The dwarf LSB galaxy population of the Virgo Cluster II. Colours and H$i$ line observations.

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ABSTRACT

In order to investigate the nature of dwarf Low Surface Brightness (LSB) galaxies we have undertaken a deep B and I band CCD survey of a 14 sq degree strip in the Virgo Cluster and applied a Fourier convolution technique to explore its dwarf galaxy population down to a central surface brightness of $\sim 26$ B mag/arcsec$^2$ and a total absolute B mag of $\sim -10$. In this paper we carry out an analysis of their morphology, (B-I) colours and atomic hydrogen content. We compare these properties with those of dwarf galaxies in other environments to try and assess how the cluster environment has influenced their evolution. Field dwarfs are generally of a more irregular morphology, are bluer and contain relatively more gas. We assess the importance that various physical processes have on the evolution of cluster dwarf galaxies (ram pressure stripping, tidal interactions, supernova driven gas loss). We suggest that enhanced star formation triggered by tidal interactions is the major reason for the very different general properties of cluster dwarfs: they have undergone accelerated evolution.

Key words: dwarf galaxies – Virgo Cluster.

1 INTRODUCTION

The effect of the environment upon bright galaxies has been well studied over the years but can still be controversial (see for example the E-to-S0 ratio controversy: Dressler et al, 1997; Andreon, 1998; Lubin et al, 1998). There are noticeable variations in the morphology, colour and magnitude of cluster bright galaxies with respect to the properties of field galaxies. A galaxy in a cluster can be subject to many different processes that are not at work (or less likely to occur) in the field: direct collisions, galaxy-galaxy or galaxy-cluster tidal interactions, high/low-speed encounters between galaxies, ram pressure stripping by the ICM, pressure confinement and combinations of the above. The two main effects produced by these various processes are in some ways opposite: if, on one hand, a cluster can diminish the gas content (and thus the star formation rate, SFR) of its galaxies by means of various stripping mechanisms, on the other hand it can also trigger star formation and accelerate evolution by means of tidal interactions. Which of these two effects is prominent remains controversial (Davies & Phillips, 1989; Hashimoto et al, 1998; Gnedin, 2003) and possibly depends on the exact nature of the environment and on the galaxy type considered. Different studies come to different conclusions: whereas some report the quenching of star formation in clusters rather than its enhancement (Kennicutt 1983; Dressler, Thompson & Shectman, 1985; Poggianti et al, 1999; Dressler et al, 1999), others find the opposite result, suggesting a similar or higher SFR in clusters than in the field (see Bothun & Dressler (1986) and Caldwell et al. (1993) for the Coma Cluster).

Also, observations of the distant ‘faint blue galaxies’ have been used to infer that star formation is enhanced (or accelerated) as galaxies initially fall into a cluster, but at the current time star formation is suppressed compared to the field.

These issues are further complicated when investigating the effects of the environment upon dwarf galaxies, due to their low magnitude and surface brightness values. If dwarfs are the first objects formed, as predicted by Cold Dark Matter (CDM) models of hierarchical structure formation

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(White & Rees 1978; White & Frenk, 1991), we should expect them to be the oldest galaxies in the universe and to be present in all environments. They should have similar properties everywhere, unless the environmentally dependent evolution is strong. The latest observational results, however, indicate that the faint-end-slope of the Luminosity Function (which quantifies the number of dwarfs) has a strong environmental dependence (Trentham & Tully 2002; Roberts et al, 2004). If the stellar mass of a dark halo is proportional to its dark matter mass, then the Luminosity Function (LF) is a direct measure of the dark matter Mass Function and model predictions require many more small dark matter halos around individual galaxies and in galaxy clusters than have been detected (Kauffmann, White & Guiderdoni 1993; Moore, Lake & Katz 1998). This failure of the standard CDM prediction is not universal: there are galaxy clusters, like Coma, Virgo and Fornax, where the faint-end-slope of the Luminosity Function is found to be steep (Kambas et al. 2000; Milne & Pritchet 2002; Sabatini et al. 2003). Compared to these clusters, there is a real lack of low luminosity galaxies in lower density environments, like the Local Group and the field (Pritchet & van der Bergh, 1999; Norberg et al. 2002; Roberts et al, 2004). These results imply that there cannot be a global dwarf galaxy formation suppression mechanism as is invoked in many simulations. This normally takes the form of gas loss through supernova driven winds (a ‘feedback’ mechanism).

Ignoring the possibility of many dark halos with no baryons at all, there are two possible interpretations consistent with the observations:

1) CDM predictions are correct, but we need to invoke some mechanisms that preserve primordial dwarf galaxies in some environments, while destroying them in others;
2) the dwarf galaxies found in rich clusters are a different population from the primordial one predicted by CDM - meaning that some processes must have actually formed them solely in some environments and/or suppressed them in others.

The most popular environment dependent mechanisms proposed in support of the former hypothesis are:

a) Squeezing (Tully at al. 2002) - a suppression of dwarf galaxy formation in low density environments due to photoionization occurring at a critical phase in the structure formation. Note, however, that WMAP results now place the ionisation epoch at $z \approx 20$ (Spergel et al, 2003) and fluctuations of order $10^7 M_\odot$ in CDM models are extremely rare at that epoch (Miralda-Escude, 2003). Also, the star formation histories of Local Group satellites show evidence of several (also recent) star formation bursts, some continuing to the present day. For these reasons we will not consider this process further.

b) Pressure confinement (Babul & Rees, 1992) - the pressure of the intra-cluster medium (ICM) reduces the gas loss produced by a feedback mechanism such as supernova driven winds.

On the other hand, in support of the second hypothesis, mechanisms that can form dwarf galaxies after the CDM dwarf galaxy formation epoch are:

c) Tidal interactions (Okazaki & Taniguchi, 2000) - galaxy-galaxy interactions and mergers can result in the formation of so-called tidal dwarfs.

b) Harassment (Moore et al, 1999) - infalling LSB disc galaxies in a cluster are subject to many high speed encounters that can result in their morphological transformation into dwarf Ellipticals (dE) galaxies.

Trying to disentangle these issues requires a better understanding of how the mechanisms involved in galaxy evolution relate to the environment, and thus a detailed study of the properties of the dwarfs found in different environments: in what follows we will try to analyse what makes a cluster different from the field or from a loose group, and which observables (e.g., galaxy colours, H I content, velocity dispersion) can help distinguishing between the two different interpretations stated above.

Being the nearest cluster ($d \sim 16$ Mpc; Graham et al, 1999; Jerjen, Binggeli & Barazza, 2003) with several hundreds of bright galaxies ($\sim 1277$ sure members are listed in the Virgo Cluster Catalogue (VCC); Binggeli, Sandage & Tarenghi, 1984), the Virgo cluster offers the best opportunity for the detailed study of large numbers of bright galaxies and faint dwarfs in the cluster environment. The most complete optical survey of the Virgo cluster to date, the VCC, compiled using photographic plates and a visual detection method, is complete for objects of moderate surface brightness with $M_B < -14$. At present, however, there is no published catalogue of candidate dwarf galaxy members of the entire Virgo cluster which is complete for objects fainter than $M_B = -14$ and central surface brightness values as low as 26 B mag/arcsec$^2$. These are the properties of the numerous low luminosity galaxies dominating the numbers in the Local Group (Mateo, 1998).

There are several studies in the literature that point to evolving populations of dwarfs in clusters of galaxies (see Conselice et al 2001, 2003; Poggianti et al, 2001; Jerjen et al, 2004; Rakos & Schombert 2004), but none of them reaches the faint magnitude values of Local Group dwarfs. In order to investigate the possibility that previous surveys have missed a fainter population of Virgo Cluster dwarfs, we have applied (Sabatini et al, 2003; paper I) an optimised Fourier convolution technique to deep CCD images of one strip in the cluster, detecting LSB dwarfs in the B band down to surface brightness values of 26 mag/arcsec$^2$ and absolute magnitudes of -10 at the assumed Virgo cluster distance. A detailed description of the selection procedure and a determination of the Luminosity Function of the cluster dwarfs is given in Paper I. Over a search area of $\sim 14$ deg$^2$ we have identified 231 dwarf low surface brightness candidates, 105 of them being previously uncatalogued galaxies (see VCC; Impey & Bothun 1988; Trentham & Hodgkin 2002).

With all this in mind, and with the aim of improving our understanding of the nature of very faint dwarf galaxies in the cluster environment, we have supplemented our deep B band data with I band data and H I line follow up observations. In a separate paper (Roberts et al, 2004) we compare our results with those from an identical dataset (same detector, telescope, exposure time, detection method) of both the Ursa Major Cluster and the general field.

The paper is organized as follows: in sections 2 and 3 we describe the data and the data reduction; in section 4 we discuss the spatial distribution of the dwarf galaxies and its relation with the giants; in 5 we present the B-I colours of the galaxies in our sample and compare these results with different environments of the Local Universe; in section 6 we describe the Arecibo 21cm H I line observations, data
cluster (identified as M87) eastwards for 7°, with a total area of ~14 deg². This region of the cluster is part of the dynamical unit named cluster A (M87), excluding members of other units like cluster B, clouds M and W.

The data in both bands were preprocessed and fully reduced using the Wide Field Survey pipeline: this includes de-biasing, bad pixel replacement, non-linearity correction, flat-fielding, defringing (for i band) and gain correction. The photometric calibration makes use of several (5-10 per night) standard stars and the zero-points are accurate to 1-2 per cent. For more details, see http://www.ast.cam.ac.uk/~wfserv/pipeline.html. The results throughout the paper are given in the B and I magnitudes, with the exception of 6:3 have very low signal-to-noise ratios on the B band images and are not visible at all on the i band images; for the other 3 the i band image is corrupted. For the errors on the B-I colours we refer to Sec 5 and for more detailed comments on single objects to Sec 6.3.

The total B magnitudes and central surface brightness values used in the plots were all calculated using our convolution algorithm (see paper I for estimated errors).

Table 2 lists some of the global optical and H1 properties of the dwarf LSB galaxies of our sample that have been detected in H1: centre position, morphological classification, total apparent magnitude, central surface brightness and scale-length in B, B-I colour, rms noise of the H1 spectra, integrated H1 line flux, \( I_{\text{H1}} \), the \( W_{50} \) and \( W_{20} \) line widths, measured at respectively, the 50% and 20% level of peak maximum, the centre velocities, \( V_{\text{H1}} \), \( M_{\text{HI}} \) and the relative H1 content, \( M_{\text{HI}}/L_B \) (see Sec. 6 for details on the H1 data).

3 DATA REDUCTION

For the analysis of (B-I) colours, we need consistent measurements of the magnitudes in both bands. Even when fully reduced, the i band images are still affected by a fringing signature. This makes it impossible to apply our convolution technique to measure fluxes in this band. The data analysis for this section was therefore performed using the aperture photometry routine from the GAIA package on both the i and B band data for the sake of consistency. Photometry was done using for each galaxy an aperture large enough to include its total flux and yet avoiding contamination by nearby objects. For each object the aperture and centre position determined in the B band was subsequently used in the i band as well.

Although morphological classification is very difficult for some of the objects, due to their very low surface brightness, we classified the galaxies of our sample either as dE, dI or VLSB. We describe as dE the spherical diffuse ones and the more compact elliptical objects; dE,N denotes objects in this category that show a nucleus. The dIs are the irregularly shaped objects, often showing clumps. The objects that could not be assigned to either of these category we refer to as VLSB (very low surface brightness). The overall sample is dominated by dE types (54%, a quarter of which have a nucleus), whereas the dIs represent 27% and the VLSBs 14%.

B-I colours we measured for practically all the galaxies, with the exception of 6: 3 have very low signal-to-noise ratios on the B band images and are not visible at all on the i band images; for the other 3 the i band image is corrupted. For the errors on the B-I colours we refer to Sec 5 and for more detailed comments on single objects to Sec 6.3.

4 THE DWARF-TO-GIANT RATIO

In paper I we have shown the radial profile of the galaxy number density of our sample. This can be compared with that of the bright galaxies. We have defined a Dwarf-to-Giant Ratio (DGR) as the ratio of dwarf galaxies (defined as those with \(-14 \leq M_B \leq -10\)) to giant galaxies (with

\[ M_B \sim -10 \]
$M_B \leq -19$). This is a simpler and more versatile measure to quantify the Luminosity Distribution than the LF. We have shown that the DGR remains rather flat with distance from M87 with a median value of $\sim 20$. This number has to be compared with a value of about 6, for the field population (Roberts et al, 2004).

It is difficult to compare our results with other studies, as different papers use different definitions for the DGR. Ferguson & Sandage (1991) studied 7 groups and clusters and defined an elliptical giants-to-dwarf-ratio EDGR. Our results are consistent with the strong correlation found by these authors of the EDGR with the cluster richness: they found as well that the EDGR in the Virgo Cluster appears to be independent of distance from the cluster centre. Secker & Harris (1996), however, find an EDGR in the Coma Cluster identical to the one in the less rich Virgo Cluster and thus in contrast with the EDGR-richness correlation. They point out that the presence of substructure could be an important factor and that the Coma Cluster result would be consistent with the cluster being built up from the mergers of less rich clusters. Also, more recently, Driver et al (1998) studied 7 rich clusters at redshift $\sim 0.15$ and found an anti-correlation between richness (or density) of the cluster and DRG; their definition of dwarfs, however, comprise all galaxies fainter than $-19.5$ and it is therefore difficult to compare their results with ours.

Our results have also to be compared to the values in the Local Group: in a hierarchical structure formation scenario, clusters like Virgo, should be formed by accretion of smaller groups. It is thus possible that some or all the dEs in Virgo were once part of structures like the Local Group that fell into Virgo with their spirals and satellites. The expected DGR from hierarchical structure formations, should be the same for all these environments, or a smaller one in the cluster if the disruptive processes are the dominant ones for dwarf galaxies, as often assumed in LCDM models of galaxy formation. Contrary to these predictions, the observed increase in the DGR that we find in clusters would instead imply that some galaxies are actually ‘formed’ in the assembling of the cluster.

Dwarfs in the Local Group are mainly associated with bright galaxies: 75% of them cluster in 3 subgroups respectively around M31, the MW and NGC3109 and the other 25% are part of the Local Group Cloud, populated only by dwarf irregular systems (Mateo 1998). It is interesting to compare these properties with the spatial distribution that we find in the Virgo Cluster. Fig. 2 shows the spatial distribution of our sample dwarfs and of the Virgo Cluster giants ($M_B \leq -19$) from the VCC. We have also plotted the tidal radius around each giant galaxy in the strip (larger circles). This is the truncation radius of the dark matter halos in the cluster and it can therefore be considered as the one within which sub-halos remain bound to the galaxy potential well. Describing the cluster and the galaxy halos with a singular isothermal distribution $\dagger$, the tidal radius $R_t$ can be approximated as:

$$R_t \approx \frac{\sigma_g}{\sigma_d} R_p$$  

where $R_p$ is the distance of the closest approach to the centre of the cluster, and $\sigma_g$ and $\sigma_d$ are respectively the velocity dispersions of the galaxy and of the cluster (Merritt 1984; Gnedin, 2003). For many galaxies the distance of closest approach to the cluster centre is of order the cluster core radius (Gnedin 2003) and for the Virgo Cluster we can therefore approximate it with 0.5 Mpc (Binggeli, Tammann & Sandage, 1987). Assuming the velocity dispersion of the galaxies in the cluster to be $\sim 700$ km/s and the rotational velocity of a giant $\sim 200$ km/s, the typical tidal radius for a giant galaxy in the Virgo cluster is $R_t \sim 150$ Kpc.

Although the spatial distribution in Fig 2 is just a projection and it is difficult to know what the real distribution is, it is interesting that a significant part of the dwarf galaxy population does not seem to be associated with the giants. A similar result was found by Ferguson (1992): in his analysis of bound companions in the Virgo Cluster, he suggested the existence of a free-floating cluster member population made of stripped companions. In agreement with this view, a more recent paper by Conselice et al (2001) showed that there is little evidence for a dynamically cool dE component, as might be expected if a significant fraction of dE were bound to individual cluster galaxies (see also Binggeli, Popescu & Tammann, 1993; Binggeli, Tammann & Sandage, 1987). Our results indicate as well that there appears to be a cluster dwarf population: $\sim 40\%$ of the galaxies in our sample are apparently not bound to the giants and this is a larger number than that in the Local Group. Again this number cannot be accounted for if the Virgo Cluster was simply made up of groups like the Local Group. Also, after

$\dagger$ This definition for the giants is assumed in order to easily compare our numbers with the ones in the Local Group, as this is the magnitude limit in order to include its three giants M31, M33 and the Milky Way.

$\ddagger$ Whether the Virgo Cluster is relaxed is still a matter of debate (see Binggeli et al 1987; Binggeli et al 1993; Schindler et al 1999); nevertheless substructures in the cluster will amplify the truncation effect (Gnedin 2003) and would therefore reduce the radii of the circles in Fig 2.
The dwarf LSB galaxy population of the Virgo Cluster II.

Figure 3. B-I colours plotted as function of distance from M87, assumed as the centre of the cluster. Different symbols refer to different morphological types: filled circles for dE and diamonds for dI and VLSB. The sample does not seem to have any dependence upon distance from the cluster centre. Average error on the (B-I) colour value is 0.25. Points which deviate more from the mean value have larger errors, as shown in Fig 5.

Figure 4. dE-to-dI ratio as a function of cluster-centric distance.

subtracting the average number density of this 'un-bound' dwarf population from the average number of dwarf galaxies within a projected tidal radius from a giant, the number of dwarfs possibly associated with each giant is $\sim 13 \pm 3$. This has to be compared with a value of 3 for the Milky Way (this would be obtained if the Milky Way was at the Virgo Cluster distance and for dwarf galaxies that match our selection criteria) and 4 for the Local Group, suggesting that infalling galaxy groups cannot supply sufficient dwarfs in cluster (see also Conselice et al, 2001; Tully et al, 2002).

5 B-I COLOURS

Being interested in the nature of the dwarf galaxies in our sample and in possible environmental effects on the evolution of galaxies in the cluster, we firstly investigated the possibility of a relationship between colours and cluster-centric distance. In Fig 3 we plot the B-I integrated colours of our galaxies as a function of their position in the cluster (identified as the distance from M87); different symbols refer to different morphologies: filled dots for dEs and open diamonds for dIs and VLSBs. The range of colours is quite wide, with an average value of about 1.7. Even if this figure shows that the colours do not appear to have any dependence upon distance from the centre of the cluster, the numerical ratio of dEs to dIs (Fig 4) shows a morphology-density relation. This, we believe, could be an important clue to the nature of the cluster dwarf galaxy population: the well ordered spherically symmetric galaxies (dE) are preferentially found towards the cluster centre, the more irregular galaxies (dI) towards the cluster edge. This is directly analogous to the bright galaxy morphology-density relation (Dressler, 1984). In the same way as it has been proposed that spiral galaxies are being transformed into S0 galaxies in the cluster environment (Kodama & Smail 2001 and references therein) this could indicate that infalling dI galaxies are transformed into dEs (Davies & Phillipps 1989; Conselice et al 2003).

Figures 5 and 6 show the distribution of colours as a function of total absolute magnitude and central surface brightness, respectively. Again, the distributions do not show any correlation. Fig 5 clearly shows that the scatter in colours has a dependence on total magnitude. In this figure we also give an estimate of the average error at each magnitude. The errors on the colours were calculated considering the following two independent contributions: 1) a systematic error due to the aperture photometry procedure; 2) the error in the calculation of the sky subtraction, that depends on the area of the object. Although the errors on the colour increase at the fainter magnitudes, the scatter is still much larger than the calculated errors. Fig 7 shows that dE galaxies also have a narrower range of colours across the whole magnitude range ($\langle B-I \rangle_{\text{med}} = 1.76; \sigma = 0.30$), while dI galaxies have a much broader range ($\langle B-I \rangle_{\text{med}} = 1.70; \sigma = 0.70$) possibly indicating their different evolutionary states i.e. undergoing, fading from or between a burst of star formation. For comparison, Karick, Drinkwater & Gregg (2003) also find a wide range of colours for their Fornax cluster dwarf galaxies, larger than that of brighter galaxies.

5.1 Comparison with synthetic colours

For comparison with our colour distribution, in Fig. 8 we show the (B-I) colour predictions obtained using the
Figure 6. B-I colours plotted as function of central B surface brightness. The colours appear to be spread out along the range of magnitudes considered without any evident correlation, although it has to be noticed that the extremely blue colours are found for $\mu_0 < 1 \sigma_{sky}$ ($\sim 26$ B mag/arcsec$^2$). Average error on the (B-I) colour value is 0.25. Points with large deviation from the mean value have larger errors, as shown in Fig 5.

Figure 7. (B-I) colour distribution for dE and dI respectively. Median and standard deviation values for the 2 distributions are respectively: (B-I)$_{dE}$=1.76, $\sigma_{dE}$=0.30 ; (B-I)$_{dI}$=1.70, $\sigma_{dI}$ = 0.70.

Figure 8. Synthetic (B-I) colours as function of time produced using the PEGASE evolutionary synthesis code. Overlayed in the plot, as explained in the legend, are the median (B-I) colour of our distribution (filled line) and for comparison a typical value for an Elliptical Galaxy (dotted line) and for a late-type Spiral (dashed line). These latter values are taken from Fukugita et al, 1995.

PEGASE evolutionary synthesis code (Fioc & Rocca-Volmerange 1997). The figure shows (B-I) as a function of time and different points for each age refer to different initial metallicities and star formation rates chosen in the simulation. Aware that one colour is not enough for disentangling the effects of metallicity and age (i.e. the age-metallicity degeneracy; Worthey 1994 and references therein), we did not explore the synthesis code in all its potentialities and we run it instead, using the default choices for the many allowed parameters: a Salpeter IMF (with lower mass 0.1 $M_\odot$ and upper mass 120 $M_\odot$), a range of metallicities (0.1, 0.05, 0.02, 0.008, 0.004, 0.0004, 0.0001 $Z_\odot$) and different exponential star formation rates with decay times $1,2,4,8,16,32$ Gyr.

The main intention with this comparison is to show that the distribution of galaxy colours of our sample lies well in the average range of the expected values from synthetic models (Fig 8, filled line). Also, some of our extremely blue colours are compatible with very young ages, but one colour is not enough to claim any definitive conclusion and, as we have shown, errors on these extremely blue colours are quite large. As a comparison, average values for an Elliptical galaxy and a late-type Spiral (Fukugita et al, 1995) have been overlayed in the plot of Fig 8. It is interesting that the average colour of the dwarfs in our sample is closer to that of a Spiral and bluer than that of an Elliptical, suggesting that these dwarfs have possibly consumed their gas until recent epochs. However, Fig 8 clearly shows that it is not possible to obtain conclusive results from this analysis with one colour only; combined observations in a third band (e.g. the K band) would help disentangling the age-metallicity degeneracy. We will be doing this as part of the near infrared survey UKIDSS - (see, www.ukidss.org). In the following sections, however, as a working hypothesis, we will assume that the galaxies in our sample have similar metallicity so that the relative B-I colour differences are indicative of differences in age.

5.2 Comparison with different environments of the Local Universe

Although it is in principle difficult to combine results from samples selected in different ways, in Fig. 9 we plot the distribution of the (B-I) colours of galaxies from our sample and for comparison the same distributions for dwarf galaxies in different environments of the nearby universe: the field (Makarova, 1999), the Ursa Major Cluster (Trentham, Tully & Verheijen 2001), the Virgo Cluster (from our catalogue) and the Fornax Cluster (Karick, Drinkwater & Gregg 2003). Table 1 gives the median and standard deviation for these distributions, along with some relevant properties of the environments.

Table 1 and figure 9 suggest that the average colour distribution of dwarf galaxies becomes progressively redder, when proceeding from the field to denser, more elliptical galaxy-dominated environments. Gallagher & Hunter (1986) found the same trend comparing dI of the Virgo Cluster to...
6  H I OBSERVATIONS

The H I data are 21cm H I line pointed observations with the 305m Arecibo telescope of a subsample of galaxies from our catalogue. Many H I surveys have been made of, or in, the Virgo cluster area, also aimed at detecting dwarf galaxies (Conselice et al., 2003; Hoffman et al., 1985, 1989). A blind H I line survey of the entire cluster, providing a comprehensive census of gas-rich objects, has recently been carried out by the HIPASS team, but the data is, as yet, unavailable.

Davies et al (2004) have carried out a deep blind Jodrell Bank survey of a 4×8 deg region in the Virgo Cluster. The results from this survey indicate a relative lack of low mass H I objects compared to the field: galaxies in the cluster environment are depleted in gas compared to field galaxies - either through the gas loss mechanisms or through accelerated star formation. This survey has also, surprisingly, shown the presence of 2 objects without optical counter parts (Davies et al, 2004). Although a further investigation is required in order to confirm these objects, this result shows how H I observations can still provide new and interesting results in the Virgo Cluster.

The 3σ H I mass detection limit for a typical 75 km s$^{-1}$ wide flat-topped dwarf profile for the Davies et al blind survey is about $10^8 M_\odot$, corresponding to a gas-rich $(M_\text{HI}/L_B)_v \sim 1$ dwarf of absolute magnitude $M_B \sim 14.5$ at d=16 Mpc. This is the typical value of the brightest dwarfs in our sample. With its extraordinary sensitivity the Arecibo telescope offers the opportunity to go deeper on specific targets and easily reach typical H I mass detection limits at the Virgo Cluster distance of an order of magnitude smaller (see Sec 6.3.2).

The general gas deficiency of Virgo Cluster members is a well established phenomenon (Solanes et al, 2002 and references therein; Davies et al, 2004). Deep H I pointed observations of 59 Virgo cluster dEs from the VCC by Conselice et al. (2003) yielded only 7 clear detections (just 2 of which are new) for objects having a mean blue absolute magnitude $M_B \sim -15$, corresponding to a gas-rich dwarf of mass $10^7 M_\odot$. Even if the expected detection rate was low, we carried out H I follow ups of a sub-sample of our galaxies, because dwarf galaxies in clusters do include star-forming, and generally H I-rich, dwarf irregulars (e.g., Gallagher & Hunter 1984) as well as quiescent, gas-poor dwarf elliptical/spheroidals (e.g., Ferguson & Binggeli 1994; Gallagher & Wyse 1994). H I observations are required for a clearer understanding of their nature, in order to confirm their cluster membership, place lower limits on the H I mass of the non-detected objects, obtain $M_\text{HI}/L_B$ ratios or upper limits and look for environmental effects on their gas content.

6.1 Sample description

From our catalogue of 231 candidate LSB dwarf members of the Virgo Cluster, we observed 100 objects in H I according to the following priorities during the observing run: we firstly selected objects that were not part of the VCC catalogue,
that didn’t lie within 1 degree from the strong continuum source M87 (see Sec. 6.2) and we gave priority to dI or VLSB morphological types. The galaxies observed at Arecibo are listed in Table 2 if detected in H I. The galaxies are given a name from our catalogue and a name from the literature, if previously catalogued; the cross-correlation with other catalogues was made within a 15″ radius search area around our optical centre positions.

In addition, included in our observations are 15 LSB objects listed in the literature (Trentham & Hodgkin (2002); VCC) as candidate Virgo Cluster members, that are located in the E-W strip, but were not picked out by our detection algorithm (for discussion on this point see paper I). We observed these 15 sources in H I as most were classified as dI and therefore are potentially H I gas-rich.

6.2 Data reduction

Data were taken with the L-Band Narrow receiver using nine-level sampling with two of the 2048 lag subcorrelators set to each polarization channel. All observations were taken using the position-switching technique, with the blank sky (or OFF) observation taken for the same length of time, and over the same portion of the Arecibo dish as used for the on-source (ON) observation. Each 3min+3min ON+OFF pair was followed by a 10s ON+OFF observation of a well calibrated noise diode. The overlaps between both subcorrelators with the same polarization allowed a wide velocity search while ensuring an adequately coverage in velocity. The velocity search range was -1000 to 11,000 km s$^{-1}$, as the Virgo Cluster extends from 500 to 2500 km s$^{-1}$ (Binggeli, Popescu & Tammann 1993). The instrument’s HPBW at 21 cm is 3′×3′5 and the pointing accuracy is about 15″.

A filter was used in order to cut off all emissions at frequencies below 1371 MHz, thus eliminating radio frequency interference (RFI) from radars on Puerto Rico. The strongest RFI signal noted was centred on 1381 MHz (or 8300 km s$^{-1}$), which however did not occur frequently.

Using standard IDL data reduction software available at Arecibo, corrections were applied for the variations in the gain and system temperature with zenith angle and azimuth, a baseline of order one to three was fitted to the baselines in a sizeable area (≃15′) surrounding it. M87 is a 220 Jy source at 1415 MHz, with a core and two lobes extending some 15′ from the core. Attempts were made to correct the bandpass by applying a double-switching technique in which an ON+OFF spectrum of a target galaxy is normalised with an ON+OFF spectrum of the continuum source influencing the data, i.e. M87, taken just after. Although this technique has been applied successfully at Arecibo to H I data of galaxies with continuum sources (e.g., Ghosh & Salter, 2002), the situation near M87 is fundamentally different as it is detected through the far side-lobes of the telescope, rather than through the main beam, and it is strong enough to cause non-linear saturation effects in the receiver system. Since we could not obtain proper quality data within about a degree from M87, we stopped observing objects in that area (see Fig 1).

6.3 Results

Out of the 115 objects we observed in H I just 5 were detected, 3 of which are members (i.e. have line centre velocities in the range 500 to 2500 km s$^{-1}$). Optical B band images from our deep CCD frames and H I spectra of these sources are shown in Fig 10 and a discussion on individual objects is given in next section. Table 2 gives their global optical properties measured in the B band as well as the integrated line fluxes of the detections: $I_{HI}$, the $W_{50}$ and $W_{20}$ line widths, the centre velocities $V_{HI}$, the total H I mass $M_{HI}$ and the H I mass-to-light ratio $M_{HI}/L_B$. The total H I mass, given in $M_\odot$, is derived from the total flux according to the formula:

$$M_{HI} = 2.365 \times 10^{5} \times D^2 \int S(v)dv$$

where the distance D is given in Mpc, the flux S(v) in Jy and the velocity v in km s$^{-1}$ (Roberts, 1968).

All the given radial velocities are heliocentric and expressed according to the conventional optical definition $(V = c(\lambda - \lambda_0)/\lambda_0)$. For objects with radial velocities that lie inside the range occupied by Virgo Cluster members, $\sim$ -500 to 2500 km s$^{-1}$, a distance d of 16 Mpc was assumed. For other objects distances were calculated using radial H I velocities corrected to the Galactic Standard of Rest, following the procedure given in the RC3, and assuming a Hubble constant of $H_0$=75 km s$^{-1}$ Mpc$^{-1}$.

6.3.1 Notes on individual objects

144: This object is a cluster member, which we detected at $V_{HI}$=1036 km s$^{-1}$. Its projected distance from the cluster centre is $\sim 2'$ . Its extremely low central surface brightness (26.6 B mag/arcsec$^2$) makes it almost impossible to see on the B band image. With an H I mass-to-light ratio of 6.2, it is an extreme case of either a very young galaxy or a galaxy where the conversion of gas into stars has been very efficient. The (B-I) colour for this galaxy is not available, because the noise in the I band image is too high to measure its flux.

158 (= T152): This object is a cluster member at a cluster-centric distance of $\sim 5'$, which we detected at $V_{HI}$=1788 km s$^{-1}$. It is an irregularly shaped galaxy with several clumps in the B band image.

249 (= UGC 8661): This object is an irregular LSB VCC galaxy at cluster-centric distance of $\sim 6.5'$. Although our centre velocity and line flux are in agreement with those of Schombert, Pildis & Eder (1997) and Huchtmeier et al. (2000), who found $V_{HI}$= 562 km s$^{-1}$ and $I_{HI}$= 2.0 Jy km s$^{-1}$, our $W_{50}$ of 72 km s$^{-1}$ is larger than their 55 km s$^{-1}$. The B band image shows a very irregular galaxy with several clumps surrounded by diffuse light.

4 (= T225): This object, also classified as dI by Trentham et al. (2003), is a background galaxy, which we detected at
Figure 10. B band images and H\textsc{i} spectra for the 5 non-confused H\textsc{i} detections; respectively nos 144, 158, 249, 4, 27 from our catalogue.
Table 2. Objects detected in H\textsubscript{i} at Arecibo. [1] Object’s number from our catalogue, [2] identification from other catalogues (T: Trentham & Hodgkin 2002; U: UGC), [3] right ascension (J2000.0), [4] declination (J2000.0), [5] morphological type, [6] total apparent blue magnitude, [7] central blue surface brightness, [8] disc scale-length, [9] B-I , [10] rms noise level of H\textsubscript{i} spectrum, [11] integrated H\textsubscript{i} line flux, [12] H\textsubscript{i} profile width at 50% of peak maximum, [13] same at 20%, [14] H\textsubscript{i} line centre velocity, [15] distance, [16] H\textsubscript{i} mass and [17] H\textsubscript{i} mass to blue luminosity ratio.

| Obj | Id | RA(J2000.0) | Dec | $m_B$ | $\alpha$ | $\delta$ | B-I | rms | $I_{HI}$ | $W_{50}$ | $W_{20}$ | $V_{HI}$ | d | $M_{HI}$ | $M_{HI}/L_B$ |
|-----|----|-------------|-----|------|-------|-------|-----|-----|---------|---------|---------|----------|--|----------|-----------|
| 144 |    | 123841      | 115843 | dI   | 19.8  | 26.6  | 9   | -   | 0.8    | 0.47    | 77      | 125      | 1036    | 16 | 0.3      | 0.2       |
| 158 |    | 125167      | 120339 | dI   | 17.1  | 23.3  | 7   | 1.61| 0.9    | 1.71    | 63      | 83       | 1788    | 16 | 1.0      | 1.7       |
| 249 |    | 125644      | 115557 | dI   | 17.0  | 23.7  | 9   | 1.26| 1.5    | 2.12    | 69      | 89       | 563     | 16 | 1.3      | 1.9       |
| 4   |    | 124112      | 105601 | dI   | 17.7  | 23.6  | 6   | 1.17| 0.9    | 1.13    | 175     | 125      | 5688    | 85.5| 19.8     | 2.0       |
| 27  |    | 124934      | 121411 | dI   | 18.2  | 23.3  | 4   | 1.04| 1.0    | 1.03    | 157     | 197      | 297     | 7146    | 94.7| 22.0     | 3.1       |

$V_{HI}=$6468 km s\textsuperscript{-1}. Its $W_{50}$ line width of 174 km s\textsuperscript{-1} is much larger than what is usually found for dwarf galaxies. It could resemble the extreme late type field galaxies discussed by Matthews & Gallagher (1997) in terms of its optical structure and H\textsubscript{i} line profile.

**27:** This edge-on object is a background galaxy, which we detected at $V_{HI}=$7146 km s\textsuperscript{-1}.

### 6.3.2 Notes on non-detections

The average noise for our spectra is 1 mJy at a velocity resolution of 15 km s\textsuperscript{-1}. Assuming a typical full width at half maximum (FWHM) for the H\textsubscript{i} profile of the dwarfs to be 75 km s\textsuperscript{-1} and a 3σ detection threshold, at a distance of 16 Mpc, the non-detections have an average upper mass limit of $\sim 1.5 \times 10^{10}$ $M_\sun$ which translates into a column density limit of $\sim 5 \times 10^{18}$ atoms cm\textsuperscript{-2} (assuming a limiting mass galaxy filling the beam at the cluster distance).

The estimated upper limits of the ($M_{HI}/L_B$) ratio range from 0.1 to 12, depending on the galaxy absolute magnitude. In Fig 11 we show this detection limit as a function of absolute B magnitude for Virgo Cluster dwarf the galaxies, for an assumed 75 km s\textsuperscript{-1} line width. Dots in the plot are dwarf galaxies from the Local Group that have H\textsubscript{i} emission (Mateo 1998); diamonds are our detections.

![Figure 11](image.png)

**Figure 11.** $M_{HI}/L_B$ 3σ detection limit for our survey as a function of absolute B magnitude of Virgo Cluster dwarf the galaxies, for an assumed 75 km s\textsuperscript{-1} line width. Dots in the plot are dwarf galaxies from the Local Group that have H\textsubscript{i} emission (Mateo 1998); diamonds are our detections.

Signatures of a young stellar population, suggesting that the cluster environment has accelerated their evolution.

A pilot sample of LSB dwarf galaxies identified in the Millennium Galaxy Strip (MGS) was also observed during this Arecibo run. As already pointed out, this is a dataset in the field that is identical to ours in the Virgo Cluster and the same detection algorithm was applied to it, in order to obtain a catalogue of dwarf LSB galaxies (Roberts et al., 2004). The H\textsubscript{i} detection rate for this pilot sample is considerably higher than for our sample in the Virgo Cluster: 4 out of the 14 (~ 30%) observed MGS field galaxies show H\textsubscript{i} emission, compared to 5 out of 115 (~ 4%) in the cluster. Consistent with the well-established trend for clusters to host gas-poor dwarfs, this result confirms the importance of the role played by the environment in the evolution of the gas content of dwarf galaxies.

As a last remark, our H\textsubscript{i} observations of the Virgo Cluster sample are also important because they rule out the possibility that our catalogue is highly contaminated by gas-rich background or foreground galaxies - this being one of the main worries when discussing the faint-end-slope of the Luminosity Function of a cluster or its dwarf galaxy content. According to our observations, the non-detections are also non-background/foreground (H\textsubscript{i} -rich) galaxies in the velocity range of -1000 to 11000 km s\textsuperscript{-1}.
7 DISCUSSION

Before discussing our results, let us summarise them for clarity:

(i) There are cluster dE galaxies that have a small range of colours that are preferentially found towards the centre of the cluster and are gas poor. Dwarf ellipticals are usually passively evolving (no or little star formation) galaxies and the average colours that we found are consistent with this picture and possibly indicative of an older stellar population.

(ii) There are cluster dI galaxies that have a wider range of colours which tend to reside in the outskirts of the cluster. They appear to have star formation regions and the wide range of colours may reflect different current star formation states.

(iii) There seems to be an environmental dependency of the B-I colour distribution of dwarf galaxies in the Local Universe.

(iv) There are about 5 times as many dwarf galaxies (−14 < M_B < −10) per giant galaxy (M_B < −19) in the Virgo cluster than in the general field and in the Local Group (paper I). A considerable part of these galaxies seem to constitute a cluster dwarf population rather than being associated with the giants. Also, the number of dwarfs possibly associated with giant galaxies in Virgo (i.e. their projected distance is within the giant tidal radius) is on average ∼13, compared with ∼4 for the Local Group. Because of this excess of dwarfs, the cluster cannot have been simply constructed by infalling small groups like the Local Group.

(v) On the whole, the cluster dwarf galaxy population is gas poor compared to the dwarf galaxies in the Local Group and in the field.

(vi) The luminosity function of the cluster over the range (−14 < M_B < −10) is steeper than that in the field. Also, distinguishing inner and outer regions for the cluster, the LF in the former region is flatter than in the latter (paper I).

(vii) The H I mass function of the cluster appears to be less steep than the H I Mass Function of the field. Combining this with the observed steep LF leads suggests that, in the cluster, gas has been more efficiently converted into stars (Davies et al., 2004); stripping mechanisms might also however produce this result.

(viii) In addition, Conselice et al (2003) have shown that the Virgo Cluster dE population is dynamically similar to the spiral rather than the elliptical galaxy population. They argue that this implies that the dE population is not primordial; rather it is a population that has fallen into the cluster at a later date.

In the sections below we discuss possible physical processes acting on the dwarf galaxies in the cluster environment and the influence that they have on the results described above. In particular there have been numerous attempts in the past to look for mechanisms that remove gas from cluster dwarf galaxies to explain their red colours (no recent star formation) and their lack of gas. Contrary to this, we believe that our results can be explained by accelerated star formation that consumes the galaxy gas, rather than gas stripping mechanisms (see sec 7.4).

Part of the analysis below is similar to that extensively and comprehensively discussed in a series of papers by Conselice et al (2001, 2002, 2003, 2003a). We formulate the problem in a slightly different way, concentrating on the mass-to-light ratios required to avoid gas stripping (see also Davies and Phillipps, 1989). Dwarf galaxies may in fact be very robust objects in the inter-galactic medium. For example the recent work by Klenya et al (2002) on the velocity dispersion of stars in the outskirts of the Local Group galaxy Draco has revised its mass-to-light ratio from about 100 to 440.

7.1 Ram pressure stripping

A cluster like Virgo has a substantial intra-cluster medium (ICM) which is detected via its x-ray emission (Vollmer et al, 2001). A galaxy moving through the ICM is subject to a ram pressure that can possibly strip its gas, if the ICM pressure on the galaxy is stronger than its internal gravitational force (Gunn & Gott, 1972). Ram pressure stripping has often been used in order to explain the H I deficiency of galaxies in clusters compared with galaxies in the field (Chamaraux, Balkowski & Gerard, 1980; van Gorkom 2003; Lee, McCall & Richer, 2003).

Following Davies & Phillipps (1989), we can set a limit for the dynamical mass-to-light ratio $M_{dyn}/L_B$ that a galaxy requires to survive the ram pressure stripping:

$$
\left( \frac{M_{dyn}}{L_B} \right) > \rho_0 \left( 1 + \frac{r^2}{r_\star^2} \right)^{-3/2} \times \frac{v_\perp^2}{\sigma_{gal}^2} \times 10^{0.4(\Sigma - 26.8)}
$$

where $v_\perp$ is the orthogonal velocity of the galaxy through the ICM (km/s), $\sigma_{gal}$ is the gas surface density in the galaxy (M⊙ pc⁻²), $\Sigma$ is the average surface brightness of the galaxy (B mag/arcsec²) and the density of the ICM (atom cm⁻³) is a function of position in the cluster and was parametrized according to a β-model (Cavaliere & Fusco-Femiano 1976). For the Virgo Cluster $\beta = 0.45$, $\rho_0 = 4 \times 10^{-2}$ cm⁻³ and $r_\star = 13.4$ kpc (Vollmer et al. 2001). Also, assuming $v_\perp = 700$ km/s (i.e. the average velocity dispersion of dwarfs in the Virgo Cluster) and $\sigma_{gal} = 5 M_{int}/pc^2 = 5 \times 10^{20}$ atoms cm⁻², i.e. an average value for dwarf galaxies; Blitz & Robishaw, 2000), we obtain limits for the mass-to-light ratio for different central surface brightness values of galaxies as a function of distance from the cluster centre. We take $\Sigma$ to be the mean surface brightness over the half light radius ($\Sigma = \mu_{0,B} + 1.15$). We plot these curves in Fig 12: different colours refer to different central surface brightness. For each curve and each colour, only galaxies above the curve are not affected by the ram-pressure stripping and retain their gas. The open diamonds in the plot show the galaxies in our sample with H I detection and the dots indicate the non-detections (see sec 6).

For galaxies without an H I detection the M/L ratio was calculated using a dark matter halo ($M_h$) to baryonic ($M_b$) mass given in Persic, Salucci & Stel (1996). Note that this formula may severely underestimate the mass-to-light ratio (Klenya et al 2002).

For the 3 galaxies with H I detection, the M/L ratio was calculated making use of the measured velocity width as follows:

$$
M_{dyn} \geq V_{rot}^2 R_{opt}/G
$$

and assuming the rotational velocity $V_{rot}$ of the galaxy to be half of $W_{50}$, and the optical radius $R_{opt}$ to be 2 disc scale lengths (h):
Curves of the M/L ratio limit for ram pressure stripping to occur, as a function of distance from the centre of the cluster. Galaxies with M/L above the curves are able to retain their gas, having a gravitational force stronger than the ram pressure of the ICM. Different colours refer to different average surface brightness values in eq 3: red for \( \mu_0 = 24 \); yellow for \( \mu_0 = 25 \); green for \( \mu_0 = 26 \); blue for has \( \mu_0 = 27 \). Dots are all the galaxies from our sample and open diamonds are the 3 cluster galaxies that have been detected in \( \text{H} \text{i} \). The dots’ colours are related to the galaxy average surface brightness according to the lines’ colours.

\[
M_{\text{dyn}} \geq 0.5 \times W_{20}^2 \times h
\]  

Note that the values obtained in this way are actually lower limits, as the \( \text{H} \text{i} \) radius is usually larger than the optical one. Our calculated values for the 3 galaxies with \( \text{H} \text{i} \) detections lie above the corresponding \( M_{\text{dyn}}/L_B \) limit for the occurrence of ram pressure stripping.

According to the lines of different surface brightness in Fig 12, we can see that the majority of galaxies are not likely to be currently affected by ram pressure stripping. In fact, regardless of their central surface brightness, the plot shows that galaxies are subject to stripping only if they lie within the core radius of the cluster, which corresponds to \( R_c = 0.5 \text{ Mpc} \) for the Virgo Cluster. This is in agreement with the observed gas deficiency of bright galaxies in the centre of the cluster (see for example Solanes et al (2001) for spiral galaxies in the Virgo Cluster). Note that the cluster gas density falls rapidly to \( 2.8 \times 10^{-4} \text{ cm}^{-2} \) at the core radius of 0.5 Mpc - thus over most of the cluster the gas density is much lower than that assumed in simulations of ram pressure stripping (Marcolini et al., 2003). We should also take into account that the positions plotted for our galaxies are projected ones: galaxies at a small projected distance to the centre may actually lie in the outskirts of the cluster. The actual distance of such a galaxy would then be larger and the point representing it would move to the right in our plot, thus increasing the number of dwarfs that are not affected by ram-pressure stripping.

In fact, it is possible that none of our detected dwarfs are actually in the cluster core at all. Dwarf galaxies within the core are subject to tidal forces that could pull them apart. We can estimate the minimum size \( (r_{\text{min}}) \) of a dwarf galaxy that would not be tidally disrupted at the cluster core (that is the distance at which the tidal stress is maximum; Merritt 1984), using the definition of Roche limit:

\[
r_{\text{min}} = R_c \left( \frac{M_{\text{dwarf}}}{3M_{\text{cluster}}} \right)^{1/3}
\]

where \( R_c \) is the cluster core radius (0.5 Mpc; Binggeli, Tammann & Sandage 1987), \( M_{\text{dwarf}} \) is the mass of the dwarf \( (\approx 10^7 M_\odot) \) and \( M_{\text{cluster}} \) is the mass within the core radius \( (\approx 10^{14} M_\odot) \). This leads to a size of order 3 kpc, very similar to the sizes of our dwarf galaxies (1 kpc \( \approx 10 \text{ arcsec at the distance of the Virgo cluster} \)), see also Merritt (1984). We conclude that dwarf galaxies passing through the core will be severely disrupted by tidal forces (cf intra-cluster light, stars and planetary nebulae; Gregg & West, 1998; Arnaboldi et al 2002). Given that most of our galaxies in the projected core region are mainly spherical dEs (Fig 4), we conclude that it is unlikely that they are actually in the core (see also Ichikawa et al. 1988, AJ, 96, 62 ; Carey et al., 1996; Secker et al (1998); Adami et al., 2000; Oh & Lin, 2000; Conselice et al, 2001; Gnedin 2003).

Dwarf galaxies are resilient in the cluster because they have high values of M/L, but the ICM ram pressure may be important in triggering starbursts. Numerical simulations carried out with smoothed-particle hydrodynamics (Abadi, Moore & Bower 1999; Shulz & Struck 2001 ) and with N-body codes (Vollmer et al 2001) show that, for small inclination angles (nearly edge-on) the ram pressure leads to a temporary increase of the central gas surface density. This, in turn, may give rise to an episode of star formation. We will consider the gas consumption through induced starbursts in the last section of this chapter.

7.2 Supernovae driven winds

In almost all CDM models, supernova driven winds play a crucial role in suppressing the formation of stars in small dark matter halos (dwarf galaxies), since they could, in principle, completely blow away its gas. As stated in the introduction this cannot be the complete solution to the substructure problem, because of the large numbers of dwarfs found in some, but not in other, environments.

For a supernova driven wind to expel the gas from a dwarf galaxy, the energy in the wind has to exceed the gravitational binding energy (Dekel & Silk, 1986). Davies & Phillipps (1989) showed that these energies are about equal for a dwarf galaxy with M/L of 100, leading to some uncertainty in whether this is a viable method at all for removing gas from dwarf galaxies. Following Davies & Phillipps 1989, we can write this condition as:

\[
T_W > 10^3 (M_{\text{dyn}}/L)r^2 10^{4.5(26.8 - \Sigma)}
\]

where \( T_W \) is the wind temperature and \( r \) is the galaxy radius in kpc. For \( \Sigma = 24.5 \text{ B mag/arcsec}^2 \) and \( r = 1 \text{ kpc} \), \( T_W > 10^3 (M_{\text{dyn}}/L) \) for gas stripping to occur. Dekel and Silk (1986) give the range of \( T_W \) as \( 6 \times 10^5 \) to \( 6 \times 10^6 \) (Davies & Phillipps, 1989). This uncertainty is further compounded by the confining pressure of the ICM for cluster galaxies (Babul & Rees, 1992) and supported by the recent evidence of the large value of the \( M_{\text{dyn}}/L \) for dwarf galaxies in the Local Group (Klenya et al, 2002).

The above conclusion is also further supported by recent, more detailed simulations, by Mac Low & Ferrara
(1999) who investigated starbursting dwarf galaxies with baryonic masses \( M_b = 10^6 - 10^9 \, M_\odot \) and supernova (SN) rates from one per \( 3 \times 10^4 \) yr to one per \( 3 \times 10^6 \) yr. They showed that the critical masses for which the whole gas content is blown away are very low (\( \lesssim 10^6 \, M_\odot \)); in almost all the cases, the starburst is not energetic enough and creates only holes in the regions surrounding the supernovae event. Note that the total baryonic (stellar + gas) mass that we expect for our galaxies lies within the range they investigated: the stellar masses for our galaxies are \( \sim 1.6 \times 10^6 \) to \( 6 \times 10^7 \, M_\odot \) (since their magnitude range is \( M_B \approx -10 \) to -14); our H\( \alpha \) observations (see sec 6.3.2) indicate that they have H\( \alpha \) masses below about \( 1.5 \times 10^7 \, M_\odot \). The SN rates explored by them are also consistent with the starbursts that we consider. These results, along with the observed high values of \( M/L \), must give concern as to whether SN driven winds are a viable gas stripping mechanism (see also Mayer and Moore 2003).

### 7.3 Tidal interactions

Gravitational interactions can cause mergers, reshape the galaxy and its content or trigger starbursts. Contrary to ram pressure stripping, numerical simulations show that they may be important even at large distances from the cluster centre and that the numerous high-speed encounters occurring in clusters can give rise to morphological transformations, i.e. disc systems into dwarf Spheroidals and dEs (Moore et al., 1999; Moore 2003).

Tidal interactions in the cluster could have produced in the past instabilities that accelerated the star formation activity of the galaxies, resulting in the currently observed B-I colours\(^5\) and depletion of the atomic gas. This possibility is discussed in the following section.

The colour distributions in figure 9 and the dynamical timescales in table 1 indicate a dependence of galaxy properties with the crossing time. The crossing time is related to the density of the cluster (not its total mass), with the most dense clusters having the shortest crossing time. This suggests that local interactions of galaxies have a large influence on their subsequent evolution. The importance of these interactions depends on the encounter rate, which is related to the number density (\( n \)) of galaxies in the specific environment considered, the interaction cross-section (\( \sigma \)), the velocity of the galaxy through the cluster (\( v \)) and the age of the cluster (\( t \)). Using a simple rate argument we can write the characteristic number of interactions per galaxy as:

\[
N \approx n \sigma v t
\]  
(8)

If, for the sake of simplicity, we assume the cluster age to be the same for the different environments that we considered in sec 5.2, then we can calculate the relative number of encounters compared to that occurring in the Virgo Cluster as a function of \( n \) and \( \sigma \) \( (\approx v/\sqrt{2}) \) only, the cross section being the same. Using, for consistency, the information we need in eq 8 for the 3 clusters (the total number of galaxies, virial radius and velocity dispersion) given by Tully et al. (1996), we find that the number of encounters experienced by galaxies in the Virgo Cluster is 3 times lower than in Fornax and 20 times higher than in the Ursa Major cluster \( \dagger \). If encounters promote star formation, this would have lead to an increased past star formation activity going from the Ursa Major to the Virgo and Fornax Clusters and could thus account for the reddening of the colour distribution.

The rate of interaction is obviously density dependent and the balance between the destruction vs. production rates is delicate, as noted for example in the Coma Cluster by Adami et al. (2000). Conseil (2002) show that a steepening or a flattening of the faint-end-slope of the evolved LF in a cluster is function of the maximum number of tidal interactions experienced by the galaxies. These simulations show that there should be a density threshold above which destruction is more efficient than creation. This argument can also be easily used to interpret the difference in the inner and outer Luminosity Functions of the Virgo Cluster that we showed in paper I. The dwarfs that now remain in the cluster would then be ‘survivors’ to this processes and they would have continued to form stars over a longer period than systems that were destroyed (for example in the cluster core).

To complete this picture, we can also investigate how likely it is that a dwarf galaxy will have an interaction with another cluster galaxy capable of completely disrupting it and/or stripping its gas away. To estimate this we can calculate the interaction cross section, \( \sigma \approx \pi R^2 \), with \( R \) (impact parameter), as the square of the Roche limit distance, \( R\approx \frac{a}{1-\frac{M_g}{2M_d}} \)

\[
\sigma \approx R^2 \approx \frac{r^2}{(3M_g/M_d)^{2/3}}
\]  
(9)

where \( M_g \) is the mass of the galaxy the dwarf is interacting with and \( r \) is the dwarf galaxy radius. For a given cluster the number of interactions depends only on the cross-section \( \sigma \). It is straightforward to show that a \( 10^{10} \, M_\odot \) galaxy is about 45 times more likely to interact in this way with another \( 10^{10} \, M_\odot \) galaxy than it is with a \( 10^{7} \, M_\odot \) dwarf galaxy. The reason is that the dwarf galaxy, because of its small size has to be very close to the large galaxy (\( \lesssim 10 \) kpc) for severe tidal disruption to occur (e.g. the Sagittarius dwarf galaxy of the Local Group). This would be a problem if most of the Virgo dwarf galaxy population were closely associated with the giant galaxy population. In Fig 2, however, we have shown that there is a population of Virgo dwarf galaxies that is not associated with the giants. As we do not see large numbers of large galaxies undergoing disruptive tidal interactions we have to conclude that dwarf galaxy disruptive interactions are also uncommon. This also does not appear to be a viable method of gas loss.

If the cluster dwarf galaxy population originated from a tidally truncated population of larger field galaxies then their tidal radii should be of order \( R_{tidal} \approx \frac{\sigma_{halo}}{\sigma_{dwarf}} \), where \( \sigma_{dwarf} \) \( (\lesssim 10 \, \text{km s}^{-1}) \) and \( \sigma_{clust} \) \( (\approx 700 \, \text{km s}^{-1}) \) are the dwarf galaxy and cluster velocity dispersion respectively. The smallest calculated radius is of order 7 Kpc; this is larger than the dwarf galaxies in our sample (\( \approx 1 \) kpc) implying that they must sit in much larger dark matter halos.

\( \dagger \) Note that introducing a dependence on the estimated cluster ages, does not alter this result.

\( \frac{\sigma_{dwarf}}{\sigma_{clust}} \)
et al 1998 also give a prediction for values of harassed galaxies’ effective radii; these range from 5.3 to 1.6 Kpc, again larger than the typical values for galaxies in our sample. This poses a problem to the harassment scenario as a means of producing the dwarf galaxies in our sample through morphological transformation of large discs. The transformation of infalling gas rich (already small) dwarf irregulars, like those detected by us, is however still quite possible.

7.4 Gas loss through enhanced star formation

Direct evidence for galaxy evolution in clusters is given by the Butcher & Oemler effect (BOE; Butcher & Oemler, 1978). Three triggering mechanisms have been suggested for the BOE: ram pressure by the hot intra-cluster medium (Dressler & Gunn 1990), galaxy-galaxy interactions (Lavery & Henry 1988) and tidal triggering by the cluster potential (Henriksen & Byrd 1996). The lack of correlation of the BOE with the X-ray luminosity, however, rules out the possibility that the former mechanism is the unique one at work. On the other hand, several studies of both statistical samples and individual interacting systems have shown that the optical and infrared colours of peculiar galaxies can be explained in terms of bursts of star formation triggered by tidal interactions (Larson & Tinsley, 1978; Young et al, 1986; Larson 1986; Liu & Kennicutt, 1995; Barton Geller & Kenyon, 2000, 2003). Theoretical work employing smoothed particle hydrodynamics (SPH) also gives support to the notion that galaxy interactions can drive significant inflows of gas under a wide range of conditions and rise the star formation rate by more than an order of magnitude (Noguchi & Ishibashi, 1986; Barnes & Hernquist, 1995; Mihos & Hernquist 1996).

Our view is that our observations can be explained not by gas stripping mechanisms, as described above, but by accelerated star formation in infalling harassed dI galaxies or dark haloes that have no stars - the gas that once was there is still there, but now in the form of stars. This is witnessed by the very different cluster and field Luminosity and H\textsc{i} Mass Functions, the spatial distribution of dE and dI galaxies, their very different morphologies and gas content. We suggest that cluster dwarf galaxies have undergone accelerated evolution compared to the field.

Although we have shown that tidal interactions that strip a dwarf galaxy of its gas must be rare, numerical simulations do show that the several high-speed encounters that disc systems undergo in clusters can transform infalling galaxies into dEs. The continually varying tidal force compresses the gas, promoting enhanced star formation compared to dI galaxies in the field. As we have suggested in the previous section we believe that the galaxies that undergo this transformation are the gas rich dIs observed on the cluster edge.

Can enhanced star formation alone explain the colour distribution of our galaxies and the possible lack of H\textsc{i} emission from the dwarfs of our sample? If we assume the initial H\textsc{i} mass of a dwarf to be $10^7 M_\odot$ and that each tidal interaction triggers a starburst of $\sim 10^8$ yr duration and consumes $\sim 10^6 M_\odot$ of gas (Leitherer & Heckman, 1995), then 10 such starbursts can fully exhaust the H\textsc{i} content of the dwarf. This would make dwarfs in clusters very different from isolated dwarf irregulars that typically have long gas depletions timescales of $\sim 20$ Gyr and which have experienced (and will continue to experience for at least another Hubble time) a slow, but constant, star formation activity (van Zee, 2001).

What would happen to the colours and absolute magnitudes of the dwarfs in our simple model of several starbursts? Numerical simulations on the effects of starburst on low surface brightness galaxies show that surface brightness is virtually unaltered by these episodes, while the total colours can change significantly (O’Neil, Bothun & Schombert, 1998). According to Leitherer & Heckman (1995) the change in (B-I) colour in $10^8$ yr would be $\sim 1$ mag, regardless of metallicities and for either continuous star formation activity or a single starburst. The colour distribution of our sample is consistent with such a scenario. The galaxies’ average (B-I) colour is $\sim 1.7$, which is about the typical colour for metal poor globular clusters (Reed, 1985). We should also note here that the three H\textsc{i} detections in our sample are extremely blue if compared with the average value of the colour distribution and with the colours of metal poor globular clusters: 144 is not visible at all in the I band, 249 and 158 have (B-I) colours of 1.26 and 1.01 respectively, indicating a younger population. These galaxies might then be interpreted as being part of an infalling population of initially gas-rich dIs that are possibly undergoing morphological transformations that will eventually turn them into gas-poor galaxies (see also Conselice et al 2003).

There are two further points to consider: the presence of intra-cluster light and planetary nebulae has been used to argue for the large scale stripping of material from galaxies in the cluster. All of the above have only been detected within the Virgo Cluster core. We argued earlier that galaxies entering the core would be tidally disrupted and use this to suggest that our sample galaxies are not in the core, but their positions are projected on to it. Total tidal disruption is possible within the cluster core. Secondly the observed luminosity-metallicity relation of dwarf galaxies has been used to argue that the more massive dwarfs retain their gas longer and so produce more generations of stars and have an higher metallicity. Phillips & Davies (1989) showed that this can be also explained as a surface brightness-metallicity relation, in which there is a gas column density cut-off for star formation.

8 CONCLUSIONS

We have presented (B-I) colour and sensitive 21cm observations of a sample of Virgo Cluster dwarf low surface brightness galaxies that includes previously un-catalogued cluster members. These follow ups complete our work in paper I on the contribution of these galaxies to the faint-end-slope of the Luminosity Function. The H\textsc{i} observations also complete an earlier paper (Davies et al, 2004) aimed at investigating possible under-evolved H\textsc{i} clouds in the cluster.

We find that, on average, colour trends are weak functions of both total B magnitude and central surface brightness of the galaxies. We have also compared the properties would not blow away the gas of the galaxy, as shown in section 7.2.
of dwarf galaxies in the cluster with those in other environments: dwarfs follow a similar density-morphology relation as the brighter galaxies. This is strange, given their predicted very different histories according to CDM theories (building blocks as opposed to fully assembled objects).

Cluster dwarfs are generally gas poor and red compared to dwarfs in the field, but they have average (B-I) colour and a velocity dispersion more like the spiral galaxy population. The dwarfs in our sample do not seem to come from the infall of units like the Local Group: the dwarf-to-giant ratio is too high.

The cluster luminosity function is steep while the H1 mass function is shallow compared to the field. Different mechanisms at work in the cluster environments were discussed and their relative efficiencies compared. We conclude that enhanced star formation activity due to tidal interactions might account for the different properties of dwarfs in the different environments we compared. We believe that the dwarfs in our sample are not larger galaxies stripped of their gas or tidally transformed and have not been created in tidal interactions of larger galaxies.

The picture that we suggest is a scenario where tidal interactions play a fundamental role in triggering the star formation in cluster galaxies. We conclude that the dwarfs in our sample arrived (are arriving) in the cluster as gas rich dwarfs converting their gas into stars rapidly. It is not clear to us how this might be accommodated within the CDM model.

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