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An Automated Census of Globular Cluster Systems in Virgo Cluster Dwarf Galaxies

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***Abstract*- This study outlines a method to detect globular cluster (GC) systems within Virgo cluster dwarf galaxies with the aim of creating a robust new census of GCs. Compact objects are selected in each image with the Source Extractor software package, and color-selection is performed to pick out possible GC candidates — objects within each dwarf galaxy that match the color and brightness profile of known GCs. Additionally, artificial GC sources are added to the image, and the percentage recovered by Source Extractor is used as a means to quantify the degree of completeness of their detection algorithm. Combined with an analysis of the GC background and the known shape of the GC luminosity function, this study obtains a statistical estimate of the total number of GCs associated with several dwarf galaxies. Further analysis of the new clusters discovered using this method could provide insight into the hierarchical formation of galaxies and the tidal events that modify them within the Virgo Cluster.**

I. Introduction

Residing over 65 million light years away from the Milky Way is the Virgo Cluster, the closest galaxy cluster to the Local Group. The Virgo Cluster is home to a particular abundance of dwarf galaxies, the most common being dwarf ellipticals, smaller galaxies with an ovular, rather than spiral or irregular, shape. In and around these dwarf galaxies are agglomerations of some of the oldest stars in the universe. These star clusters, known as globular clusters (GCs), are tightly bound by self-gravity and contain a range of 10,000 to 10 million stars. GCs have played key roles in the understanding of stellar evolution and dynamics and have served as fossil records of their host galaxies. One of the most significant impacts of GC research to date has been the accurate estimation of the minimum age of the universe from the study of GCs within the Milky Way [1]. By studying the metallicity, or amount of non-hydrogen elements in a star cluster, it is possible to determine the approximate age of a GC. It is also believed that galaxies are formed hierarchically, growing larger by accreting smaller star systems; thus, the study of GC systems could shed light onto the evolution of galaxies.

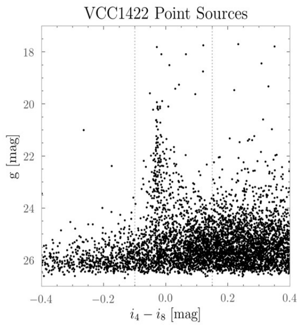
The dataset analyzed in this paper is part of the Next Generation Virgo Cluster Survey (NGVS), a 104 deg^2 optical survey of the Virgo Cluster in the *u*g'i'z'* bands using the MegaCam instrument on the Canada-France-Hawaii Telescope [4]. For the purposes of this project, the selection process relies on the *u*, g,* and *i* filters, or absorption colors of ultraviolet, blue light, and near infrared wavelengths, as well as making use of the point source depth of g ≈ 25.9 mag to obtain a complete census of GCs of lower brightness than has been recorded so far. To develop the GC selection method, two images of Virgo dwarf galaxies that have been processed and calibrated by the NGVS collaboration are analyzed. Specifically, this process uses images in which the galaxy light is subtracted using smooth model images with elliptical symmetry and ring median filtering.

Our main work involved running Source Extractor (SExtractor), a light-source detection software that uses aperture photometry to record the brightness of each light source in an image, producing a catalog of several thousand sources of interest.

II. Methods

The process of GC selection begins by running SExtractor on the two model-subtracted dwarf galaxy images. The flux of each source detected by SExtractor was estimated using 4- and 8-pixel diameter apertures. As a result of SExtractor's aperture photometry, the light not captured by each aperture must be corrected for, as well as extinction, or dimming of light by interstellar dust; the average of these corrections was applied to all of the sources. In this process, the Source Extractor photometry data is compared to a pre-calibrated NGVS catalog with *some* of the sources in the dwarf galaxy image. With such a narrow field of view, it is safe to employ constant extinction and aperture corrections across the image; applying the average of these corrections across every source gives accurate photometric data for the dimmer GCs of interest.

Sources with a g-band magnitude brighter than 24.5 and a concentration index between $-0.1 < i_4 - i_8 < 0.15$ were selected, as these are likely objects with the same compactness that is typical of Virgo Cluster GCs. Based on a previous study of the Virgo Cluster [7] conducted by astronomy researchers using imaging from the Hubble Space Telescope (HST), the GC luminosity function peaks at around a g-magnitude of 24. Thus, a cut at 24.5 will detect roughly 70% of all GCs, as seen in Figure 1. On the other hand, this range in concentration index was determined empirically by looking at the distribution of concentration indices for known GCs. Exact point sources should have a concentration index of zero, but GCs are slightly extended and there is some scatter that must be accounted for. After plotting these compact sources on a color-color diagram, all sources that fit inside the color-space typical of GCs in M87 were taken to be GC candidates [5].



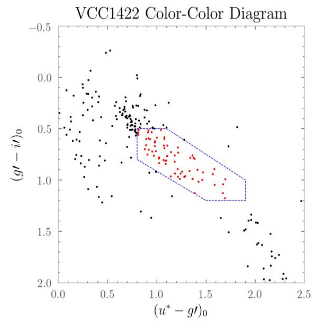


Figure 1 (left). g-band magnitude as a function of concentration index for the galaxy VCC 1422. The dashed lines show the range of values that we selected point source candidates from.
Figure 2 (right). Color-color diagram *(u*-g') vs. (g'-i')* of point sources in the dwarf galaxy VCC 1422. GC candidates are highlighted in red, and the blue polygon constrains the color-space for our GC candidates.

However, SExtractor was not able to detect all sources in an image, as some objects are obscured by image artifacts, bright foreground stars, etc. To correct for these 'missed' GCs, a checking procedure must be prepared to calculate a completeness ratio, or the percentage of sources in the image that are detected by SExtractor.

The first step in this procedure was to create a controlled number of artificial GCs. After light from a point source travels through interstellar dust and the earth's atmosphere, it reaches the telescope as a two-dimensional flux distribution, which can be modeled by a point spread function (PSF) [3]. Depending on the galaxy's location in the sky, a corresponding 31 by 31 pixel PSF is retrieved from the NGVS PSF server, which is added instead of a clean point source. Gaussian noise was also added to each pixel of the PSF to make them more realistic. Artificial GCs were positioned in a uniform square grid across the image, with their spacing and quantity set as adjustable parameters. In order to generate more data, four more output images are produced by shifting the PSF grid a half step to the right, a half step down, and a half step diagonally down and to the right for a fuller coverage of the pixels in the image. Our Python code iterated through all galaxies and color bands for magnitudes in the range 23.0 to 28.0 (four times each to accommodate the dithering of our GC grid). Then, the completeness ratio is computed by dividing the number of SExtractor-detected artificial stars by the total number of stars added.

Two details must be considered: the relationship between the completeness and the magnitude, and the position of the stars in the image. The completeness ratio was found to decrease as the magnitudes increased, since larger magnitudes equate to fainter images. This completeness testing is split into five distinct annuli based on their radius from the center, as shown in Figure 3. Finally, the completeness test is run in rings of range 10 arcsec, beginning from 0-10 arcsec and ending at 40-50 arcsec.

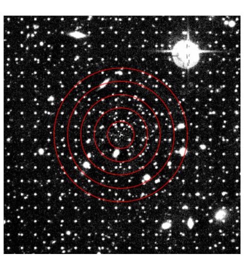


Figure 3. Galaxy VCC 940 has been divided into five annuli as shown by the red rings, ranging from a radius of 0-50'' from the galaxy center.

A sample of the completeness graph from 0-10 arcsec is shown in Figure 4, with each of the red crosses representing the completeness ratio at that specific magnitude. The resultant completeness ratios are fit to the Pritchet function algorithm [6]. A particularly useful characteristic of the Pritchet Function is the "g_limit." It returns the magnitude when source detection is at 50% accuracy, providing a uniform measure for completeness across the magnitude bins.

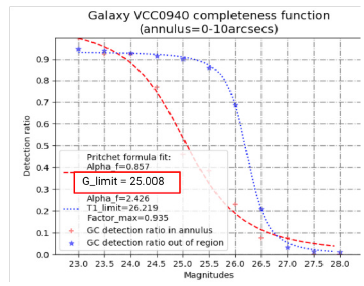


Figure 4. A completeness graph of the region of the image with a radius of 0-10'' from the center fit to the Pritchet Function. Completeness within the 10'' annulus is shown in red, and completeness outside 10'' is shown in blue.

III. Data Analysis

As seen in Figure 5, the g_limit generally increased as the artificial stars moved farther away from the center of the galaxy, indicating a higher completeness ratio for the outer annuli. This effect occurs because the patch of sky behind a light-subtracted galaxy still retains its original, higher noise floor. This leads to a low signal-to-noise ratio, crowding out GCs and making source detection more difficult. An increase in the magnitude corresponded to a lower completeness ratio and g_limit since larger magnitudes produce a fainter image, making source detection more difficult.

	0-10 arcseconds	10-20 arcseconds	20-30 arcseconds	30-40 arcseconds	40-50 arcseconds
g_limit	25.008	26.07	26.167	26.229	26.086

Table I. The g_limit, or g-band magnitude for which Source Extractor detects GCs with 50% accuracy, for each annulus in galaxy VCC 940.

The detection process was refined on galaxies VCC 940 and VCC 1422, selected due to good light subtraction quality, clear elliptical shape and the presence of confirmed GCs. Photometric analysis was also run on seven other galaxies of varying light subtraction quality. In the case of VCC 940, SExtractor detected 3,055 objects, 41 of which passed the criteria for concentration index, magnitude, and color. Out of these, 22 GC candidates were contained visually within the core of the galaxy with a radius of ~50''. Accounting for the Globular Cluster Luminosity Function, correcting for completeness, and calculating a calculated GC background of ~0.612 GCs per arcmin^2 gives approximately 47 GCs in VCC 940 – a slightly larger number than was found by our research group using Hubble Space Telescope images without accounting for completion or implementing model subtraction.

IV. Results and Further Implications

In the future, we hope to run this method on the full dataset of 1,145 galaxies, and we are currently constructing a computerized pipeline to automatically detect the total number of GCs within each dwarf galaxy's gravitational influence. To enhance the accuracy of our data, we also plan to develop a program to determine the completeness of the color selection process by placing artificial GCs with brightnesses set in *multiple* filter bands in each image and feeding them through the GC color selection program.

By comparing the colors of our GCs across galaxies of varying surface brightness, size, and composition, we believe that this GC catalog will be useful to pin down correlations between galaxy GC properties. By analyzing this data across the entire Virgo Cluster, it will be possible to draw conclusions about the formation of galaxies through the merging of globular clusters with a higher resolution than previously possible.

V. Acknowledgments

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VI. References

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