X-RAY OBSERVATIONS OF CLUSTERS OF GALAXIES

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X-ray astronomy has, in the past year, seen the publication of the second Ariel (2A) and fourth Uhuru (4U) catalogues of X-ray sources. A number of new X-ray cluster identifications and the confirmation of several others has resulted. In this review I will briefly summarise the situation regarding identifications and, for the 2A clusters, discuss the luminosity function and the possible relationships between a number of cluster X-ray and optical properties. Superclusters have been tentatively proposed as a class of X-ray sources and I will comment briefly on recent observations of these objects. Cluster structure has been studied by the Copernicus and SAS-3 spacecraft and by a number of rocket observations with imaging X-ray telescopes undertaken by the Harvard Centre for Astrophysics. I will review the current situation regarding structural measurements. Finally I will discuss the present status of Iron line observations at 6.7 keV in cluster spectra and the estimates of Fe abundance that result from these data.

X-RAY CLUSTER IDENTIFICATIONS AND CORRELATIONS

Although as many as 62 clusters have been proposed as X-ray sources by a variety of workers (see Culhane (1977)), the number of reasonably secure identifications as of July 1977 is probably between 32 and 40 (Culhane (1977) Jones and Forman (1977), McHardy et al. (1977)). The 2A* cluster sample of 38 objects includes 25 Abell clusters and from the well known 2A sky coverage, McHardy et al. have deduced the differential luminosity function shown in Figure 1 using the maximum volume method. The high luminosity upper limit corresponds to the absence of sources of power greater than 3.10^{38} watts at a flux above 1 Ariel count s^{-1} ($\sim$3 Uhuru counts s^{-1}) over 90% of the sky. The total density of X-ray clusters approaches that of all Abell clusters at $L_x \sim 10^{36}$ watts and thus all clusters should emit X-rays at luminosities above this value. Luminosity functions for richness class 0, 1 and 2 are shown in Figure 2.

*Compiled from the 2A catalogue of Cooke et al (1977). Observations carried out with the Leicester University Sky Survey instrument on Ariel V.

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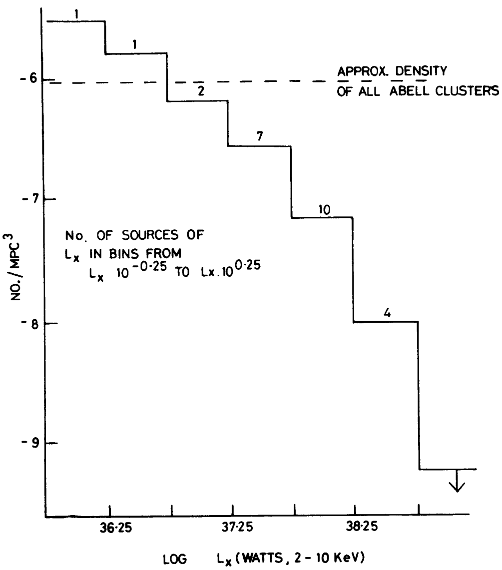

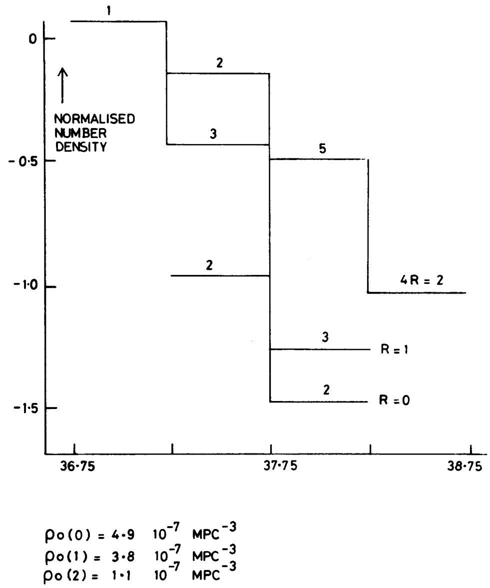

Figure 1. The differential luminosity function for 2A X-ray sources associated with Abell clusters (McHardy et al. (1977)). The number of sources in each luminosity interval is indicated.

Figure 2. Luminosity function for richness class 0, 1 and 2 Abell clusters normalised to the space density of the appropriate richness class (McHardy et al. (1977)).

The function for each class has been normalised to the total space density of clusters of that richness. It is clear that L_X is an increasing function of richness with each richness class increasing the probability of finding an X-ray source of given luminosity by a factor three.

From the overall luminosity function, the contribution of clusters to the diffuse X-ray background can be set at 14% for the 2 - 10 keV range. X-ray emitting Seyfert galaxies could be responsible for a further 6% and hence these two source classes could account for 20% of the flux assuming no source evolution.

For the 2A Abell clusters, McHardy et al. have computed the probability of a random coincidence between a 2A X-ray source and an Abell cluster as less than 0.7%. Although the southern clusters associated with 2A sources do not form a complete sample, it is clear that no gross inconsistencies exist between the two hemispheres.

For those 2A clusters which have measured values of velocity dispersion (σ_V), L_X is plotted against σ_V in Figure 3. The dashed line indicates the $L_X \propto \sigma_V^4$ relation proposed by Solinger and Tucker (1972) which is clearly not a good fit to the data although there is an indication that clusters with large L_X will also tend to have large σ_V. The relation between kT_X* and $\sqrt{3}\sigma_V$ is shown in figure 4 (**Mitchell, Ives and** Culhane (1977)). Although the sample of clusters is smaller, the data indicate that $kT_X \propto \sigma_V^2$ which is consistent with a hot gas origin for the X-rays.

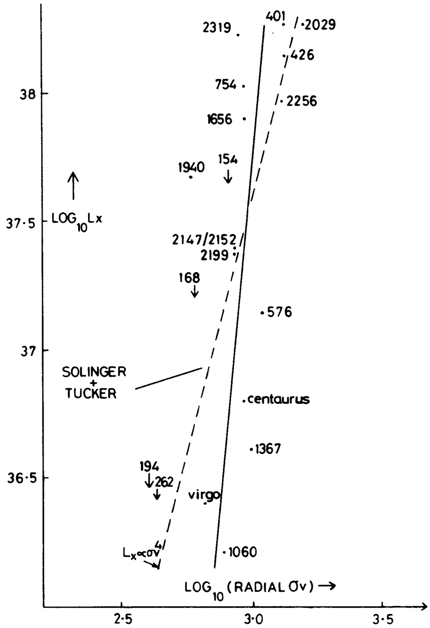

Figure 3. X-ray luminosity (L_X) plotted against cluster velocity dispersion (σ_V). The original Solinger and Tucker (1972) relationship is also shown (McHardy et al. (1977).

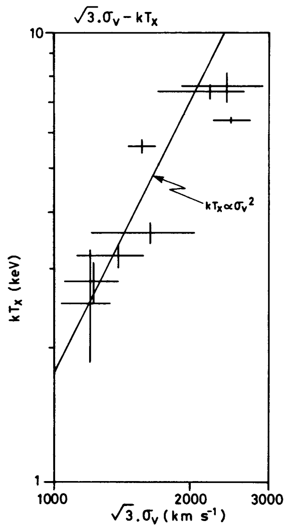

Figure 4. Temperature (T_X) against σ_V for 8 clusters (Mitchell, Ives and Culhane (1977)).

It has been apparent for some time that clusters with high L_X frequently contain a dominant central cD galaxy. Since this type of morphology is well described by the Bautz-Morgan class I, McHardy et al. have

*kT_X values are from X-ray spectral observations with the University College London proportional counter spectrometer on Ariel V.

plotted the distribution of both X-ray and general clusters with Bautz-Morgan class. From their results (Figure 5), it is clear that the probability of a cluster producing an X-ray source of $L_X \geqslant 10^{37}$ watts is three times greater for Bautz-Morgan class I clusters than for clusters in general. This conclusion is also supported by the work of Bahcall (1977a) who has, in addition shown that the relation between L_X and central galaxy density (Figure 6) is consistent with a hot gas origin for the X-ray emission.

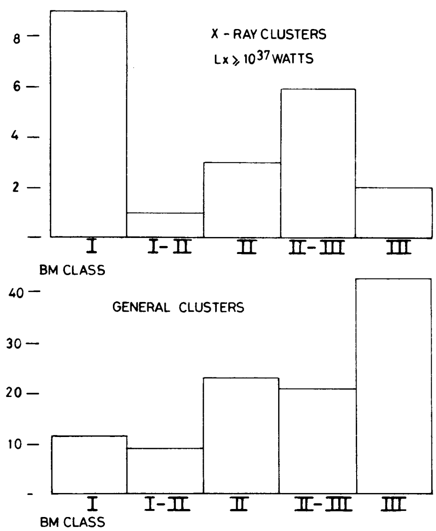

Figure 5. Bautz-Morgan distributions for X-ray clusters and for clusters in general. All clusters of distance class $\leqslant 4$ and $L_X \geqslant 10^{37}$ watts.

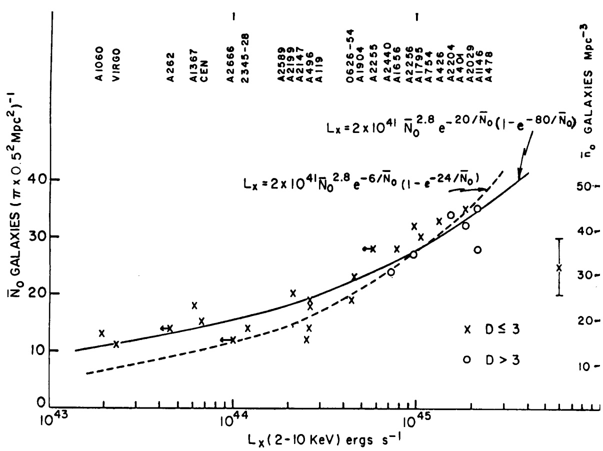

Figure 6. Central galaxy density plotted against L_X for the clusters indicated. Relationships between L_X and $\bar{N}_0$ are also shown (Bahcall (1977a)).

A relation between spiral galaxy content and L_X is proposed by Bahcall (1976b) and McHardy et al. Using the 2A cluster sample for L_X values and spiral content results from Oemler (1976) and Melnick and Sargent (1977), both groups have demonstrated that clusters with the highest values of L_X have the lowest percentages of spiral galaxies. The correlations observed are consistent with thermal emission from a hot intracluster gas which strips the spiral galaxies by ram pressure.

The 2A clusters discussed above were identified as a result of scans of the detector fields of view around the sky and the observation of significant departures from background counting rates when detectable X-ray sources were in view. Ricketts et al. (1977) have searched the Ariel V survey data for clusters using a point summation technique (PST) in which the position of known clusters are used as arguments of entry to the Ariel V data base and all data referring to individual source positions are summed and checked for significance. A total of 360 cluster positions were searched in this way. In addition to detecting the cluster sources mentioned above, a further 13 Abell clusters were observed to have significant X-ray emission while upper limits were assigned to 22 further clusters. The list of positive detections includes Abell 2218, a rich distance class 6 cluster for which Gull and Northover (1976) have measured a drop in microwave background temperature due to scattering by hot intracluster gas (Sunyaev and Zel'dovich (1972)).

THE RELATION BETWEEN X-RAY SOURCES AND SUPERCLUSTERS

Following the circulation of the 4U catalogue, Murray et al. (1977) have suggested the possibility of an association between unidentified high latitude X-ray sources and superclusters. Using a definition based in part on Abell's (1961) discussion of second rank clusters, they find 12 such objects within the area of sky covered by the 4U catalogue. Five X-ray sources are candidates for association with the superclusters and three of these have their error box centres within less than 1.5^{o} of a supercluster centre. Murray et al. point out that with an expected number of accidental coincidences of less than 0.17, the probability of observing three coincidences is less than 0.003 ($<3\sigma$). However the proposed identifications are based purely on the association since the sources are too weak to permit measurement of their X-ray extent.

The five supercluster locations have been the subject of an Ariel V PST search by Ricketts et al. The results of this search are given in table 1. Only one of the five candidates is detected at the 4U level (4U1203-06). Upper limits are set to the X-ray emission from the remaining four Uhuru sources that are between two and four times less than the 4U flux values.

Table 1 - X-ray supercluster candidates

4U source	4U intensity (4U CPS)	2A intensity or 3σ upper limit (2A CPS)
0134-11*	2.7 ± 0.6	$\lesssim 0.43$ (1.3U)†
0443-09	1.8 ± 0.3	$\lesssim 0.30$ (0.9U)†
1203-06	2.2 ± 0.4	0.6 (4.9σ) (1.8U)†
1456+22	3.0 ± 0.5	$\lesssim 0.32$ (0.7U)†
2259+16	3.0 ± 0.6	$\lesssim 0.47$ (1.5U)†

* GSFC OSO-8 result gives a 99% confidence upper limit of $\lesssim 0.4$ Uhuru counts s^{-1}.

† 1 Ariel count s^{-1} ~ 3 Uhuru counts s^{-1}.

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In addition, OSO-8 observations (Pravdo et al. (1977)) place an upper limit on the X-ray flux from 4U0134-11 that is a factor 6.5 below the 4U value. Thus the association of X-ray emission with superclusters rather than with individual clusters which may be members of a supercluster is perhaps premature.

THE X-RAY STRUCTURE OF CLUSTERS

Uhuru observations have explicitly demonstrated the extent of cluster X-ray sources in six cases (Kellogg and Murray (1974)). A variety of observations of structure have been made in the case of the brighter cluster and a number of these have been summarised elsewhere (Culhane (1977, 1978)). Unfortunately the X-ray structural data available do not yet discriminate between the various models.

In the case of the Perseus cluster, it is clear that up to 20% of the emission is associated with the active galaxy NGC1275 while the remainder of the flux originates in a diffuse source of about 1° in angular extent (Wolff et al. (1976), Gorenstein et al. (1976)). The extended emission may be explained by an isothermal gas sphere or by various adiabatic models. The origin of the X-ray emission from around NGC1275 is not yet clear but the similarity between X-ray and radio (Miley and Perola (1975)) brightness distribution is striking.

The structure of the Virgo cluster has been studied by Gorenstein et al. (1977) whose 0.5 - 1.5 keV map of this source is shown in Figure 7. The diffuse emission is centred on M87 and not on the optical centre of the cluster. The measured surface brightness distribution and two possible models are illustrated in Figure 8. The solid line results from an isothermal gas sphere and requires a source associated with M87 to contribute about 10% of the total cluster flux. The dotted line is obtained from a power law (in radius) surface brightness distribution and could result from gas infall onto M87 where accretion is regulated by cooling at the centre (Cowie and Binney, (1977)). The observed increase of diffuse source size with energy also favours this model.

The other clusters are less well studied at present. Mitchell et al. (1975) have observed the central 10' of the Centaurus cluster using the Copernicus X-ray reflectors and find that the flux (0.5 - 1.5 keV) is four times larger than is predicted by an isothermal gas sphere model. This may indicate emission from an active galaxy (NGC4696) or an accretion process dominated by the central galaxy. The effect of a central galaxy on cluster emission has received further support from the recent work of Schnopper et al. (1978) who find a point like source coincident with a cD galaxy at the centre of Abell 478. The X-ray luminosity of this source is approximately 30% of that of the cluster as a whole.

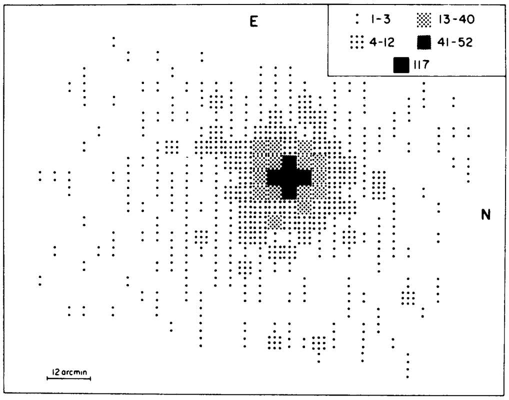

Figure 7. An X-ray map (0.5 - 1.5 keV) of the Virgo cluster (Gorenstein et al (1977)). The bright central region is coincident with M87.

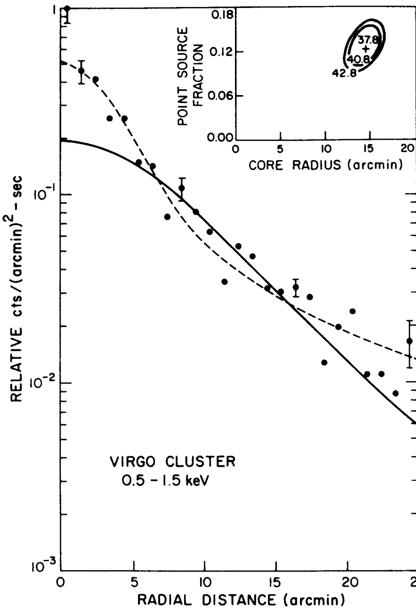

Figure 8. Relative surface brightness deduced from the map in figure 7 plotted against radial distance. The solid line represents an isothermal gas sphere, the dotted line is a power law in radial distance.

THE DETECTION OF IRON LINE EMISSION IN CLUSTER X-RAY SPECTRA

Studies of X-ray spectra over a limited energy range (e.g. 2 - 10 keV) can not discriminate between thermal and non thermal emission processes. Although some evidence in favour of thermal emission has been obtained from observations over more extended energy intervals (Ricker et al. (1976), Davidsen et al. (1975), Malina et al. (1978)) the detection of an emission feature due to highly ionised iron in the Ariel V spectrum of the Perseus cluster by Mitchell et al. (1976) (Figure 9) has established the presence of hot ($T \sim 10^8$K) gas in clusters of galaxies. The Perseus observation was confirmed by Serlemitsos et al (1977) who also detected similar features in the spectra of the Virgo and Coma clusters (Figure 10). The Coma observation has been confirmed by Ariel V with increased significance (Culhane 1978) while Mitchell and Culhane (1977) have detected an iron feature in the spectrum of the Centaurus cluster.

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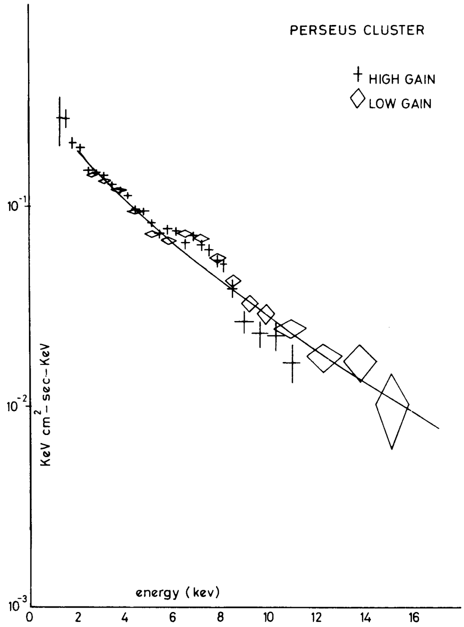

Figure 9. The X-ray spectrum of the Perseus cluster with the Fe emission feature indicated (Mitchell et al. (1976)).

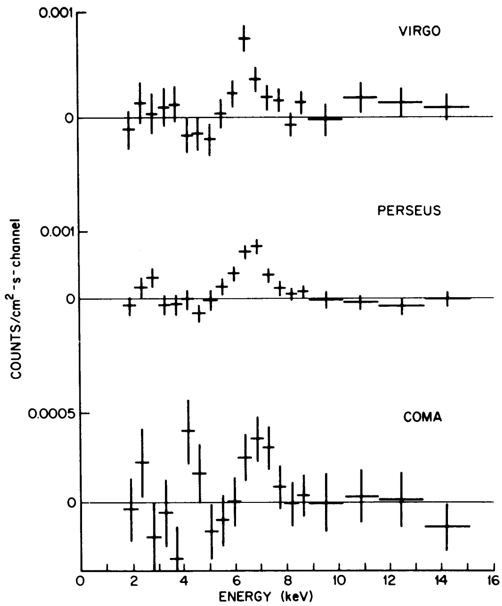

Figure 10. Fe emission features for the Perseus, Virgo and Coma clusters (Serlemitsos et al. (1977))

The observations made by Ariel V and OSO-8 are summarised in table 2. It is apparent that in cases where both instruments have observed the same cluster, there is good agreement between the measured fluxes although the uncertainties are necessarily large due to the low fluxes and the relatively poor energy resolution of the detectors. There is no evidence for intrinsic broadening in the lines. Furthermore all the observations indicate

Table 2 - Cluster iron line fluxes

Cluster	Feature Flux (10^{-3} photons cm^{-2} s^{-1})		Feature equivalent width (eV)	
	Ariel V	OSO-8	Ariel V	OSO-8
Perseus	3.4±0.4	4.4±0.8	360±50	490±90
Coma	0.7±0.1	1.2±0.7	400±60	280±170
Virgo	-	2.1±0.6	-	850±250
Centaurus	1.0±0.2	-	890±170	-

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that peak feature emission occurs at around 6.8 keV with an uncertainty of 0.2 keV. Since the underlying continuous spectra indicate temperatures in the range 30 - 100. 10^6 K, the emission features must be due mainly to transitions in Fe XXV and Fe XXVI. However a large number of lines from these ions are blended into the observed emission features.

In order to estimate the iron abundance in the gas, it is necessary to calculate a feature to continuum ratio as a function of temperature and compare it with the observed values. This may be done by assuming that the hot intra cluster gas is a coronal plasma in ionisation equilibrium. Transitions contributing to the feature include the Fe XXV and XXVI resonance lines (k), the Fe XXV ^{3}P and ^{3}S transitions (I,F) and a variety of satellites of the resonance lines which arise due to dielectronic recombination and inner shell excitation (Bhalla et al. (1975)). The total feature flux is shown plotted against temperature in Figure 11 together with the percentage contributions of the transitions mentioned above. The ion balance calculations used are those of Jacobs et al. (1977) which are currently the best available. The calculated feature to

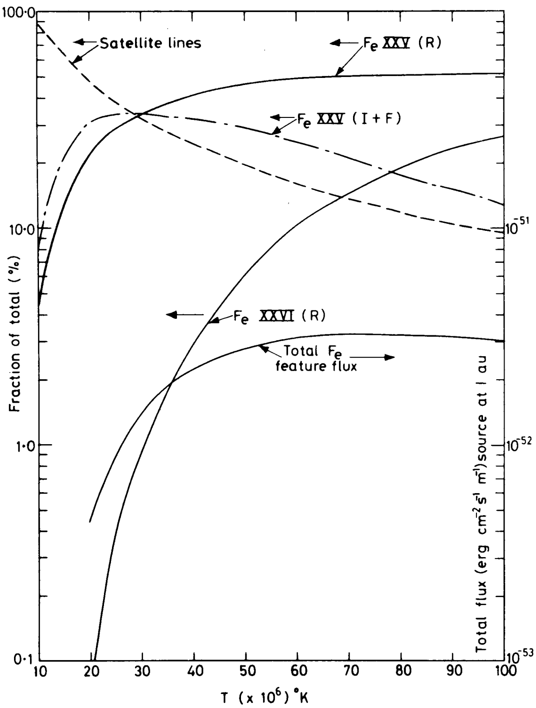

Figure 11. Calculated Fe feature flux plotted against temperature. The fractional contributions of groups of transitions are also shown (R-resonance, I-intersystem(^{3}P), F-forbidden (^{3}S), dielectronics and inner shell satellites).

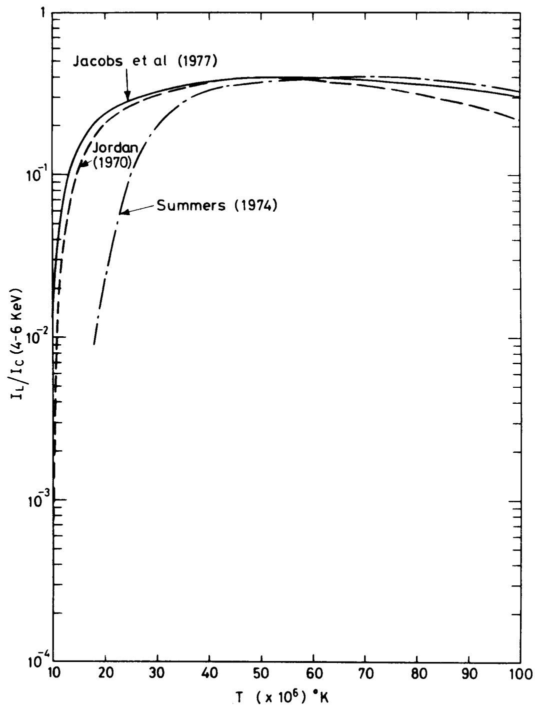

Figure 12. Calculated line to continuum ratio plotted against temperature for three different ionisation balance calculations.

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continuum ratio is shown in figure 12 for three different ion balance assumptions. Although the latter lead to gross disagreement below 30.10^6K, little difference is apparent in the temperature range appropriate to the cluster spectra.

The iron abundances deduced are given in table 3. Although there are significant differences between the values derived by the Ariel V and OSO-8 groups, data are only available for both the Perseus and Coma clusters and the errors are large.

Table 3 - Iron abundance

Cluster	$T(10^6K)$	$\frac{N_{Fe}}{N_{Fe}}$ (Cosmic)*	
		Ariel V	OSO-8
Perseus	66	0.23 ± 0.06	0.45 ± 0.08
Coma	70	0.13 ± 0.04	0.38 ± 0.23
Virgo	43	-	0.46 ± 0.20
Centaurus	32	0.40 ± 0.12	-

* Assumed Cosmic Iron Abundance $\frac{N_{Fe}}{N_H} = 4.10^{-5}$

CONCLUSIONS

In the past year considerable progress has been made in our understanding of the extended X-ray sources in clusters of galaxies. Between 30 and 40 clusters are known X-ray sources. The cluster luminosity function has been determined and indicates that essentially all clusters of galaxies will be X-ray sources. There is a good correlation between L_X and cluster richness, central galaxy density and the percentage of spiral galaxies present. The latter point is strongly suggestive of the presence of hot gas whose role is also indicated by the relation between kT_X and σ_V. Searches for further X-ray identifications are in progress but the proposed association between X-ray emission and supercluster gas may be premature.

Studies of cluster structure are at present confined to the brighter sources. Although these data are as yet unable to throw much light on the mechanism of heating the intracluster gas, there are indications that massive central galaxies play a significant role in the process. Both isothermal and a variety of polytropic gas sphere models are still permitted by the available data.

The discovery of line emission in the cluster X-ray spectra demonstrates the presence of hot gas and indicates a a model dependant iron abundance of between 10% and 40% of the cosmic value.

The subject of cluster X-ray emission is now firmly established as a major source of data on both the evolution of galaxies and the large scale structure of the universe.

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DISCUSSION

Chincarini: How many random associations would you expect between superclusters and X-ray sources? How was the Supercluster sample selected?

Culhane: I would refer you to the preprint of Murray and co-workers for a detailed discussion but, so far as I can remember, the probability of the three X-ray sources accidentally coinciding with superclusters is less than 0.003. The selected superclusters were broadly Abell class II clusters with a number of additional criteria. However, you will recall that Ariel V and OSO-8 place 3σ upper limits on the flux from four of the five candidate Uhuru X-ray sources that are between two and six times lower than the reported Uhuru values.

Sunyaev: Can you distinguish experimentally the K_α line of weakly ionized iron from the L_α line of hydrogen or helium-like iron ions?

This is very important because we are all very interested in the chemical composition of the intergalactic gas in clusters. If there is a lot of iron, a large fraction of the gas must be secondary and not primaeval. In this case explosions of supernovae are an extremely important source of IGG. More speculative, but still possible, situations may exist in which active galactic nuclei give a significant part (but not all) of the radiation from clusters. The K_α line may be formed in the cold gas in the vicinity of nuclei. In this case hot gas ($kT \sim 10^8$ K) inside the cluster may be of a primaeval chemical composition.

Culhane: Yes, we can distinguish between these lines at 6.4 and 6.8 keV.

Audouze: In relation to the last part of your talk, I would like to call attention to the work of one of my colleagues - Laurent Vigroux (1977, *Astr. and Astroph. Letters*). He used the iron abundance obtained by the Goddard group and assumed that the iron distribution is homogen-

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eous in clusters such as Coma and Perseus. He concluded from his model that the production of heavy elements should occur at the beginning of the evolution of the galaxies in the cluster (i.e. prompt initial enrichment).

Culhane: A problem with this model arises from the present lack of spatial information on the distribution of Fe emission in the cluster to which I drew attention during my talk. But in any case the abundance estimates refer only to the X-ray emitting gas which is $\leqslant 8 \times 10^{12}\ M_{\odot}$. The X-ray abundance estimates then tell us that the detected mass of Fe is $\leqslant 5 \times 10^{9}\ M_{\odot}$, which is much less than the value of $\gtrsim 10^{11}\ M_{\odot}$ deduced by Vigroux who assumes that the Fe/H ratio is constant throughout the cluster gas.

Chernin: Is there any room for clumpiness to reduce the Fe abundance?

Culhane: At the present time the only condensations in the X-ray emission are seen in the case of NGC 1275 in Perseus (< 20% of total flux) and M87 in Virgo (< 10% of total flux) but the available X-ray maps of these and other clusters have a low resolution, so data of a better angular resolution are required.

Ostriker: I cannot resist remarking that several years ago anyone who built models of galactic evolution (such as Thuan and myself),and estimated the ejecta from stars which are an extrapolation of those which we see now, would have found exactly the amount of intracluster iron which is now observed.

Tinsley: Models for the early evolution of galaxies allow a large amount of chemically enriched gas to be ejected. In a 1975 paper in P.A.S.P., Larson and Dinerstein predicted that clusters of galaxies should contain a significant mass of gas with approximately the solar metal abundance, as a result of ejection from young galaxies, and this gas has subsequently been observed.