Hot Gas in Clusters of Galaxies

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Hot gas in clusters of galaxies

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The title of the paper indicates that our understanding of cluster X-ray sources has progressed considerably since their discovery in 1971. We now believe that the extended X-ray emission that is observed is due to the presence of high temperature ($T \approx 10^8$ K) gas in the clusters. The paper includes a review of the present status of cluster X-ray observations and an account of the evidence that points to bremsstrahlung from hot plasma as the X-ray emission mechanism. Current ideas about the origin of the intracluster plasma and its heating mechanism are examined and the possible role of cluster X-raystudies in furthering out understanding of the evolution of the Universe is discussed.

1. Introduction

Soon after the extended X-ray sources in clusters of galaxies were discovered from observations with the Uhuru satellite (Gursky *et al.* 1971), two fundamentally different models were put forward to explain the observations. The first of these involved inverse Compton interactions between photons of the 3 K microwave background radiation and populations of relativistic electrons that were believed to exist in the clusters. The substantial increases in photon energy caused by these interactions would lead to a power law X-ray energy spectrum whose extended surface brightness would be governed by the distribution of the electrons in the intra-cluster space. The second model was based on the assumed existence of an intra-cluster medium which consisted of high temperature ($T \approx 10^8$ K) plasma. Bremsstrahlung emission from such a gas would give rise to an exponential spectrum while the brightness distribution of the extended X-ray source would depend on the distribution of gas density and temperature in the intra-cluster medium.

It is apparent from the title of the paper that progress in our understanding of cluster X-ray sources since their discovery has lead to a preference for the second of the two models outlined in the previous paragraph. Since studies at X-ray energies provide the most direct means of obtaining information about high temperature gas, I shall review the present state of the observations of cluster X-ray sources. The available evidence for the existence of hot gas in clusters will then be presented with special reference to the detection of highly ionized iron emission features in the X-ray spectra of several clusters, since these observations may also constrain models for the origin of the plasma. Present ideas on the origin and heating of the intra-cluster gas will then be described and finally the possible role of cluster X-ray studies in furthering our understanding of the evolution of the Universe will be examined.

2. Observations of cluster X-ray sources

At the time of writing the most complete X-ray sky surveys available are those described in the second Ariel (2A) and fourth Uhuru (4U) catalogues (Cooke *et al.* 1978; Forman *et al.* 1979). Based on these surveys, between 40 and 50 secure identifications have been made of X-ray sources with clusters of galaxies. Marshall *et al.* (1979) have made three additional identifications from observations with the Goddard–Caltech instrument on the HEAO-1 spacecraft while a further 30–40 identifications may perhaps be expected when a source catalogue based on observations made with the US Naval Research Laboratory instrument on HEAO-1 becomes available. Thus the observations already made have established a clear connection between X-ray sources and clusters of galaxies.

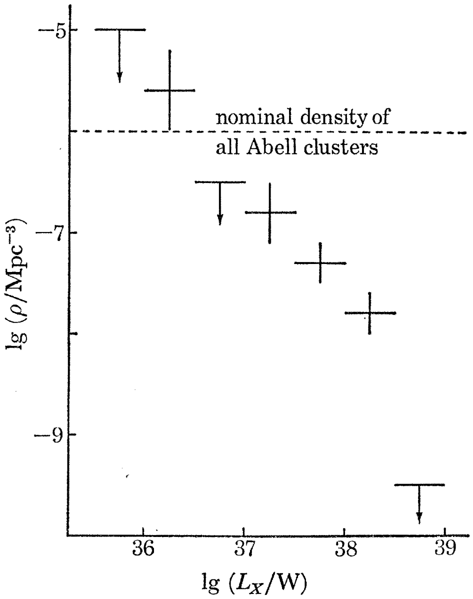

FIGURE 1. The luminosity function for X-ray clusters (after McHardy 1978). The space density of all Abell clusters is also indicated.

The essence of this connection is well summarized in the X-ray luminosity function for 2A X-ray sources derived by McHardy (1978) for the Virgo cluster and those 2A objects associated with Abell clusters (figure 1). McHardy has used the maximum volume method corrected for 2A sky coverage. The luminosity function has two interesting features. The high luminosity upper limit corresponds to the fact that no sources of power greater than $10^{38.75}$ W are seen with an X-ray flux greater than *ca.* 6×10^{-12} erg cm^{-2} s^{-1}† in the 2–10 keV band. This is a strong upper limit since the 2A survey is complete to this limit for 90 % of the sky. It is also apparent that the space density of X-ray clusters approaches that of all Abell clusters at an X-ray luminosity of around 10^{36} W. Thus it is clear that all clusters of galaxies should emit X-rays at some level and it is of interest to identify those properties of clusters that lead to their being strong or weak X-ray sources.

A number of authors have examined the relationship between X-ray and other cluster properties. McHardy has shown that X-ray luminosity (L_X) is correlated with cluster richness such that each richness class increment increases the probability of finding an X-ray source of given L_X by a factor of about three. He also finds that clusters of high L_X frequently contain a dominant central cD galaxy (a comment first made by Bahcall (1974)). More generally, he has shown that regular centrally condensed clusters that exhibit Bautz–Morgan type I (B.M. I) morphology have a much greater probability of association with a cluster of high L_X than do

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† 1 erg = 10^{-7} J.

the loose irregular B.M. III clusters. This kind of relation is also found with Rood–Sastry (R–S) morphology: Bahcall (1977*a*) has shown that L_X increases with increasing central galaxy density ($\bar{N}_0$) of clusters. If we accept for the moment that clusters do contain high temperature plasma, Mitchell *et al.* (1979) have shown that the gas temperature (kT_X) and emission measure ($\int N_e^2\,dV$) are similarly correlated with cluster regularity and high central condensation. All of these relations are naturally interpreted with models that involve the heating of the intra-cluster gas as it falls into the cluster gravitational potential well (see §4). It has also been shown (Bahcall 1977*b*; Titler & Vidal 1978; McHardy 1978; Mitchell *et al.* 1979) that the fraction of spiral galaxies in a cluster (S_p) decreases strikingly with increasing L_X and $(\int N_e^2\,dV)^{\frac{1}{2}}\,kT_X$, a quantity proportional to the ram pressure experienced by galaxies as they move through the intra-cluster medium. I shall discuss this point in greater detail in the next section.

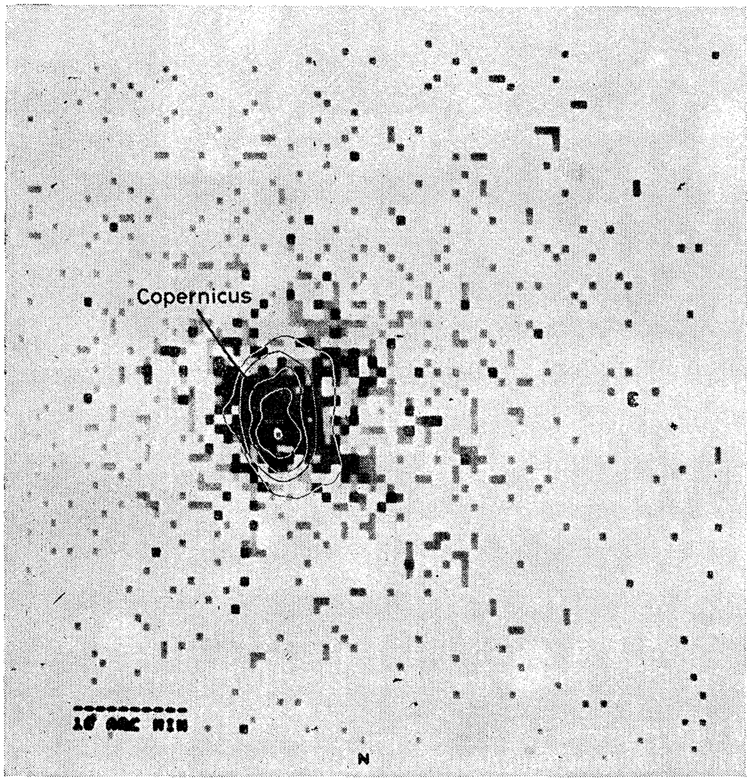

FIGURE 2. Observations of the Perseus cluster by the Copernicus X-ray telescope (Wolff *et al.* 1976) and by an imaging telescope flown on a rocket (Gorenstein *et al.* 1978) in the 0.2–2.0 keV range.

Although X-ray extent has so far been demonstrated explicitly for only five or six clusters, it is generally believed that clusters of galaxies are a class of extended X-ray sources. Preliminary indications are that this belief will be substantiated by observations being made with the imaging X-ray telescope on the HEAO-2 spacecraft. One of the sources for which X-ray extent has been measured is A 1656 or the Perseus cluster. Recent observations of this source in the energy range 0.5–2.0 keV are summarized in figure 2. The solid contour lines are from observations with the Copernicus X-ray telescopes (Wolff *et al.* 1976) and show an extended source associated with the unusual galaxy NGC 1275. These contours are superimposed on a map of the entire cluster obtained by Gorenstein *et al.* (1978) with a rocket-borne imaging X-ray

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telescope having an angular resolution of 4′. These observations show that there is an extended X-ray source in the Perseus cluster but that emission associated with NGC 1275 accounts for around 25 % of the total. No other galaxies are detected as X-ray sources at a level of more than 3 % of the total cluster emission. The observed surface brightness can be fitted by either an adiabatic or an isothermal hot gas model but the latter is somewhat preferred since the cluster core size appears to be independent of X-ray energy. The nature of the source associated with NGC 1275 remains somewhat uncertain. The X-ray emission may be due to activity within the galaxy, or possibly infalling matter is accreted subsonically by the slow moving galaxy as proposed by Fabian & Nulsen (1977).

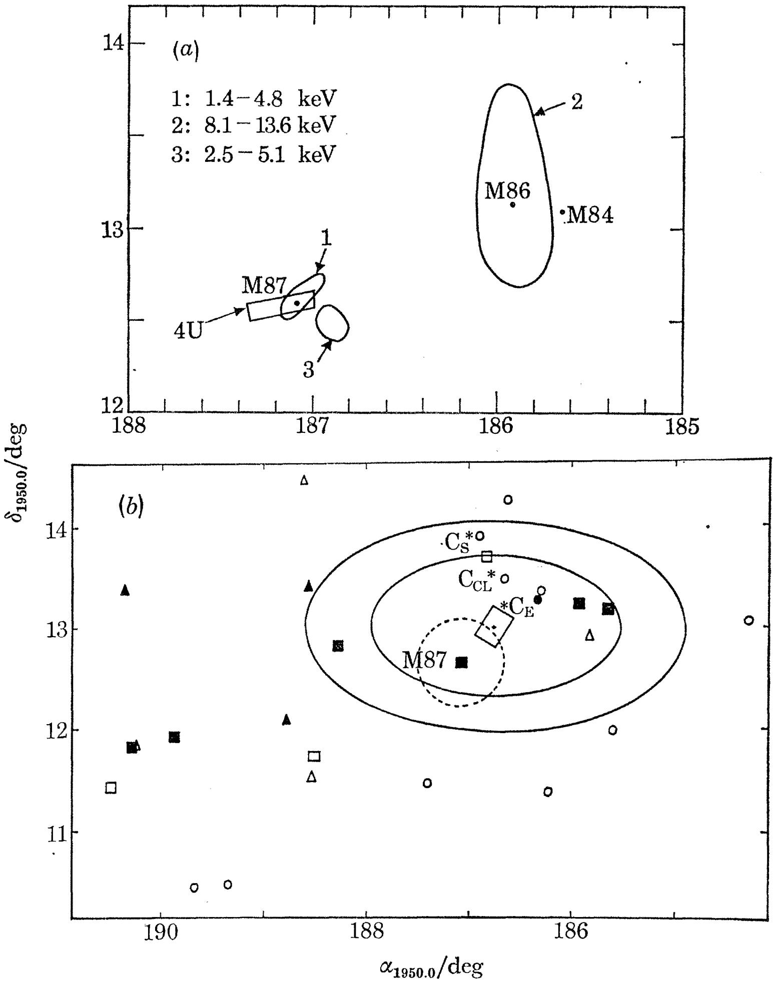

FIGURE 3. Extension of the Virgo cluster X-ray source observed (*a*) by Davison (1978) with the Ariel 5 spectrometer (1 and 2 both referenced to one attitude solution) and (*b*) by Laurence (1978) with the Ariel 5 sky survey instrument.

X-ray extent has also been explicitly demonstrated in the case of the Virgo cluster. Gorenstein *et al.* (1977) show have used their rocket borne telescope to map an extended region of X-ray emission centred on M87. However, Davison (1978), using the Ariel 5 X-ray spectrometer, has demonstrated that while the centroid of lower energy X-ray emission is located on M87, higher energy X-rays appear to originate from the neighbourhood of M84 and M86, which is closer to the centre of the Virgo cluster (figure 3*a*). This observation has been confirmed and extended by Laurence (1978), who used the Ariel 5 sky survey instrument to demonstrate explicitly that the Virgo extended X-ray source embraces the centre of the cluster and the galaxies M84 and M86 (figure 3*b*). The restricted field of view of Gorenstein's telescope did not allow it to include the cluster centre, but preliminary indications from HEAO-2 suggest that the region is complex with emission associated with M84 and M86 as well as with M87.

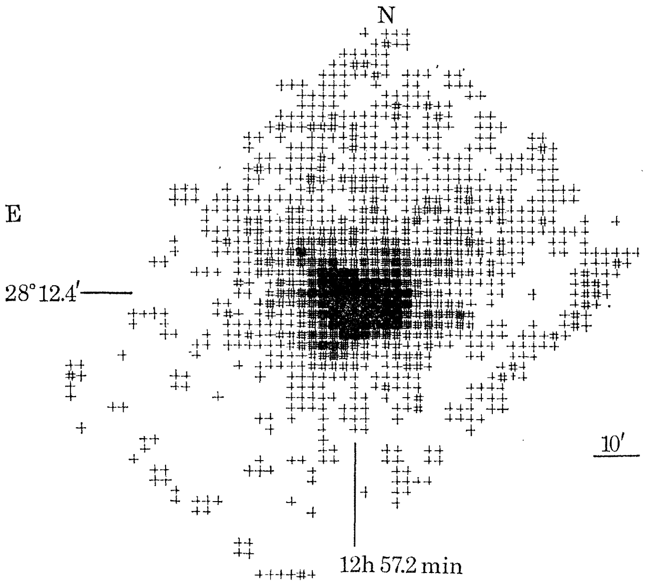

FIGURE 4. An X-ray map of the Coma cluster obtained by Gorenstein *et al.* (1979).

Thus the Virgo cluster observations again demonstrate the importance of X-ray emission associated with individual galaxies. However, in the Coma cluster, a recent observation by Gorenstein *et al.* (1979) (figure 4) shows that no individual galaxy has associated X-ray emission that is more than 3% of the entire cluster flux. In particular the two massive galaxies NGC 4774 and NGC 4889 show no associated X-ray emission. The X-ray centroid of the extended emission in fact occurs at a local minimum in the intensity. There is some evidence for non-uniformity in the central region on a scale of 4′ that is significant at the 98.5% level. Both isothermal hydrostatic and adiabatic hot gas models have been fitted to the data but, within a radial distance of 25′, they gave indistinguishable results. However, a comparison of the total 0.5–2 keV X-ray flux measured by Gorenstein *et al.* from a region of radius 25′ with an extrapolation of the 2–15 keV OSO-8 intensity measured by Mushotzky *et al.* from a region 5° in size suggests that the rocket X-ray telescope is only detecting about half of the total flux. If this result is confirmed, it would indicate that an isothermal description is preferred for the hot gas.

It is therefore clear that Coma, a rich cluster of high central galaxy density, does not show any X-ray emission associated with individual galaxies. However, Schnopper *et al.* (1977), using the rotation modulation collimator (r.m.c.) instrument on the SAS-3 spacecraft, have shown that in A 478 the central cD galaxy is responsible for about 30% of the total flux from the source; in the Centaurus cluster, Mitchell *et al.* (1975) have demonstrated that there may be a significant concentration of softer X-ray emission in the neighbourhood of the central galaxy NGC 4696. Thus the role of individual galaxies in independent X-ray sources in clusters requires further study and observation. It may be that galaxies that are moving at a high velocity relative to the intra-cluster medium can not accrete effectively and so do not become individual X-ray sources in the manner prescribed for NGC 1275 by Fabian & Nulsen. In this connection, it is interesting that Gorenstein *et al.* (1979) have drawn attention to the high relative velocities of NGC 4874 and NGC 4889 with respect to the Coma cluster as a whole.

3. Evidence for the presence of high temperature gas in clusters

Many of the observations described in the previous section are naturally explained on the basis of the hot gas model. However, in the interval since the discovery of X-ray emission from clusters of galaxies, a number of specific developments have strongly indicated that the observed extended X-ray sources are due to the presence of a high temperature intra-cluster medium. The discovery of an emission feature due to transitions of highly ionized iron in the spectrum of the Perseus cluster by Mitchell *et al.* (1976) (figure 5) strongly suggests a hot gas origin for the majority of the X-rays, especially since a detailed analysis of the iron emission indicates that the iron abundance is close to its cosmic value (see §4).

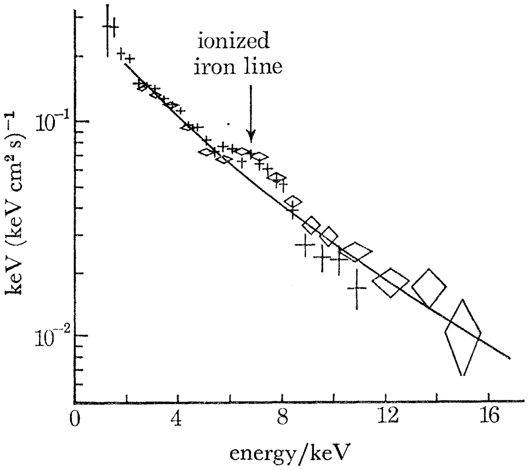

FIGURE 5. Ariel 5 X-ray spectrum of the Perseus cluster (Mitchell *et al.* 1976) showing the iron emission feature at 6.7 keV. +, High gain; ◇, low gain.

Several other observations also support the hot plasma hypothesis. The phenomenon of radio 'head and tail' galaxies, well exemplified by NGC 1265 in the Perseus cluster (figure 6) has a natural explanation if a hot intra-cluster medium is present. If the head and tail configuration is due to ejected relativistic plasma being contained by a hot medium and by the motion of the galaxy through the cluster, then the required values of temperature and density for the hot medium agree very closely with the values of these same parameters that are required to produce the observed X-rays.

Yet another striking indication of the presence of hot plasma emerges from a consideration of the relation between the fraction of spiral galaxies (S_p) present in a cluster and its X-ray properties. This relation, which was mentioned briefly in the previous section, is best indicated by a plot of S_p against $(\int N_e^2 \mathrm{d}V)^{\frac{1}{2}}\, kT$ as shown in figure 7. If a hot gas is present and if the cluster galaxies are moving at speed through this gas, then the plot in figure 7 represents the

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relation between S_p and a quantity proportional to ram pressure. It is clear, as was originally suggested by Gunn & Gott (1972), that a single cluster crossing by a spiral galaxy through a hot intra-cluster medium will result in the removal of the gas and dust content of the spiral owing to the ram pressure generated by the motion of the galaxy. Thus the absence of spiral galaxies from clusters of high L_X is naturally explained by the presence of a hot intra-cluster medium.

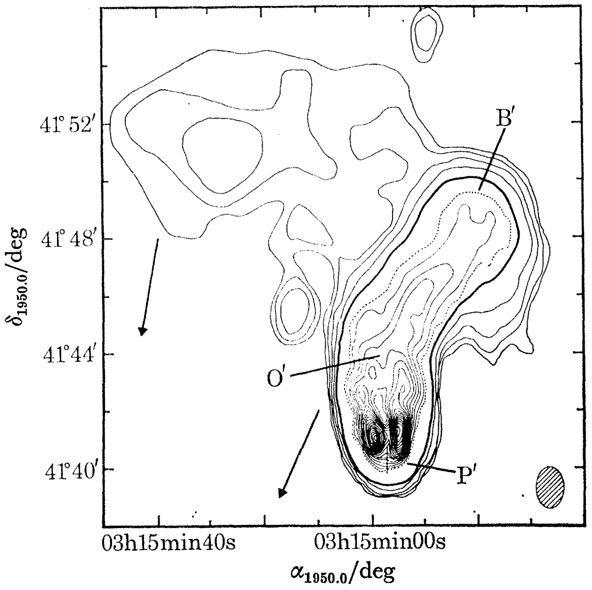

FIGURE 6. A radio map of the galaxy NGC 1265 in the Perseus cluster (Gisler & Miley 1980), indicating the pronounced 'head and tail' structure seen on many radio galaxies owing to their motion through the intra-cluster medium.

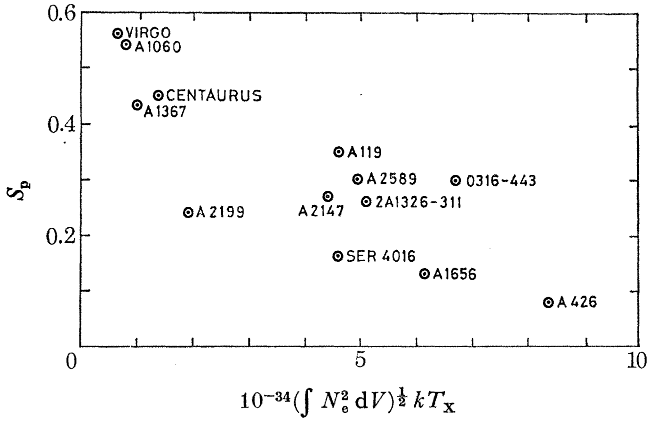

FIGURE 7. A plot of spiral fraction (S_p) against $(\int N_e^2\,dV)^{\frac{1}{2}}\,kT_X$, which indicates that S_p decreases markedly with increasing ram pressure in the intra-cluster medium.

Further evidence in favour of the hot gas hypothesis is provided by the detection (Gull & Northover 1978; Lake & Partridge 1977) of a slight drop in the brightness temperature of the microwave background in the direction of a number of clusters of galaxies. This effect, first predicted by Sunyaev & Zel'dovich (1972), is due to the Compton scattering of microwave background photons on the electrons in a hot intra-cluster gas. In a medium with an electron density of around 10^{-3} cm^{-3}, the effect is observed as a slight drop in the background brightness temperature or $\Delta T_B/T_B \approx 10^{-4}$. Thus the available evidence now strongly favours the idea that high temperature gas in clusters is responsible for the observed extended cluster X-ray sources and, though a small contribution by the inverse Compton mechanism cannot be entirely ruled out, I shall in the remainder of this paper discuss the cluster X-ray emission in terms of high temperature plasma, and shall examine the proposed theories for the origin of the gas and the mechanisms that have been suggested for heating it.

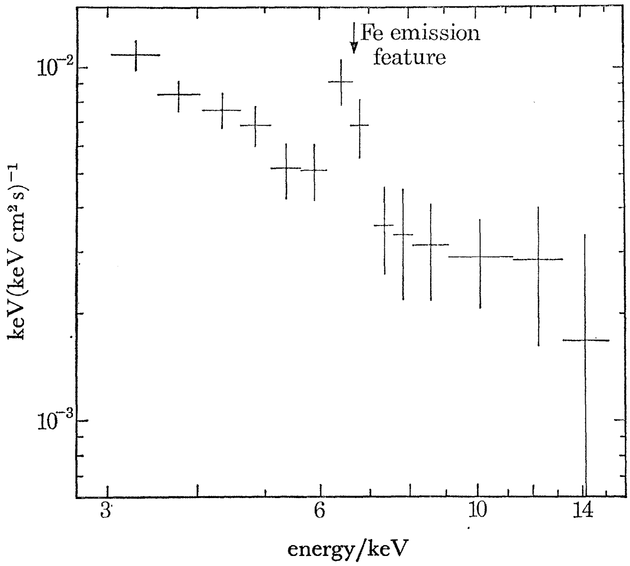

Figure 8. Ariel 5 X-ray spectrum of the southern cluster SC 0627 – 544 (Berthelsdorf & Culhane 1979), indicating the presence of an iron emission feature.

4. The origin and heating of the gas in clusters

After the discovery of extended X-ray sources in clusters, two quite divergent theories were put forward to explain the presence of high temperature gas. The first of these was proposed by Gunn & Gott (1972) and envisaged the falling of primordial material into the cluster gravitational potential well. Given a typical cluster mass and accompanying gravitational potential, an intra-cluster medium with $T \approx 10^8$ K could easily be created in this way. The second theory, which was suggested by Yahil & Ostriker (1973), involved the outflow of material from the member galaxies of a cluster in the form of galactic winds. They suggested that the required energy would be supplied by non-thermal processes in the galaxies or by frictional heating of the intra-cluster medium. We shall see that elements of both of these theories survive in our present view of the heating and origin of the gas although the preferred method of heating the medium involves the infall of gas into a gravitational potential well that is due to the entire cluster.

Since the detection of highly ionized emission features in the spectra of a number of clusters places some constraints on theories that seek to explain the origin of the gas, I shall briefly describe the current status of iron feature observations before summarizing views on the origin and heating of the intra-cluster gas. After the discovery of an emission feature at 6.7 keV in the spectrum of the Perseus cluster by Mitchell *et al.* (1976), confirmation of this observation was provided by Serlemitsos *et al.* (1977), who also detected iron features in the spectra of the

Virgo and Coma clusters. Mitchell & Culhane (1977) added a feature detection in the spectrum of the Centaurus cluster. Mushotzky *et al.* (1978) reported the detection of emission features in the spectra of a number of additional clusters, but it later transpired that two of the X-ray sources involved had been incorrectly identified with the clusters SC 1251 – 288 and A347 or A396 (Watson *et al.* 1978; Mitchell *et al.* 1979). However, Berthelsdorf & Culhane (1979) have recently detected an emission feature in the spectrum of SC 0627 – 544 (figure 8). This observation brings to five the total number of cluster spectra from which there are emission feature detections at a confidence level of better than 99 %. These clusters are listed in table 1 together with a number of their properties. It is clear from this list that iron line emission does not seem to be associated with any particular kind of cluster.

Measurements of equivalent width for the emission features detected in the spectra of the five clusters are shown plotted against temperature in figure 9. Observations from Ariel 5 and OSO-8 are included. Temperature values measured by OSO-8 tend to be systematically higher

Table 1. Properties of Fe line emitting clusters

cluster	Bautz–Morgan class	Rood–Sastry class	$\sigma_v/(\mathrm{km\ s^{-1}})$	$\bar{N}_0$	reference
Perseus (A426)	II–III	L	1420 ± 140	33	Mitchell *et al.* (1979), Serlemitsos *et al.* (1977)
SC 0627 – 544	II–III	F	—	19	Berthelsdorf & Culhane (1979)
Virgo	III	I	705 ± 48	11	Serlemitsos *et al.* (1977)
Centaurus	II	I	870 ± 80	15	Mitchell & Culhane (1977)
Coma (A1656)	II	B	910 ± 40	28	Serlemitsos *et al.* (1977), Culhane (1978*a*)

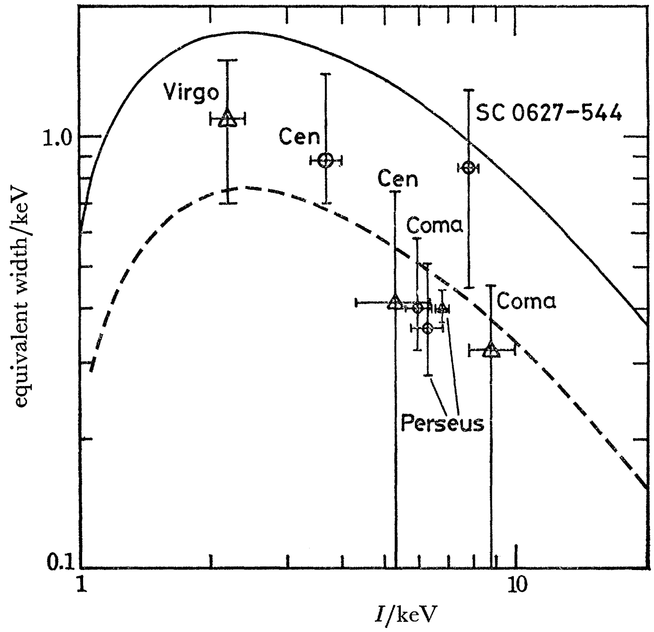

Figure 9. Measurements of iron emission feature equivalent width plotted against continuum temperature for several clusters. The calculated equivalent width is represented by the solid line while the dotted line indicates the effect of an iron abundance of 17×10^{-6} on the calculation. ○, Ariel 5; △, OSO-8.

than those measured by Ariel 5. This could be due to the difference in response of instruments with different fields of view to sources which are not isothermal. The solid line in figure 9 is the calculated feature equivalent width for a 'cosmic' iron abundance ($N(\mathrm{Fe})/N(\mathrm{H}) = 4 \times 10^{-5}$). In carrying out this calculation (Culhane 1978*b*), all of the individual iron transition intensities that contributed to the observed feature have been calculated assuming an optically thin coronal plasma. The dotted line represents the same calculation reduced by a factor of 0.43 to provide the best agreement with the observations. If this factor is due entirely to a reduction in iron abundance, the implied value of $N(\mathrm{Fe})/N(\mathrm{H})$ is 1.7×10^{-5} but the uncertainties in both theory and observation are such that the iron abundance in the gas could easily be consistent with the cosmic value.

The presence of iron in the cluster gas is further supported by the HEAO-1 observations of Lea *et al.* (1979) who found evidence for Fe-L type transitions at 1.1 keV from Fe XXIII and Fe XXIV in the spectrum of the Virgo cluster. Although the temperature measured by these workers was somewhat higher than value obtained from Ariel 5 and OSO-8 observations, the iron abundance estimate of around 80 % of the cosmic value that results from their analysis is in good agreement with the OSO-8 value that is based on the Fe XXV–XXVI emission feature. Evidence for the presence of the L emission feature has also been claimed by Fabricant *et al.* (1978) from their imaging X-ray telescope observations of the region around M87. The data also suggest an essentially cosmic iron abundance and when an equivalent width is published it may be possible to compare the strength of the feature around M87 with its strength for the entire Virgo cluster. Thus while it remains to be established that the iron is distributed throughout the intra-cluster gas rather than being confined to neighbourhoods of individual galaxies, the detection of the emission features requires us to recognize that not all of the intra-cluster gas can be primordial. At least some of it must have been processed either in the member galaxies or in a pregalactic phase of star formation.

Realistic models to explain the heating of the intra-cluster gas may eventually contain elements of both the infall (Gunn & Gott) and outflow (Yahil & Ostriker) mechanisms but, at present, the two classes of model tend to be considered separately. Pure infall models envisage the flow of primordial matter into the cluster potential well. Early descriptions involve self-gravitating isothermal gas spheres (Lea *et al.* 1973), but these models are clearly unphysical since they ignore the potential due to the cluster. More realistic models are based on the following three approaches.

(i) *Infalling gas in hydrostatic equilibrium with the cluster potential well.* Models of this type have been proposed by Lea (1975), Gull & Northover (1975), Cavaliere & Fusco-Femiano (1976) and Bahcall & Sarazin (1977). The heated gas can be isothermal if thermal conduction is important, or adiabatic if random magnetic fields are effective in suppressing conduction. These models are unrealistic in assuming a constant cluster potential and this leads to difficulties if such models are used to predict the evolution of cluster properties with z.

(ii) *Time-dependent hydrodynamical models with constant cluster gravitational potential.* Models of this type have been put forward by Gull & Northover (1975), Lea (1976), Takahara *et al.* (1976) and Cowie & Perrenod (1978). With the exception of Lea's model, which may have problems with numerical instabilities, the other models give similar results and predict the establishment of constant core density and X-ray luminosity after $2\text{–}3 \times 10^9$ years. Again there is no strong variation of cluster properties with z owing to the assumption of constant gravitational potential.

(iii) *Infall models with time dependent cluster gravitational potential.* Models of this type have been discussed by Perrenod (1978). The main impact of this work is to predict a strong evolution of cluster properties with z. I shall return to a discussion of this later.

All of these models lead to predictions of the size and temperature distribution (for polytropic cases) of the extended X-ray sources but the data are, in general, not yet of adequate quality to discriminate between the various possibilities. However, the detection of iron emission features does suggest that injected material must play some role in establishing the properties of the intra-cluster medium. Thus a number of models based on gas injection from galaxies have been proposed.

(*a*) *Radiative regulation of gas flow within clusters*

This mechanism was proposed by Cowie & Binney (1977) and in fact involves elements of both injection and infall. Gas ejected by galaxies in the outer regions of a cluster flows towards the core and is ultimately accreted by the central galaxies. Radiation from the gas regulates the central gas density to a value at which the cooling time equals the lifetime of the system. Details of the gas accretion by individual galaxies and of the associated X-ray emission have been discussed by Fabian & Nulsen (1977).

(*b*) *Gas injection into a constant cluster gravitational potential*

A family of models of this type are described by Cowie & Perrenod with mass injection in the form suggested by Gisler (1976). The matter was assumed to be injected at zero temperature in the absence of additional heating mechanisms. Energy was supplied to the gas by the constant gravitational potential. Injection could be due to ram pressure stripping or thermal evaporation by primeval intro-cluster medium (Cowie & Songalia 1977) or by galactic winds.

(*c*) *Gas injection with time dependent cluster gravitational potential*

Perrenod (1978) has discussed injection with an evolving cluster potential. These models, which can also involve any of the gas injection schemes described above, show a strong evolution of cluster properties with z.

(*d*) *Gas injection followed by shock heating*

De Young (1978) postulates the injection of iron rich material following an *early* phase of evolution of massive stars. Clouds of ejected gas surround the member galaxies as they move through the cluster. Collisions between these clouds lead to the production of a high temperature intra-cluster medium. A medium produced in this way would have too large an iron abundance and too small an X-ray luminosity to match the observations, but De Young points out that both of these difficulties can be overcome by mixing the ejected material with hot primordial gas.

Gas injection must have a role in producing the intracluster medium if the presence of iron with cosmic abundance is to be explained, although a pregalactic population of stars or other massive objects could have supplied the iron and could provide a source of mass to bind the clusters in the present epoch. However, it is clear from the preceding paragraphs that a variety of models involving both infall and injection are still permitted by the observations available at present. The models can provide quite detailed predictions about the surface brightness and temperature of the X-radiation and about the distribution of iron emission. Observations with improved spectral and spatial resolution are required to constrain the range of models.

5. Cluster X-ray observations and the nature of the Universe

The study of the extended X-ray sources associated with clusters of galaxies can further our understanding of the Universe in two distinct ways. First, it is apparent that the sequence of events in the 'matter' era remains uncertain in a number of important respects. Two simple alternative routes may be examined. Galaxies could have formed first from primordial matter with or without a pregalactic stage of star formation. Galaxies and 'dead' stars could then have aggregated to form the clusters that we now observe. The hot gas that produces the extended X-ray emission could have been ejected by the galaxies or left over from the galactic formation stage. Alternatively cluster-sized gas clouds of *ca.* $10^{14}\ M_\odot$ could have separated, cooled and begun to form individual galaxies. The hot material that we now observe would then be matter which escaped incorporation into individual galaxies. Fabian & Rees (1978) have reviewed these two descriptions of the early Universe with reference to much of the previous work in support of both schemes. A detailed understanding of the origin and heating of the intra-cluster gas could allow us to distinguish between these two possibilities. In particular, it will be necessary to establish the relative importance of primordial and processed material in producing the observed X-rays. Studies of distant clusters will allow us to examine the evolution of cluster properties with z. Studies of nearby clusters could allow us to separate the role of individual galaxies from that of the cluster as a whole. They may also allow us to discover whether the gas is isothermal or adiabatic.

A detailed understanding of the physics of the high temperature plasma could allow the realization of a second objective, namely the use of the extended X-ray sources in performing cosmological tests. Tests (Cowie & Perronod 1978; Perrenod 1978) that could permit estimates to be made of the deceleration parameter, q_0, involve using the extended X-ray sources as 'standard rulers' or as 'standard candles'. In addition, Schwartz (1976) has suggested estimating q_0 on the basis of measurements of cluster X-ray source number density as a function of z. Perrenod (1978) has considered the impact of evolutionary effects on the validity of these tests. A method of estimating H_0 from a comparison of the X-ray luminosity with observations of the Sunyaev–Zel'dovich effect has also been proposed (Birkinshaw 1978; Silk & White 1978).

Observations with the imaging X-ray telescope on HEAO-B should permit the detection and study of clusters back to $z \approx 1$. Since it is now apparent that all clusters will be X-ray sources at some level of luminosity, they present us with a category of object which will allow us to greatly enlarge our understanding of the Universe after we understand the details of how the intracluster gas is heated and how the X-ray parameters evolve with z. A great deal of observational and theoretical work remains to be done but the fundamental simplicity of a high temperature intracluster gas may allow us to make progress in this most challenging area of astronomy.

References (Culhane)

Bahcall, J. N. & Sarazin, C. L. 1977 *Astrophys. J.* **213**, L99.
Bahcall, N. A. 1974 *Astrophys. J.* **193**, 529.
Bahcall, N. A. 1977*a* *Astrophys. J.* **217**, L77.
Bahcall, N. A. 1977*b* *Astrophys. J.* **218**, L93.
Berthelsdorf, R. F. & Culhane, J. L. 1979 *Mon. Not. R. astr. Soc.* **187**, 17P.
Birkinshaw, M. 1978 *Mon. Not. R. astr. Soc.* **184**, 387.
Cavliere, A. & Fusco-Femiano, R. 1976 *Astron. Astrophys.* **49**, 137.

Cooke, B. A., Rickets, M. J., Maccacaro, T., Pye, J. P., Elvis, M., Watson, M. G., Griffiths, R. E., Pounds, K. A., McHardy, I., Maccagni, P., Seward, F. D., Page, C. G. & Turner, M. J. C. 1978 *Mon. Not. R. astr. Soc.* **182**, 455.

Cowie, L. L. & Binney, J. 1977 *Astrophys. J.* **215**, 723.

Cowie, L. L. & Perrenod, S. C. 1978 *Astrophys. J.* **219**, 354.

Culhane, J. L. 1978*a* *Q. Jl R. astr. Soc.* **19**, 1.

Culhane, J. L. 1978*b* In *The large scale structure of the Universe* (*I.A.U. Symp.* no. 79) (ed. J. Einasto & M. Longair), p. 165. Dordrecht: D. Reidel.

Davison, P. J. N. 1978 *Mon. Not. R. astr. Soc.* **183**, 39P.

De Young, D. S. 1978 *Astrophys. J.* **223**, 47.

Fabian, A. C. & Nulsen, P. E. J. 1977 *Mon. Not. R. astr. Soc.* **180**, 479.

Fabian, A. C. & Rees, M. J. 1978 Paper presented at I.A.U./COSPAR Symposium, Innsbruck 31 May – 3 June, 1977.

Fabricant, D., Topka, K., Harnden, F. R. & Gorenstein, P. 1978 *Astrophys. J.* **226**, L107.

Gisler, G. 1976 *Astron. Astrophys.* **51**, 137.

Gisler, G. R. & Miley, G. K. 1980 *Astron. Astrophys.* (In the press.)

Gorenstein, P., Fabricant, D., Topka, K., Tucker, W. A. & Harnden, F. R. 1977 *Astrophys. J.* **217**, L95.

Gorenstein, P., Fabricant, D., Topka, K., Harnden, F. R. & Tucker, W. H. 1978 *Astrophys. J.* **224**, L718.

Gorenstein, P., Fabricant, D., Topka, K. & Harnden, F. R. 1979 *Astrophys. J.* **230**, 26.

Gull, S. F. & Northover, K. J. E. 1975 *Mon. Not. R. astr. Soc.* **173**, 585.

Gull, S. F. & Northover, K. J. E. 1976 *Nature, Lond.* **263**, 572.

Gunn, J. E. & Gott, J. R. 1972 *Astrophys. J.* **176**, 1.

Gursky, H., Kellogg, E. M., Tananbaum, H. & Giacconi, R. 1971 *Astrophys. J.* **167**, L81.

Lake, G. & Partridge, R. B. 1977 *Nature, Lond.* **270**, 502.

Lawrence, A. 1978 *Mon. Not. R. astr. Soc.* **185**, 423.

Lea, S. 1975 *Astrophys. Lett.* **16**, 141.

Lea, S. 1976 *Astrophys. J.* **203**, 569.

Lea, S., Mason, K. O., Richert, G., Charles, P. A. & Reigler, G. 1979 *Astrophys. J.* **227**, L67.

Lea, S., Silk, J., Kellogg, E. & Murray, S. 1973 *Astrophys. J.* **184**, L105.

McHardy, I. 1978 *Mon. Not. R. astr. Soc.* **184**, 783.

Marshall, F., Serlemitsos, P. J., Holt, S. S., Boldt, E. A. 1979 In preparation.

Mitchell, R. J. & Culhane, J. L. 1977 *Mon. Not. R. astr. Soc.* **178**, 75P.

Mitchell, R. J., Culhane, J. L., Davison, P. J. N., Charles, P. A. & Fabian, A. C. 1975 *Astrophys. J.* **200**, L5.

Mitchell, R. J., Culhane, J. L., Davison, P. J. N. & Ives, J. C. 1976 *Mon. Not. R. astr. Soc.* **175**, 29P.

Mitchell, R. J., Dickens, R. J., Bell Burnell, S. J. & Culhane, J. L. 1979 *Mon. Not. R. astr. Soc.* **189**, 329.

Mushotzky, R. F., Serlemitsos, P. J., Smith, B. W., Boldt, E. A. & Holt, S. S. 1978 *Astrophys. J.* **225**, 21.

Perrenod, S. C. 1978 *Astrophys. J.* **226**, 566.

Schnopper, J. W., Delvaille, J. P., Epstein, A., Helmken, H., Harris, D., Strom, R. G., Clark, G. W. & Jernigan, J. G. 1977 *Astrophys. J.* **217**, L15.

Schwartz, D. A. 1976 *Astrophys. J. Lett.* **206**, L95.

Serlemitsos, P. J., Smith, B. W., Boldt, E. A., Holt, S. S. & Swank, J. H. 1977 *Astrophys. J. Lett.* **211**, L63.

Silk, J. & White, S. P. 1978 *Astrophys. J.* **226**, L103.

Sunyaev, R. A. & Zel'dovich, Y. B. 1972 *Comm. Space Sci.* **4**, 173.

Takahara, F., Ikeuchi, S., Shibazaki, N., Hoshi, R. 1976 *Prog. theor. Phys.* **56**, 1093.

Watson, M. G., Sherrington, M. R. & Jameson, R. F. 1978 *Mon. Not. R. astr. Soc.* **184**, 79P.

Wolff, R., Mitchell, R. J., Charles, P. A. & Culhane, J. L. 1976 *Astrophys. J.* **208**, 1.

Yahil, A. & Ostriker, J. P. 1973 *Astrophys. J.* **185**, 787.

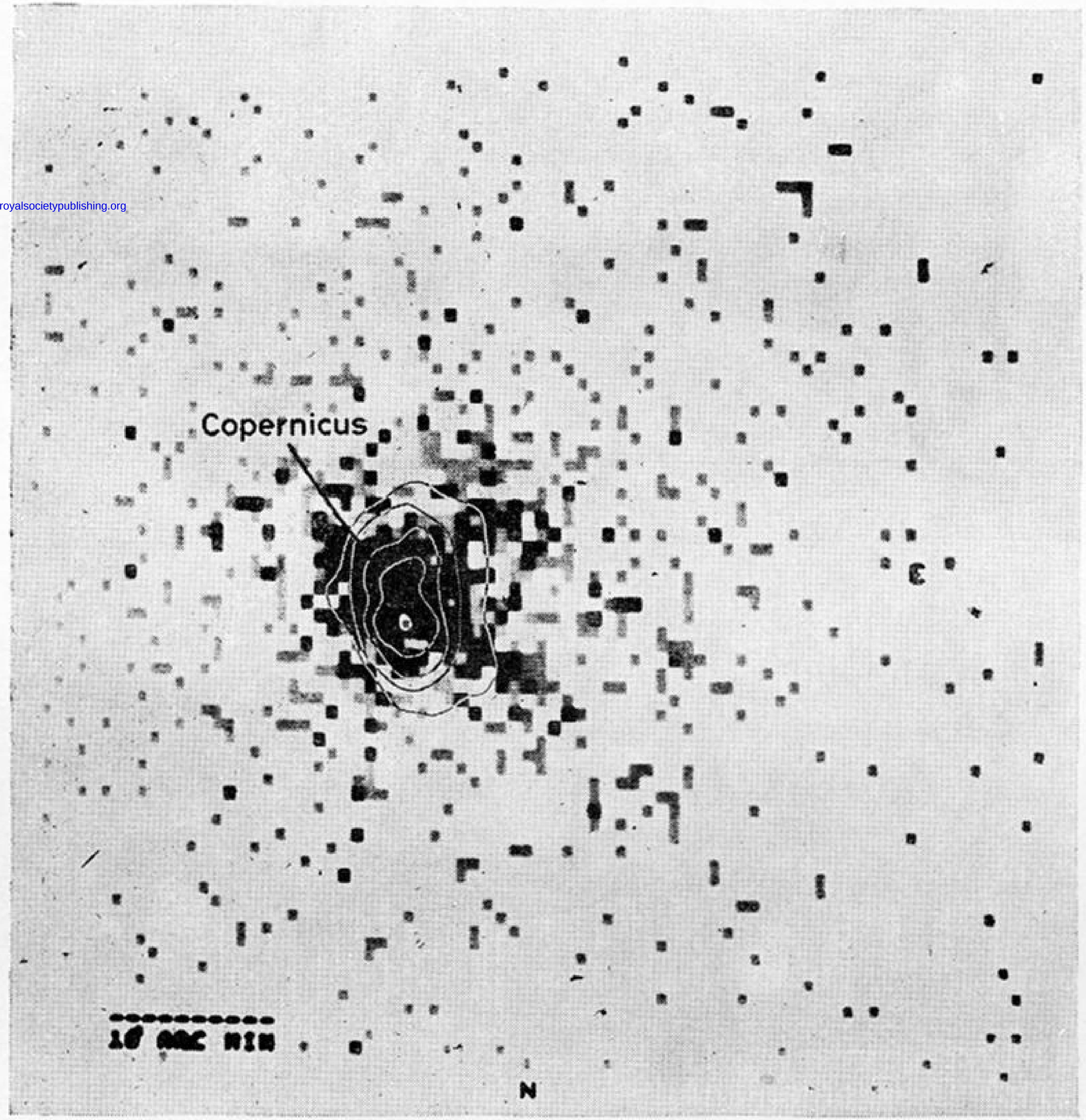

FIGURE 2. Observations of the Perseus cluster by the Copernicus X-ray telescope (Wolff *et al.* 1976) and by an imaging telescope flown on a rocket (Gorenstein *et al.* 1978) in the 0.2–2.0 keV range.