Notes on Clusters of Galaxies

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July 1976

Throughout the history of astronomy increasingly larger scales of clustering of matter have been uncovered. After the initial discovery and a period of adjustment, the new scale of interest, such as the Galaxy, has always been found to possess a discrete morphology and physics all its own. In keeping with this pattern, the intense study of clusters of galaxies has just begun. Even though a few clusters were evident in early catalogues of nebulae, it was not until Hubble and others in the 1920's demonstrated the nature of galaxies that clusters of galaxies were truly comprehended.* Shapley in 1933 catalogued and described 25 discrete clusters of galaxies. However, it was Zwicky in 1938 who first suggested that clustering of galaxies is a widespread, general property of the universe. Later, further studies by Shane, Neyman, Scott, Abell and others re-emphasized this conclusion (de Vaucouleurs, 1971).

Since the completion of the Palomar Sky Survey, two large catalogues of the richest clusters have been compiled using this source. In 1958 Abell published his list of 2712 rich clusters of galaxies. Only galaxies within ($4.6 \times 10^5/cz$) mm of the estimated cluster center were considered on the 48 inch Schmidt Sky Survey plates, where z is the cluster redshift and c is the speed of light in km/sec. This radius corresponds to about 3 Mpc if H = 50 km s^{-1} Mpc^{-1}.

Only clusters with 30 or more galaxies within 2 magnitudes of the third brightest cluster galaxy were included. The catalogue is presumed to be complete only for clusters with 50 or more members.

The redshift was estimated by assuming the absolute magnitude of the tenth brightest cluster to be nearly invariant with distance and population, following Humason, Mayall and Sandage (1956). The limits imposed by the plate size and the limiting magnitude place the redshift range between about 0.02 and 0.20, far enough away for the redshift to be a valid distance indicator but close

*Much of the information in this introductory general discussion is taken from Abell's chapter in Vol. 9 of <u>Stars and Stellar Systems</u>.

enough so that non-linear cosmological effects can be ignored or well approximated within the possible range of q_o.

Abell avoided areas of high galactic obscuration. Thus the catalogue is incomplete within 25° from the galactic plane or near apparent patches of obscuration.

Abell divided the clusters into richness and distance groups as shown in Table 1. The catalogue is approximately complete for distance groups 1 and greater.

Table 1

SUMMARY OF ABELL CLUSTER PARAMETERS

Richness Group	Counts of Galaxies	Distance Group	Magnitude Range (10th brightest galaxy)
0	30-49	1	13.3-14.0
1	50-79	2	14.1-14.8
2	80-129	3	14.9-15.6
3	130-199	4	15.7-16.4
4	200-299	5	16.5-17.2
5	300 or over	6	17.3-18.0
		7	Over 18

Zwicky (1960, 1963, 1965, 1966, 1968a,b) compiled a somewhat more complete list of clusters north of declination -3°, also from the sky survey plates. However, the properties and definitions of these clusters are much more subjective. Zwicky used his long term experience to estimate the half power density outline of each cluster. The size of his clusters varies a great deal and may refer to different types and scales of clustering.

In spite of the homogeneous definition used by Abell, a variety of morphological and structural types are included in his catalogue. Abell recognizes two fundamental types: regular spherical clusters like the well-known Coma cluster, and irregular, more chaotic clusters like those in Hercules or Virgo.

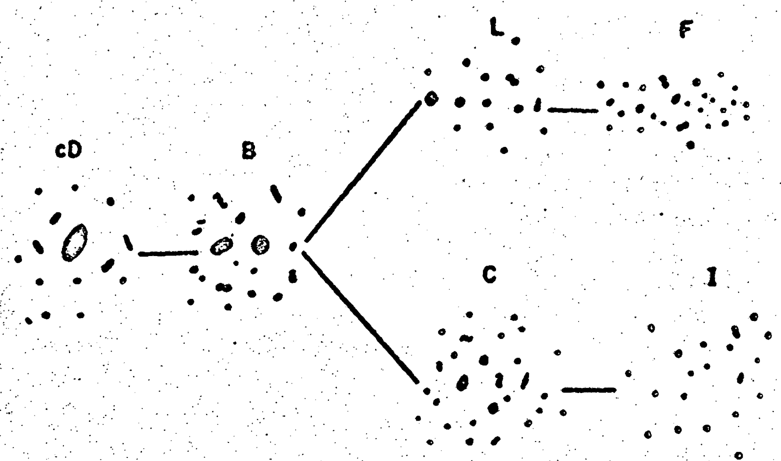
Irregular clusters are very common in Abell's list, probably accounting for about 50% of the catalogue.

Other investigators recognize more divisions. Zwicky divides clusters into compact, medium compact and open. A compact cluster must have a pronounced concentration in which 10 or more galaxies seem to be touching (in projection). Medium compact clusters consist of single condensations in which the galaxies are separated by several of their diameters. Open clusters have no pronounced concentrations but simply appear to be loose clouds superimposed on the general field.

Bautz and Morgan (1970) recognize another morphological property of clusters. They classify clusters of galaxies on a scale from I to III in order of the decreasing degree of domination by the brightest galaxy. Rood and Sastry (1971) combine aspects of the Morgan and Bautz classification with the general shape of the distribution of galaxies. In their classification, illustrated in Figure 1, cD clusters contain a single giant galaxy surrounded by a circular cloud of fainter members. In B systems, two roughly equal, somewhat less dominant galaxies lie at the center of the cloud. C and L systems show only a small degree of domination, the difference in the two being that L (line) clusters have a linear, possibly flattened shape, while C clusters are circular. Similarly, F and I clusters both show no domination, but F clusters look flattened while I (irregulars) show no clear shape at all.

Recently investigations have been made of another cluster parameter: spiral versus elliptical galaxy content (Oelmer, 1974; Krupp, 1972). Briefly, both studies conclude that cD clusters are virtually always spiral poor (≤20% spirals). Among less dominated cluster types, both spiral rich and spiral poor clusters are found.

The most classical observational problem concerning clusters of galaxies concerns their stability. Systems such as Coma appear to be relaxed spherical condensations which certainly look gravitationally bound. However, comparison of the virial theorem masses, estimated from the velocity dispersion of galaxies in the cluster, with the sum of the masses estimated from internal motions in the individual galaxies, results in too little mass being accounted



The "Tuning fork" classification for rich clusters of galaxies from Rood and Sastry, 1971, Pub. Astr. Soc. Pacific, 83, 315 (figure 1)

FIGURE 1.

for in the galaxies by factors of 5 to 100. This leads one to suggest that either the clusters are unstable or a hidden mass exists, possibly in the form of intergalactic gas. Since the dispersion time for a typical cluster is on the order of 10^9 years if it is not bound, and cluster formation from the field cannot account for the number of clusters seen, the former possibility can probably be ruled out as a general explanation unless clusters are just now breaking up. The intracluster intergalactic medium, on the other hand, has been searched for optically. Broad-band optical observations of extensive optical coronas in clusters of galaxies have been made by de Vaucouleurs (1969), Arp and Bertola (1969), de Vaucouleurs and de Vaucouleurs (1970), Welch and Sastry (1971, 1972) and Oemler (1973). If these coronas consist of normal stars, not enough mass to bind the clusters is accounted for. It seems that the medium necessary to bind the clusters consists either of a very hot gas (10^6 to 10^8 K), low luminosity stars or large optically thick condensations of some kind to explain the negative H-β, Lyman-α, and 21 cm line results (Woolf, 1967; Bohlin, Henry and Swandic, 1973; Allen, 1969, and De Young and Roberts, 1974) and the positive x-ray detection (Gursky et al., 1972). More recent x-ray observations although positive do suggest too little hot gas to bind most clusters (Lea et al., 1973).

Radio emission from clusters was first discovered by Mills (1960). Since then a number of studies of the general properties of cluster sources have been made including Pilkington (1964), Wills (1966), Fomalont and Rogstad (1966), and Owen (1974a). Detailed studies of particular cluster radio sources include Ryle and Windram (1968), Willson (1971), and Miley, Perola and van der Kruit (1972). Detection of x-ray emission from clusters has been reported by Gursky et al. (1972) and Kellogg et al. (1973).

Radio emission is found most frequently from cD, B, L and C clusters with about equal probability. The probability drops by roughly a factor of three for I and F clusters. On the other hand, x-ray emission is found almost exclusively in cD or B clusters which also contain a radio source with a steep spectrum. X-ray emission also correlates with richness. Both the radio and x-ray emission in these clusters are often extended up to about 1 Mpc. The gross features of the x-ray correlations can be understood either if the x-ray emission is thermal bremsstrahlung radiation from a hot intergalactic gas with T ~ 10^8 K or if it is inverse Compton scattering of the 3 degree background radiation by the same relativistic particles producing the synchrotron radiation. (See Owen, 1974b and references therein for further details.)

The thermal explanation of the x-ray emission from rich clusters of galaxies fits in well with our present understanding of the morphology of cluster radio galaxies. Most of these radio sources appear much more relaxed than the classical double sources discussed earlier, as if they were statically confined by a hot thermal gas rather than by dynamical pressure. Using the equipartition field strengths, when estimates are made of the nkT pressure necessary to confine the radio sources, values are obtained in agreement with the parameters estimated from the x-ray data alone.

Among the most striking types of radio sources found in rich clusters are the head tail radio galaxies. These sources consist of a long thin tail of emission extending away from a brighter head region which is always near the nucleus of a cluster galaxies. These sources are probably produced by the motion of the parent galaxy as it plows through the intergalactic cluster medium at velocities on the order of a few thousand km/sec. At high resolution these sources often are found to have twin tails suggest a similarity with other double sources. Other radio galaxies are also seen with wider angles between their tails suggesting that they may be moving more slowly with respect to the intergalactic medium.

In the future detailed studies of sources in rich clusters along with higher resolution x-ray observations and optical velocity measures should provide clearer pictures of the intergalactic medium. This in turn should provide insight into the evolution of rich clusters and eventually into the formation of the universe.

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