Searches for ultracompact dwarf galaxies in galaxy groups

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Accepted 2007 April 9. Received 2007 April 9; in original form 2007 January 24

ABSTRACT
We present the results of a search for ultracompact dwarf galaxies (UCDs) in six different galaxy groups: Dorado, NGC 1400, 0681, 4038, 4697 and 5084. We searched in the apparent magnitude range $17.5 < b_J < 20.5$ (except NGC 5084: $19.2 < b_J < 21.0$). We found one definite plus two possible UCD candidates in the Dorado group and two possible UCD candidates in the NGC 1400 group. No UCDs were found in the other groups. We compared these results with predicted luminosities of UCDs in the groups according to the hypothesis that UCDs are globular clusters formed in galaxies. The theoretical predictions broadly agree with the observational results, but deeper surveys are needed to fully test the predictions.

Key words: astronomical data bases: miscellaneous – surveys – galaxies: distances and redshifts – galaxies: dwarf – galaxies: star clusters.

1 INTRODUCTION

Ultracompact dwarf galaxies (UCDs) have recently been proposed as a new type of stellar system. They were discovered independently by Hilker et al. (1999) (two objects) and Drinkwater et al. (2000a) (five objects including two Hilker’s objects) in spectroscopic surveys of the centre of the Fornax cluster. The discovered objects have absolute magnitudes in the range $-13.5 < M_V < -11.5$, properties intermediate between globular clusters (GCs) and dwarf galaxies, and are mostly unresolved in ground-based imaging (half-light radii $<100$ pc). Searches for similar objects in the Virgo cluster have revealed a population of nine confirmed UCDs in the centre of the cluster (Jones et al. 2006). Further spectroscopic surveying of the Fornax cluster by Drinkwater et al. (2004), 1.5 mag deeper than the original observations (Drinkwater et al. 2000a), has found more than 50 new UCDs in a 0.9 radius field centred on the first ranked galaxy NGC 1399. Mieske, Hilker & Infante (2004a), in their spectroscopic study of the Fornax cluster, identified 54 ultracompact objects with magnitudes down to $V < 21.0$ ($M_V \approx -9.5$ mag) within $\sim 20$ arcmin of NGC 1399. UCD candidates were also found from Hubble Space Telescope imaging of the more distant cluster Abell 1689 (Mieske et al. 2004b).

The main formation scenarios for UCDs are as follows. (i) They are very massive (intracluster) GCs (Hilker et al. 1999; Drinkwater et al. 2000a; Phillipps et al. 2001; Mieske, Hilker & Infante 2002; Evstigneeva et al. 2007). (ii) They are the remnant nuclei of stripped (threshed) early-type dwarf galaxies (Bekki, Couch & Drinkwater 2001; Bekki et al. 2003). (iii) They are evolved products of YMGCs (young massive GCs) – massive superstar clusters formed in galaxy interactions (Fellhauer & Kroupa 2002; Maraston et al. 2004).

To date, confirmed UCDs have only been found in the centres of rich galaxy clusters. The aim of this work is to determine if UCDs exist in less dense environments such as galaxy groups and, if they do, to compare their properties to Fornax and Virgo UCDs. Previous studies of UCDs in galaxy groups are limited to the photometric search for UCDs in the NGC 1023 group by Mieske, West & Mendes de Oliveira (2006). 21 possible UCD candidates were found. Mieske et al. showed that the mass spectrum of the UCD candidates in NGC 1023 is restricted to $\sim 1/4$ of the maximum Fornax and Virgo UCD mass. However, spectroscopy is required to confirm UCD candidates in the NGC 1023 group.

In this paper we present a spectroscopic search for UCDs in a range of galaxy group environments. Identifying UCDs and defining their properties in different environments can help us to put constraints on UCD formation mechanisms.

2 SELECTION OF GALAXY GROUPS

We have chosen six galaxy groups at redshifts similar to the Fornax and Virgo clusters. These redshifts (around 1500 km s$^{-1}$) are sufficiently large to separate UCDs from Galactic stars in velocity, but not too high to require very long exposure times. The group properties are summarized in Table 1. Column (2) is the distance...
modulus derived from the mean group radial velocity (as in table 4 of Firth et al. 2006), corrected for large-scale motions using equation (A2) of Mould et al. (2000). The Hubble constant is assumed to be $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Columns (3)–(5) show the properties of the most luminous galaxies in the observed field. Column (4) is the morphological type from HyperLeda (Paturel et al. 2003). Column (5) is the absolute $B$-band magnitude, calculated using the total apparent corrected $B$ magnitude from HyperLeda and distance modulus from Column (2). Column (6) is the number of galaxies (spectroscopically confirmed group members) with positions within the $2\degree$ diameter field centred on the group centre of mass for Dorado, NGC 1400/1407, 0681 and 1.6 diameter field for NGC 4038, 4697, 5084. The numbers are based on Ferguson & Sandage (1990) and Garcia (1993) galaxy group catalogues, supplemented with NASA/IPAC Extragalactic Database (NED) data and our 2dF galaxy observations (Firth et al. 2006).

We selected groups with a range of properties such as number of galaxies and a dominant central galaxy type. The groups have both early- and late-type central galaxies and may contain different numbers of UCDs if morphology is an indicator of the dynamical evolutionary state of the system. The number of galaxies, spectroscopically confirmed group members, within the observed $2\degree$ /1.6 diameter field centred on the group centre of mass ranges from eight to 34 for individual groups. If UCDs are stripped nuclei of early-type dwarf galaxies, the efficiency of UCD formation (the number of early-type dwarfs initially presented in the group (Bekki et al. 2003). Some of these early-type dwarfs will survive till nowadays. The NGC 1400/1407 group contains many dE and dS0 dwarfs among spectroscopically confirmed members, all other groups do not (at least within the observed fields). If UCDs are star clusters – GCs or YMGCs – formed in galaxies, the mass (luminosity) of the most massive (luminous) UCD should scale with the host galaxy mass (Kravtsov & Gnedin 2005).

One of our selected groups, NGC 4038, includes the famous Antennae system (NGC 4038/4039), an interacting pair, and is important in understanding UCDs as YMGCs in interacting systems. The group includes lots of galaxies with peculiar morphology: mergers, interacting systems and irregular type galaxies.

The NGC 5084 group is one of the most massive disc galaxies known with a mass of $M \approx 6 \times 10^{12} – 1 \times 10^{13} \text{ M}_\odot$ (at a distance of 15.5 Mpc and the mass-to-light ratio $M/L_B \gtrsim 200 \text{ M}_\odot / \text{L}_\odot$ indicating a considerable amount of dark matter (Carignan et al. 1997). According to Carignan et al. (1997) this galaxy has survived the accretion of several satellites.

The NGC 1400/1407 group is known by an extremely large difference in velocities between the second brightest member, NGC 1400 ($cz \approx 600 \text{ km s}^{-1}$), and all other galaxies in the group, including the brightest member, NGC 1407 (group mean velocity $cz \approx 1700 \text{ km s}^{-1}$, Firth et al. 2006). However, it was shown that NGC 1400 is at the distance of the group (Gould 1993) and the difference in velocities was interpreted as the evidence for a large dark matter content (Quintana, Fouque & Way 1994). Nevertheless, the spatial distribution and population size of the NGC 1400 and 1407 GC systems show no anomalies (Perrett et al. 1997).

\begin{table}[h]
\centering
\begin{tabular}{lcccc}
\hline
\textbf{Group} & \textbf{Distance modulus (mag)} & \textbf{Most luminous galaxies in observed field} & \textbf{Number of spectroscopically confirmed members within observed field} \\
(1) & (2) & (3) & (4) & (5) & (6) \\
\hline
Dorado & 30.92 & NGC 1553 & $S_0$ & $-20.71$ & 11 \\
 & & NGC 1549 & E & $-20.31$ & \\
NGC 1400/1407 & 31.46 & NGC 1407 & E & $-21.07$ & 34 \\
 & & NGC 1400 & E–S0 & $-19.80$ & \\
NGC 0681 & 31.51 & NGC 0681 & SABa & $-19.12$ & 10 \\
 & & NGC 0701 & Sbc & $-19.37$ & \\
NGC 4038 & 32.26 & NGC 4038 & SBn & $-21.99$ & 10 \\
 & & NGC 4039 & SBm & $-21.81$ & \\
 & & NGC 4027 & Sbd & $-21.13$ & \\
NGC 4697 & 31.93 & NGC 4731 & Sbc & $-20.98$ & 8 \\
 & & NGC 4775 & Scd & $-20.60$ & \\
NGC 5084 & 32.40 & NGC 5084 & S0 & $-21.33$ & 12 \\
 & & NGC 5087 & E–S0 & $-20.65$ & \\
Fornax & 31.39$^a$ & NGC 1399 & E & $-21.04$ & 161/147$^b$ \\
Virgo & 30.92$^a$ & M87 & E & $-21.48$ & 76/53$^c$ \\
\hline
\end{tabular}
\caption{Galaxy groups. The numbers for the Fornax and Virgo clusters are given for a comparison.}
\end{table}

\textsuperscript{a}Distance modulus derived from Cepheid distances (Freedman et al. 2001). \textsuperscript{b}Number of galaxies with positions within the $2\degree$ /1.6 diameter field centred on NGC 1399 and velocities between 0 and 3000 km s$^{-1}$ (the Fornax cluster recession velocity limits) obtained from NED. \textsuperscript{c}Number of galaxies with positions within the $2\degree$ /1.6 diameter field centred on M87 and velocities between $-1000$ and 3000 km s$^{-1}$ (the Virgo cluster recession velocity limits) obtained from NED.
3 OBSERVATIONS

Searches for UCDs were done with the 2dF multi-object spectrograph on the Anglo-Australian Telescope in a single 2° or 1° diameter field in each group centred on the group centre of mass. The coordinates of the group centres were taken from NED. The source of these positions is Garcia (1993). We had two observing runs: in 2004 November and 2005 April. The summary of the observations is given in Table 2.

To improve our chances of finding UCDs, we defined a sample of objects looking similar to Fornax and Virgo UCDs.

(i) They are unresolved (star-like) in photographic plates.

(ii) The magnitude limits for our targets were set so as to match approximately the absolute magnitude range of the brightest Fornax and Virgo UCDs. We were unable to search for fainter UCDs because of the limited observing time allocated.

(iii) A colour cut $b_{r} - r < 1.7$ was applied to remove Galactic M-dwarfs (no UCDs have been found redder than $b_{r} - r = 1.5$).

The UCD candidates for the November observing run – Dorado, NGC 1400/1407 and 0681 – were taken from the APM sky catalogues based on APM measurements of United Kingdom Schmidt Telescope (UKST) blue and red photographic survey plates. We selected objects classified as ‘stellar’ and ‘merged’. For the April observing run, UCD candidates were selected as star-like objects from the APM sky-survey catalogues for the NGC 4038 and 5084 groups and SuperCOSMOS scans of photographic UKST survey plates for the NGC 4697 group. Targets were grouped by apparent magnitude, with exposures of about 45 min ($b_{T} < 18.5$), 2 h ($18.5 < b_{T} < 19.5$) and 3 h ($19.5 < b_{T}$) to obtain spectra with a similar signal-to-noise ratio for all the targets. Poor weather conditions did not allow us to follow the observing plan for the NGC 5084 group and to obtain data in the bright magnitude range ($b_{T} < 19.2$). In the case of NGC 4038, 4697 and 5084, we had a problem of too many targets per 2dF field due to the proximity of Galactic plane. To observe a more complete sample within the limited observing time we restricted our observations to a 1° diameter field for these groups.

The observing set-up and data reduction procedure are identical to those used for the Fornax cluster spectroscopic survey (Drinkwater et al. 2000b). We measured redshifts (radial velocities) for the UCD candidates by cross-correlation with a set of template spectra (see Table 2).

Drinkwater et al. 2000b, for more details). Only velocities obtained with R $\geq 3$ (Tonry & Davis 1979) were accepted. The number of objects with measured velocities and completeness are given in Table 2.

We also obtained redshifts of galaxies, candidates for group members, simultaneously with the UCD candidate observations by using a small number of the available 2dF fibres to improve our knowledge about the groups themselves (Firth et al. 2006).

4 RESULTS

Fig. 1 represents the histogram of heliocentric radial velocities. The distribution of star-like objects from our observations is shown with the hatched histogram. The solid line histogram shows the distribution of galaxies, group members. The galaxy data were taken from Ferguson & Sandage (1990) and Garcia (1993) galaxy group catalogues and supplemented with NED data and our 2dF galaxy observations (Firth et al. 2006).

There is no overlap between the star-like object and galaxy distributions for the NGC 0681, 4038, 4697 and 5084 groups. No new group members (UCDs) were found in these groups. In the case of Dorado, one star-like object has a velocity of $1142 \pm 50$ km s$^{-1}$, which makes it a definite group member (UCD). Two star-like objects have velocities similar to the velocities of some galaxies in the group ($\sim 600 \pm 300$ km s$^{-1}$). However, these objects could be in the tail of stellar velocities once we allow for their large errors. High-resolution imaging is needed to distinguish galaxies with ultracompact morphology or GCs from Galactic stars. In the case of NGC 1400/1407, two ‘stars’ lie close to the NGC 1400 galaxy in the velocity space ($\sim 500$–$600$ km s$^{-1}$), but if we check their positions, neither of them seems associated with NGC 1400. High-resolution imaging is required to make conclusions on the nature of these objects.

The new definitive and possible group members are listed in Table 3. Their positions in the galaxy groups are shown in Fig. 2 with circles. The new definitive member in Dorado is situated in intragroup space, far from any galaxies, and appears stellar in UKST photographic plates. It has an absorption-line spectrum, similar to that of Fornax and Virgo UCDs and early-type dwarfs (Drinkwater et al. 2000a; Jones et al. 2006).

As we did not observe all the candidate objects in each group, we have estimated (95 per cent confidence) upper limits on the number of UCDs in each group in the observed magnitude range (listed in Table 4). The upper limits were estimated by using the binomial distribution to find the (largest) UCD fraction among the candidates at which the probability of finding no more UCDs than observed was 5 per cent.

3 The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
4 http://www.ast.cam.ac.uk/~apmcat/
5 http://www-wfau.roe.ac.uk/sss/index.html
Figure 1. Histograms of radial velocities. The distribution of star-like objects from our observations is shown with the hatched histogram. The solid line shows the distribution of galaxies, group members, from Ferguson & Sandage (1990) and Garcia (1993) galaxy group catalogues, supplemented with NED data and our 2dF galaxy observations (Firth et al. 2006).

Table 3. New definite (in bold face) and possible members in the Dorado and NGC 1400/1407 groups. \( \text{cz} \) is the heliocentric radial velocity. The best template Sp type is the spectral type of the template (star) which gave the highest \( R \) coefficient (given in the last column) when using the cross-correlation method (Tonry & Davis 1979).

| Object  | RA (J2000)  | Dec. (J2000)    | \( b_j \)  | \( b_j - r \) | \( \text{cz} \) | Best template | Sp type | \( R \) |
|--------|-------------|----------------|-----------|--------------|-------------|---------------|---------|-------|
| Dorado | 04:16:24.55 | −56:37:19.7     | 19.7      | 1.1          | 585 ± 71    | G6 V          | 4.5     |
| 2      | 04:16:50.79 | −55:53:03.0     | 19.9      | 0.5          | 638 ± 95    | F3 V          | 4.6     |
| 3      | 04:13:16.91 | −55:46:26.0     | 20.2      | 0.9          | 1142 ± 82   | G6 V          | 4.6     |
| NGC 1400 | 03:42:32.46 | −18:23:00.1     | 19.9      | 0.7          | 477 ± 73    | F6 V          | 4.3     |
| 2      | 03:41:54.81 | −18:08:37.8     | 19.5      | 0.9          | 652 ± 65    | G6 V          | 5.7     |

5 DISCUSSION AND SUMMARY

Only one definite UCD candidate was detected in the six galaxy groups observed. To interpret this result we estimate the expected luminosity range of UCDs in groups in the context of the UCD formation scenarios. In particular, we consider the hypothesis that UCDs are GCs formed in galaxies. This is the only hypothesis for which we have quantitative theoretical predictions.

If UCDs are GCs formed in galaxies (and subsequently escaped their host galaxy potential as, e.g. suggested by Bekki & Yahagi 2006), then we can use predictions by Kravtsov & Gnedin (2005). They found that the most massive cluster contributes a significant fraction of the total cluster mass and that the mass of the most massive cluster correlates with the mass of its host galaxy. This picture is consistent with what we found in both Fornax and Virgo galaxy clusters (Drinkwater et al. 2004; Evstigneeva et al. 2007; Gregg et al. 2007; Hilker et al. 2007): there is one very massive (luminous) UCD and there are other, less massive (less luminous) ones. Also, the fainter in luminosity we go, the more UCDs we have. Therefore, if we find the luminosity (mass) of the most luminous (massive) UCD for each group, we immediately find the luminosity (mass) of all other UCDs in the group: they will be fainter (less massive) than the most luminous UCD.

Formula (8) of Kravtsov & Gnedin (2005) gives the relation between the mass of the most massive GC and mass of its host galaxy. The formula works very well for Fornax UCDs and the NGC 1399
galaxy’ and ‘Virgo UCDs and the M87 galaxy’ (Evstigneeva et al. 2007). We used this relation to predict the mass of the most massive UCD for each group. Most massive UCDs are obviously formed in most massive galaxies (according to the adopted hypothesis). The mass values for the most massive galaxies in the groups were taken from: NGC 1407 and 1400 – Quintana et al. (1994); NGC 5084 – Carignan et al. (1997); NGC 4038 and 4039 – Amram et al. (1992); NGC 4027 – Phookun et al. (1992); NGC 0681 – Kyazumov & Barabanov (1980); NGC 4731 – Gottesman et al. (1984); NGC 1553 and 1549 – virial masses, estimated from the internal velocity dispersion as given in HyperLeda and half-light radius as given in RC3 (de Vaucouleurs et al. 1991). The most massive galaxies in the groups are usually the most luminous ones, but there are exceptions. In the NGC 4038 group, for example, NGC 4027 seems to be the most massive galaxy. To convert the UCD masses into luminosities, the value of $M/L_B = 3$ was taken (to reproduce the mass range of

Figure 2. Digitized Sky Survey (DSS) images of six galaxy groups with some galaxies (spectroscopically confirmed group members) labelled. All the images have a size of $2 \times 2$ deg$^2$ and were retrieved from the Canadian Astronomy Data Centre (http://cadcwww.dao.nrc.ca/). The circle represents the $2' \times 1'$.6 diameter field centred on the group centre of mass. Definite and possible UCDs in Dorado and NGC 1400/1407 are labelled as in Table 3.
The most luminous UCD in each group. The uncertainty is due to the scatter around the relation described by formula (8) of Kravtsov & Gnedin (2005). We can now compare our observational results – one definite plus two possible UCD candidates in Dorado and two possible UCD candidates in the NGC 1400 group – with the predictions given in Table 5. According to the predictions, we expect to find UCDs in the Dorado, NGC 1400 and 5084 groups. This broadly agrees with the observational results (the exception is NGC 5084). We would also expect to find UCDs in the NGC 4038 group if they were the likes of YMGCs in Antennae (see notes for Table 5), but we did not. It is possible that we did not find UCDs in NGC 5084, because the dominant galaxy (NGC 5084) was near the edge of the observing field and our coverage was incomplete. The same can be said about YMGCs in the NGC 4038 group and the Antennae system.

To make better tests of this and other hypotheses for UCD formation in the galaxy group environment, we clearly need deeper observations (compare the predictions in Table 5 with our observational limits). This would require much larger allocations of observing time, although the efficiency of the UCD candidate selection could be substantially improved by using multicolour CCD photometry for the input catalogues (e.g. Firth et al., in preparation).

In this paper we have presented the results of a search for UCDs in six different galaxy groups. We found one definite plus two possible UCD candidates in the Dorado group and two possible UCD candidates in the NGC 1400 group. No UCDs were found in the other groups. We compared these predictions with predicted luminosities of UCDs in the groups according to the hypothesis that UCDs are GCs formed in galaxies. The predictions broadly agree with the observational results.

ACKNOWLEDGMENTS

EAE and MJD acknowledge support from the Australian Research Council. We thank Rob Sharp for his assistance during observations. We are grateful to the referee for helpful suggestions, which have improved this paper. This research used the facilities of the Canadian Astronomy Data Center operated by the National Research Council of Canada with the support of the Canadian Space Agency.

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