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LOW ENERGY X-RAY EMISSION FROM FIVE GALAXY CLUSTER SOURCES

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ABSTRACT

We report the detection of soft (0.2–2.5 keV) X-ray emission from several known cluster X-ray sources using the low energy detectors of the *HEAO 1* A-2 experiment. Soft X-ray emission was observed from five clusters—the Centaurus cluster, Abell 2147, SC 1329−314, Abell 2319, and Abell 133. Spectral parameters estimated from the soft X-ray fluxes are inconsistent with those reported at higher energies for the Centaurus cluster, Abell 2147, and SC 1329−314, indicating the presence of more than one spectral component in these clusters. No evidence for more than one component was found for either Abell 2319 or Abell 133. The temperature of Abell 133 is constrained to be less than 2×10^7 K, making it the coolest X-ray cluster yet detected.

Subject headings: galaxies: clusters of — X-rays: sources

I. INTRODUCTION

Clusters of galaxies are well established as a class of X-ray sources in the 2–10 keV energy range, with about 30 known sources and about 20 or 30 probable or suspected identifications. At least five clusters—the Perseus, Virgo, and Centaurus clusters, Abell 1060, and Abell 2147—show evidence of more than one spectral component (Mitchell *et al.* 1976; Serlemitsos *et al.* 1977; Davison 1978; Mushotzky *et al.* 1978; Mitchell and Mushotzky 1980; Pravdo *et al.* 1979). Using data from the A-2 experiment of *HEAO 1*, we have studied the soft X-ray emission from known or suspected medium energy X-ray clusters in an attempt to discover whether other clusters also show evidence of multi-component emission. We report our observations of five galaxy clusters which were detected in the 0.2–2.5 keV energy range—the Centaurus cluster, Abell 2147, SC 1329−314, Abell 2319, and Abell 133.

II. OBSERVATIONS

The A-2 experiment aboard *HEAO 1*[6] (fully described by Rothschild *et al.* 1979) consisted of two Low Energy Detectors (LEDs) sensitive in the range of 0.2–2.5 keV, one Medium Energy Detector (MED) sensitive in the range of 1.7–18 keV, and three High Energy Detectors (HEDs) sensitive in the range of 3–60 keV. Data from LED-1 and the MED were used in the present analysis. The locations of the five sources detected with the 1°5 × 3°0 field of view of the LED-1 detector, which are consistent with the positions of the Centaurus cluster, Abell 2147, SC 1329−314, Abell 2319, and Abell 133, respectively, are shown in Figure 1.

The LEDs accumulated counts in three broad energy bands (0.2–0.48 keV; 0.48–1.85 keV; and 0.75–2.5 keV), as well as in 29 pulse-height analyzer (PHA) channels. Since the sources discussed in this paper are weak, with typical total count rates of only 5–15 counts s^{-1}, the PHA data are of low statistical quality. Thus there is no advantage in fitting the PHA data as opposed to the broad-band scalars. Moreover, the count rates from the broad-band scalars were sampled more frequently (every 1.28 s as opposed to every 10.24 s for the PHA data); in the scanning mode, this higher sampling rate allows us to separate the weak cluster sources from neighboring sources and nearby galactic background features and to determine the diffuse background contribution at the source more precisely than is possible for the PHA data. Accordingly, we have used the broad-band data rather than the PHA data in our analysis. For each cluster we have fitted the LED-1 discovery scalar count rates together with either the *Ariel V* 2–10 keV intensity (the Centaurus cluster; Cooke *et al.* 1978), the *HEAO 1* A-2 2–6 keV intensity (Abell 2147; Pravdo *et al.* 1979), or the total count rate in the MED (SC 1329−314, Abell 2319, Abell 133) to a simple one-component thermal bremsstrahlung model.

We will now discuss the results of these fits for each cluster individually and compare them with existing data. The broad-band fluxes (keV cm^{-2} s^{-1} keV^{-1}), assuming the best-fit spectra, are shown in Figure 2, together with the 90% and 99% confidence contours for the parameters. A summary of the broad-band fluxes, together with their systematic uncertainties, is shown in Table 1. In the following sections, cluster distance and richness class data were taken from Abell (1958), while optical morphological types were taken from Rood and Sastry (1971), Bahcall (1977*a*), Lugger (1978), Bautz and Morgan

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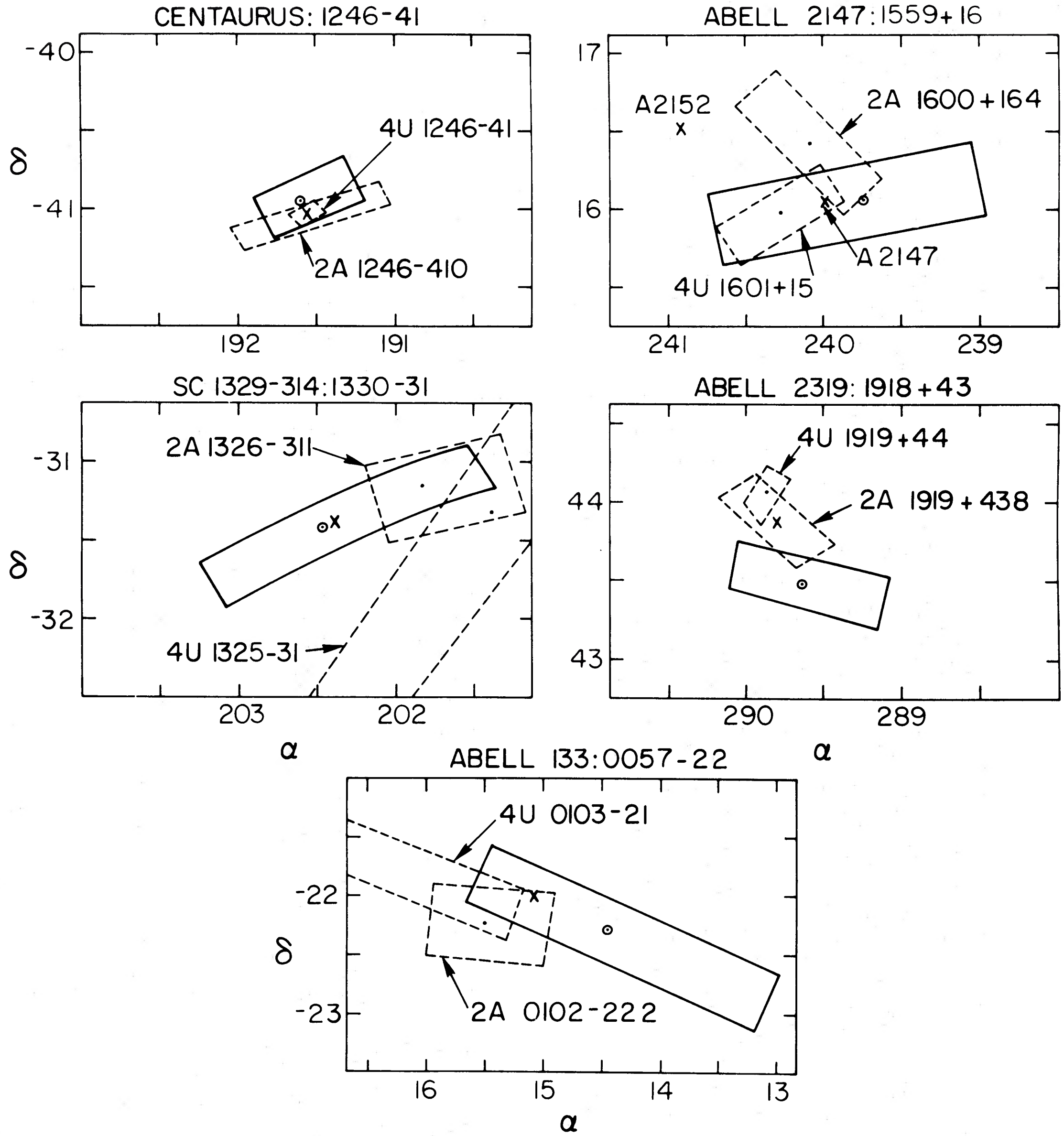

FIG. 1.—Comparison of best-fit LED source positions (*dotted circles*) and 90% confidence error boxes (*solid lines*) with the associated cluster positions (*X*'s) and previously determined *Uhuru* and *Ariel V* course best-fit positions (*plain dots*) and error boxes (*dashed lines*).

(1970), and Leir and van den Bergh (1977). Mean cluster redshifts were taken from Yahil and Vidal (1977) and Lugger (1978), and mean dispersions were taken from Faber and Dressler (1976, 1977) and Yahil and Vidal (1977). Galactic neutral hydrogen column densities were taken from Heiles (1976), unless otherwise noted.

a) *The Centaurus Cluster*

The Centaurus cluster is a rich, irregular cluster with a spiral-poor core and a spiral-rich halo (Dawe, Dickens, and Peterson 1977). The cluster has a redshift of 0.0113 and a mean velocity dispersion of 945 km s^{-1}. The brightest galaxy in the cluster, NGC 4696, is associated with the radio source PKS 1245−41 (Mills, Slee, and Hill 1960). The cluster is a strong X-ray source and shows evidence for iron line emission at 6.7 keV (Mitchell and Culhane 1977; Mushotzky *et al.* 1978; Mitchell and Mushotzky 1980) and at 7.9 keV (Mitchell and Mushotzky 1980), corresponding to an abundance of iron relative to hydrogen of about half the cosmic value. The best-fit temperature derived from the *OSO 8* data is about 6×10^7 K (Mushotzky *et al.* 1978), somewhat higher than the best-fit *Ariel V* temperature of 4×10^7 K (Mitchell and Culhane 1977). However, Mushotzky *et al.* note that their best-fitting model indicates a definite excess at energies greater than 10 keV relative to a single temperature fit.

TABLE 1

OBSERVED X-RAY FLUXES: *HEAO 1*

Cluster	Band (keV)[a]	Best Fit Flux (keV cm^{-2} s keV)	90% Conf. Flux Range[b]
Centaurus............	0.23–0.29	~0	$<2 \times 10^{-2}$
	0.41– 1.9	5.2×10^{-2}	$(5.0–6.2) \times 10^{-2}$
	0.72– 2.6	4.6×10^{-2}	$(4.5–4.7) \times 10^{-2}$
A2147	0.18– 0.29	5.7×10^{-2}	$(5.7–6.0) \times 10^{-2}$
	0.33– 1.7	1.1×10^{-2}	$(1.0–1.2) \times 10^{-2}$
	0.68– 2.5	1.8×10^{-2}	$(1.7–2.0) \times 10^{-2}$
SC 1329−314	0.26– 0.29	~0	$<2.4 \times 10^{-2}$
	0.62– 2.1	2.8×10^{-2}	$(2.1–4.1 \times 10^{-2}$
	0.78– 2.5	4.6×10^{-2}	$(4.1–5.1) \times 10^{-2}$
	1.2 – 6.4	1.6×10^{-2}	$(0.7–2.0) \times 10^{-2}$
A2319	0.21– 0.29	1.9×10^{-3}	$<2.6 \times 10^{-3}$
	0.37– 1.9	3.0×10^{-2}	$(2.6–2.8) \times 10^{-2}$
	1.4 –10.6	1.2×10^{-2}	$(1.2–1.8) \times 10^{-2}$
A133	0.18– 0.29	1.2×10^{-1}	$(1.2–1.4) \times 10^{-1}$
	0.32– 1.5	1.0×10^{-2}	$(0.9–2.3) \times 10^{-2}$
	0.66– 2.1	1.4×10^{-2}	$(1.4–2.3) \times 10^{-2}$
	1.2 – 6.1	3.6×10^{-3}	$(0.2–1.9) \times 10^{-2}$

[a] LED and MED energy ranges calculated for the best-fit spectrum. Limits are those energies at which the best-fit spectral flux, weighted by the detector efficiencies, falls to 10% of its maximum value within each band.

[b] Range of spectral fluxes calculated for spectra within the 90% confidence contour.

A single-component thermal model gives an acceptable fit to the LED count rates and the *Ariel V* 2–10 keV intensity, with a minimum χ^2 of 1.65 (1 degree of freedom). However, the best-fit absorbing column, 2×10^{21} cm^{-2}, is unrealistically high compared to the galactic neutral hydrogen column, 1.8–2.0 $\times 10^{20}$ cm^{-2} (Heiles 1979), even after allowing for the fact that the column derived from X-ray data is likely to be somewhat higher than the radio column, because of the possible presence of molecular and ionized hydrogen (Mason *et al.* 1976). If we fix the absorbing column at the neutral hydrogen value, then the A-2 99% confidence limits on the temperature are only marginally consistent with the *OSO 8* 90% confidence limits. Thus the temperature derived from the A-2 data is certainly not consistent with that derived from the *OSO 8* data at the 90% confidence level. (Unfortunately, we do not know the location of the *OSO 8* contours that correspond to confidence levels greater than 90%.) A single-temperature model is therefore not a good fit to the *HEAO* LED and the *OSO 8* data. This conclusion is further supported by recent MED and HED pointing-mode observations of the cluster, in which two- component models are required in order to fit the spectrum (Mitchell and Mushotzky 1980). We note that the temperature derived by these authors for the low temperature component, 2.7×10^7 K, is comparable to the best-fit LED temperature, 2.5×10^7 K.

b) *Abell 2147*

Abell 2147 is a richness class 1, distance class 1, spiral-poor (Bahcall 1977*b*) F cluster of Bautz-Morgan class III[7]. The cluster has a redshift of 0.0377 and a mean velocity dispersion of 1120 km s^{-1}. Three of the cluster members are giant elliptical radio galaxies (1559+16W2, 1559+15W1, 1600+15W2; Jaffe and Perola 1975); the first of which is a cD galaxy (Cooke *et al.* 1977). The cluster is both a 4U source (Forman *et al.* 1978) and an *Ariel V* source (Cooke *et al.* 1977) and shows iron line emission at 6.7 keV (Pravdo *et al.* 1979).

[7] The cluster has also been classified as Bautz-Morgan type II (Corwin 1974) and as Bautz-Morgan type II–III (McHardy 1974).

Abell 2147 is also a member of the Hercules supercluster of galaxies; the next closest member cluster is Abell 2152, which is separated by 0°.9 from Abell 2147. Although as much as 2.2 LED counts s^{-1}, (99% confidence upper limit) may arise from Abell 2152, this does not significantly affect the count rates we derive for Abell 2147. Our upper limit for Abell 2152 is equivalent to an X-ray intensity from 0.2–2.5 keV of 5×10^{-11} ergs cm^{-2} s^{-1} ($L_x \lesssim 3 \times 10^{44}$ ergs s^{-1}), assuming a spectrum with temperature $T = 3 \times 10^7$ K and absorbing column $N_x = 4 \times 10^{20}$ cm^{-2}.

The LED discovery scalar count rates were fitted together with the 2–6 keV intensity derived by Pravdo *et al.* (1979) from the MED PHA data. A single-component thermal model gives a poor fit to the data with a minimum reduced χ^2 of 2.40 (for 1 degree of freedom). Our spectrum is also inconsistent with the single-component *OSO 8* spectrum (Mushotzky *et al.* 1978) at the 99% confidence level for column densities above 3×10^{19} cm^{-2}, even though the A-2 2–6 keV intensity is consistent with the flux at 5 keV detected by *OSO 8*. Our best-fit temperature is 3.3×10^7 K, in fair agreement with the 2×10^7 K derived by Pravdo *et al.* (1979) for the low temperature component of the MED spectrum. Our best-fit column density is extremely low; indeed, the 99% confidence upper limit to the column is only marginally consistent with the galactic value of 4–5 $\times 10^{20}$ cm^{-2}. If

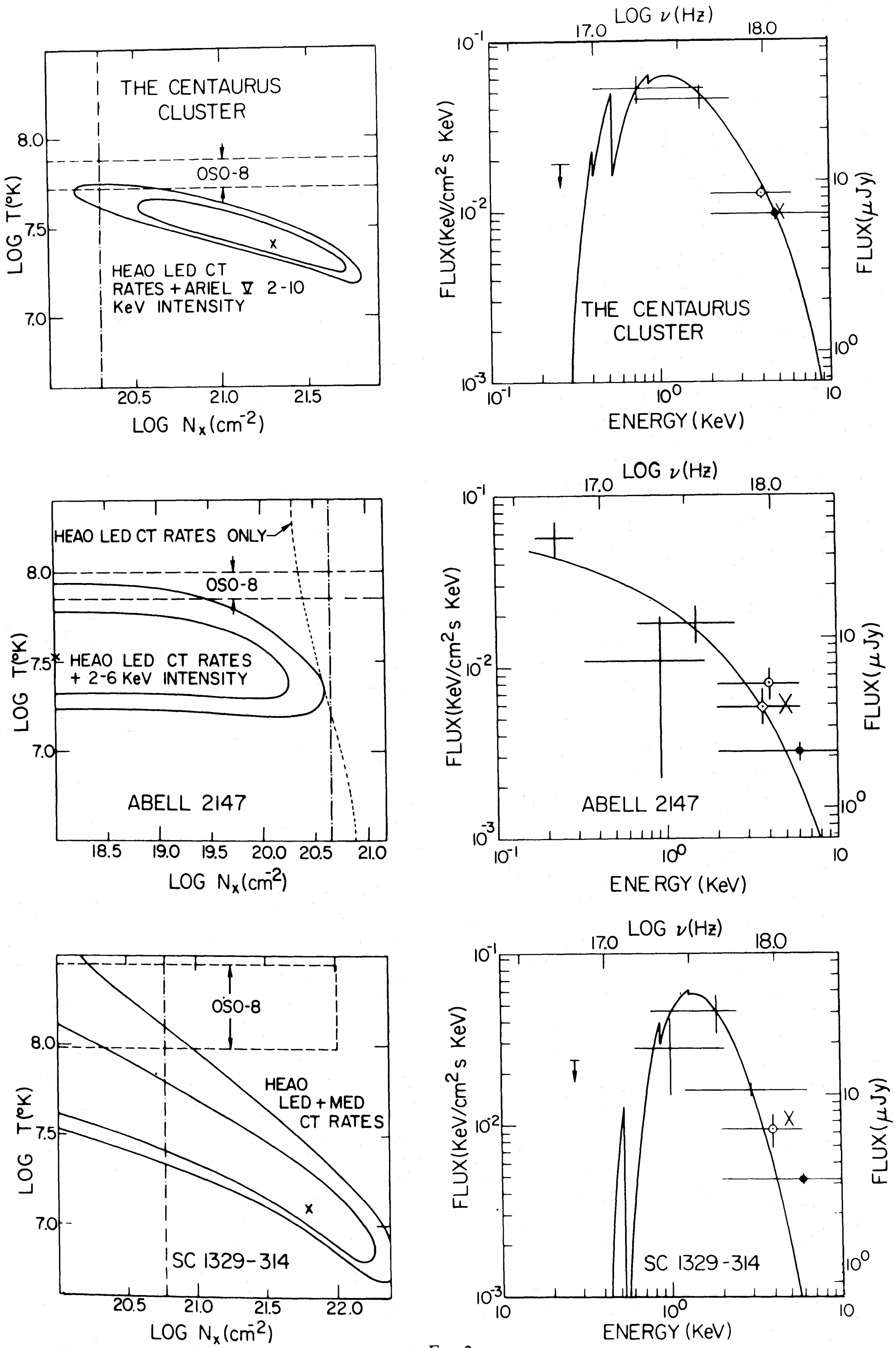
THE CENTAURUS CLUSTER
OSO-8
HEAO LED CT RATES + ARIEL V 2-10 KeV INTENSITY
LOG T(°K)
LOG N_x(cm^-2)
LOG ν (Hz)
17.0
18.0
FLUX(KeV/cm^2 s KeV)
FLUX(μJy)
ENERGY (KeV)
HEAO LED CT RATES ONLY
HEAO LED CT RATES + 2-6 KeV INTENSITY
ABELL 2147
HEAO LED + MED CT RATES
SC 1329-314

FIG. 2

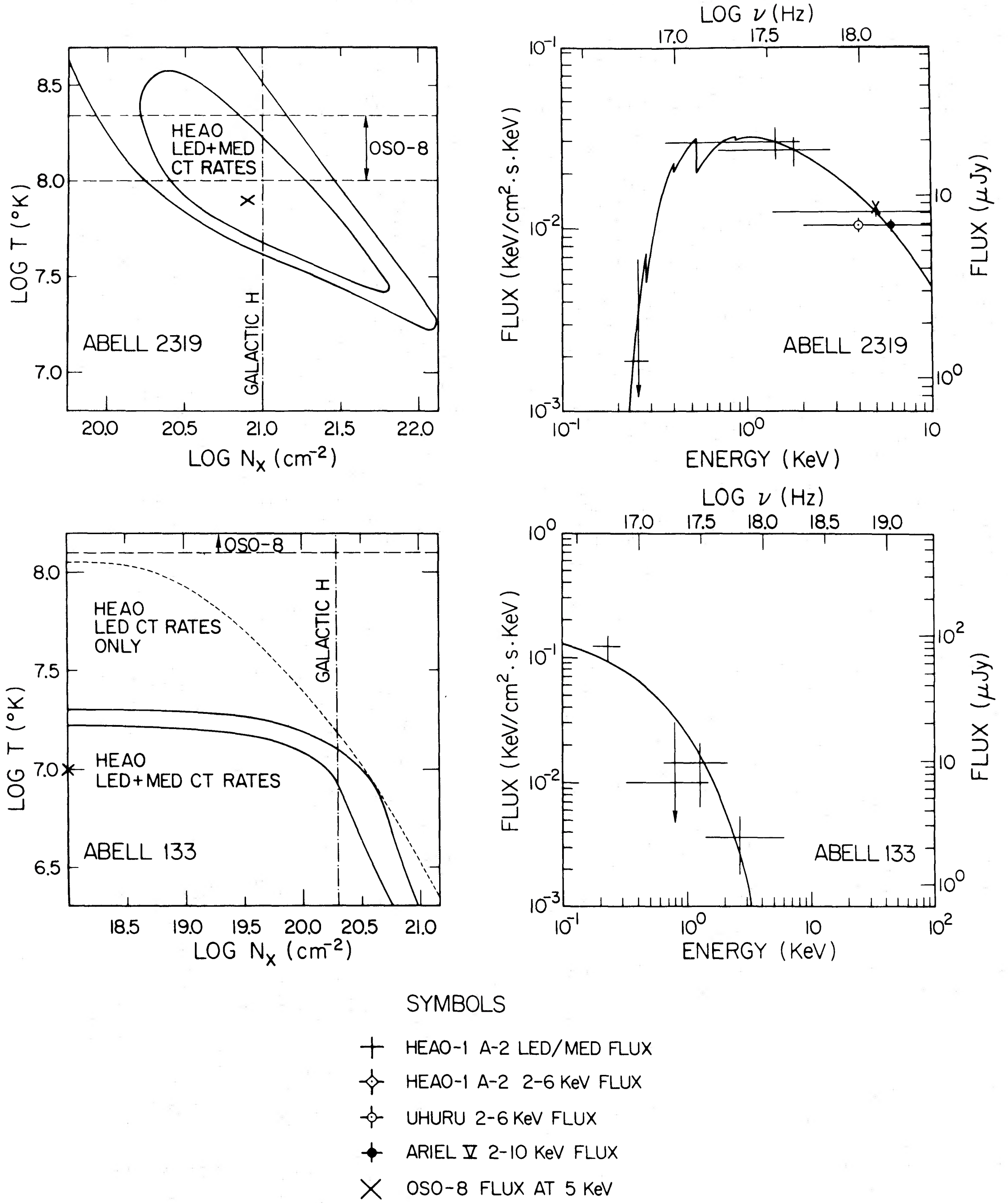

FIG. 2-*Continued*

FIG. 2.—LED and MED broad-band spectral fluxes and best-fit (*right column*) shown with *HEAO 1* A-2 90% and 99% confidence contours (*solid lines*), boxes containing *OSO 8* 90% confidence contours (*large dash lines*), galactic hydrogen column density measured from 21 cm data (*dot-dash lines*), and, for Abell 2147 and Abell 133, 99% confidence contours from fits to LED count rates only (*small dash lines*) (*left column*). The fluxes are calculated from the best-fit spectra and are drawn to show the relative contribution to χ^2 from each band; their uncertainties reflect the statistical counting errors (see Table 1 for systematic uncertainties). *Uhuru*, *Ariel V*, and *OSO 8* fluxes (see key) are also shown for Centaurus, Abell 2147, SC 1329–314, and Abell 2319.

we adopt the galactic value as a lower limit to the column, then the LED broad-band count rates alone constrain the temperature to be less than 2×10^7 K with a confidence of 99%. Thus, the LED discovery scalar data suggest that the temperature of the cool component is less than the value derived from the MED PHA data.

Recent observations of Abell 2147 by the Imaging Proportional Counter (IPC) on the *Einstein* Observatory (Giacconi *et al.* 1979) show that the X-ray emission from this cluster is broad and highly clumped (Jones *et al.* 1979). Jones *et al.* derive a value of 330 kpc for an isothermal sphere core radius (see, e.g., Lea *et al.* 1973), although they note that the surface brightness distribution is clearly aspherical. The reported 0.5–3.0 keV luminosities observed with *Einstein* are 2.73×10^{43} ergs s^{-1} within 3′ of the cluster center and 1.73×10^{44} ergs s^{-1} within 11′ of the center, where $3.7\ (+4, -4) \times 10^{42}$ ergs s^{-1} originate from the radio galaxy WE 1601+16W3. The total luminosity expected from an isothermal sphere with the reported core radius and central luminosity is 1.9×10^{44} ergs s^{-1}, a factor of 2 less than the observed luminosity derived from the *HEAO 1* LED of 4×10^{44} ergs s^{-1}.

A possible explanation for this discrepancy is that the gas distribution in Abell 2147 is actually more extended than that for an isothermal sphere. However, this is not necessarily the case, because the emission from this cluster is highly clumped. Particles which are clumped emit more bremsstrahlung radiation than the same number of particles dispersed throughout the same total volume. Assuming that the observed emission is due to a smooth distribution of gas particles rather than a clumpy distribution thus leads to an underestimate of the emission measure per particle. Moreover, if the degree of clumpiness is not constant throughout the cluster but increases with distance from the cluster center, gas particles in the outer regions of the cluster will contribute proportionately more emission than gas particles in the inner regions. In this way, clumping the gas in a cluster can have the same effect on the radial dependence of emission as extending the gas distribution. The data so far do not distinguish between the two effects, but they only indicate that $n(r)f(r)$, where $n(r)$ is the mean number density of particles and $f(r)$ is the degree of clumpiness, decreases less rapidly than $(1 + r^2/a^2)^{-3/2}$.

c) SC 1329−314

SC 1329−314 is a richness class 0, distance class 4, I cluster with a redshift of approximately 0.07. The radio source PKS 1327−31, which is within one Abell radius of the cluster center, is probably not associated with the cluster since it is identified with a QSO with a redshift of 1.326 (Peterson *et al.* 1979). The cluster is a 4U source (Lugger 1978) and an *Ariel V* source (Cooke *et al.* 1978) and shows iron line emission at 6.7 keV (Mushotzky *et al.* 1978). The best-fit temperature derived from a single-component fit to the *OSO 8* data is about 1.5×10^8 K. The cluster lies approximately 4° from the X-ray emitting Seyfert galaxy MCG−6-30-15 (Pineda *et al.* 1978), which has been detected as a separate source by our experiment.

A single-temperature model gives a poor fit to the LED and MED broad-band count rates; the minimum χ^2 is 2.92 for 1 degree of freedom. Moreover, our spectral parameters are not in agreement with the parameters derived from the *OSO 8* data (Mushotzky *et al.* 1978). For values of the absorbing column greater than or equal to the galactic value of 6×10^{20} cm^{-2}, our spectrum is not consistent with the *OSO 8* spectrum at confidence levels of 90% or less. If the A-2 source is correctly identified with the cluster, then two components are necessary to describe its spectrum—a cool component with a temperature in the range of 10^7–7×10^7 K, as well as a hot component with a temperature of 1.5×10^8 K.

d) Abell 2319

Abell 2319 is a richness class 1, distance class 3, cD cluster of Bautz-Morgan type II–III.[8] The cluster has a redshift of 0.0563 and a mean velocity dispersion of 873 km s^{-1}. The cD galaxy is associated with the radio galaxy at $\alpha = 19^h10^m$, $\delta = 43°50'$, given in Owen (1975). The cluster is a 4U source (Forman *et al.* 1978) and an *Ariel V* source (Cooke *et al.* 1978) and shows iron line emission at 6.7 keV (Mushotzky *et al.* 1978).

A single-temperature model gives a good fit to the A-2 broad-band count rates with a minimum χ^2 of 0.10 per degree of freedom. The results of the fit are in good agreement with the *OSO 8* results (Mushotzky *et al.* 1978). Although our best-fit temperature of 8×10^7 K is somewhat lower than the best-fit *OSO 8* temperature of 1.5×10^8 K, the A-2 spectrum agrees with the *OSO 8* spectrum at the 90% confidence level. From our 90% confidence contour, we can constrain the absorbing column in the direction of Abell 2319 to lie between 1.6×10^{20} and 1.8×10^{21} cm^{-2}; the galactic neutral hydrogen column is 1×10^{21} cm^{-2}. The MED flux, derived assuming the best-fit spectrum, is also in good agreement with the *Uhuru*, *Ariel V*, and *OSO 8* values.

Einstein observations of Abell 2319 show a smooth, broad, centrally peaked X-ray surface-brightness distribution characterized by an isothermal core radius of approximately 500 kpc (Jones *et al.* 1979). Jones *et al.* report X-ray luminosities in the 0.5–3.0 keV energy range of 2.29×10^{44} ergs s^{-1} within 11′ of the center. The total luminosity expected from such an isothermal sphere is only 8×10^{44} ergs s^{-1}, 50% below the observed A-2 luminosity of $(1.2 + 0.2) \times 10^{45}$ ergs s^{-1}. Moreover, Jones *et al.* assume a temperature of 12.5 keV; if the lower temperature of 7 keV is used as suggested by the *HEAO 1* A-2 data, the IPC luminosities are reduced by approximately 20%. Since the observed surface-brightness distribution is not clumpy, our data suggest that the gas distribution in the cluster is actually more extended than that of an isothermal sphere. This conclusion is supported by the results of Schwarz *et al.* (1979), who derive an isothermal sphere core radius of 0.7 (+0.32, −0.16) Mpc on the basis of the source demodulation in the Scanning Modulation Collimators of *HEAO 1* and the flux detected by the A-2 MED.

[8] Abell 2319 has also been classified as Bautz-Morgan type I-II by Corwin (1974).

e) *Abell 133*

Abell 133 is a richness class 0, distance class 4, cD cluster of Bautz-Morgan type I. We have measured the redshift of the cluster using the Lick 3 m telescope with the image tube scanner (Robinson and Wampler 1972) and found it to be 0.06. The bright cD galaxy has been associated with the steep-spectrum low-frequency radio source MSH 01−201 (Tovmassian and Moiseev 1967), whose radio properties are described by Ghigo and Owen (1973) and Véron (1977). The cluster has been identified as an *Ariel V* source (Cooke *et al.* 1978), with an intensity of 3.6×10^{-11} ergs cm^{-2} s^{-1} (2–10 keV), and as an *OSO 8* source (Mushotzky *et al.* 1978), with a significantly higher intensity of 6×10^{-11} ergs cm^{-2} s^{-1}.

A single-temperature model fits the LED and MED broad-band count rates acceptably with a minimum χ^2 of 1.97 (1 degree of freedom). Our spectral fits constrain the temperature of the source to be less than 2×10^7 K, with a best-fit temperature of only 10^7 K. We can also place a 99% confidence upper limit to the column density of roughly 2×10^{21} cm^{-2}.

The count rate recorded for Abell 133 by the MED detector is about a factor of 3 less than expected on the basis of the *OSO 8* flux reported by Mushotzky *et al.* (1978), but is comparable to that predicted from the *Ariel V* count rate (Cooke *et al.* 1978) when allowance is made for the low temperature of the spectrum. The most likely explanation of the discrepant *OSO 8* measurement is that the region of sky containing Abell 133 is confused in the 5° FWHM field of view of the *OSO 8* detector. We note that Mushotzky *et al.* estimate a spectral temperature of $> 1.2 \times 10^8$ K for the source of emission they detect, which is inconsistent with our measurements ($T < 2 \times 10^7$ K). We cannot exclude the possibility that there is an additional, variable component of emission associated with the radio-emitting cD galaxy. The spectrum of such an object might be expected to be hard and could therefore explain the higher temperature measured with *OSO 8*. It is also possible that the source is not associated with the cluster, but we have checked the *HEAO 1* error box against lists of objects which might be likely candidates, such as cataclysmic variables, RS CVn stars, Seyfert galaxies, BL Lac objects, and quasars, and have found no other candidates.

If the source is correctly identified with Abell 133, as seems likely, then the cluster has the lowest mean temperature of any cluster yet found to emit X-rays.

III. DISCUSSION

Six clusters of galaxies now show evidence for multi-component emission—the Perseus, Virgo, and Centaurus clusters, Abell 1060, Abell 2147, and SC 1329−314. A summary of the optical and X-ray properties of these clusters is shown in Table 2. In this table, the temperatures listed for the Centaurus cluster, Abell 1060, and Abell 2147 are those derived from fits to two-component models (Mitchell and Mushotzky 1980; Pravdo *et al.* 1979), while the temperatures listed for the other clusters were derived from single-component fits in different spectral regimes.

It is interesting to note from Table 2 that the temperature of the low energy component does not appear to correlate with any of the global cluster properties. While the clusters vary considerably in richness, central galaxy density, galaxy content, and velocity dispersion, the cool component temperatures range only from 1–2.5 keV. We note that this is not a selection effect due to finite detector bandpass, since the LEDs are sensitive to emission at temperatures well above 2.5 keV. Nor is it likely that a true correlation has been disguised by fitting the spectra of some clusters to one-component models and the spectra of others to two-component models. This is particularly clear in the case of low temperature versus cluster velocity dispersion, as shown in Figure 3. We conclude that the independence of the lower temperatures from global cluster properties indicated by the data thus far is real, and that it has important implications for the dynamics of the intracluster gas.

The fact that the cool component temperature does not correlate with any global cluster properties suggests that the cool gas detected by the LEDs is physically distinct from the hotter gas detected at higher energies. A likely explanation of the emission detected by the LEDs is that it arises from gas trapped in the potential wells of cluster galaxies themselves, rather than from an ambient intracluster medium. The temperature expected for gas

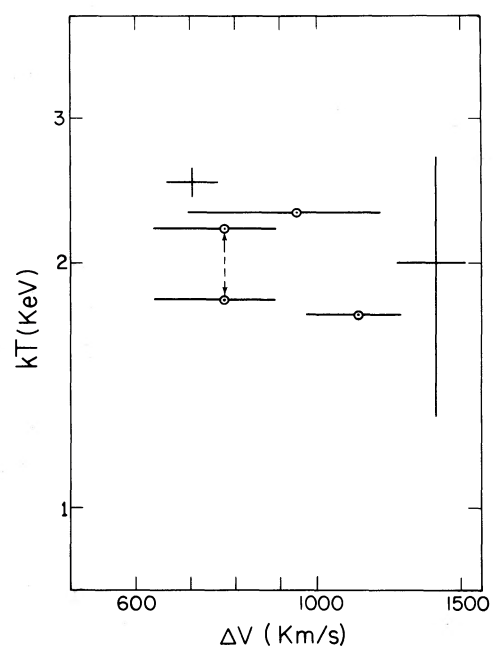

FIG. 3.—Temperature of low energy component kT plotted against cluster velocity dispersion Δv. Clusters for which the temperature was determined by single-component fits to A-2 LED PHA data are represented by plain crosses; clusters for which two-component fits were done are represented by dotted circles. SC 1329−314 is not plotted because the velocity dispersion for this cluster is not known.

TABLE 2

CLUSTER PROPERTIES

CLUSTER	Z	$N_H(10^{21}\ cm^{-2})$	R	RS	BM	No.	F(Sp.)	Δv (km s^{-1})	Low Temperature Component: kT(keV)[a]	Low Temperature Component: $EI(10^{67}\ cm^{-3})$	High Temperature Component: kT(keV)[b]	High Temperature Component: $EI\ (10^{67}\ cm^{-3})$
A426 (Perseus)	0.0183	~1.6	2	L	II–III	33	0.09	1396 ± 140	2.0 ± 0.7[c]	17.9	$6.79^{+0.15}_{-0.13}$	14.0
Virgo	0.0037	0.39	1?	I	III	11	0.55	705 ± 48	2.5 ± 0.1	1.3	...[d]	...[d]
Centaurus	0.0109	0.18–0.20	2	I	II	15	0.45	945 ± 250	~2.3[e]	1.3	~7.2 –8.8	0.3
A1060	0.011	1–2	1	C	III	13	0.54	771^{+116}_{-139}	~1.8–2.2[e]	0.5	11.9–14.4	0.2
A2147	0.0377	0.4–0.5	1	F: (2Bb)	III	12	0.27	1120 ± 150	1.7[e]	...[f]	$7.2^{+1.4}_{-1.1}$	3.6
SC 1329 – 314	~0.073	0.5	0	I	...	...	...	...	$1.1^{+2.7}_{-0.3}$	...[f]	$8.2^{+7.3}_{-3.0}$	31.0

[a] Errors (where given) from box containing *HEAO 1* A-2 68% confidence contour.
[b] Errors (where given) from box containing *OSO* 90% confidence contour.
[c] Lea *et al.* 1979.
[d] Comparison of *HEAO 1* A-1 and A-4 data for this cluster indicate that the spectrum between ~8 and 100 keV is better described by a power-law model than a thermal model (Lea *et al.* 1981).
[e] These temperatures were derived from two-component fits.
[f] The emission integrals for these clusters are inherently much less reliable than those for the other clusters, because they are derived from single-component fits which included both LED and MED data.

trapped in such a potential is (to within a model-dependent factor of 2 or so):

$$kT \approx 1.6 \times \left(\frac{M_{\rm gal}(r)}{10^{12}\ M_{\odot}}\right)\left(\frac{r_{\rm gal}}{30\ \rm kpc}\right)^{-1}\ \rm keV\ ,$$

and the temperature is constant throughout the "halo" if the galaxy density decreases with distance as $1/r^2$ $[M(r) \propto r]$ outside the optical radius of the galaxy (e.g., Yahil 1977).

Mitchell and Mushotzky (1980) have derived emission integrals for the low and high temperature components in the spectra of the Centaurus cluster and Abell 1060. By assuming pressure balance between the cooler gas and the hotter gas, they derive volume ratios $V_{\rm cool}/V_{\rm hot}$ of a few tenths and density ratios of $n_{\rm cool}/n_{\rm hot}$ of 4–6. Since a typical galaxy only occupies 0.001 of the core volume of a cluster, cool gas must be present around a few hundreds of galaxies in each cluster. If we assume that the other clusters in our sample are similar in this regard, then two consequences follow directly. The X-ray emission from nonisothermal clusters should appear clumpy and irregular, due to the higher mean density of the cooler gas. IPC observations available in the literature support this hypothesis. The gas distributions in the Virgo cluster and in Abell 2147, clusters with multi-component spectra, appear to be highly clumped about individual galaxies; whereas the gas distribution in Abell 2319, whose spectrum is well-fit by a single temperature, is smooth and symmetric about the cluster center (Forman *et al.* 1979; Jones *et al.* 1979). We predict that observations of other multi-spectral component clusters will show their emission to be clumpy as well. The contrast may, however, be difficult to detect if the X-ray emission is dominated by a single, central massive galaxy (e.g., NGC 1275 in the Perseus cluster), and/or if the ratio of emission measure in the cool component to that in the hot component is low.

Furthermore, if cool gas is present around a large fraction of the galaxies in a typical nonisothermal cluster, then the emission integral of the cooler gas should increase as the total number of galaxies in the cluster increases. If we adopt central galaxy density as a measure of total number of galaxies, then we do see some evidence for this trend (see Table 2). However, this can only be a tentative conclusion, since the emission integrals for the Virgo and Perseus clusters may be contaminated by contributions from the higher energy components. Spectral fits to two-component models are needed to confirm this trend.

We conclude that a scenario for nonisothermal clusters in which cool gas is trapped in the gravitational potential wells of several hundred cluster galaxies and exists in pressure balance with a hotter, ambient intracluster medium is physically reasonable and is consistent with the data available thus far.

A separate topic which we mention briefly here concerns the spatial distribution of the intracluster medium in Abell 2319. A comparison of the luminosity extrapolated from the IPC surface-brightness distribution and the observed A-2 LED luminosity shows that the surface brightness distribution of this cluster must be more extended than that of a standard isothermal sphere (King 1972). Thus the density of the intracluster medium at distances greater than ~ 500 kpc from the cluster center must decrease less rapidly than $(1 + r^2/a^2)^{-3/2}$. Moreover, the data indicate that the dynamics of the gas in Abell 2319 cannot be dominated by radiatively regulated accretion, since this would give rise to a surface brightness distribution practically indistinguishable from that of a standard isothermal sphere (Bahcall and Sarazin 1977). This does not exclude the possibility that radiatively regulated accretion occurs on a smaller scale about individual galaxies.

IV. SUMMARY

We have obtained spectra for five clusters of galaxies in the 0.2–2.5 keV energy range—the Centaurus cluster, Abell 2147, SC 1329–314, Abell 2319, and Abell 133—and compared them with previous higher energy results. The A-2 data confirm the multi-component nature of the Centaurus cluster and Abell 2147 and show that SC 1329–314 also has more than one spectral component. This brings the number of clusters which thus far show evidence of multi-component emission to six (including the Perseus and Virgo clusters and Abell 1060). The spectra of Abell 2319 and Abell 133 are consistent with single-temperature thermal bremsstrahlung models. Our best-fit spectral parameters for Abell 2319 agree with the parameters derived from *OSO 8* data (Mushotzky *et al.* 1978), whereas the A-2 spectrum of Abell 133 is significantly cooler than the lower limit on the temperature estimated by Mushotzky *et al.* on the basis of the *OSO 8* detection. Comparison of the *HEAO 1* A-2 and *Einstein* IPC data show that the gas in Abell 2319 and possibly in Abell 2147 is more extended than an isothermal sphere. Our data also suggest that the cooler gas in multi-spectral component clusters is physically distinct from the hotter gas, since the cooler temperatures do not appear to correlate with any global cluster properties. Investigations of the spectra of other clusters are necessary to confirm this result.

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