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ARIEL 5 OBSERVATIONS OF THE X-RAY SPECTRUM OF THE PERSEUS CLUSTER

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SUMMARY

An X-ray spectrum of the Perseus Cluster in the energy range 1·3–16 keV has been obtained with the MSSL collimated proportional counter on *Ariel 5*. An emission feature has been detected at about 7 keV of strength 0·0035 ± 0·0004 photon $\mathrm{cm^{-2}\,s^{-1}}$ (equivalent width 360 ± 50 eV). The existence of this feature, which is due to Fe XXV and Fe XXVI transitions, provides strong evidence for the presence of hot plasma in the cluster. In addition the overall spectrum is well described by the bremsstrahlung emitted from an adiabatic hydrostatic atmosphere of hot gas in the gravitational potential well of the cluster.

INTRODUCTION

Following their discovery by the *Uhuru* satellite (Gursky *et al.* 1971; Forman *et al.* 1972), the extended sources of X-ray emission associated with clusters of galaxies have been studied in some detail. The two types of emission mechanism which have been proposed are thermal bremsstrahlung from a hot isothermal gas sphere (e.g. Lea *et al.* 1973) and the inverse Compton radiation from the interaction of the 3 K microwave background photons with a population of relativistic electrons in the cluster (e.g. Brecher & Burbidge 1972). Observations of the X-ray spectra of these clusters, while capable in principle of allowing a choice between the two emission mechanisms, have not yet permitted definite conclusions to be drawn although there has been some evidence in favour of a thermal origin for the X-rays (Solinger & Tucker 1972).

We report here a new measurement of the X-ray spectrum of the Perseus Cluster source. The spectrum which covers the energy range 1·3–16 keV, was obtained by the MSSL proportional counter (experiment C) on *Ariel 5*. There is good evidence for the presence of an emission feature at about 7 keV. In addition it is not possible to provide a good fit to the observed data in this energy range with either a simple thermal or a simple power law spectrum. However, the observed spectrum agrees well with that predicted by the adiabatic gas sphere model of Gull & Northover (1975).

THE OBSERVATIONS

The detector system and its mode of operation were essentially as described by Stark, Davison & Culhane (1976). Spectra are obtained with the aid of an on-board 32-channel pulse height analyser (PHA) which may be operated in either of two gain modes so as to cover the nominal energy band 1·3–25 keV with a region of overlap from 3 to 13 keV. Both gain modes were used in obtaining the spectrum presented below. PHA counts are integrated on-board the spacecraft for a complete orbit, giving integration times of 30–40 min. The Perseus Cluster was observed between 1975 September $5^{\mathrm{d}}\ 15^{\mathrm{h}}\!\cdot\!9$ and 1975 September $7^{\mathrm{d}}\ 12^{\mathrm{h}}\!\cdot\!0$, for a total of 27 satellite orbits.

The high and low gain data were fitted separately by both thermal and power law spectra. Detector resolution and escape effects were taken account of in the fitting programme. The power law expression was of the usual form while the exponential thermal spectrum included a Gaunt factor $\bar{g}$ for which we used the approximation:

$$\bar{g} = 0{\cdot}9\left(\frac{kT}{E}\right)^{(0\cdot3+E/200)}. \qquad (1)$$

The average absorption coefficients of Brown & Gould (1970) were used to represent the interstellar medium. The data did not show a measurable interstellar column density, so its value was fixed at $N_{\mathrm{H}} = 5\times10^{20}$ atom cm^{-2} which is consistent with both our data and with the column obtained from 21-cm radio observations for the line of sight to the Perseus Cluster.

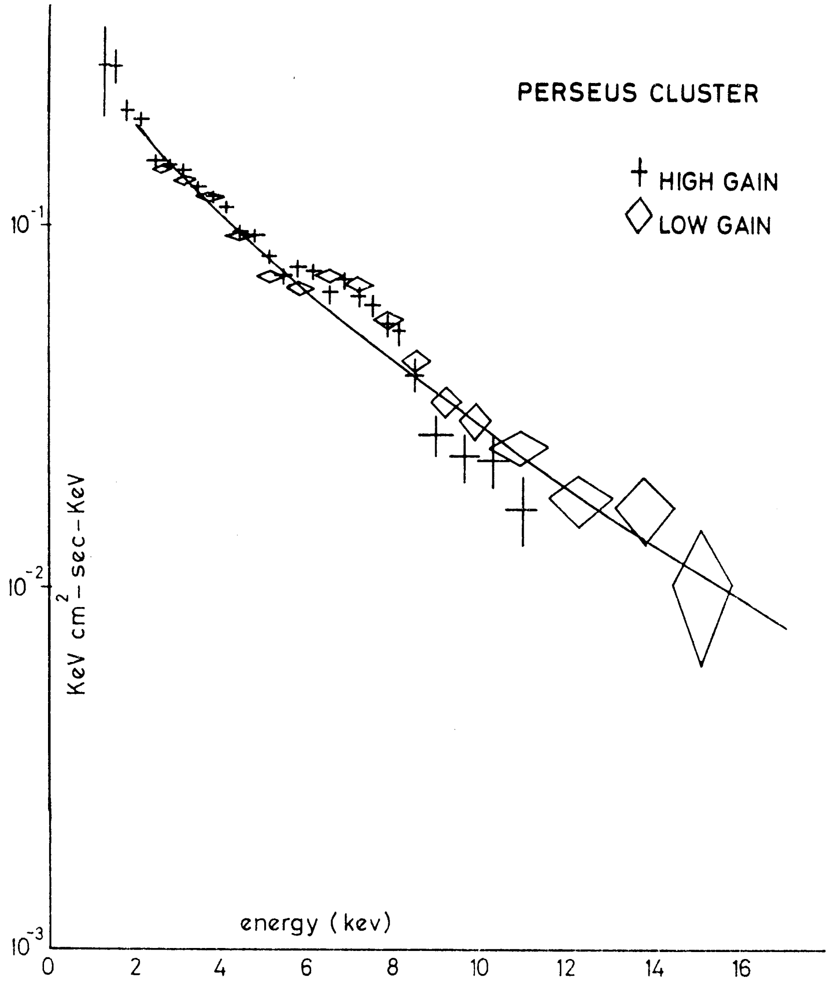

Fig. 1. *The Ariel 5 X-ray spectrum of the Perseus Cluster in the energy range* 1·3–16 *keV. The two detector gain modes are selected by ground command. The solid line represents the computed continuous spectrum from a Gull & Northover adiabatic gas sphere with central temperature* $(T(0))$ 32 *keV and* $T_\infty = -4$ *keV. The emission feature at around* 7 *keV is visible in both gain modes.*

The high and low gain spectral parameters differ significantly from each other, indicating that a simple thermal or power law spectrum cannot adequately represent the data over the entire range of observations. Data points representing the energy flux in each channel are shown in Fig. 1, from which the complex nature of the spectrum is apparent. There is good evidence for the presence of an emission feature at around 7 keV. In addition the emission from a hot gas with components at a number of different temperatures is required to explain the data over the 1·3–16 keV range.

The significance of the emission feature may be judged from Fig. 2 where we plot the deviation of the flux in each channel from that given by the best fitting simple continuous spectrum for the 3–12 keV range. The high gain data show an

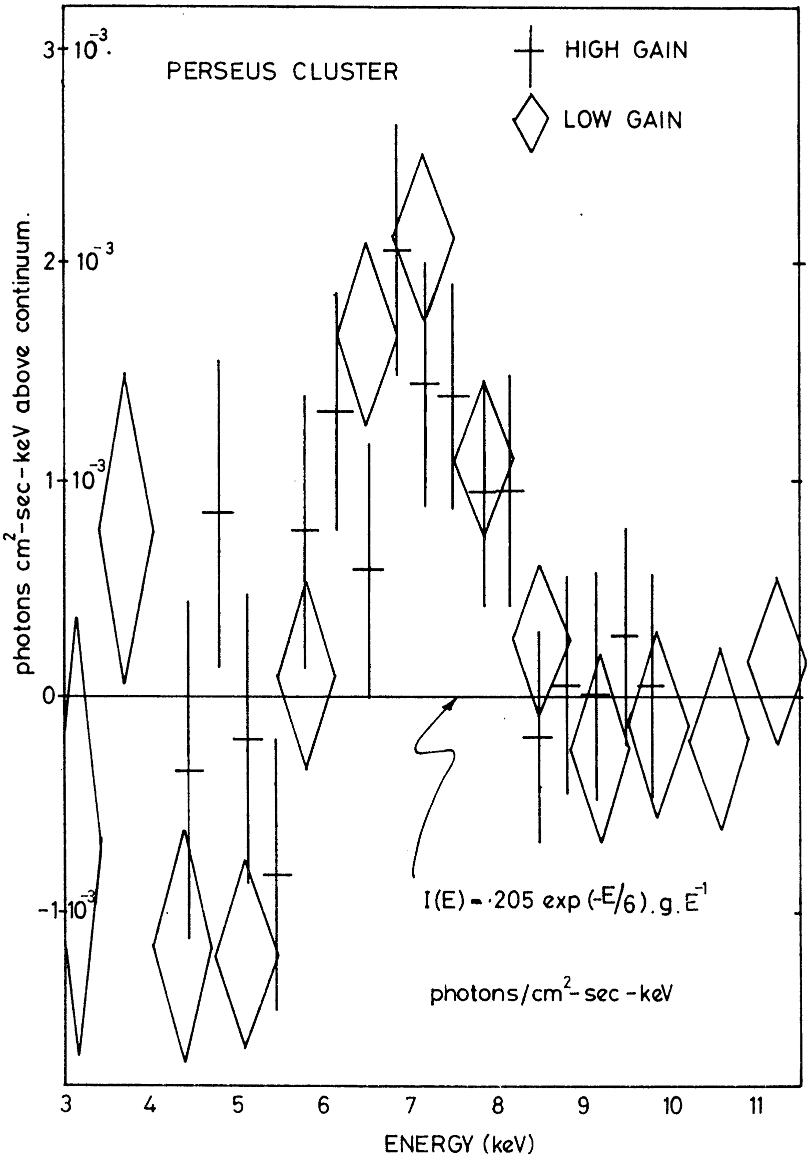

Fig. 2. *The deviation of the flux in each energy channel from that predicted by the best-fitting single temperature continuum is plotted for the range 3–11 keV. Data from both gain modes show a systematic departure from the continuum in the energy range around 6·9 keV. The width of the feature is consistent with that of the gaussian energy resolution function for the detector at 7 keV. Each gain mode shows departures from continuum that are significant at the 5·6 and 6 σ levels.*

excess flux of $3{\cdot}15 \times 10^{-3}$ photon $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which is $5{\cdot}4\ \sigma$ above the continuum. The low gain data give a $6\ \sigma$ signal, with an intensity of $3{\cdot}56 . 10^{-3}$ photon $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. These two independent measurements average to a value of $3{\cdot}35 \pm 0{\cdot}4 \times 10^{-3}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for the flux in the line feature, the line being $7{\cdot}5\ \sigma$ above the continuum. The corresponding equivalent width is 360 ± 50 eV.

A number of possible continuous spectra were computed following the model of Gull & Northover (1975, GN). This model describes the adiabatic hydrostatic atmospheres of hot gas in the gravitational potential wells of clusters of galaxies. We computed composite thermal continuous spectra in terms of the (GN) parameters $T(0)$, T_∞ and T_0. Here, $T(0)$ is the central temperature of the cluster, T_∞ is a constant of integration whose value and sign specify whether the hot gas is bound to the cluster or extends to infinity and

$$T_0 = T(0) - T_\infty. \qquad (2)$$

A somewhat similar description of the nature of the hot gas in clusters has been published independently by Lea (1975).

The best adiabatic gas sphere model is represented by the solid line in Fig. 1. This computed spectrum, which has parameter values $T_0 = 28$ keV and $T(0) = 24$ keV (i.e. $T_\infty = -T_0/7$) keV was obtained by summing the contributions to the emission from regions of the cluster gas at different temperatures. The summation was performed for 10^6 K temperature intervals. An integration of the observed continuum flux in the 1·5–6 keV band leads to a *measured* emission feature to continuum ratio of 0·02.

Although it is difficult to resolve emission features in proportional counter detectors because of their relatively poor energy resolution, 7 keV features have been detected in three other sources. Examples are given in the work of Serlemitsos *et al.* (1975) and Sanford, Mason & Ives (1975) on the Cyg X-3 spectrum in the work of Serlemitsos *et al.* (1973) and Davison, Culhane & Mitchell (1976) on the spectrum of Cas A while the latter authors have also detected iron line emission in the X-ray spectrum of Tycho's SN. *Ariel 5* X-ray spectra of the Crab Nebula, of Cygnus X-1 and of a number of weaker sources, obtained with the same detector as was used in the Perseus observation show no evidence of emission features.

DISCUSSION

The detection of an emission feature at about 7 keV in the Perseus spectrum provides good evidence for the presence of hot plasma in this source. Although the spectrum in Fig. 1 is best described by the adiabatic hot gas model a statistically acceptable fit is provided at energies above 4 keV by a thermal continuous spectrum at a temperature of 6 keV (66×10^6 K). At this temperature, the 7 keV emission feature includes contributions from the resonance and forbidden transitions of Fe XXV together with a contribution from a number of satellites to the resonance line (Grineva *et al.* 1973; Gabriel 1972) and the Lyman-α line of Fe XXVI. When allowance is made for all of these contributions, calculations of the line to continuum ratio for a 60–70×10^6 K plasma (Mewe 1972; Tucker & Koren 1971) suggest that the ratio should be $\simeq 0{\cdot}07$ for a cosmic iron abundance ($N(\mathrm{Fe})/N(\mathrm{H})$) of 5×10^{-5}. Thus the observed value of 0·02 would indicate that iron is underabundant by a factor of 4 for the entire cluster source. However, the adiabatic gas sphere model suggests that the hot intracluster plasma is mainly intergalactic material which has fallen into the cluster potential well. If this is so, it would be rather surprising to find significant concentrations of heavy elements in such material. It is possible that active galaxies in the cluster, such as NGC 1275, could enrich the gas in their immediate neighbourhood with iron and other heavy elements. While it is difficult to estimate how much of the intracluster gas has been so enriched, it is possible to consider an extreme case in which the iron line emission originates only in the neighbourhood of NGC 1275. Earlier work (Fabian *et al.* 1974; Wolff *et al.* 1976) has shown that about 10–20 per cent of the total flux from the cluster is associated with NGC 1275. If only the hot material near the galaxy is enriched, then the iron abundance in the neighbourhood of NGC 1275 could be up to 2·5 times greater than the cosmic value assumed above.

It was remarked earlier that simple thermal or power law spectra are unable to fully explain the observations which require the presence of gas having a range of temperatures. It will be of interest to correlate the presence or absence of active galaxies and the distribution of galaxies in the cluster with the X-ray spectral features observed and with the shape of the continuous spectrum. A more detailed discussion of these aspects for a number of the brighter X-ray cluster sources is in preparation. However, high spatial resolution maps of the X-ray cluster sources with sufficient spectral resolution to detect emission lines will ultimately be required if we are to separate the emission associated with individual active galaxies from that of the cluster as a whole.

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