

A wide-field study of globular clusters in the nearest giant elliptical: Subaru/Suprime-Cam observations of Maffei 1*

Samuel Hinton^{1,2}, Ricardo Salinas³ Aaron J. Romanowsky^{4,5}, and maybe some others

¹School of Mathematics and Physics, University of Queensland, QLD 4072, Australia

²Australian Astronomical Observatory, North Ryde, NSW 2113, Australia

³Gemini Observatory

⁴Department of Physics & Astronomy, San José State University, San Jose, CA 95192, USA

⁵University of California Observatories, 1156 High Street, Santa Cruz, CA 95064, USA

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ABSTRACT

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Key words: Galaxies: individual: Maffei 1 – Galaxies: star clusters

1 INTRODUCTION

Add some general remarks on globular cluster systems.

Maffei 1 is a giant elliptical galaxy (Maffei 1968; Spinrad et al. 1971) located at only 0.5° North of the Galactic plane. This position implies large obscuration by dust from the Galactic disc which has hampered the measurement of even the most basic parameters of the galaxy.

Give main results from the literature

Its particular relative position has also conspired against the study of its globular clusters (GCs). Studies of its globular cluster system (GCS) have produced only a handful of GC candidates (Davidge 2002; Buta & McCall 2003; Davidge & van den Bergh 2005), whereas for its luminosity ($M_V \sim -20.80$, Fingerhut et al. 2007), the size of its GCS should be comparable to the one of Cen A, hosting ~ 1300 GCs (Harris 2010).

In this paper we present the first wide-field study of the Maffei 1 GCS system using Subaru/SuprimeCam imaging. In Sect. 2 we present the imaging data used, as well as its reduction and photometry. In Sect. 3 we present the GCs selection, together with the derived properties of the GCS. Sect. 4 puts our results on a wider context, while Sect. 5 summarizes the work and give conclusions.

2 SUBARU/SUPRIME-CAM OBSERVATIONS AND DATA REDUCTION

Maffei 1 images were obtained using Suprime-Cam (Miyazaki et al. 2002) located on the Subaru telescope, Mauna Kea, Hawaii. Suprime-Cam comprises 10 CCD detectors separated by $\sim 15''$ covering a field-of-view of $34' \times 27'$ with a pixel scale of $0.2''$. SDSS r' , i' and z' -band images were obtained during the night of January 5th, 2011. Several short exposures were taken with a $\sim 1'$ dither pattern, totalling 385, 280, and 280 seconds in the r' , i' and z' -bands, respectively.

Suprime-Cam images reduction was conducted within the SD-FRED2 pipeline (Ouchi et al. 2004). Reduction steps include bias subtraction, flat-fielding, correction for atmospheric distortions, point spread function (psf) equalization (i.e. the normalization of the psf to a single shape across the detectors and exposures), sky subtraction, image alignment and finally, the combination of all exposures and detectors into single images. Final averaged images have a field-of-view of $\sim 37' \times 31'$ and a seeing quality of $0.72''$, $0.68''$ and $0.63''$, for r' , i' and z' , respectively. The field of view in z' is shown in Figure 1, and a detailed colour image of the galactic core is presented in Figure 2.

For the z' image set, which is used as the basis for the GC candidates identification given its higher image quality (see Sect. 3.1), a parallel alternative reduction process was adopted. The z' dataset not only provides the reddest band to pierce through the Galactic plane, but also contains the best seeing images. Even though the same SD-FRED2 pipeline was mostly used, a couple of the aforementioned reduction steps were skipped in order to maintain image manipulations that could alter the image quality to a minimum.

* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

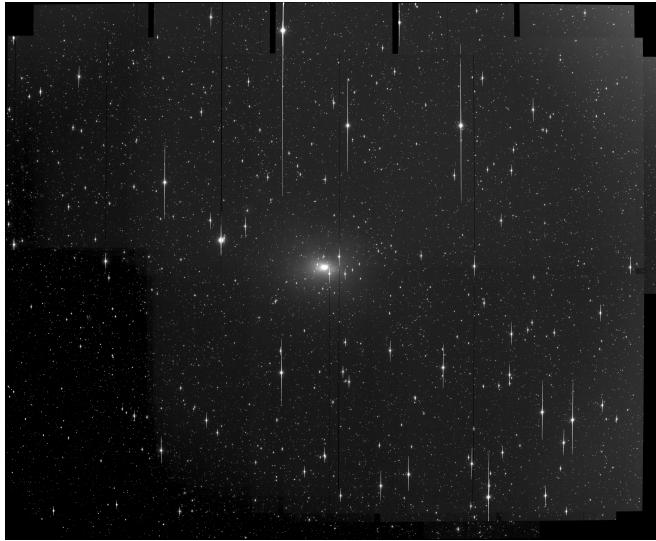


Figure 1. The Maffei 1 field as seen by Subaru-SuprimeCam in z' . Image size is approximately $37' \times 31'$. North is up and East is to the left.

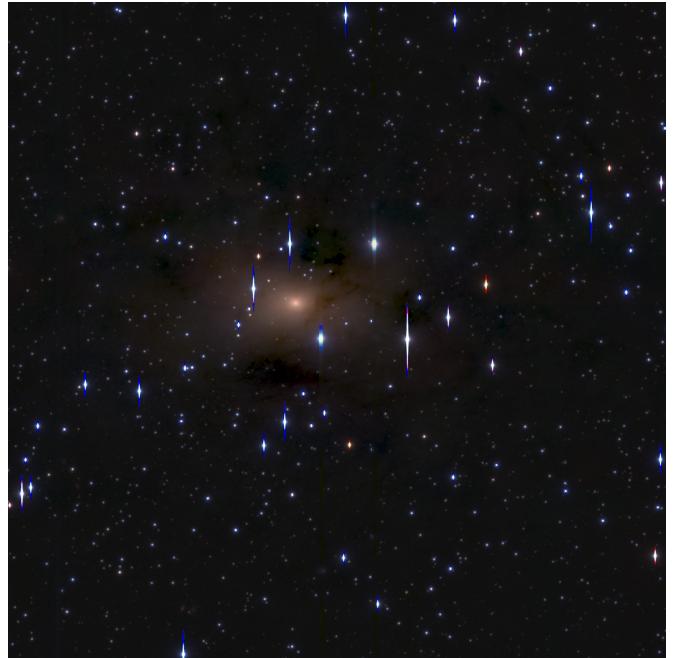


Figure 2. The core of Maffei 1 shown in z' , i' and r' , generated by STIFF (Bertin 2012). The image size is approximately $6.5' \times 6.5'$. North is up and East is to the left.

Firstly, given the slight degradation of the psf towards the outer detectors, psf equalization across the chips would imply a loss of information on the best chips. For this reason the detectors were reduced independently and not combined into a single image as a final step. As a second difference, we did not apply any correction for atmospheric distortions, since it resulted in an increase of about 10% of the measured stellar full width at half maximum (fwhm) due to charge shifting to neighbor pixels. Finally, images with psf sizes significantly larger than the mean were excluded from the final image combination. This resulted in the rejection of zero to two exposures per chip.

Coordinate transformations and image combination for the individual detectors were carried out with DAOMASTER/MONTAGE2 (Stetson 1993, 1994), which give more flexibility than SDFRED2 for images with a small overlapping area. Measured fwhm on the combined z' images varies between $0.52''$ to $0.58''$ from detector to detector, which are noticeably better than the $0.62''$ measured on the combined full frame image given by SDFRED2.

As a last step prior to initial photometry, images presenting large background variations (containing Maffei 1 light or Galactic cirrus), were median filtered with an annulus kernel, with outer radius size of 150 pixel and an inner radius of 105 pixels; a large size that preserves point-like sources unaltered. Photometry and astrometry were performed on the images fully processed with the SDFRED2 pipeline.

2.1 Stellar photometry

Manual aperture and psf-fitting photometry were carried out on a chosen example tile using the stand-alone DAOPHOT2 photometric suite (Stetson 1987). The psf was modelled selecting ~ 120 – 140 bright and isolated stars on each detector. A quadratically varying Moffat function was found to provide the best description of the psf behaviour within the detectors.

Photometry for all the sources was also obtained using SExtractor (Bertin & Arnouts 1996), which additionally provides measurements of the size, orientation and ellipticity of the sources.

3 RESULTS

3.1 Selecting globular clusters candidates

The basic selection criterion for GCs in Maffei 1 rests on the non-stellar shape of their light profiles. This shape, usually smeared out for distant systems or in images with low spatial resolution, should be noticeable for the largest GCs in Maffei 1 given the galaxy's distance and the quality of the imaging. A similar approach has been applied successfully on ground-based imaging of GCs in the slightly more distant elliptical galaxy Centaurus A (Rejkuba 2001; Gómez et al. 2006; Gómez & Woodley 2007). As manual inspection of all sources was infeasible due to the number of sources, a machine learning approach was adopted in order to differentiate between stellar sources and extended sources. Initially, the neural network classifier contained inside SExtractor was utilised, but a posterior analysis has shown that clearly resolved sources have been assigned a CLASS_STAR parameter value as high as 0.98, which on a blind approach would have been classified as stars. Thus the algorithm was found to be insufficient, and a new algorithm was developed. Training of the machine learning algorithms was performed by combining artificially generated data and manual classification on a single tile.

Manual classification was performed by visual analysis of the star-subtracted z' -image of the chosen CCD tile produced by the psf-fitting algorithm in ALLSTAR. The image was visually inspected to look for residuals that revealed the presence of extended sources. The light profile of GCs (but also galaxies) would be over-subtracted in the central parts and under-subtracted in the wings, leaving an easily recognizable “ring-shaped” residual (see Fig. 3). A visual inspection of the residuals in a tile is a painstaking process, but provides benefit over only artificial data that does not model the full distribution of extended sources accurately. Our selected approach revealed the presence of 77 extended sources in the Clarisse tile.

Artificial stars and extended sources were added to the Clarisse tile by the use of the `mksynth` task in BAOLAB (Larsen 1999). The psf input into the `mksynth` function was determined using by automatically selecting a number of candidate psf stars (based on flux criterion, star classification and source isolation), and generating a subsampled psf using the `digiphot` package in IRAF CITE. For generation of artificial extended objects, the `mkcmppsf` task was also used to generate a compositie psf with a King model (King 1962) with concentration of 30. The fwhm of the model was randomised to allow variation in the size of the artificial globular clusters. Both stars and extendeds were generated with uniform randomised magnitudes. The input data set was then created by using SExtractor to detect source properties of both the artificial sources and manually classified sources.

The input data was split into training, testing and validation sets, using ratios 0.5, 0.25 and 0.25 respectively, where multiple machine learning algorithms were trained on the training data, and the algorithm with the highest Matthews correlation coefficient(Matthews 1975) when evaluated on the validation was selected as the final algorithm. The Matthews correlation coefficient was chosen to be maximised over other coefficients such as classifier accuracy, due to its fairness in dealing with unbalanced classes (Baldi et al. 2000; Jurman et al. 2012), which we expect to find with the number of point sources far exceeding the number of extended sources. Expected performance of the algorithm was determined by fitting to the test data set, and indicate that of the more than 85% of the extended sources in the input data were correctly identified, and greater than 99% of point sources (stars) were correctly identified.

The extended candidates for each tile given by the initial machine learning algorithm were then processed through the task `iShape`, a procedure in the BAOLAB software package, to gather more information on the candidates. This step is done separately as computational constraints hinder the ability to run `iShape` on all detected sources, and so an initial candidate round must be selected. Information on χ^2 of the King fit, χ^2 of the delta model fit, and the fwhm of the King profile are added to the original data set. The manually selected candidates and artificially generated sources were also processed by `iShape`, and the improved dataset was used to train a second classifier in a similar fashion to the first, which was designed to remove many of the false positives from the initial classifier. Comparison to the test data set indicated an improvement from 85% of correctly classified extendeds up to 95%, and an improvement in point source idenification from 99% to 99.5%. It important to note that these success rates cannot be directly applied to the real data, and the matching accuracy on other tiles is expected to be lower due to artificial modelling not reflecting all the variations and subtleties of real global clusters and the lack of modelling other sources, such as compact dwarfs, stanard galaxies and other astronomical phenomenon outside stars and globular clusters. When run over all tiles, 977 globular cluster candidates were identified.

Each candidate underwent aperture photometry on the fully reduced mosaics mentioned in Section 2, where colour magnitude corrections were performed by interpolating the dust maps from Schlegel et al. (1998) and applying the band extinction to redding ratios from Schlafly & Finkbeiner (2011). **PUT MAGNITUDE BASELINE IN WHEN YOU DO IT. IT GOES BEFORE THE DUST CORRECTION MAYBE, ASK RICARDO**

Further pruning of the globular cluster candidates was performed removing unphysical outliers in the analysis, such as removing objects with a detected fwhm of over a ten arcseconds. In

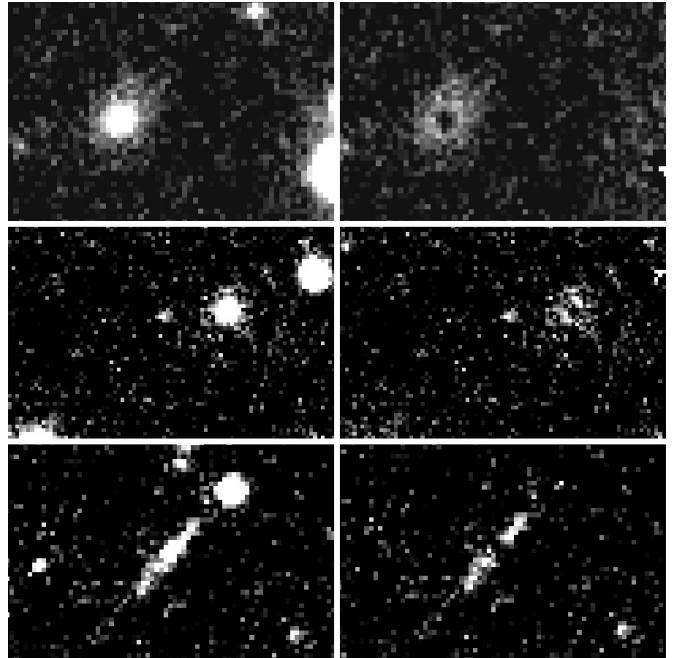


Figure 3. Three examples of the psf-subtraction technique applied on the final z images to reveal extended sources. The left panels show the original image, while the right panels are the psf-subtracted images. Top panels: A round “Class A” object revealing a highly confident classification. Middle panels: A similar classification with a lower confidence due to the image noise. Bottom panels: An elongated extended object, in this case a galaxy viewed from the side, where the high ellipticity of the source allows differentiation between globular cluster and galaxy.

addition, ellipticity cutoffs and colour cuts were introduced to remove galaxies in the globular cluster candidate list.

The extended sources were separated into 3 classes based on the visual appearance of their residuals in combination with their structural parameters measured with SExtractor: circular residuals with $\text{fwhm} < XX$ (class A), symmetric but elongated residuals where the source has $\epsilon < 0.3$ (class B), and finally, elongated residuals with $\epsilon > 0.3$ together with sources with very extended ($\text{fwhm} > 6$ pixels) or asymmetric residuals (class C). In the few cases where the source was not detected by SExtractor (usually because of the proximity of a bright star or the patchy Maffei 1 center), the classification was made only based on their visual appearance. The ellipticity limit of 0.3 was chosen since it contains all the ellipticities found for GCs in Local Group galaxies (e.g. van den Bergh 2008). These classes correlate with the likelihood of the sources being genuine Maffei 1 GCs based on their structure, with the round class-A objects having a higher probability of being genuine Maffei 1 GCs, and the elongated or large class-C sources, being most probably background galaxies.

3.2 Globular clusters color-magnitude diagram

3.3 Globular cluster sizes

4 DISCUSSION

5 SUMMARY AND CONCLUSIONS

ACKNOWLEDGMENTS

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APPENDIX A: GLOBULAR CLUSTER CANDIDATES PHOTOMETRY

This paper has been typeset from a \TeX / \LaTeX file prepared by the author.

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Table A1. Photometry of “Class A” (see main text for its definition) globular cluster candidates.

ID	RA	Dec	r'	i'	z'	ϵ	Notes
GC1	XX:XX:XX.XX	XX:XX:XX.XX	99.99 ± 99.99	99.99 ± 99.99	99.99 ± 99.99	9.99	

Table A2. Photometry of “Class B” globular cluster candidates.

ID	RA	Dec	r'	i'	z'	ϵ	Notes

Table A3. Photometry of “Class C” globular cluster candidates.

ID	RA	Dec	r'	i'	z'	ϵ	Notes