VEGAS-SSS. A VST Early-type GAlaxy Survey: analysis of Small Stellar System^{*}

Cantiello Michele on behalf of the VEGAS team

Abstract VEGAS-SSS is a program devoted to study the properties of small stellar systems (SSSs) around bright galaxies, built on the VEGAS survey. At completion, the survey will have collected detailed photometric information of ∼100 bright early-type galaxies to study the properties of diffuse light (surface brightness, colours, SBF, etc.) and the clustered light (compact stellar systems) out to previously unreached projected galactocentric radii. VEGAS-SSS will define an accurate and homogeneous dataset that will have an important legacy value for studies of the evolution and transformation processes taking place in galaxies through the fossil information provided by SSSs.

---

1 Motivation of the study, data and data-analysis

The surroundings of massive galaxies are populated by a zoo of dynamically hot SSSs: globular clusters (GCs), ultra-compact dwarfs (UCDs), dwarf spheroidals (dSphs), ultra-faint dwarfs (UFD), dwarf ellipticals (dEs), compact ellipticals (cE), etc. (e.g. [**?**, **?**]).

Characterizing the properties of SSSs in the potential well of the host galaxy is fundamental, not only because of the key role in understanding the basic processes of formation and evolution of the structures in the Universe from star clusters to galaxies, but also because i) the stellar populations of SSSs are less complex than those of massive galaxies, allowing for a more accurate comparison of their ages and metallicities with stellar population models; ii) SSSs are relatively easy to detect out to large distances, which offers the unique opportunity to scrutinize various environments beyond the Local Group, and thus to study how SSS properties vary across space and time. SSSs are then ideal tracers of the host galaxy's

gravitational potential and of the assembly history of the galaxy's stellar populations.

With the VEGAS-SSS program, by taking advantage of the large field of view of the VLT Survey Telescope, VST [1], we intend to dig into the zoo of SSSs host by bright galaxies in different environments observed as part of the VEGAS survey, and comprehensively study their properties out to very large galactocentric radii R_{gal} on a homogeneous and self-consistent basis.

VEGAS is a deep multiband *gri* imaging survey of early-type galaxies, ETGs, carried out with the 1 square degree field-of-view camera OmegaCAM, mounted at the VST. The survey plan is to analyze the photometry of ∼100 galaxies with $V_{rad} \leq 4000$ km/s in different environments and covering the parameter space. More details on the survey are provided by M. Spavone in this volume, and in [2].

We started the VEGAS-SSS project analyzing the *g* and *i*-band data of NGC 3115, an isolated S0 galaxy at $d \sim 10$ Mpc. The choice of NGC 3115 was also motivated by the many photometric and spectroscopic studies available in the literature, which were particularly useful for testing the procedures and the methods that will be used for the future targets of the survey.

In [3] we provided a step-by-step description of the procedures adopted to *a*) derive photometry of compact and extended sources, *b*) model and subtract the galaxy, *c*) obtain and apply the extinction and aperture corrections, *d*) match the *g* and *i*-band catalogs and analyze colours, *e*) obtain a separation between compact objects in the galaxy and fore/background contaminants.

We compared our photometry against the various catalogs existing in the literature, and obtained in all cases satisfactory agreement.

Thanks to the large area covered, we succeeded in inspecting the properties of SSSs in NGC 3115 out to $\sim 23'$, more than twenty times the galaxy effective radius, the largest projected distance ever reached to inspect the SSSs in the galaxy. This allowed us to adopt a statistical approach to study the properties of the GCs population versus R_{gal},

as follows. First, we estimated the surface density of objects satisfying some well-defined criteria (colour, magnitude, size, etc.) at different R_{gal}, and analyzed the properties of the residual over-density of the central galaxy regions with respect to the background regions.

Second, we analyzed the half-light radii R_h of the objects in the field of the galaxy as a further attribute to discriminate between SSSs in the potential well of NGC 3115 and contaminating objects. Overall, we obtained a catalog of ~ 30000 sources with both photometry and R_h estimates, including ~ 6000 objects with $R_h \leq 1.5$ pc as well as very extended sources having $R_h \geq 500$ pc, i.e. likely foreground stars and background galaxies[2]. For the few candidates with R_h available in the literature the matching with our measurement is on average satisfactory.

Some of the results of our study, based on the statistic decontamination are described in the following section. More details can be found in [3].

2 Results

GC Luminosity function

We analyzed the luminosity function, LF, of sources in the field of NGC 3115, with the specific purpose of inspecting the GCs LF to *i*) estimate the galaxy distance modulus μ_0 using the GCLF Turn-Over Magnitude (TOM; e.g. [4] and references therein), and *ii*) to study how, and if, the TOM changes as a function of R_{gal}.

The left panel of Figure 1 shows the histogram of the residual density Σ_{Host}[3] versus magnitude.

The density distribution has a peak at ~ 22.8 mag. Using the TOM calibration from the

---

[2] The full catalog is available at vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/A%2BA/576/A14.

[3] The residual density at various radii is obtained from the total density at fixed radius R_{gal}, after subtracting the density background sources at $R_{gal} \geq 23' \equiv R_{bg}$.
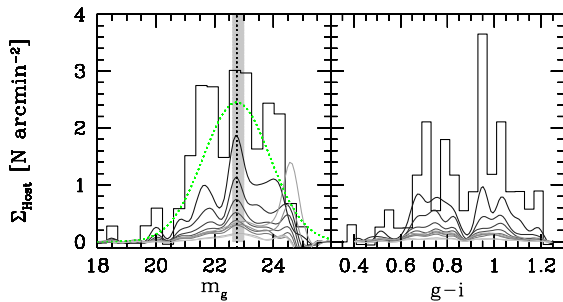
Fig. 1 Residual surface density versus magnitude (left) and colour (right). Darker colour refers to areas with smaller R_{gal}, starting from $2'$ out to $R_{gal} = R_{bg} = 23'$. In the left panel the thin dotted line, gray shaded area and green dotted gaussian curve show the position of the TOM, the 1-σ error for the TOM, and the GCLF, respectively.

ACSVCS team we estimate $\mu_0 = 29.9 \pm 0.3$ mag, or 9.8 ± 1.4 Mpc.

For what concerns the study of the properties of the TOM versus R_{gal}, to date the scarce literature on the topic shows both galaxies with and galaxies without a radial dependence of the TOM [4, 5]. For this galaxy we find no obvious variation of with R_{gal} (gray region in Fig. 1, left panel). The peak of luminosity of the GCLF is influenced by various physical factors. To first approximation, the simplest interpretation of a gradient in the peak luminosity of the GCLF is a correlation of the mean GCs mass with R_{gal}.

We further inspected how the TOM differs between red and blue GCs. After dividing the blue/red GCs adopting a sharp colour separation at $g-i$=0.9 mag, we found a $\sim$0.2 mag offset exists between the red and blue GCLF, with the red system being fainter. Indeed, from a stellar population viewpoint, such behavior is expected if the GCs mass function is universal across metallicity.

With the future VEGAS-SSS studies, we will further explore the dependence of TOM with the projected radii and the possible systematic differences between the blue and red GCLFs, for galaxies in different environments and with different masses.

GCs colour distribution

The choice of NGC 3115 as first VEGAS-SSS target was also motivated by the fact that the galaxy is the first one beyond the Local Group with confirmed bimodal metallicity distribution [7, 8]. In the last decade, the nearly universal presence of two well-separated peaks in the optical colour distribution of GCs in ETGs, has inspired a vigorous and prolific debate. Historically, the bimodal GCs colour distribution in optical bands has been equated to metallicity [Fe/H] bimodality, implying a fundamental constraint on GCs and galaxy formation scenarios. This assumption became the subject of debate when various authors demonstrated that the presence of non-negligible nonlinearities in the colour-metallicity relations of GCs naturally produces bimodal colour histograms from non-bimodal [Fe/H] distributions [9, 10, 11].
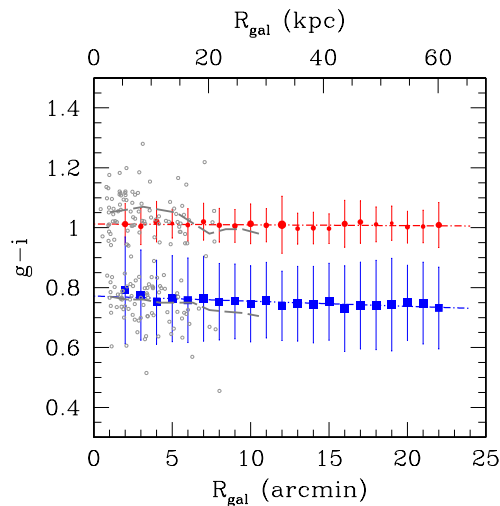

Fig. 2 Position and width of the blue and red GCs at different R_{gal}. Symbol size is proportional to the fraction of objects associated to each peak. A fit to the data is shown with dot-dashed lines. Grey dots show spectroscopic confirmed GCs, gray long-dashed lines mark the rolling fits of the blue and red GC peaks obtained from a combination of spectroscopically and photometrically selected GCs [6].

Using the same approach adopted for the GCLF (i.e. by subtracting the background surface density to the total density at various radii), we analyzed the colour distribution of GC candidates. The results are shown in the right panel of Fig. 1. The plot shows *i*) the presence of a dip at $g-i \sim 0.9$ mag with two well-defined peaks at ~ 0.75 and 1.00 mag, and *ii*) the dip and the peaks are seen at all inspected radii.

To investigate the properties of the GC color distributions at each given radius, we used the Gaussian mixture modelling, GMM, code [**?**]. GMM uses the likelihood-ratio test to compare the goodness of fit for double-Gaussians versus a single-Gaussian. It also provides the positions, relative widths, and fraction of objects associated with each peak.

Figure 2 shows positions (blue/red points), widths (bars), and fractions (given by symbol sizes) of the blue and red colour distributions obtained with GMM, as a function of R_{gal}. Various features appear: *i*) a colour-R_{gal} correlation for the blue GC component, and no or only a very weak correlation for the red GCs (Pearson correlation coefficients $r_{xy}^{blue} \sim -0.8$, $r_{xy}^{red} \sim -0.25$); *ii*) the fraction of red GCs has a slight but significant decrease with respect to the blue GCs at large radii; *iii*) the width of the two sequences is relatively stable with radius, with the blue distribution being broader at all radii.

In the figure we also added data from the SLUGGS survey [6]. There is a good matching between the VEGAS-SSS and SLUGGS results. In particular, we highlight the very good matching with the colours of spectroscopically confirmed GCs (gray dots). The agreement appears even more striking if one takes into account that the SLUGGS data were obtained by coupling photometry and spectroscopy from the 8-10m class telescopes Subaru and Keck-II.

Finally, we analyzed the radial profiles of the projected surface density of GC candidates inspecting the full sample, and the red and blue GCs separately. The results, shown in Figure 3, highlight that the total, red and blue GCs follow very
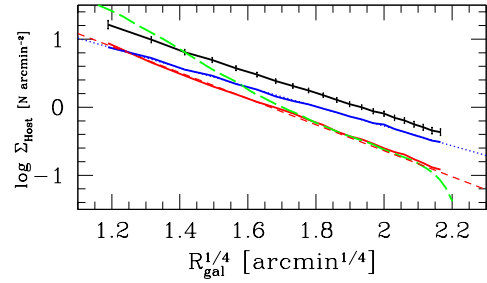

Fig. 3 Surface density profiles of blue, red, and total GC population (blue, red and black line, respectively). The green long-dashed shows the *g*-band surface brightness profile from [2] with arbitrary scale. The linear fit to the surface density is shown with dotted lines.

closely a de Vaucouleurs profile, and that the profile of red GCs is steeper than that for the blue GCs while both are shallower than the galaxy profile. Moreover, the red GCs and the galaxy profile match at $R_{gal} \geq 7.5$', while the GCs density is lower at smaller radii. Such depletion, already observed in other galaxies, has been interpreted with an higher efficiency of GC-disruption mechanisms in the inner galaxy regions by dynamical friction, two-body relaxation, and GC tidal shocking mechanisms [12].

Overall, the observed properties support a scenario where blue GCs are associated with the galaxy halo, while red ones are more centrally concentrated and associated with the bulge stellar component in the galaxy, suggesting that NGC 3115 has undergone a relatively quiescent evolution, without major star-forming events.

3 Future perspectives

The final catalogs from VEGAS-SSS will contain accurate photometry, position and sizes for thousands of SSS candidates in the field of bright ETGs. The program will have a twofold legacy value. First, for preparing future observational studies, like near-IR imaging and spectro-

scopic follow-ups. Second, future analysis with the other VEGAS targets, and extended to other SSS classes, will have great value in studies of the evolution and transformation processes taking place in galaxies in a range of environments, as suggested by the results on the GCs population in NGC 3115 summarized here.

References

1. M. Capaccioli, P. Schipani, The Messenger **146**, 2 (2011)
2. M. Capaccioli et al., in preparation (2015)
3. M. Cantiello, M. Capaccioli, N. Napolitano, A. Grado, L. Limatola, M. Paolillo, E. Iodice, A.J. Romanowsky, D.A. Forbes, G. Raimondo, M. Spavone, F. La Barbera, T.H. Puzia, P. Schipani, A&A in press (2015)
4. W.E. Harris, W. Morningstar, O.Y. Gnedin, H. O'Halloran, J.P. Blakeslee, B.C. Whitmore, P. Côté, D. Geisler, E.W. Peng, J. Bailin, B. Rothberg, R. Cockcroft, R. Barber DeGraaff, ApJ **797**, 128 (2014). DOI 10.1088/0004-637X/797/2/128
5. A. Jordán, D.E. McLaughlin, P. Côté, L. Ferrarese, E.W. Peng, S. Mei, D. Villegas, D. Merritt, J.L. Tonry, M.J. West, ApJS **171**, 101 (2007). DOI 10.1086/516840
6. J.A. Arnold, A.J. Romanowsky, J.P. Brodie, L. Chomiuk, L.R. Spitler, J. Strader, A.J. Benson, D.A. Forbes, ApJL **736**, L26 (2011). DOI 10.1088/2041-8205/736/2/L26
7. J.P. Brodie, C. Usher, C. Conroy, J. Strader, J.A. Arnold, D.A. Forbes, A.J. Romanowsky, ApJL **759**, L33 (2012). DOI 10.1088/2041-8205/759/2/L33
8. M. Cantiello, J.P. Blakeslee, G. Raimondo, A.L. Chies-Santos, Z.G. Jennings, M.A. Norris, H. Kuntschner, A&A **564**, L3 (2014). DOI 10.1051/0004-6361/201323272
9. S.J. Yoon, S.K. Yi, Y.W. Lee, Science **311**, 1129 (2006). DOI 10.1126/science.1122294
10. M. Cantiello, J.P. Blakeslee, ApJ **669**, 982 (2007). DOI 10.1086/522110
11. J.P. Blakeslee, M. Cantiello, E.W. Peng, ApJ **710**, 51 (2010). DOI 10.1088/0004-637X/710/1/51
12. P. Goudfrooij, F. Schweizer, D. Gilmore, B.C. Whitmore, AJ **133**, 2737 (2007). DOI 10.1086/516634