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HEAO 1 HARD X-RAY OBSERVATIONS OF THREE ABELL CLUSTERS OF GALAXIES

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ABSTRACT

We present the results of hard X-ray measurements of A1367, Coma (A1656), and A2319 clusters of galaxies made with the UCSD/MIT Low Energy Detectors on *HEAO 1*. Nonthermal components were not detected above the level of 10^{-5} photons (cm^{-2} s^{-1} keV^{-1}), but the energy extensions of the thermal spectra of Coma and A2319 seen at lower energies were observed. These results are then used, together with radio measurements of the diffuse intracluster emission, to set lower limits on the mean magnetic field and upper limits on the energy density of relativistic electrons in the intracluster space of these clusters of galaxies.
Subject headings: galaxies: clustering — galaxies: X-rays

I. INTRODUCTION

Clusters of galaxies have been extensively observed in the energy range 1–10 keV and are by now a well-established class of thermal X-ray sources (e.g., Forman and Jones 1982). These observations have contributed significantly to our understanding of clusters (for a recent review, see Sarazin 1986). In comparison, there are very few reported measurements of clusters at energies above 30 keV. Since the temperature of the intracluster (IC) gas is typically below 10 keV, the detection of hard X-ray (HXR) emission from clusters may yield additional astrophysical information on the IC environment beyond what we have already deduced from analyses of the thermal emission. In particular, knowledge may be gained on a population of energetic electrons which can Compton scatter the cosmic microwave background (CMB) photons giving rise to HXR emission. If diffuse radio emission exists within the cluster, then its measurement, together with HXR data, can lead to a determination of the energetic electron density and the strength of the mean IC magnetic field, based only on *observables*. This is valuable as our knowledge of the values of these quantities in extragalactic environments is very poor.

Bounds on the values of the electron density and the mean field can be obtained by using the results of analyses (e.g., Harris and Romanishin 1974; Rephaeli 1977) based on the (now nonviable) interpretation of cluster soft X-ray emission as nonthermal (Compton) emission. Doing so leads to an upper limit on the electron density and to a lower limit on the value of the IC magnetic field. When using only radio measurements one can *estimate* these quantities (e.g., Jaffe 1977; Hanisch 1981).

HXR measurements of clusters were reported by Serlemitsos *et al.* (1977) and Bazzano *et al.* (1984). *HEAO 1* HXR observations have been analyzed for only three clusters—A2142 and Virgo (Lea *et al.* 1981) and the Perseus cluster (Primini *et al.* 1981; see also Rothschild *et al.* 1981). In the latter two clusters the emission is dominated by M87 and NGC 1275, respectively, so only the reported observation of A2142 constitutes a clear cluster measurement. Moreover, none of these clusters is known to have diffuse IC radio emission. In this paper we report the results of an analysis of the *HEAO 1* HXR measurements of three more clusters—the Coma cluster, A1367, and A2319. These clusters were selected primarily because they all have been observed to have diffuse, extended radio emission in their central regions. We then analyze these results, together with the radio measurements, in order to determine the energetic electron density and the strength of the mean IC magnetic field in these clusters, based upon the detailed calculations presented in Rephaeli (1979).

II. OBSERVATIONS

a) Summary of Radio Observations

As we have stated, our choice of clusters for the present investigation is based on the existence of clear evidence for diffuse IC radio emission. In addition to Coma (A1656), A1367, and A2319, there is only one other cluster, A2256, for which there is strong evidence for diffuse emission (Hanisch 1982).

Of the three clusters, Coma is the best studied in the radio (as well as in other regions of the electromagnetic spectrum). Its radio spectrum is based on measurements in the frequency band 40–1400 MHz. We adopt Jaffe's (1977) fit for the radio spectral flux of $9.9 \times 10^{-13}\nu^{-1.2}$ ergs cm^{-2} s^{-1} Hz^{-1} (see also Hanisch 1981, who deduces a slightly higher power-law index of 1.3).

Diffuse radio emission in A1367 was reported by Gavazzi (1978) and by Hanisch (1981). The emission is much weaker than in Coma; it constitutes only a small fraction of the total (including radio galaxies) emission from A1367. Hanisch (1981) only sets a lower limit of 0.93 to the radio spectral index. Gavazzi (1978), based on measurements at 610 and 1415 MHz, deduced a spectral index of 1.5 which we adopt here.

The radio halo of A2319 was measured to have a flux of 1 Jy at 610 MHz (Harris and Miley 1978). These authors deduce a spectral index of 1.4 using the measurements of Erickson, Mathews, and Viner (1978) at 26 MHz.

The radio data are summarized in Table 1, including redshifts, electron spectrum power-law indices, and estimates of source radius which are taken from the references quoted for each cluster.

TABLE 1

RADIO DATA

Cluster	Z	Radio Flux (ergs cm^{-1} s^{-1} Hz^{-1})	P	Radio Radius
A1367	0.0213	$1.9 \times 10^{-11} \nu^{-1.5}$	3.0	16′
A1656 (Coma)	0.0235	$9.9 \times 10^{-13} \nu^{-1.2}$	2.4	20
A2319	0.0529	$2.0 \times 10^{-11} \nu^{-1.4}$	2.8	10

b) *HEAO 1 HXR Observations*

The hard X-ray and Low Energy Gamma-Ray Experiment (A-4) aboard *HEAO 1* (Matteson 1978) scanned the entire sky for 17 months from late 1977 to early 1979. The observations reported here used the two low-energy scintillation detectors (LEDs) which covered the energy range 13–175 keV, had net area 103 cm^2 each, and were collimated to a field of view of $1\overset{\circ}{.}5 \times 20°$ FWHM. A given source within 15° of the scan circle was viewed for about 15 s during each 33 minute satellite rotation period. About half of the source scans were lost to Earth occultations, to detector turn-off when the satellite passed through the South Atlantic Anomaly, a region of high trapped particle fluxes, and finally to occasional periods of special detector operation, such as the daily calibration period.

No pointed observations were made in a manner which permitted short-term (a few minutes) subtraction of the variable detector background counting rate, which arises from the X-ray diffuse component and from detector radioactivity induced by ambient charged particles. Background observations were made just before and just after each 15 s source transit. The fields surrounding the three sources were checked for confusing sources in a catalog containing all known X-ray sources of intensity ≥ 1 *Uhuru* counts s^{-1}. In the case of A2319, about 20% of the data had to be discarded because of confusion with Cyg X-3 in on-source or background accumulations. Each source was observed during two epochs separated by 6 months. Following tests for consistency, data from the two epochs were added for a single mean observation.

Photon spectra were obtained from the observed spectral counting rates through the standard process of assuming a model spectrum, transforming it through a computer simulation of the detection process, then adjusting model intensity and shape parameters for best fit, using the χ^2 statistic.

i) *Abell 1367*

No emission was detected from this cluster. The observed thermal spectrum at lower X-ray energies (Mushotzky *et al.* 1978) is weak and has a relatively low temperature of 2.8 keV, and thus is well below our threshold even at 15 keV. Extrapolation of the *OSO 8* data to 14 keV gives only a 5% contribution to our observed flux at 12.67–15 keV. In fitting for the nonthermal component above 12.67 keV, we therefore ignored this small thermal contribution, obtaining a slight overestimate. A fit for nonthermal power-law emission of index 2.5 was made; the best-fit flux at 30 keV was $(0.5 \pm 0.8) \times 10^{-5}$ photons cm^{-2} s^{-1} keV^{-1}. Since this is a null detection, we calculate a 2 σ upper limit of 2.1×10^{-5} photons cm^{-2} s^{-1} keV^{-1}. The observed spectrum and best-fit power law are shown in Figure 1.

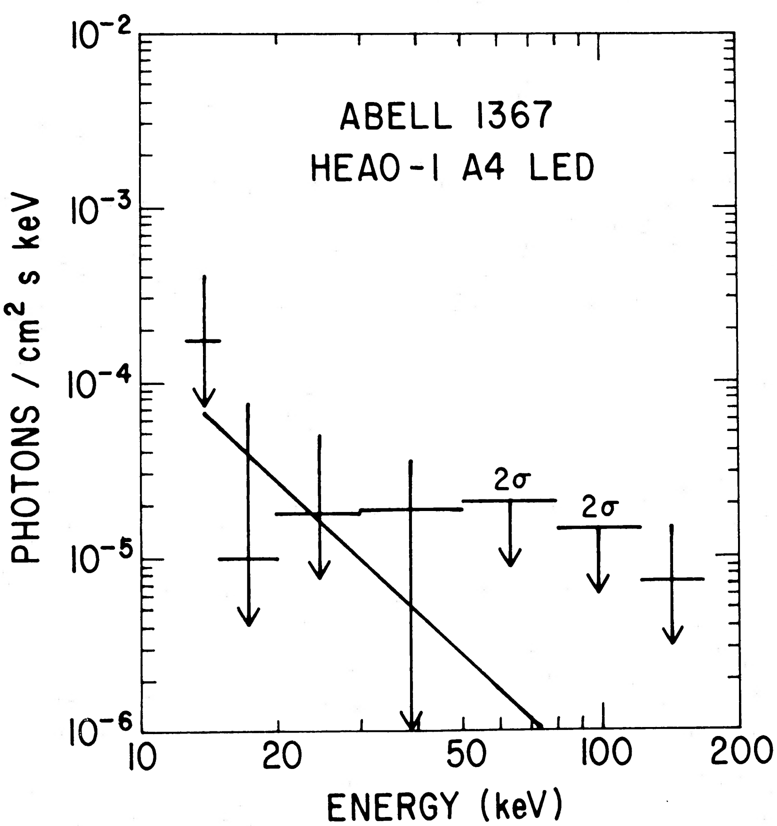

FIG. 1.—The hard X-ray spectrum of A1367. The solid line is the best-fit power law with a slope of 2.5. A thermal bremsstrahlung component at 2.8 keV (Mushotzky *et al.* 1978) was also included, but it is at a level too low to be shown in the figure.

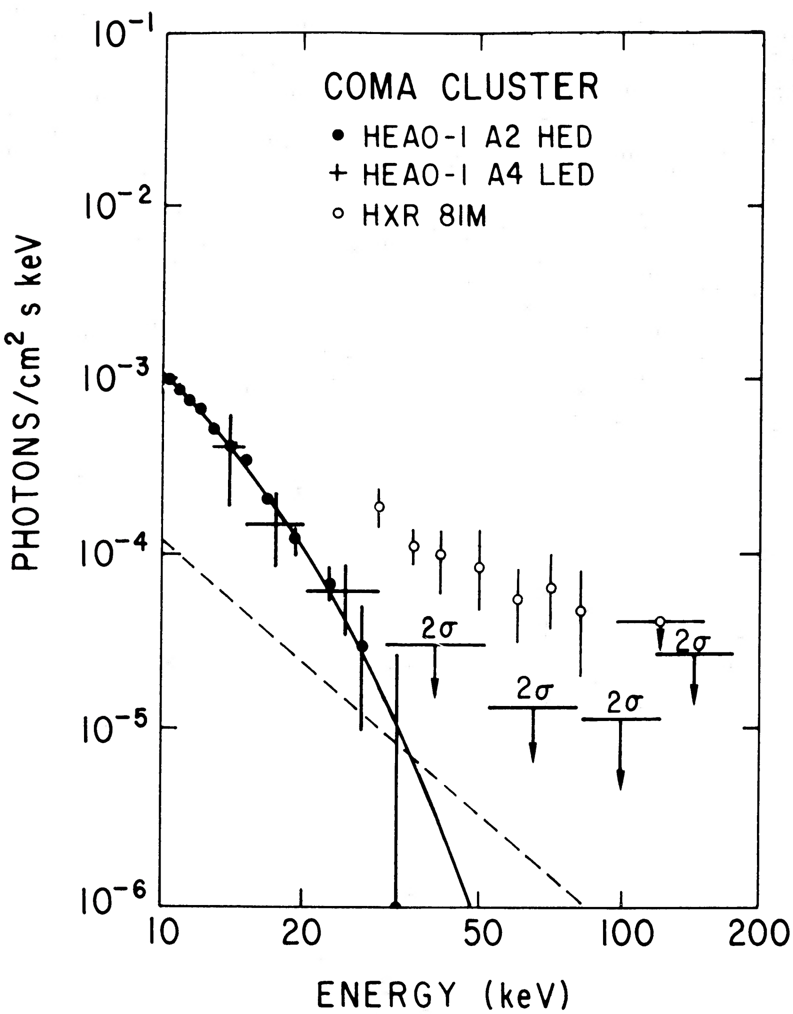

FIG. 2.—The hard X-ray spectrum of the Coma Cluster. The *HEAO 1* A-2 HED data and the best-fit A-2 thermal bremsstrahlung model with a temperature of 7.6 (*solid line*) are taken from Henriksen and Mushotzky (1986). The dashed line is the A-4 best-fit power-law residual component with a slope of 2.2. Also shown are the HXR 81M measurements of Bazzano *et al.* (1984).

ii) *Coma*

The A-4 observations of Coma, as seen in Figure 2, show significant flux levels in the energy band 12.5–30 keV. These are in excellent agreement with the measurements (Henriksen and Mushotzky 1986) obtained with the Goddard Space Flight Center Cosmic X-Ray Experiment (A-2) coaligned with A-4 on *HEAO 1*. Both A-2 and A-4 results show excellent agreement with an isothermal thin thermal bremsstrahlung spectral form with $kT = 7.6$ keV. When data at lower energies are also considered, the A-2 results are actually much more consistent with a polytropic temperature distribution with core temperature between 15 and 21 keV. But the isothermal spectrum forms an adequate heuristic representation of the data above 10 keV, and we have employed it in examining the A-4 data for an excess nonthermal emission. We have fit the residuals from the thermal form to a power law of index 2.2 and obtained a best-fit flux at 30 keV of $(0.22 \pm 1.07) \times 10^5$ photons cm^{-2} s^{-1} keV^{-1}. This flux is not significant, and a 2 σ upper limit of 2.4×10^{-5} photons cm^{-2} s^{-1} keV^{-1} is obtained. A more extreme upper limit for the nonthermal component can be obtained by using the isothermal bremsstrahlung spectral form with the temperature at the 90% confidence lower bound of 7.3 keV given by Henriksen and Mushotzky (1986). With this value the thermal flux is lowered by about 20% at 30 keV, and the formal 2 σ upper limit to nonthermal flux at 30 keV is 2.6×10^{-5} photons cm^{-2} s^{-1} keV^{-1}. It is evident from Figure 2 that the A-4 results are inconsistent with those of Bazzano *et al.* (1984). Using the same spectral form as Bazzano *et al.* (1984) the A-4 2 σ flux upper limit is a factor of 8 below their result.

iii) *Abell 2319*

Significant positive fluxes, as shown in Table 2 and Figure 3, were detected below 30 keV. A2319 was observed at lower energies by *OSO 8* (Mushotzky *et al.* 1978). These authors reported a thermal bremsstrahlung spectrum with a temperature of 12.5 (+7, −4) keV and a flux at 5 keV of 2.1×10^{-11} ergs cm^{-2} s^{-1} keV^{-1}. Later a refined temperature of 8.9 ± 2.3 keV was obtained (reported in Forman and Jones 1982). The solid curve in Figure 3 is the 8.9 keV thermal spectrum normalized to the 5 keV datum. It agrees well with the best fit to the A-4 data below 30 keV. Assuming this level of thermal emission, we have fitted a power law of index 2.4 to the residuals, obtaining a best fit flux at 30 keV of $(0.55 \pm 0.81) \times 10^{-5}$ photons cm^{-2} s^{-1} keV^{-1}. The 2 σ upper

TABLE 2

HXR Fluxes

Cluster	Energy (keV)	X-Ray Flux (10^{-5} photons cm^{-2} s^{-1} keV^{-1})	B (G)	ρ_e (ergs cm^{-3})
A1367	12.67–15	16.9 ± 23.0	$\geq 5.6 \times 10^{-8}$	$\leq 7.7 \times 10^{-13}$
	15–20	1.0 ± 8.0		
	20–30	1.8 ± 3.4		
	30–50	1.8 ± 1.8		
	50–80	-0.4 ± 1.0		
	80–120	-0.2 ± 0.7		
	120–160	0.7 ± 1.1		
A1656 (Coma)	12.67–15	49.0 ± 21.8	$\geq 1.1 \times 10^{-7}$	$\leq 2.6 \times 10^{-13}$
	15–20	12.7 ± 6.1		
	20–30	7.1 ± 2.7		
	30–50	0.5 ± 1.5		
	50–80	-0.2 ± 0.9		
	80–120	-0.2 ± 0.6		
	120–160	0.9 ± 1.0		
A2319	12.67–15	43.4 ± 24.0	$\geq 1.1 \times 10^{-7}$	$\leq 1.0 \times 10^{-12}$
	15–20	5.9 ± 5.2		
	20–30	5.6 ± 2.3		
	30–50	1.2 ± 1.2		
	50–80	1.7 ± 0.7		
	80–120	-0.8 ± 0.5		
	120–165	-1.1 ± 0.8		

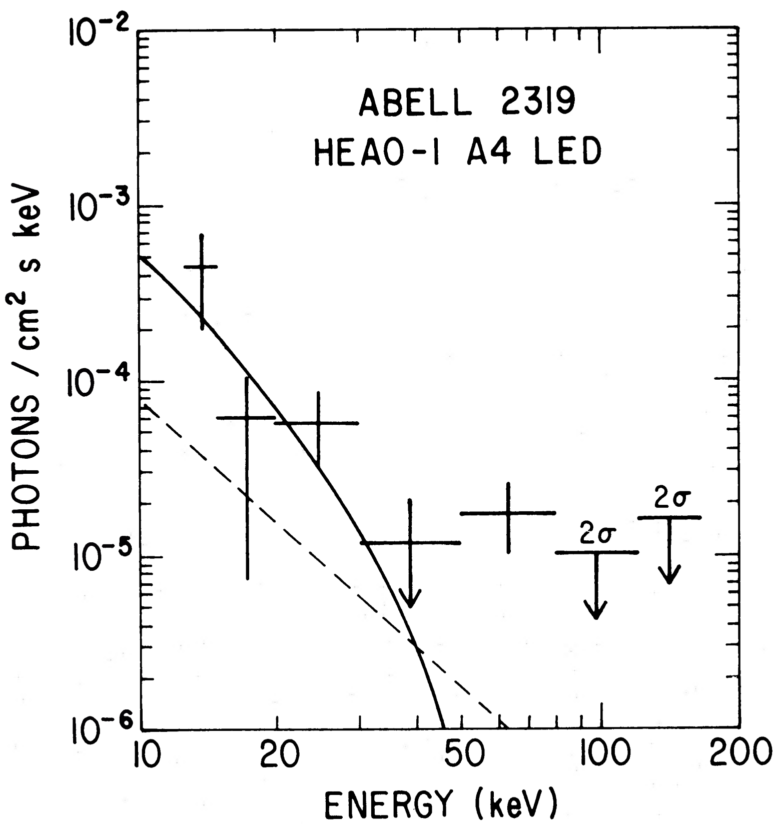

Fig. 3.—The hard X-ray spectrum of A2319. The solid line is 8.9 keV thermal bremsstrahlung flux (taken from Forman and Jones 1982). The dashed line is the best-fit power-law residual component with a slope of 2.4.

limit corresponding to this null detection of a nonthermal tail is 2.2×10^{-5} photons $cm^{-2}\ s^{-1}\ keV^{-1}$.

It is important to recognize that this null detection for a nonthermal tail depends entirely on the assumption that the temperature of the thermal emission is at the *OSO 8* best-fit value. Because this proportional counter measurement is best determined at about 5 keV, the flux above 10 keV is less well determined, given the 2.3 keV formal standard error in temperature. If we assume a temperature of 5.4 keV, which is at the lower edge of the 90% confidence interval, then the thermal flux above 12 keV is reduced greatly and the A-4 observations can then primarily be of nonthermal flux. For this case, $kT = 5.4$ keV, we find that the A-4 residuals are well fitted by a power law with index 2.4 and an intensity at 30 keV of $(2.68 \pm 0.81) \times 10^{-5}$ photons $cm^{-2}\ s^{-1}\ keV^{-1}$. We do not claim this as evidence for a nonthermal X-ray flux above 12 keV. This interpretation is *permitted* by the data; however, thermal origin is a more natural explanation for the 12–30 keV data, since they agree so well with the *OSO 8* spectrum.

III. THEORETICAL ANALYSIS

The phase space distribution of energetic electrons in the IC space can be calculated given a source term for the electrons and their mode of propagation (Brecher and Burbidge 1972; for a detailed analysis see also Rephaeli 1977). Since the mode of propagation is unknown, and because no knowledge about the spatial distribution of the IC magnetic field exists, one must average over the spatial dependence of both the electron density and the magnetic field, as has been done in Rephaeli (1979). If the electrons are introduced to the IC space with an energy distribution characterized by a power-law index p, then their steady state distribution is

$$n(\gamma) = n_0 \gamma^{-(p+1)} , \quad (1)$$

where γ is the Lorentz factor, and n_0 is the electron number density per unit interval. The coefficient n_0, which can be viewed as a normalization factor to be determined from the HXR data, is related to the rate of ejection (per unit volume and per unit γ interval), q_0, out of the central radio sources in the cluster. If the dominant energy loss mechanism is Compton scattering off the CMB (energy density ρ) photons, which is true for $\gamma > 0\,(10^3)$ as long as the value of the magnetic field, B, is lower than 3×10^{-6} G, then $n_0 = 3mcq_0[4\sigma_T \rho(p-1)]^{-1}$, where m is the electron mass and σ_T is the Thomson cross section. The spectral synchrotron and Compton fluxes can then be readily calculated using basic formulae (e.g., Blumenthal and Gould 1970). These lead to the following expressions (Rephaeli 1979).

$$F_s(\gamma) = a_2(p) n_0 R^3 (3d^2)^{-1} B^{(p+2)/2} \nu^{-p/2} \quad \text{ergs cm}^{-2}\ \text{s}^{-1}\ \text{Hz}^{-1} \quad (2)$$

$$F_c(\epsilon) = a_2(p) a_3(p) n_0 R^3 (3d^2)^{-1} (kT)^{(p+6)/2} \epsilon^{-p/2} \quad \text{cm}^{-2}\ \text{s}^{-1} , \quad (3)$$

where ν and ϵ are the frequency and energy of the radio and HXR photons, respectively; R is the radius of the emitting region; d is the distance to the cluster; and $T = 2.7$ K is the CMB temperature. The functions $a_2(p)$ and $a_3(p)$ are defined in Rephaeli (1979) in terms of numerical factors which are tabulated in Blumenthal and Gould (1970). For the clusters of interest here we know the observed radio flux, which we write as $F_s(\nu) = A\nu^{-p/2}$, so the predicted HXR Compton flux is

$$F_c(\epsilon) = A a_3(p) (kT)^{(p+6)/2} B^{-(p+2)/2} \epsilon^{-p/2} \ \text{cm}^{-2}\ \text{s}^{-1} . \quad (4)$$

A comparison of an observed HXR flux with equation (4) determines B based only on observables, independent of the radio source size or the distance to the cluster. An observational upper limit on $F_c(\epsilon)$ will translate to a lower limit on the value of B. Knowing R and d we can also calculate n_0 and estimate the energetic electron energy density. From equation (2),

$$n_0 = \frac{3Ad^2}{a_2(p)R^3} B^{-(p+2)/2} , \quad (5)$$

and the electron energy density is

$$\rho_e = mc^2 \int_{\gamma_m}^{\gamma_M} \gamma n(\gamma) d\gamma = \frac{3mc^2 Ad^2}{(p-1)a_2(p)R^3} B^{-(p+2)/2} (\gamma_m{}^{1-p} - \gamma_M{}^{1-p}) . \quad (6)$$

The limits γ_m, γ_M are the end points of the energy interval over which our expression for the steady state electron density, equation (1), is valid. Because the integrand is proportional to γ^{-p} with $p > 2$, the dependence of ρ_e on γ_M is negligible (as long as $\gamma_M \gg \gamma_m$). We restrict ourselves to electrons with energy high enough to boost a typical CMB photon to an energy higher than at least a few keV, so $\gamma_m = 0\,(10^3)$. We could have integrated over a wider energy interval had we confidently known the various energy losses at lower energies (Rephaeli 1979). We will here, however, content ourselves only with those electrons having energies in the observationally deduced range.

Our reported HXR measurements show no evidence for a power-law component in the spectra of A1367, Coma, and A2319. To derive the limits on B and ρ_e in Table 2, we use 2 σ upper limits on the HXR flux, based on a 90% lower limit to the temperature as discussed in § II. In calculating ρ_e, we have taken $\gamma_m = 10^3$ and $\gamma_M = 3 \times 10^4$.

IV. DISCUSSION

The derived lower limits on the value of the mean IC magnetic field in Coma, A1367, and A2319 are not unexpected but nevertheless useful since they are observationally based. A value as high as 10^{-6} G has been estimated for the field in the Coma Cluster (Jaffe 1977). Our lower limit of 1.1×10^{-7} G is about a factor of 4 higher than the lower limit obtained when requiring that the nonthermal emission does not dominate the soft X-ray flux (Rephaeli 1977). We can compare our lowest value for the field in A2319 with a recent observational result, based on Faraday rotation measurements (Broten, Vallee, and MacLeod 1986). In their analysis of these measurements, Vallee, Broten, and MacLeod (1987) assume a cellular morphology for the IC field and obtain $B \approx 2 \times 10^{-7}$ G, a mean value which is very close to our lower limit. We should also mention that in an analysis similar to ours using the *HEAO 1* A-4 measurements, Lea *et al.* (1981) obtained a lower limit of 5×10^{-8} G for the field in A2142.

The meaning of our observational results should be restated explicitly: there is no clear evidence for nonthermal flux in the spectra of the above three clusters at the sensitivity limit of the A-4 detectors. As we have just mentioned, however, the mean IC magnetic field may assume values above our derived lower limits. If so, and because the Compton HXR flux is predicted to be proportional to $B^{-(p+2)/2}$, which is at least as steep as $B^{-2.2}$ in these clusters, the nonthermal component could perhaps be detected by higher sensitivity detectors.

Our upper limits on the energy density of relativistic electrons in the IC space of the above three clusters are not very sensitive as they only imply that the energy is at most comparable to its Galactic value. Nevertheless, our results set a limit on the intergalactic energy density of cosmic ray electrons.

Future higher sensitivity HXR measurements will be made by both the OSSE instrument on the Gamma-Ray Observatory and the HEXTE instrument on the X-ray Timing Explorer. These instruments will allow a factor of 10 or more improvement in sensitivity in measurements of a nonthermal component in the spectra of clusters of galaxies.

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