars, but closely follow the stellar sequence. We used the CI plot of the long exposure g band as shown in Figure 5.1 and randomly selected candidates close to the stellar sequence. There were 14 candidates chosen for further analysis. The candidates' (marked in purple) CI ranged from $0.55 < (g_4 - g_8) < 0.65$ and g magnitudes from $19 < m_g < 21$. The 14 GC candidates' positions (RA and DEC in degrees) and g and i filter magnitudes are shown in Table 5.1. Out of the 14 GC candidates, 4 of them were close to the disk of NGC 247.

Figure 5.1: Plot of g -band concentration index $\Delta g = g_4 - g_8$ vs the g magnitudes (m_g) for sources in the long exposure with the violet points showing probable GCs.

The GC candidates selected using the CI criteria were located on the CMD plot in Figure 4.2. The plot confirmed that all the GC candidates were within the color range for GCs and is shown in Figure 5.2.

Figure 5.2: CMD diagram of sources from the central region around NGC 247 (long exposure) with violet colored symbols marking GC candidates.

The 14 GC candidates' positions and magnitudes are shown in Table 5.1.

They are named as NGC_247_1P, with 1P indicating the first probable GC candidate.

Table 5.1: List of GC candidates and their g and i band magnitudes

GC candidates				
	RA-J2000 (deg)	DEC-J2000 (deg)	g -mag	i -mag
NGC_247_1P	11.85026	−21.06753	19.80	18.72
NGC_247_2P	11.90455	−20.76728	20.54	19.42
NGC_247_3P	11.72100	−20.74223	19.97	19.02
NGC_247_4P	11.81935	−20.69915	20.94	19.95
NGC_247_5P	11.72753	−20.69151	20.72	20.10
NGC_247_6P	11.97651	−20.67356	21.50	20.81
NGC_247_7P	11.76337	−20.57399	21.74	21.12
NGC_247_8P	11.70917	−20.56848	19.46	18.55
NGC_247_9P	11.59859	−20.53546	19.27	18.71
NGC_247_10P	11.79105	−20.50526	20.47	19.70
NGC_247_11P	11.64965	−20.49027	19.76	18.61
NGC_247_12P	11.75808	−20.45682	19.38	18.72
NGC_247_13P	11.65397	−20.44870	19.26	18.56
NGC_247_14P	11.83761	−20.43769	21.44	20.56

5.2 Visual Inspection of GC candidates

The 14 GC candidates were visually inspected using DS9 in the g -band long exposure image. The thumbnail images of all of the candidates are shown in Figures 5.3 and 5.4. Most of the GC candidates appear round and slightly extended (resolved). Spectroscopy is needed to confirm the GC candidates.

Figure 5.3: 1st 12 GC candidates from our selection (size of thumbnail ~ 10.5 arcsec ~ 180 pc).

Figure 5.4: GC candidates 13 and 14 (size of thumbnail ~ 10.5 arcsec ~ 180 pc).

We also looked at some of the candidates in the Hubble Legacy Archive (HLA) designed to optimize science from the *Hubble Space Telescope* and were able to locate a few of our GC candidates as shown in Figure 5.5. The observation was based on GC selection from the short exposure HSC images, which include more objects in the disk.

Figure 5.5: Three GC candidates observed in the Hubble Legacy Archive (HLA).

5.3 Elimination of candidates classified as GCs

We visually inspected GC candidates from Olsen et al. (2004) that either had a weak or no spectrum. We were able to eliminate several objects classified as GC

candidates. This elimination was possible due to the deep imaging, with 0.6 arcsec seeing of the HSC. Table 5.2 shows the magnitudes of the confirmed GCs and one of the GCs (NGC_247_64) is shown in Figure 3.11. Figure 5.6 shows the thumbnails of objects originally classified as GC candidates and Table 5.3 tells about their spectroscopy results. From the images, the candidates look extended like galaxies in the HSC image. Table 5.2 shows the SDSS g and i , Washington C and M , and Harris R magnitudes of the three spectroscopically-confirmed GCs.

Table 5.2: Spectroscopically-confirmed GCs and their 5 filters' magnitudes

	RA(J2000)	DEC(J2000)	m_g	m_i	C -mag	M -mag	R -mag
NGC_247_53	11.70664	−20.74894	21.40	20.60	22.35	21.37	20.59
NGC_247_64	11.98445	−20.64441	19.01	18.96	19.84	19.06	18.45
NGC_247_73	11.83308	−20.77761	20.05	19.33	21.10	20.35	19.63

Figure 5.6: Candidates considered to be GCs by Olsen et al. (2004) appear as background galaxies in the HSC imaging. The name of each object is written in yellow below each thumbnail (size of thumbnails ~ 10 arcsec ~ 170 pc).

Table 5.3: Spectroscopy observations of GC candidates

	RA	DEC	
NGC_247_45	11.66306	-20.79249	no spectrum
NGC_247_51	11.70169	-20.86508	weak spectrum
NGC_247_81	11.87785	-20.92932	no spectrum
NGC_247_84	11.91002	-20.57307	weak spectrum
NGC_247_86	11.92046	-21.06153	weak spectrum

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Concluding Remarks

In this thesis, we have described in detail the extraction and cross-identification of catalogs using SExtractor. The catalogs were used to make color–color, color–magnitude, and concentration index plots from HSC images of the dwarf spiral galaxy NGC 247 and defined criteria for GC selection. In conjunction with visual inspection, we thereby selected 14 promising GC candidates. We are hoping that at least 50% of these GC candidates can be confirmed. Only spectroscopy can definitively confirm the GC candidates and is planned in the near future. There are many more GC candidates that fit our selection criteria and require follow-up visual inspection. Although there were 6 filters (SDSS g and i , Washington C and M , Harris R , and *Spitzer* 3.6 μm - infra red), we were not able to distinguish the stellar sequence from the GCs using the color–color diagrams. There could also be GC candidates that are less compact than our FWHM criteria allow, implying that those GCs would be missed by our current selection. Since there are so far only three spectroscopically confirmed GCs in NGC 247, confirmation of some of our GC candidates can help in understanding the spatial positions of the GCs and in verifying the existence of bimodality.

6.2 Future Work

We are planning on finding more GC candidates that fit our criteria and then carrying out visual inspection. We also need to refine on our selection criteria and narrow down the list of GC candidates to a manageable size for visual inspection.

The search for GCs in NGC 247 also needs to extend to larger radii using the full HSC field of view. Spectroscopic follow-up is also envisioned to confirm some of our GC candidates.

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