X-RAYS FROM CLUSTERS OF GALAXIES

J. L. Culhane,
Mullard Space Science Laboratory,
University College London,
Holmbury St. Mary,
Dorking, Surrey,
England.

1. INTRODUCTION

The discovery of the extended sources of X-ray emission associated with clusters of galaxies was undoubtedly one of the most significant observations carried out by the Uhuru satellite (Gursky et al (1971), Giacconi et al (1974)). At the present time, there are more than 30 identifications and suggested associations of X-ray sources with clusters of galaxies although extended emission has been directly observed in less than 10 cases.

The mechanism for X-ray emission from such large objects is of considerable interest. X-rays could be generated by the inverse Compton interactions of microwave background photons with populations of relativistic electrons distributed throughout the clusters. Alternatively the radiation may be due to Bremsstrahlung from hot ($T \simeq 10^8$ °K) gas which constitutes an intracluster medium. Progress in understanding the extended X-ray sources and in determining the emission mechanism has come from observations of the X-ray structure and spectra of the cluster sources and it is the purpose of this review to present the current status of these observations.

In the following sections the available information on cluster spectra and structure will be reviewed and a list of proposed identifications presented.

2. THE SPECTRA AND STRUCTURE OF X-RAY SOURCES IN CLUSTERS OF GALAXIES

In order to separate the contribution of individual galaxies from the diffuse cluster emission, X-ray observations with an angular resolution of an arc minute or better are required. Since data of this quality are, in general, not yet available there are uncertainties in the interpretation of the present cluster source observations. Most of the emphasis in model building has so far been placed on the extended emission from the cluster as a whole but the available data may contain

Edith A. Müller (ed.), Highlights of Astronomy, Vol. 4, Part I, 293-309.

substantial unresolved contributions from individual active galaxies.

Because of their large X-ray flux, more information is at present available for the Perseus, Coma, Virgo and Centaurus clusters and so the observations of these sources will be discussed in greater detail. In addition the spectral and other data available for several of the weaker cluster sources will also be presented.

2.1 Perseus Cluster

This object was first recognised as an X-ray source by Fritz et al (1971) but its extended nature only became apparent from the Uhuru observations (Gursky et al (1971)). The Perseus Cluster was already known to be associated with an extended radio source 3C84B (Ryle and Windram (1968)) and to contain the unusually active galaxy NGC1275. A number of other galaxies in the cluster are also radio sources including NGC1265 and IC310. In addition Ryle and Windram draw attention to the unusual chain of galaxies running between NGC1275 and IC310. Thus the radio appearance of the cluster is clearly complex.

The Uhuru observations were fitted to an isothermal gas sphere (Lea et al (1973)) of core radius 15 arc minutes and did not require a point source contribution at the centre of the cluster. A more detailed series of observations of the central regions surrounding NGC1275 was carried out by Fabian et al (1974) using the Copernicus X-ray telescopes. It was clear from these results that the central region included a source of order 3 arc min in size which was responsible for 10 - 20% of the cluster emission together with a more extended X-ray emitting volume. However no significant X-ray emission was detected from regions of the cluster more than 6 arc min from the centre of NGC1275. In addition upper limits of 2.10^{43} ergs sec^{-1} were set to the luminosity of NGC1265 and IC310 in the 0.5 - 1.5 keV band. Wolff et al (1974) confirm the existence of a central component associated with NGC1275 but, in addition, find a markedly different distribution of emission on two mutually perpendicular scans (N - S and E - W) carried out by their rocket borne one dimensional X-ray collector. They attribute this to emission from the line of galaxies referred to above. The existence of a central component associated with NGC1275 is also confirmed by Catura and Acton (1975).

An attempt to fit some of these observations together was undertaken by Wolff et al (1976) using the Copernicus satellite and Columbia rocket data referred to above. Using an algebraic reconstruction technique (ART), data from the region surrounding NGC1275 taken in the 0.5 - 1.5 keV range with the Copernicus 6' field of view telescope were combined to provide the contour map shown in Figure 1a. Features of the map that remain stable when the data points are perturbed randomly within limits set by their statistical quality include the elongation along the N - S axis and the rather rapid drop in intensity in the south-east. A radio map (Miley and Perola (1975)) is shown for comparison (Figure 1b). A number of similarities may be seen.

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

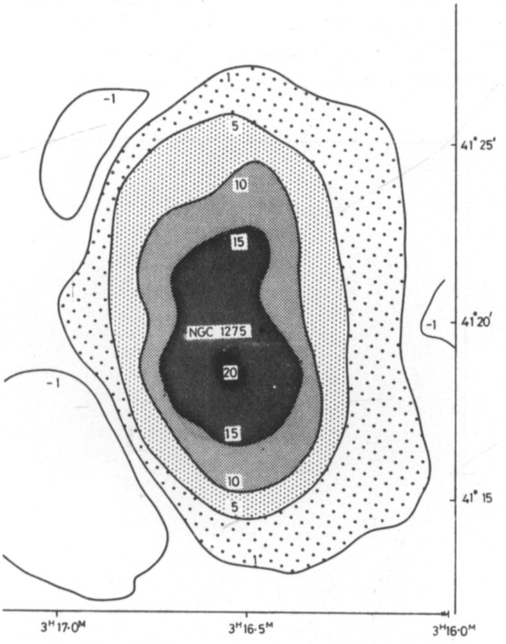


Figure 1a. Spatial structure (0.5-1.5keV) from a fit to 16 data points obtained with the MSSL X-ray telescope on Copernicus using the 5.5' field of view. Intensity contours were obtained using the algebraic reconstruction technique (ART).

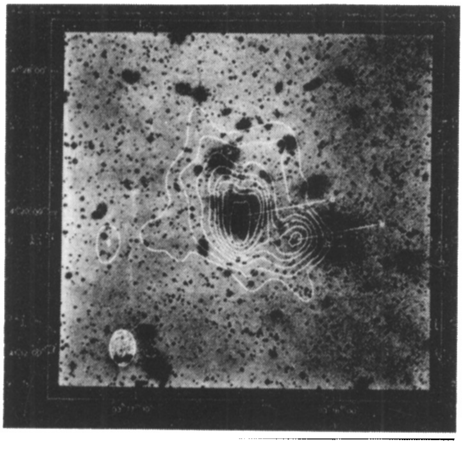


Figure 1b. The radio halo of NGC1275 with a resolution of 67" by 102". The contours are superimposed on an optical photograph from Arp and Bertola (1971). Contours representing flux density per synthesized beam area are shown at levels of 0.02, 0.04 and thereafter at intervals of 0.04 fu. The synthesized half power beam width is indicated by the shaded ellipse. (After Miley and Perola).

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

In addition to the studies of the central region, Wolff et al (1976) have obtained a model dependent surface brightness distribution of the cluster as a whole. This is shown in Figure 2 along with a surface brightness distribution based on Uhuru data (Lea et al (1973)).

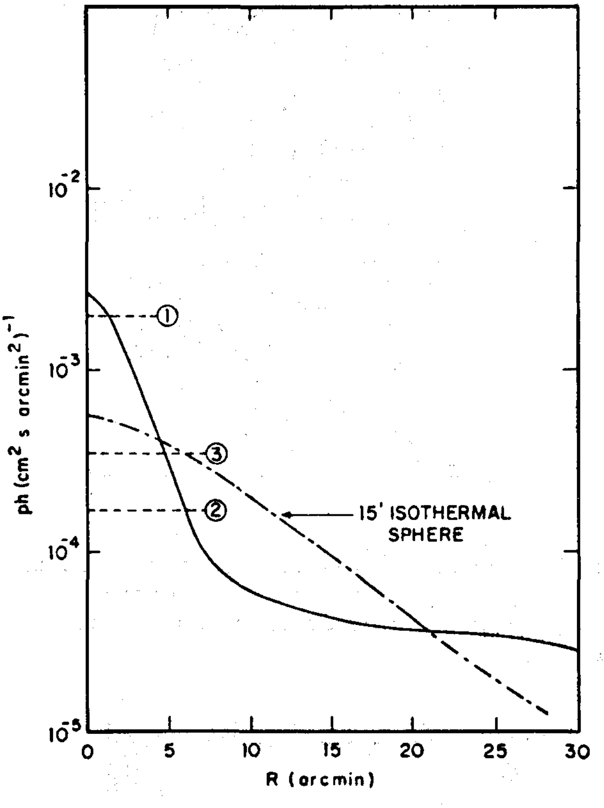


Figure 2. Spatial distribution of surface brightness for the best model. Lines (1), (2), and (3) represent the limiting sensitivities for the three irises used (3σ above background). The aperture FWHM for irises 1, 2, and 3 are 2', 12', and 6', respectively. For comparison, the brightness distribution of a 15' core radius (cf. Uhuru) is also displayed. (After Wolff et al (1976)).

The central peak in surface brightness in the Copernicus and Columbia data is apparent. The combined data do not support a 15' core radius isothermal gas sphere.

The first X-ray picture of the Perseus Cluster obtained with an imaging X-ray telescope of the Baez-Kirkpatrick type with an angular resolution of 2' - 3' was reported by Gorenstein (1976). It indicates the complexity of the region surrounding NGC1275 and that the galaxy is not centrally placed with respect to the diffuse cluster emission. The shape of the central region is broadly consistent with that shown in Figure 1a and has a characteristic dimension of about 10'.

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

However the centroid of this region is located 5' ± 2' west of the centre of NGC1275. Although a small spur of emission projects from the neighbourhood of NGC1275 in the direction of IC310, the emission from the line of galaxies reported by Wolff et al (1974) and discussed again by Cash et al (1976) is not apparent. The diffuse cluster emission region is extended by about 30'.

A preliminary report of Rotation Modulation Collimator observations by the SAS-3 satellite (Schnopper (1976)) points to the existence of a point like (< 2') component in the centre of NGC1275 which appears to have a somewhat harder spectrum than that of the rest of the cluster.

The extended cluster source has estimates of core radius that vary from 4' (Malina et al (1976) to 30' (Wolff et al (1974, 1976).

The extended emission region has been related to isothermal and adiabatic gas sphere models (Lea et al (1973), Lea (1975) Gull and Northover (1975)). The principal emission components that have been suggested by the observations together with the data available on their extent are summarised in Table I.

Component	Extent	Observation	Remarks
Point in NGC1275	< 2' (diam) < 3' (")	Schnopper (1976) Fabian et al (1974)	Harder spectrum, intensity data not yet available. 10-25% of total cluster flux.
Extended region around NGC1275	9' (NS) x 5' (EW) ~10' 9' (NS) x 15' (EW)	Wolff et al (1976) Gorenstein (1976) Cash et al (1976)	Copernicus ART map. Baez-Kirkpatrick telescope map. Contains feature extending 2' towards IC310 Berkeley rocket data.
Extended cluster source.	~15' (radius) ~30' (") ~30' (") ~ 4' (")	Lea et al (1973) Wolff et al (1974,1976) Gorenstein (1976) Malina et al (1976)	Isothermal sphere fitted to Uhuru data. Columbia rocket data. Preliminary estimate from map. Isothermal sphere fitted to Berkeley rocket data.
Line of Galaxies	~40' (EW) ~40' (EW) x 3' (NS)	Wolff et al (1974) Cash et al (1976)	Columbia rocket data. Columbia and Berkeley rocket data.

Table I. X-ray Emitting Components of the Perseus Cluster.

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

It is apparent from the number and variety of these components that it will be particularly difficult to determine the origin of the diffuse emission in the case of the Perseus Cluster. For example it appears likely that a single radiation mechanism (thermal or inverse Compton) can not be responsible for all of the observed components.

In spite of the spatial complexity of the Perseus X-ray emission, it is nevertheless worthwhile to examine the spectrum of the entire cluster in attempting to identify the emission mechanism on the grounds that about 75% of the flux appears to originate from a distributed source. Although the detectors used so far in cluster studies have low energy resolution, observations over a large energy range can help to clarify the situation. While the Uhuru data in the 2-10keV range (Kellogg et al (1975)) can be fit equally well by thermal bremsstrahlung or power law spectra, the observations of Ulmer et al (1973) and the upper limits established by Scheepmaker et al (1976) in the 10-150keV range favour a thermal spectrum on the grounds that they lie well below a power law extrapolation of the Uhuru data. In the energy range below 2keV, the rocket observations of Davidsen et al (1975) also favour a thermal spectrum when compared with the Uhuru data, on the grounds that a power law extrapolation of the Uhuru spectrum would require an unreasonably high gas column if it were to match the rocket observations. The permitted thermal spectrum has parameters $T=10^8$ ^oK and $N_H=1.9 \cdot 10^{21}$ H atoms/cm^2 column. The latter value is in good agreement with the 21cm column (Hughes et al, 1971)

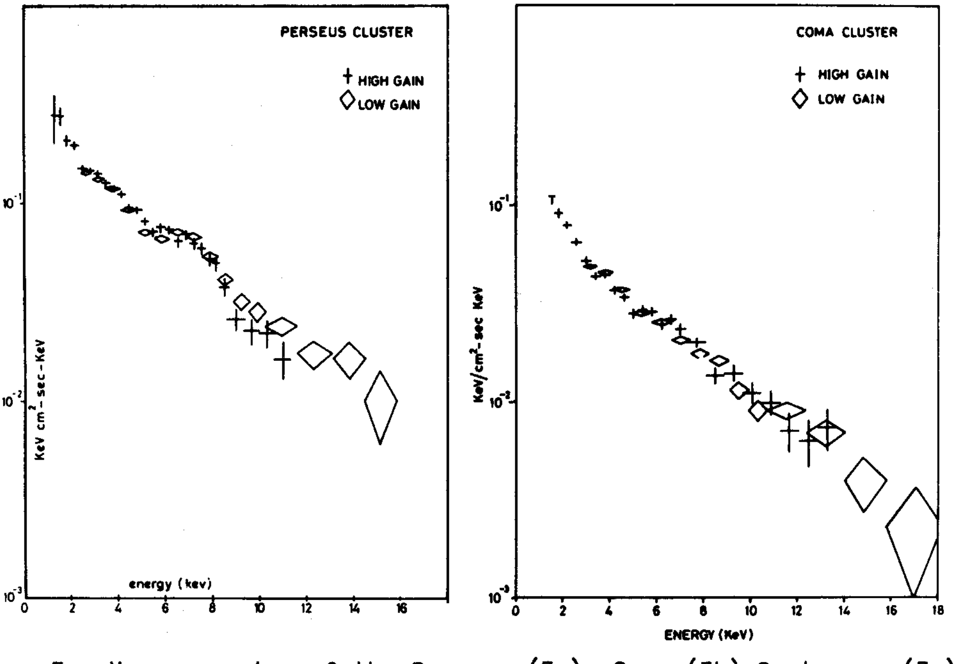
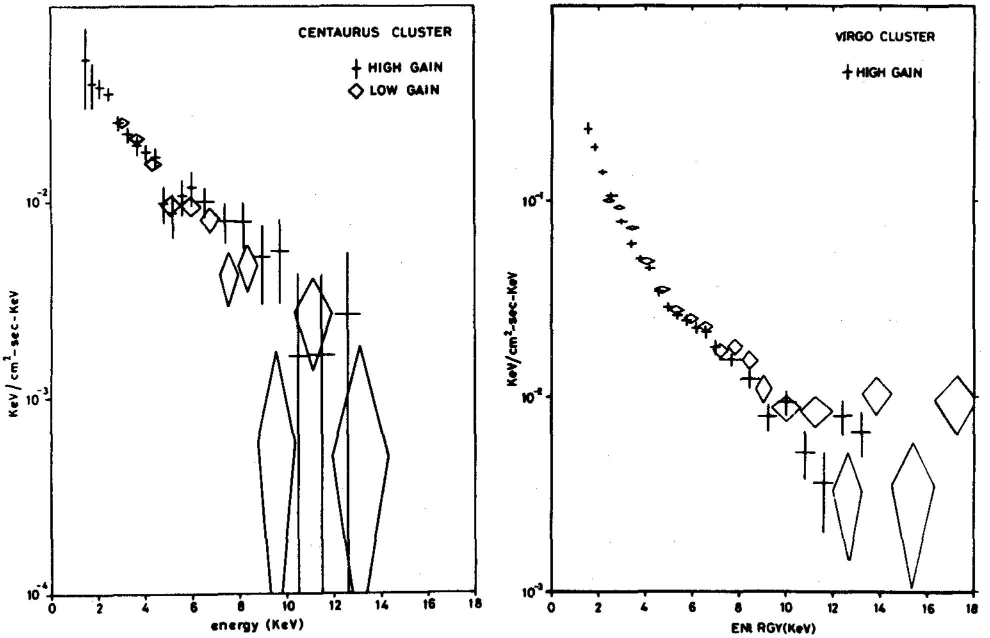


Figure 3. X-ray spectra of the Perseus (3a), Coma (3b) Centaurus (3c) and Virgo (3d) clusters obtained with the MSSL proportional counter on Ariel V. The presence of an emission feature is apparent in the Perseus spectrum.

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press



The 1.3-16keV spectrum of the cluster obtained by Mitchell et al (1976) using the Ariel V satellite (Figure 3a) provides strong evidence for a thermal emission mechanism. The emission feature centered on 6.9 keV is significant at the 7.5σ level as a departure from a thermal continuous spectrum of temperature 6 keV (Figure 4). The flux of

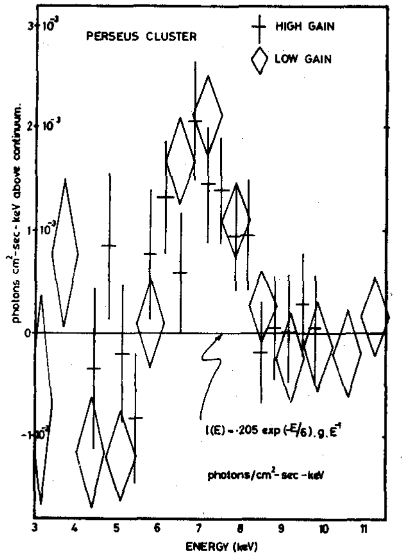


Figure 4. The departure from the best fitting continuous spectrum for the Perseus Cluster plotted against photon energy. The existence of the emission feature is apparent in data from both detector gain modes.

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

$3.5.10^{-3}$ photons cm^{-2} sec^{-1} in the emission feature is due to lines from Fe XXV and Fe XXVI ions. A comparison of this flux with the calculations of Tucker and Koren (1971), which included an iron abundance of 5.10^{-5}, suggests that iron is four times less abundant for the cluster as a whole. However it is not clear that the emitting iron ions are distributed throughout the cluster. Because of the 3.5^{0} detector field of view, the Ariel V observation provides no information on this point. It may be that ejecta from NGC1275 enrich a part of the cluster gas. The entire Ariel V spectrum is not well fit by a gas at a single temperature but can be better described as the emission from an adiabatic atmosphere with a range of gas temperatures (e.g. Gull and Northover (1975), Lea (1975)).

2.2 Coma Cluster

Although not studied in the same detail as Perseus (its 2 - 10 keV flux is three times less), the lack of a galaxy as active and unusual as NGC1275 in the cluster and the absence of any compact features in the X-ray observations carried out so far suggest that the Coma Cluster may eventually provide more information on the nature of the diffuse emission from clusters.

Using Uhuru data, Lea et al (1973) find the X-ray core radius of an isothermal gas sphere to be $16' \pm 3'$. This value is supported by Copernicus observations of the central region of the cluster in the 1.5 - 4.6 keV band (Griffiths et al (1974)) which suggest a core radius of $15' \pm 3'$. The absence of flux in the 0.5 - 1.5 keV band leads to a lower limit of 19.5' for the core radius in this energy range. However, Gorenstein et al (1973) find the angular diameter of the source to be less than 30' in the 0.5 - 2 keV band. Malina et al (1976) find a core radius of 10^{+8}_{-5} arc min for the 0.5 - 3.2 keV band. Thus all of the structural data obtained so far are consistent with an isothermal gas sphere model and, although the Copernicus observation provides some evidence for increased size at lower energies, this is not conclusive. Observations of the Coma Cluster by the Ariel V sky survey instrument (Elvis (1976)) suggest that a 2σ upper limit of 20% can be set to variability on timescales from 6 days to 1 year in the 2 - 10 keV range.

The 2 - 10 keV spectrum of the Coma Cluster has been observed with Uhuru and presented in final form by Kellogg et al (1975). As in the case of Perseus, data in this energy range do not permit a distinction between thermal and power law spectral forms. Because this source is weaker than Perseus, the upper limits in the range above 10 keV set by Ulmer et al (1973) and Scheepmaker et al (1976) are also unhelpful in this regard. A comparison of the Uhuru spectrum with the observations of Gorenstein et al (1973) below 1.4 keV shows the latter data to lie well above the Uhuru points so it is once again not possible to constrain the emission mechanism.

The Ariel V spectrum (Figure 3b) agrees within errors with the Uhuru data in the range 3 - 10 keV. The spectrum steepens somewhat

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

below 3 keV resulting in good agreement with the data of Gorenstein et al (1973). Altbough a thermal spectrum with Gaunt factor fits for a temperature of 5.6 $\pm$ 0.22 keV, the data are once again better explained by an adiabatic gas atmosphere with a range of temperatures. There is no significant evidence for an iron emission feature.

2.3 Centaurus Cluster

This source is about 8 times weaker than Perseus in the 2 - 10 keV range. However its core radius has been estimated by Kellogg et al (1975) as $16.2^{+7'}_{-5.4}$' for an isothermal gas sphere. Copernicus observations in the 0.5 - 1.5 keV range using the 12' field of view X-ray telescope at the centre of the cluster found a considerably larger flux than would have been expected on the basis of the isothermal gas sphere model (Mitchell et al (1975)). This could be due to the presence of the active galaxy, NGC4696, in the Copernicus field of view or to the greater concentration of flux near the centre of the cluster that would result from an adiabatic gas sphere. If the Copernicus observation is used to deduce a core radius, its value of $6'^{+3'}_{-2}$ does not agree with the Uhuru sphere size.

The Ariel V spectrum of this cluster is shown in Figure 3c. The best fitting single temperature value is 3.6 $\pm$ 0.17 keV. Once again an adiabatic atmosphere would explain the data points more easily although the need for material at a range of temperatures is not so compelling. Although there appears to be an anomaly in the spectrum at around 6.7 keV, there is, once again, no significant evidence for iron line emission available at this time.

2.4 Virgo Cluster

For this object, the core radius is determined by Lea et al as 25' $\pm$ 4' on the basis of an isothermal gas sphere. Other estimates of core radius (Griffiths et al (1974), Malina et al (1976)) are consistent with this value. The extended emission appears symetric about and centred on M87.

Catura et al (1972) suggested the presence of a point source associated with M87 which could contribute 60 $\pm$ 30% of the total cluster flux. While Griffiths et al (1974) set an upper limit of 10% to a point source flux, Malina et al (1976) find that their best fitting model of cluster structure could include a point component of up to 25% of the cluster flux. Definitive data on this question are now available and will be presented later in the meeting by Paul Gorenstein. Malina et al have set a 3σ upper limit of 2.10^{-11} ergs cm^{-2} sec^{-1} in the 0.5 - 3.2 keV band on emission from the galaxy M84.

Spectra obtained for this source are as yet unable to significantly constrain the emission mechanism. Kellogg et al (1975) obtain a best fitting temperature of 2.6 keV but claim that their data (2 - 10 keV are better fitted by a power law. However a combination of the Uhuru

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

data with rocket observations of Catura et al (1974) below 1 keV favours a thermal spectrum.

The Ariel V spectrum of the Virgo cluster is shown in Figure 3d. While power law and thermal fits are both possible, it is again apparent that an adiabatic atmosphere with gas at a range of temperatures could also fit the data. However the spectrum has some puzzling features and further observations are required. There is no significant evidence of iron line emission.

2.5 Summary

Properties of the four clusters discussed above are listed in table II. The approximate size values refer to Uhuru data. Although

Cluster	Approximate size of diffuse source		Best fitting single temperature (keV)	L_x(2-10keV) (erg sec^{-1})	Optical core radius
	Angular	Linear			
Perseus	15'	0.5Mpc	$7.5\pm0.3^{(1)}$ $6.4\pm0.1^{(2)}$	9.10^{44}	8'
Coma	16'	0.6Mpc	$8.7\pm1.7^{(1)}$ $5.6\pm0.3^{(2)}$	$4.5.10^{44}$	6'
Centaurus	16'	0.3Mpc	$3.6\pm0.2^{(2)}$	4.10^{43}	-
Virgo	25'	0.1Mpc	$2.6\pm0.1^{(1)}$ $2.8\pm0.3^{(2)}$	9.10^{42}	-

(1) Uhuru. Kellogg et al (1975)
(2) Ariel V.

Table II Summary of Properties of Principal X-ray Clusters

there is evidence in some cases that size increases with decreasing energy, this has not yet been established conclusively. While the evidence for a thermal emission mechanism is strongest in the case of the Perseus Cluster, it now seems likely that all of the extended emission is from hot gas. However, non thermal components associated with individual active galaxies are by no means ruled out.

2.6 Other Clusters

In addition to the above sources, some size and spectral measurements are available from Uhuru and Ariel V for a number of other clusters. The Ariel V spectra of four weaker cluster sources are shown

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

in Figure 5. Because of the lower flux, it has been necessary to bin

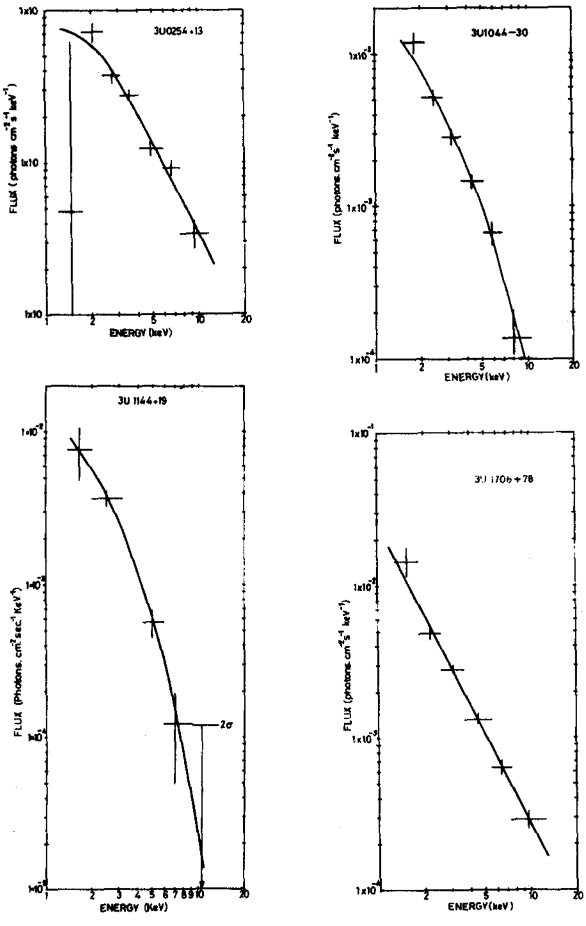


Figure 5. X-ray spectra of Abell 401(a), Abell 1060(b), Abell 1367(c) and Abell 2256(d) obtained with the MSSL proportional counter on Ariel V.

the data in larger pulse height intervals than was the case for the spectra shown in Figure 3. It is therefore not possible to differentiate between thermal and power law spectra or to discover emission features. The properties of a number of clusters are summarised in table III. Although the spectral parameters are not well determined, the temperature ranges are consistent with the values listed in table II for the brighter clusters.

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

Cluster Abell/3U	Approximate size of Diffuse source Angular	Linear	Best fitting temperature range (keV)	L_x(1.5-12keV) (erg sec^{-1})
262/0151+36	45'	1.3Mpc	-	4.10^{43} (1)
401/0254+13	⩽24'	⩽3.0	3.5 - 8.2	$2.2.10^{45}$ (2)
1060/1044-30	⩽15'	⩽0.3	1.7 - 3.6	$3.2.10^{43}$ (2)
1367/1144+19	⩽22'	⩽0.8	1.4 - 5.2	$8.4.10^{43}$ (2)
2256/1706+78	16'	2.0	3.8 - 7.0	$1.5.10^{45}$ (2)

(1) Uhuru. Kellogg et al (1975). Luminosity refers to 2-10keV band.
(2) Ariel V.

Table III Properties of Several Clusters

3. THE IDENTIFICATION OF X-RAY SOURCES WITH EXTRA-GALACTIC CLUSTERS

The majority of X-ray source identifications with clusters of galaxies that have been suggested up to now are listed in the Uhuru catalogue. A number of presently proposed cluster identifications are listed in table IV. In cases where there is no entry in the remarks column, the suggested identification was originally proposed in the 3U catalogue (Giacconi et al (1974)). In a number of cases the Ariel V sky survey experiment has either confirmed suggested Uhuru identifications (Pye and Cooke (1976), Pye et al (1976)) or proposed new identifications (Cooke and Maccagni (1976), Cooke and Maccacaro (1976)). A recent example of work carried out with the Ariel V sky survey instrument is shown in Figure 6a. The evidence for confirmation of the identification of 3U1044-30 obtained by Ives and Sanford (1976) using the Ariel V proportional counter spectrometer is shown in Figure 6b.

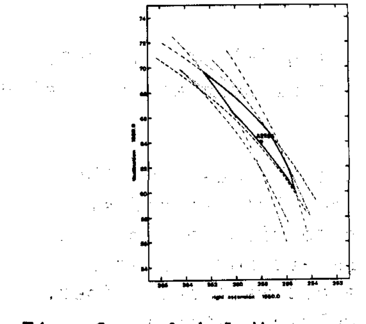


Fig. 6a. Ariel V error box for a new X-ray source that is associated with A2255 obtained by the Leicester University sky survey experiment.

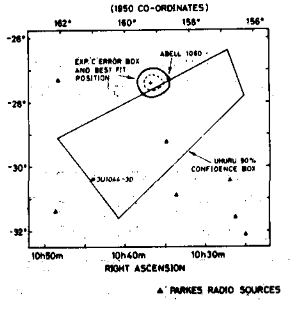


Fig. 6b. A new position for Abell 1060 obtained by the MSSL proportional counter on Ariel V (after Ives and Sanford (1976)).

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

Both Ariel V instruments continue to be used for cluster identification work and further results may be expected particularly for southern objects and for clusters in regions of the sky not covered by the Uhuru survey.

X-ray Source	Cluster	L_x (erg sec^{-1})	Flux A→Ariel Counts Sec^{-1} U→Uhuru " "		Remarks
3U0001-31	CA0007-306	$2.4.10^{44}$	3.2 ± 0.4	(U)	Melnick and Quintana (1975)
3U0151+36	Abell 262	4.10^{43}	2.4 ± 0.4	(U)	
3U0227+43	Abell 396	$1.6.10^{44}$	4.2 ± 0.6	(U)	
3U0254+13	Abell 401	$2.2.10^{45}$	3.4 ± 0.3	(U)	
3U0316+41	Abell 426 (Perseus)	9.10^{44}	47.4 ± 0.6	(U)	
3U0328-52	CA0340-538	$6.3.10^{44}$	1.7 ± 0.4	(U)	Melnick and Quintana (1975).
			1.3 ± 0.2	(A)	Confirmed by Pye and Cooke (1976)
3U0405+10	A478	$5.4.10^{45}$	3.4 ± 0.4	(U)	
3U0446+44	3C129	9.10^{44}	6.2 ± 0.5	(U)	
3U0901-09	Abell 754	$9.8.10^{44}$	4.4 ± 0.8	(U)	Confirmed by Pye
			1.9 ± 0.2	(A)	et al (1976)
3U1044-30	Abell 1060	$3.2.10^{43}$	2.2 ± 0.8	(U)	Confirmed by Ives and Sanford (1976)
3U1144+19	Abell 1367	$8.4.10^{43}$	3.6 ± 0.3	(U)	
3U1228+12	Virgo	9.10^{42}	21.7 ± 0.3	(U)	
3U1247-41	Centaurus	4.10^{43}	6.2 ± 0.3	(U)	
3U1257+28	Abell 1656 (Coma)	$4.5.10^{44}$	14.8 ± 0.3	(U)	
A1346+26 (3U1349+24)	Abell 1795	$5.5.10^{44}$	3.8 ± 0.9	(U)	Cooke and Maccacaro (1976)
			0.9 ± 0.1	(A)	
"3U1514+06" OSO-7 source	Abell 2052	$4.7.10^{44}$	9.4 ± 0.8	(U)	Heinz et al (1974) - OSO-7
3U1551+15	Abell 2151	$1.6.10^{44}$	2.1 ± 0.5	(U)	
3U1555+27	Abell 2142	3.10^{45}	5.1 ± 0.7	(U)	Cooke and Maccagni (1976)
			1.4 ± 0.3	(A)	
3U1639+40	Abell 2199	$1.7.10^{44}$	4.0 ± 0.6	(U)	Confirmed by Cooke and Maccagni (1976)
			0.9 ± 0.2	(A)	
3U1706+78	Abell 2256	$1.5.10^{45}$	3.2 ± 0.3	(U)	
A1710+64	Abell 2255	7.10^{44}	0.6 ± 0.2	(A)	Cooke and Maccagni (1976)
3U1809+50	Z1810.2+4949	7.10^{44}	5.1 ± 0.3	(U)	Bahcall et al (1976)
3U1921+43	Abell 2319	$1.1.10^{45}$	6.3 ± 0.6	(U)	
3U1957+40	Cyg A	$9.4.10^{44}$	5.6 ± 1.6	(U)	
3U1959-69	CA2013-710 CA1955-692	4.10^{43} $1.4.10^{45}$	2.8 ± 0.4	(U)	
A2344-28	Klemola 44		0.9 ± 0.1	(A)	Cooke and Maccacaro (1976)
3U2346+26	A2666	3.10^{44}	7.0 ± 1.2	(U)	

Table IV. Suggested Identifications of X-ray Sources with Clusters.

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

4. THE EMISSION OF X-RAYS FROM CLUSTERS OF GALAXIES

If we ignore for the present the emission associated with individual galaxies, then two principal mechanisms have been thought of as being possibly responsible for the diffuse emission. As remarked above, these are the Inverse Compton process and thermal Bremsstrahlung from a hot intra-cluster gas.

Inverse Compton radiation could be generated in interactions between photons of the microwave background radiation and a population of relativistic electrons released into the cluster from the member galaxies. The evidence presented in the previous section would seem to suggest that this model is unlikely to explain the diffuse emission although it may account for radiation generated in the immediate neighbourhood of active galaxies such as NGC1275 in the Perseus Cluster.

While the existence of a hot gas would provide a more reasonable explanation for the present observations, the question of the origin of this gas remains unanswered. Two extreme theories have been put forward. The first is the galactic wind model of Yahil and Ostriker (1973). This model envisages a steady state outflow of gas from the clusters caused by the evolution of the member galaxies. The second model involves the accretion of material from the intergalactic medium into the gravitational potential well of the cluster. While there are a number of variants of this model, the first proposal of this kind was due to Gunn and Gott (1972).

While the galactic wind model has been criticized on grounds of there being insufficient energy available to drive the wind, the observation of iron line emission in the Perseus Cluster might require some sort of outflow of material from the member galaxies into an otherwise primordial medium. Observations of the spatial distribution of line emission are urgently required to clarify the situation. First attempts at calculating the emission from a hot gas were based on the isothermal gas sphere (Lea et al (1973). However it has been more recently suggested that, in models involving the infall of matter from the intergalactic medium, a hydrostatic adiabatic gas atmosphere may represent a more appropriate description. Gull and Northover (1975) have presented such a model. Lea (1975) has independently discussed adiabatic cluster atmospheres (see also these proceedings), and has found the Coma Cluster X-ray emission to be well represented by a model with a polytropic index $\gamma = 1.35$. Calculated X-ray spectra, based on the model of Gull and Northover (1975) are shown in Figure 7 for a range of central temperatures.

While the spectra in Figure 3 are not well fitted by single temperature models, they are better explained by the calculated spectra shown in Figure 7. Thus although there may be some evidence in the Ariel V spectra for the existence of cooler material in the outer parts of an adiabatic cluster atmosphere, it is not yet conclusive.

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press

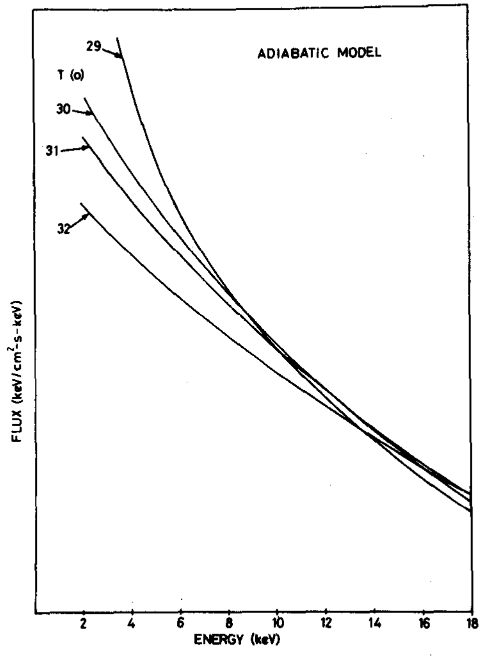


Figure 7. Cluster X-ray spectra computed on the basis of the adiabatic gas atmosphere models of Gull and Northover (1975) for different values of cluster central temperature T(0).

In conclusion, we may summarise a number of activities that could be undertaken in the next several years using both presently available data and the results that will be obtained in the course of the HEAO-A, UK-6 and HEAO-B missions.

It is obviously necessary to continue with high galactic latitude X-ray surveys in order to establish new optical cluster - X-ray source identifications. Work of this kind is already in progress using the Leicester University Ariel V sky survey experiment and will be continued by HEAO-A.

Studies of the X-ray structure of the cluster sources must first separate the truly diffuse emission from components due to individual galaxies. Since adiabatic models predict the existence of loosely found cooler gas in the outer parts of the cluster atmospheres, studies of cluster source size as a function of photon energy would allow the validity of these models to be tested. The UK-6 and HEAO-B spacecraft are likely to obtain pertinent results in this area.

The X-ray spectra that are at present available for the brightest clusters could be subjected to detailed comparison with adiabatic and perhaps other models of cluster atmospheres. Higher sensitivity observations are required at energies above 20 keV and these could be undertaken by the instruments on the HEAO-A mission. The observation of an iron line in the Perseus Cluster requires confirmation and the search for this feature should be extended to other clusters. As was remarked above, it is of the greatest importance to establish the spatial distribution of the iron line emission within the cluster source. Unfortunately there are at present no approved missions which could allow such observations to be undertaken. There is also a need for observations with good spectral resolution to permit the identification of features due to individual transitions and to search for redshifts.

Acknowledgements

I would like to thank my colleagues at MSSL who are contributing to the programme of X-ray cluster observations with the Ariel V satellite. Particular thanks are due to Rick Mitchell, John Ives and Jocelyn Bell Burnell.

References

Arp, H., and Bertola, F., (1971), Ap. J., 163, 195.
Bahcall, N.A., Harris, D.E., and Strom, R.G., (1976), Ap. J., 209, L17.
Cash, W., Malina, R. and Wolff, R., (1976), Berkeley Preprint.
Catura, R.C., Risher, P.C., Johnson, H.M., and Meyerott, A.J., (1972), Ap. J., 177, L1.
Catura, R.C., Acton, L.W., Johnson, H.M., and Zaumen, W.T., (1974), Ap. J., 190, 521.
Catura, R.C., Fisher, P.C., Johnson, H.M., and Meyerott, A.J., (1972), Space. Vol II, P970, Calgary, Canada, 14-21 August, 1974.
Cooke, B.A. and Maccagni, D., (1976), M.N.R.A.S., 175, 65P.
Cooke, B.A., and Maccacaro, T., (1976), Private Communication.
Davidsen, A., Bowyer, S., Lampton, M., and Cruddace, R., (1975), Ap. J., 198, 1.
Elvis, M., (1976), Submitted to M.N.R.A.S.
Fabian, A.C., Zarnecki, J.C., Culhane, J.L., Hawkins, F.J., Peacock, A., Pounds, K.A., and Parkinson, J.H., (1974), Ap. J., 189, L59.
Fritz, G., Davidsen, A., Meekins, J.F., and Friedman, H., (1971), Ap. J., 164, L81.
Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., Matilsky, T., Koch, P., and Tananbaum, H., (1974), Ap. J., Suppl. 27, PP37-64.
Gorenstein, P., Bjorkholm, P., Harris, B., and Harnden, F.R., (1973), Ap. J., 183, L57.
Gorenstein, P., (1976), Paper presented at the meeting of the AAS High Energy Astrophysics Division. January 1976, Boston.
Griffiths, R.E., Peacock, A., Davison, P.J.N., Rosenberg, F., and Smart, N.C., (1974), Nature, 250, 471.
Gunn, J.E., and Gott, J.R., (1972), Ap. J., 176, 1.
Gull, S.F., and Northover, K.J.E., (1975), M.N.R.A.S., 173, 585.
Gursky, H., Kellogg, E.M., Murray, S., Leong, C., Tananbaum, H., and Giacconi, R., (1971), Ap. J. Letters, 167, L81.

Heinz, C.J., Clark, G.W., Lewin, W.H.G., Schnopper, H.W., and Sprott, G.F., (1974), Ap. J., 188, L41.
Ives, J.C., and Sanford, P.W., (1976), M.N.R.A.S., 176, 13P.
Kellogg, E.M., Baldwin, J.R., and Koch, D., (1975), Ap. J., 199, 299.
Lea, S.M., Silk, J., Kellogg, E., and Murray, S., (1973), Ap. J., 184, L105.
Lea, S., (1975), Astrophys. Lett., 16, 141.
Malina, R., Lampton, M., and Bowyer, S., (1976), Berkeley Preprint.
Melnick, J., and Quintana, H., (1975), Ap. J., 198, L97.
Miley, G.K., and Perola, G.C., (1975), Astr. and Ap., 45, 223.
Mitchell, R.J., Charles, P.A., Culhane, J.L., and Davison, P.J.N., (1975), Ap. J., 200, L5.
Mitchell, R.J., Culhane, J.L., Davison, P.J.N., and Ives, J.C., (1976), M.N.R.A.S.
Pye, J.P., Cooke, B.A., and Elvis, M., (1976), Nature, 262.
Pye, J.P., and Cooke, B.A., (1976), M.N.R.A.S., In press.
Ryle, M. and Windram, M.D., (1968), M.N.R.A.S., 166, 513.
Scheepmaker, A., Ricker, G., Brecker, K., Ryckman, S.G., Ballintine, J.E., Doty, J.P., Downey, P.M., and Lewin, W.H.G., (1976), Ap. J., 205, L65.
Schnopper, H., (1976), Paper presented at the meeting of the AAS High Energy Astrophysics Division. January, 1976, Boston.
Tucker, W.H., and Koren, M., (1971), Ap. J., 168, 283.
Ulmer, M., Baity, W., Wheaton, W., and Peterson, L., (1973), Ap. J., 183, 15.
Wolff, R.S., Helava, H., Kifure, T., and Weisskopf, M.C., (1974), Ap. J., 193, L253.
Wolff, R.S., Mitchell, R.J., Charles, P.A., and Culhane, J.L., (1976), Ap. J., 208.
Yahil, A., and Ostriker, J.P., (1973), Ap. J., 185, 787.

https://doi.org/10.1017/S1539299600002719 Published online by Cambridge University Press