Cambridge University Press
978-0-521-11313-7 - X-Ray Emission from Clusters of Galaxies
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# 1

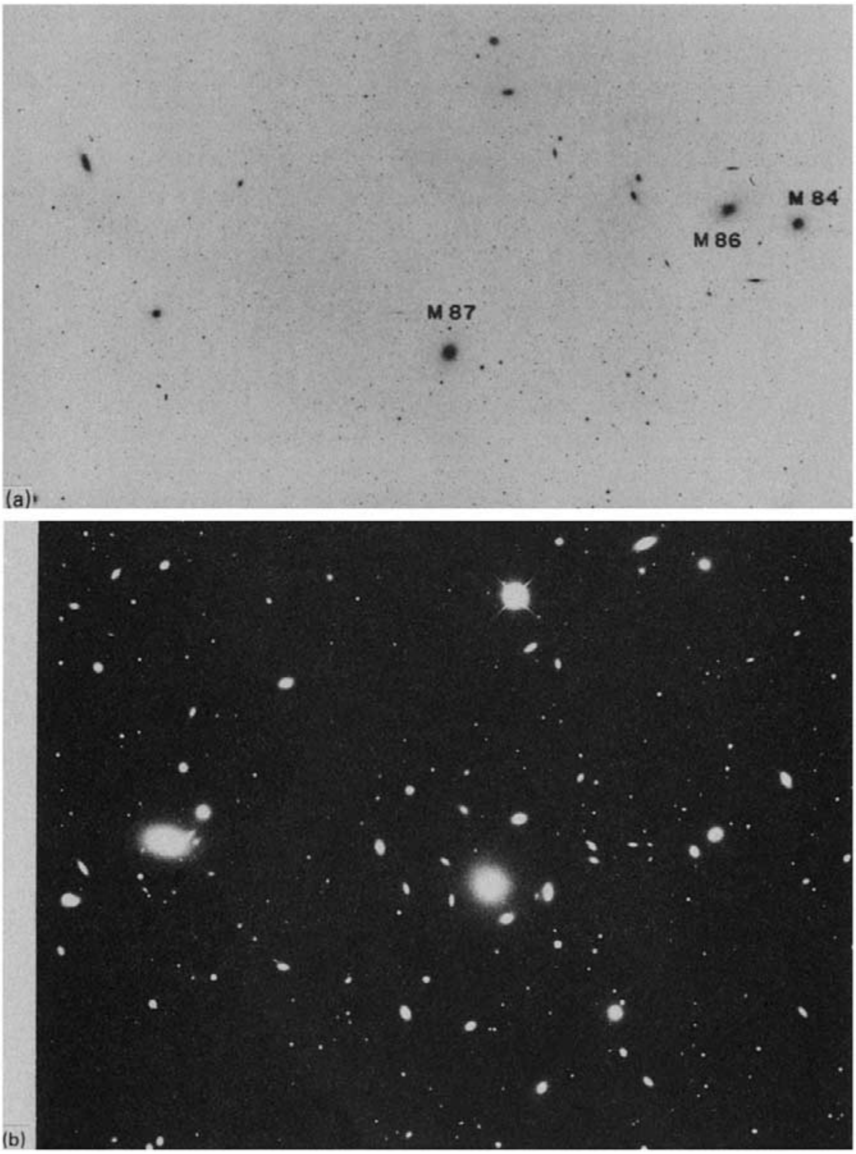
# INTRODUCTION

Regular clusters of galaxies are the largest organized structures in the universe. They typically contain hundreds of galaxies, spread over a region whose size is roughly $10^{25}$ cm. Their total masses exceed $10^{48}$ gm. They were first studied in detail by Wolf (1906), although the tendency for galaxies to cluster on the sky had been noted long before this. A great advance in the systematic study of the properties of clusters occurred when Abell compiled an extensive, statistically complete catalog of rich clusters of galaxies (Abell, 1958). For the last quarter century, this catalog has been the most important resource in the study of galaxy clusters. Optical photographs of several of the best studied clusters of galaxies are shown in Figure 1.[1] The Virgo cluster (Figure 1a) is the nearest rich cluster to our own galaxy; the Coma cluster (Figure 1b) is the nearest very regular cluster.

In 1966, X-ray emission was detected from the region around the galaxy M87 in the center of the Virgo cluster (Byram *et al.*, 1966; Bradt *et al.*, 1967; Figure 1a). In fact M87 was the first object outside of our galaxy to be identified as a source of astronomical X-ray emission. Five years later, X-ray sources were also detected in the directions of the Coma (Figure 1b) and Perseus (Figure 1c) clusters (Fritz *et al.*, 1971; Gursky *et al.*, 1971a, b; Meekins *et al.*, 1971). Since these are three of the nearest rich clusters, it was suggested that clusters of galaxies might generally be X-ray sources (Cavaliere *et al.*, 1971). The launch of the *Uhuru* X-ray astronomy satellite permitted a survey of the entire sky for X-ray emission (Giacconi *et al.*, 1972) and established that this was indeed the case. These early *Uhuru* observations

[1] Unless otherwise indicated, all the figures in this book showing optical, X-ray, or radio brightness on the sky have north at the top and east at the left. When coordinates are given, the east–west coordinate is right ascension (in hours, minutes, and seconds) and the north–south coordinate is declination (in degrees, minutes, and seconds).

Fig. 1. Optical photographs of clusters of galaxies. (a) An optical photograph of the Virgo cluster of galaxies, an irregular cluster that is the nearest cluster to our galaxy. The galaxy M87, on which the X-ray emission is centered, is marked, as are the two bright galaxies M84 and M86. Photograph from the Palomar Observatory Sky Survey (Minkowski and Abell, 1963). (b) The Coma cluster of galaxies (Abell 1656), showing the two dominant D galaxies. Coma is one of the nearest rich, regular clusters. Photograph copyright 1973, AURA, Inc., the

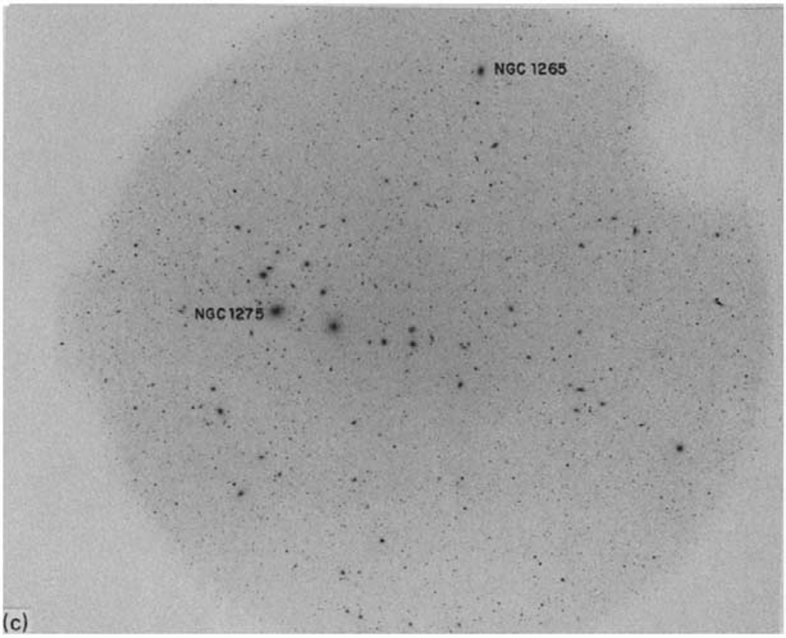


indicated that many clusters were bright X-ray sources, with luminosities typically in the range of $10^{43-45}$ erg/s. The X-ray sources associated with clusters were found to be spatially extended; their sizes were comparable to the size of the galaxy distribution in the clusters (Kellogg *et al.*, 1972; Forman *et al.*, 1972). Unlike other bright X-ray sources but consistent with their spatial extents, cluster X-ray sources did not vary temporally in their brightness (Elvis, 1976). Although several emission mechanisms were proposed, the X-ray spectra of clusters were most consistent with thermal bremsstrahlung from hot gas.

This interpretation requires that the space between galaxies in clusters be filled with very hot ($\approx 10^8$ K), low density ($\approx 10^{-3}$ atoms/cm$^3$) gas. Remarkably, the total mass in this intracluster medium is comparable to the total mass in all the stars in all the galaxies in the cluster. As to the origin of this gas, it was widely assumed that it had simply fallen into the clusters from

Fig. 1 *continued*

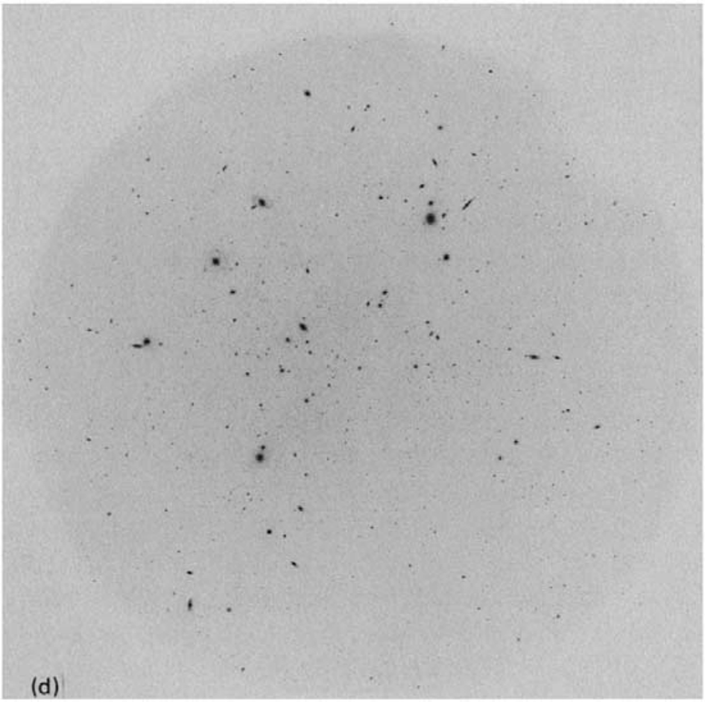
National Optical Astronomy Observatories, Kitt Peak. (c) The Perseus clusters of galaxies (Abell 476), showing the line of bright galaxies. NGC1275 is the brightest galaxy, on the east (left) end of the chain. NGC1265 is a head-tail radio galaxy. Photograph from Strom and Strom (1978c). (d) The irregular cluster Abell 1367. Photograph from Strom and Strom (1978c).



the great volumes of space between them, where it had been stored since the formation of the universe (Gunn and Gott, 1972).

In 1976, X-ray line emission from iron was detected from the Perseus cluster of galaxies (Mitchell *et al.*, 1976), and shortly thereafter from Coma and Virgo as well (Serlemitsos *et al.*, 1977). The emission mechanism for this line is thermal, and its detection confirmed the thermal interpretation of cluster X-ray sources. However, the only known sources for significant quantities of iron or any other heavy element in astronomy are nuclear reactions in stars, and no significant population of stars has been observed which does not reside in galaxies. Since the abundance of iron in the intracluster gas was observed to be similar to its abundance in stars, a substantial portion of this gas must have been ejected from stars in galaxies in the cluster (Bahcall and Sarazin, 1977). This is despite the fact that the total mass of intracluster gas is on the same order as the total mass of stars presently observed in the clusters. Obviously, these X-ray observations suggest that galaxies in clusters have had more interesting histories than might otherwise have been assumed.

Fig. 1 *continued*



In this book, the X-ray observations of clusters of galaxies and the theories for the intracluster gas will be reviewed. Because clusters are still largely defined by their optical properties, I shall first review the optical observations of clusters (Chapter 2). I shall particularly emphasize information on their dynamical state, and the possibility that the galaxy population has been affected by the intracluster gas. Radio observations of clusters also provide information on the intracluster gas, which is summarized in Chapter 3. For example, certain distortions seen in radio sources in clusters are most naturally explained as arising from interactions with this gas. Moreover, extensive searches have been made for 'shadows' in the cosmic microwave radiation due to electron scattering by intracluster gas. Then the X-ray observations will be reviewed (Chapter 4), including the recent results of X-ray imaging and spectroscopy from the *Einstein* X-ray satellite. In Chapter 5 theories for the X-ray emission mechanism, the physical state, the distribution, the origin, and the history of the intracluster medium will be reviewed. Finally, I shall comment briefly on the prospects for further observations of X-ray clusters, particularly with the AXAF satellite, in Chapter 6.

Review articles on clusters of galaxies emphasizing their optical properties include Abell (1965, 1975), van den Bergh (1977b), Bahcall (1977a), Rood (1981), White (1982), and particularly Dressler (1984). Superclusters of galaxies are reviewed by Oort (1983). Some recent reviews which include the X-ray properties of clusters are Gursky and Schwartz (1977), Binney (1980), Cavaliere (1980), Cowie (1981), Canizares (1981), and Holt and McCray (1982). Fabian *et al.* (1984b) give an excellent review of cooling flows in X-ray clusters (see Sec. 5.7). Up-to-date reviews of the spectroscopic properties of X-ray clusters are given by Mushotzky (1984, 1985). Forman and Jones (1982) give a comprehensive review of the X-ray images of clusters. This book is based in large part on my review paper on X-ray clusters (Sarazin, 1986a).

# 2

# OPTICAL OBSERVATIONS

## 2.1 Catalogs

The two most extensive and often cited catalogs of rich clusters of galaxies are those of Abell (1958) and Zwicky and his collaborators (Zwicky *et al.*, 1961–1968). As is conventional, in this book Abell clusters will be denoted by giving A and then the number of the cluster in Abell's list. Both of these catalogs were constructed by identifying clusters as enhancements in the surface number density of galaxies on the National Geographic Society – Palomar Observatory Sky Survey (Minkowski and Abell, 1963) and thus are confined to northern areas of sky (declination greater than $-20°$ for Abell and $-3°$ for Zwicky). Abell surveyed only clusters away from the plane of our galaxy.

As clustering exists on a very wide range of angular and intensity scales (Peebles, 1974), it is not possible to give a unique and unambiguous definition of a 'rich cluster'. Thus the membership of a catalog of clusters is determined by the criteria used to define a rich cluster. These criteria must specify the required surface number density enhancement for inclusion and the linear or angular scale of the enhancement. The scale is necessary in order to exclude small groupings of galaxies; for example, a close pair of galaxies can represent a very large enhancement above the background galaxy density on a small angular scale. Alternatively, specifying the surface density and scale is equivalent to specifying the number of galaxies (the 'richness' of the cluster) and the scale size. Because the number of galaxies observed increases as their brightness diminishes (Section 2.4), one must also specify the range of magnitudes of the galaxies included in determining the cluster richness. Finally, because galaxies grow fainter with increasing distance, the catalog can only be statistically complete out to a limiting distance or redshift, and only clusters within this distance range should be included in a statistically complete sample.

Abell's criteria were basically (1) that the cluster contain at least 50 galaxies in the magnitude range $m_3$ to $m_3 + 2$, where $m_3$ is the magnitude of the third brightest galaxy; (2) that these galaxies be contained within a circle of radius $R_A = 1.7/z$ minutes of arc or $3h_{50}^{-1}$ megaparsecs,[2] where $z$ is the estimated redshift of the cluster (Section 2.2); (3) that the estimated cluster redshift be in the range $0.02 \leqslant z \leqslant 0.20$. $R_A$ is called the Abell radius of the cluster. The Abell catalog contains 2712 clusters, of which 1682 satisfy all these criteria. The other 1030 were discovered during the search and were included to provide a more extensive finding list for clusters. The Abell catalog gives estimates of the cluster center positions (see also Sastry and Rood, 1971), distance, and richness of the clusters, as well as the magnitude of the tenth brightest galaxy $m_{10}$.

For the Zwicky catalog, the criteria were as follows: (1) the boundary (scale size) of the cluster was determined by the contour (or isopleth) where the galaxy surface density fell to twice the local background density; (2) this isopleth had to contain at least 50 galaxies in the magnitude range $m_1$ to $m_1 + 3$, where $m_1$ is the magnitude of the first-brightest galaxy. No distance limits were specified, although in practice, very nearby clusters such as Virgo (Figure 1a), were not included because they extended over several Sky Survey plates. Obviously, the Zwicky catalog criteria are much less strict than Abell's, and the Zwicky catalog thus contains many more clusters that are less rich. For each cluster, the Zwicky catalog gives a classification (Section 2.5), and estimates of the coordinates of the center, the diameter, the richness, and the redshift. Finding charts showing the cluster isopleths and positions of brighter galaxies and stars are also presented.

A number of smaller catalogs have been compiled, consisting of clusters in the southern sky or clusters at higher redshifts ($z \gtrsim 0.2$). Early southern cluster catalogs or lists include those of de Vaucouleurs (1956), Klemola (1969), Snow (1970), Sersic (1974), and Rose (1976). Until recently, the search for southern clusters was severely handicapped by the lack of deep survey plates. The first deep optical survey of the south, the European Southern Observatory Quick Blue Survey (ESO-B), was completed in 1978 (West, 1974; Holmberg *et al.*, 1974). A catalog of southern clusters from the first portion of this survey was prepared by Duus and Newell (1977) and a list of southern clusters near X-ray sources was given by Lugger (1978). More recently, portions of the ESO/SRC-J survey of very deep blue plates have been used to compile southern cluster catalogs by Braid and MacGillivray (1978) and White and Quintana (1985). Before his untimely death, Abell was preparing a southern

[2] For convenience, in this book the Hubble constant $H_o$ will be parameterized as $H_o = 50h_{50}$ km/sec/Mpc.

continuation of the Abell catalog in collaboration with Corwin. The red portion of the ESO/SRC survey is currently being done, and these plates are being used to detect high redshift clusters (West and Frandsen, 1981).

The discovery of higher redshift clusters ($z \gtrsim 0.2$) is of great importance to cosmological studies; lists of such clusters include Humason and Sandage (1957), Gunn and Oke (1975), Sandage, Kristian, and Westphal (1976), Spinrad *et al.* (1985), and Vidal (1980). In addition, the lists of southern clusters from the ESO/SRC surveys discussed in the last paragraph contain many high redshift clusters.

## 2.2 Redshifts

The clusters in the Abell (1958) catalog were assigned to distance groups, based on the redshift estimated from the magnitude of the tenth brightest galaxy in the cluster. Leir and van den Bergh (1977) have given improved estimates of redshifts for 1889 rich Abell clusters, using the magnitudes of the first and tenth brightest galaxies, and an estimate of the cluster radius. Their distance scale is calibrated using measured redshifts for 101 clusters. Photometric distance estimators derived from a larger sample of redshifts have been given by Sarazin *et al.* (1982). Similarly, clusters in the Zwicky catalog were placed in distance groups, based on the magnitudes and sizes of the brightest cluster galaxies.

Spectroscopic redshifts are now available for about 500 Abell clusters. Sarazin (1986a, Table I) gives an extensive list of the redshifts for Abell clusters, taken primarily from Sarazin *et al.* (1982), Noonan (1981), Struble and Rood (1982, 1985), and Hoessel, Gunn, and Thuan (1980).

Of course, many redshifts are known for non-Abell clusters as well. The compilation of Noonan (1981) includes many such redshifts.

## 2.3 Richness – the number of galaxies in a cluster

The richness of a cluster is a measure of the number of galaxies associated with that cluster. Because of the presence of background galaxies, it is not possible to state with absolute confidence that any given galaxy belongs to a given cluster. Thus one cannot give an exact tally of the number of galaxies in a cluster. Richness is a statistical measure of the population of a cluster, based on some operational definition of cluster membership. The richness will be more useful if it is defined in such a way as to be reasonably independent of the distance to and morphology of a cluster.

Zwicky *et al.* (1961–1968) define the richness of their clusters as the total number of galaxies visible on the red Sky Survey plates within the cluster isopleth (Section 2.1); the number of background galaxies expected is subtracted from the richness. These richnesses are clearly very dependent on a cluster redshift (Abell, 1962; Scott, 1962). First, a wider magnitude range is counted for nearby clusters, because the magnitude of the first brightest galaxy is further from the plate limit. Second, a larger area of the cluster is counted for nearby clusters, because the point at which the surface density is twice that of the background will be farther out in the cluster.

Abell (1958) has divided his clusters into richness groups using criteria that are nearly independent of distance (see Section 2.1); that is, the magnitude range and area considered do not vary with redshift. Just (1959) has found a slight richness–distance correlation in Abell's catalog; however, the effect is small and is probably explained by a slight incompleteness (10%) of the catalog for distant clusters (Paal, 1964). When more accurate determinations have been made, it has been found that the Abell richness generally correlated well with the number of galaxies, but that the Abell richness may be significantly in error in some individual cases (Mottmann and Abell, 1977; Dressler, 1980a). Thus the Abell richnesses are very useful for statistical studies, but must be used with caution in studies of individual clusters. Note also that it is generally preferable to use the actual Abell counts rather than just the richness group (Abell, 1982).

## 2.4 Luminosity function of galaxies

The luminosity function of galaxies in a cluster gives the number distribution of the luminosities of the galaxies. The integrated luminosity function $N(L)$ is the number of galaxies with luminosities greater than $L$, while the differential luminosity function $n(L)dL$ is the number of galaxies with luminosities in the range $L$ to $L+dL$. Obviously, $n(L) \equiv -dN(L)/dL$. Luminosity functions are often defined in terms of galaxy magnitudes $m \propto -2.5\,log_{10}(L)$; $N(\leqslant m)$ is the number of galaxies in a cluster brighter than magnitude $m$. Observational studies of the luminosity functions of clusters include Zwicky (1957), Kiang (1961), van den Bergh (1961a), Abell (1962, 1975, 1977), Rood (1969), Gudehus (1973), Bautz and Abell (1973), Austin and Peach (1974b), Oemler (1974), Krupp (1974), Austin *et al.* (1975), Godwin and Peach (1977), Mottmann and Abell (1977), Dressler (1978b), Bucknell *et al.* (1979), Carter and Godwin (1979), Thompson and Gregory (1980), and Kraan-Korteweg (1981). Figure 2 gives the observed integrated luminosity function for a composite of 13 rich clusters as derived by Schechter (1976) from Oemler's (1974) data.

Three types of functions are commonly used for fitting the luminosity function. Zwicky (1957) proposed the form

$$N(\leqslant m) = K(10^{0.2(m-m_1)} - 1), \tag{2.1}$$

where $K$ is a constant and $m_1$ is the magnitude of the first brightest galaxy. In general, the Zwicky function fits the faint end of the luminosity function adequately, but does not fall off rapidly enough for brighter galaxies (see Figure 2). Clearly, equation (2.1) implies that $N(L) = K[(L_1/L)^{1/2} - 1]$, where $L_1$ is the luminosity of the first brightest galaxy, and $K$ is the expected number of galaxies in the range $1/4L_1 \leqslant L \leqslant L_1$.

Abell (1975) has suggested that the luminosity function $N(L)$ be fit by two intersecting power laws, $N(L) = N^*(L/L^*)^{-\alpha}$, where $\alpha \approx 5/8$ for $L < L^*$, and $\alpha \approx 15/8$ for $L > L^*$. $L^*$ is the luminosity at which the two power laws cross, and $N^*$ is the expected number of galaxies with $L \geqslant L^*$. Of course, this form is intended only as a simple and practical fit to the data; the real luminosity function certainly has a continuous derivative $n(L)$, unlike Abell's function. The magnitude luminosity function corresponding to Abell's form is often written as

$$\log_{10} N(\leqslant m) = \begin{Bmatrix} K_1 + s_1 m & m \leqslant m^* \\ K_2 + s_2 m & m > m^* \end{Bmatrix} \tag{2.2}$$

Fig. 2. The luminosity function of galaxies in clusters. $N(\leqslant M_V)$ is the number of galaxies brighter than absolute magnitude $M_V$. The circles are the composite observed luminosity function derived by Schechter (1976). The solid circles exclude cD galaxies, while the open circles show the changes when they are included. The solid, dashed, and dash-dotted curves are the fitting functions of Schechter, Abell, and Zwicky, as discussed in the text.