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# SOFT X-RAY FLUX OF THE COMA CLUSTER OF GALAXIES

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## ABSTRACT

Soft X-rays ($<2$ keV) from the Coma cluster of galaxies were detected with a focusing collector. The 0.5–2.0 keV intensity is $1.7 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$. With 90 percent confidence the angular diameter of the source is less than 30′. Our spectral data in combination with results from *Uhuru* show a strong preference for an exponential spectrum as compared to a power law, implying that the X-ray emission of the Coma cluster is a thermal process. The present measurement constrains the temperature of supposed intracluster gas that is needed to account for the stability of the Coma cluster to be below $10^6$ ° K.

*Subject headings:* galaxies, clusters of — intergalactic medium — X-ray sources

## I. OBSERVATIONS

The Coma cluster is a typical example of a rich cluster of galaxies which as a class appear to be strong, extended X-ray sources (Meekins *et al.* 1971; Gursky *et al.* 1971; Forman *et al.* 1972). We have made a new observation of the Coma cluster at lower energies with a focusing X-ray collector sensitive to 0.1–1.5 keV X-rays aboard a sounding rocket that was fired from the White Sands Missile Range on 1972 April 1.

The instrument was an improved version of the focusing collector described by Gorenstein *et al.* (1971). The detector system provided several independent 0°.3 image elements along the direction of focusing. The field of view (FWHM) was 1°.5 in the focusing direction and $\pm 6°$ in the nonfocusing direction.

The collector scanned the Coma cluster along a line inclined about 45° to the meridian. Figure 1 shows the data in the energy band 0.5–1.5 keV accumulated in bins of 3′. We have determined the angular size and center of the X-ray source by fitting the data to an isothermal sphere model folded with the instrument response (Lea *et al.* 1973). In this model the assumed density distribution $\rho(r)$ is

$$\rho(r) = \rho_o/(1 + r^2/a^2)^{3/2},$$

where $r$ is the radial coordinate from the center of the cluster and $a$ is a free parameter that represents the characteristic core radius. The distribution of galaxies in the Coma cluster is consistent with this function (Rood *et al.* 1972). We obtain $2a < 30'$ within a confidence level of 90 percent. A uniform source will also fit the data giving about the same value for the diameter. Our data are consistent with all of the following: (1) a point source, (2) the value of 6′.4 for the optical core radius found by Rood *et al.* (1972), and (3) the *Uhuru* diameter of $36' \pm 4'$ for a uniform source as reported by Forman *et al.* (1972) for 2–10 keV X-rays. Although there appears to be only a small probability that the two X-ray measurements agree, we did not include a size uncertainty due to possible use of an improper model. The two instruments had different characteristics: in the present observation there is about a factor of 2 better angular resolution but much less sensitivity to regions of low surface brightness. For example, if there were a weak point source at the center in addition to a uniform source, it would simulate a uniform source of smaller angular size in the present measurement as compared to *Uhuru*. The angular size as seen by the focusing collector and *Uhuru* applies only to the one dimension along our scan direction which also happens to be

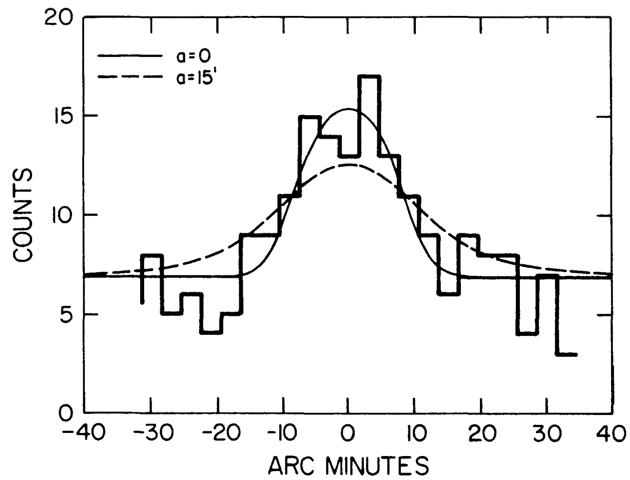


FIG. 1.—Distribution of counts versus angle for the Coma cluster in the energy range 0.5–1.5 keV. The curves are the theoretical response of the instrument (for very narrow collection bins) in an isothermal gas sphere model to sources of characteristic diameter equal to 0 and 30′ plus background. There is 90% confidence that the source is smaller than 30′.

the direction of most of the *Uhuru* scans. The centroid of the source in the rocket data, although much less precise, is consistent with the *Uhuru* centroid.

The observed intensity flux of the Coma cluster in three energy bands corrected for the instrument response are given in table 1. In order to determine the intrinsic spectrum of the Coma cluster, absorption of soft X-rays by our Galaxy and the intergalactic medium (IGM) should be taken into account. The column density of galactic hydrogen, $N_{\mathrm{H}}$, along the line of sight to the Coma cluster has been estimated from the measurements of 21-cm radiation reported by Tolbert (1971). We obtain $N_{\mathrm{H}} = 1.8 \times 10^{20}$ H atoms cm$^{-2}$. From the X-ray absorption properties of the interstellar gas (Brown and Gould 1970) we conclude that interstellar absorption is significant only in the 0.15–0.28 keV band and that there is no large uncertainty in correcting for it. Absorption in the IGM would be due mainly to He assuming that the IGM consists only of H (90%) and He (10%) and that H is mostly ionized (cf. Field 1972). From the He X-ray absorption coefficient as given by Henke and Elgin (1970), we conclude that as much as $5 \times 10^{21}$ H atoms per cm$^2$ (He unionized) in the IGM to Coma could be tolerated without changing the conclusion we reach below. If the distance to Coma is 90 Mpc, this corresponds to an average density of $1.9 \times 10^{-5}$ H atoms per cm$^3$, which is about 7 times the critical density of a closed universe (Field 1972). If He is ionized, even a larger density could be tolerated. We assume that such a large density is unlikely; therefore, absorption in the IGM is neglected. We also assume no self-absorption in the Coma cluster.

The most sensitive way of determining the spectrum of the Coma cluster is to

TABLE 1

OBSERVED FLUX

| Energy Band (keV) | Flux (ergs cm$^{-2}$ s$^{-1}$) |
|---|---|
| 0.15–0.28 .......................... | $<1.5 \times 10^{-11}$ (3 $\sigma$ upper limit) |
| 0.5–1.0 ............................ | $4.6 \times 10^{-11} \pm 1.8$ |
| 1.0–2.0 ............................ | $1.2 \times 10^{-10} \pm 0.3$ |

combine the present data with the *Uhuru* results so as to have observations extending over two decades of energy. In so doing we assume there is no disagreement concerning the size and location of the source. Forman *et al.* (1972) fitted *Uhuru* data to two models, (1) and (3), with the following results:

(1) $dN/dE = 1.7\ E^{-\alpha}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ power law,
$\alpha = 2.0 \pm 0.1$

(2) $dN/dE = 0.044\ G \exp(-E/Kt)/E$ thermal ($G$ energy dependent),
$G = 0.8\ (E/Kt)^{-0.4}$ $(E/Kt > 0.1)$
$= 1 - \log_{10}(E/Kt)$ $(E/Kt < 0.1)$,
$kT = 8.1 \pm 1.5$ keV,

(3) $dN/dE = 0.094 \exp(-E/Kt)/E$ Thermal ($G = 1$),
$kT = 5.3 \pm 0.6$ keV.

Model 2 has been derived from the published results of models (1) and (3).

Model 2 includes $G$, an energy-dependent Gaunt factor (Karzas and Latter 1961). For a thin hydrogen plasma with $kt > 1$ keV and data over a wide energy range, it is important to include the energy dependence of the Gaunt factor for a proper estimate of $kt$ (Gorenstein, Gursky, and Garmire 1968; Margon 1973). The use of a Gaunt factor in a thermal model does not always give a better fit to spectral data as noted by Holt, Boldt, and Serlemitsos (1969) and Rappaport *et al.* (1969) for Sco X-1. However, the use of the Gaunt factor probably improves the description of the data in the case of the Coma cluster.

The three models have been extrapolated to lower energies and folded with the instrument response. Their agreement with the three data points can be evaluated from the $\chi^2$ test. These results are listed in table 2 and shown in figure 2 for $N_{\mathrm{H}} = 2 \times 10^{20}$ H atoms cm$^{-2}$. Within the range of acceptable values for $N_{\mathrm{H}}$, 1.5 – $2.5 \times 10^{20}$, model 1 is not compatible with the present rocket data. The power-law fit is not acceptable even if the spectrum becomes less steep by one-half power below 1 keV. Both thermal models provide an acceptable fit to the data, although only model 2 is presumably physically correct. With a thermal spectrum the observed intensity of the Coma cluster $E > 0.5$ keV is $8 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$. For an assumed distance of 90 Mpc, its intrinsic X-ray luminosity is $8 \times 10^{44}$ ergs s$^{-1}$.

## II. DISCUSSION

The most straightforward interpretation of our results is that the spectrum of the Coma cluster is thermal and that the emission occurs in a rather narrow temperature range. A power law which is often characteristic of synchrotron radiation or inverse Compton radiation can be excluded. Our interpretation may be changed if absorption in the IGM or self-absorption turns out to be significant. The absence of self-absorp-

TABLE 2

VALUES OF $\chi^2$ (3 degrees of freedom)

| Model | | $N_{\mathrm{H}}$ ($10^{20}$ cm$^{-2}$) 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|
| (1) | Power law | 435 | 240 | 154 | 109 | 82.4 |
| (2) | Bremsstrahlung ($G > 1$) | 6.1 | 3.0 | 1.6 | 1.0 | 0.6 |
| (3) | Bremsstrahlung ($G = 1$) | 4.1 | 2.0 | 1.0 | 0.5 | 0.3 |

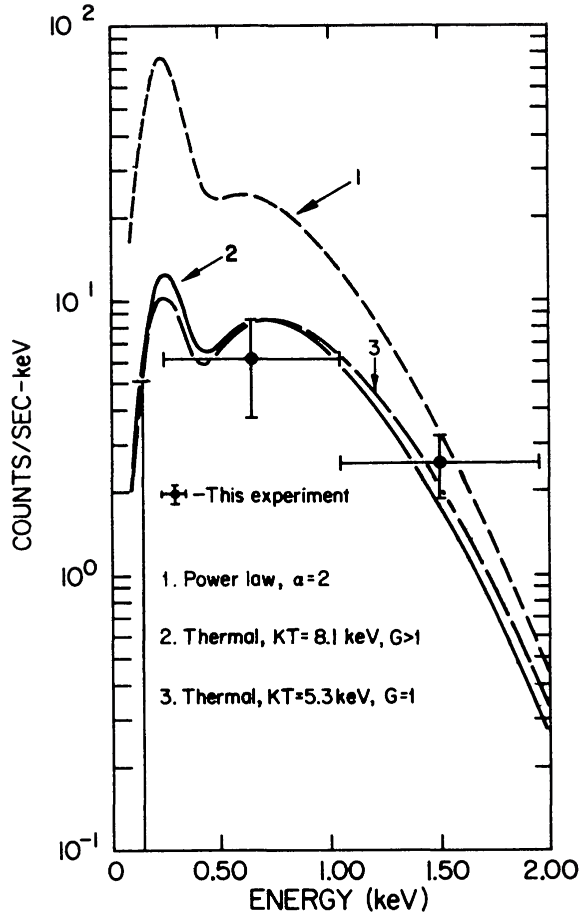


FIG. 2.—Spectrum of the Coma cluster. The curves are three model spectra which fit the 2–10 keV *Uhuru* data extrapolated below 2 keV and convolved with the response of the focusing collector. It is assumed that $2 \times 10^{20}$ H atoms per $cm^2$ are along the line of sight in our Galaxy. The vertical bars on the data points (this experiment) are 1 sigma errors. The horizontal bars indicate the energy range of the data bins.

tion is consistent with the observed extent of $\sim \frac{1}{2}$ Mpc and the temperature of $\sim 10^8$ ° K. Hydrogen and helium in the source region would be completely ionized, and the heavy-element concentration is probably low like that of the IGM. Thus, unless the source actually consists of a number of unresolved compact objects, it should be optically thin at essentially all wavelengths. We would not expect the outlying regions of the cluster to absorb X-rays even if they were much cooler than the central source region because their density is likely to be much lower.

The finite size for the X-ray source in the Coma cluster plus the present result that its spectrum is exponential imply the existence of a hot ionized intracluster medium (ICM) in the central region. The temperature of the ICM is $\sim 10^8$ ° K, and the density needed to explain the X-ray emission is $\sim 10^{-3}$ atoms per $cm^3$.

A previous report on the spectrum of the Virgo cluster found that it is much more likely to be exponential than a power law (Gorenstein, Harris, and Gursky 1972). The present result on the Coma cluster is more observational evidence that X-ray sources in the central regions of rich clusters of galaxies emit by a thermal process. There are several theoretical models for thermal emission from clusters (e.g., Gott and Gunn 1971, 1972; Hunt and Sciama 1972. Solinger and Tucker (1972) have pointed out a relation between the X-ray luminosity and the velocity dispersion of the cluster which suggests a thermal process.

The hot gas in the Coma cluster which emits X-rays in the *Uhuru* energy range is only about $10^{-2}$ of the amount of supposed "missing mass" needed to stabilize the cluster (Gursky *et al.* 1971). Our observation did not detect soft X-ray emission at a level exceeding the extrapolated *Uhuru* spectrum. We conclude that the Coma cluster does not contain large quantities of gas with $kT$ in the range 0.1–1 keV. Thus an additional constraint can be placed upon the missing mass of the Coma cluster; its temperature must be less than $10^6$ ° K or it would have resulted in a much stronger soft X-ray flux than the one observed.

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