X-RAY SPECTRA OF CLUSTERS OF GALAXIES

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Now that the predominantly thermal nature of the X-ray emission from clusters of galaxies is well established (see e.g. Mushotzky et al. 1978, Smith et al. 1979), it is appropriate to ask what further information can be gleaned from X-ray spectroscopic observations. While the above publications made use of data from the OSO-8 satellite, two newer experiments have been flown by our group on the HEAO-1 and HEAO-2 (Einstein) satellites. The first of these, the A-2 experiment, was comprised of gas proportional counters like our OSO-8 detectors, while the second, the Solid State Spectrometer (SSS), is a cooled Si detector with narrow field of view and heightened energy resolution.

Using the GSFC A-2 detectors for pointed observations of clusters of galaxies, great statistical accuracy is possible across a broad energy band from 2 to 30 keV. Figure 1 is one representation (see Pravdo et al. 1976) of what the incident spectrum from the Perseus cluster would have to look like, showing allowable errors, in order to produce our observed counting rate spectrum. This spectrum is perfectly isothermal within the estimated few percent uncertainty in energy calibration, and iron lines are evident at about 6.7 and 7.9 keV. The equivalent widths of these features are in agreement with those expected from a hot gas in collisional equilibrium having an Fe/H ratio of 1.4×10^{-5} by number (Raymond and Smith 1977; tables of equivalent widths of the 6.7 and 7.9 keV line blends based on improved atomic data are given by Pravdo and Smith 1979). Figure 2 shows the incident spectrum from M87 in the Virgo cluster required to fit the Einstein SSS observation. In this figure the counting spectrum has been directly inverted using the technique of Blisset and Cruise (1979). Line features of Mg, Si, S (all K-shell transitions), and Fe (L-shell) are present with high significance and the intensities they would have with roughly solar abundances, proving that other elements besides iron are present in the intracluster gas around this massive galaxy.

Table 1 summarizes the state of knowledge concerning X-ray spectra of clusters available from satellite experiments. In column 1 we give the cluster name identified with the X-ray source. Columns 2 and 3 give

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 735–740.

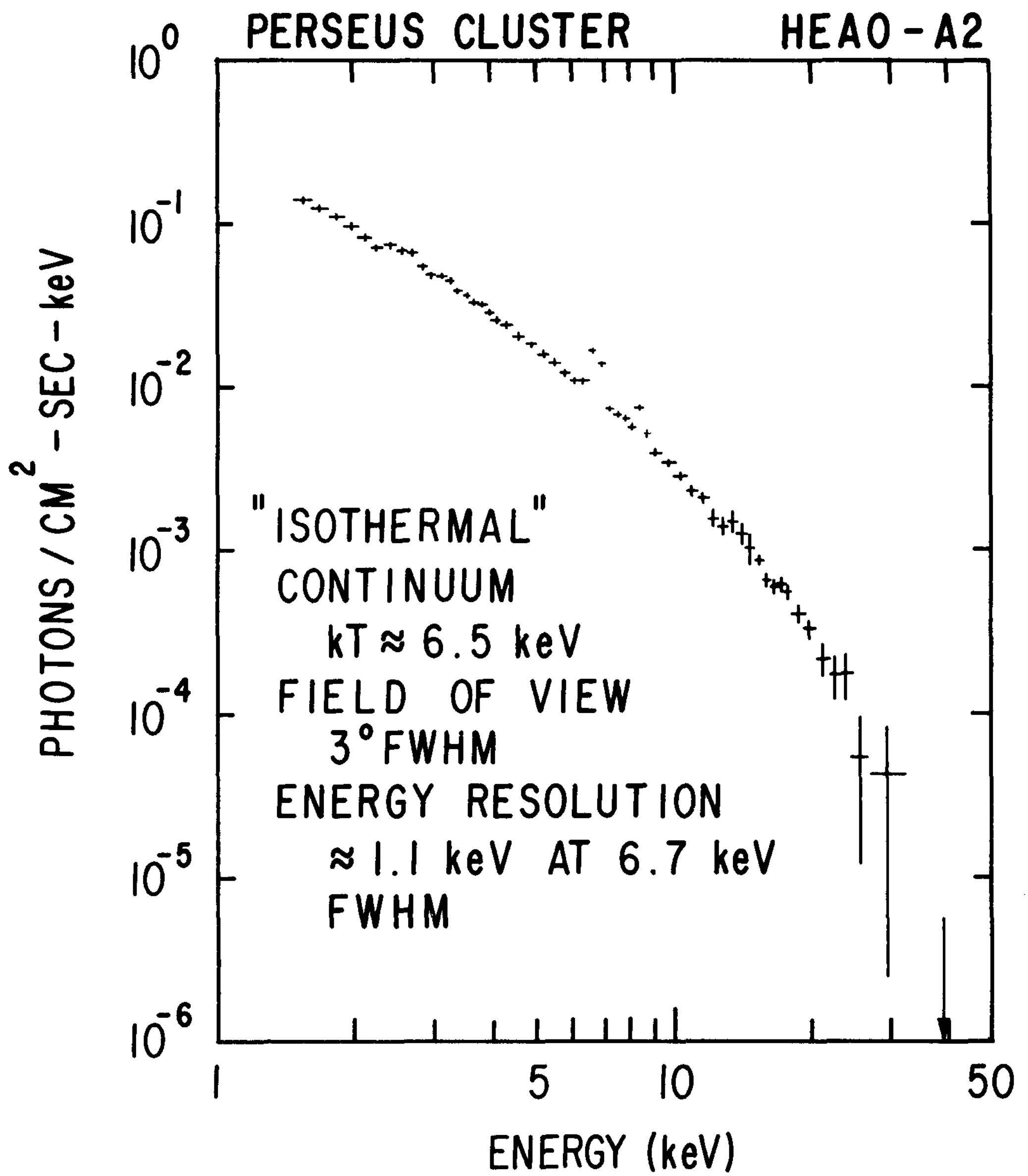
PERSEUS CLUSTER
HEAO - A2
PHOTONS / CM2 - SEC - keV
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
"ISOTHERMAL" CONTINUUM
kT ≈ 6.5 keV
FIELD OF VIEW
3° FWHM
ENERGY RESOLUTION
≈ 1.1 keV AT 6.7 keV
FWHM
1
5
10
50
ENERGY (keV)

Figure 1.

Table 1

Name	kT_1	kT_2	6.7 keV E.W.	Fe/H	7.9 line?	Other lines?	L_x^{44}	Observations*
A85	6.8±.5	No	300	1.2	?	?	6.7	4
A119	5.4±.5	?	300	0.95	?	?	3.7	1,4
A262	2.4±.8	?	?	?	?	?	0.38	1,2,4
NGC 1129 group	>10	4.1±.3	630	1.8	Yes	?	2.0	2,4
A401	7.6±1.5	No	300	1.3	?	?	21.9	2,4
A426	6.4±.4	Very weak	400	1.4	Yes	Si,S,Fe	12.4	1,2,3,4,5
0340-538	6.5±1.0	?	800	2.9	?	?	4.3	4
A478	7.3±1.0	No	360	1.5	?	?	22	2,3,4
Ser 40/6	9.0±.5	?	150	0.77	?	?	7.6	3,4
3C 129 cluster	5.4±1.0	?	330	1.0	?	?	2.7	2
0626-54	6.3±3	?	800	2.9	?	?	6.9	2,3
A754	11.0±3.0	No	<150	<1.0	?	?	10.4	4
A1060	>10	2.0	800	2.5	?	?	0.17	2,4
A1367	2.8±1.0	?	?	?	?	?	0.49	2
Virgo	>10	2.2	1100	3.2	Yes	Mg,Si, S,Fe	0.29	1,2,4,5
Centaurus	8±2	2.4±.3	600	>1.4	Yes	?	0.71	1,2,3,4
A1656	7.9±.3	No	200	0.88	Yes	No?	8.47	1,2,3,4,5
1326-311	$8.2^{+7.3}_{-3.0}$	?	?	?	?	?	12.0	2
A1795	5.8±1.0	No	360	1.2	?	?	10.1	3,4
A2029	$6.2^{+2.6}_{-1.6}$	?	?	?	?	?	19.5	2
A2065	2.4-4.5	?	?	?	?	?	5.6	1
A2142	10.9±1.0	No?	200	1.3	?	?	16.1	2,3,4
A2147	>10	<2	600	>1.0	?	?	2.7	2,4
A2199	>9	1.8	1000	>3.3	?	?	2.8	2,4
A2256	7,+3,-2	?	?	?	?	?	8.2	2
A2319	12.5^{+7}_{-4}	?	?	?	?	?	12.7	2
Klem 44	<6	?	?	?	?	?	0.7	4

*1 = Uhuru, 2 = OSO-8, 3 = Ariel V, 4 = HEAO-1 A-2, 5 = HEAO-2 SSS

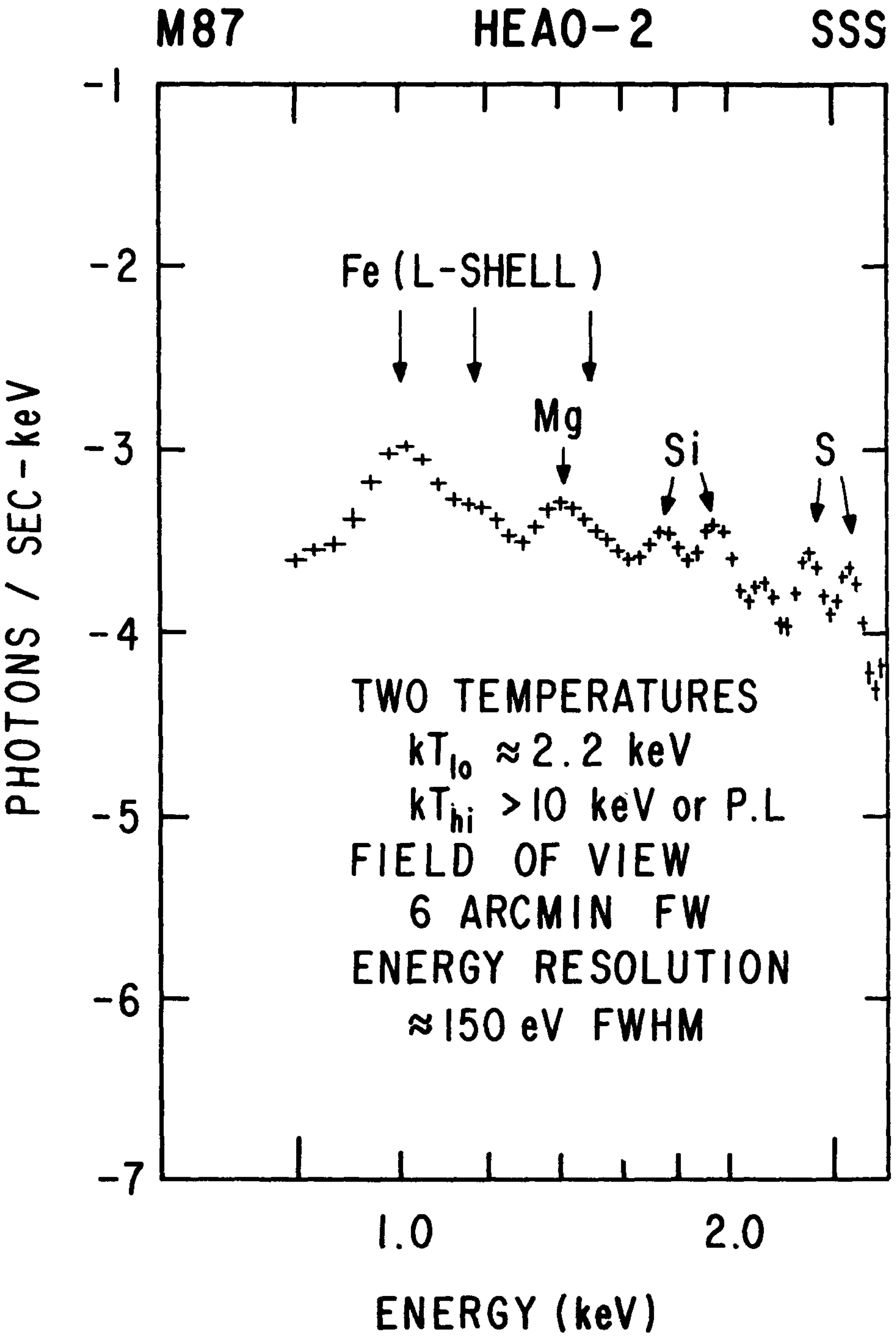

Figure 2

https://doi.org/10.1017/S1539299600004664 Published online by Cambridge University Press

the one or two temperatures, in keV, required to fit the best data, usually A-2. "No" in col. 3 means a second temperature lower than the major one has been tried as an added component, but this did not improve the fit. Errors in cols. 2 to 4 are 1σ, where given, and the numbers from A-2 data should be considered preliminary. In col. 4 we give the the equivalent width of the prominent 6.7 keV line in eV, in col. 5 the derived iron abundance Fe/H by number, multiplied by 10^5. The next two columns show the presence of other lines in A-2 and SSS data. Col. 8 shows the 2 to 10 keV luminosity in units of 10^{44} erg/s. The last column lists the satellites which have made spectroscopic observations.

This summary demonstrates that cluster spectra are more complex than simple thermal bremsstrahlung. The clusters requiring two temperatures must have separated regions of higher and lower temperature, which may, if the scales are large enough, be related to the varied cluster surface brightness morphologies cataloged by the imaging experiments on HEAO-2 (Jones et al. 1979). For example Mitchell and Mushotzky (1980) have made a detailed study of the A-2 data for the Centaurus and A1060 clusters. They found that two temperature components and both the 6.7 and 7.9 keV lines were required for Centaurus, two temperatures and the 6.7 keV line for A1060. If the two regions were hot gases in pressure equilibrium, they would occupy comparable fractions of the cluster volume, which implies the existence of inhomogeneous heating or cooling mechanisms. Alternatively, the data allow the higher temperature component to be replaced by a power law component from inverse Compton emission, but this would force the remaining thermal component to have higher than solar iron abundance. Maps of such clusters made in the band below 4 keV, such as those possible with HEAO-2, will show the distribution of the lower temperature component. Comparing the optical velocity dispersion of the galaxies or the central galaxy density as listed in Mushotzky et al. (1978), we see some evidence that the *lower* temperature component is more correlated with the depth of a cluster's gravitational potential.

In SSS observations of NGC 1275 in the Perseus cluster, the same lines as those in Fig. 2 were found, but with lower strengths. Since the continuum from A-2 (Fig. 1) shows only a temperature of 6.4 keV, one would expect to see from Si and S only Lyman alpha of hydrogen - like ions. The presence of resonance line emission from helium-like ions of these two elements in the Perseus spectrum in fact requires the addition of a low temperature component with kT about 1 keV. A detailed spectral fitting analysis thus reveals a low kT component which is observable only by its line emission. Since the 6 arcminute field of view gives an upper limit to the volume within which the 1 keV gas must exist, it implies a minimum density for the gas, $n_e > 6 \times 10^{-3}$ cm^{-3}. The cooling time of this gas is less than about 2 billion years, indicating that, in the absence of an unseen heating mechanism, the cooling inflow predicted by Cowie and Binney (1977) and Fabian and Nulsen (1977) is taking place around NGC 1275.

https://doi.org/10.1017/S1539299600004664 Published online by Cambridge University Press

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