Notes on Clusters of Galaxies

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I. HISTORICAL INTRODUCTION TO CLUSTERS OF GALAXIES

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

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*Much of the information in this introductory general discussion is taken from Abell's chapter in the unpublished Vol. 9 of Stars and Stellar Systems.

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.

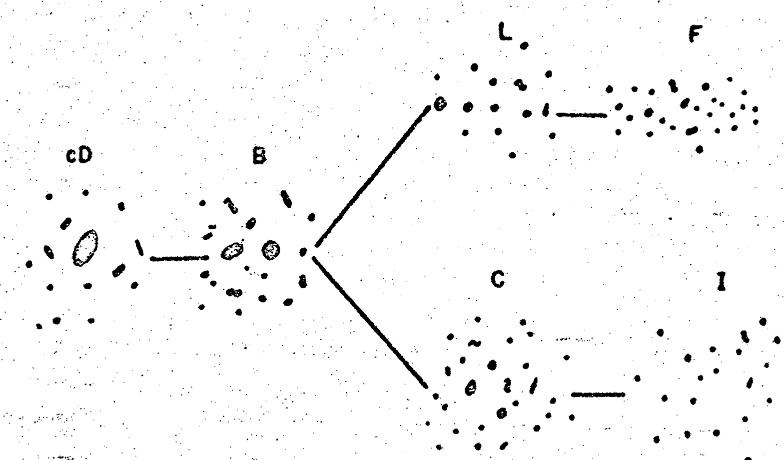
Irregular clusters are very common in Abell's list, probably accounting for about 50% of the catalogue.

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 ($\leq$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).

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 $T \sim 10^8$ 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.)

II. SYNCHROTRON SPECTRA

Following mainly Pacholczyk (1970) and Kellermann (1966), if one considers a cloud of relativistic electrons with a power law energy distribution,

$$N(E)dE \quad = \quad KE^{-\gamma}dE, \tag{1}$$

trapped in a magnetic field, H, the spectral density of synchrotron emission observed is given by

$$S_\nu \propto r^3 K H_\perp^{(\gamma+1)/2} \left(\frac{\nu}{2c_1}\right)^{(1-\gamma)/2} \tag{2}$$

where r is the equivalent spherical radius of the cloud,

$$c_1 \quad = \quad 3e/4\ m^3c^5 \quad = \quad 6.27 \times 10^{-18}$$

and the region is assumed to be optically thin. The observed spectrum is thus also a power law with

$$S \quad = \quad k\nu^{-\alpha} \tag{3}$$

and

$$\alpha \quad = \quad (\gamma-1)/2\ . \tag{4}$$

Given an initial situation defined by (1), the spectrum can be modified in a number of ways depending on the nature of the energy losses. These changes can generally be expressed by the continuity equation for a uniform and isotropic distribution function of electrons as

$$\frac{\delta N(E,t)}{\delta t} + \nabla E \cdot [N(E,t)\frac{dE}{dt}] = q(E,t) - p(E,t) \tag{5}$$

where q(E,t) and p(E,t) represent the additional source and loss functions not described by the left hand side of the equation, dE/dt is now assumed to be dependent on energy alone. Thus,

$$\frac{dE}{dt} = \phi(E) \ . \tag{6}$$

If one assumes $p(E,t) = 0$, the total loss rate can be written as

$$\phi(E) = \zeta - \eta E - \xi E^2 \tag{7}$$

where ζ refers to ionization losses, ηE to free-free losses and ξE^2 to both synchrotron and inverse Compton losses. For all of the densities and particle energies considered in this work, only the last term of equation (7) is important or

$$\frac{dE}{dt} = -\xi E^2 = -(\xi_s + \xi_c)\, E^2 \ . \tag{8}$$

Synchrotron losses are given by

$$\xi_s = 2.37 \times 10^{-3}\, H_\perp^{\,2} \tag{9}$$

and inverse Compton losses by

$$\xi_c = 3.97 \times 10^{-2}\, u_{rad} \tag{10}$$

where u_{rad} is the local radiation energy density. If a single instantaneous injection of energetic particles occurs with

$$N(E,0)\,dE = \begin{cases} KE^{-\gamma}dE & E_1 \leq E \leq E_2 \\ 0 & E < E_1 \text{ and } E > E_2 \end{cases} \tag{11}$$

then using (5) and (8),

$$N(E,t)dE = \begin{cases} \dfrac{KE^{-\gamma}}{(1-\xi Et)^{2-\gamma}} & E_1' \le E \le E_2' \\ 0 & E < E_1' \text{ and } E > E_2' \end{cases} \qquad (12)$$

where $$E' = E/(1 + \xi Et) \; . \qquad (13)$$

Thus even if the energy range extends to infinity, there will be a cutoff energy,

$$E = \frac{1}{\xi t} \qquad (14)$$

and a corresponding upper cutoff frequency.

If continuous injection occurs so that

$$\frac{dN}{dt} = 0 \qquad (15)$$

then

$$N(E) = N(E,t) = \left(\frac{k}{\gamma_o+1}\right)\left(\frac{E^{1-\gamma}}{\xi E^2}\right) \qquad (16)$$

and thus

$$\alpha = \frac{\gamma_o}{2} = \alpha_o + 1/2 \qquad (17)$$

where γ_o and α_o are the instantaneous injection values. This form is valid for injection frequencies high enough that the cutoff frequency does not have time to move into the frequency range considered. For a general source which experiences injections at some particular rate, the lowest frequencies should maintain the initial spectral index, α_o. At intermediate frequencies the continuous injection approximation will apply and $\alpha = \alpha_o + 1/2$. At the highest frequencies the limit to the instantaneous injection case applies and $\alpha = 4/3\ \alpha_o + 1$. The range of frequencies to which any one of the three approximations applies may range over three of four decades and thus may dominate the region available for study with a given instrument.

III. SYNCHROTRON AND INVERSE COMPTON ENERGY LOSSES

Both synchrotron and inverse Compton energy losses result in observable radiation. Synchrotron radiation produces the radio emission reported in this dissertation. On the other hand, inverse Compton losses from the same electrons results in x-ray emission. Following Felten and Morrison (1966) for a given value of the Lorentz factor, Λ, where the total energy $E = \Lambda m_0 c^2$, the characteristic synchrotron frequency emitted is

$$\nu_s = 4.20 \times 10^6 H_\perp \Lambda^2 . \tag{18}$$

For a single event as described in the previous section, the time scale to reach the synchrotron cutoff frequency, ν_{sc}, is from equation (9)

$$T_{sc} \sim \frac{E}{\frac{dE}{dt}} = 3 \times 10^4 H_\perp^{-3/2} \nu_{sc}^{-1/2} \text{ years} . \tag{19}$$

The characteristic Compton frequency of emission for a blackbody distribution of ambient photons is

$$\nu_c = 3.6 \Lambda^2 \frac{kT}{h} \sim 7.5 \times 10^{10} \Lambda^2 T \tag{20}$$

or

$$\langle \varepsilon_1 \rangle = h\nu_c = 3.1 \times 10^{-4} \Lambda^2 T \text{ ev} \tag{21}$$

where h is Planck's constant,
k is Boltzmann's constant, and
T is the temperature, °K.

The timescale for reaching the Compton cutoff frequency, ν_{cc}, from (10) and (20) is

$$T_{cc} \sim 2.7 \times 10^5\ T^{1/2}\ \nu_{cc}^{-1/2}\ u_{rad}^{-1} \text{ years} \tag{22}$$

or in terms of ν_{sc},

$$T_{cc} \sim 2 \times 10^3\ H^{1/2}\ \nu_{sc}^{-1/2}\ u_{rad}^{-1} \text{ years} . \tag{23}$$

The inverse Compton x-ray flux takes the form,

$$S_\nu \propto r^3 \left(\frac{h}{3.6K}\right)^{(3-\gamma)/2} K\ u_{rad}\ T^{(\gamma-3)/2}\ \nu^{(1-\gamma)/2} . \tag{24}$$

Taking advantage of the fact that equation (24) has the same power law dependence on frequency as equation (2), the ratio of the synchrotron flux to the inverse Compton flux for a given Λ may be written

$$\frac{S_{\nu s}}{S_{\nu c}} = 4 \times 10^{-2}\ H_\perp^{\ 2}\ u^{-1} \left(\frac{2 \times 10^4 T}{H}\right)^{(3-\gamma)/2} . \tag{25}$$

The relation between the two frequencies considered is

$$\nu_c = 1/8 \times 10^4\ \frac{T}{H}\ \nu_s . \tag{26}$$

Thus for a given H and radio emission frequency one can simply extrapolate the x-ray intensities and vice versa. For clusters most of the inverse Compton losses are produced by scattering off the 3° background. For this case

$$u_{rad} = 6 \times 10^{-13} \text{ erg/cm}^3 \tag{27}$$

and thus

$$T_{cc} \sim 8 \times 10^{17}\ \nu_{cc}^{-1/2} \tag{28}$$

or

$$T_{cc} \sim 3 \times 10^{15} H^{1/2} \nu_{sc}^{-1/2} . \tag{29}$$

These time scales are for significant losses to take place in the single event case or for the spectral index to steepen by 0.5 in the continuous injection case.

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