The dwarf low surface brightness galaxy population of the Virgo cluster – III. Comparisons with different environments

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ABSTRACT
We have previously described the results of a search for low surface brightness (LSB) objects in data drawn from an east–west strip of the Virgo cluster and have compared this to a large-area strip outside the cluster. In this paper, we compare the cluster east–west data with new data along a cluster north–south strip and with data obtained for the Ursa Major (UMa) cluster and fields around the spiral galaxy M101. Our intention is to look for differences in the nature of the dwarf galaxy population with location in the cluster and within other environments. These uniform data sets reach central surface brightness values of $\sim 26 \mu B$, and an apparent $B$ magnitude of 21 ($M_B = -10$ for a Virgo cluster distance of 16 Mpc). Over a north–south strip area of $\sim 15 \text{ deg}^2$, we find $\sim 22$ LSB objects per square degree. This compares with $\sim 4 \text{ deg}^{-2}$ in both the UMa and the M101 fields. These results are very similar to what we have previously found for the east–west cluster strip and for other fields outside the cluster. There are far more small LSB features detected in Virgo cluster fields and we associate them with an extensive cluster dwarf galaxy population. In the cluster north–south strip there is an average dwarf-to-giant number ratio of $31 \pm 9$, which is much higher than would be expected from observations of galaxies in the Local Group, but significantly less than that required by $\Lambda$ cold dark matter galaxy formation models. The dwarf-to-giant ratios in UMa and M101 are consistent with those in the Local Group. Comparing the cluster east–west and north–south data, we find clear differences in the way the number density of dwarfs decreases with cluster radius and the distributions of galaxy magnitudes and sizes. The north–south strip covers a region of the cluster that contains not only the main cluster region associated with M87, but also two more distant infalling clouds. Additionally, the north–south strip lies approximately along the extended filamentary structure associated with Virgo while the east–west strip is perpendicular to it. We interpret the differences between the two strips as being due to these different environments. We suggest that the Virgo cluster is assembling itself out of subclusters and clouds that are already rich in dwarf galaxies compared to the environment of the general field. There is no evidence for any systematic difference in dwarf galaxy $(B - I)$ colour between dwarf galaxies of different magnitudes or in different parts of the Virgo cluster. A typical value of $(B - I) = 1.8$ is consistent with the colours of a wide range of stellar systems including the globular clusters of the central elliptical galaxy M87, but is bluer than is typical for giant ellipticals. We discuss and interpret our results in the context of various physical processes that are thought to act on galaxies as they form and evolve. Additionally, we give images and positions of possible new dwarf galaxy companions of M101.

Key words: surveys – galaxies: clusters: individual: Virgo cluster – galaxies: dwarf.
1 INTRODUCTION

In this paper, we continue our work to try and quantify the numbers of low surface brightness (LSB) dwarf galaxies as a function of environment and to assess and compare their properties. In our first Virgo cluster paper (Sabatini et al. 2003), we described a new detection method that enabled us to identify faint LSB features which we take to be galaxies in the Virgo cluster. These have intrinsic properties of $23 \leq \mu_B^p \leq 26$ and $-10 \geq M_B \geq -14$ (Virgo distance of 16 Mpc), where $\mu_B^p$ and $M_B$ are the $B$-band exponential central surface brightness and absolute magnitude, respectively. At these limits these galaxies are fainter than those typically detected in the comprehensive survey of the Virgo cluster carried out by Binggeli, Sandage & Tarenghi (1984) and extends down towards the properties of the dSph galaxies of the Local Group. We found on average about 18 galaxies per square degree but ranging from about 40 per square degree at the cluster centre to approximately four per square degree at the cluster edge. This decline in numbers with cluster radius, we believe, is a good indicator that we have selected a predominately cluster population rather than background galaxies. Comparing these numbers to that of the Virgo giant galaxy population ($M_B < -19$) over the same region of sky gave a dwarf-to-giant ratio (DGR) of about 16 [DGR = Num($M_B < -19$)/Num($-14 < M_B < -10$)]. In a related paper (Roberts et al. 2004), we compared the Virgo cluster result with data obtained in an identical way but over a region outside the cluster [from the Millennium Galaxy Survey (MGS), Liske et al. 2003]. Over this region the number of galaxies detected was only four per square degree, consistent with the numbers we detected at the edge of the Virgo cluster, again indicating that our cluster data consist predominately of cluster galaxies. The DGR of the MGS strip was at most 6, consistent with the numbers of dwarf and giant galaxies found in the Local Group (Mateo 1998). The Virgo cluster clearly supports many more dwarf galaxies per giant than do galaxies in less-rich environments.

An important question is how well do these observations fit in with our present picture of galaxy formation and evolution [A cold dark matter (CDM) hierarchical theory]? This can be quantified by comparing the faint end of the predicted luminosity function (LF) (derived from a dark matter (DM) simulation i.e. Klypin et al. 1999) with the observed LF (Blanton et al. 2001; Norberg et al. 2002). The observational result is that the LF at the faint end is much flatter than that predicted by the models. In Roberts et al. (2004) we show that there is no large field population of LSB low-luminosity galaxies that would steepen the LFs of Blanton and Norberg et al. at fainter magnitudes, which could account for this discrepancy. In the special environment of the Virgo cluster, the relatively large numbers of dwarf galaxies found provide a little closer match to theory (Moore et al. 1999a). In the second Virgo cluster paper (Sabatini et al. 2005), we considered the colours and gas content of the Virgo cluster dwarf galaxies detected and compared them to field dwarf galaxies. As expected from previous observations, the cluster population is redder and gas poor compared to dwarf galaxies in the field. In the final part of Paper II, we discuss the environmental influences that particularly affect dwarf galaxies in the cluster environment (ram pressure stripping, tidal interactions, etc.). Our conclusion was that if dwarf galaxies have mass-to-light ratios as large as those found for dSph galaxies in the Local Group (440 for the Draco dwarf galaxy, Kleyna et al. 2002), then they will be rather robust objects in the cluster environment. We suggest that the cluster environment is one in which small DM haloes (with baryonic gas) are lit up – weak tidal encounters ‘kick start’ and accelerate the star formation process in clusters compared to dwarf galaxies in the field.

Our Virgo cluster survey consists of deep CCD images of two perpendicular strips both extending 7° from the centre outwards, one from east to west (E–W), the other from north to south (N–S). These two data strips sample different regions of the Virgo cluster, with one lying roughly perpendicular to the supergalactic plane (E–W), and one almost parallel to it (N–S). Sabatini et al. (2003) described the results from the (E–W) strip only. In this, the fourth paper describing dwarf galaxy populations in different environments, we compare a second region of the Virgo cluster (N–S) with our previous Virgo data. We also compare both Virgo cluster regions with our previous field (MGS) data, with some sparse fields in the Ursa Major (UMa) cluster and an extensive survey of the region around the nearby spiral galaxy M101.

Although there is a large discrepancy between predicted numbers (CDM) of dwarf galaxies and observed numbers, this issue is clouded by non-uniform data sets. Different surveys reach different magnitude and surface brightness limits and detection methods and selection criteria vary in the way they identify dwarf galaxies. We aim to eliminate this source of confusion with the uniformity of our data and by using exactly the same detection algorithm and selection criteria for identifying dwarf galaxies in all environments.

2 DATA

2.1 The instrument

The optical data for this paper and our previous papers listed above were obtained using the Wide Field Camera (WFC) on the Isaac Newton Telescope, La Palma, Canary Islands as part of the Wide Field Survey (WFS), a multicolour data survey covering over 200 deg$^2$ of sky. The WFC is a mosaic of four thinned EEV 4 K × 2 K CCDs with a pixel size of 0.33 arcsec and total sky coverage of 0.29 deg$^2$. Images on CCD 3 were not used due to its vignetting; this reduced our total field of view to 0.21 deg$^2$. The Virgo data, taken during observing runs in 1999 and 2002, consists of two perpendicular strips extending from the centre of the Virgo cluster (defined as M87) as shown in Fig. 1. The UMa data were obtained in 2002. The positions of the fields are shown as the diamonds in

![Figure 1](https://academic.oup.com/mnras/article-abstract/379/3/1053/1040413/1054-S-Roberts-et-al). Positions of subclusters and clouds in the Virgo cluster together with the areas covered by the N–S and E–W data strips. Subcluster A is centred on M87 and subcluster B is centred on M49. The dots mark the positions of galaxies in the Virgo cluster catalogue of Binggeli, Sandage & Tammann (1985).
whilst the exposure time for the 2.2 The optical detection algorithm

total signal-to-noise ratio (S/N) in these pixels needs to be high; thus, low-S/N LSB galaxies are selected against. In this paper, we use a fully automated detection algorithm which convolves the images with matched filters, thus using the total flux of the galaxy for detection. This program was specifically written for the purpose of detecting faint, diffuse objects on CCD data. The details of this detection algorithm and the selection criteria have been extensively discussed in Sabatini et al. (2003) and Roberts et al. (2004). The data described in this paper have been obtained, reduced and analysed in an identical way to the data discussed in our previous papers. The result of this process is that we are able to select galaxies that, at the distance of the Virgo cluster (16 Mpc, Jerjen, Binggeli & Barazza 2004), satisfy the following criteria – a central surface brightness of $23 \leq \mu_0^B \leq 26$, and an exponential scale-size ($\alpha$) in arcseconds of $4 \leq \alpha \leq 9$.1

3 THE VIRGO CLUSTER

The Virgo cluster of galaxies is a complex structure, consisting of at least five different components (Fig. 1) (Binggeli 1999). The subcluster centred on M87 is known as subcluster A, while that centred on M49 is known as subcluster B. Subcluster A is more extended in velocity and space than subcluster B, and contains many early-type galaxies. Subcluster B is dominated by late types. Using planetary nebula data for the Virgo cluster, Feldmeier et al. (2004) estimate upper limits for the distances to subclusters A and B as 12.7 ± 0.4 and 14.1 ± 0.8 Mpc, respectively. They also give an estimate of the depth of the cluster – that they it . . . is more than 2.6 times as deep as it is wide. This result agrees well with that from other Virgo cluster studies, such as Yasuda, Fukugita & Okamura (1997), Jerjen et al. (2004) and Solanes et al. (2002).

As well as the subclusters, the Virgo cluster also consists of smaller ‘clouds’ (Binggeli, Tammann & Sandage 1987), namely, the M cloud which is to the north-west of M86, and the W cloud which is to the south-west of M87 (Fig. 1). The M and W clouds are thought to be at about twice the distance of the main Virgo subclusters, making them near-background groups of galaxies. Binggeli, Popescu & Tammann (1993) use velocities and morphological criteria to distinguish between cluster galaxies and nearby background objects, that is, those objects in the clouds. They give the mean velocity of the Virgo cluster as $1050 \pm 35$ km s$^{-1}$, so since the galaxies in the M and W clouds have mean velocities of ~2000 km s$^{-1}$, they are considered to be at about twice the distance. Ftaclas, Struble & Fanelli (1984) also consider the M and W clouds to be farther away than the subclusters due to their mean velocities; they estimate the cluster mean velocity to be 960–1000 km s$^{-1}$ with M and W cloud mean velocities of 2179 and 2198 km s$^{-1}$, respectively. Ftaclas et al. also claim the existence of another cloud, the N cloud. With a mean velocity of 1500 km s$^{-1}$, they also assume this cloud to be more distant than the main subclusters. Binggeli et al. (1987), however, consider it to be part of the Virgo cluster proper based on their velocity estimates and morphological criteria.

The identification of these subclusters and clouds means that the Virgo cluster is not the smooth well-ordered cluster that we might like it to be – as expected from $\Lambda$CDM models it appears that it is currently assembling itself out of smaller groupings of galaxies. The implication is that we might find quite different numbers and types of galaxies if we look into different parts of the cluster. The E–W

data strip, as described in Sabatini et al. (2003), covers exclusively subcluster A and may be closer to us than our assumed value of 16 Mpc – at 13 Mpc (Feldmeier et al. 2004) these galaxies would have absolute magnitudes about 0.5 mag fainter than that we have assumed. The N–S strip, however, overlaps in part with the N and M clouds, as well as subcluster A. If the clouds are twice the distance of the subcluster, then any dwarfs associated with them will be intrinsically 1.5 mag brighter than those in the subcluster. These possible differences need to be kept in mind when comparing data from the two strips.

3.1 Results

Essentially, we detect LSB ‘smudges’ that we take (for good reason, see below) to be LSB galaxies. In Roberts et al. (2004) we describe a search for LSB galaxies in the general field (MGS) and compare the results to that of the Virgo cluster E–W data (Sabatini et al. 2003). We have selected the objects from the Virgo cluster N–S strip in exactly the same way as these two previous surveys. Our final list of galaxies contains 336 objects, 218 of which were previously uncatalogued. This gives a mean value of \( \sim 22 \) LSB dwarf galaxies per square degree, compared to a value of \( \sim 18 \) per square degree found by Sabatini et al. (2003)\(^2\) for the E–W strip. Simple Poisson counting errors would lead us to conclude that there are marginally more dwarf galaxies per unit area detected in the north–south strip than in the east–west strip.

3.1.1 Number density profile

Fig. 4 shows a plot of the number density of galaxies with increasing distance from the cluster centre (defined as the position of M87). The plot begins at a distance of \( \sim 1^\circ \) from M87, as the N–S data strip is offset slightly to the north-west of M87. Again, as for the E–W strip there is an indication of a fall in galaxy numbers in the very inner region. This happens at a radius of less than about \( 2^\circ \) which corresponds roughly to the cluster core radius of about 1.5. We have suggested in Sabatini et al. (2005) that dwarf galaxies like these will be totally tidally destroyed in the core region and so those that we detect within about \( 2^\circ \) of the centre are actually at much larger radii than their projected distance from M87.

We have carried out a least-squares fit to the N–S data (an exponential function plus constant background) surface number densities. This gives a background value of \( 9 \pm 2 \) galaxies per square degree and a scalelength of \( 1.6 \pm 0.7 \). With nine galaxies per square degree, a substantial part (40 per cent) of our sample are predicted to be in a roughly uniform background component. This is much higher than that found by us for the background value at both the edge of the E–W strip and in the field (approximately four galaxies per square degree in the MGS). An exponential function and constant (background) fit to the E–W strip data gave a background value of \( \sim 5 \pm 1 \) galaxies per square degree, which is comparable to the field value of four, and a scalelength of \( 2.2 \pm 0.2 \). This fit is also plotted for comparison in Fig. 4 (dashed line).

A fit to the N–S data with a fixed background of four galaxies per square degree appears shallower than the best fit for the same data, but a comparison of the reduced \( \chi^2 \) values for the functions illustrates the similarity of their goodness-of-fit; the reduced \( \chi^2 \) value for the best-fitting function is 3.8, whilst for the fit with a fixed background of 4, is 3.7. These values imply that neither of these is a particularly good fit to the data.

Although we have carried out and presented these fits to the N–S data, it is probably not a very meaningful thing to do. While the E–W strip essentially samples subcluster A only, as described above, the cluster is much more complex over the region of the N–S strip.

As shown in Fig. 1 the N–S strip covers parts of subcluster A, and the M and N clouds. Thus, we might not expect these data to be fitted with a smooth monotonically decreasing function centred on M87. In addition, the surface number density of objects for the N–S data strip at the edge of the cluster does not blend in with the field value, as would be expected if the cluster edge had been reached (and as the E–W strip does). The important question is whether the differences in the two strips can be explained by the differences in the structures associated with the cluster or with a real increase in the background level.

In Roberts et al. (2004), we discussed the results of simulations carried out for a cone of Universe randomly populated with galaxies in the field in order to determine the limits of our chosen selection criteria. Fig. 5 shows the distribution of distances to which we can compare the background level of 9 galaxies per square degree and a scalelength of 1.6 ± 0.7. With nine galaxies per square degree, a substantial part (40 per cent) of our sample are predicted to be in a roughly uniform background component.

\[ \theta = \alpha \theta_0 \]

\[ \alpha = 0.6 \]

\[ \alpha = 1.0 \]

\[ \alpha = 1.2 \]

\[ \alpha = 1.4 \]

\[ \alpha = 1.6 \]

\[ \alpha = 1.8 \]

\[ \alpha = 2.0 \]

where \( \theta \) is the angular distance from the cluster centre, \( \alpha \) is the log-linear slope, and \( \theta_0 \) is the angular scalelength.

Fig. 5. Simulation of the distribution of distances for selected objects with properties in the range \( 23 \leq \mu_0 \leq 26 \) B mag and \( 4 \leq \alpha \leq 10 \) arcsec at an increasing distance for varying values of the LF faint-end slope \( \alpha \).

expect to detect objects with the selection criteria defined above, for different LF faint-end slopes. The peak at about 20 Mpc shows that we should be predominantly selecting objects within the distance of the Virgo cluster, as long as there is no large overdensity of galaxies in the near (<100 Mpc) background. We have already pointed out that the N–S strip covers the two near-background clouds M and N and these may be the explanation (see below) of the difference between the N–S and E–W strips. However, are there more-distant structures, not associated with Virgo, behind these two strips?

We have obtained data from LEDA (http://leda.univ-lyon1.fr/) for all objects covered by the two strips that have redshifts. Although LEDA is not a homogeneous data set, it can provide evidence of a large-scale structure. Fig. 6 shows a plot of velocities versus distance from M87 for those objects that are within 7500 km s\(^{-1}\) (∼100 Mpc assuming \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\)). There are comparable numbers of far-background (>2000 km s\(^{-1}\)) objects in the N–S strip area compared to the E–W strip although in the E–W strip plot there are no objects with velocities higher than 2000 km s\(^{-1}\) which are farther than 3° from the cluster centre. In the N–S strip there are a few objects in this area, but there is no real indication of any background structure that would give rise to an increase in background galaxies in the N–S strip. There are also more objects in the N–S strip towards the end of the strip (from 4° outwards) compared to the E–W strip at lower velocities (\(v < 2000\) km s\(^{-1}\)). Therefore, we assume that we have a higher number density of objects at the end of the N–S strip compared to the E–W strip, because there really are more Virgo objects (\(v < 2000\) km s\(^{-1}\)) here than in the E–W strip. The N–S strip, unlike the E–W strip, does lie along the supergalactic plane and so the cluster edge may not be so well defined.

3.1.2 Are the N–S and E–W strip objects similar?

To investigate if the objects being detected in the two data strips have the same properties (i.e. are they drawn from the same population), we have carried out a Kolmogorov–Smirnov (K–S) goodness-of-fit test on both the distributions of central surface brightnesses and apparent magnitudes (Fig. 7). Here, the null hypothesis is that the objects in the two data strips are from the same population. The distribution of surface brightness of the two samples appears to be similar and the K–S tests give an 81 per cent chance of being wrong if the null hypothesis is rejected. The result is very different for the magnitude distribution. There are relatively more faint objects in the N–S strip and the K–S test gives only a 37 per cent chance of being wrong if the null hypothesis is rejected. This is consistent with our previous suggestion that the N–S strip contains galaxies from the more-distant N and M clouds. If this is the case we would expect more objects with fainter apparent magnitudes, though the surface brightness (independent of distance) would remain the same – this is just what we find. Fig. 7 shows that there are many more

\[\text{Figure 6. Plot of velocity versus distance from cluster centre for all catalogued objects within a heliocentric recession velocity of 7500 km s}^{-1}\ \text{in the areas of the N–S (left-hand panel) and E–W (right-hand panel) data strips.}\]

\[\text{Figure 7. Distribution of numbers of central surface brightness (left-hand panel) and apparent magnitude (right-hand panel) for both the N–S and the E–W data strips.}\]
faint galaxies in the north–south strip than in the east–west strip and that the shift in the peaks between the two distributions of apparent magnitudes is just about as expected (1.5 mag) if the clouds are twice as far away as subcluster A. If there is a surface brightness–magnitude relation (Driver 1999), then as we pick galaxies of the same surface brightness we must also be picking them at the same absolute magnitude.

3.1.3 How does dE:dIrr vary with distance from cluster centre?

The galaxies selected in the survey were morphologically classified by eye. The dE-type objects are those which are diffuse, smooth and spheroidal in appearance. The dIrr objects are irregularly shaped objects with an underlying diffuse brightness, and other objects are those for which the morphology was unsure. Examples of dE and dIrr galaxies are shown in Figs 13 and 14. Since the classification of galaxy types was done by eye, it is rather subjective. As a check we compared our classification with that of the Virgo Cluster Catalogue (VCC) and found that we agreed in 90 per cent of the cases where the two samples overlapped. Thus, we believe our classification to be reasonably consistent with others.

A comparison of the results for both strips is shown in Table 1, together with the morphology of objects found in our survey of the field (Roberts et al. 2004). Excluding the other types, the dE objects are the most numerous type of galaxies in the cluster, whereas in the field the dIrr objects predominate.

It is known that dE objects are more likely to be found at the centres of galaxy clusters whilst dIrr objects are more prevalent in the outskirts of clusters (e.g. Fornax – Drinkwater et al. 2001, Virgo – Binggeli et al. 1987; Sabatini et al. 2003). A dwarf morphology–density relation is similar to that found for giant galaxies (Dressler 1980). Fig. 8 shows a plot of the ratio of dE to dIrr objects with increasing distance from the cluster centre for both the N–S and E–W data strips. Again in the E–W strip we see a regular decline in the ratio with distance from M87. It is quite different in the N–S strip where there is no decline in the outer regions. The dE–dIrr ratio peaks at just under 4° from M87. In Fig. 9, we show concentric annuli around M87 and it is clear that both the N and the M clouds are prominent at a radius of about 4°. Thus, if the clouds are also rich in dE galaxies in their inner regions we might expect the dE-to-dIrr ratio to be higher at about this point. This provides yet another indication that the regions sampled by the two strips are quite different.

3.1.4 Dwarf-to-giant ratio

Given that we sample the LF over a very limited range, we use for comparison purposes, as in past papers, a DGR instead of an LF. We have previously defined the DGR as the number of dwarfs with $-10 \leq M_B \leq -14$ divided by the number of galaxies with $M_B \leq -19$. The absolute magnitudes of the dwarfs are derived, as before, assuming a distance for all the dwarf galaxies of 16 Mpc. The data for the giant galaxies are taken from LEDA, that is, bright galaxies over the same area of sky that have $v < 2000$ km s$^{-1}$ (Binggeli et al. 1987). We have calculated the DGR for the N–S strip as a whole and for the inner (<4°) and outer regions (>4°) this is compared with the E–W strip in Table 2. Within the errors there is no difference between the DGR of the inner and outer regions of each strip, but the overall DGR of the N–S strip is higher (though only marginally so within the quoted errors) than that of the E–W strip. Thus, either the cluster is more dwarf rich in the region of the N–S strip or there are more dwarfs in the clouds. In both strips the DGR of the field is far less at a value no greater than 6 (Roberts et al. 2004). It appears that the cluster is being assembled out of discrete units that each has a DGR that is already high compared to field galaxies and those in groups like the Local Group. An interesting question is at what point does a group become a cloud and end up with a much larger dwarf galaxy population?

Table 1. Percentage morphologies in the Virgo cluster and field.

<table>
<thead>
<tr>
<th>Data strip</th>
<th>dE type</th>
<th>dIrr</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>N–S</td>
<td>40 per cent</td>
<td>23 per cent</td>
<td>37 per cent</td>
</tr>
<tr>
<td>E–W</td>
<td>49 per cent</td>
<td>25 per cent</td>
<td>26 per cent</td>
</tr>
<tr>
<td>Field</td>
<td>24 per cent</td>
<td>33 per cent</td>
<td>43 per cent</td>
</tr>
</tbody>
</table>

Table 2. The inner, outer and mean DGRs for the Virgo strips.

<table>
<thead>
<tr>
<th>Region</th>
<th>DGR (&lt;4°)</th>
<th>DGR (4°–8°)</th>
<th>Mean DGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>N–S</td>
<td>27 ± 11</td>
<td>35 ± 16</td>
<td>31 ± 9</td>
</tr>
<tr>
<td>E–W</td>
<td>16 ± 5</td>
<td>15 ± 9</td>
<td>16 ± 4</td>
</tr>
</tbody>
</table>

Figure 8. Ratio of dE to dIrr objects with increasing distance from cluster centre for the N–S and E–W strips.

Figure 9. This figure illustrates the position of the data strips in the Virgo cluster, together with all VCC galaxies. Also plotted are circles of radii from 1° to 8° from the cluster centre (defined as M87).
sufficient energy, through the first supernovae (SNe), to expel their masses, it is predicted that the first generation of stars would provide the majority forming at the earliest epochs. For galaxies of these models they are expected to have formed since 2007 The Authors. Journal compilation C

Giant galaxy Number of objects Percentage objects Number of objects

Table 3. The association of detected objects with giant galaxies.

<table>
<thead>
<tr>
<th>Giant galaxy type</th>
<th>Number of objects within 150 kpc radius</th>
<th>Percentage objects within 150 kpc radius</th>
<th>Number of objects per giant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elliptical</td>
<td>69</td>
<td>21</td>
<td>~23</td>
</tr>
<tr>
<td>Spiral</td>
<td>80</td>
<td>24</td>
<td>~16</td>
</tr>
<tr>
<td>Lenticular</td>
<td>30</td>
<td>9</td>
<td>~10</td>
</tr>
</tbody>
</table>

remaining gas and so stop or at least substantially halt further star formation (Dekel & Silk 1986). Contrary to these recent observations indicate that star formation has proceeded at a much faster rate in the most-massive galaxies and that it is the lower mass galaxies that have had their star formation delayed (Cowie et al. 1996; Gavazzi, Pierini & Boselli 1996; Kauffmann et al. 2003; Heavens et al. 2004). Given the complexities of modelling stellar populations (due to changes in the initial mass function, metallicity of the gas and star formation history), it is extremely difficult to learn very much from the one broad-band colour we have here. Ideally, we would like to observe individual stars and construct stellar colour–magnitude diagrams as has been done for Local Group galaxies (Grebel 1997; Mateo 1998) and other nearby galaxies (Pritzl et al. 2003; Grossi 2005), but this is currently not possible at the distance of the Virgo cluster. We have been exploring the use of combined near-infrared and optical colours as a means of distinguishing between age and metallicity (James et al. 2006). Given the limitations of the data we have, we will restrict our discussion to a comparison of the colours of the galaxies we detect with those of other stellar systems.

In Sabatini et al. (2005) we previously discussed the \((B − I)\) colours of the galaxies detected in the E–W strip. In this paper, we use the same technique (aperture photometry) to derive the colours of the galaxies in the N–S strip. The conclusions from the E–W strip were that there was no systematic change in colour with absolute magnitude (unlike that for giant elliptical galaxies), that there was no systematic change in colour with projected distance from the cluster centre and that there is no significant difference between the colours of those galaxies we describe as dE and dlrr. These conclusions are confirmed for the N–S strip. The only difference between the two strips is that on the whole there are larger errors on the N–S data colours because there are a larger fraction of faint galaxies, as described earlier. The two strips are compared in Tables 4 and 5.

Below we compare our \((B − I)\) colours to those of other stellar systems. The errors on our individual colours are typically 0.2 mag, but they can be much larger for some of the faint objects. We have used Cousins/Johnson filters calibrated against Landolt standards. The other papers, cited below, almost invariably use Landolt standards, but they are often less clear about the exact \(B\) and \(I\) filters used.

As a first comparison our mean colours of galaxies classified as dE compare well with those published by van Zee, Barton & Skillman (2004), though their sample galaxies are all brighter than \(M_B = −15.5\). They have photometry for 16 dE galaxies 13 of which have \((B − I)\) colours with a mean of \(1.9 ± 0.1\). This compares to our mean value for dE objects of \((B − I) ≈ 1.8\).

Giant elliptical galaxies are generally redder than the colours given above for dE galaxies. For a sample of 26 elliptical galaxies with \((B − I)\) colours Michard (2000) find a mean value of

Table 4. Mean colours of objects in the N–S and E–W data strips.

<table>
<thead>
<tr>
<th>Data Strip</th>
<th>Type</th>
<th>Mean ((B − I))</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>N–S</td>
<td>dE</td>
<td>1.8</td>
<td>0.4</td>
</tr>
<tr>
<td>E–W</td>
<td>dE</td>
<td>1.8</td>
<td>0.3</td>
</tr>
<tr>
<td>N–S</td>
<td>dlrr</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>E–W</td>
<td>dlrr</td>
<td>1.8</td>
<td>0.6</td>
</tr>
<tr>
<td>N–S</td>
<td>All</td>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td>E–W</td>
<td>All</td>
<td>1.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

2.1 ± 0.1. They also give a value of \((B - I) = 2.1\) for the central Virgo cluster galaxy M87. This is redder than both its globular cluster (GC) systems (see below) and its dE cluster companions. Giant ellipticals are red because they are both old and metal rich. GCs are bluer generally because they are metal poor. Our cluster dE galaxies then are either relatively metal poor or younger or some combination of the two compared to the giant ellipticals. Given a hierarchical formation process, the dE galaxies should not, in the main, be younger than the giant ellipticals unless their star formation has been delayed. Given the observed rather complex star formation history of Local Group dwarf galaxies and the observed downsizing, we favour this latter conclusion – they are both younger and more metal poor than the giant ellipticals.

In many ways the simplest stellar systems to compare with are GCs. Couture, Harris & Allwright (1990) have derived \((B - I)\) colours for the GC population of M87. The brighter GCs overlap with the faintest dwarf galaxies in our sample. If we assume that each GC arises from a single star formation burst, then their star formation history is easy to model. If we also assume (as does Couture et al.) that they all have about the same age, then their colours are just a reflection of their metallicities. In Fig. 11, we show a histogram of the \((B - I)\) colours of the M87 GCs compared to our data from the two Virgo strips. The similarity of the colour distribution for the two strips is apparent along with that of the M87 GCs. Formally, the mean value of \((B - I)\) for the two strips is 1.8 compared to 1.65 ± 0.25 for the GCs. Using the Couture et al. calibration from \((B - I)\) to metallicity gives a mean value of \([\text{Fe}/\text{H}] = -0.93\) for our dwarfs. From their \((B - I)\) colours alone there is no reason to suspect that the star formation history of these Virgo cluster dwarf galaxies is very different from that of the GCs of M87.

Two problems with this simple interpretation must be considered. First, there are multiple pathways to these \((B - I)\) colours for galaxies that have different ages, star formation histories and metallicities. For example, we know that Local Group dwarf galaxies have more complex star formation histories than GCs (Grebel, Gallagher & Harbeck 2003). Secondly, the formation mechanism of these two stellar systems could be quite different. Elliptical galaxy GCs are thought to form as either the result of previous mergers or as part of the monolithic collapse that formed the galaxy (depending on your view of elliptical galaxy formation, Forbes et al. 1998). In hierarchical models dwarf galaxies are the seeds of giant galaxy formation while the GCs are the fruits. The possibility of a link between dwarf galaxies and GCs is something that does require further investigation particularly in light of the continued debate over objects like oCen which may have a dual personality as both an ex-dwarf galaxy and a GC (Freeman 1993; Ideta & Makino 2004).

Heller & Brosch (2001) have presented \((B - I)\) colours for a sample of 28 Virgo cluster dIrr galaxies. Again these galaxies are brighter than the galaxies in our sample \((M_B < -15)\). The mean \((B - I)\) colour of their sample is 1.3 ± 0.4 compared to our dIrr sample which has a mean of \((B - I) = 1.8\). Although systematically bluer than our dIrr population, the scatter is large and there are some surprisingly red galaxies in their sample, for example, \((B - I) = 2.1\). Their sample also includes (as does ours) some extremely blue galaxies, \((B - I) = 0.52\) for example. For our sample the scatter in colour is much larger at fainter magnitudes, possibly because we have underestimated the errors, but an alternative is that we have a sample of galaxies that are still progressing through their star formation cycle. The galaxies we classify as dIrr have a much wider range of colours than those classified as dE. Fig. 12. For galaxies like this star formation may occur in a series of bursts and the cluster environment may promote this to a greater extent than in the field (Sabatini et al. 2005). What we see are galaxies at various stages in this star formation process just starting a burst of star formation either a long way from a new burst or at some stage in between. Such a model of star formation bursts has been proposed by Gerola, Seiden & Schulman (1980) (stochastic self-propagating star formation or SSPSF). In this model it is the feedback from star formation that eventually leads to further delayed star formation in other parts of the galaxy – not a complete removal of the interstellar medium. Bursts of star formation at intervals of the order of 10^8 yr can lead to variations in colour consistent with those observed here (Davies & Phillipps 1988; Evans, Davies & Phillipps 1990). We have insufficient S/N to consider variations in colour within each galaxy to identify star-forming and quiescent regions.

### 4 THE UMa CLUSTER

The UMa cluster is situated at approximately the same distance (18.6 Mpc, Trentham & Tully 2002) as the Virgo cluster. However, unlike Virgo, it is populated almost exclusively by late-type
The galaxy population of the Virgo cluster

galaxies and there is no concentration towards a central cluster core. It has a lower velocity dispersion than Virgo, of $\sim 150$ km s$^{-1}$. The cluster is also located on the supergalactic plane at a position where other galaxy clouds and filaments are located. Tully et al. (1996) undertook an extensive study of the UMa region in order to define criteria for membership of the cluster. They define the extent of the cluster in terms of position by a radius of 7.5 centred on $\alpha = 11^h 56^m 9$, $\delta = 49^\circ 22'$ (B1950) and in velocity by $700 < V_{\text{helio}} < 1210$ km s$^{-1}$. We will use this definition in all that follows. We calculate the surface number density of giant galaxies (using our definition of a giant as having $M_B \leq -19$) over the extent of the cluster to be approximately five times less than that for Virgo. The crossing-time for UMa is comparable to a Hubble time (Tully et al. 1996) about an order of magnitude longer than that for Virgo. The low density of the cluster has even led to comments (Zwaan, Verheijen & Briggs 1999) that when compared to other classical clusters, UMa is more like an overdensity of galaxies rather than a cluster. Certainly, galaxy interactions within the cluster, interactions with the cluster potential and/or harassment processes should be minimal. Again, unlike Virgo, UMa does not have any detectable X-ray emission, so its galaxies will not be affected by the presence of a hot intracluster gas. Processes such as pressure confinement and ram pressure stripping will hence have had a minimal effect.

4.1 Results

In total we found just six objects in the eight UMa fields which satisfied our selection criteria for LSB dwarfs. This corresponds to approximately four objects per square degree for the cluster, which is very similar to the value obtained for the MGS (Roberts et al. 2004), but is much less than that obtained for the Virgo cluster (as shown above). The UMa data are consistent with observations of the general field showing no enhancement of dwarf galaxy numbers. Out of the six galaxies identified in the UMa data, two had identifications in NED. One was found to be a background galaxy at a redshift of 0.014 (corresponding to $V_{\text{helio}}$ $\sim 21.5$). It is the dominant galaxy of the M101 group which, being nearby, has been the subject of a number of studies. Holmberg (1950) undertook the first study into possible members of the M101 group by looking at the redshifts, positions and resolvability of galaxies near M101. He concluded that the M101 group consisted of M101, M51 and its companions NGC 5195, NGC 5204, NGC 5474 and NGC 5585. He also named four possible members for which there were no redshift data available. In 1964, he revised his results for the M101 group; he decided that NGC 5195 and M51 were farther away than M101; the remaining members were considered to be at an intermediate distance, and M101 was concluded to be an isolated foreground galaxy. This uncertainty relating to the group members led Sandage & Tammann (1974) to study new redshifts of the possible M101 group members to verify if they were indeed part of the same group. They found that the majority of Holmberg’s original group members from 1950 were part of the same group at the same distance, except for M51 and NGC 5195 which they stated to be at a farther distance. Thus, Sandage & Tammann’s definition of the M101 group consisted of M101, NGC 5204, NGC 5474, NGC 5477, NGC 5585 and Ho IV (DDO185). Karachentsev (1996) also undertook a search for companions around nearby ($V < 500$ km s$^{-1}$) massive ($M > 3 \times 10^{11} M_\odot$) galaxies. Around M101, he found eight possible members – those found by Sandage & Tammann, and alsoUGC 9405 and NGC 5238. The deepest and most-recent study of M101 and its companions was undertaken by Bremnes, Binggeli & Prugniel (1999) who carried out CCD photometry of the dwarf-type galaxies in and around the M101 group as part of their multicolour survey of dwarf galaxies within the 10 Mpc volume. They found 13 members and possible members of the group as shown in Fig. 3. There was just one early-type dwarf galaxy in the vicinity of M101 (UGC 0882). The remaining dwarfs are all late types with absolute magnitudes in the range $\sim -14 \leq M_B \leq -17$. In comparison, the Milky Way (MW) has a number of companions fainter than this (Mateo 1998) and some much fainter (Belokurov et al. 2006; Zucker et al. 2006). Thus, a deeper search may hopefully find similar diffuse dSph galaxies around M101 as are found around the MW.

5 M101

This large, face-on spiral galaxy is situated at a distance of $\sim 6.6$ Mpc (Karachentsev 1996) and has an absolute magnitude, $M_B$ $\sim -21.5$. It is the dominant galaxy of the M101 group which, being nearby, has been the subject of a number of studies. Holmberg (1950) undertook the first study into possible members of the M101 group by looking at the redshifts, positions and resolvability of galaxies near M101. He concluded that the M101 group consisted of M101, M51 and its companions NGC 5195, NGC 5204, NGC 5474 and NGC 5585. He also named four possible members for which there were no redshift data available. In 1964, he revised his results for the M101 group; he decided that NGC 5195 and M51 were farther away than M101; the remaining members were considered to be at an intermediate distance, and M101 was concluded to be an isolated foreground galaxy. This uncertainty relating to the group members led Sandage & Tammann (1974) to study new redshifts of the possible M101 group members to verify if they were indeed part of the same group. They found that the majority of Holmberg’s original group members from 1950 were part of the same group at the same distance, except for M51 and NGC 5195 which they stated to be at a farther distance. Thus, Sandage & Tammann’s definition of the M101 group consisted of M101, NGC 5204, NGC 5474, NGC 5477, NGC 5585 and Ho IV (DDO185). Karachentsev (1996) also undertook a search for companions around nearby ($V < 500$ km s$^{-1}$) massive ($M > 3 \times 10^{11} M_\odot$) galaxies. Around M101, he found eight possible members – those found by Sandage & Tammann, and alsoUGC 9405 and NGC 5238. The deepest and most-recent study of M101 and its companions was undertaken by Bremnes, Binggeli & Prugniel (1999) who carried out CCD photometry of the dwarf-type galaxies in and around the M101 group as part of their multicolour survey of dwarf galaxies within the 10 Mpc volume. They found 13 members and possible members of the group as shown in Fig. 3. There was just one early-type dwarf galaxy in the vicinity of M101 (UGC 0882). The remaining dwarfs are all late types with absolute magnitudes in the range $\sim -14 \leq M_B \leq -17$. In comparison, the Milky Way (MW) has a number of companions fainter than this (Mateo 1998) and some much fainter (Belokurov et al. 2006; Zucker et al. 2006). Thus, a deeper search may hopefully find similar diffuse dSph galaxies around M101 as are found around the MW.

5.1 Results

To investigate the dwarf galaxy population around and associated with M101 which have similar properties of surface brightness and
conditions we would expect galaxies around M101 to satisfy the following

Scaling by the relative distances of the Virgo cluster and M101 detected in the Virgo cluster

5.1.2 Companions of M101 with properties similar to those for M101 companions. we believe, based on morphological grounds, immersed in the background count. Below we will comment on what per square degree in any random field the companions of M101 are

Thus, we would expect to detect only $\leq 0.27$ true companions of M101 per square degree. However, because we expect to detect $\sim 4$ objects per square degree in any random field the companions of M101 are immersed in the background count. Below we will comment on what we believe to be good candidates, based on morphological grounds, for M101 companions.

5.1.1 Field objects in the M101 data set

To find objects in the field we used the selection criteria of $4 \leq \alpha \leq 9$ arcsec and $23 \leq \mu_0 \leq 26$ as previously used with the MGS field data (Roberts et al. 2004). These selection criteria produced approximately four per square degree. This is in excellent agreement with our MGS field result where again we found approximately four per square degree. There is no evidence of an excess of galaxies in this region of sky above that expected from any other random piece of sky.

Although the objects selected in this way, in these fields, almost certainly consist of a wide range of objects in the distant and near Universe we have still classified them in the same way as we have done for the Virgo cluster fields. In Table 6, we compare our classification with that of our previous MGS data. There are, within the errors, comparable percentages of dE- and dIrr-type objects in the M101 field region and the MGS field.

Mateo (1998) lists the dwarf galaxy companions of the MW, which all lie within 250 kpc. If the MW was placed at the distance of M101, just three of these companions would satisfy the selection criteria of $4 \leq \alpha \leq 9$ arcsec and $23 \leq \mu_0 \leq 26$. At an M101 distance of 6.9 Mpc, the area covered by a radius of 250 kpc is $\sim 13.5$ deg$^2$. Thus, we would expect to detect only $\sim 0.2$ true companions of M101 per square degree. However, because we expect to detect $\sim 4$ objects per square degree in any random field the companions of M101 are immersed in the background count. Below we will comment on what we believe to be good candidates, based on morphological grounds, for M101 companions.

5.1.2 Companions of M101 with properties similar to those detected in the Virgo cluster

Scaling by the relative distances of the Virgo cluster and M101 we would expect galaxies around M101 to satisfy the following conditions $9 \leq \alpha \leq 27$ arcsec and $23 \leq \mu_0 \leq 26$ if they had the same physical properties as those detected in the Virgo cluster. This leads to the detection of just one object which is shown in Fig. 13. If at the distance of M101 (which needs to be confirmed), then its absolute magnitude is $M_B \sim -10.44$ which would make it a newly discovered faint dSph companion of M101.

Bremnes et al. (1999) in their study found 11 definite and possible companions of M101, three of which would satisfy our selection criteria and so would be similar to the types of objects we detect in the Virgo cluster. However, two of these objects were located just outside the region covered by us and the third object was missed by the detection algorithm as it was positioned right on the edge of the CCD frame.

As we found just one object satisfying these criteria in our data, we have a DGR of 1:1. The MW and its companions at the distance of M101 would lead to an observed DGR of 0. These numbers compare to a Virgo cluster DGR of about 30. This again illustrates the huge excess of faint LSB galaxies in the Virgo cluster region and importantly this is not just because there is an excess of bright galaxies.

Since our primary motivation for surveying the area round M101 was to search for possible dwarf galaxy companions, we have selected seven objects (in addition to the object described above) that we believe, on morphological grounds, to be good candidates for dwarf galaxy companions. These are shown in Figs 14 and 15. This also illustrates the way in which we have classified galaxies of different morphological type.

6 SUMMARY OF RESULTS

As discussed in the Introduction, the hierarchical clustering theory of structure formation in the Universe predicts the existence of large

<table>
<thead>
<tr>
<th>Region</th>
<th>dE type</th>
<th>dIrr type</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>M101</td>
<td>40 ± 9 per cent</td>
<td>38 ± 9 per cent</td>
<td>22 ± 7 per cent</td>
</tr>
<tr>
<td>MGS Field</td>
<td>24 ± 7 per cent</td>
<td>33 ± 8 per cent</td>
<td>43 ± 9 per cent</td>
</tr>
</tbody>
</table>

Table 5. Summary of results for N–S and E–W data strips.

Table 6. Percentage morphologies of objects in M101 fields and the MGS field.

numbers of small-mass objects in all regions of the Universe today, and if star formation occurs in these objects then they should be visible as dwarf galaxies. However, observations have failed to find the large numbers of dwarfs in the lower density regions, whereas in higher density environments, such as the Virgo cluster, larger numbers have been found. There are the following two possibilities.

(i) CDM is incorrect and the dwarf galaxies observed in clusters are not the predicted primordial population. In some way, dwarf galaxy numbers are enhanced in clusters.

(ii) CDM is correct but the formation of dwarf galaxies in the lower density environments is suppressed in some way compared to high-density environments.

Our data sampled environments of increasing density in the Universe – the general field, the region around M101, the lower density UMa cluster and the higher density Virgo cluster. By using identical data sets in our surveys and probing fainter magnitudes than previous surveys, we have been able to extend our knowledge of dwarf galaxy populations to include objects as faint as \( M_B \sim -10 \).

(i) Virgo cluster. We have made a large number of faint LSB detections over the area of the cluster \((\sim 16–22 \text{ deg}^{-2})\) in both the area extending east–west which samples the main body of the cluster, and the north–south area which also samples two background infalling clouds. We assume that these LSB features are due to an extensive cluster dwarf galaxy population. The Virgo cluster appears to be assembling itself out of subclusters and clouds that are already rich in dwarf galaxies compared to the environment of the general field. The DGR of the cluster is much higher than that of the Local Group and M101, so the enhancement of dwarf galaxy numbers is not just as a consequence of the large numbers of bright galaxies. Many of the cluster dwarf galaxies do not appear to be spatially associated with the brighter galaxy population; there is a ‘cluster’ dwarf galaxy population. Within the errors, the \((B-I)\) colours of the objects in the two data strips are the same at 1.8. There is no evidence for any systematic difference in dwarf galaxy \((B-I)\) colour between dwarf galaxies in different parts of the cluster, although there are larger errors on the N–S strip colours due to a larger fraction of fainter galaxies.

(ii) UMa cluster. The numbers of faint LSB detections are about the same as that expected for the field. There is no evidence of an enhanced cluster dwarf galaxy population even though there is an enhancement of bright galaxy numbers.

(iii) M101. There are comparable numbers of dwarfs per square degree \((\sim 3 \pm 2)\) in the field around M101 as in the MGS field data (Roberts et al. 2004). One possible companion of M101 was found using the selection criteria adjusted for objects at the distance of M101.

6.1 Comparison of DGRs

A comparison of the DGRs for each environment is given in Table 7. Also given for comparison is the DGR from integrating the 2dF LF of Norberg et al. (2002) between \(-10 \geq M_B \geq -14\) and \(-19 \geq M_B \geq -24\) for varying faint-end slopes. For \(\alpha \sim -1.2\) we find a DGR of \(18:1\). For steeper LFs, consistent with CDM simulations \((\alpha = -1.6 \text{ to } -2.0, \text{ but keeping } M_{\text{lim}} \text{ constant})\) we have DGRs in the range \(367:1–8371:1\) (note that these numbers are for galaxies of all surface brightnesses, not just the limited range of surface brightness that we sample); none of the environments has the numbers of dwarf galaxies as might be expected from a galaxy formation theory that

<table>
<thead>
<tr>
<th>Survey/simulation</th>
<th>DGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGS field</td>
<td>&lt;6</td>
</tr>
<tr>
<td>Virgo cluster N–S strip</td>
<td>22</td>
</tr>
<tr>
<td>Virgo cluster E–W strip</td>
<td>14</td>
</tr>
<tr>
<td>LF ((\alpha = -0.6))</td>
<td>0.24</td>
</tr>
<tr>
<td>LF ((\alpha = -0.8))</td>
<td>1</td>
</tr>
<tr>
<td>LF ((\alpha = -1.0))</td>
<td>4</td>
</tr>
<tr>
<td>LF ((\alpha = -1.2))</td>
<td>18</td>
</tr>
<tr>
<td>LF ((\alpha = -1.4))</td>
<td>80</td>
</tr>
<tr>
<td>LF ((\alpha = -1.6))</td>
<td>367</td>
</tr>
<tr>
<td>LF ((\alpha = -1.8))</td>
<td>1735</td>
</tr>
<tr>
<td>LF ((\alpha = -2.0))</td>
<td>8371</td>
</tr>
</tbody>
</table>
does not include some mechanism to inhibit star formation in small haloes.

7 DISCUSSION

Lemson & Kauffmann (1999) investigated the influence of environment on DM haloes using $N$-body simulations and found that the mass function is ‘skewed towards high-mass objects in overdense regions of the Universe and towards low-mass objects in underdense regions’. Thus, from these results, one would expect to find a lower DGR in the Virgo cluster, and higher DGR in the general field. This is completely opposite to what we find from our surveys. Kauffmann, White & Guiderdoni (1993) suggest that the missing DM haloes must remain dark and so undetectable. If this is so, then a much larger fraction of field DM haloes remain dark compared to those in clusters. The cluster environment must have played an important role in making these galaxies visible. Alternately, if these dark haloes do not exist the cluster environment must have created the excess of dwarf galaxies compared to the field.

7.1 Creation of dwarf galaxies

7.1.1 Harassment

Moore et al. (1999a) suggested ‘galaxy harassment’ as a solution to the observed excess dwarf galaxy population in the Virgo cluster. In this scenario, infalling LSB disc galaxies are ‘harassed’ by giant cluster galaxies and morphologically transformed into dE objects. However, Sabatini et al. (2005) calculated that if the dwarf galaxies found in the cluster originally came from a population of larger field galaxies, then they should have tidal radii of the order of \( \sim 7 \) kpc. The dwarf galaxies in our sample have scalelengths between 4 and 9 arcsec, which, at the distance of Virgo, correspond to physical scale-sizes of 0.25–0.75 kpc. Moore et al. (1999b) give the smallest 9 arcsec which, at the distance of Virgo, correspond to physical

\[
\text{The dwarf galaxies in our sample have scalelengths between 4 and 0.75 kpc.}
\]

Thus, from these results, one would expect to find a lower DGR in the Virgo cluster, and higher DGR in the general field. This is completely opposite to what we find from our surveys. Kauffmann, White & Guiderdoni (1993) suggest that the missing DM haloes must remain dark and so undetectable. If this is so, then a much larger fraction of field DM haloes remain dark compared to those in clusters. The cluster environment must have played an important role in making these galaxies visible. Alternately, if these dark haloes do not exist the cluster environment must have created the excess of dwarf galaxies compared to the field.

7.1.2 Tidal interactions

Tidal interactions between galaxies in clusters result in gas and stars being pulled out from the interacting galaxies into giant streams, along which clumps of gas and stars form. Over time the stream fades, and the clump is classified as a tidal dwarf galaxy (TDG). Hunsberger, Charlton & Zaritsky (1996) investigated the formation of these dwarf galaxies in a study of 42 compact Hickson groups. Down to \( M_g \sim -14 \), they found 47 candidate TDGs, all with diameters in the range 1–6 kpc. Although these galaxies are brighter than those in our sample of dwarf galaxies in Virgo, Hunsberger et al.’s study none the less illustrates the possibility that a number of dwarf galaxies in clusters could have formed in the tidal tails of giant galaxies. Simulations of TDGs, however, predict that only one to two form with each interaction (Okazaki & Taniguchi 2000). We can estimate how many TDG-producing interactions there could be in Virgo by considering a simple rate equation. The number of interactions \( N \) which may produce a TDG in a cluster depends on four parameters – the number density of galaxies \( \rho \), their interaction cross-section \( \sigma \), their velocity \( v \) and the age of the cluster \( T \). Thus,

\[
N \sim \rho \sigma v T. \tag{1}
\]

If we assume that only interactions between disc galaxies (S0 and spirals) produce TDGs (Okazaki & Taniguchi 2000), then using the information in Tully & Shaya (1984) and assuming that the interaction cross-section is the virial radius we estimate there to be about 13 interactions per Gyr. Thus, if we assume that each interaction makes, at most, two TDGs, this means that we would expect 26 TDGs to be formed every Gyr. Thus, it seems extremely unlikely that TDGs make up a large fraction of the cluster dwarf galaxy population, and certainly not large enough to account for the dwarf galaxy population we find in Virgo today.

7.1.3 Morphological transformation

Another explanation for the large number of predominantly dE galaxies which we find in the Virgo cluster is the possibility that infalling dIrr objects have been transformed into dE objects. It has been postulated (van Zee et al. 2004) that as dIrr objects fall into the cluster, they have their gas stripped by ram pressure stripping and become the objects which we classify as dE objects. However, the importance of ram pressure stripping on the evolution of cluster dwarf galaxies in Virgo was investigated by Sabatini et al. (2005) who found that only those dwarfs within the cluster core \((< 0.5 \text{ Mpc or } 1.67 \text{ kpc})\) would be affected by this process. For the E–W strip, they also conclude that the dwarfs they detect within the projected cluster core would be severely tidally disrupted if they were actually located in the core; thus, they must be outside the core region, and therefore will not be subject to ram pressure stripping. The majority (99 per cent) of the galaxies detected in our N–S Virgo cluster strip are outside the projected core region due to the offset of this strip from the cluster centre. Thus, the effect of ram pressure stripping on these galaxies must be small. Sabatini et al. suggest that enhanced star formation triggered by interactions with the cluster and galaxy potentials, accelerates the evolution of infalling DM haloes so that they resemble the dE objects which we see in Virgo today, a process that does not happen in the field. We have discussed the colours of our detections in Section 3.1.6 and conclude that galaxy \((B - I)\) colours are consistent with a stellar population that is younger than the giant elliptical galaxies.

7.2 Suppression of dwarf galaxies

We have described the possible mechanisms which could create dwarf galaxies in the Virgo cluster region to produce the large population which we found in our survey. We now discuss reasons why we detect very few dwarf galaxies in the general field, the region around M101 and the low-density UMa cluster.
7.2.1 Supernova winds and pressure confinement

The most common mechanism invoked when attempting to suppress the formation of dwarf galaxies is that of gas expulsion via SN winds. This was first suggested by Dekel & Silk (1986). In this scenario, the first generation of SNe inject energy into the halo gas, giving it enough energy to escape the halo and thereby preventing further star formation, rendering the halo invisible. Babel & Rees (1992) have suggested that this mechanism for gas expulsion may be environment-dependent because the pressure of the intracluster gas will reduce gas loss in clusters. However, it is not now clear how efficient this mechanism for gas loss will be in any environment. MacLow & Ferrara (1999) have investigated this idea using numerical simulations. They consider whether SN winds could blow out the gas completely from dwarf galaxies with masses in the range $10^6$–$10^7 M_\odot$. They showed that gas was only lost via SN winds in haloes $<10^6 M_\odot$, and this was only a few per cent of the total mass of the galaxy. Sabatini et al. (2005) have also questioned the viability of this gas loss mechanism in light of the very high mass-to-light ratios that have been derived for some dwarf galaxies. Thus, gas expulsion via SN winds does not appear to be able to explain why we see only small numbers of dwarf galaxies in low-density environments.

7.2.2 Photoionization

Are there many DM haloes present in low-density environments that are not observable because they have not been lit up by star formation? One explanation for this is that of the presence of a photoionizing background preventing the gas in the halo from cooling.

In the ‘squelching’ scenario (Tully et al. 2002), dwarf galaxy sized objects are assumed to form before the epoch of re-ionization in high-density cluster-sized regions such as Virgo; thus, their SF is not inhibited and they are observable optically. In lower density regions such as UMa and the field, they form later and thus the ultraviolet background heats the gas, preventing it from cooling and forming stars. However, in their model, Tully et al. used $z_{\text{ion}}$ of 6 and more recent results of WMAP have pushed the epoch of re-ionization to $\sim20$ (Spergel et al. 2003), a time when the formation of dwarf galaxy sized objects is rare.

Although the squelching scenario may have problems explaining the environmental dependence of dwarf galaxy populations, the effect of photoionization on low-mass DM haloes may well play a part in the formation of galaxies in the idea known as ‘dowsnsizing’ (Cowie et al. 1996). This scenario, born out of observational evidence that larger galaxies have older stellar populations than lower mass ones, is at first sight contrary to hierarchical theory of structure formation. However, it is not contrary if for some reason star formation in low-mass haloes is in some way delayed, possibly delayed so long that large numbers of small haloes have not yet undergone any star formation at all.

If photoionization does result in there being many low-mass DM haloes in the Universe which have not been able to form stars to make them visible as dwarf galaxies, then gravitational lensing could be used as a probe of substructure. This is an ideal tool to use since light is deflected gravitationally by matter, whether it is light or dark; thus, if there were small dark haloes present in the Universe, they could be detected by this means. Such studies have been carried out (Bradac et al. 2002; Metcalf & Zhao 2002) and preliminary results show evidence for the presence of substructure. Dalal & Kochanek (2002) studied seven four-image lens systems, six of which had flux anomalies which they commented could be due to the effects of substructure. They also rule out the possibilities of other effects causing the flux anomalies in a further study of their data (Kochanek & Dalal 2003), concluding that ‘low-mass haloes remain the best explanation of the phenomenon’. However, if these low-mass DM haloes do exist in the numbers predicted by ΛCDM, then as they fall through the disc of their parent galaxy, they should heat the disc and cause it to thicken (Toth & Ostriker 1992). This is contrary to some observations of old thin disc systems or galaxies with no thick disc components, although it is now being argued that the amount of heating and thickening has been overestimated (Velazquez & White 1999; Font et al. 2001). This is clearly a matter for further investigation.

Our preferred solution to these problems is that there must be many very LSB or totally dark galaxies in the Universe that we have not yet discovered. In the cluster environment many of these have been ‘lit up’ by enhanced star formation due to being pulled and pushed around within the cluster environment. In support of this we cite the following six lines of evidence.

(i) The dE galaxies in Virgo are bluer than the giant ellipticals because their star formation was delayed until the cluster was formed.

(ii) Downsizing implies low-efficiency star formation in the lowest mass objects (but more rapid in clusters?).

(iii) The galaxies we detect in Virgo are too small to be the result of harassment.

(iv) There are too few tidal interactions in Virgo for them to be created tidally.

(v) There is a clear lack of dwarf galaxies in the dynamically young UMa cluster.

(vi) If the dwarfs have high mass-to-light ratios, then they will not be subject to gas loss by SN-driven winds.

8 CONCLUSIONS

In this paper, we compare observations of a N–S strip of deep CCD data with that of an E–W strip, both extending outwards from the centre of the Virgo cluster. We find clear differences in how the number density of detected galaxies changes with cluster radius. In the E–W strip there is a smooth decline with radius with an exponential scalelength of $2.2\pm2$ and a predicted background of five galaxies per square degree. This is consistent with the contaminating background estimate from our survey of the field. With a background of about four galaxies per square degree, about 75 per cent of the sample should be cluster members. For the N–S strip carrying out the same analysis leads to a much higher background value (nine per square degree) and only $\sim30$ per cent of the sample would be cluster members. However, previous observations suggest that the N–S strip covers a number of Virgo substructures and may include two infalling clouds. Comparing the number distribution of galaxy surface brightnesses and magnitudes between the strips, we find that the surface brightness distributions are very similar while the distribution of apparent magnitudes is quite different – there are more faint galaxies in the N–S strip, consistent with many of the galaxies being in the more-distant infalling clouds. The same signature of the clouds is seen in the ratio of dE to dI galaxy numbers with radius – for the E–W strip this is smoothly declining while for the N–S strip there is a peak at about 4′, just where the infalling clouds are expected to be. The ratio of numbers of dwarfs detected to the number of giant galaxies is higher in the N–S strip than in the E–W strip. There does not seem to be a prevalence for dwarfs to cluster around the giants in either of the two strips. The range and mean of the $(B-I)$ colours of the galaxies in both strips is about
the same and does not change systematically with galaxy magnitude or position in the cluster. The dwarf galaxy population is generally bluer than that of giant elliptical galaxies and is very similar to that of the M87 GC systems. A crucial test of hierarchical models is just how dwarf galaxies get these relatively blue colours. Is it because they are old and metal poor like GCs or because they have populations of younger stars. The E–W strip samples a smoothly declining number of dwarf galaxies associated with subcluster A centred on M87. The N–S strip samples a much more complex environment associated with subcluster A and the infalling M and N clouds. The different subcomponents of the cluster, and how they are assembling themselves around M87 is not a new discovery. However, with our data set we are sampling a new parameter space as we reach fainter magnitudes than previous surveys, and the properties of our newly discovered galaxies still agree with this picture of the Virgo cluster forming out of discrete units. An important observation is that the infalling clouds seem to have associated with them similar relative numbers of dwarf galaxies to the cluster as a whole. Given the lack of dwarf galaxies in the field and in groups like the Local Group – when and how do they obtain these dwarfs?

The recent discovery of extremely low luminosity and LSB dSph companions to the MW (Willman et al. 2005) has highlighted the possibility that the predicted population of low-mass haloes in ΛCDM may actually exist. Klyna et al. (2005) comment that this new dSph, which has a mass-to-light ratio of over 500 M⊙/L⊙ and absolute magnitude, M_v ~ −6.75, ‘may represent the best candidate for a ‘missing’ ΛCDM halo’. They conclude that there must be more dark and massive dwarfs hiding in the region around the MW. It is therefore extremely important that searches for such objects are carried out if we are to properly check the consistency of observations with ΛCDM predictions.

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