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X-radiation From Clusters of Galaxies: Spectral Evidence For A Hot Evolved Gas

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ABSTRACT

OSO-8 observations of the X-ray flux in the range 2-60 keV from the Virgo, Perseus, and Coma clusters provide strong evidence for the thermal origin of the radiation, including iron line emission. The data are adequately described by emission from an isothermal plasma with an iron abundance in near agreement with cosmic levels. A power law description is generally less acceptable and is ruled out in the case of Perseus. Implications on the origin of the cluster gas are discussed.

I. INTRODUCTION

Spectral measurements of X-ray emission from several clusters of galaxies (Kellogg, Baldwin, and Koch 1975; Davidsen et al. 1975; Scheepmaker et al., 1976) have already resulted in substantial evidence that favors the thermal origin of the radiation over the inverse Compton hypothesis.

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The Ariel 5 discovery by Mitchell et al. (1976) of an emission feature near 7 keV in the spectrum of the Perseus cluster has, in addition, introduced implications concerning the history of the emitting gas. If this feature is indeed due to thermally excited iron lines, is it an isolated case, perhaps due to the presence of the active galaxy NGC1275, or is it an inherent feature common to other clusters as well? In addition to Perseus, the Virgo and Coma clusters emit radiation resulting in strong enough fluxes at the earth to allow a search for iron lines with data presently at hand. The three clusters form a diverse and, therefore, interesting sample with differences in richness, morphology, and predominance of active galaxies.

The Goddard X-ray Spectroscopy Experiment aboard OSO-8 has observed these three clusters as part of an observing program that will eventually result in spectra in the range 2-60 keV for most known X-ray sources. We report in this paper results from an analysis of "Quick Look" data seeking to confirm the iron line in Perseus and to search for lines in Virgo and Coma.

II. THE EXPERIMENT

The Perseus, Virgo, and Coma clusters were observed in that order in February, June, and July, 1976, each observation lasting some 3-6 days. Only 10-15 percent of the data are presently available corresponding to exposures of .91, .93 and .78 x 10^6 cm^2-s and net counts of $\sim$ 12 x 10^4, 6 x 10^4 and 4 x 10^4 respectively. The detector involved in all three measurements is a multi-wire xenon-methane proportional counter fitted with a .002 inch beryllium window, having a net area of 263 cm^2 and 5.1

degree circular collimation. The center of the field of view is in continuous motion via a 5 degree precession about the spacecraft spin axis. This mode of observation both optimizes the exposure to a source and allows us to obtain source and background spectra each spacecraft revolution (∿ 10 sec). On board calibration confirms that near optimum energy resolution (∿ 1.1 keV at 6.7 keV) has been maintained since launch (21 June 1975). For additional information on this experiment see Serlemitsos et al. (1976).

III. RESULTS

Our method of analyzing spectra is adequately described by Pravdo et al. (1976). Net counts from each source were fitted to two types of spectra: a single temperature thermal continuum and a power law, adding in each case a narrow line at 6.7 keV and treating its equivalent width as a free parameter. Absorption by cold matter was also included with relative abundances as given by Brown and Gould (1970). We utilized the Gaunt factor computer approximation of Kellogg, Baldwin and Koch (1975) for hydrogen and helium in our thermal fits, since these elements dominate the contribution to the continuum emission. All parameters and their errors were derived from a χ^2 comparison between the actual data and the predictions of the assumed source spectrum folded through the detector response. In estimating parameter errors, we followed the approach of Lampton et al. (1976).

In Table 1 we summarize our results. We note that the thermal model provides acceptable fits although the confidence level for Virgo is only ∿ 4 percent, partially due to a possible additional component indicated at the high energy end. The power law spectrum gives a poorer fit in each case, being ruled out in the case of Perseus where the statistical significance of the data is highest. In addition, the power law requires substantially larger absorption. In every case, the addition of the iron line reduces the χ^2 substantially. The deduced equivalent widths are roughly the same for both types of spectra. In the weakest case, (i.e. Coma with poorer statistics and lower equivalent width), confidence in the presence of the line is at the 3σ level. The line stands out in the inferred incident spectrum for Coma shown in Figure 1 along with the best fit thermal continuum including the deduced absorption. In Figure 2 we show the residuals obtained after subtracting from the three sets of data the best fit continua. In all three cases the data are consistent with narrow lines, i.e. the observed broadening can be accounted for by the detector response.

The same detector observed the Crab nebula in March 1976. We fitted a sample of the Crab data in precisely the same manner using a power law spectrum with an iron line at 6.7 keV. The 3σ upper limit to the equivalent width of line emission from the Crab is 35 eV.

IV. DISCUSSION

Results presented in this paper greatly enhance the already mounting evidence for the thermal origin of the X-ray emission from clusters of galaxies. They support a model for the emitting plasma more in agreement with the simple isothermal case of Lea et al. (1973) rather than the more complex adiabatic model discussed by Mitchell et al. (1976). They confirm the iron line in Perseus, and add Virgo and Coma to the list of cluster sources with similar lines. Support is given to source models that would predict iron and presumably other heavy element abundances to be at or near cosmic levels in the emitting gas.

The gas temperatures derived from this work are generally in agreement with the thermal fits of Kellogg, Baldwin and Koch (1975) including the required amounts of absorbing matter in the line of sight. We assume that the reason these authors did not report line emission must arise from insufficient spectral resolution and/or stability of the UHURU counters over the time of the measurements. The statistical significance of their data certainly appears to be comparable with that of these observations.

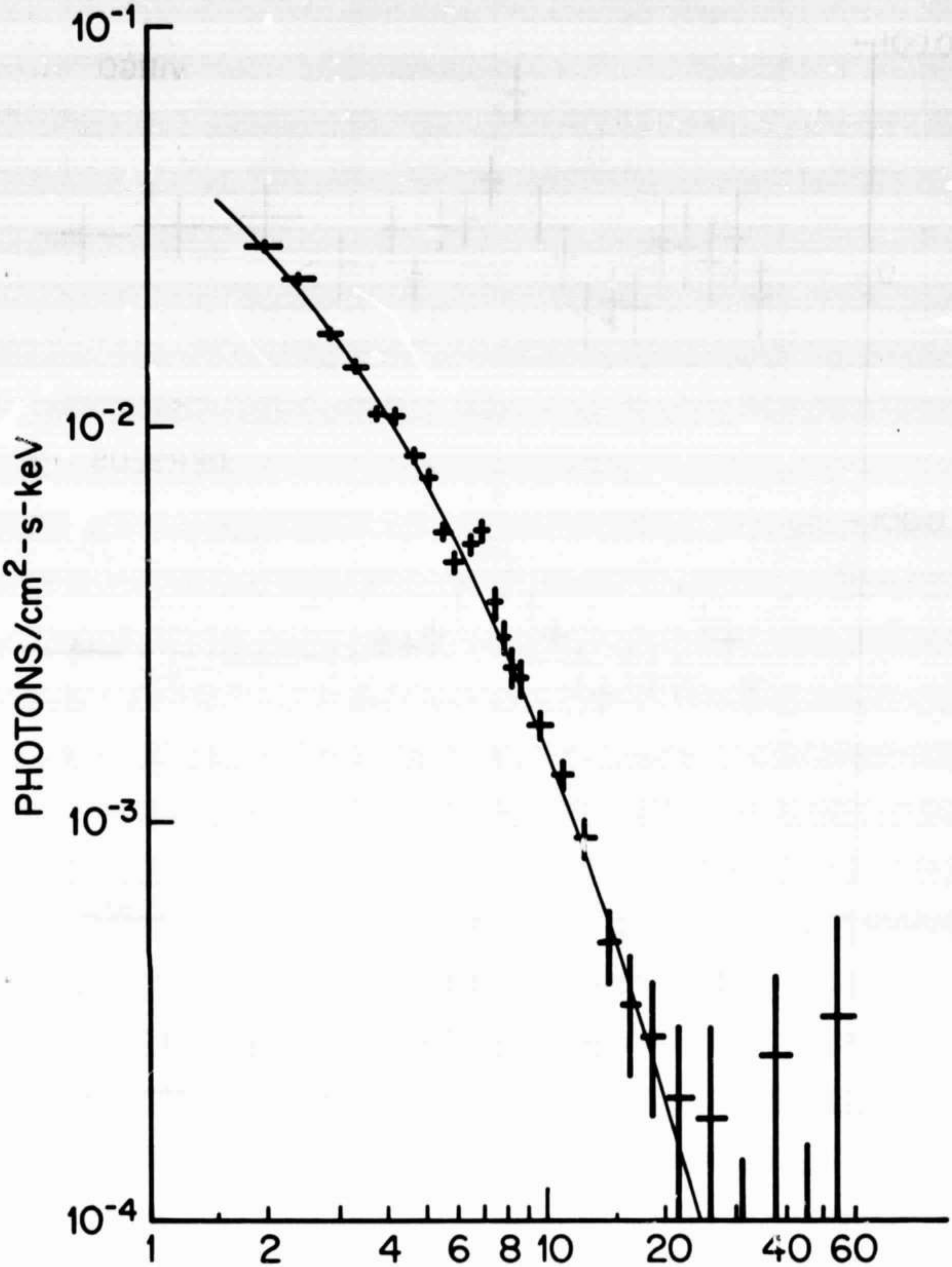
In computing the equivalent widths we have used the collisional equilibrium calculations for spectra of optically thin plasmas by Raymond, Smith, and Cox (1976). Assuming a cosmic abundance of iron relative to hydrogen of 4×10^{-5} (Allen 1973), we infer iron abundances for cluster sources as given in Table 1. Our OSO-8 observations of Cas A (Pravdo et al. 1976) have, using the same optically thin model, given a relative iron abundance of .64 for that supernova remnant, which is within $\sim 2\sigma$ of the abundances deduced for Virgo, Perseus, and Coma. As in the case of Cas A, had we used the model of Tucker and Koren (1971), we would have deduced higher iron abundances by about a factor of 3. Mitchell et al. (1976) would obtain an equivalent width for Perseus in better agreement with our result if they were to use 6.9 keV instead of 6 keV as the temperature for the continuum.

Although the values inferred for plasma temperature and iron line equivalent width vary significantly among the three clusters considered

FIGURE CAPTIONS

Figure 1 The inferred incident spectrum for the Coma cluster of galaxies. The solid line represents the best fit thermal continuum with parameters as shown in Table 1.

Figure 2 Residual counts for Virgo, Perseus, and Coma obtained by subtracting from the data the best fit thermal continua from Table 1.



10^{-1}
10^{-2}
10^{-3}
10^{-4}
PHOTONS/cm^2-s-keV
1
2
4
6
8
10
20
40
60
ENERGY (keV)

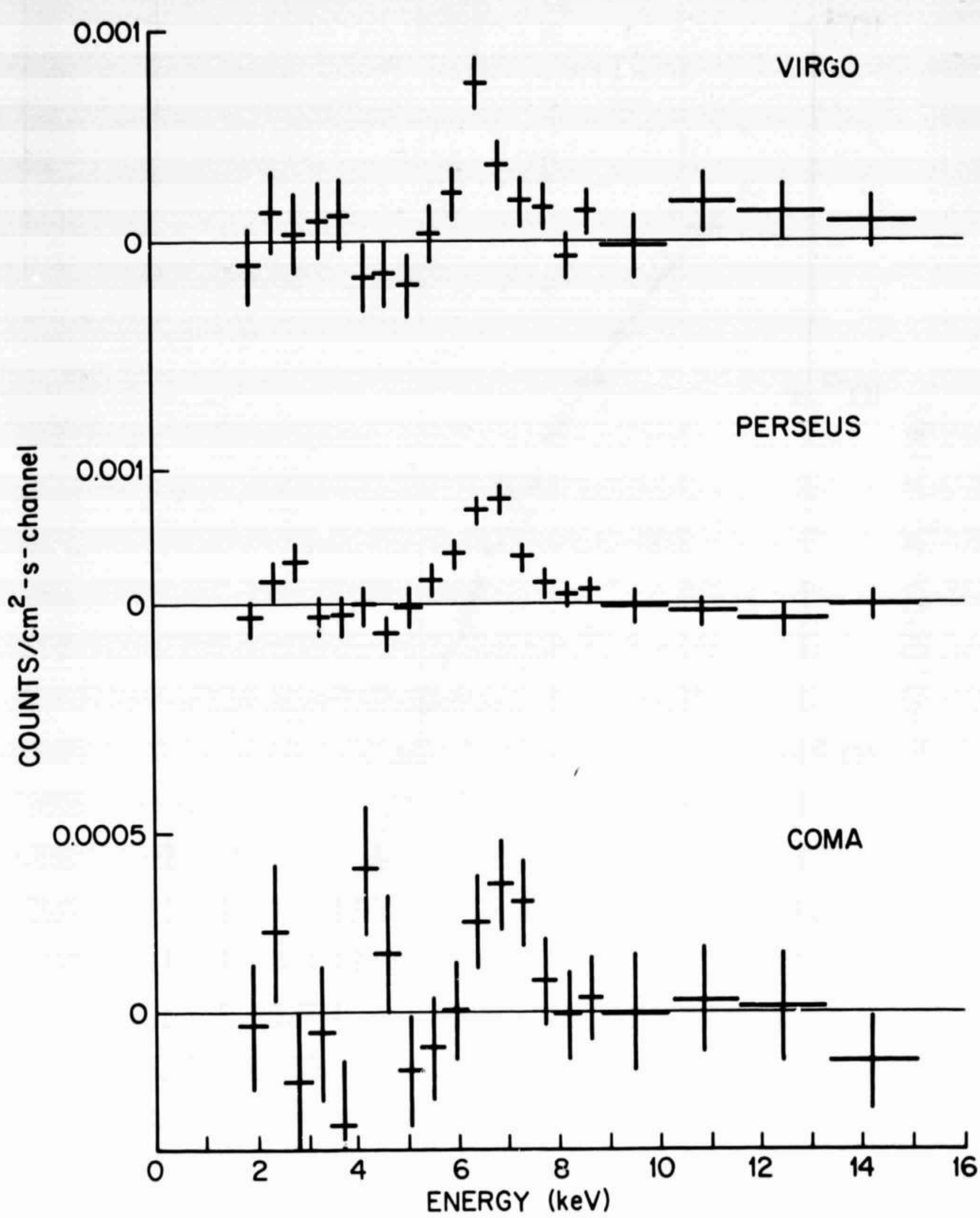

VIRGO
PERSEUS
COMA
0.001
0
0.001
0
0.0005
0
COUNTS/cm^2-s-channel
0
2
4
6
8
10
12
14
16
ENERGY (keV)

TABLE I

THERMAL*

	VIRGO	PERSEUS	COMA
kT(keV)	$2.85 \pm .25$	$6.95 \pm .35$	9.3 ± 1.3
N_H(x 10^{21})	≤ 3.2	≤ 1.8	$3.3 \pm 2 \times 10^{21}$
2-6 keV Intensity** (ergs/cm^2-s)	$3.53 \pm .05 \times 10^{-10}$	$6.62 \pm .05 \times 10^{-10}$	$2.55 \pm .04 \times 10^{-10}$
Line strength** (photons/cm^2-s)	$.0021 \pm .0006$	$.0044 \pm .0008$	$.0012 \pm .0007$
Equ. Width (eV)	850 ± 250	490 ± 88	280 ± 170
Fe abundance*** rel. to cosmic	$.40 \pm .12$	$.45 \pm .08$	$.38 \pm .23$
χ^2****	37.5	20.5	23.8
POWER LAW*			
Number Index	3.38	2.41	2.22
N_H(x 10^{21})	18	16	17
χ^2****	38	78	35

*Including narrow line at 6.7 keV and absorption by cold matter in the line-of-sight

**Errors shown are statistical. We estimate larger (∿20%) uncertainties due to incomplete aspect information in quick look data.

***Based on model of Raymond, Smith and Cox (1976)

****24 degrees of freedom

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