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THE LUMINOSITY DISTRIBUTION IN GALAXY CLUSTERS: A DWARF POPULATION–DENSITY RELATION?

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ABSTRACT

Recent work suggests that rich clusters of galaxies commonly have large populations of dwarf (i.e., low-luminosity) members, that is, their luminosity function turns up to a steep slope at the faint end. This population, or more particularly the relative numbers of dwarfs to giants, appears to be very similar for clusters of similar morphology but may vary between cluster types. We have previously suggested that dwarfs may be more common in less compact, spiral-rich clusters. Similarly, we have found evidence for population gradients across clusters, in that the dwarf population appears more spatially extended. In the present Letter, we summarize the current evidence and propose, in an analogy to the well-known morphology-density relation, that what we are seeing is a dwarf population–density relation: dwarfs are more common in lower density environments. Finally, we discuss recent semianalytic models of galaxy formation in the hierarchical clustering picture, which may give clues as to the origin of our proposed relation.

Subject headings: galaxies: clusters: general — galaxies: luminosity function, mass function — galaxies: photometry

1. INTRODUCTION

Much recent work has been devoted to the question of the galaxy luminosity function (LF) within rich clusters, particularly with regard to the faint end, which has become accessible to detailed study through various technical and observational improvements (see, e.g., Driver et al. 1994; Biviano et al. 1995; Bernstein et al. 1995; Mohr et al. 1996; Wilson et al. 1997; Smith, Driver, & Phillipps 1997, hereafter Paper I; Trentham 1997a, 1997b).

For the most part, these studies concur that the LF becomes steep (Schechter slope $\alpha \leq -1.5$; Schechter 1976) faintward of about $M_B = -17.5$ or $M_R \simeq -19$ (for $H_0 = 50$ km s^{-1} Mpc^{-1}), and Paper I suggested that such a dwarf-rich population might be ubiquitous. In a subsequent paper (Driver, Couch, & Phillipps 1997a, hereafter Paper III), we have examined the luminosity distribution in and across a variety of clusters, examining the possible dependence of the dwarf population (in particular the ratio of dwarfs to giants) on cluster type and position within the cluster. In the present Letter, we summarize the evidence to date for the (dis)similarity of the dwarf population in different environments.

2. DWARF LUMINOSITY FUNCTION

2.1. *Dwarfs in Rich Clusters*

Several papers (e.g., Driver et al. 1994; Paper I; Wilson et al. 1997) have recently demonstrated remarkably similar dwarf populations in a number of morphologically similar dense rich clusters like (and including) Coma. This similarity appears not only in the faint-end slope of the LF, around $\alpha = -1.8$, but also in the point at which the steep slope cuts in, $M_R \simeq -19$ (i.e., about $M^* + 3.5$). The latter implies equal ratios of dwarf to giant galaxy numbers in the different clusters.

However, there clearly do exist differences between some clusters. For example, several of the clusters in the Paper III sample do not show a conspicuous turnup at the faint end. Either these clusters contain completely different types of dwarf galaxy population or, as we suggest, the turnup occurs at fainter magnitudes (i.e., the dwarf-to-giant ratio [DGR] is smaller; we will define the DGR, as in Paper III, as the number of galaxies with $-16.5 \geq M_R \geq -19.5$ compared with those with $-19.5 \geq M_R$). This later upturn is, in principle, verifiable with yet deeper photometry, although background contamination uncertainties eventually dominate (see, e.g., Driver et al. 1997b [Paper II]; Trentham 1997a).

The clusters in question are not distinguished by their richness, but we can also check for morphological differences. As is well known, structural and (giant galaxy) population characteristics are well correlated, with, for example, dense regular clusters being of early Bautz-Morgan (B-M) type (dominated by cD galaxies) and having the highest fractions of giant ellipticals. We can therefore choose to characterize the clusters by their central (giant) galaxy number densities, for instance, the number of galaxies brighter than $M_R = -19.5$ within the central 1 Mpc^2 area. (An alternative would be to use Dressler's 1980 measure of the average number of near neighbors; see Paper III.) We find that the clusters with less prominent dwarf populations (lower DGRs ~ 1) are just those with the highest projected galaxy densities (e.g., A3888). The equivalent effect of earlier B-M type clusters having fewer dwarfs (A3888 is B-M type I-II) was illustrated in Paper III (see also Lopez-Cruz et al. 1997). Earlier, Turner et al. (1993) had noted that the rich but low-density cluster A3574, which is very spiral rich (Willmer et al. 1991), had a very high low surface brightness (LSB) dwarf-to-giant ratio. This is now backed up by the observations (see Paper III) of clusters like A204, which are dwarf rich (DGR ~ 3) and have low central densities and late B-M types (A204 is B-M type III). In addition, it appears that

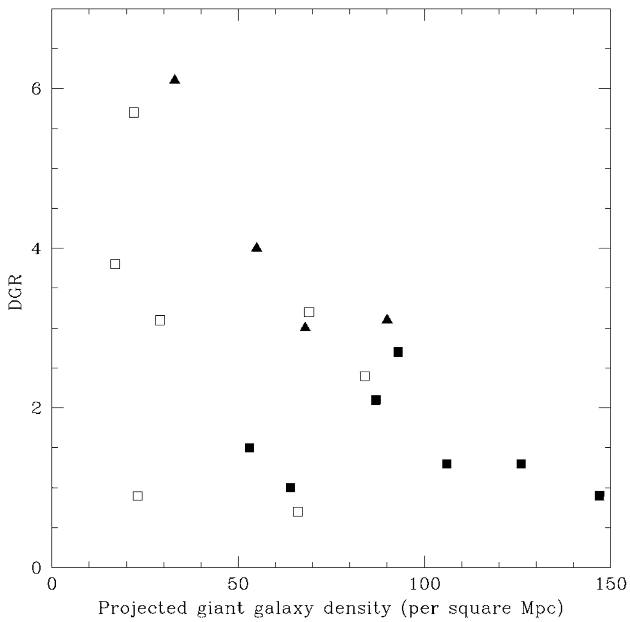

FIG. 1.—Variation of the DGR, as defined in the text, with projected density of cluster giants (per square megaparsecs). The filled squares represent the central 1 Mpc^2 regions of the clusters, the open squares the outer regions (data from Paper III). The filled triangles show the variation over a wider range of radii for Abell 2554 (data from Paper I). Note that typical error bars (due to the combination of Poisson errors and background subtraction errors) are 10% in density and 20% in DGR for the denser regions, rising to 30% in density and 50% in DGR at the lowest densities (and hence object numbers). The outlier at low density and low DGR (the outskirts of A22) has a very large error in DGR (∼100%).

the Virgo Cluster, an archetypal loose (moderately rich) cluster, has a very large dwarf population (Binggeli, Sandage, & Tammann 1985), with many LSB dwarfs down to the sizes of Local Group dwarf spheroidals (Schwartzenberg, Phillipps, & Parker 1996; Phillipps et al. 1998).

2.2. *Population Gradients*

It was already suggested, by the results on A2554 in Paper I, that the dwarf population was more spatially extended than that of the giants; i.e., the dwarf-to-giant ratio increased outward. This type of population gradient has been confirmed by the results in Paper III. (We also consider this in more detail elsewhere [Smith et al. 1998 (Paper IV)] using observations extending over larger areas.) It is also found in Virgo (Phillipps et al. 1998), where the dwarf LSB galaxy (LSBG) population has an almost constant number density across the central areas, while the giant density drops by a factor of ∼3. For Coma, the apparent discrepancy between, for example, the LF slopes of Bernstein et al. (1995), for the core, and those of Biviano et al. (1995), for a larger area, could similarly be attributed to an increase in the dwarf fraction in the outer parts (see also Thompson & Gregory 1993, Karachentsev et al. 1995, and § 3).

2.3. *The Field*

An environment that is the extreme opposite of the elliptical-rich core of a dense cluster is of course the spiral-rich "field," which we can think of as made up of loose groups, and possibly the outskirts of richer systems. Extending the above arguments, we would therefore expect to see a very large dwarf population in the field. This is contrary to the usual perception of the field LF at the faint end (e.g., Efstathiou, Ellis, & Peterson 1988; Loveday et al. 1992), but the evidence has begun to accumulate suggesting that the field LF may indeed turn up at the faint end, at a similar point to that seen in the clusters, around $M_R \simeq -19$ (e.g., Marzke, Huchra, & Geller 1994; Zucca et al. 1997; see also Driver & Phillipps 1996). Very recently, considerations of the satellites of nearby spiral galaxies have suggested that the field dwarf LF may be just as steep as that in clusters (Morgan, Smith, & Phillipps 1998), or indeed much steeper (Loveday 1997). A contributory factor to this revision of the field dwarf LF is clearly the inclusion of LSBGs missed from earlier surveys (Phillipps & Driver 1995; Ferguson & McGaugh 1995), but it should be said that in the Local Group, where extremely low surface brightness dwarfs are in principle detectable from their resolved stars, the LF appears quite flat. From the relationship derived in Paper III, a field LF with a faint-end slope, say, $\alpha = -1.5$ would have a DGR of 4–5. This would be nicely consistent with the extrapolation of the trend seen in the clusters (see below) down to low (volume) densities.

3. A POPULATION-DENSITY RELATION

The obvious synthesis of the above results is to posit a relationship between the local galaxy density and the fraction of dwarfs (i.e., the relative amplitude of the dwarf LF). The inner, densest parts of rich clusters would have the smallest fraction of dwarfs, while loose clusters and the outer parts of regular clusters, where the density is lower, would have high dwarf fractions. This is illustrated in Figure 1, which is based on our homogeneous rich cluster data from Papers I and III. It is particularly interesting to note the clear overlap region, where regions of low density on the outskirts of dense clusters (*open squares*) have the same DGRs as the regions of the same density at the centers of looser clusters (*filled squares*). The triangles show in slightly more detail the run of the DGR with radius (hence density) across an individual cluster, A2554.

The proposed relation of course mimics the well-known morphology-density relation (Dressler 1980), wherein the central parts of rich clusters have the highest early-type galaxy fraction, this fraction then declining with decreasing local galaxy density. Putting the two relations together, it would also imply that dwarfs preferentially occur in the same environments as spirals. This would be in agreement with a weaker clustering of low-luminosity systems in general (Loveday et al. 1995; see also Dominguez-Tenreiro et al. 1996), as well as for spirals compared with ellipticals (Geller & Davies 1976). Thuan et al. (1991) have previously discussed the similar spatial distributions of dwarfs (in particular dwarf irregulars) and larger late-type systems.

In Figure 2, we have added to our data (*filled squares*) values derived from the work of other observers. A problem here, of course, is the lack of homogeneity due to different observed wave bands, different object detection techniques, and so forth. Nevertheless, we can explore whether or not the results of the literature support our results. First, several points are shown for various surveys of Coma (*filled hexagons*). These surveys (Thompson & Gregory 1993; Lobo et al. 1997; Secker & Harris 1996; Trentham 1998) cover different areas and hence different

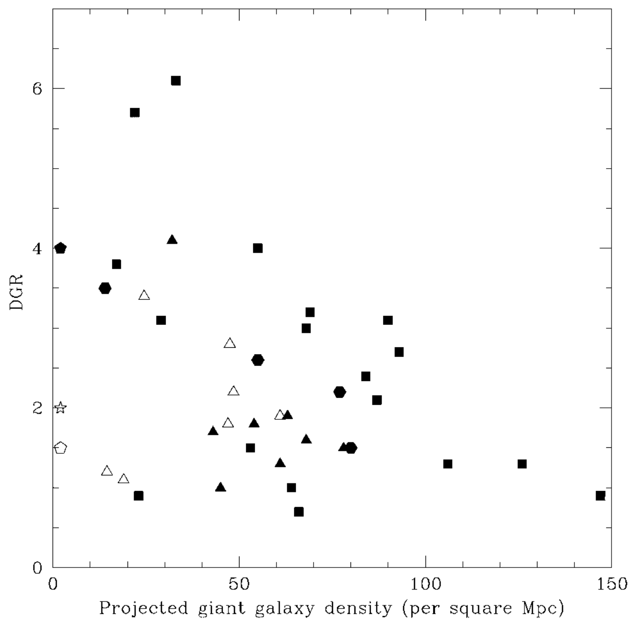

FIG. 2.—Same as Fig. 1, but including data from other observers. The filled squares are our data repeated from Fig. 1, the filled hexagons are for various Coma surveys detailed in the text, the filled triangles are from Lopez-Cruz's sample, and the open triangles are for Ferguson & Sandage's poor clusters and groups. The open pentagon at low density represents a conventional "flat" field LF, the filled pentagon represents a possible steep ($\alpha \simeq -1.5$) field LF, and the Local Group is represented by the open star at DGR = 2.

mean projected densities. All of these lie close to the relation defined by our original data, with the larger area surveys having higher DGRs. Points (*filled triangles*) representing the rich B-M type I clusters studied by Lopez-Cruz et al. (1997) fall at somewhat lower DGRs than most of our clusters at similar densities. However, we should note that these clusters were selected (from a larger unpublished sample) *only* if they had LFs well fitted by a single Schechter function. This obviously precludes clusters with steep LF turnups and hence high DGRs. The one comparison cluster they do show *with* a turnup (A1569 at DGR $\simeq$ 4.2) clearly supports our overall trend. Although there is now considerable scatter (and the errors on some of the points are quite large), a weighted least-squares fit to the trend gives log (DGR) = const $-$ (0.86 $\pm$ 0.22) log (giant density), indicating a significant variation. Within the overall rich cluster sample, if we differentiate by the clusters' B-M types, there is a suggestion that the type I's lie at lower DGRs than the others, but again this may be biased by the Lopez-Cruz sample's selection criteria. Finally, a steep field LF ($\alpha \simeq -1.5$) would also give a point (*filled pentagon*) consistent with the trend seen in the clusters.

On the other hand, Ferguson & Sandage (1991, hereafter FS), from a study of fairly poor groups and clusters, deduced a trend in the opposite direction, with the early-type dwarf-to-giant ratio *increasing* for denser clusters. However, this is not necessarily as contradictory to the present result as it might initially appear. For instance, FS select their dwarfs by morphology, not by luminosity (morphologically classified dwarfs and giants significantly overlap in luminosity), and they also concentrate solely on early-type dwarfs. If, as we might expect, low-density regions have significant numbers of late-type dwarfs (irregulars), then the FS definition of the DGR may give a lower value than ours for these regions. Furthermore, FS calculate their projected densities from *all* detected galaxies, down to very faint dwarfs. Regions with high DGRs will therefore be forced to much higher densities than we would calculate for giants only. These two effects may go much of the way to reconciling our respective results. This is illustrated by the open triangles in Figure 2, which are an attempt to place the FS points on our system; magnitudes have been adjusted approximately for the different wave bands, the DGRs have been estimated from the LFs, and the cluster central densities (from Ferguson & Sandage 1990) have been scaled down by the fraction of their overall galaxy counts that are giants (by our luminosity definition). Given the uncertainties in the translation, most of the FS points now lie reassuringly close to our overall distribution.

Nevertheless, there are two exceptions, the FS points of lowest density (the Leo and Doradus groups), which also have a low DGR (and lie close to our main "outlier," the point for the outer region of A22). The Local Group (shown by the open star in Fig. 2) would also be in this regime, at low density and with a DGR = 2, as would the "conventional" field, with $\alpha \simeq -1.1$ and a DGR $\simeq$ 1.5 (*open pentagon*). This may suggest that at very low density, the trend is reversed (i.e., it is in the direction seen by FS) or that the cosmic (and/or statistical) scatter becomes large. More data in the very low density regime are probably required before we can make a definitive statement on a possible reversal of the slope of the DGR versus density relation. In particular, the scatter in the derived faint end of the field LF between different surveys (see, e.g., the recent discussion in Metcalfe et al. 1998) precludes using this to tie down the low-density end of the plot.

4. DISCUSSION AND SUMMARY

As with the corresponding morphology-density relation for giant galaxies, the cause of our population-density relation could be either "nature" or "nurture," i.e., initial conditions or evolution. Some clues may be provided by the most recent semianalytic models of galaxy formation, which have been able to account in a general way for the excess of (giant) early-type galaxies in dense environments (e.g., Baugh, Cole, & Frenk 1996).

The steep faint-end slope of the LF appears to be a generic result of hierarchical clustering models[1] (e.g., White & Frenk 1991; Frenk et al. 1996; Kauffmann, Nusser, & Steinmetz 1997), so it is naturally accounted for in the current generation of models. The general hierarchical formation picture envisages (mainly baryonic) galaxies forming at the cores of dark matter halos. The halos themselves merge according to the general Press-Schechter (1974) prescription, in order to generate the present-day halo mass function. However, the galaxies can retain their individual identities within the growing dark halos because of their much longer merging timescales. The accretion of small halos by a large one then results in the main galaxy (or cluster of galaxies, for very large mass halos) acquiring a number of smaller satellites (or the cluster gaining additional, less tightly bound, members).

Kauffmann et al. (1997) have presented a detailed study of the distribution of the luminosities of galaxies expected to be associated with a single halo of given mass. The LFs are some-

[1] And it was considered a problem until observational evidence for steep LFs increased!

what disjoint owing to the specific halo masses modeled; especially for the low-mass halo, there is a preferred luminosity for the central galaxy plus a tail to lower luminosities. For a realistic mix of halo masses, these would no doubt be smoothed to look more like conventionally observed LFs. Nevertheless, we can still easily compare the numbers of dwarf galaxies per unit giant galaxy luminosity (rather than the amplitude of the giants' LF) between halos of different mass.

The Kauffmann et al. models mimic a "Milky Way system" (halo mass $5 \times 10^{12}\ M_\odot$), a sizable group (halo mass $5 \times 10^{13}\ M_\odot$), and a cluster mass halo ($10^{15}\ M_\odot$). Using their Figure 2 (which also emphasizes the identical faint-end slopes predicted for all the different environments), we choose to quantify the number of dwarfs by N_{-18}, the number of dwarfs per system in the $M_B = -18$ bin. Because of the very similar slopes, the choice of bin or range of bins does not affect our conclusions, so this is the equivalent of the total number of dwarfs used in Figure 1. To quantify the giant population, we choose the total light of galaxies of $M_B = -20$ or brighter, in units of L_* galaxies (taking $M_B^* = -21$), which we call N_{-21}. Using this definition, rather than the actual number of galaxies brighter than some value (as in our observational data), allows for the discretization of the LFs for small halos. The results are summarized in Table 1. The ratio of these two values, N_{-18} and N_{-21}, then quantifies the relative dwarf galaxy populations. Roughly speaking, for smooth LFs with a shape similar to that observed, we should multiply these values by about 5, giving a range from about 1 to 3, to compare with our observational DGRs.

We see that the Milky Way and small group halos have similar numbers of dwarf galaxies per unit giant galaxy light, whereas the dense cluster environment has a much smaller number of dwarfs for a given total giant galaxy luminosity. Thus, the predictions of the hierarchical models (which depend, of course, on the merger history of the galaxies) are in general agreement with our empirical results if we identify loose clusters and the outskirts of rich clusters with a population of (infalling?) groups (cf. Abraham et al. 1996), whereas the central dense regions of the clusters originate from already massive dark halos. By inputting realistic star formation laws, etc., Kauffmann et al. can further identify the galaxies in the most massive halos with old elliptical galaxies and those in low-mass halos with galaxies with continued star formation. This would imply the likelihood that our dwarfs in low-density regions may still be star forming or at least may have had star formation in the relatively recent past (cf. Phillipps & Driver 1995 and references therein). Note, too, that these galaxy formation models would also indicate that the usual (giant) morphology-density relation and our (dwarf) population-density relation arise in basically the same way. Finally, we can see that if these models are reasonably believable, then we need not expect the field to be even richer in dwarfs than in loose clusters; the dwarf-to-giant ratio seems to level off at the densities reached in fairly large groups.

TABLE 1

DWARF NUMBERS AS A FUNCTION OF HALO MASS

Halo Mass ($M_\odot$)	N_{-18}	N_{-21}	N_{-18}/N_{-21}
5×10^{12}	0.2	0.34	0.6
5×10^{13}	2.2	3.8	0.6
1×10^{15}	40	190	0.2

To summarize then, we suggest that the current data on the relative numbers of dwarf galaxies in different clusters and groups can be understood in terms of a general dwarf population versus local galaxy density relation, similar to the well-known morphology-density relation for giants. Low-density environments are the preferred habitat of low-luminosity galaxies; in dense regions, they occur in similar numbers to giants, but at low densities, dwarfs dominate numerically by a large factor. This fits in with the general idea that low-luminosity galaxies are less clustered than high-luminosity ones (particularly giant ellipticals). Plausible theoretical justifications for the population-density relation can be found within the context of current semianalytic models of hierarchical structure formation.

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