VEGAS-SSS: A VST Programme to Study the Satellite Stellar Systems around Bright Early-type Galaxies

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The VEGAS-SSS programme is devoted to studying the properties of small stellar systems (SSSs) in and around bright galaxies, built on the VLT Survey Telescope early-type galaxy survey (VEGAS), an ongoing guaranteed time imaging survey distributed over many semesters (Principal Investigator: Capaccioli). On completion, the VEGAS survey will have collected detailed photometric information of ~100 bright early-type galaxies to study the properties of diffuse light (surface brightness, colours, surface brightness fluctuations, etc.) and the distribution of clustered light (compact "small" 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.

Satellites of massive ellipticals

The surroundings of massive galaxies are populated by a zoo of dynamically hot satellite stellar systems: globular clusters (GCs), extended clusters (ECs), ultracompact dwarfs (UCDs), dwarf spheroidals (dSphs), dwarf ellipticals (dEs), compact ellipticals (cE), etc; see, for example, Forbes et al. (2013) and references therein.

Characterising the properties of SSSs in the potential well of their host galaxy is fundamental, not only because they play a key role in understanding the basic processes of formation and evolution of the structures in the Universe from star clusters to galaxies, but also for a variety of other reasons. These include: i) the stellar populations of SSSs are less complex than those of massive galaxies, which allows 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 scrutinise various environments beyond the Local Group, and thus to study how the properties of SSSs vary across space and time. SSSs are thus ideal tracers of the host galaxy's gravitational potential as well as of the assembly history of the galaxy's stellar populations. Therefore, increasing the sample of SSSs with accurate estimates of their physical properties is of paramount interest to scrutinise the scaling relations of SSSs over a complete and unbiased range of parameters.

The characteristic magnitude, colours, half-light radii R_h, etc., of objects in different SSS classes can change significantly. Nevertheless, the distinction between different SSS types is sometimes not trivial because of the lack of a clear-cut distinction between the classes of SSSs. A natural explanation for this lack is that there is none. Indeed, the transformation processes occurring in dense environments may disrupt or transform massive SSSs, littering the galaxy field with the remains of disrupted systems, such as low-mass SSSs, stellar streams, etc. (e.g., West et al., 1995).

Small stellar systems, especially GC systems, have been studied for decades, and progress has been limited not so much by telescope collecting area, but by the field of view and the image quality (both to reduce contamination and to reduce the exposure times). Thus, the use of telescopes with large collecting areas (4-metre or even 8-metre-class) is not compelling, at least for the photometry, and original achievements are possible from smaller telescopes.

Through the VEGAS-SSS programme, and taking advantage of the large field of view of the 2.6-metre VLT Survey Telescope (VST), we intend to dig into the zoo of SSSs hosted by bright galaxies in different environments, observed as part of the VEGAS survey, and comprehensively study their properties out to very large galactic radii on a homogeneous and self-consistent basis. Here, we present an overview of the project and some first results for the galaxy NGC 3115.

VEGAS: Observational strategy, aims of the survey and SSSs

VEGAS is a deep multiband *gri* imaging survey of early-type galaxies (ETGs) carried out with the VST. The large field of view of OmegaCAM, mounted at the VST (Capaccioli & Schipani, 2011), together with its high efficiency and spatial resolution will allow us to map, with a reasonable integration time, the galaxy surface brightness from the core out to isophotes encircling about 95 % of the total light. Observations started in October 2011 (ESO Period 88), and data for about 20 galaxies for a total of 80 hours have been acquired up to Period 93. The survey plan is to analyse the photometry of about 100 galaxies with radial velocity ≤ 4000 km s^{-1} in different environments and covering the range of parameter space. The observational plan is designed to reach a depth of 27.3, 26.8 and 26 mag $arcsecond^{-2}$ with signal-to-noise > 3 in the *gri*-bands.

The data reduction, including dither combination, exposure correction, CCD gain harmonisation, illumination correction, astrometric solution and photometric calibration was performed with the VST-Tube pipeline (Grado et al., 2012). VST-Tube is a very versatile software package for astronomical data analysis, tested against imaging data taken with different telescopes/detectors and adaptable to existing or future multi-CCD cameras (e.g., Cantiello et al., 2013). Further details about the survey and the overall data quality can be found in Capaccioli et al. (2015, in preparation).

The main science goals of the VEGAS survey are: 1) to study the 2D light distribution out to at least ~ 10 effective radii, R_e, focusing on the galaxy structural parameters and the diffuse light component, highlighting the presence of inner substructures as a signature of recent cannibalism events and/or inner discs and bars fuelling the active nucleus that is present in almost all objects of our sample; 2) to map the surface brightness profile and isophote geometry out to $10R_e$ or more; 3) to analyse the colour gradients and their connection with galaxy formation theories, also taking advantage of stellar population synthesis techniques; 4) to study the external low surface brightness structures of the galaxies and the connection with the environment; 5) to measure the surface brightness fluctuations (SBF), and SBF gradients for the chemical characterisation of the stellar population within $2R_e$, or more.

The survey depth will allow the light distribution, colour gradients and SBF magnitudes to the largest galactocentric distances to be characterised on a homogeneous and self-consistent basis. At large radii, from ~ $10R_e$ and beyond, the dynamical times are of the order of 10^9 yr, and the signatures of the secondary merging events due to the interaction with the environment last longer. VEGAS will look for the expected signatures of processes occurring at various scales of the galaxy environment by the study of surface brightness, colours and SBF analysis.

In addition to the diffuse light, the wealth of SSSs in the potential well of the host galaxy is the other fossil tracer of the past formation events in ETGs. Hence, one further science goal of VEGAS is to derive the census of SSSs out to several tens of R_e, allowing the study of the properties of dynamically hot stellar systems in the outermost galaxy regions. This latter part of the survey is also called VEGAS-SSS.

VEGAS-SSS

We started the VEGAS-SSS project with the study of *g*- and *i*-band data of NGC 3115, an isolated, relatively nearby lenticular galaxy, at a distance ~ 10 Mpc, mostly focused on the properties of the GC system in the galaxy. The choice of NGC 3115 was also motivated by the many photometric and spectroscopic studies available in the literature (both from 8–10-metre class ground-based telescopes, and from the Hubble Space Telescope [HST]), which were particularly useful for testing the procedures and the methods that will be used for the future targets of the survey. A VST colour-composite image of the galaxy is shown in Figure 1.

To improve the detection and the analysis of the spatial extent of the sources in the frame, we did not use the full sample of images available for the study of diffuse light, and restricted our analysis to the data with average seeing better than ~ 0.8 arcseconds. With this choice, the total exposure time available is ~ 2700 s in *g*-band and ~ 1250 s in *i*-band.

In order to obtain accurate photometry over the entire VST frame, including the brightest inner regions of NGC 3115, we modelled and subtracted the galaxy. Then using our own procedure, based on various common astronomical tools

Figure 1. The lenticular galaxy NGC 3115 is shown in a VST colour-composite (*u*, *g* and *i* filter) image; the size is about 52 arcminutes square.

(Pyraf, SExtractor, SuperMongo, etc.), we obtained accurate photometry of the compact sources, derived and applied the proper extinction and aperture corrections, matched the *g* and *i* photometric catalogues and analysed source colour, obtaining a separation between compact objects in the galaxy and fore–background contaminants (Milky Way stars, background galaxies along the line of sight, etc.).

Our photometry was verified against the various catalogues existing in the literature, and provided in all cases satisfactory agreement. As an example, we took as reference the recent study of the Advanced Camera for Surveys (ACS) on the HST, based on a mosaic of six pointings covering the central ~ 6 × 9 arcminute region of NGC 3115 (~ 1.5 % of the total VST field of view). By comparing our *g*-band photometry with the ACS results from Jennings et al. (2014), a median ~ 0.01 mag difference is found over a sample of ~ 200 matching GCs.

In addition to photometry, a further physical parameter that can be estimated using imaging data is the physical extent of the source. Size measurements can be very challenging, especially with ground-based imaging data. Moreover, only angular sizes can be measured, which require the knowledge of the object distance to be transformed to linear scale. Nevertheless, angular sizes and shapes have been estimated for a large sample of SSSs using both space- and ground-based telescopes (e.g., Larsen et al., 1999; Jordan et al., 2004). To estimate object sizes we used the software Ishape (Larsen et al., 1999), a commonly used tool for the purpose, which, in our case, proved very efficient.

We inspected the properties of SSSs out to ~ 23 arcminutes, which is more than twenty times the R_e of NGC 3115, and the largest distance ever used to inspect SSSs in this galaxy. Thanks to the large field of view of the images, we applied a statistical approach to study the properties of the GC population versus galactocentric radius R_{gal}. The basic idea is simple: fore–background objects are evenly distributed in the field around the galaxy, while SSSs "trapped" in the potential well of the galaxy have a power-law radial density profile. Thus, we estimated the surface density of objects satisfying some well-defined criteria (colour, magnitude, size, etc.) at different R_{gal}, and analysed the properties of the residual over-density, Σ, of the central galaxy regions with respect to the background regions.

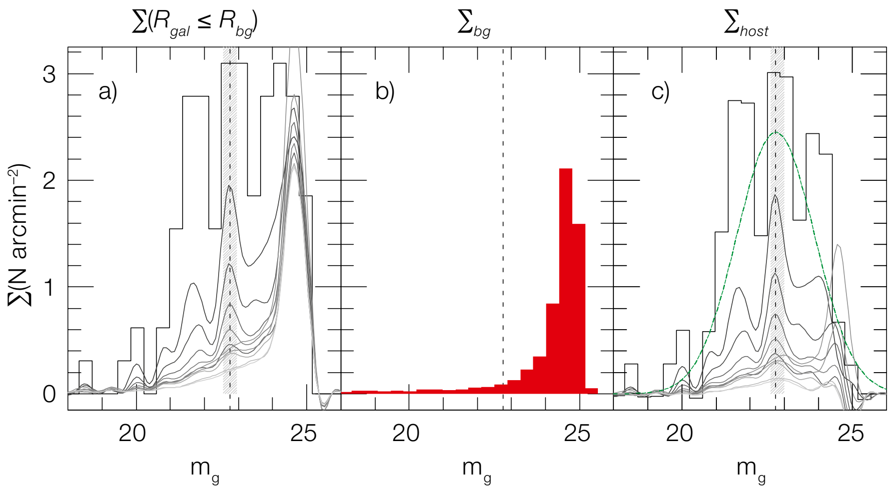

Figure 2. Surface density histograms versus magnitude. Panel (a): Surface density Σ for sources within $R_{gal} \leq R_{bg}$. Darker colours refer to areas with smaller galactocentric radii. Panel (b): Same as left, but for background sources at $R_{gal} \geq R_{bg}$. Panel (c): residual surface density $\Sigma_{host} = \Sigma\,(R_{gal} \leq R_{bg}) - \Sigma_{bg}$.

To describe how the method works, in Figure 2 we show the diagrams related to the GC luminosity function (GCLF) analysis. Panel (a) shows the GCLF at various projected R_{gal}, starting from the innermost regions with the largest surface densities Σ. In the plot, different colours show the surface density histograms at different radii, starting from 2 arcminutes out to R_{bg} = 23 arcminutes. Panel (b) shows the surface density Σ_{bg} of objects beyond R_{bg} = 23 arcminutes. The difference between the surface density $\Sigma - \Sigma_{bg}$ inside and outside of the galaxy is clearly visible in the two panels, as shown in panel (c).

The effectiveness of the method adopted is demonstrated by the extremely good agreement with other existing studies covering smaller areas. In the following, we describe the first VEGAS-SSS results and show the potential of the project in providing original results on SSS-related science. More details can be found in Cantiello et al. (2014b).

First results of VEGAS-SSS

GC luminosity functions

We analysed the luminosity function of sources in the field of NGC 3115, with the specific purpose of inspecting the GCLF to estimate the galaxy distance modulus μ_0 using the GCLF turn-over magnitude (TOM; Harris et al. [2014] and references therein), and to further study how, and whether, the TOM in *g*-band, m_g^{TOM}, changes as a function of galactocentric distance.

As shown in Figure 2, panel (c), the density distribution of sources in the host galaxy has a peak at m_g^{TOM} ~ 22.8 mag. Using the calibration of the absolute TOM from the ACS Virgo Cluster Survey, we estimated a distance modulus μ_0 = 29.9 ± 0.3 mag, or 9.8 ± 1.4 Mpc, in good agreement with the literature distance of the galaxy.

The approach adopted allowed us to investigate how the GCLF might change with R_{gal}. To date, the scarce literature on the topic shows galaxies both with (Harris et al., 2014) and without (Jordan et al., 2007) a radial dependence of the TOM. Our result is that for this galaxy there is no obvious variation of m_g^{TOM} with the projected galactocentric distance. The peak of luminosity of the GCLF is influenced by various physical factors. However, to a

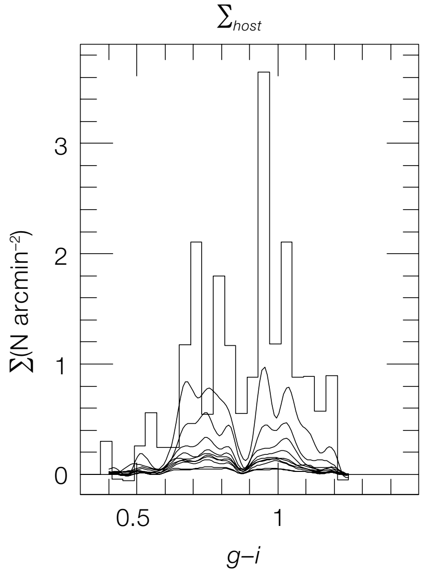

Figure 3. Residual surface density, as the right panel of Figure 2, but shown versus colour.

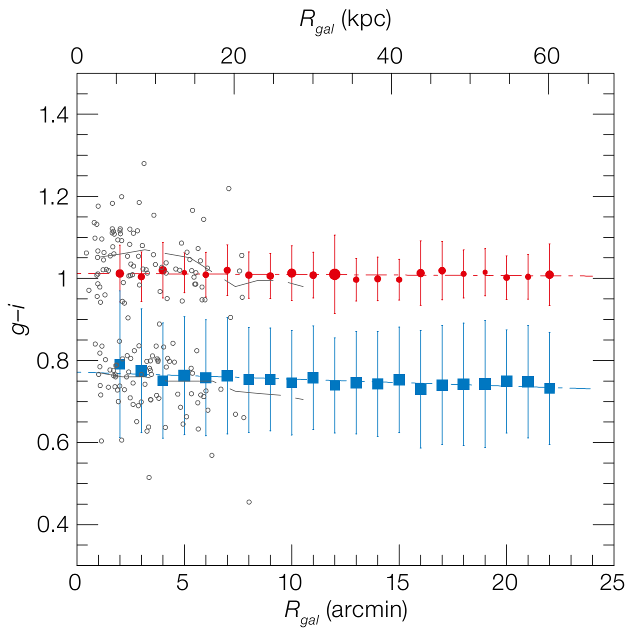

Figure 4. Position and width of the blue and red GCs (blue squares and red circles respectively) plotted at different R_{gal}. Symbol size is proportional to the fraction of objects associated with each peak. A fit to the data is shown with dot-dashed lines. Grey dots show spectroscopically confirmed GCs; grey long-dashed lines mark the rolling fits of the blue and red GC peaks as derived by Arnold et al. (2011) obtained from a combination of spectroscopically and photometrically selected GCs.

first approximation, the simplest interpretation of the gradient (or lack of it) in the peak luminosity of the GCLF is a trend (or lack of it) in the mean GC mass with R_{gal}.

We further inspected how the TOM differs between the red and blue GCs, after dividing the blue/red GCs by adopting a sharp colour separation at $g - i = 0.9$ mag (see below). Our analysis showed that the GCLF of the blue and of the red GCs has a peak consistent with the TOM of the total GC selection. The interesting point here is that a ≈ 0.2 mag offset exists between the red and blue GCLF, with the red system being fainter. Indeed, from a stellar population viewpoint, such behaviour is expected if the GC mass function is universal across metallicity (Jordan et al., 2007).

With the future VEGAS-SSS studies, we will further explore the dependence of m_g^{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.

GC colour distribution

The choice of NGC 3115 as the first VEGAS-SSS target was also motivated by the fact that the galaxy is the first one beyond the Local Group with a confirmed bimodal metallicity distribution (see Brodie et al., 2012; Cantiello et al., 2014a; and references therein for more details). 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 colour of GCs in optical bands has been equated to metallicity ([Fe/H]) bimodality, implying a fundamental constraint on GCs and galaxy formation scenarios. Metallicity bimodality requires two distinct epochs or mechanisms of formation, or both, for the blue/metal-poor and red/metal-rich GC subpopulations. However, this assumption became the subject of debate when various authors independently, using observations and stellar population models, pointed out non-negligible nonlinearities in the colour–metallicity relations of GCs, and demonstrated that the presence of such nonlinearities naturally produces bimodal colour histograms from non-bimodal [Fe/H] distributions. This interpretation provided a simple, alternative explanation for the ubiquity of bimodal GC colour distributions, based on stellar evolution.

Using the same approach adopted for the GCLF, we analysed the colour distribution of GC candidates in NGC 3115. The results are shown in Figure 3. The figure shows the "total - background" density distribution, similar to panel (c) in Figure 2, versus colour. The plot shows two obvious features: 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.

By analysing the position of the blue and red peaks as a function of R_{gal} (Figure 4), various features appear:
- A clear colour–R_{gal} correlation for the blue GC component, and no correlation, or only a very weak one, for the red GCs;
- The fraction of red GCs has a slight but significant decrease with respect to the blue GCs at large radii;
- The width of the two sequences is relatively stable with radius, with the blue distribution being broader at all radii.

In Figure 4 we also added data from Arnold et al. (2011) from the SAGES Legacy Unifying Globulars and GalaxieS (SLUGGS) survey. The grey symbols show spectroscopically confirmed GCs (dots), and the rolling fits for the blue and red GC peaks as derived by combining the spectroscopic and photometric samples (grey dashed lines). There is a good match between the VEGAS-SSS and SLUGGS results. In particular, we highlight the very good match with the colours of spectroscopically confirmed GCs. The agreement appears even more striking if one takes into account that the SLUGGS data were obtained by coupling *gri*-band imaging data from Suprime-Cam at the 8.2-metre Subaru Telescope and spectroscopy from the 10-metre Keck-II telescope with DEIMOS.

Finally, we analysed the radial profiles of the projected surface density of GC candidates, inspecting the full GC sample, and the red and blue subsystems separately. The results are shown in Figure 5. Our analysis reveals that the total, red and blue GCs follow very closely an $R^{1/4}$ de Vaucouleurs profile, and that the profile of red GCs appears steeper than that for the blue GCs while both are shallower than the galaxy light profile. Moreover, the red GCs and the galaxy light profile match at $R_{gal} \geq 7.5$ arcminutes, while the density of GCs is lower at smaller radii. Such a depletion, already observed in other galaxies brighter than NGC 3115, has been interpreted as a higher efficiency for GC-disruption mechanisms in the inner galaxy regions by dynamical friction, two-body relaxation and GC tidal shocking (see Goudfrooij et al. [2007] and references therein).

Overall, the properties observed 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, and suggest that the galaxy has undergone a relatively quiescent evolution, without major star-forming events.

SSS sizes

The selection of SSSs based on one single colour is inherently uncertain and results in a catalogue with large fractions of contaminating sources. An additional optical colour certainly reduces the fraction of contaminants, especially if *u*-band photometry is available. To partly overcome the problem of using one optical colour alone, we also estimated the physical extent of SSSs using the aforementioned tools. We finally obtained a catalogue containing ~ 30 000 sources with both photometry and R_h estimates; the latter have been compared with literature studies, with encouraging results.

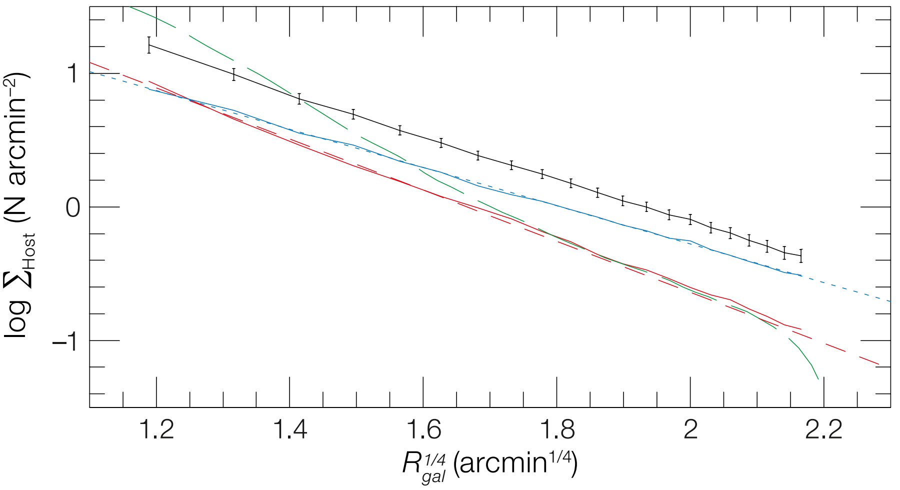

Figure 5. Surface density profiles of blue, red and total GC population (blue, red and black lines respectively). The galaxy surface brightness profile in *g*-band from Capaccioli et al. (2015, in prep.) is also shown by a green long-dashed line. The linear fit to the surface density is shown by a dotted line. The scale of the galaxy profile is arbitrary.

Object sizes provided another attribute to discriminate between real SSSs hosted in the field of NGC 3115, and fore/background sources. Future studies with new deep VEGAS-SSS *gri*- and *u*-band data will be used to further study the issue, and — for targets at larger distances, where GC sizes cannot be reliably estimated — constrain even more tightly the properties of other, less populated classes of SSSs, such as UCDs and cEs.

Future perspectives

The final catalogues from VEGAS-SSS will contain accurate photometry, positions and sizes for thousands of SSS candidates in the field of bright ETGs. The programme will have a twofold legacy value. First, for preparing future observational studies. The coupling of optical data with just one near-infrared band is very effective in reducing the fraction of SSS contaminants to ≈ 5 % or less. The VEGAS-SSS catalogues will then be perfectly suited to be complemented by single-band near-infrared imaging (e.g., with a large-format near-infrared imager like VISTA). Moreover, having complete and clean SSS catalogues is essential for the preparation of spectroscopic follow-up campaigns.

Second, the results obtained for the GC population in NGC 3115, based on *g*- and *i*-band data, suggest that a similar analysis carried out on the final VEGAS-SSS target list, 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.

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