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HEAO 1 HARD X-RAY OBSERVATION OF CLUSTERS OF GALAXIES AND INTRACLUSTER MAGNETIC FIELDS

YOEL REPHAELI AND D. E. GRUBER
University of California, San Diego
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ABSTRACT

We report the results of *HEAO 1* hard X-ray measurements of three clusters of galaxies, Abell 401, Abell 2255, and Abell 2256. Nonthermal components were not detected above the level of 10^{-5} photons cm^{-2} s^{-1} keV^{-1}. Comparison of our flux upper limits with theoretical predictions yields lower limits of about 10^{-7} gauss on the mean value of the intracluster magnetic fields in the central regions of these clusters.

Subject headings: galaxies: clustering — galaxies: intergalactic medium — X-rays: sources

I. INTRODUCTION

Whereas intracluster (IC) soft X-ray emission has been extensively searched and detected, thereby increasing our understanding of clusters (for a review, see Sarazin 1986), relatively little effort has been devoted to cluster hard X-ray (HXR) measurements. This is unfortunate, as the detection of HXR emission will open up a new channel for the study of clusters through nonthermal phenomena. The most likely mechanism giving rise to IC HXR emission is Compton scattering of the cosmic microwave background (CMB) photons off-relativistic (GeV) electrons. This is of particular interest in clusters where diffuse radio emission has been detected, a fact which strongly indicates the presence there of such electrons. The combined radio and HXR measurements directly yield some of the basic properties of IC magnetic fields and cosmic-ray electrons. This is quite important as we know very little about these quantities in extragalactic environments.

The possibility of IC HXR emission was first mentioned by Felten *et al.* (1966); detailed calculations of the predicted IC Compton X-ray spectra have been presented by Rephaeli (1977, 1979). HXR measurements of clusters were reported by Serlemitsos *et al.* (1977) and Bazzano *et al.* (1984). *HEAO 1* HXR observations were analyzed for six clusters—A2142 and Virgo (Lea *et al.* 1981), the Perseus Cluster (Primini *et al.* 1981), and, more recently A1367, A1657, (Coma), and A2319 (Rephaeli, Gruber and Rothschild 1987, hereafter RGR). The last three clusters were selected because of strong evidence for diffuse radio emission from a ~ 1 Mpc region around their centers. No significant evidence was found for power-law spectra by RGR, but the extension of the thermal emission from the IC gas in the Coma Cluster and in A2319 is seen at energies roughly in the range 12–30 keV (see Fig. 2 and 3 of RGR). The 2 σ upper limits on nonthermal emission at 30 keV are 2–3 $\times 10^{-5}$ cm^{-2} s^{-1} keV^{-1}.

The analyses of the HXR data are very useful, even when they result only in upper limits. Combined with the radio measurements, the data yield lower limits on the value of the IC magnetic field, B, and upper limits on the energy density of relativistic electrons, ρ. The significance of these determinations is in that they are based essentially only on observations, whereas to determine B and ρ from the radio data alone resort must be made to additional theoretical assumptions (e.g., equipartition). It is of interest to enlarge the small sample of clusters for which we have HXR data so as to allow making some general deductions about the level of nonthermal emission and the IC values of these quantities. In this paper we report the results of an analysis of the *HEAO 1* A-4 data for three more clusters—A401, A2255, and A2256—for which there also is evidence for diffuse radio emission.

II. OBSERVATIONS

a) Review of Radio Observations

A401.—Evidence for diffuse radio emission from the central region of A401 is based on measurements at 610 and 1415 MHz (Harris, Kapahi and Ekers 1980), and 2.7 GHz (Roland *et al.* 1981). The former authors estimate the size of the emitting region, from which we infer a mean radial extent of about 15′. Roland *et al.* (1981) determine the value of the power-law index, α, to be about 1.4, a value consistent with that deduced by the former authors. The spectral radio flux, f, is 80 MJy at 610 MHz (Roland *et al.* 1981), so that $f \approx 1.6 \times 10^{-12} \nu^{-1.4}$ ergs cm^{-2} s^{-1} Hz^{-1}. (Roland *et al.* [1981] also noted that this flux is below the detection threshold at 40 MHz of Hanisch and Erickson [1980], who reported no evidence for diffuse emission in their measurements.) The redshift of A401 is 0.075 (Hintzen, Scott, and Tarenghi 1977).

A2255.—Diffuse emission from a central region, about 4′ in radius, has been measured at 100, 610, and 1415 MHz (Jaffe and Rudnick 1979; Harris, Kapahi, and Ekers 1980). The latter authors determine $\alpha \approx 1.7$, and a flux of 0.2 Jy at 610 MHz; thus, $f \approx 1.7 \times 10^{-9} \nu^{-1.7}$ ergs cm^{-2} s^{-1} Hz^{-1}. Stauffer, Spinrad, and Sargent (1979) have measured a redshift of $z = 0.08$ for this cluster.

A2256.—Radio emission from this cluster has a complex structure. Diffuse emission from a region of radius $\sim 5'$ has been measured by Bridle and Fomalont (1976) and Bridle *et al*, (1979) at 610 and 1415 MHz. According to these authors the diffuse source has a flux of 0.1 Jy at 610 MHz and $\alpha \approx 1.8$, so that $f \approx 6.5 \times 10^{-9} \nu^{-1.8}$ ergs cm^{-2} s^{-1} Hz^{-1}. For this cluster, $z = 0.06$ (Faber and Dressler 1977).

Measurements of a diffuse component in cluster radio spectra require a detailed subtraction of emission from discrete sources. The subtraction process is not simple (which may explain, perhaps, why there are only a few clusters with reported diffuse emission) and involves uncertainties of a few tens of percent. This will be taken into account when we estimate the uncertainty in the quantities we deduce below, although no

TABLE 1

RADIO DATA

Cluster	z	Radio Flux (ergs cm^{-2} s^{-1} Hz^{-1})	p	Radio Radius
A401	0.075	$1.6 \times 10^{-2}\nu^{-1.4}$	2.8	15′
A2255	0.080	$1.6 \times 10^{-9}\nu^{-1.7}$	3.4	4′
A2256	0.060	$6.5 \times 10^{-9}\nu^{-1.8}$	3.6	5′

formal error has been reported for the radio data, which are summarized in Table 1.

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°.5 by 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 to occasional periods of special detector operation, such as daily calibration.

Measurements of detector background were made just before and just after each 15 s source transit. The fields surrounding the three clusters were checked for confusing sources in a catalog containing all known X-ray sources of intensity greater than 1 *Uhuru* count s^{-1}. A2255 and A2256 were observed at 6 month intervals during three epochs of scanning; A401 was observable during only two epochs. Following tests for consistency, data from the individual epoch were added for a single mean observation of each cluster.

i) *Abell 401*

A total observing time of 10,200 s was collected on Abell 401, and the average exposed area of each detector was 36 cm^2. No significant flux was observed. Before obtaining an upper limit, however, it was necessary to first substract a small expected contribution from the cluster thermal emission. But to obtain a conservative upper limit to the HXR, it is desirable to subtract a lower limit to the thermal emission. Therefore a 95% lower bound of 4.90 keV to the cluster was employed, based on the reported *OSO* 8 temperature of 6.55 ± 1.0 keV (Mushotzky 1984). The cluster thermal flux was taken from Kowalski *et al.* (1984). This substaction resulted in only a slight increase in the 13–60 keV HXR upper limit, which is $f_c \approx 1.90 \times 10^{-5}$ cm^{-2} keV^{-1} (95% confidence), where f_c is the differential flux at 30 keV. A spectral index equal to the radio index of 1.4 has been assumed.

ii) *Abell 2255*

For Abell 2255, 32,800 s of on-source data with an average exposed area of 50 cm^2 per detector were collected. HXR emission was not detected. Again, a slight correction was made for IC thermal emission by using the IPC lower bound of 3.8 keV to the cluster temperature (Forman and Jones 1982) and the thermal flux of Kowalski *et al.* (1984). Using the radio spectral index of 1.7, the upper limit (95% confidence) to HXR emission is $f_c \approx 1.20 \times 10^{-5}$ cm^{-2} s^{-1} keV^{-1}.

iii) *Abell 2256*

A total of 35,800 s of on-source data were collected with average area 48 cm^2. No HXR emission was detected. The small thermal contribution to the emission was subtracted, using the thermal flux of Kowalski *et al.* (1984) and a 95% confidence lower limit of 4.5 keV to the IPC temperature (Jones and Forman 1984). The resulting 95% confidence upper limit to the HXR flux is $f_c \approx 0.5 \times 10^{-5}$ cm^{-2} s^{-1} keV^{-1}, assuming the radio spectral index of 1.8.

III. THEORETICAL ANALYSIS

Diffuse IC radio emission most likely is by relativistic electrons traversing magnetic fields. These electrons also scatter off photons of any IC radiation field, boosting the photon energies by a factor of order γ^2, where γ is the electron Lorentz factor. As the most intense radiation field is the CMB, Compton scattering leads to X-ray emission with a spectrum which is characterized by the same power-law index as that of the radio emission. As mentioned earlier, a detailed calculation of the predicted Compton flux has been carried out (Rephaeli 1977). For reasons mentioned in RGR, the less detailed calculations presented by Rephaeli (1979) are more applicable to the present case. The starting point is specifying the electron energy spectrum in the IC space, $n(\gamma)$, which can be gotten from the electron source spectrum. If the latter is characterized by a power-law index p, then

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

where n_0 is the electron number density per unit γ interval. The synchrotron flux can be written down using standard formulae (e.g., Blumenthal and Gould 1970, and eq. [2] of RGR) which obviously involve the (suitably averaged value of the) synchrotron radio flux, which we write as $A\nu^{-p/2}$, leading to

$$F_c = A \times a_3(p) \times (kT)^{(p+6)/2} \times B^{-(p+2)/2} \times \epsilon^{-p/2}, \tag{2}$$

where ϵ is the energy of the scattered (x) photon, $a_3(p)$ is defined in Rephaeli (1979), and T is the CMB temperature 2.75 K. Note that since we expressed the Compton flux in terms of the observed radio flux, the distance to the source and the size of the emitting region (so long as the radio and X-ray sizes are roughly equal) do not enter.

Our analysis of the *HEAO 1* data leads only to upper limits on the HXR flux from the above clusters. Therefore, using the radio fluxes (from § II) and equation (2), we can now obtain lower limits on the mean IC value of B and upper limits on the energy density (see eqs. [5] and [6] of RGR) of relativistic electrons in these clusters. The limits on the electron energy density are substantially uncertain as they depend on the not very well known size of the radio source, and on the low-energy cutoff (in the integration over all electron energies; for details, see RGR). These limits were derived after subtraction of the known thermal bremsstrahlung contribution to the flux, using the 90% lower limit to the best-fit temperature. Bounds on B and ρ in Table 2 were calculated using our measured 95% confidence limits on the HXR flux at 30 keV. In view of the uncertainty in the radio data, the derived limits should be accurate to within a factor of ~ 2.

IV. DISCUSSION

The results of the analysis reported here and those of our previous investigation (RGR) comprise a *HEAO 1* study of essentially all Abell clusters for which there is clear evidence for

TABLE 2

BOUNDS ON THE HARD X-RAY FLUX, B, AND ρ

Cluster	Flux at 30 keV (cm^{-2} s^{-1} keV^{-1})	B (Gauss)	ρ (ergs cm^{-3})
A401	1.9×10^{-5}	$>0.4 \times 10^{-7}$	$<2 \times 10^{-13}$
A2255	1.2×10^{-5}	$>1.2 \times 10^{-7}$	$<7 \times 10^{-12}$
A2256	0.5×10^{-5}	$>1.5 \times 10^{-7}$	$<3 \times 10^{-12}$

diffuse radio emission. These results clearly establish the reality of IC fields and should motivate interest in investigations of such issues as the origin of the fields and their morphology (e.g., Rephaeli 1988). Our derived lower limits of about 1×10^{-7} G on the value of IC magnetic fields are of interest because they are observationally based. Theoretical estimates range from few $\times$ 10^{-8}–few $\times$ 10^{-6} G (see, e.g., Harris and Romanishin 1974; Rephaeli 1977; Jaffe 1977). An independent observational determination of the mean value of B in the central region of A2319 from Faraday rotation measurements gives 2×10^{-7} G (Vallee, Broten, and MacLeod 1987). This value is only twice our (RGR) lower limit.

We can conclude from our results that nonthermal HXR emission from clusters is not found at X-ray flux levels of a few times 10^{-5} cm^{-2} s^{-1} keV^{-1}. The level at which nonthermal emission will eventually be detected depends very much on the mean value of the magnetic field in the central ~ 1 Mpc region. The predicted HXR flux (in eq. [2]) is proportional to $B^{-(p+2)/2}$. Thus, if B is higher than the deduced lower limit by a factor of 2, the expected flux is lower than our upper limits by a factor of at least 5. If $B \approx$ few $\times$ 10^{-7} G is typical, then it can be predicted that IC HXR emission should be observed at the few 10^{-6} cm^{-2} s^{-1} keV^{-1} level. For the HEXE experiment on *MIR/KVANT*, we calculate a 3 σ sensitivity for a typical observation of 2 hr on-source amounting to 9×10^{-6} cm^{-2} s^{-1} keV^{-1}. This instrument can offer, therefore, a modest improvement in the determination of the lower limit to the magnetic field strength. In the case of A2319, for which RGR observed a possible 2 σ excess above the thermal emission, this could be confirmed at the 6 σ level. Another factor of 3 improvement in sensitivity, $f_c \approx 3 \times 10^{-6}$ cm^{-2} s^{-1} keV^{-1}, will be achieved by *XTE* in an 8 hr observation.

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DUANE E. GRUBER: Center for Astrophysics and Space Sciences, C-011, University of California, San Diego, La Jolla, CA 92093-0111.

YOEL REPHAELI: School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69778, Israel