C O N T E N T S

4. CLUSTERS OF GALAXIES, COSMOLOGY AND INTERGALACTIC MATTER

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DENSITY PROFILES OF CLUSTERS OF GALAXIES

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Data on the surface distribution of galaxies in a number of clusters has been given by several authors (see, for example, Shane & Wirtanen 1954; Zwicky 1956, 1957; Omer, Page & Wilson 1965; Clark 1968; Noonan 1971, 1974; Bahcall 1971, 1972a, b, 1973a, b, 1974, 1975; Rudnicki 1963; Rudnicki & Baranauska 1966a, b; Rood et al. 1972; Rood & Sastry 1972; Oemler 1974; Austin & Peach 1974a, b; Chincarini & Rood 1975, 1976; and references quoted therein). The distributions show a relatively smooth fall-off from a high density at the center of the cluster to a low density tail at the outskirts of the cluster. Secondary maxima or subclustering are sometimes superimposed on an otherwise smooth and monotonic profile.

Several analytical representations of the galaxy distribution have been suggested, each providing a good fit to the observed data in most cases. The density profiles of rich clusters are described, to a good approximation, by three parameters: a central density or normalization factor, a scale-length or core radius, and a cut-off important at large distances from the cluster center. Zwicky (1957) and Bahcall (1972a, b, 1973a, b, 1974, 1975) obtained good fits of the projected distribution of galaxies in clusters with a projected bounded Emden isothermal gas sphere distribution. This distribution, which Zwicky (1957) tabulates as a function of distance from the center, involves three adjustable parameters. Following Bahcall (1972a, 1975), the observed surface distribution of cluster members (after correcting for background), σ_{obs} (r), can be fitted well with the Emden isothermal function, σ_{is} (r), through the relation $\sigma_{obs} (r) = \alpha [\sigma_{is} (r/\beta)-C]$, where α is a normalization factor, β is the scale-length parameter, and C is a constant that describes the cut-off of a bound isothermal sphere. The scale length β is related to the core radius of the cluster (i.e. the radius at which the density drops to $\frac{1}{2}$ its central value) by $r_c = 3\beta$. As has been shown by Bahcall (1975), the core-radii defined in this way have a similar linear value. She obtains $r_c \approx 0.25$ Mpc x (50/H), for all rich regular clusters she studied so far. Bahcall also finds that the cutoff parameter C needed to bind the cluster has a small spread in values in her sample; C is approximately $1\frac{1}{2}$% of the

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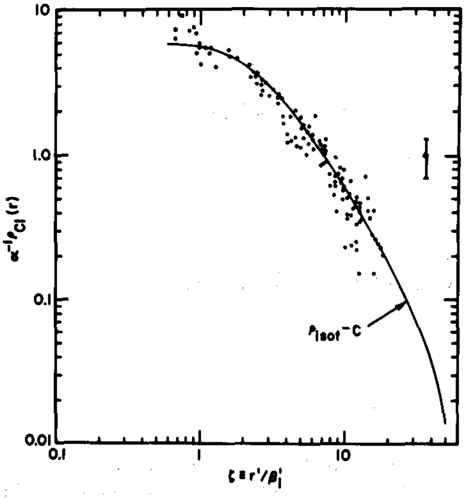

Fig. 1. The projected galaxy distributions in all the 15 studied clusters plotted as a function of distance from the clusters' centers. All distributions are normalized with their best-fitted parameters α (normalization in density) and β (scaling in distance). The solid line is the projected Emden isothermal gas sphere model, with a cutoff C = 0.1. A typical error bar (corresponding to the square root of the number of counts) is shown at the right.

isothermal central density.

The fit of the observed galaxy distributions in all fifteen clusters studied by Bahcall (1975) with the projected Emden isothermal gas sphere model (with a constant cutoff for all clusters) is shown in Figure 1. In Figure 2, the linear core-radii obtained by Bahcall for the fifteen clusters are plotted as a function of redshift, showing an average deviation of only ± 15% around the constant value of 0.25 Mpc. The theoretically expected dependence of a standard linear size on redshift for different values of q_o is also shown. The study of clusters with higher redshifts will reveal whether they are similar in structure to the nearby clusters and whether it is possible to use the core-size redshift relation of rich regular clusters to put new constraints on the parameter.

Avni & Bahcall (1976) have recently studied by Monte-Carlo techniques the statistics of the agreement between the observed and the model profiles. By comparing observed and simulated rich clusters of galaxies, they show that the observed clusters possess physical cores, and find the accuracy (∿ ± 30%) with which core radii can be determined. The intrinsic dispersion among different calculational procedures is about half of the above dispersion. The observed distributions fit the model profile somewhat better than expected by the most naive considerations largely due to the process of analysis and the limited statistics.

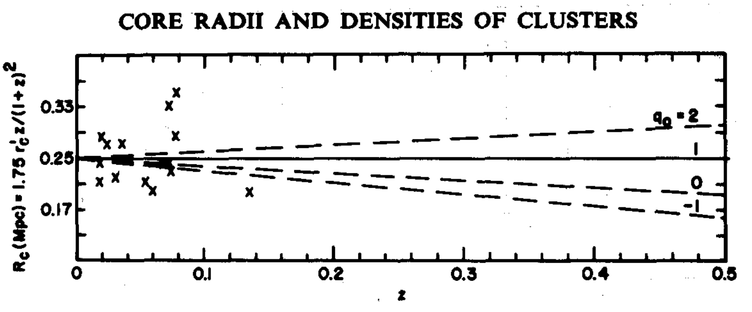

Fig. 2. Linear core radii of 15 clusters plotted as a function of redshift. The lines are the theoretically expected dependence of a standard linear size on redshift for different values of q_0.

The best fits with the observed distributions are described by a <u>bounded</u> isothermal model (i.e. $C > 0$). Hence, the slope of the projected distribution is <u>not</u> -1.0 as is expected for an unbounded isothermal model. The slope of the distribution of the bounded model changes with distance from the center (cf. Figure 1). In the central region, $r \lesssim \beta$, the profile is flat (zero slope). In the intermediate range of roughly $4\,\beta \lesssim r \lesssim 25\,\beta$, the slope is about -1.6 (i.e. $\sigma(r) \propto r^{-1.6}$). The model slope gets steeper ($\sim$ -3.0 to -4.0) in the outer regions of the cluster, but large uncertainties due to the field galaxies make it very difficult to determine the cluster profile at these distances.

Other investigators have suggested various analytical representations of the galaxy distribution. de Vaucouleurs (1948, 1960) and Shane & Wirtanen (1954) find that the surface density of galaxies in the Coma cluster follows closely a law of the form $\log\,[\sigma(r)/\sigma(r_e)] = A\,[(r/r_e)^{1/4}-1]$, where r_e is the effective-radius of the cluster, and A is a constant. King (1966) has introduced a set of surface-brightness profiles to describe the distributions in globular clusters and elliptical galaxies, which can also be applied to clusters of galaxies. The King curves are also described by three parameters: a scale length, density normalization, and a cut-off. The projected distribution in the central regions of the King-models can be described by $\sigma(r) = \sigma_0(1+r^2/r_c^2)^{-1}$, where σ_0 is the central projected density, and r_c is the core-radius of the distribution (King 1972).

The reason why so many different models can be made to fit the data is that the density profiles of clusters of galaxies can be determined reliably only down to about $10^{-2}\,\sigma_0$, and three parameters are adequate to describe the observed distributions in this range. It is difficult to extend accurately the profiles of rich clusters to still lower values of density because of the large uncertainties in the clumpy background distributions.

Chincarini & Rood (1975, 1976) have determined the projected

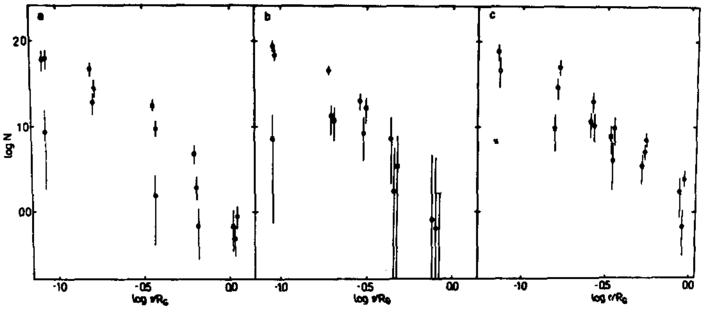

Fig. 3. Composite projected number density profiles for spiral-rich (a), spiral-poor (b), and cD clusters (c). Spirals are denoted by stars; SO's, by open circles; and ellipticals, by filled circles.

distribution of galaxies in the outer regions of the Coma cluster (distances from 1°.7 to 12°.4), and find a good fit to a power law such that $\sigma(r)\alpha r^{-1.3 \pm 0.2}$. This slope is in agreement with the slope observed at closer distances for Coma and other regular clusters, and with the fit to the bounded isothermal model. However, the bounded isothermal model predicts a steeper gradient at the outermost edges of clusters.

Oemler (1974) determined surface-brightness profiles for fifteen rich clusters. He finds that the outer envelopes of all clusters have steep slopes of the projected density, with a gradient of about -3.0.

A correlation is found (Oemler 1974) between the shape of the surface-brightness profile and the content-type of the cluster. The spiral-rich clusters have a flat central density gradient and little central concentration. For the spiral-poor and the cD clusters, the central concentration and density gradient progressively increases, although the gradient never becomes as steep as that of the envelope. Oemler also notices that midway in the profiles there is a plateau or local minimum at about 0.4 R_G (where R_G is the gravitational radius of the cluster) which grows in importance as one moves from spiral-rich to spiral-poor to cD clusters. It is found to be most prominent in some of the individual cD clusters (A1904, A2199 and A2670). This feature is more significant in the three-dimensional mass profiles. A similar secondary maximum (or local minimum) was reported previously by other investigators in several clusters (Sharov 1959, Omer, Page & Wilson 1965, Clark 1968, Bahcall 1971, Austin & Peach 1974a). It is observed in both the luminosity distribution and the number density distribution. Bahcall (1971) showed that the secondary maximum (in A31) appeared in all four quadrants of the approximate ring, thus ruling out the possibility of localized subclustering. This interesting feature in the projected distribution is statistically not larger than about a 2σ effect in any one case, although it seems likely to be a real feature because it occurs in a number of different clusters.

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The profiles have also been separated (Oemler 1974) according to the morphological types of the galaxies (E, SO and S). Although the uncertainties are rather large it appears that the distributions of the various types of galaxies are similar except that in the cD and spiral-poor clusters, the projected density of spirals decreases toward the cluster center (see Figure 3 here from Oemler 1974). The decrease is steep enough to make the space density of spirals zero in the core, as would be expected from some collisional stripping models.

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