A search for massive UCDs in the Centaurus Galaxy Cluster *  
(Research Note)

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ABSTRACT

Context. We recently initiated a search for ultra-compact dwarf galaxies (UCDs) in the Centaurus galaxy cluster (Mieske et al. 2007), resulting in the discovery of 27 compact objects with $-12.2 < M_V < -10.9$ mag. Our overall survey completeness was 15-20% within 120 kpc projected cluster-centric distance.

Aims. In order to better constrain the luminosity distribution of the brightest UCDs in Centaurus, we continue our search by substantially improving our survey completeness specifically in the regime $M_V < -12$ mag ($V_0 < 22.3$ mag).

Methods. Using VIMOS at the VLT, we obtain low-resolution spectra of 400 compact objects with $19.3 < V_0 < 21.3$ mag ($-14 < M_V < -12$ mag at the Centaurus distance) in the central 25º of the Centaurus cluster, which corresponds to a projected radius of ~150 kpc. Our survey yields complete area coverage within ~120 kpc.

Results. For 94% of the sources included in the masks we successfully measure a redshift. Due to incompleteness in the slit assignment, our final completeness in the area surveyed is 52%. Among our targets we find three new UCDs in the magnitude range $-12.2 < M_V < -12$ mag, hence at the faint limit of our survey. One of them is covered by archival HST WFPC2 imaging, yielding a size estimate of $r_h \approx 8-9$ pc. At 95% confidence we can reject the hypothesis that in the area surveyed there are more than 2 massive UCDs with $M_V < -12.2$ mag and $r_{eff} \leq 70$ pc. Our survey hence confirms the extreme rareness of massive UCDs. We find that the radial distributions of Centaurus and Fornax UCDs with respect to their host clusters’ centers agree within the 2σ level.

Key words. galaxies: clusters: individual: Centaurus – galaxies: dwarf – galaxies: fundamental parameters – galaxies: nuclei – galaxies: star clusters

1. Introduction

A new class of compact stellar systems called 'ultra-compact dwarf galaxies' (UCDs; Phillipps et al. 2001) has been established during the last decade (Hilker et al. 1999; Drinkwater et al. 2000, 2002; Hasegan et al. 2005; Jones et al. 2006; Mieske et al. 2007; Firth et al. 2007; Misgeld et al. 2008). UCDs are characterised by typical luminosities of $-13.5 < M_V < -11.0$ mag, half-light radii of $10 < r_h < 100$ pc and masses of $2 \times 10^6 < m < 10^8$ $M_\odot$. An intriguing finding from recent studies is that on average, the dynamical M/L ratios of UCDs are about twice as large as those of Galactic globular clusters of comparable metallicity (e.g. Hasegan et al. 2005; Hilker et al. 2007; Evstigneeva et al. 2007; Rejkuba et al. 2007; Mieske et al. 2008a). Indications exist that M/L ratios may be some-

what higher for UCDs in Virgo than in Fornax (e.g. Hasegan et al. 2005; Hilker et al. 2007; Evstigneeva et al. 2007), which could be explained by differences in age, stellar mass function, or, dark matter content.

In our efforts to broaden the environmental baseline of UCD research, we have embarked on UCD searches in the Centaurus galaxy cluster (Mieske et al. 2007) and the Hydra I galaxy cluster (Misgeld et al. 2008), based on data obtained with VIMOS at the VLT (program 076.B-0293). From the UCD search in Centaurus, we found 27 compact objects with radial velocities consistent with them being members of Centaurus, covering an absolute magnitude range $-12.2 < M_V < -10.9$ mag. Their distribution in magnitude and space was found to be consistent with that of the GC population. We did not find very luminous UCDs with $-13.5 < M_V < -12.2$ mag as found in the Virgo and Fornax cluster (Jones et al. 2006; Chilingarian & Mamon 2008; Drinkwater et al. 2000), which may be due to the moderate overall completeness of 15-20%.
within 120 kpc: the survey covered about 50-60% of the total area within 120 kpc, within which only 30% of photometrically selected sources were observed, due to too high candidate density (see Mieske et al. [2007] and Fig. 2).

In this Research Note, we report on the second part of our search for UCDs in Centaurus with VIMOS (program 380.B-0207), with the aim to better constrain their luminosity distribution at the bright end. We increase the area coverage and focus on the bright luminosity regime $M_V < -12$ mag. Our medium-term strategy is to derive dynamical mass estimates for UCDs beyond the Fornax and Virgo clusters to investigate in depth whether average M/L ratios of UCDs systematically vary with environment. Technically, ground-based medium-to-high resolution spectroscopy (R~10000) is only possible for objects with $V < 21.5$ mag (e.g. Mieske et al. [2008]), which translates to a feasibility limit of $M_{V,0} \lesssim -12$ mag at the distance of the Centaurus cluster ($m-M$)=33.3 mag, Mieske et al. [2005]. This is another driver for focusing on the bright luminosity regime $M_V < -12$ mag.

2. The data

The data for this publication were obtained in service mode with the Visible MultiObject Spectrograph VIMOS (Le Fevre et al. [2003]) mounted on UT3 Melipal at the VLT (programme 380.B-0207). VIMOS allows simultaneous observing of 4 quadrants, each of dimension $7' \times 8'$, and separated by about 2'. We observed four multi-object spectroscopy (MOS) pointings close to NGC 4696, the central galaxy of the main cluster component Cen30 (see Fig. 2). Two of those pointings had been targeted already as part of our previous observing program in Period 76 (Mieske et al. [2007]). However, given the slit allocation completeness of about 30% in that run, we re-observed these pointings. We observed two further pointings slightly offset, with the aim to fill the chip gaps, increasing the area coverage within ~120 kpc to almost 100% (see Figs. 2 and 3). Within the four pointings, a slit could be allocated for 54% of the photometrically selected objects (see Sect. 2.2).

2.1. Candidate selection

The candidates for our search for bright UCDs were selected from the VIMOS pre-imaging in the $V$ and $R$ filters which were taken under clear conditions. Prior to applying any selection, we matched the detections in $V$R to the catalog of well calibrated FORS photometry (Mieske et al. [2005]) of the central Centaurus cluster in $V$ and $I$, whose areas overlap with the VIMOS pre-imaging. From this matching we were able to verify that the $V$-band VIMOS zeropoints available from the ESO QC web page[4] for the date of the pre-imaging (17-01-2008) were accurate to within 0.03-0.05 mag.

For de-reddening the apparent magnitudes we used Schlegel et al. [1998]. To select sources as compact object candidates, we defined three criteria regarding size, colour and luminosity.

1. Be unresolved on the VIMOS pre-imaging (as judged by SExtractor star-galaxy separator, Bertin & Arnouts [1996]). At the distance of the Centaurus cluster (45 Mpc, Mieske et al. [2005]), the typical PSF FWHM of 0.85'' corresponds to ~190pc. In Fig. 1 we show that the limit up to which SExtractor classifies a source as unresolved corresponds to $r_{\text{eff}} \approx 70$ pc at the Centaurus cluster distance. Our size selection criterion hence encompasses all known UCDs except the two most massive ones, each of which have $r_{\text{eff}} \approx 100$ pc (Evstigneeva et al. 2008). This corresponds to ~95% of all known UCDs, and ~85% of known UCDs with $M_V < -12$ mag.

2. Have de-reddened colours $0.42 < (V - R)_0 < 0.9$ mag. This $(V-R)_0$ range corresponds to a $(V-I)_0$ range of 0.65 to 1.50 mag (see Fig. 3), which is the colour range typically covered by GCs (e.g. Gebhardt & Kissler-Patig [1999] Larsen et al. [2001] Kundu & Whitmore [2001]). This also covers the colour range of UCDs discovered in the first part of our search (Mieske et al. [2007]). Fig. 3 shows the directly measured $(V-R)_0$ colours, and the corresponding $(V-I)_0$ scale. This scale is derived from matching the $V$,R pre-imaging photometry of unresolved sources with $V$,I photometry from spatially overlapping FORS data (see above; Mieske et al. [2005]). The derived scaling in apparent magnitude space is

\[ (V - I) = -0.163 + 1.911 	imes (V - R) \]

with an rms of 0.11 mag.

3. Have de-reddened apparent magnitudes $19.3 < V_0 < 21.3$ mag ($14 < M_V < -12$ mag). The faint magnitude cut is more than a magnitude brighter than in the first part of our search (Mieske et al. [2007]).

2.2. Spectroscopic observations

Within our 16 masks (4 pointings $\times$ 4 quadrants) the VIMOS mask creation software VMMS enabled the allocation of slits for 412 objects (minimum slit length 6''), compared to a total of 766 photometrically selected sources. We were able to measure redshifts for 389 out of those 412 sources. Our completeness in the entire area surveyed is hence 51% (Fig. 4), about three times higher than in the previous part of our survey (Mieske et al. [2007]). Within the central 120 kpc, the completeness is 52%, only marginally higher.

We used the medium resolution MR grism with the order sorting filter GG475. This covers the wavelength range from 4800 to 10000 Å at a dispersion of 2.5 Å per pixel. The average seeing for the spectroscopic observations was around 0.8'', at a slit width of 1.0''. With a pixel scale of 0.2'', the instrumental resolution (FWHM) is 10-12 Å, corresponding to a velocity resolution of ~600 km/s. For each pointing the total exposure time was 2100 seconds. Arc-lamp exposures for wavelength calibration were attached to each science exposure.

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1 http://www.eso.org/observing/dfo/quality/index_vimos.html

2 A complementary observing campaign targeting canonical dwarf galaxies – including resolved UCD candidates – in Centaurus has been approved for ESO observing period P83.
2.3. Data reduction

For the data reduction from 2D raw spectra to wavelength calibrated 1D spectra we used the recipe vmmosobstare provided by the ESO VIMOS pipeline. This recipe performs bias subtraction, flat field division, wavelength calibration, and spectrum extraction. Fig. 5 shows four examples of calibrated 1D spectra.

The radial velocity measurements of the calibrated 1D spectra were performed via cross-correlation using the IRAF task fxcor (Tonry & Davis 1979) in the RV package. As template for cross-correlation we used a synthetic spectrum created to resemble a typical early-type galaxy (Quintana et al. 1996). This template has proven most reliable for such kind of radial velocity surveys (e.g. Mieske et al. 2004a, Misgeld et al. 2008). For a measurement to be accepted as reliable, we demanded the cross-correlation confidence value $R$ to be larger than 5.5. We then re-run fxcor for those spectra for which $R < 5.5$ was achieved in the first run, and accepted $v_{rad}$ measurements for those that showed clearly identifiable cross-correlation peaks, see Fig. 5 for an example. For more than 90% of our observed sources we could reliably measure a redshift (see Fig. 6).

The radial velocity measurement errors were of the order 50-100 km/s. As a cluster membership criterion we required $1750 < v_{rad} < 5550$ km/s, excluding both foreground stars and background galaxies.

3. Results

Fig. 6 shows a radial velocity histogram of the 389 sources with measured redshifts. Of these 389 sources, 380 are foreground stars, and six objects are background galaxies with $9400 < v_{rad} < 41000$ km/s. Only three objects are members of the Centaurus cluster. At the cluster’s distance modulus $(m-M)$=33.3 mag, Mieske et al. 2005), they cover the magnitude range $-12.2 < M_V < -12.0$ (Fig. 5), at the faint limit of our survey. Table 1 shows the properties of these three confirmed UCDs. We list their $V_0$ and $(V-R)_0$ magnitudes, their radial velocities and errors, and the confidence level $R$ of the radial velocity measurement. Also given is the estimated $(V-R)_0$ colour, as derived from equation (1). For one of the UCDs, CCOS J192.200-41.334, archival HST imaging in the F555W filter (WFPC2, Proposal 5956, PI Sparks) is available. To measure its size, we use the program KINGPHOT (Jordán et al. 2004 and 2005), which was already successfully applied to measure half-light radii $r_h$ of GCs in Virgo and Fornax, and UCDs in Centaurus (Jordán et al. 2005 and 2007). From this fit, we derive a $2\sigma$ upper limit of the projected half-light radius of 0.43 WFPC2 wide-field pixel, corresponding to $r_h \leq 8.9$ pc at the assumed distance modulus of 33.3 mag.

Note that we have not discovered a UCD in the bright luminosity regime $-13.5 \leq M_V \leq -12.2$, within which also only very few UCDs are found in Fornax and Virgo. This confirms the rareness of these extreme objects. Given our overall survey completeness of $\sim 50\%$ and assuming a Poisson distribution for UCD number counts, we can exclude at 95$\%$ confidence the existence of more than two UCDs with $M_V < -12$ mag and $r_{eff} < 70$ pc, within 120 kpc of NGC 4696.

In spite of the lack of such very bright UCDs, there is now a total of eight confirmed UCDs with $M_V < -12$ mag in Centaurus (this paper, Mieske et al. 2007), comparable to the numbers in Virgo/Fornax (Jones et al. 2006, Firth et al. 2007). Seven of those eight sources belong to the main cluster Cen30. Given our completeness of $\sim 50\%$ within the central 120 kpc of Cen30, we can constrain the true number of UCDs with $M_V < -12$ mag in that area to $14 \pm 5$. How does this compare to the number of GCs expected from extrapolating a Gaussian globular cluster luminosity function $M_V < -12$ mag? For the central Cen30 galaxy NGC 4696, we would expect a total

\[\frac{14 \pm 5}{120} \approx 0.11\]

This translates to $\sim 0.5-2$ GCs within 120 kpc of NGC 4696, indicating that the number of UCDs is at least comparable to the number of GCs in Centaurus. This is surprising given the difference in ages between UCDs and GCs, and the different environments in which they are found.
of ~14000 GCs, adopting a specific frequency of 7.3 (Mieske et al. 2005) and an absolute magnitude of $M_V = -23.2$ mag (Misgeld et al. 2009) for NGC 4696. Since we observe within a radius of 120 kpc, we assume that we include most of the GC systems (e.g., Rhode & Zepf 2001) show the GC system of NGC 4472, the most luminous early-type galaxy in Virgo, extends to ~80 kpc). Adopting an absolute turnover magnitude of $M_V = -7.4$ mag (Kundu & Whitmore 2001) and a GCLF width of 1.35 mag (Jordán et al. 2006, 2007), the expected number of GCs with $M_V < -12$ mag is about 5. Although being on the low side, this is still within 2σ of the estimated number of UCDs. Note that only for $M_V < -12.8$ mag the expected number of GCs drops below 0.5. From a purely statistical point of view, only the very brightest UCD luminosities ($M_V \approx -13.5$ mag) are thus unaccounted for by a Gaussian GCLF.

With the database of Centaurus UCDs at hand, it is worthwhile to compare their spatial distribution to those in Fornax. In Fig. 2 we show the projected distance of these two UCD populations (with UCDs defined as compact stellar systems with $M_V < -11$ mag) relative to the central galaxies of Centaurus and Fornax. The Fornax UCD database is the same as used in Mieske et al. (2008b). The distances are normalised to the $r_{500}$ radii of either cluster, for which Reiprich & Boehringer (2002) give $r_{500}=840$ kpc for Fornax, and $r_{500}=1.14$ Mpc for Centaurus. Within the radius of 120 kpc surveyed for this publication, the Centaurus UCD population is slightly more clustered than the Fornax UCD population, at the 96.5% confidence level according to a KS-test. However, this may at least partially be due to the fact that all Centaurus UCDs with $M_V > -12$ mag were discovered in our P76 survey, which had a more complete area coverage for $r < 50$kpc than for $r > 50$kpc (see Fig. 2). When restricting to $r < 50$ kpc in Centaurus and the corresponding $r < 35$ kpc Fornax, the cumulative radial distribution of both samples is indistinguishable. When considering only UCDs with $M_V < -12$ mag – for which the spatial survey coverage is comparable between Fornax and Centaurus – we also find indistinguishable distributions according to a KS-test. We can therefore state that within $2\sigma$, Fornax and Centaurus UCDs have the same radial distribution, when scaled to the respective $r_{500}$ radius of their host clusters.

There are a number of ongoing investigations of the UCD luminosity function towards very bright luminosities ($M_V < -12$ mag) in a range of environments, (e.g. the present work, Wehner & Harris 2008, Misgeld et al. 2008). It will be interesting to investigate how the luminosities/masses of the most massive UCDs correlate with the properties of their host environments (Hilker et al. 2009, in preparation), as previously studied in an analogous fashion for globular cluster systems (Whitmore 2003, Larsen 2002) and systems of young massive clusters (e.g. Weidner et al. 2004).

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Fig. 2. Map of the central Centaurus cluster. The relative coordinates are with respect to NGC 4696, the central galaxy of the Cen30 subcluster. The dotted squares indicate the VIMOS pointing observed in P76 (Mieske et al. 2007). Note that the VIMOS field-of-view consists of four quadrants. The small pointing observed in P76 (Mieske et al. 2007). Note that the Cen30 subcluster. The dotted squares indicate the VIMOS ordnates are with respect to NGC 4696, the central galaxy of Fig. 2.
Fig. 7. Positions of confirmed UCDs in the Fornax (open red circles; Mieske et al. 2008b) and Centaurus clusters (filled blue circles; this paper and Mieske et al. 2007), relative to the central galaxies and normalized to the $r_{500}$ radius of the respective clusters. UCDs are selected as compact stellar systems with $M_V < -11$ mag. The dashed circle indicates the coverage of the search for bright UCDs in Centaurus presented in this paper. The dotted square indicates the central quadrant of the P76 Centaurus survey (Mieske et al. 2007), within which the survey completeness was twice as large as outside (see also Fig. 3).

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**Table 1.** Properties of the 3 massive UCDs detected in our survey, ordered by magnitude. Errors are given in parentheses. “CCOS” in the object identifier stands for Centaurus Compact Object Survey, see also Mieske et al. (2007). The last column gives a $2\sigma$ upper limit for the half-light radius in pc estimated from HST WFPC2 archival imaging.

| ID           | RA (J2000)          | DEC (J2000)         | $V_0$ | $(V-R)_0$ | $(V-I)_0$ | $v_{rad}$ [km/s] | $R$   | $r_h$ [pc] |
|--------------|---------------------|---------------------|-------|-----------|-----------|-----------------|-------|------------|
| CCOS J192.129-41.401 | 12:48:30.88 | -41:24:04.96        | 21.15 | 0.51      | 0.77      | 2650 (47)       | 8.06  |            |
| CCOS J192.200-41.334  | 12:48:48.01 | -41:20:01.52        | 21.22 | 0.64      | 1.03      | 2061 (76)       | 5.79  | $\lesssim 8 - 9$ |
| CCOS J191.958-41.258  | 12:47:49.93 | -41:15:28.04        | 21.34 | 0.90      | 1.52      | 3185 (60)       | 5.94  |            |

**Fig. 3.** Map (left) and CMD (right) of the objects observed in the VIMOS P80 run. Dots indicate all objects to which a slit was assigned. Small (black) circles indicate foreground stars. Large (red) open circles indicate background sources ($v_{rad} > 6000$ km/s). Magenta crosses mark objects for which no radial velocity could be measured. Filled (blue) circles indicate objects with radial velocities in the Centaurus cluster range, hence the UCDs found. In the CMD, the upper x-axis shows the approximate scale of $(V-I)_0$ colours. The scaling of $(V-R)$ with $(V-I)$ was derived from matching the V,R pre-imaging photometry with spatially overlapping FORS V,I photometry (Mieske et al. 2005).
Fig. 4. Completeness of our survey. **Left panel:** Plotted are all photometrically selected objects (small dots) and successfully observed objects (small hexagons). Note the difference to Fig. [3] where only objects included in the masks are plotted. The circle indicates a projected radius of \(~\)120 kpc at the Centaurus cluster distance. **Right panel:** Ratio of successfully observed objects to all photometrically selected objects within the central 120 kpc, as a function of magnitude.
Fig. 5. Four example spectra of our VIMOS data-set, with the corresponding cross-correlation results for radial velocity measurement indicated on top. Y-axis units are flux in ADU for the bottom plots, and cross-correlation height $h$ for the top plots. Objects from upper left to bottom right: A foreground star with cross-correlation confidence level $R > 5.5$; one of the three Centaurus cluster members (CCOS J192.129-41.401), also with $R > 5.5$; a foreground star with $R = 5.0$, whose radial velocity measurement was accepted; a source for which no radial velocity could be measured.
**Fig. 6. Left panel:** radial velocity histogram of the observed sources. The background regime (> 6000 km/s) is excluded. The three Centaurus cluster members are clearly distinguishable. **Right panel:** histogram of the confidence level $R$ achieved in the radial velocity measurement via cross-correlation with a template spectrum. The solid histogram indicates the sources with reliable measurement, the dotted histogram indicates sources without an acceptable cross-correlation result.