THE GALAXY CONTENT OF CLUSTERS

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1. INTRODUCTION

Clusters of galaxies are easily identifiable collections of galaxies, all at the same distance and all observed under similar conditions of galactic obscuration, etc. They are, therefore, very convenient samples with which to study the matter content of the universe. However, clusters are also very particular physical environments, and from this latter point of view it is their atypical character which is of interest. The differences in the contents of one cluster from another, and of each from the contents of small groups and the "field" can teach us much about how the properties of galaxies depend on the environments in which they were born and have evolved.

Because of the interrelatedness of these two points of view, one cannot really understand the galaxy populations of clusters until one also understands the populations of galaxies which are not in clusters. Therefore, while this review will concentrate on the contents of rich clusters of galaxies, it will also be necessary to discuss the properties of non-cluster galaxies.

2. LUMINOSITY FUNCTIONS

2.1 The mean luminosity function of cluster galaxies

Luminosity functions have now been obtained for about 30 rich clusters of galaxies; a summary of the published data may be found in Hoffman and Crane (1976). The first fact which one notices about these is their great similarity of form. Figure 1 shows a composite luminosity function constructed by Schechter (1976) using photometry of 13 clusters by Oemler (1974). None of the 13 individual luminosity functions differs in a statistically significant way from this composite. The smooth curve is the best fit to the data of a function due to Schechter:

$$\phi(L)dL = \phi'(L/L')^{\alpha}\exp(-L/L')d(L/L'). \qquad (1)$$

Edith A. Müller (ed.), Highlights of Astronomy, Vol. 4, Part I, 253-260.

https://doi.org/10.1017/S1539299600002641 Published online by Cambridge University Press

It must be significant that this formula fits the data so well since it represents almost the simplest imaginable form for a luminosity function: a power law - surely the most a priori plausible form for a mass spectrum - with an exponential cutoff at the bright end to prevent the total luminosity from diverging. Apart from the abundance normalization, ϕ', there are only two parameters, α and L', specifying the power law slope and a characteristic luminosity.

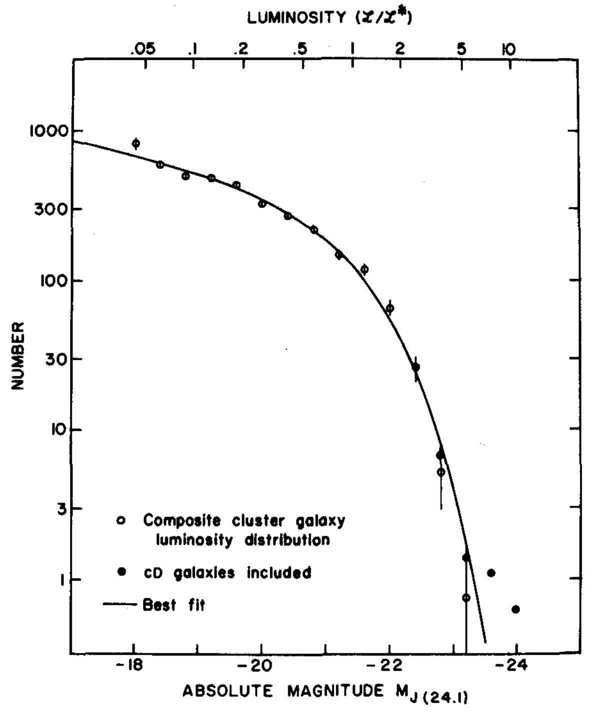

Figure 1. Composite of 13 cluster luminosity functions from Schechter (1976). Line is the best fit of equation 1.

An older analytical form for the luminosity function is due to Abell (1976), who found that the integrated luminosity function could be well described by two power laws

$$N(L) = C_1 L^{-\beta} \qquad L > L^*$$
$$N(L) = C_2 L^{-\gamma} \qquad L < L^* \qquad (2)$$

where $\beta > \gamma$.

This form for the integrated luminosity function has the consequence that the differential function must have a local maximum near L^*. If

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true, this is an important fact since it reflects the existance of an additional physical process operating at a particular mass scale during galaxy formation. Abell asserts that this feature is indeed present in $\phi(L)$ but there is no sign of it in Figure 1, nor, in my opinion, is there any statistically significant evidence for it if one differentiates Abell's published plots of N(L). That data seem to fit quite well onto the curve in Figure 1.

Whatever the exact shape of $\phi(L)$, the longstanding assertion by Abell (1976) that both the shape and the value of L^* are constant from cluster to cluster seems to be substantially correct. For 6 clusters, Abell found a dispersion in $M^* = -2.5 \log L^* + C$ of 0.1 mag, while for 15 clusters Oemler (1974) found $\sigma(M^*) = 0.24$ mag, larger but still quite small considering the uncertainties in the data.

One unanswered question, at present, concerns the faint end of the luminosity function. Because of the problem of background galaxies and because low luminosity galaxies tend to be of low surface brightness, and therefore easy to miss, we do not know with any confidence what the luminosity function of galaxies is below about $M_V = -16$. Our incomplete knowledge of the contents of the local group suggests that there are no extraordinary departures from equation 1, but it would be nice to know with more precision.

2.2 Deviations from the mean

The clusters which contributed to Figure 1 are composed, predominantly, of elliptical and SO galaxies. Turner and Gott (1976) have recently obtained a luminosity function for the E and SO members of nearby small groups of galaxies, and found that it may be fitted with a Schechter function with the same power law, $\alpha = -1.25$, as that of the rich clusters. Christiansen (1975) has obtained a luminosity function for field E's and SO's which, again, may be fitted by the same function with the same power law. The evidence thus indicates that,to first order, all early-type galaxies are characterised by a universal luminosity function, independant of their location.

The case of spiral galaxies is more confused and more interesting. One would reasonably expect the luminosity function of spirals to be very different from that of E's and SO's. The <u>mass</u> function of spirals need not be the same as that of early-type galaxies. The mean mass-to-light ratios are undoubtedly considerably different. And finally, the variation of M/L with mass could also be different. It is therefore, very surprising to find that the luminosity function of spirals is quite similar to that of E's and SO's. Oemler (1974) found no statistically significant differences between the luminosity functions of spiral dominated and elliptical dominated clusters, nor did Schechter (1976) between the spiral dominated field and the composite in Figure 1. Turner and Gott did find a difference between spiral and elliptical members of small groups, but only at the 1σ level. Unfortunately, the sensitivity of these comparisons has been limited by the small sizes of the spiral

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galaxy samples and it is quite possible that real differences exist at a lower level.

While, in the above, I have emphasized the uniformity of galaxy luminosity functions, there is some intriguing marginal evidence for differences in individual clusters. The evidence is only marginal because, in all but the richest clusters, the sampling statistics obscure any subtle differences. Although Oemler (1974) presented photometry of 15 clusters, Schechter (1976) only included 13 in the composite in Figure 1. The luminosity functions of the other two, A665 and A2670, - perhaps significantly, the richest - showed significant deviations in form. Although they have little in common, A665 being an irregular cluster while A2670 is a beautifully symmetrical cD cluster, both have luminosity functions which quickly flatten out fainter than M'.

Dressler (1976) has recently completed a study of a number of very rich clusters. He finds that half of the luminosity functions are very similar to Schechter's composite, while the other half show significant deviations at the bright end. There is some indication of a correlation with cluster morphology, in that the cD clusters often show a depletion of bright galaxies - suggestive, if true, of cannibalism by the cD galaxy.

2.3 The bright end of the luminosity function

More attention has been devoted to the bright end of the luminosity function than to any other aspect, because of the usefulness of the brightest cluster member as a cosmological tool. There has been a long-standing, and still unresolved, argument over whether the observed small dispersion in the magnitudes of the brightest members of clusters (Sandage 1972) is consistent with the existence of a universal luminosity function. If the luminosities of all members of a cluster are determined by a universal luminosity function, the magnitude, M_1, of the brightest galaxy must depend on the richness of the cluster, since the luminosity at which the integral, $\int_{\infty}^{L} \phi(L)dL$, of equation 1 equals unity depends on the normalization ϕ'.

Sandage (1975), especially, has argued that the value of M_1 is so weakly dependent on cluster richness that a special mechanism is required to standardize the luminosities of brightest cluster members. Many authors (Scott 1957, Peebles 1969, Schechter 1976) have argued to the contrary; but the entire argument, I believe, has been due to an attempt to compare incommensurable data. Sandage's magnitudes are <u>metric</u> magnitudes, measuring all of the light of a galaxy within a radius of 43 kpc. Most luminosity functions, on the other hand, are derived from some type of <u>isophotal</u> magnitudes, measuring all of the galaxy light out to some limiting surface brightness. Unless metric luminosities are a constant multiple of isophotal luminosities, and there is no reason to think that they are, one cannot use the available data to predict the dependance of Sandage's magnitudes on cluster

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richness.[1]

One spectacular exception to any concept of a universal luminosity function is the cD galaxy phenomenon, since cD galaxies can be an order of magnitude brighter than normal brightest cluster members. cD galaxies will be discussed in more detail in §3.3.

2.4 Evolution of the luminosity function

Recent work on the dynamical interractions of galaxies, which is covered in the following paper, has suggested that bright galaxies in a cluster can grow in luminosity by absorbing their smaller neighbors. If this process is significant over the lifetime of a cluster, we may hope to see its effects in the cluster luminosity function. Dressler (vid. §2.2) may have discovered signs of this, and three other pieces of evidence exist. Most obvious are the cD galaxies, to be discussed later. Secondly, we can compare the luminosity function of elliptical galaxies in clusters with that of ellipticals in small groups and the field. As mentioned above, these are identical to the limits of accuracy of the available data. Finally, one can compare the luminosity functions of very distant clusters with those of nearby clusters. The most distant cluster with a measured luminosity function is Cl0024 + 1654, at a redshift of 0.39 (Butcher and Oemler 1976). Its luminosity function looks entirely normal. Thus, the evidence, as it stands, is weak. Even the positive evidence is ambiguous, since we do not know how to separate the effects of initial conditions and subsequent evolution.

3. MORPHOLOGY OF CLUSTER GALAXIES

3.1 Normal galaxies

It has been known for many years that the galaxy population of clusters differs significantly from that of the field. While most field galaxies are spirals, spirals are almost entirely absent from the central parts of clusters like Coma. However, the galaxy populations of clusters vary and it is another well known fact that this variation is correlated with other properties of the clusters. Elliptical-rich clusters like Coma are dense, symmetrical and centrally concentrated, while spiral rich clusters like Hercules are of low density, chaotic and have no well defined center. Figure 2 is a plot of the elliptical to spiral ratios of clusters versus their mean densities, from data in Oemler (1974). The correlation is quite good and suggests that density is the physically significant parameter in determing the galaxy population of a cluster.

1 Schechter has also pointed this out.

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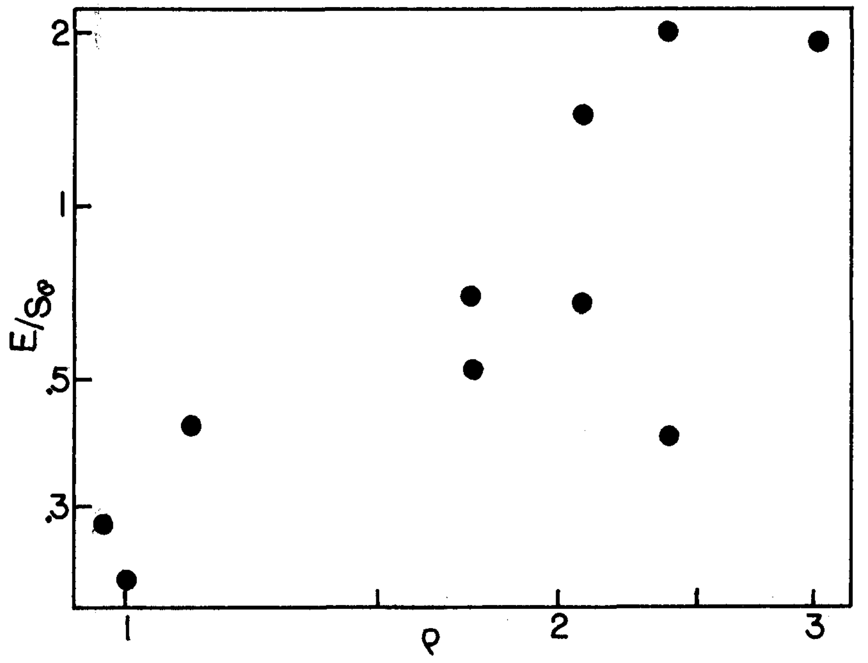

Figure 2. The ratio of the abundance of ellipticals to that of spirals in rich clusters versus the clusters' mean density.

Figure 3 is a schematic plot of the variation of galaxy population with density in clusters, showing how the S0 population first rises

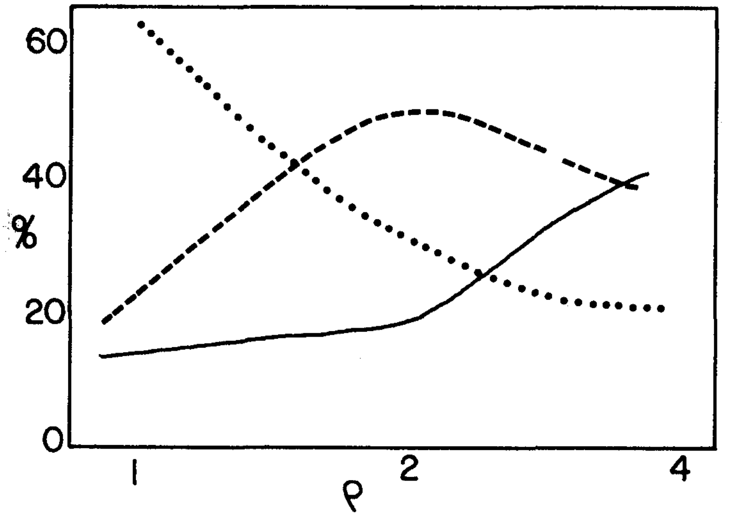

Figure 3. The variation of galaxy populations with the mean density of clusters. Solid line-ellipticals; dashed line-S0's; dotted line-spirals.

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sharply at the expense of the spirals, while finally falling somewhat as ellipticals become more numerous. Among those clusters dominated by ellipticals and S0's, this variation with density is repeated within each cluster itself. The outer parts of dense clusters like Coma have populations not dissimilar from those of spiral rich clusters; but within a radius of about 1 Mpc the spiral population rapidly falls to zero to be replaced, in the center, by almost equal numbers of ellipticals and S0's.

Although the effects are necessarily obscured by small number statistics, Giuliani (1976) has found that the same trends exist in small groups. The abundance of early-type galaxies is higher in the denser and more centrally condensed groups. Also, the elliptical-rich groups, but not those that are spiral-rich, show a significant population gradient, with the abundance of E and S0 galaxies increasing toward the centers. Equally significant is the fact that the trends of population versus density in Figure 3 seem to extend to even lower densities. Christiansen (1975) found that the population of field galaxies - i.e. all those not in rich clusters - was composed of 81% spirals, 17% S0's, and 2% ellipticals. At an even greater extreme, Turner and Gott (1975) found that truly isolated field galaxies are almost always spirals.

If density is the factor which determines the populations of galaxies both inside and outside of clusters, how does it do this? In clusters, at least, there are two obvious possibilities. First, the density of the protogalactic medium may directly determine the morphology of the galaxies that form. Secondly, the density of a cluster determines its dynamical time scale, and thus the state of dynamical evolution at which we view it. In particular, if S0's are formed by stripping the gas from spirals, either by the ram pressure of a hot intergalactic medium (Gunn and Gott 1972), or by galaxy-galaxy collisions, as originally proposed by Baade and Spitzer (1951), the degree to which these processes have operated will depend on the dynamical age of the cluster. Two recent observations supporting the latter hypothesis are the "anemic spirals" described in the Virgo Cluster by Van den Bergh (1976), and the observation by Thompson and Gregory (1976) that many of the S0's in the core of the Coma cluster seem to possess some spiral pattern in their stellar disks.

However, it is difficult to understand how either of these hypotheses can, by itself, explain the entire trend of galaxy populations from the isolated field to the cores of dense clusters. At the time of galaxy formation, clusters probably represented a very small perturbation on the mean cosmological mass density, and it is hard to imagine how protogalaxies could be so sensitive to their environment as to be much affected by this. On the other hand, it is doubtful whether any stripping process could be very effective anywhere but in the dense cores of clusters.

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3.2 cD galaxies

Unlike the normal stages along the Hubble sequence of galaxy types, cD galaxies are, apparently, found only in the cores of dense, elliptical-rich clusters of galaxies. They thus have a particularly intimate, if not yet understood, relationship to the clustering phenomenon itself. The cD galaxy is usually located at the center of such a cluster, and is by far the brightest member. Carter (1976) and Oemler (1976) have recently measured light distributions in a number of these objects. Their central parts are similar to those of an ordinary giant elliptical, but, unlike the ellipticals, they possess extraordinary extended envelopes, reaching - in at least one case - to a radius of more than 2 Mpc. These envelopes can contain a substantial fraction of the total cluster luminosity, and make the total luminosity of the cD galaxy as much as a factor of 10 brighter than that of a normal brightest cluster member.

However, the large envelope, although always centered on the dominant galaxy in the cluster, must be really considered as a characteristic of the cluster as a whole, since it cannot be gravitationally bound to the central galaxy itself. Another indication that the envelope is due to cluster-wide processes is the fact that its luminosity is strictly related to the total luminosity of the cluster, increasing as approximately the square of the cluster luminosity. What these processes might be is discussed in the following paper.

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