Are small-scale substructures a universal property of galaxy haloes? 
The case of the giant elliptical NGC 5128

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ABSTRACT
We present an analysis of the spatial and chemical substructures in a remote halo field in the nearby giant elliptical galaxy Centaurus A (NGC 5128), situated \(~\sim 38\) kpc from the centre of the galaxy. The observations were taken with the Advanced Camera for Surveys instrument on-board the Hubble Space Telescope, and reach down to the horizontal branch. In this relatively small \(3.8 \times 3.8\) kpc\(^2\) field, after correcting for Poisson noise, we do not find any statistically strong evidence for the presence of small-scale substructures in the stellar spatial distribution on scales \(\sim 100\) pc. However, we do detect the presence of significant small spatial-scale inhomogeneities in the stellar median metallicity over the surveyed field. We argue that these localized chemical substructures could be associated with not fully mixed debris from the disruption of low-mass systems. NGC 5128 joins the ranks of the late-type spiral galaxies the Milky Way, for which the stellar halo appears to be dominated by small-scale spatial substructures, and NGC 891, where localized metallicity variations have been detected in the inner extraplanar regions. This suggests that the presence of small-scale substructures may be a generic property of stellar haloes of large galaxies.

Key words: galaxies: formation – galaxies: haloes – galaxies: individual: NGC 5128 – galaxies: stellar content.

1 INTRODUCTION
The early history of galaxy assembly leaves its signatures in the properties of the stellar content of the outer regions of galaxies. The currently favoured scenario of galaxy formation in a hierarchical context predicts that the vast majority of stars in the outskirts of galaxies should be accreted from disrupted satellite galaxies (e.g. Abadi, Navarro & Steinmetz 2006; Zolotov et al. 2009). The ages, metallicities, spatial distribution and amount of substructures in the faint outskirts of present-day galaxies are therefore directly related to their assembly histories, and to issues such as the suppression of star formation in small haloes.

Recent wide field observations of the Milky Way have led to the identification of a number of large-scale stellar features, attributed either to past accretion of identified satellites (e.g. Ibata, Gilmore & Irwin 1994; Yanny et al. 2000, 2003; Majewski et al. 2002; Newberg et al. 2002), others of unknown progenitors (e.g. Grillmair & Dionatos 2006; Belokurov et al. 2007) and others to the disruption of globular clusters (e.g. Odenkirchen et al. 2001; Grillmair 2009). The accretion of stars from satellites is clearly a contributor to the stellar haloes of galaxies. Quantitative analysis of wide-field imaging data from the Sloan Digital Sky Survey indicates that the stellar halo of the Milky Way is highly structured on small scales (Bell et al. 2008).

For the nearest Milky Way analogue NGC 891, the analysis of deep and high resolution imaging data sampling a quadrant running parallel to the high surface brightness disc of the galaxy, and extending outward to more than 10 kpc from the plane of the galaxy, identified strong evidence for the presence of highly significant small-scale substructures in the median metallicity map (Ibata, Mouhcine & Rejkuba 2009). The degree of substructures present on the stellar density distribution in the halo of NGC 891 is found to be strikingly comparable to what is present in the Milky Way (Ibata et al. 2009). The extraplanar regions of NGC 891 appear to be composed of a large number of incompletely mixed subpopulations. The discovery of a giant stream that loops around the galaxy and a series of low surface brightness features in its outskirts demonstrates that NGC 891 had an active accretion history (Mouhcine, Ibata & Rejkuba 2010a).

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Being the nearest giant elliptical galaxy, NGC 5128 and its outer regions in particular have been targeted extensively as a unique testing ground for stellar population and formation models of elliptical galaxies (Soria et al. 1996; Harris, Harris & Poole 1999; Harris & Harris 2000, 2002; Marleau et al. 2000; Rejkuba et al. 2001, 2002, 2005). The colour–magnitude diagrams (CMDs) of the stellar populations in the remote regions of the galaxy suggest that those regions are dominated by moderately metal-rich stars, i.e. [M/H] \sim -0.65, with a very wide red giant branch (RGB), suggesting that stars at large radii span a wide range of metallicities (Harris et al. 1999; Harris & Harris 2002). Different stellar age indicators, i.e. the red clump, the asymptotic giant branch (AGB) bump, the period distribution of long period variables, globular clusters, suggest that the outer regions of NGC 5128 are populated by old stars, with a likely presence of a small fraction of intermediate-age stars (Soria et al. 1996; Rejkuba et al. 2001, 2003; Woodley et al. 2010).

Possible formation histories of elliptical galaxies come generally in three flavours, first an early and rapid in situ formation (e.g. Larson 1974; Harris, Pritchet & McClure 1995), secondly later mergers of pre-existing disc galaxies (e.g. Toomre 1977; Ashman & Zepf 1992) and finally as the results of multiple dissipationless mergers and accretions of distinct protogalactic fragments (e.g. Côté, Marzke & West 1998). Significant effort has been devoted over the years to test these scenarios using a variety of discriminants e.g. stellar ages, chemical abundances, kinematics and globular cluster systems. These different formation histories should give rise also to different stellar halo structures. The in situ formation would predict relatively few substructures, as the formation epoch was many dynamical times ago. The stellar haloes of elliptical galaxies that have grown hierarchically through mergers and accretions would be however substantially lumpy, and possibly as structured as those predicted by the most extreme cold dark matter hierarchical formation models.

The purpose of the present paper is to examine the distribution of the stellar populations in the outer regions of NGC 5128, and to investigate in particular the clumpiness of the spatial and chemical structure of the halo population of a giant early-type galaxy for the first time. The data upon which this study is based have been presented in detail in Rejkuba et al. (2005, hereafter referred to as R05). The layout of this paper is as follows: in Section 2 we briefly introduce the data set used in the paper, while Section 3 presents the analysis to uncover small-scale substructures over the surveyed area. The implications of our findings are discussed in Section 4, and we draw our conclusions in Section 5.

Throughout this paper we assume a distance of 3.8 Mpc, i.e. distance modulus of (m − M)_0 = 27.92 (R05; Harris, Rejkuba & Harris 2010). We note that NGC 5128 is located at relatively low Galactic latitude (\ell = 309.52, b = 19.42), and therefore the targeted field suffers from significant (though not large) extinction from foreground dust. Following R05, we adopt a reddening value of E(B − V) = 0.11 (Burstein & Heiles 1982; Schlegel, Finkbeiner & Davis 1998), which corresponds approximately to A_V = 0.36 and A_I = 0.21.

2 DATA

As described in detail in R05, a single deep pointing was observed with the Advanced Camera for Surveys (ACS) camera on-board the Hubble Space Telescope (HST) in the halo of the galaxy NGC 5128 (program GO-9373), at a location approximately \sim 38 kpc south of the nucleus (Fig. 1). The target field was chosen to avoid any peculiarities of the galaxy, such as jet-induced star-forming regions (Mould et al. 2000; Rejkuba et al. 2002), shells (Malin, Quinn & Graham 1983) and dust lanes (Stickel et al. 2004). The F606W and F814W passbands were used (approximately broad-band Johnson V and Kron–Cousins I), with a total exposure of 8.58 h (12 full orbits) in each filter, which reaches F606W \sim 30, F814W \sim 29. ALLFRAME software (Stetson 1994) has been used to measure the photometry of all detected sources on the ACS images. To select stellar objects, we applied the criteria of R05 (summarized in their fig. 3), namely those sources with ALLFRAME sharpness parameter within their defined hyperbolic envelope, and with \chi^2 < 3. The left-hand panel of Fig. 2 shows the foreground reddening-corrected CMD of all objects detected in our images and classified as stars in the deep ACS halo field. The CMDs are shown as density contours to reveal features in otherwise crowded regions. In addition to the wide sequence of red giant stars, red clump stars are visible at I_c \sim 27.5 and (V − I)_c \sim 1.0, and those on the AGB bump at I_c \sim 26.5 and (V − I)_c \sim 1.3.

Careful analysis of the completeness corrections and photometric uncertainties has been conducted via Monte Carlo simulations. Artificial stars were added to the frames, which were then reprocessed in the same way as the original data, locating the 50 per cent completeness level of the data at I_c \sim 28.8 and V \sim 29.7. The distribution of photometric differences between input and recovered magnitudes as a function of magnitude shows that the photometry is excellent with virtually no bias down to very faint magnitudes; for instance, at I_c = 27 the uncertainty is \σ_I \sim 0.1. We have fitted the R05 uncertainty functions with the following relations:

\begin{align}
\σ_V(V) &= 2.883 \times 10^{-9} \exp(0.592 V + 0.672), \\
\σ_I(I) &= 3.029 \times 10^{-7} \exp(0.530 I - 1.548),
\end{align}

\text{(1)}

\text{(2)}

Figure 1. The location of the ACS field studied in this contribution lies \sim 38 kpc to the south of NGC 5128, superimposed on a photographic image extracted from the Digitized Sky Survey. The scale of the region is shown both in arcmin and kpc at the distance of NGC 5128. The X and Y axes of the ACS mosaic, as constructed by R05, are displayed on the image; these correspond approximately to the directions north and east, respectively.
which give a good approximation to the uncertainty estimates for \( V < 29 \) and \( I < 28 \). In the analysis below we will assume that the \( I \) and \( V \) uncertainties are uncorrelated (i.e. with no colour terms, which is a reasonable assumption), so we adopt the above fitting functions to assign uncertainties to the individual stars in the survey. To investigate the properties of the stellar spatial distribution, we select only stars with excellent photometry, i.e. \( \sigma_{\text{FK06}} < 0.2 \) and \( \sigma_{\text{FK15}} < 0.2 \). We further limited the selection to stars with \(-0.5 < (V-I) < 4.0\), yielding a catalogue of approximately 43,400 stars.

As well as encompassing stars in the outskirts of NGC 5128, the deep ACS observations also intersect the foreground Galaxy. To estimate the foreground counts, we used the Besançon Galactic population model (Robin et al. 2003) to estimate the foreground contamination. The model predicts 70–80 stars in the range of \( I = 21–28 \) over a field-of-view comparable to that of ACS in the direction of NGC 5128. The right-hand panel of Fig. 2 shows a typical predicted CMD of the Galaxy foreground stars. The model predicts about 15–20 Galaxy foreground stars with colours and magnitudes similar to those of RGB stars at the distance of NGC 5128. This constitutes much less than 1 per cent of the total number of stellar objects classified as red giant stars in our photometric catalogue, indicating that the foreground contamination is not an issue for the analysis presented below.

Large background galaxies as well as bright foreground stars cause holes in the stellar distribution map. To correct for this, and for the gap between the two CCDs in the camera, when studying the two-dimensional distribution of stellar density and metallicity, a mask was constructed by choosing suitably large elliptical areas around these problematic regions; in all, 3 per cent of the image was discarded in this manner. Only those stars outside of the masked regions were kept in the final catalogue.

It is well known that the photometric properties of old RGB stars are linked to their metallicities, offering therefore a way to determine the metallicity distribution of old stellar populations by comparing their CMDs to RGB tracks. The metallicity of stars on the red clump cannot be estimated however by comparing their photometry to RGB tracks; we therefore imposed a faint cut-off at \( M_I < -0.75 \) to the catalogue selected above in order to retain only bona-fide RGB stars. This limit corresponds to \( I < 27.17 \), or \( I < 27.38 \), where the \( I \)-band measurement uncertainty is \( \sigma_I = 0.13 \). An additional quality cut of \( \sigma_V = 0.13 \) was imposed to ensure that the \( V \)-band measurements were also of good quality, yielding a catalogue of about 13,300 RGB stars. It is worth mentioning that these magnitude cuts do not exclude metal-rich RGB stars. To estimate the metallicities of the selected RGB stars, we repeat the procedure explained in Mouhcine, Rejkuba & Ibata (2007), interpolating between the models of VandenBerg et al. (2006) of \( \alpha \)-enhanced, i.e. [\( \alpha/\text{Fe} \)] = 0.3, RGB stars of mass 0.8 M\( \odot \). The models span \(-2.014 < [\text{M}/\text{H}] < -0.097 \) approximately in steps of 0.1 dex, and are complemented at the metal-rich end by two models with \([\text{M}/\text{H}] = 0.0 \) and \(+0.4 \). Stars outside of the colour–magnitude range covered by these RGB tracks were flagged and not used in subsequent analysis (i.e. no extrapolation beyond the validity of the models was attempted). At the distance of NGC 5128, the AGB bump is found to be located at \( I \sim 26.8 \) with a dispersion of 0.12 mag (see R05 for more details). The sample of selected bona-fide RGB stars therefore contains AGB bump stars. To examine the effects of this on the estimates of the chemical properties of the population of RGB stars, we constructed two samples by selecting stars brighter than \( I = 27.38 \) and 26.6, respectively. The metallicity distribution functions of both samples are found to be almost identical, i.e. the overall shape is unchanged and the changes in the median and/or average metallicities are much smaller than the typical estimate of the metallicity error. This indicates that the presence of AGB bump stars in the selected sample of RGB stars does not bias the results discussed below.

3 Analysis

3.1 Spatial substructure

We first perform an analysis of the number density variations over the area of the ACS survey. Panel (a) of Fig. 3 shows the star-count density map in the \( X, Y \) CCD coordinate system chosen by R05. We opted to bin the stars in a grid of \( 25 \times 25 \) superpixel, to contain \( \sim 100 \) sources (to ensure a signal-to-noise ratio of \( \sim 10 \)).

The star number density has been corrected for the mask, and only superpixels with a usable surface area larger than 50 per cent were kept. The map appears approximately homogenous, with no obvious gradient. This is not very surprising since the observed field covers a small physical size at the distance of NGC 5128 compared to its projected radial distance. Since we do not have an a priori model of the large-scale stellar distribution over the targeted field, we fit the observed stellar distribution with a two-dimensional Legendre...
Figure 3. Panel (a) shows the surface density of RGB stars in the ACS field in the coordinate system of Fig. 1, binned into a 25 × 25 superpixel array. Clearly, at this distance from the centre of the galaxy, the density is approximately uniform. Fitting a smooth two-dimensional model to the data (panel b – fitting details are given in the text) and subtracting shows the small-scale variations apparent in panel (c); the significance of these variations is displayed in panel (d).

A polynomial function (shown in panel b), with up to quadratic terms in $X$ and $Y$ including cross-terms (i.e. six parameters), which is sufficient to provide a smooth empirical template to compare the data. The residuals between the data and the best smooth model are shown in panel (c), along with their statistical significance in panel (d), where we have assumed only Poisson noise uncertainties (the effect of the mask is properly accounted for). There appears to be no coherent large-scale structure in the residuals that might indicate the presence of, for instance, streams or shells of stellar debris.

How likely are these small-scale variations about the model of the stellar spatial distribution? A way to quantify the significance of the presence of substructure in a survey is to estimate the rms deviation of the data around a smooth model, taking into account the expected Poisson noise in the model. Bell et al. (2008) proposed the following statistic: 

$$\sigma/\text{total} = \sqrt{(1/n) \sum (D_i - M_i)^2 - (1/n) \sum (M'_i - M_i)^2 / (1/n) \sum D_i},$$

where $n$ is the number of discrete bins the sample is divided into, $D_i$ are the individual observed counts in those bins, $M_i$ are the model values in the pixels and $M'_i$ is a Poisson realization of the model with mean $M$. Thus the numerator is the pixel scatter of the data around the model minus the expected scatter in the model, while the denominator was chosen to be the total of the Poisson scatter. This statistic is convenient because it is independent of the choice of binning scale (provided that the substructures are well sampled by the chosen binning scale), and the number of sources in the survey, and furthermore the Poisson noise contribution is removed.

For a bin size ranging from 100 to 350 pc, i.e. grids of 42 × 42 to 12 × 12, respectively, the fractional rms deviation $\sigma/\text{total}$ varies from 0.04 to 0.02 with probabilities of finding those values of this statistic by chance ranging from 12 to 22 per cent, assuming the smooth model shown in panel (b) of Fig. 3. This clearly indicates that the small-scale deviations of the data around the model shown in Fig. 3 are consistent with what would be expected from Poisson noise deviations from a smooth model. The stellar populations within the surveyed field are then most likely smoothly distributed at physical scales larger than ∼100 pc.

This contrasts with what was reported for the two large late-type galaxies where the properties of small-scale substructures have been investigated so far. Bell et al. (2008) found that the fractional rms deviation exceeds $\sigma/\text{total} = 0.4$ in the Galactic halo region probed by the SDSS. For the Milky Way analogue NGC 891, Ibata et al. (2009) have estimated $\sigma/\text{total} = 0.14$ for the extraplanar regions within ∼10kpc from the galactic plane, with an extremely small probability of finding this value by chance. This clearly indicates that the spatial distribution of halo stars in both large late-type spiral galaxies is most likely dominated by significantly lumpy components.

The catalogue used in the present analysis integrates stellar populations along the line of sight through the entire halo of the galaxy.
The contrast introduced by any substructure will be then reduced, especially in the presence of multiple substructures along the probed line of sight. It should then be appreciated that the low fractional rms deviation found here does not necessarily imply that localized spatial overdensities are absent in the halo of NGC 5128. Furthermore, the present survey samples a halo region much smaller than that studied in NGC 891 by Ibata et al. (2009), and a tiny fraction of the halo when compared to the vast region of the Galactic halo sampled by the SDSS data examined in Bell et al. (2008). Wide-field observations covering a representative volume of the outskirts of the galaxy are needed to establish (or to rule out) firmly the predominance of a smooth stellar component at large radii in NGC 5128, and to quantify comprehensively the amount of substructures in those regions.

3.2 Metallicity substructures

In this section we investigate the properties of the two-dimensional distribution of stellar metallicities over the surveyed region. Given the smaller size of the sample of stars for which we can measure photometric metallicities, we decided to distribute stars in a $12 \times 12$ bin grid ($350 \times 350$ pc$^2$) to ensure a high signal-to-noise ratio in each superpixel. The star number density has been corrected for the mask, and we have discarded the few superpixels where the usable surface area was less than 50 per cent. As in Ibata et al. (2009), we use the median metallicity as a statistic to investigate the spatial variations of stellar populations in the outer regions of the galaxy. This choice presents the advantages of being insensitive to e.g. variations of the population spatial density, holes due to bright stars, etc.

The map of median metallicities estimated in the superpixels is shown in the upper panel of Fig. 4. The lower panel of the figure shows the map of the uncertainties of median metallicities. The errors on the median metallicity in each superpixel is estimated by simulating the effects of both the photometric uncertainties on the metallicity estimate for each star belonging to the superpixel and the sampling uncertainty due to the limited number of stars per superpixel (see Ibata et al. 2009, for a detailed description). The map shows that the combined random errors on the median metallicities in the superpixels are of the order of 0.02–0.04 dex.

The first clear feature of the median metallicity map is the presence of a large-scale gradient over the field, with the average median metallicity decreasing when moving diagonally with increasing $Y$ (i.e. moving from the west to the east). A second striking feature of the median metallicity map is that the pixel-to-pixel variations are significantly larger than the random errors. Note that while we notice the presence of numerous superpixels dominated by stellar populations with lower median metallicities, i.e. $[\text{M/H}] \lesssim -0.7$, than that of the overall stellar population, i.e. $[\text{M/H}] \sim -0.6$, it appears however that metal rich, i.e. $[\text{M/H}] \gtrsim -0.5$, superpixels are rare. How likely are those small-scale variations about a large-scale smooth model of the median metallicity distribution?

To represent the large-scale spatial distribution of median metallicities, we fitted the observed distribution with a two-dimensional Legendre polynomial (up to order 3 in both spatial directions, i.e. 10 parameters). The fit is shown in the top panel of Fig. 5, and exhibits clearly a large-scale median metallicity gradient. The middle panel of Fig. 5 shows the difference between the map of median metallicities and the best smooth model, while the lower panel shows the map of the significance levels of these differences. The lower panel of the figure shows clearly the presence of localized variations at the 3–5$\sigma$ level in the median metallicity map, occurring on the scale of a superpixel or a few superpixels, and distributed over the field. When comparing the significance map of the deviations of the median metallicity map about the best smooth model to the maps of the spatial density distribution and the deviation about the best smooth model (see Fig. 3), we notice that the small-scale substructures in the median metallicity map are not systematically associated to small-scale stellar density substructures. As already discussed in detail in our study of NGC 891, the number density of stars required to cause statistically significant deviations about a smooth median metallicity map is rather small, causing only a modest enhancement in the stellar distribution that is much harder to detect from its density contrast. The stellar number density needed to cause a deviant superpixel in the median metallicity map depends on the shape of the metallicity distribution functions of both the smoothly distributed population and the superimposed substructures, but in broad terms an additional stellar population numbering 10–15 per cent of the smooth population could induce a $\sim 0.1$ dex metallicity variation (Ibata et al. 2009). While this mass fraction of the superimposed population is of the order of the change in density over a typical superpixel, the induced change in the median metallicity of the superpixels is many times larger than the typical errors on the estimate of the median metallicity (see the lower panel of Fig. 4). It is then not surprising that substructures detected in the

Figure 4. Panel (a) displays the median metallicity calculated in each of the spatial superpixels. A slight gradient is apparent, with the top left-hand corner being more metal poor than the bottom right. The corresponding uncertainties, calculated from Monte Carlo simulations accounting for both the photon noise and the sampling errors, are shown in panel (b).
Figure 5. A two-dimensional polynomial model fit to the median metallicity map (panel a of Fig. 4) is shown in panel (a). The residuals between the data and this model are displayed in panel (b). Using the uncertainty estimates on the metallicity from panel (b) of Fig. 4, the statistical significance levels of the metallicity variations are shown in panel (c).

median metallicity map are not inducing significant deviations in the number density map.

The distribution function of the statistical significance of the variations about the best smooth model of the median metallicities map is shown in Fig. 6. The dashed line shows a fitted Gaussian of dispersion equal to 1.58. The probability of finding such a large dispersion by chance (we expect unit dispersion if the uncertainties have been correctly estimated), given the large number of bins, is smaller than 0.1 per cent. This strongly indicates that the variations about the best smooth model of the spatial distribution of median metallicities are significantly larger than expected for a population where the median metallicity varies spatially in a smooth manner.

Perhaps the simplest explanation of these large deviations is that we have underestimated the uncertainties in the median metallicity by 30–50 per cent. This would require that the photometric errors reported by R05 to be underestimated by a similar factor. In our study of NGC 891 we were able to verify our uncertainty estimates by comparing measurements in overlapping fields. Unfortunately, we do not have the necessary complementary data to perform a similar check here. Although we cannot dismiss this possibility, experience from our NGC 891 study (and other projects) suggests that artificial star simulations give reliable uncertainty estimates.

The large pixel-to-pixel variations reported in the median metallicity map are unlikely to result from errors in the zero-point over the ACS field. To induce the observed small-scale metallicity changes, large variations in the zero-point (of the order of 0.1 mag or more) are required, which is extremely unlikely for the very stable instrument that the ACS is.

Could the large-scale metallicity gradient and the small-scale chemical substructures we have uncovered be due to systematic biases? To convert the RGB photometric properties into metallicities, we have had to assume that the stellar populations dominating the surveyed field are uniformly old. Because of the so-called age–metallicity degeneracy, a red RGB star can be either more chemically evolved than a bluer one or older. In the interpolation procedure, we have assumed a single old age for all the stars, which may introduce a bias of up to 0.1 dex, if the age is ~4 Gyr younger (e.g. R05).

The AGB stars are known to be efficient tracers of intermediate-age (1–6 Gyr) stellar populations (Mouhcine & Lancson 2002; Marigo & Girardi 2007). The abundance of AGB stars normalized to RGB stars, which are tracing predominantly older populations, is a good indicator of a stellar population age (e.g. Frogel, Mould & Blanco 1990). The map of the ratio of AGB stars, selected as stars with 22.0 < I < 23.5 and 1.5 < (V – I) < 3.0, and all other quality criteria identical to the RGB sample summarized in Section 2, to...
The spatial distribution of the AGB to RGB ratio is fairly smooth, with no apparent spatial gradient. This suggests the absence of an AGB gradient and then most likely the absence of an age gradient across the observed field. Furthermore, no enhancements of AGB stars relative to RGB stars are associated to any of the superpixels that are deviants from a smooth model of the median metallicity map by more than $3\sigma$. Interestingly, the typical AGB to RGB ratio, i.e. $\lesssim0.2$, is consistent with an old stellar population (Mould 2005). The pixel-to-pixel variations of the AGB to RGB ratio are significantly smaller than what is required for the pixel-to-pixel variations of the median metallicities to be due only to age differences: to account for the $\gtrsim0.15\,$dex variations in median metallicity about the best smooth model for the most deviant superpixels (i.e. $\pm3\sigma$ or more) as a result of age differences, the stellar populations of those superpixels have to be dominated by $\lesssim6\,$Gyr stars, which is not supported by the morphology of the CMD (see R05 for a detailed discussion).

The localized median metallicity variations are also unlikely to result from the effects of small-scale structures in the foreground Galactic interstellar medium. Following Ibata et al. (2009), by using the reasonable assumption that reddening variations scale approximately linearly with mean reddening, we expect less than a couple hundredths of a magnitude scatter at most in colour excess from foreground dust. For the small-scale metallicity variations to be due solely to variation in foreground extinction, the required offset in colour excess are either much larger than the expected scatter, or, more problematically, negative in the case for deviant metal-poor superpixels. Small angular scale variations in foreground dust are therefore unlikely to contribute significantly to the observed small-scale variations in median metallicity.

We conclude that there is no evidence for systematic biases affecting the measure of stellar metallicities. So, under the assumption that the photometric uncertainties have been well estimated, we conclude that the statistically significant small-scale variations in the median metallicities of the stellar populations are present in the targeted halo field. To highlight the differences between the detected small-scale chemical inhomogeneities, Fig. 8 shows the CMDs of all stellar objects populating a metal-poor superpixel, i.e. with a median metallicity of $[M/H]=−0.77$, and a metal-rich superpixel, i.e. with a median metallicity of $[M/H]=−0.47$, located at $(X/kpc=1.75, Y/kpc=3.00)$ and $(X/kpc=2.40, Y/kpc=0.48)$, respectively. Fiducials of RGB sequences for Galactic globular clusters spanning a wide range of metallicities and shifted to the distance of NGC 5128 are overplotted. The stellar populations occupying both superpixels appear to be different. A significant fraction of bright RGB stars populating the metal-poor superpixel exhibit photometric properties consistent with metallicities in the range of $[Fe/H]=−2.2$ and $−1.3$. Such metal-poor stars are absent in the metal-rich superpixel. Furthermore, the reddest stars in the metal-rich superpixel extend clearly to higher metallicities than those occupying the metal-poor superpixel. The stellar population differences between the localized substructures in the median metallicity spatial distribution would suggest that the survey has revealed the presence of inhomogeneities that have not yet been fully blended into the smooth halo.

### Figure 7
The spatial distribution of the ratio of AGB stars to RGB stars over the ACS field.

The metallicity distribution function of the stellar populations in the outer regions of NGC 5128 has been determined over an extended range of radial distances, 10–40 kpc (Harris et al. 1999; Harris &

### Figure 8
CMDs of stars populating two superpixels with their respective positions indicated in each panel. The left-hand panel shows the CMD of the most metal-poor superpixel in the map shown in Fig. 4 with a median metallicity of $[M/H]=−0.77$, while the right-hand panel shows the CMD of a typical metal-rich superpixel with a median metallicity of $[M/H]=−0.41$. Note that the median metallicity for the whole field is $[M/H]=−0.53$. Shown also as solid lines are the red giant sequences of the indicated Galactic globular clusters from Da Costa & Armandroff (1990) assuming an intrinsic distance modulus for NGC 5128 of 27.9. It is clear that the metal-poor side of the RGB is much more populated in the case of the metal-poor spatial superpixel than for the metal-rich one.
Harris 2002; R05). The overall shape, mean metallicty, metallicity dispersion, fraction of metal-poor stars are found to be strikingly similar (R05) over these fields. This indicates that the metallicity gradient present within the field at ∼40 kpc (see Fig. 5) could not be associated to a large-scale metallicity gradient, as it would lead to metallicities significantly higher than observed if extrapolated inward. The most likely explanation is that the median stellar metallicity gradient present within the ACS halo field is related to chemical inhomogeneities present locally.

Using the predictions of a Λ cold dark matter semi-analytical galaxy formation model, and by summing the total star formation occurring over all the progenitors, Beasley et al. (2003) computed the metallicity distribution function of spheroid stars of early-type galaxies comparable in luminosity and environment to NGC 5128. Despite some differences, the predicted metallicity distribution function resembled qualitatively the observed distribution function of stellar metallicities in the outer regions of NGC 5128, i.e. mean metallicity, metal-rich end cut-off and extent of the metal-poor tail (see R05). This broad agreement suggests that the stellar populations in the outer regions of NGC 5128 could have been assembled in a hierarchical fashion. If this is indeed the case, one can expect to find the presence of chemical substructures caused by the remnants of the disruption of the predicted large populations of subhaloes orbiting around massive galaxies.

The localized chemical inhomogeneities could be in principle potential candidate satellites or remnants of past accretion events. Upon inspecting the stacked ACS image visually, none of the strongly deviant superpixels shows any plausible stellar concentration, although clear RGB sequences are detected for all of them, apart from the superpixel at (X ∼ 1.8 kpc, Y ∼ 3 kpc) which contains the faint, old and metal-poor extended globular cluster reported in Mouhcine et al. (2010b). The extended nature and the low luminosity of that globular cluster become very important when considered in light of the emerging consensus that extended clusters are formed preferentially in low-mass galaxies (e.g. Elmegreen 2008; Da Costa et al. 2009). In M31, all but one extended globular cluster in the outer halo, i.e. at projected distances larger than 30 kpc, are found to be projected on to stellar substructures or are members of a cluster overdensity (Mackey et al. 2010), supporting the scenario where this class of globular clusters originate in low-mass systems.

The properties (luminosity, surface brightness, size, central concentration) of the globular cluster found in the halo field resemble in every way one those of the faint and extended globular clusters populating the Milky Way outer halo (Mouhcine et al. 2010b). This suggests that the extended cluster in the targeted field could have been formed in a similar environment as its Galactic counterparts, and experienced potentially a similar dynamical history. Strong evidence is accumulating that extended and faint globular clusters in the outer Galactic halo, i.e. the so-called young halo globular clusters, were formed in now-defunct dwarf galaxies (e.g. Zinn 1993; Mackey & Gilmore 2004; Forbes & Bridges 2010). Mackey et al. (2010) have argued that the vast majority of globular clusters in the outer halo of M31 are most likely associated with tidal debris features observed in those regions, thus strongly supporting the scenario where the outer globular cluster system of M31 has been built up via the accretion of satellite host galaxies. It is then tempting to suggest that the extended faint cluster in the surveyed halo field in NGC 5128 could have originated in a now disrupted dwarf galaxy. Interestingly, the median metallicity of the diffuse stellar population within the superpixel containing the extended faint cluster is comparable to those measured for metal-poor superpixels deviants at the 3–4σ levels in the observed halo field, i.e. [M/H] ∼ −0.75, suggesting that the stellar populations dominating the metal-poor superpixels could be sharing the same origin. Put together, these properties provide circumstantial evidence that the chemical inhomogeneities detected in the observed field could be related to the disruption of low-mass satellites.

The restricted spatial extent of the present survey limits however our ability to investigate the large-scale distribution of the chemical substructures, to quantify the degree of spatial substructures in the halo of the galaxy and to search for signs of the disruption of the hypothetical progenitor(s) of the detected chemical substructures. Extending the survey of the outer regions of NGC 5128 should be undertaken to tackle comprehensively these questions. When compared to the properties of substructures in the outskirts of late-type galaxies, it will be possible to constrain the assembly histories of galactic haloes as a function of galaxy e.g. morphology, type and mass.

5 SUMMARY AND CONCLUSIONS

To make the first attempt to quantify the degree of substructure in the outer regions of elliptical galaxies, we have undertaken a structural and chemical analysis of the stellar content of a 3.8 × 3.8 kpc² halo field situated ∼38 kpc from the centre of the nearest giant elliptical galaxy NGC 5128. The very deep CMD of the stellar populations used in the analysis reaches the red clump.

Comparing the observed stellar number density map of halo stars to smooth models, we find no statistically significant evidence for the presence of spatial density variations. Deviations from the smooth models, quantified using the rms deviation of the data around the best-fitting model are consistent with what would be expected from Poisson noise deviations in a smooth model. The measured statistics appears to suggest the presence of a smooth stellar halo component at spatial scales larger than ∼100 pc in the region probed by the present survey.

Estimating metallicities of RGB stars from their optical photometry, we investigated the spatial distribution of stellar metallicities. On top of a smoothly distributed large-scale map, we detect the presence of small-scale substructures in the median metallicity across the surveyed field. Although the absolute median metallicity variations are relatively modest, i.e. ranging from ∼0.08 to ∼0.2 dex, they are nevertheless statistically significant. Those small-scale chemical substructures do not appear to be associated with any statistically significant stellar spatial density variations. We argue that these subtle small-scale metallicity variations are related to accretions of low-mass systems.

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