HOT GAS IN CLUSTERS OF GALAXIES

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1. INTRODUCTION

The discovery of extended X-ray sources associated with clusters of galaxies which resulted from the Uhuru X-ray sky survey was one of the most important observations to come from that programme. Following Uhuru, the Ariel V and HEAO-1 sky surveys have found many more cluster X-ray sources and the recently launched Einstein observatory has begun to increase further the number of identifications. However there is in any case evidence from the X-ray cluster luminosity function that all rich clusters of galaxies will emit X-rays at some level.

Preliminary results from the Einstein observatory (Murray, 1979) suggest that the extended X-ray emission from centrally condensed (cD) clusters is itself centrally condensed and spherically symmetrical in appearance. However irregular clusters have non-uniform X-ray surface brightness distributions. In addition there are some galaxies in clusters of irregular morphology that have associated X-ray halos.

In this review we will discuss the evidence for the presence of hot plasma and describe its properties. We will examine the available models for the origin and heating of the gas and will discuss the evidence for the presence of a gas of lower temperature associated with certain galaxies. Finally we will discuss briefly the interactions between the hot plasma with the cluster galaxies.

2. EVIDENCE FOR HOT GAS AND ITS PROPERTIES

For several years after the discovery of extended X-ray sources in clusters of galaxies, the choice between two different emission mechanisms was vigorously debated. On the one hand, the observation of extended radio sources in some clusters (Ryle and Windram, 1968) suggested that intra-cluster populations of relativistic electrons were present. It was therefore proposed that inverse Compton interactions between the photons of the microwave background and these electrons could lead to

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the production of extended X-ray sources. As an alternative, the existence of a high temperature (T $\sim 10^8$ K) intra-cluster medium which would give rise to extended X-ray sources by thermal bremsstrahlung radiation, was proposed. The title of this review indicates that the second of these hypotheses is now preferred. However it is worthwhile to summarise the principal arguments in favour of the existence of a hot intra-cluster plasma. These are as follows:

i) The Nature of the X-ray Spectra

The discovery of an emission feature, due to transitions in Fe XXV and Fe XXVI, in the spectrum of the Perseus cluster (Mitchell et al., 1976, see Figure 1) was followed by the observation of similar features in the spectra of several other cluster sources (Serlemitsos et al., 1977; Mitchell and Culhane, 1977; Mushotzky et al., 1978; Berthelsdorf and Culhane, 1979). In addition, an Fe XXIV L emission feature at 1.1 keV has been observed in the spectrum of the Virgo cluster (Gorenstein et al., 1978; Lea et al., 1978). The existence of these ions can only be due to the presence of a high temperature plasma.

ii) The Decrease in the Microwave Background Brightness Temperature

Sunyaev and Zel'dovich (1972) suggested that the scattering of microwave background photons by a high temperature intra-cluster plasma should lead to a slight reduction in brightness temperature which would be observed in the direction of clusters. The effect is small and its measurement correspondingly difficult. However three groups (Gull and Northover (1976), Lake and Partridge (1977), Birkinshaw et al., (1978)), have reported detection of the effect.

iii) Existence of "Head and Tail" Radio Galaxies

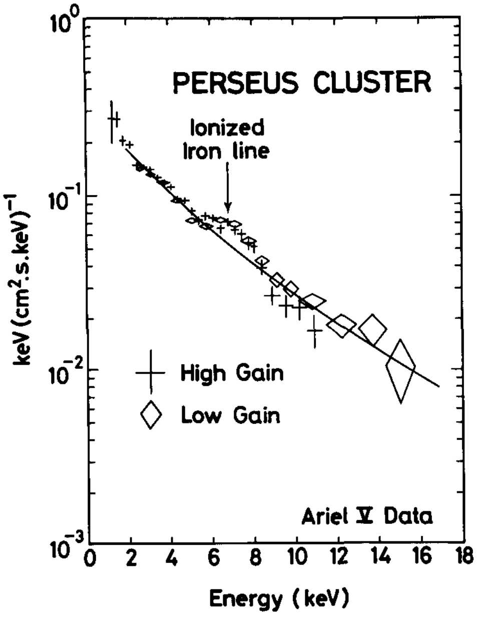
This radio galaxy morphology has been known for some time (Miley et al., 1972, see also Figure 5). It is most naturally explained by the assumption that radio galaxies are moving through a hot medium within the cluster. The pressure due to this medium can contain the ejecta from the radio galaxies and so give rise to the observed structures.

iv) Relations between X-ray Luminosity and other Cluster Properties

The observed decrease in the fraction of spiral galaxies present in a cluster with increasing cluster X-ray luminosity (L_X) (Bahcall, 1977a). The ram pressure due to the motion of galaxies in the intra-cluster medium can strip gas and dust from normal spiral galaxies. Thus the greater the temperature and density of the intra-cluster medium, the smaller the number of spirals that can survive to the present epoch.

Bahcall (1977b) and others have noted a correlation between L_X and the central density of galaxies. Once again this would be explained most naturally if gas were being heated by falling into the gravitational potential well created by the cluster as a whole.

The detection of emission features due to highly ionised iron provides the most convincing evidence for the presence of high temperature plasma as was mentioned in i) above. However the existence of iron emission lines also permits estimates of iron abundance to be made. Published data indicate the presence of 6.7 keV iron emission features in the spectra of six clusters but it is clear that similar features exist in many of the HEAO-1 cluster spectra (Mushotzky, 1979) and hence the presence of this feature is quite common. By calculating the intensities of the transitions that are blended in the proportional counter iron feature and comparing the calculations with the observations, it is possible to estimate the abundance of iron in the intra-cluster gas. The results of this comparison are shown in Figure 2. The solid line indicates the feature equivalent width as a function of temperature for cosmic



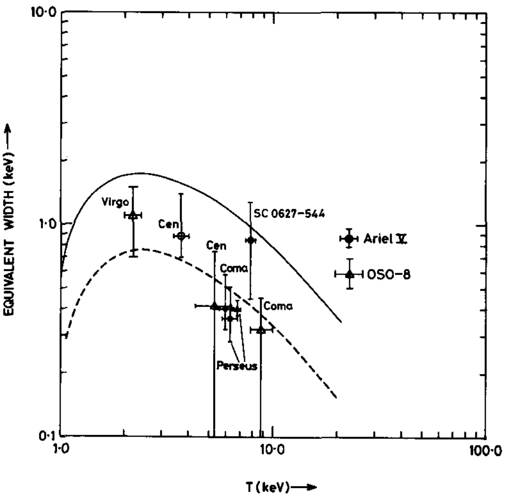


Figure 1. Ariel V spectrum of the Perseus cluster. The emission feature due to Fe XXV and Fe XXVI is apparent in the data (Mitchell et al. (1976)).

Figure 2. A comparison of calculated and measured equivalent widths of the Fe feature shown plotted against temperature. The solid line is calculated for a cosmic Fe abundance (Berthelsdorf and Culhane (1979)).

iron abundance. The dotted line which best fits the data points, requires an iron abundance that is about 40% of the cosmic value. Note that differences exist between the Ariel V and OSO-8 temperature estimates. This is probably due to the presence of lower temperature plasma

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components to which the two detectors respond in different ways. We will discuss the evidence for lower temperature material later.

On the basis of Ariel V and OSO-8 observations of some 30 X-ray clusters, the following ranges have been established for the X-ray properties.

1. Temperature $1.3\ \text{keV} < kT < 18\ \text{keV}$
2. Emission Measure $5.10^{66}\ \text{cm}^{3} < \int N_e^{2} dV < 5.10^{68}\ \text{cm}^{-3}$
3. X-ray Luminosity $3.10^{43}\ \text{erg s}^{-1} < L_X(2\text{-}10\ \text{keV}) < 4.10^{45}\ \text{erg s}^{-1}$
4. Core Radius $R_{CORE} \sim 0.3$ MPc
5. Density $N_e \sim 10^{-3}\ \text{cm}^{-3}$
6. Mass of gas $M_x \sim 10^{14}\ M_\odot$ (note $M_{vt} \sim 10^{-15}\ M_\odot$)

3. MODELS FOR THE ORIGIN AND HEATING OF THE GAS

Following the discovery of extended X-ray sources in clusters of galaxies, two extreme hot plasma models were proposed namely the primordial gas infall model of Gunn and Gott (1972) and the galactic gas outflow (galactic wind) model of Yahil and Ostriker (1973). While it is now clear that models involving only primordial material cannot be correct given the presence of heavy elements in the gas, the infall of such material could still provide some of the observed X-ray bremsstrahlung luminosity.

For a time self gravitating isothermal gas spheres were used to describe the extended sources (Lea et al.; 1973). While such models are unphysical because they ignore the cluster potential, they were nevertheless useful for a time in providing a basis for comparison with the early observations.

The simplest models which take account of the cluster potential are those which assume the infalling primordial gas to be in hydrostatic equilibrium with the cluster potential well (Lea (1975), Gull and Northover (1975), Cavaliere and Fusco-Femiano (1976), Bahcall and Sarazin (1977)). In these models the gas is isothermal if conduction is important but will be adiabatic if the cluster magnetic field can suppress conduction. In either case the X-ray properties do not evolve strongly with z.

Time dependent hydrodynamical models which assume a constant cluster potential generally lead to the establishment of constant core densities and X-ray luminosities after $2\text{-}3.10^{9}$ years (Gull and Northover (1975), Takahara et al., (1976), Lea (1976), Cowie and Perrenod (1978)).

Hydrodynamical models with evolving cluster potentials have been discussed by Perrenod (1978). He used the n-body simulation of White (1976) to describe the development of the cluster potential and found that cluster X-ray properties depended strongly on z.

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Although primordial infall models are useful in bringing about the development of modelling techniques that are required for a better understanding of clusters, it seems unlikely that the intra-cluster medium can consist solely of primordial gas. A somewhat wider range of models can be considered if the injection of processed material from galaxies is involved. However the same progression in sophistication from hydrostatic equilibrium models to those that envisage an evolving potential well is appropriate. Cluster gas injection can be due to ram pressure stripping by the motion of galaxies through an initially primordial medium, to thermal evaporation or to galactic winds.

A class of model favoured by the recent detection of cooler material associated with some prominent galaxies involves the radiative regulation of gas flow within clusters. The first version of this scheme (Cowie and Binney (1977)) involved the flow of mass, ejected by galaxies in the outer regions of clusters, onto the central galaxies in the cores. Radiation from this material may regulate the central density to the value at which the cooling time is equal to the lifetime of the system. The details of the accretion of the infalling gas by the central galaxies has been considered by Fabian and Nulsen (1977) and others.

Yet other models have been proposed which involved mixtures of primordial gas with iron rich processed material from an early phase of evolution of massive stars (De Young, 1978). Although a complete understanding of the heating and origin of the intra-cluster gas has not yet been achieved, it seems likely that the ideas summarised above probably contain the ingredients required for a successful description of these systems. Such a description should shortly be formulated given the wealth of data now available.

4. THE EXISTENCE OF A LOW TEMPERATURE COMPONENT

Soon after the discovery of the extended X-ray sources, it became apparent that some individual galaxies were surrounded by X-ray halos which could be distinguished from the emission due to the intra-cluster gas. The halo around NGC 1275 was the first to be identified,(Wolff et al. (1976). However its nature and origin remained uncertain for several years. A recent observation by the Goddard Space Flight Centre's solid state spectrometer on the Einstein observatory has indicated that the material around NGC 1275 must have a temperature of about 1 keV while the Perseus intra-cluster medium is at 7 keV (Mushotzky, 1979) (Figure 3). This lower temperature is further supported by observations with the Einstein focal plane crystal spectrometer (Canizares, 1979) which have indicated that the resonance line of O VIII is emitted by the halo gas. The emission measure of the cool material is about 10% of that of the hot medium.

Similar results have been obtained from Einstein crystal spectrometer observations of M87 (Canizares et al. 1979). Their observation of the O VIII resonance line is shown in Figure 4 and indicates that the

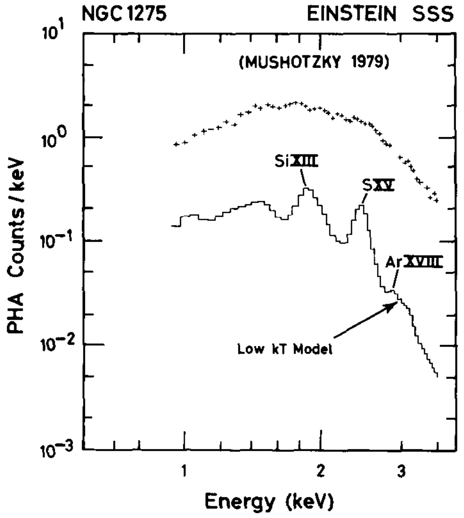

Figure 3. A count rate spectrum obtained with the Goddard Space Flight Centre's solid state spectrometer on the Einstein observatory. The 6 arc min field of view is centered on NGC 1275. The upper curve includes contributions from NGC1275 and from the intra-cluster medium. The lower curve shows the contribution of a cool component associated with the NGC 1275 halo. (Mushotzky, 1979).

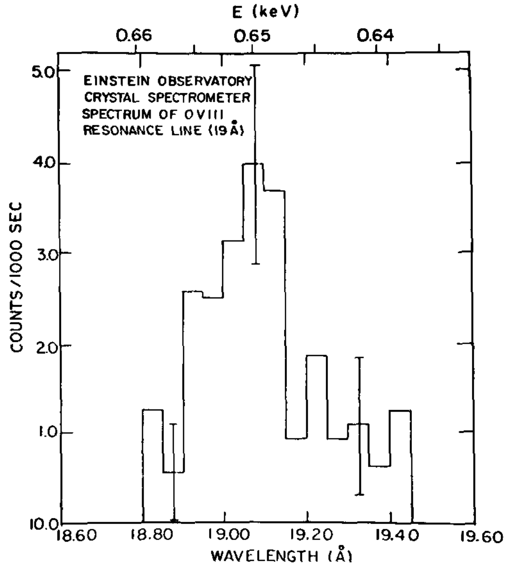

Figure 4. Counting rate plotted against wavelength from the MIT focal plane crystal spectrometer on the Einstein observatory. The 3x30 arc min field of view is centered on M87 (Canizares et al., 1979).

halo gas temperature is less than 1 keV although the intra-cluster gas in Virgo has a temperature greater than 3 keV. This conclusion is supported by the work of Mushotzky et al. 1979 with the solid state spectrometer who also find evidence for a cooler halo around M87 similar to that associated with NGC 1275.

Finally there is some evidence for the existence of a lower temperature halo around NGC 4696 in the Centaurus cluster. Observations with Copernicus (Mitchell et al. 1975) had previously indicated the presence of an excess of low energy X-ray emission in a 12 arc min field of view centered on NGC 4696. More recently Mitchell and Mushotzky (1979) have shown that the Centaurus cluster spectrum obtained with the GSFC proportional counter on HEAO-1 cannot be adequately explained by a single high temperature component. The spectrum is better fitted by two components with temperatures of 2.3 keV and 7.2 keV. Observations with the Einstein focal plane instruments could show if the lower temperature component is caused by a halo around NGC 4696.

There is therefore strong evidence for the existence of cooler halos around some massive galaxies in clusters. The presence of such material would be a natural consequence of the radiative cooling and accretion models mentioned above and thus its detection lends some support to these models. However the influence of galactic velocity on the accretion process needs to be investigated. It would also be interesting to search for cool halos associated with the massive central galaxies in cD clusters.

5. INTERACTIONS BETWEEN THE INTRA-CLUSTER GAS AND THE MEMBER GALAXIES

The two principal interactions of this sort have already been discussed since their operation provides evidence that favours the presence of a high temperature intra-cluster plasma.

The existence of radio "head and tail" galaxies in clusters has been known for some time (Ryle and Windram, 1978; Miley et al., 1972). A good example is NGC 1265 shown in Figure 5 as observed at 610 MHz and 1415 MHz by Gisler and Miley (1979). The head and tail morphology is well explained by the motion of these galaxies through the hot intra-cluster medium and by the ejection from the galaxies of plasmoids containing relativistic particles, magnetic fields and cold plasma. Early estimates of the properties of a medium needed to contain and stop such relativistic ejecta lead to the conclusion that the same high temperature gas which could emit X-rays by bremsstrahlung would also explain the head and tail structures. The study of the interactions between these galaxies and the intra-cluster gas is now a fruitful field of investigation.

The relation between the fraction of spiral galaxies found in a cluster and its X-ray properties has also been referred to earlier. The relationship is best demonstrated by plotting the spiral fraction (Sp) against a quantity $((\int N_e^2\, dV)^{\frac{1}{2}}\, kT)$ which describes the ram pressure (Figure 6). The relation suggests that gas is stripped from the galaxies by a ram pressure which is due to their motion through the hot intra-cluster gas. Thus the relative absence of spiral galaxies in early or evolved clusters is explained. In addition, the process of spiral stripping may provide a mechanism for enriching a primordial medium with heavy elements such as iron.

6. CONCLUSIONS

Our understanding of the intra-cluster medium may therefore be summarised as follows:

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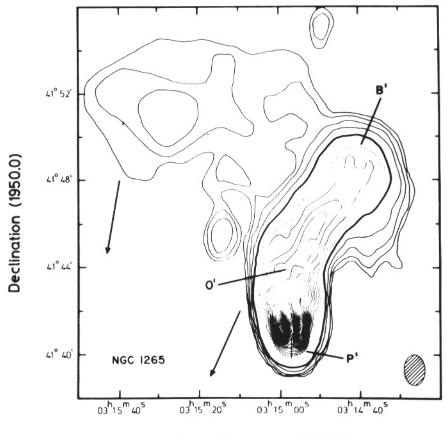

Figure 5. A radio image of NGC 1265 in the Perseus cluster. The heavy contour and those outside are at 610 MHz. The dashed contours are at 1415 MHz. Arrows indicate the direction of the cluster centre (Gisler and Miley, 1979).

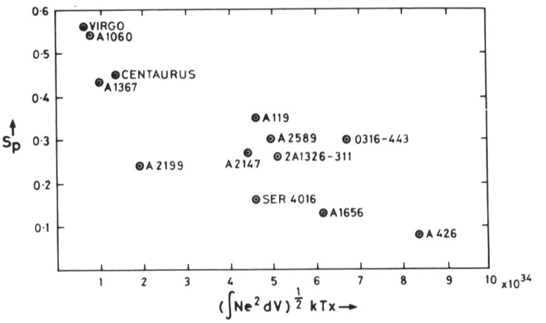

Figure 6. The fraction of spiral galaxies plotted against $(\int N_e^2\, dV)^{\frac{1}{2}}$ kT - a quantity which describes the ram pressure experienced by galaxies moving in the intra-cluster medium.

1. Clusters of galaxies contain high temperature plasma with kT$\sim$10 keV and $N_e \sim 10^{-3}$ cm^{-3}.
2. The plasma includes iron at approximately the cosmic abundance.
3. The plasma could include a mixture of primordial and processed components.
4. It is probably heated by gravitational infall.
5. The gas cooling time is approximately the Hubble time.
6. There is some evidence for radiative cooling and accretion in the neighbourhood of certain galaxies.
7. We are as yet unable to discriminate between isothermal and adiabatic conditions in the gas.

The study of hot intra-cluster media seems certain to provide us with a great deal of new information about cluster dynamics, the nature of the member galaxies and even about the formation and evolution of the clusters themselves. But in addition we can even dare to hope that when we finally understand the origin and heating of the intra-cluster gas, we can employ distant clusters as "standard candles" or "standard rulers" in our search for a greater understanding of the Universe as a whole.

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