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# HIGH-ENERGY X EMISSION FROM THE COMA CLUSTER

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## ABSTRACT

A detailed assessment is given of conflicting high-energy X measurements of the Coma cluster region. Various considerations lead to the conclusion that the recent detection of intense emission in the band 18–130 keV is very unlikely to be diffuse intracluster emission from the Coma cluster. Therefore, the detection of diffuse intracluster emission would require detector sensitivity better than a few $\times 10^{-6}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$ in the few tens of keV range. If the observed emission originates in the Seyfert galaxy X Comae, its implied X luminosity would make it one of the strongest currently known high-energy X sources.

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

## 1. INTRODUCTION

Clusters of galaxies are the largest known X sources, whose intracluster (IC) hot gas is typically at temperatures of up to $\sim 10$ keV (for a review, see Sarazin 1986). Whereas cluster low-energy ($\epsilon < 10$ keV) X spectra have been extensively measured, only a few attempts to detect clusters at energies above $\sim 20$ keV have been made (see references in Rephaeli, Gruber, and Rothschild 1987, hereafter RGR). This is unfortunate, since we expect to learn much more on physical conditions in the IC environment from high-energy X (HEX) measurements, due to the totally different emission mechanism: IC HEX emission is most likely nonthermal emission which results from Compton scattering of relativistic electrons (RE) by the cosmic blackbody radiation (CBR).

The presence of RE in the IC space of (at least some) clusters is directly deduced from measurements of extended radio (synchrotron) emission. This emission has been definitely detected in eight clusters, in the frequency range 0.04–2.7 GHz. Radio spectral indices are in the range 1.2–1.7, and the 0.01–10 GHz luminosities are $6 \times 10^{40}$–$7 \times 10^{41}$ ergs s$^{-1}$ (taking $h = 1$, where $h$ is the Hubble constant in units of 50 km s$^{-1}$ Mpc$^{-1}$). There are reasons to believe that diffuse IC radio emission is a more common phenomenon, not ubiquitously apparent because its detection requires very careful subtraction of galactic emissions (see Rephaeli 1988 for an expanded discussion of this and other related issues).

Radio measurements imply that RE with energies in the (approximate) range 1–100 GeV (for magnetic fields in the range 0.1–1 $\mu$G) are present in the IC space of clusters. Compton scattering of electrons in this energy range by the CBR results in radiation in low-energy X to few tens of MeV gamma rays. Detailed calculations of the predicted properties of HEX emission from clusters have been made by Rephaeli (1977a, b, 1979). For a given measured radio flux, the predicted level of the HEX emission depends strongly on the value of the mean, volume-averaged magnetic field, $B$. If $B$ assumes the relatively high value of few $\mu$G (i.e., a typical galactic value), HEX emission in the 30–60 keV range will typically be below $10^{-6}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$.

The *HEAO 1* A-4 is the most relevant currently existing, all-sky HEX data base. A-4 data from six of the eight Abell clusters with (definitely) detected radio halos have been analyzed (RGR; Rephaeli & Gruber 1988). Two clusters (Coma and A2319) were clearly detected at energies of up to 25 keV, with upper limits on the emission at higher energies. The bounds on the nonthermal emission from all the clusters resulted in very interesting lower limits on the mean magnetic field $B \sim 0.1$ $\mu$G, and upper limits on the energy densities of RE. HEX measurements of the Coma Cluster have also been made with the MIFRASO baloon-borne experiment (Bazzano et al. 1990). Emission at a flux level which is significantly higher than the A-4 upper limit of RGR was reported to have been clearly detected.

The definite inconsistency between the *HEAO 1* A-4 and MIFRASO results is quite important. From a general point of view, the Coma cluster is the most studied rich cluster in many regions of the electromagnetic spectrum and is often taken to be representative of the class of well-relaxed Abell clusters. More specifically, the two conflicting results imply very different values for such important quantities as IC magnetic fields and RE energy densities. For if the flux is at the A-4 upper limit, then $B \simeq 0.1$ $\mu$G. This in turn is an important input in models for the origin and evolution of the IC gas, to which the field is probably anchored (Rephaeli 1988). On the other hand, if emission from Coma is at the level detected by Bazzano et al., then such clusters are strong HEX sources, their mean IC field is very weak, and the energy density of RE in their IC space is very high. The determination of the values of these quantities from observables in the first *truly extragalactic* environment is very significant. Substantial observational effort will be devoted in the coming years to detect HEX emission from clusters. The present Coma HEX results imply very different required detector capabilities.

In an attempt to clarify the substantial uncertainty regarding the present conflicting HEX measurements of Coma, we examine the above results, assess the validity of their possible

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interpretations, and briefly consider some of their important implications.

## 2. RADIO AND HIGH-ENERGY X MEASUREMENTS

### 2.1. *Diffuse Intracluster Radio Emission*

Coma is the best known of the (small) class of "radio halo" clusters. Extended, diffuse emission was detected by many observers, most recently by Kim et al. (1990; see this paper for references to previous measurements) who measured it at 408 and 1420 MHz. Best-fit power-law spectrum to 21 data points yielded the following expression for the (energy) flux

$$F_R \simeq (8.3 \pm 1.5) \times 10^{-12} \nu^{-1.34 \pm 0.06} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} , \quad (1)$$

in the 10–1420 MHz band. Note that this improved spectrum is somewhat steeper than that determined by Jaffe (1977), and that the 1 $\sigma$ error on the value of the power-law index is small.

Schlickeiser, Sievers, & Thiemann (1987) presented measurements of the diffuse emission at 2.7 and 4.85 GHz according to which the spectrum steepens at these higher frequencies. This result has important consequences for models of origin and propagation of RE in the IC space (as has been illustrated by the latter authors through extensive model fitting). In our discussion here, however, we can still use the above simple power-law form because of the following reason: in the energy range of interest to us, HEX emission is (predominantly) due to electrons whose synchrotron emission is well below 1 GHz, even if $B \simeq 1$ $\mu$G. Therefore, the energy spectrum of these electrons is adequately sampled by the lower frequency radio measurements.

### 2.2. *High-Energy X Measurements*

The first reported HEX observations of the Coma cluster were the low-sensitivity *OSO 8* measurements of Serlemitsos et al. (1977). Higher sensitivity was obtained with the A-4 detectors aboard the *HEAO 1* satellite. Pointed measurements of only Virgo and the Perseus clusters were made. The detected emission from these clusters is mostly from the giant elliptical M87 and the active galaxy NGC 1275, respectively. However, the A-4 experiment performed a full-sky survey which provided homogeneous scanning data. The two A-4 low-energy detectors were sensitive in the 13–175 keV band (with geometric area of 103 $cm^2$ each, and mean efficiency of 0.7). Most of the sky was scanned 3 times.

The results of analyses of all the scanning A-4 data on Coma (and five other clusters) were reported by RGR and Rephaeli & Gruber (1988). Data from all three scans were added up to obtain a mean spectrum, which is shown in Figure 1. Significant emission was detected in the 13–30 keV band, in full agreement with the *HEAO 1* A-2 measurements analyzed by Henriksen & Mushotzky (1986). Adopting the value of 1.34 as the index, $\alpha$, of the predicted HEX (energy) flux, and subtracting the thermal component as determined by the A-2 measurements, an upper limit to nonthermal emission was set. This upper limit translates to the lower limit, $B \geq 0.1$ $\mu$G (this value is negligibly different from that of RGR, who had used Jaffe's 1977 index of 1.2).

Detections of HEX emission from the Coma region by the balloon-borne Frascati and MIFRASO experiments were reported by Bazzano et al. (1984) and Bazzano et al. (1990). In the latter experiment, which was sensitive to X-rays in the energy range 15–300 keV, radiation in the band 18–130 keV

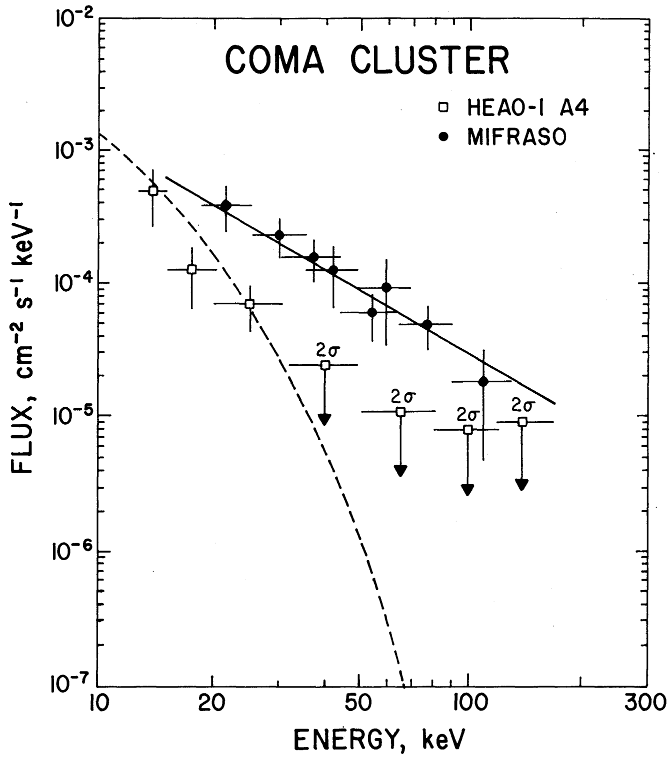


FIG. 1.—High-energy X spectrum of the Coma cluster: open squares denote *HEAO 1* A-4 (LED) measurements analyzed by RGR; MIFRASO measurements of Bazzano et al. (1991) are shown by the closed circles. The solid line is a power-law best-fit to the residual MIFRASO data (see eq. [3] in the text); the dashed line shows a thermal 8.3 keV spectrum based on *Ginga* measurements.

was detected at the 5 $\sigma$ level (see Fig. 1). Fitting their data by a power-law spectrum, Bazzano et al. (1990) determined the (photon) flux to be

$$\phi_B = (8.9 \pm 2.2) \times 10^{-5} (\epsilon/50)^{-(1.77 \pm 0.45)} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} , \quad (2)$$

where $\epsilon$ is the photon energy in keV. At 30 keV, the Bazzano et al. (1990) flux is higher by a factor $\simeq 9$ than the RGR 2 $\sigma$ upper limit of $2.4 \times 10^{-5}$ $cm^{-2}$ $s^{-1}$ $keV^{-1}$. Even at their respective 2 $\sigma$ levels, the flux values differ by a factor $\sim 3$ at this energy. Thus the two results are clearly inconsistent.

Since Bazzano et al. did not subtract the thermal component from their measured flux, the above spectrum is not an adequate representation of the presumed nonthermal emission at energies $\epsilon \sim 50$ keV. In order to determine the nonthermal component more consistently from the data of Bazzano et al., we have subtracted the thermal emission using the most recent results of *Ginga* measurements of Coma. These have been reported by Hatsukade (1989), whose best-fit analysis yields $kT = 8.31 \pm 0.08$ keV for the gas temperature, and 2–10 keV luminosity of $8.17 \times 10^{44}$ ergs $s^{-1}$. Using these values, we have calculated and subtracted the thermal contribution to the total flux. A power-law fit to the residual data of Bazzano et al. yields

$$\phi = (8.8 \pm 1.4) \times 10^{-5} (\epsilon/50)^{-(1.6 \pm 0.35)} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} , \quad (3)$$

a somewhat flatter spectrum than that in equation (2); this fit is shown in Figure 1.

## 3. ORIGIN OF THE HIGH-ENERGY X EMISSION

### 3.1. *Diffuse Intracluster Emission from Coma*

Does the emission detected by Bazzano et al. (1990) originate in the IC space of Coma? Suppose this is the case and consider the implications.

The energy power-law index deduced by the data of Bazzano et al. is $0.77 \pm 0.45$, whereas the corresponding radio index is $1.34 \pm 0.06$; these values are only marginally consistent. However, this comparison is meaningless: the radio power-law index should be compared with the index $0.6 \pm 0.35$, which corresponds to the corrected spectrum in equation (2). Therefore, the nonthermal component deduced from the data of Bazzano et al. is inconsistent with the radio spectrum. More specifically, forcing a fit to a power law with the radio index results in a $\chi^2 = 4.65$ for 7 degrees of freedom, compared with the best-fit spectrum in equation (3), for which $\chi^2 = 1.2$ (6 degrees of freedom).

Because of the inconsistency between the radio and HEX spectra, the IC magnetic field cannot be meaningfully estimated. If an identification of the spectrum of Bazzano et al. as Compton emission (by the same RE responsible for the radio emission) is forced nonetheless, then a value for the volume-averaged IC field, weighted also by the RE energy spectrum, can be calculated. Adopting a joint 1.3 power-law index for the radio and the HEX spectra, we compute $B \simeq 4.1 \times 10^{-2}$ $\mu$G, compared to a lower limit of $3.7 \times 10^{-2}$ $\mu$G given by Bazzano et al. These values should be contrasted with the lower limit of $1.0 \times 10^{-1}$ $\mu$G obtained from the *HEAO 1* A-4 upper limit on HEX emission.

The value of $B \simeq 4.1 \times 10^{-2}$ $\mu$G, as inferred from the Bazzano et al. measurements, is lower by a factor of at least 2.4 than that of RGR. First, note that the lower field value implies higher energy density in RE, $\rho$. Since $\rho \propto B^{-(\alpha+1)}$, its required value is $\rho \simeq 2 \times 10^{-12}$ ergs cm$^{-3}$, at least 8 times higher than the upper limit calculated by RGR. This value is uncomfortably high, being comparable to the energy content of cosmic-ray *protons* in the Galaxy. (Recall that the proton component of cosmic rays is estimated to be a factor $\sim 30$ times more energetic than the electron component; e.g., Ormes & Freier 1978.)

While a mean magnetic field as low as $4.1 \times 10^{-2}$ $\mu$G cannot be ruled out, various considerations lead to IC fields $B \geq 0.1$ $\mu$G. Rephaeli (1988) estimated that fields frozen into ejected interstellar media have a mean strength of $\sim 0.1$ $\mu$G when in the IC space. It is possible that IC fields can be turbulently generated through conversion of hydrodynamic energy of the cluster galaxies to magnetic energy. Estimates of the resulting fields vary, however. While Jaffe (1980) and Ruzmaikin, Sokoloff, & Shukurov (1989) estimated that this process can generate $\simeq 1$ $\mu$G fields, Goldman & Rephaeli (1991) have recently concluded that the fields will typically be $\leq 0.2$ $\mu$G.

More directly, Kim et al. (1990) have found an excess Faraday rotation of polarized emission from sources seen through the Coma cluster. From this excess rotation they estimated that $B \simeq 2$ $\mu$G. The only other cluster for which $B$ was found in a similar way is A2319; Vallée, Broten, & MacLeod (1987) estimated that $B \simeq 0.2$ $\mu$G in this cluster. Statistically analyzing rotation measures in the emission from 53 sources seen through 46 clusters, Kim, Tribble, & Kronberg (1991) determine a mean IC field of 1 $\mu$G, though a similar analysis of a somewhat smaller data sample led to a much smaller upper limit (Hennesy, Owen, & Eilek 1989).

Put together, all these estimates are certainly suggestive of IC field values significantly higher than the value deduced from the measurements of Bazzano et al. (1990). A higher value of the mean IC field implies a much lower HEX emission than Bazzano et al. attribute to Coma.

A basic inconsistency of the interpretation that the emission detected by Bazzano et al. is from the Coma cluster is the implication that nonthermal emission dominates even the low-energy X spectrum. Since we can very reasonably expect the RE energy spectrum not to flatten around 1 GeV (see Rephaeli 1979), then the fact that radio emission up to (at least) $\simeq 1$ GHz has been measured, implies that Compton scattering will yield X-rays below 1 keV. Interpolation of the Bazzano et al. (1990) spectrum to lower energies points clearly the conflict with the results of many analyses (most recently, that of *Ginga* data [Hatsukade 1989]), that the low-energy X emission is thermal bremsstrahlung for hot IC gas.

Moreover, integrating the spectrum of Bazzano et al. over their detected band of 18–130 keV, and taking the distance to Coma to be 138 Mpc ($z = 0.023$, and with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$), we compute HEX luminosity of $(1.6 \pm 0.2) \times 10^{45}$ ergs s$^{-1}$. This value is comparable to the total thermal luminosity of 8.3 keV IC gas. In fact, since there is no obvious reason why the RE energy spectrum should cut off at 6.5 GeV (corresponding to a Compton-scattered photon energy of 130 keV), the above value for the nonthermal luminosity is a lower limit. It would seem, therefore, that more energy is emitted by relativistic, rather than thermal, electrons, although the thermal gas energy is $\sim 10$ times higher. We consider this unlikely.

Consider, finally, the issue of the distributions of the radio and HEX emissions. The spatial profile of the HEX emission is not known—the required resolution was beyond the capabilities of all previous detectors used in cluster measurements. The most recent high-resolution radio measurements of Coma show that the emission is regular (though somewhat elongated) and can be fitted with an elliptical Gaussian (Kim et al. 1990). Since the structure of the radio emission is determined by the magnetic field and RE profiles, both of which are likely to decrease outward from the cluster center, we generally expect the radio emission to be more centrally concentrated than the HEX emission, which is the result of Compton scattering of RE by the spatially *uniform* CBR. Since we do not have spatial information on the HEX emission, spatial terms (in the expressions for the synchrotron and Compton fluxes) were absorbed in our expression for the mean field. Specifically, $B \propto \phi^{-1/(\alpha+1)}$, so that the exact definition of the mean field is $B \equiv B_0(j_1/j_0)^{\alpha+1}$, where $B_0$ is the central value of the field, and $j_0$ and $j_1$ are integrals over the RE and field spatial distributions (for more details, see Rephaeli 1979).

Clearly, if the HEX flux used in estimating $B$ comes from a larger region than that of the synchrotron emission, then the field value would be underestimated. However, with a mean (1.4 GHz) FWHM radius of $\sim 16'$ (from Kim et al. 1990), we calculate that the sky-projected size of the HEX emission has to be about 3.5 times higher than that of the radio size, or $\sim 4$ Mpc, in order to have underestimated $B$ by a factor of 2.4. Such an extended HEX emission is very unlikely: in the most reasonable model for origin in the central, powerful radio sources, the RE which give rise to the detected HEX emission lose their energy well before traveling a radial distance of $\sim 2$ Mpc. (Note that RE follow tangled field lines.) Thus the predicted HEX source size is smaller than required to explain the discrepant values of the field as being due to spatial factors.

### 3.2. *Galactic Emission*

If the flux detected by Bazzano et al. is not diffuse IC emission, what then is its origin? It is quite unlikely to be emanating from cluster galaxies. There are no active galaxies in the Coma cluster other than the central radio galaxies. Our estimates indicate that the strong radio sources (5C 4.81 and 5C 4.85) near the Coma center are not sufficiently powerful to account for the emission.

It is possible that there is a background source in the field of view of the MIFRASO detectors (2°.6 FWHM). Bazzano et al. (1990) do indeed consider this alternative, identifying the emission with the Seyfert galaxy X Comae. Since this galaxy is at $z = 0.092$ (Bond & Sargent 1973), its implied HEX luminosity (in the 18–130 keV band) has to be $2.6 \times 10^{46}$ ergs $s^{-1}$, a value too high even for a Seyfert galaxy. Now, although Bond & Sargent have determined that the galaxy was unusually bright in 1911, we estimate its normal optical luminosity to be less than $2 \times 10^{44}$ ergs $s^{-1}$. The galaxy was detected by the IPC aboard *Einstein* (Della Ceca et al. 1990). Integrating the IPC flux over the band 0.47–3.6 keV, we compute a luminosity of $1.9 \times 10^{44}$ ergs $s^{-1}$. Even after (generously) correcting for the narrow IPC band, it is clear that the low-energy X output of this galaxy is not indicative of a particularly intense Seyfert galaxy.

## 4. CONCLUSION

In our view, the above considerations raise serious doubts as to whether the emission detected by Bazzano et al. 1990) originates in the Coma Cluster. Thus, we can be reasonably confident that IC fields are at least 0.1 $\mu$G in strength, and that the energy density of RE in the IC space does not have to be unacceptably high to account for the observed radio emission. Adopting the realistic estimates of Rephaeli (1988) and Goldman & Rephaeli (1991) for the level of ejected galactic and turbulently generated fields, respectively, we consider it quite likely that $B \sim$ a few $\times$ 0.1 $\mu$G. If so, we would predict that IC HEX emission from Coma is at a few $\times 10^{-6}$ $cm^{-2}$ $s^{-1}$ $keV^{-1}$ level in the 30–50 keV range. In view of the high likelihood that the detected emission does not originate in the Coma cluster, it logically follows that further detector sensitivity targets should be based on the upper limit on the HEX flux set by RGR.

It seems that the only viable hypothesis which is consistent with both the *HEAO 1* A-4 and MIFRASO data is that the detected emission originates in an AGN whose X variability is such that it was in a low brightness phase during the 18 months period in 1978–1979 when the A-4 detectors completed three scans of the sky. Obviously, such an interpretation cannot be embraced before more HEX detections are made of this source. For example, the OSSE detectors aboard the Compton telescope could easily detect the HEX emission from Coma, even if the flux in the 60–130 keV is significantly lower than that detected with the MIFRASO experiment.

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