A faint extended cluster in the outskirts of NGC 5128: evidence of a low mass accretion

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ABSTRACT

We report the discovery of an extended globular cluster in a halo field in Centaurus A (NGC 5128), situated \(\sim 38\) kpc from the centre of that galaxy, imaged with the Advanced Camera for Surveys on board the Hubble Space Telescope. At the distance of the galaxy, the half-light radius of the cluster is \(r_h \sim 17\) pc, placing it among the largest globular clusters known. The faint absolute magnitude of the star cluster, \(M_V = -5.2\), and its large size render this object somewhat different from the population of extended globular clusters previously reported, making it the first firm detection in the outskirts of a giant galaxy of an analogue of the faint, diffuse globular clusters present in the outer halo of the Milky Way. The colour-magnitude diagram of the cluster, covering approximately the brightest four magnitudes of the red giant branch, is consistent with an ancient, i.e., \(\gtrsim 8\) Gyr, intermediate-metallicity, i.e., \([\text{M/H}] \sim -1.0\) dex, stellar population. We also report the detection of a second, even fainter cluster candidate which would have \(r_h \sim 9\) pc, and \(M_V = -3.4\) if it is at the distance of NGC 5128. The properties of the extended globular cluster and the diffuse stellar populations in its close vicinity suggest that they are part of a low mass accretion in the outer regions of NGC 5128.

Key words: galaxies: formation – galaxies: stellar content – galaxies: individual (NGC 5128) – galaxies: photometry

1 INTRODUCTION

The generic properties of globular clusters, which are generally considered to be free of significant amounts of dark matter, are different from those of the dark-matter-dominated dwarf galaxies. These classes of objects were found for a long time to occupy different regions of parameter space in terms of, e.g., scale size, luminosity, and internal velocity dispersion (e.g. Mateo 1998, and references therein).

New systematic surveys for globular clusters and dwarf satellites over the last few years have generated a shift in our understanding of the connection between those two classes of objects. On one hand, several of the newly discovered dwarf satellites around the Milky Way (e.g. William et al. 2005; Belokurov et al. 2007) and Andromeda (e.g. Zucker et al. 2004; Martin et al. 2006; Irwin et al. 2008) exhibit luminosities and/or sizes that are strikingly comparable to those of globular clusters. On the other hand, luminous star clusters with large sizes have been discovered around, e.g., M31 (Huxor et al. 2005) and M33 (Stonkutė et al. 2008). In contrast, in the Milky Way globular cluster system, most of the unusually extended star clusters are the Palomar-type objects that lie preferentially at large Galactocentric distances and are predominantly faint (e.g. Van den Bergh & Mackey 2004). The extended luminous star clusters are found to resemble the classical globular clusters in terms of their stellar population properties, i.e., they are generally old and metal-poor, albeit with combined structures and luminosities unlike those observed for any other globular clusters in the Local Group or beyond (Mackey et al. 2006). They are found to occupy the gap in parameter space between classical (compact) globular clusters and dwarf spheroidal galaxies (Huxor et al. 2004).

Globular clusters are typically found in much larger numbers within giant elliptical galaxies than in spirals.
such as the Local Group large galaxies. At a distance of 3.8 Mpc \cite{Rejkuba2004, Harris2009}, NGC 5128 is the closest giant elliptical. Its globular cluster system, the largest of any galaxy within \sim 15 Mpc, has been studied photometrically and spectroscopically for many years (for only the most recent such work and references to earlier papers, see, e.g. \cite{Harris2004, Woodley2007, GomezWoodley2007, McLaughlin2008, Woodley2009}, and at present a total of 605 clusters have been individually identified. Extended (and bright) globular clusters are found to represent a tiny fraction of its overall star cluster population. \cite{GomezWoodley2007} indicate that globular clusters with half-light radii exceeding 8 pc make up a few percent of the their spectroscopically confirmed globular clusters. These extended globular clusters have luminosities comparable to those of extended clusters in the outskirts of M31 (see Fig. 8 of \cite{Gomez2004}), brighter than most Galactic globular clusters of similar sizes. The most massive clusters in NGC 5128 are found to follow a mass-size relation, and to have higher mass-to-light ratios on average than clusters with masses below $10^6 M_\odot$ \cite{Rejkuba2007}.

In this contribution, we report the discovery of two faint, extended globular cluster candidates in the outskirts of NGC 5128, one of which is a high-probability old globular of the extended faint star cluster to shed light on its origin. following us to investigate the properties of the neighborhood stellar populations in the remote outskirts of NGC 5128, allowing us to study the resolution stellar populations in the remote outskirts of NGC 5128, allowing us to investigate the properties of the neighborhood of the extended faint star cluster to shed light on its origin. The layout of this paper is as follows: Section § 2 briefly describes the data set, while Section § 3 presents the properties of the reported halo globular cluster. In § 4 we will discuss the present work and its implications. § 5 gives the summary.

Throughout the paper we use an intrinsic distance modulus for NGC 5128 of $(m - M)_0 = 27.90$ following the recent synthesis of five standard-candle distance calibrations given by \cite{Harris2009}. The foreground reddening toward the field was estimated to be $E(B-V) = 0.11$ from the all-sky map of \cite{Schlegel1998}. We have neglected the effect of any possible differential reddening across the targeted field and along the line of sight from within NGC 5128 itself, since the target field is one located in its outer halo. The differential reddening due to the Galactic foreground across the 3.4' width of an HST/ACS field at this Galactic latitude (b = 19°) is also likely to be negligible.

2 DATA

The imaging data we use here is the single very deep pointing obtained by \cite{Rejkuba2005} with the Advanced Camera for Surveys (ACS/WFC) camera on the Hubble Space Telescope (HST) in program GO-9373. This field, imaged in F606W (wide V) and F814W (I), is located at a linear projected distance of approximately \sim 38 kpc South of the NGC 5128 center. The target field was chosen to avoid any known surface brightness anomalies such as jet-induced star-forming regions \cite{Mould2000, Rejkuba2002}, shells and arcs \cite{Malin1983}, and dust lanes \cite{Stickel2004}. The total exposure consisted of 12 full orbits in each filter, reaching $F606W \sim 30$, $F814W \sim 29$ and making this material by far the deepest photometric probe into the stellar population of NGC 5128. In terms of limiting absolute magnitude, it is deep enough to resolve horizontal-branch stars in the halo and to show the structure of the "red clump" (the core-helium-burning stars in the colour-magnitude diagram). The observations and reduction techniques are fully described in \cite{Rejkuba2005} and we therefore only briefly summarize this information here.

The photometry of \cite{Rejkuba2005} was measured with the DAOPHOT suite of codes \cite{Stetson1994}. From this we select stars with high quality measurements, including sharpness parameter $< 2$, goodness of fit $x^2 < 3$, and $\sigma_{F606W} < 0.3$. We further limited the catalogue to stars with $-0.5 < (V-I)_0 < 4.0$.

For an old simple stellar population, redder stars are more metal-rich than bluer ones, and the width of the red giant branch (RGB) at a given luminosity is a very direct indicator of the spread in the stellar metallicity. The analysis of the properties of the age-sensitive features of the asymptotic giant branch bump and the red clump of the stellar populations in the outskirts of NGC 5128 indicates that they are predominantly old. While we cannot rule out a modest age spread in these halo stars (see \cite{Rejkuba2003}), the colour spread of the RGB stars observed in the data is due primarily to a spread in metallicity at an old mean age and can be used to derive the halo metallicity distribution function (MDF) \cite{Harris1999, Harris2004, Mouhcine2005, Mouhcine2003, VandenBerg2008}.

To estimate the metallicities of the survey stars, we repeat the procedure explained in \cite{Mouhcine2007}, interpolating between the models of \cite{VandenBerg2008} for enhanced red giant branch stars of mass $0.8 M_\odot$. The models span $-2.314 < [\text{Fe/H}] < -0.397$ approximately in steps of 0.1 dex, and are complemented at the metal rich end by two models with $[\text{Fe/H}] = 0.0$ and $[\text{Fe/H}] = +0.4$ (see \cite{Mouhcine2004} and \cite{Harris2000} for more details on the interpolation procedure and the calibration of the track grid). 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). The metallicity of stars on the red clump cannot be interpolated from RGB tracks; we therefore imposed a faint cut-off at $M_I < -0.75$ to retain only the brighter RGB stars, which also have the advantage of being clearly brighter than the completeness limits of the data. 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 $\sigma_I = 0.13$ was imposed to ensure that the V-band measurements were also of good quality.

3 RESULTS

3.1 A new faint globular cluster

The overwhelming majority of stars in this outer-halo pointing are the rather uniformly distributed halo field stars. However, the long dynamical timescales of regions this far out (38 kpc and above) allow the possibility that identifiable substructures, such as extended globular clusters (GCs) or faint satellite dwarfs might be present as well. An effi-
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Figure 2. Thumbnail images in V of the two cluster candidate, GC0606 (left panel) and GC0607 (center panel) (see the text for the adopted numbering scheme). Field size of each thumbnail is 4 arcsec across, equivalent to 75 pc at the distance of NGC 5128. Note the very bright star just off the right side of the frame for GC0606. The right panel shows a thumbnail image for comparison of the Milky Way outer-halo cluster Palomar 14, drawn from the HST/ACS archives. Its luminosity and effective radius are similar to our two cluster candidates. To compensate for the 50× nearer distance of Pal 14, its image was resampled with a Gaussian convolution and then block-averaged to the same linear size.

Figure 1 shows the spatial distribution of RGB stars over the field. The sample of all the field stars is shown as small dots, while metal-poor RGB stars, i.e., those with photometrically determined abundances $[\text{Fe}/\text{H}] < -1.3$ dex, are shown as larger solid dots. The most striking feature in the stellar spatial distribution is a small, compact clump of metal-poor RGB stars near the west side of the frame (see Fig. 1). No such clumps are found for the more chemically evolved stellar populations.

To shed light on the nature of the identified concentration of metal-poor stars, we show on the left panel of Figure 2 a zoomed thumbnail image from the ACS $F606W$ stacked frame. The object clearly has the morphology of a faint, extended star cluster, more diffuse in structure than the classical globular clusters that have previously been observed in NGC 5128 (see, e.g., the sample images in [Harris et al. 2006]). Following the homogeneous catalogue numbering system for NGC 5128 GCs defined by [Woodley et al. 2007] and continued in [Woodley et al. 2009], we name this new GC candidate GC0606.

This new object strongly resembles the Palomar-type clusters found in the Milky Way outer halo. For more direct visual comparison, the right panel of Figure 2 shows a thumbnail image of the Milky Way outer-halo cluster Palomar 14 (which is ~70 kpc from the Sun), drawn from the HST/ACS archives. To compensate for the difference in distances between NGC 5128 and Pal 14, i.e., a factor of 50, the Pal 14 image was resampled with a Gaussian convolution and then block-averaged to the same linear size. Pal 14 has a scale size (half-light radius 24 pc) and luminosity ($M_V = -4.7$) that are similar to our NGC 5128 candidates.
Figure 1. Spatial distribution of stellar sources classified as RGB candidates over the observed field. Large solid points show the distribution of metal-poor, i.e., $[\text{Fe/H}] < -1.3$, stars. The small compact clump of metal-poor stars at top center shows the position of the candidate star cluster GC0606. The cross indicates the position of the second star cluster candidate GC0607. The position scales are normalized to (0, 0) at the cluster candidate GC0606.

Figure 3. The colour-magnitude diagram of stars lying within a radius of 2 arcsec from the centre of the cluster candidate GC0606. 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. A sequence of red giant stars is clearly visible.

Figure 4. The cluster colour-magnitude diagram of the cluster candidate GC0606 compared to red giant branches from scaled-solar (the left panels) and $\alpha$-enhanced BaSTI isochrones with $[\alpha/\text{Fe}] = +0.4$ (the right panels). The upper panels show the effect of varying the age at a fixed overall metallicity, while the lower panels show the effect of varying the overall metallicity at a fixed age.

(see below), demonstrating that these faint, extended GCs can be discovered readily with this technique.

A powerful tool to investigate the nature of the candidate is the colour-magnitude diagram (CMD) of its stars. A classical globular cluster with a half-light radius of a few parsecs would subtend only a small angle: a typical half-light radius of 3 pc converts to 3 ACS pixels, not much larger than the 2-px Full Width at Half Maximum of the stellar point spread function. The outer parts of normal, luminous GCs will have enough stars that a CMD can be obtained; this was first done for NGC 5128 by Harris et al. (1998) for the cluster C44=GC0227, an inner-halo cluster which turned out to have moderately low metallicity from its RGB locus. The deep WFPC2/PC1 ($V$, $I$) images used for their study reached to $I_{\text{lim}} \simeq 27$, not as deep as our ACS data.

In the case of faint and diffuse star clusters, the situation is less desperate. Even though the total RGB population within the cluster GC0606 is low, the crowding is not extreme and the ACS images contain a number of resolved members for which the PSF fitting procedure allows accurate photometric measurements. In order to place constraints on the stellar population properties of GC0606, we show in Fig. 3 the CMD of all stellar objects detected within a circular region with a radius of two arcseconds (40 px) around the star cluster. Fiducials of RGB sequences for Galactic globular clusters spanning a wide range of metallicities from Da Costa & Armandroff (1990) and shifted to the distance of NGC 5128 are overplotted. The brightest stars in the cluster are nicely aligned with the red-giant sequences at intermediate metallicity, between the fiducial sequences for $[\text{Fe/H}] \sim -1.3$ and $-1.55$, particularly over the upper two magnitudes where the photometry is of the
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highest quality ($\sigma_{V,I} \lesssim 0.05$). This CMD not only confirms the identity of GC0606 as an old globular cluster, but also places it comfortably within the metal-poor sub-population of the bimodal metallicity distribution function of the globular cluster system of NGC 5128 that peaks at [Fe/H] $\sim -1.5$ (e.g. [Harris et al. 2004; Beasley et al. 2008]).

To strengthen the constraints on the properties of the star cluster, we compare the stellar photometry to the BaSTI theoretical isochrones for both scaled-solar and $\alpha$-enhanced compositions [Pietrinferni et al. 2004, 2006]. Fig. 1 shows aligned Solar-scaled (left panels) and $\alpha$-enhanced (right panels) isochrones on the star cluster CMD. The upper panels show comparison with isochrones with ages ranging from 6 Gyr to 13 Gyr for an overall metallicity of [M/H] $\sim -0.96$, while the lower panels show 10 Gyr isochrones with metallicities ranging from -0.66 to -1.5. Considering first the Solar-scaled isochrones, those with a metallicity [M/H] $\sim -0.96$ and ages older than 6 Gyr are found to provide the best fit along the majority of the RGB. The BaSTI theoretical isochrones also give a metallicity estimate in good agreement with our empirical value of [Fe/H] $\sim -1.3$, keeping in mind that metal-poor GCs typically exhibit enhancement in $\alpha$-elements of approximately $[\alpha/\text{Fe}] \sim +0.3$ (see e.g. Carney 1996).

The comparison of the star cluster CMD to the BaSTI isochrones with an $\alpha$-enhanced composition, i.e., $[\alpha/\text{Fe}] = +0.4$, indicates that the isochrones with [M/H] $= -0.96$ and ages older than $\sim 6$ Gyr provide again the best fit to the cluster RGB. Once again, this is in excellent agreement with the metallicity estimate obtained by comparing the star cluster to Galactic cluster fiducials.

3.2 Structural Parameters

To characterize further the globular cluster, we measured its overall structural parameters. A surface brightness profile of the globular cluster was generated by carrying out aperture photometry of the cluster on both the V and I master images. We derived the profile from daophot/apphot direct concentric-aperture photometry, using the flux differences between apertures of adjacent radii to derive the surface brightness in successive annuli. A problem we faced in this analysis was the presence of a nearby very bright star, which prevented the profile from being measured further out than 16 px radius (0.8”) in I and 26 px (13”) in V.

The profile fitting code of [McLaughlin et al. 2008] was then used to fit King (1962) and King (1963) profiles, numerically convolved with the stellar PSF as defined from nearby bright, uncrowded stars on the frames. The best-fit results for both model profiles are shown in Figure 3. As is evident from the figure, the cluster is very much more extended in characteristic size than the PSF, so the fitting results are insensitive to the details of the PSF or any small changes it might have across the field. The center coordinates are no more certain than $\pm 2$ px (0.1”) on each axis.

The cluster is almost entirely dominated by a large, flat central core. In the sense defined by the King models, the cluster has an extremely low formal value of the central concentration $c = \log(r_c/r_e)$ and central dimensionless potential $W_0$, making it similar to the lowest-concentration globular clusters known. The half-light radius $r_h$ was determined by numerically integrating the PSF-deconvolved King profile solutions out to large radius and then finding the projected radius enclosing half the total luminosity. Lastly, we estimated central surface brightness, which is also insensitive to the details of either the profile fit or the PSF because the cluster has essentially constant surface brightness within 5 px. All the integrated magnitudes and central surface brightness values are internally uncertain to at least $\pm 0.1$ magnitude and perhaps more.

The compiled measured parameters are shown in Table 1. The apparent magnitudes and colours have been converted to luminosities and intrinsic colours assuming $(m - M)_V = 28.10$ and $E_{V-I} = 0.14$, and conversion of half-light radii to parsecs assumes $d = 3.8$ Mpc as stated earlier. It is evident that the cluster is just as diffuse and low-luminosity as its first visual impression gives.

3.3 A second extended cluster candidate

Motivated by the discovery of the candidate GC0606, we visually examined more closely the V and I master images looking for even fainter objects that could plausibly be Palomar-like GC candidates. A candidate located at $\alpha = 13^h25^m19.78^s$, $\delta = -43^\circ34^\prime40.30^\prime\prime$ was found, which we label as GC0607. The middle panel of Figure 3 shows a zoom on the vicinity of this object. This second candidate draws attention to itself primarily as a symmetric, low-surface-brightness patch that is only marginally resolved into a few stars; it has few or no obvious bright RGB stars that would have allowed it to be picked up through our initial search technique (Fig. 1). The left panel of Fig. 3 shows the CMD of all stellar objects detected within a circular region of radius of two arcminutes around the star cluster candidate. RGB fiducials are overplotted as before. No clear sequence of RGB stars is present, but the CMD contains a few stellar objects with luminosities and colours consistent with those expected for horizontal branch stars at the distance of NGC 5128. For comparison, the handful of faintest known GCs in the Milky Way such as Pal 13, Pal 1, or AM4 (all of which lie at $M_V < -4$ integrated luminosity) are almost entirely lacking in RGB stars brighter than the horizontal branch, to such an extent that the addition or subtraction of just one RGB star would change the total cluster luminosity very noticeably.

To determine the structural parameters of the cluster candidate, which is (mostly) unresolved, we used stsdas/ellipse to construct the empirical radial profile of light intensity out to a radius of 30 px (1.5”). Note that the circular aperture photometry leads to the same results to within

| Parameter | GC0606 | GC0607 |
|-----------|--------|--------|
| $\alpha$ (J2000) | 13:25:12.40 | 13:25:19.78 |
| $\delta$ (J2000) | -43:35:15.44 | -43:34:40.30 |
| $I$(tot) | 21.9 | 24.0 |
| $(V - I)$ | 1.15 | 0.84 |
| $\mu_0(I)$ (mag arcsec$^{-2}$) | 23.0 | 24.1 |
| $r_h$ (arcsec) | 0.80 ± 0.03 | 0.47 ± 0.03 |
| $M_I$ | -6.2 | -4.1 |
| $M_V$ | -5.2 | -3.4 |
| $r_h$ (pc) | 14.7 | 8.7 |
| $L_V/L_0$ | $10.3 \times 10^3$ | $1.9 \times 10^3$ |
Figure 5. Surface brightness profile for the brighter candidate, GC0606. The measurements were made through direct concentric-aperture photometry as described in the text. Solid dots show the measurements in concentric annuli with internal error bars, while open circles show the fiducial profile for the stellar PSF. The best-fit King (1966) model is shown as the solid line, while the King (1962) model fit is shown as the dashed line. Left and right panels show the $I$-band and $V$-band results separately; the vertical axis gives the surface brightness normalized to the central value $\mu_0$.

Figure 6. Left: The colour-magnitude diagram of stars lying within a radius of 2 arcsec from the centre of the faint cluster GC0607. Shown also as solid lines are the red giant sequences of the indicated Galactic globular clusters from Da Costa & Armandroff (1990). Right: Surface brightness profile for the fainter of the two cluster candidates, GC0607, measured with ellipse-fitting as described in the text. Symbols and lines are the same as in Fig. 5.

The integrated luminosity, colour, and scale size of GC0607 are all consistent with it being an extremely faint, diffuse GC. However, further and more definitive confirmation (such as by radial velocity measurement) will be exceptionally hard to obtain. Although we suggest that GC0607 should be kept as a plausible cluster candidate, the possibility cannot be ruled out that it is a faint background galaxy.

4 DISCUSSION

Fig. 7 shows the location of the two new GC candidates we have discovered here on the structural parameter plane.
of half-light radius versus V-band luminosity, compared to those of the Milky Way (Harris 1996), M31 (Barmby et al. 2007) and NGC 5128 (Gómez et al. 2006; McLaughlin et al. 2008) shown as solid dots, asterisks, and open circles respectively. M31 extended clusters from (Mackey et al. 2006) are shown as solid squares. Open and solid pentagons show respectively the extended clusters of M33 (Stonkutė et al. 2008), and Scd-E (Da Costa et al. 2009). The extended clusters discussed in the paper are shown as open stars. The solid line shows the relation $\log(r_h) = 0.2 \times M_V + 2.6$ from Van den Bergh & Mackey (2004), and the dashed line represents a constant surface luminosity of $15 L_{\odot} \times pc^{-2}$ within the half-light radius. The Galaxy GC ω Cen and NGC 2419 are labeled.

Figure 7. Half-light radius (in pc) versus V-band luminosity for globular clusters in nearby galaxies. The Milky Way GCs from Harris (1996) are shown as solid dots. Those with the central surface brightness values larger than 23 mag arcsec$^{-2}$ are encircled. GCs of M31 (Barmby et al. 2007) and NGC 5128 (Gómez et al. 2006; McLaughlin et al. 2008) are shown as asterisks and open circles respectively. M31 extended clusters from (Mackey et al. 2006) are shown as solid squares. Open and solid pentagons show respectively the extended clusters of M33 (Stonkutė et al. 2008), and Scd-E (Da Costa et al. 2009). The extended clusters discussed in the paper are shown as open stars. The solid line shows the relation $\log(r_h) = 0.2 \times M_V + 2.6$ from Van den Bergh & Mackey (2004), and the dashed line represents a constant surface luminosity of $15 L_{\odot} \times pc^{-2}$ within the half-light radius. The Galaxy GC ω Cen and NGC 2419 are labeled.

one Galactic GC beyond 25 kpc, i.e., Palomar 13, is not in this group of clusters. It is worth to mention that the central surface brightness of the object of the group of Galactic GCs with luminosities and half-light radii similar to those of G0606 that is not encircled, i.e., Pyxis, is not available.

By examining the distribution of old globular clusters in a number of different galactic systems in the size vs. luminosity diagram, Da Costa et al. (2009) have argued that the distribution function of globular cluster sizes is most likely bimodal. A first dominant subpopulation has half-light radii peaking at $\sim$3.0 pc, but there is a secondary subpopulation with half-light radii peaking at $\sim$10 pc and a dearth of GCs with half-light radii around 5 pc. They suggested that this indicates the presence of two distinct modes of star cluster formation, with the less common extended clusters being primarily formed in the gravitationally smoother environment of dwarf galaxies compared to larger galaxies.

An intriguing implication of this correlation is that extended and diffuse GCs in large galaxies, which tend to be found predominantly in their outer regions (van den Bergh & Mackey 2004; Huxor et al. 2005, 2007), may be of accretion origin. By investigating the distributions of the Milky Way globular cluster properties, their spatial distribution, and by comparing with those of globular clusters in dwarf galaxies, Van den Bergh & Mackey (2004) have suggested indeed that the faint extended globular clusters in the outer Galactic halo originate most likely from the disruption of now defunct dwarf companions. Could the diffuse and under-luminous globular cluster we have discovered in the outskirts of NGC 5128 be the counterpart of the potentially accreted Galactic outer halo extended clusters?

If a star cluster is of accretion origin, one would expect, if the accretion event is not too old and/or the accreted stars are not fully mixed yet, that the diffuse stellar populations in its close vicinity would be different from the average halo stellar populations. The depth of our ACS imaging data resolving the stellar content of the halo down to the core helium burning stars gives us the opportunity to investigate the properties of the diffuse stellar populations in the immediate neighborhood of the extended globular cluster.

The ACS image contains many large background galaxies, as well as several bright stars (see Fig. 1 of
Mouhcine et al. (2003) whose “halos” cause localised holes in the star-counts map. A mask was constructed by choosing suitably large elliptical areas around these problematic regions. We have binned the stars in a $12 \times 12$ grid in order for each super-pixel to contain $\sim 100$ sources (to have signal to noise ratio $S/N \sim 10$). Each superpixel is thus 17″ wide or 314 parsecs projected width. Only stars outside of the masked regions were kept. A detailed and quantitative analysis of the spatial sub-structures over the ACS field is deferred to a subsequent contribution, but it is worth mentioning here that the stellar surface density of RGB stars over the field shows no obvious coherent stellar structure that might indicate the presence of streams or shells of stellar debris. Figure 8 shows the two-dimensional map of the median values of metallicity of RGB stars calculated in the super-pixel grid. For reference, the extended globular cluster discussed in the present paper is located within the most metal-poor super-pixel, the dark blue spot of Figure 8. The random errors on the median metallicities in the super-pixels, due to both photometric uncertainties and population sampling effects, estimated as described in full details in Ibata et al. (2009), are small, i.e., typically $\sim 0.02$ dex.

A striking feature of the median stellar metallicity map is the large pixel-to-pixel variation, much larger than the typical random uncertainties. It is worth noting that those small-scale chemical variations have no obvious correspondence in the stellar density map. Due to the virtually negligible contamination from foreground or background sources, the present observations are extremely sensitive to the presence of sub-structures. It is in principle possible with the ACS to detect a population of $\sim 15$ RGB stars scattered over a volume of many hundred cubic kpc, making it much easier to detect sub-structures from spatial metallicity variations rather than from the enhancement they cause in the stellar density map (see Ibata et al. 2004, for more details).

The outer regions of NGC 5128 have been found to be predominantly populated by moderately metal-rich stars, with an average metallicity of $[	ext{m/H}] \sim -0.5$ and only $\sim 10\%$ of the stellar populations more metal-poor than $[	ext{m/H}] \approx -1$ (Harris & Harris 2000, 2002, Rejkuba et al. 2003). A gradient of the median metallicity is apparent in the median metallicity map, with the top half of the ACS field being more metal-poor than the lower half. As discussed at length by Rejkuba et al. (2003), the metallicity distribution function of the overall stellar populations at $\sim 40$ kpc is very similar in terms of its shape, average metallicity, and metallicity dispersion, to those determined at $\sim 20$ and $\sim 30$ kpc respectively from the centre of the galaxy (Harris et al. 1996, Harris & Harris 2000). No detectable radial metallicity gradient is present in the outskirts of NGC 5128, at least in the range of radial distances probed. The detected median metallicity gradient within the ACS field at $\sim 40$ kpc from the centre of the galaxy should thus not reflect a global metallicity gradient, which would give unreasonably high metallicities if extrapolated inward. The median stellar metallicity gradient is most likely related to localised chemical variations that have not yet been fully blended into the diffuse smooth halo. The spatial correspondence between the median metallicities between the small-scale chemical variations and the extended globular cluster suggest that this object is likely to be related to the same event that has led to the formation of the localised chemical variations.

5 SUMMARY

In this paper, we have presented a discovery and discussion of two new globular cluster candidates in the outer region ($d \sim 40$ kpc from the centre) of the nearest giant elliptical NGC 5128 using very deep HST/ACS imagery. The first and brightest of these two objects is selected based on both the presence of a clear RGB sequence and its structural parameters. The second one was selected solely on basis of its morphological appearance, colour and luminosity, and its structural parameters. The properties of the bright cluster are consistent with its identification as an old, intermediate-metallicity globular clusters resembling in every way we can verify the faint and extended clusters populating the Milky Way outer halo. This is the first time a counterpart of this populations of Galactic globular clusters has been reported for any other galaxy. The combined properties of the extended clusters and the diffuse stellar halo are consistent with the view that the reported clusters were once associated with dwarf galaxies that have disrupted.

Finally, our present work indicates that a search for faint, extended globular clusters in NGC 5128 is entirely feasible. By carefully searching just one deep ACS/WFC imaging field – which in this context is essentially a random pointing in the halo – we have successfully identified two very probable GC candidates and characterized their structural parameters. Extrapolating from just this one field of area 11.5 arcmin$^2$ to the entire NGC 5128 halo area would be extremely risky, but it is worth noting that the Milky Way has more than a dozen known GCs fainter than $M_V \sim -5$ (Harris 1996). NGC 5128 is a more luminous galaxy by an order of magnitude, so it seems quite likely that its vast outer halo should hold some hundreds of faint GCs awaiting discovery, along with their attendant substructures.

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