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DETECTION OF X-RAY EMISSION FROM DISTANT CLUSTERS OF GALAXIES

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ABSTRACT

We report the first extensive detection of X-ray emission from clusters of galaxies at cosmological distances. The properties of these objects are similar to those observed in objects at low redshifts. The 0.5–4.5 keV luminosities are in the range $<1 \times 10^{43}$ to 2×10^{45} ergs s^{-1}; the core radii are on the order of 0.5 Mpc; and Bautz-Morgan type I clusters are more luminous than types II or III. Our observations are consistent with models assuming an evolving cluster potential and moderately efficient galaxy formation, but do not require them when observational selection is considered.

Our X-ray observations of the 3C 295 cluster indicate that there is sufficient intergalactic medium to cause stripping of the cluster spirals, but the colors of these galaxies imply that they have not been stripped. We discuss a possible explanation of this discrepancy.

Subject headings: galaxies: clusters of — galaxies: evolution — X-rays: sources

I. INTRODUCTION

Clusters of galaxies compose one of the two major classes of identified extragalactic X-ray sources, with almost 50 objects in the samples of Jones and Forman (1978) and McHardy (1978). The X-ray emission is attributed to the thermal bremsstrahlung radiation from a hot intracluster gas. The properties of the X-ray emitting gas are presumably changing as a result of the evolution of the galaxies and the cluster as a whole.

The nature of the X-ray luminosity evolution is determined mainly by the efficiency of galaxy formation in the protocluster and by the evolution of the cluster gravitational potential. If galaxy formation is very efficient, so that no intracluster gas remains, then the X-ray luminosity is low until the interstellar gas is stripped by galaxy collisions (Sarazin 1979; Norman and Silk 1979). Since this stripping occurs slowly, the luminosity remains low for a substantial fraction of the cluster life. On the other hand, if galaxy formation is very inefficient, so that a large fraction of the cluster mass is in intracluster gas, then the luminosity is very high at the time the cluster forms, but decreases with time as the gas cools and condenses (Silk 1976). For moderately efficient galaxy formation, with about 10% of the protocluster mass in intracluster gas, the luminosity evolution depends on whether the cluster potential evolves, but is in general intermediate between the two extremes. A static cluster potential results in a constant X-ray luminosity, within a factor of 2, from $z = 1$ to $z = 0$ (see, e.g., Cowie and Perrenod 1978). The calculations by Perrenod (1978) use the n-body simulations of White (1976) to describe the evolution of the cluster's gravitational potential. These calculations predict a luminosity increase by a factor of 10 from $z = 1$ to $z = 0$. For all the models, any changes occur before $z = 0.5$.

In addition to studying the evolution of the X-ray properties of clusters, our observations are useful for the study of the transformation of spiral galaxies into S0's. The current hypothesis is that many S0 galaxies are produced by stripping the interstellar medium from ordinary spirals. Two processes have been suggested: ram-pressure stripping as the galaxy moves through the intergalactic medium, and evaporative stripping by the hot intergalactic material (Cowie and Songaila 1977; Gunn and Gott 1972; Oemler 1977). Theoretical calculations indicate that these processes can be very efficient (Gisler 1979; Lea and DeYoung 1976); moreover, as the spirals lose gas, their colors change from blue to red because star formation is no longer occurring (Biermann and Tinsley 1975). The entire process of stripping, with consequent color change, can occur within about 2×10^9 years after the cluster forms or the intergalactic gas is ejected (Gisler 1979). X-ray observations can be used to determine the parameters of the cluster intergalactic medium, which is the stripping material for either model.

II. OBSERVATIONS

a) Positions, Fluxes, and Luminosities

Using the imaging proportional counter (IPC) of the *Einstein* X-ray Observatory (Giacconi *et al.* 1979*a*), we have observed 11 clusters of galaxies with redshift greater than 0.1 as of 1979 March 26. The positions of the detected sources are within 75″ of the cataloged optical positions, which is consistent with the combined uncertainties of the IPC for determining the location of a weak source and the cataloged positions. The images of the clusters around 3C 295 and PKS 0116+08 are shown for illustration in Figure 1 (Plate L5).

In Table 1 we list the clusters observed in order of

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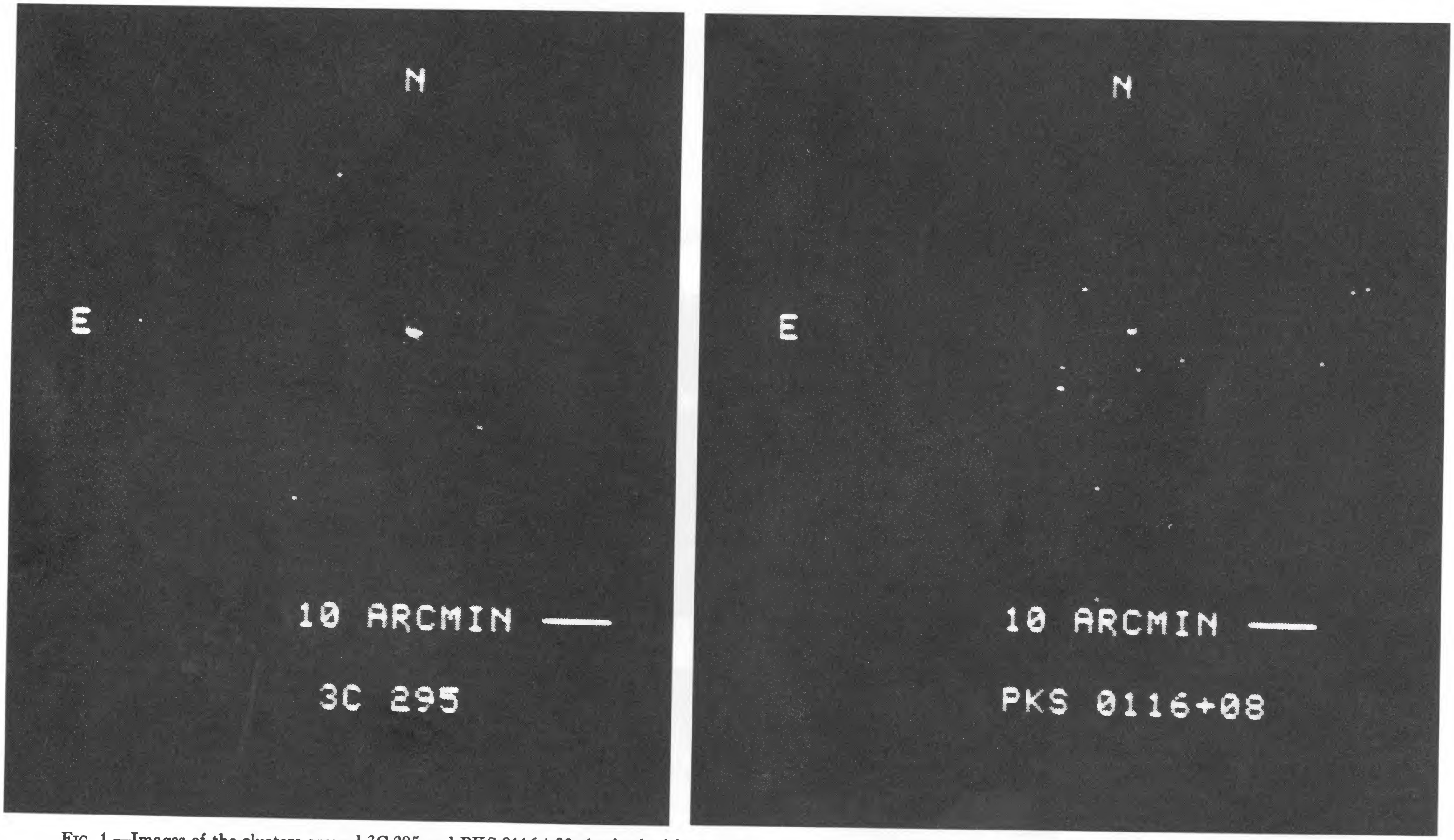

FIG. 1.—Images of the clusters around 3C 295 and PKS 0116+08 obtained with the IPC in the energy band 0.5–4.5 keV. All pixels with less than three counts are black.

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TABLE 1

Cluster	Z	BM	Rate (sec^{-1})	Energy Band (keV)	Exposure Time (sec)	F_E (2 keV/(1+Z)) (keV cm^{-2} sec^{-1} keV^{-1})	L_x (0.5 keV, 4.5 keV) (erg sec^{-1})
A 98	0.1028[1]	II - III[1]	$7.6 \pm 1.2 \times 10^{-2}$	0.20 - 2.7	2079	$3.6 \pm 0.5 \times 10^{-4}$	$1.0 \pm 0.2 \times 10^{44}$
A 2240	0.137[1]	III[1]	$< 5.2 \times 10^{-3}$	0.33 - 4.3	3093	$< 2.6 \times 10^{-5}$	$< 1.3 \times 10^{43}$
A 1413	0.1426[1]	I[1]	$3.9 \pm 0.1 \times 10^{-1}$	0.29 - 4.4	2549	$1.9 \pm 0.07 \times 10^{-3}$	$1.0 \pm 0.04 \times 10^{45}$
A 2009	0.157[5]	I - II[5]	$3.0 \pm 0.1 \times 10^{-1}$	0.19 - 4.8	3712	$1.4 \pm 0.05 \times 10^{-3}$	$9.1 \pm 0.3 \times 10^{44}$
A 115	0.1959[1]	III[1]	$7.8 \pm 0.6 \times 10^{-2}$	0.29 - 2.4	2339	$4.8 \pm 0.4 \times 10^{-4}$	$5.0 \pm 0.4 \times 10^{44}$
C 11328.1+3157	0.270[6]		$< 7.5 \times 10^{-3}$	0.32 - 4.7	1643	$< 4.1 \times 10^{-5}$	$< 8.0 \times 10^{43}$
A 348	0.274[2]	II - III[5]	$1.9 \pm 0.4 \times 10^{-2}$	0.28 - 4.2	2969	$9.7 \pm 2.1 \times 10^{-5}$	$2.0 \pm 0.4 \times 10^{44}$
3C295	0.461[1]	I[1]	$3.7 \pm 0.7 \times 10^{-2}$	0.29 - 4.4	2443	$2.1 \pm 0.4 \times 10^{-4}$	$1.3 \pm 0.2 \times 10^{45}$
3C330	0.5490[3]	II-III[3]	$< 2.4 \times 10^{-3}$	0.20 - 2.7	7448	$< 1.6 \times 10^{-5}$	$< 1.2 \times 10^{44}$
PKS0116+08	0.5936[3]	I[3]	$7.2 \pm 2.5 \times 10^{-3}$ $8.3 \pm 2.1 \times 10^{-3}$	0.28 - 2.4 0.17 - 4.6	4086 4235	$5.4 \pm 1.9 \times 10^{-5}$ $4.7 \pm 1.2 \times 10^{-5}$	$5.4 \pm 1.8 \times 10^{44}$ $4.7 \pm 1.2 \times 10^{44}$
3C343.1	0.750[4]	I[4]	$3.2 \pm 1.4 \times 10^{-3}$	0.25 - 4.4	3478	$2.1 \pm 0.9 \times 10^{-5}$	$3.4 \pm 1.5 \times 10^{44}$

References

[1] Kristian, Sandage, and Westphal (1978).
[2] Sandage, Kristian, and Westphal (1976).
[3] Spinrad et al. (1976).
[4] Spinrad et al. (1977).
[5] Lier and van den Bergh (1977).
[6] Gunn and Oke (1975).

increasing redshift. The first three columns give the source name, redshift, and Bautz-Morgan type. The fourth and fifth columns give the source counting rate and the observed energy band; the sixth column gives the on-source exposure time. The seventh column gives the spectral density at the detector at the energy corresponding to 2 keV in the cluster rest frame. The eighth column gives the luminosity in the band 0.5–4.5 keV, assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$. The errors in Table 1 reflect the uncertainties of both the source and background rates and cannot be used directly to determine the significance of the detection. We note that 3C 343.1, the weakest detected source, was detected at the 3.6 σ confidence level.

Since most of the sources are quite weak, it is not feasible to determine their spectra from the IPC pulse height data given the exposure times we have used. Hence, the usual procedure of obtaining fluxes and luminosities from best-fit spectral parameters could not be employed. Instead, we assumed a particular spectrum to be valid for all clusters and folded this spectrum (with unit normalization) through the detector. By comparing the observed counting rate to that predicted by the trial spectrum, we obtained the proper normalization for each source. To obtain the spectral density or luminosity given in Table 1, we evaluated the properly normalized trial spectrum at the appropriate energy or integrated it in the band equivalent to 0.5–4.5 keV at the source.

The trial spectrum was thermal bremsstrahlung with Gaunt factor; we assumed the temperature $kT = 7$ keV at the source, and the column density $N_H = 3 \times 10^{20}$ cm^{-2} in our Galaxy. The temperature is the average of the sample of 20 clusters measured by Mushotzky *et al.* (1978). To facilitate comparison with previous work, we note that these spectral parameters yield $L_x(2, 10) = 0.95\, L_x(0.5, 4.5)$. The spectral density and luminosity determined in this way are not very sensitive to the assumed spectral parameters. Varying kT from 5 to 10 keV and N_H from 2×10^{20} to 5×10^{20} cm^{-2} causes the spectral density and luminosity to vary by less than 10% from the values in Table 1. We estimate the total systematic uncertainties in the absolute flux calibration to be about 30%.

b) Sizes

Both preflight and in-flight calibrations show that the point response function of the IPC is, to a good approximation, a Gaussian with a width that is pulse-height dependent, but independent of energy. The pulse-height dependence is eliminated, and the best spatial resolution is obtained by considering only events in the upper half of the pulse-height analyzer. Since the sizes of the clusters discussed here are expected to be near the spatial resolution of the IPC and the statistics are poor, we will, for convenience, approximate the cluster surface brightness by a Gaussian. Determining the parameters of more realistic surface-brightness distributions does not seem warranted given the present data. This approximation has the useful property that the convolution of a Gaussian point response function with a Gaussian object yields a Gaussian image with a sigma equal to the rms sum of the sigmas of the object and point response function.

To determine the sizes of objects, we take the ratio of the counts inside a circle of radius a to those in an annulus of radii a and b. For a Gaussian image this ratio is

$$R(a, b) = \frac{1 - \exp(-a^2/2\sigma^2)}{\exp(-a^2/2\sigma^2) - \exp(-b^2/2\sigma^2)} .$$

In Table 2 we give $R(1', 2')$, the corresponding image size, and after removing the $0'.64$ instrumental response, the intrinsic size of several objects. The energy band of these measurements is approximately 1–4.0 keV at the detector, which is the band corresponding to the pulse heights which give the narrowest point response function. Linear sizes in Table 2 are computed assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$.

The source 4U 1658−48 is a bright galactic center source used as a standard. Since we are analyzing data in a pulse-height range where the spatial resolution is independent of pulse height, it is not necessary to consider the effects of differing spectra when comparing this source with others. The source QSO 1635+119 is a quasar with a counting rate and observation time similar to the clusters. This source is used to check for the effects of any long-term drifts in either the detector or aspect solution which could broaden the image. We do not expect any such effects on the scale of 30″ and the measured size of the quasar is consistent with a point source, thereby confirming this.

The other four sources in Table 2 are the detected clusters from Table 1 with $z > 0.2$. The sizes of clusters with $z < 0.2$ are discussed by Murray *et al.* (1979) and Jones *et al.* (1979). The measured sizes of A348 and 3C 295 and the upper limit for PKS 0116+08 are consistent with $\sigma = 0.25$ Mpc. Since the core radius of an isothermal sphere is about 2 σ, the core radii of the distant clusters are similar to clusters at the present epoch (Murray *et al.* 1979; Jones *et al.* 1979).

III. THE CLUSTER AROUND 3C 295

The color distribution of the galaxies in the 3C 295 cluster is consistent with a spiral-rich population, yet its morphology and richness are similar to nearby spiral-poor clusters (Butcher and Oemler 1978*a*, *b*). One explanation that has been proposed to explain this discrepancy is that we are observing this cluster before the galaxies have been stripped so that there is no intergalactic medium (Sarazin 1979; Norman and Silk 1979).

The luminosity and size that we have measured for this cluster can be used to determine the intergalactic medium density, assuming a thermal bremsstrahlung emission process from an isothermal sphere. In this case, the luminosity in the 0.5–4.5 keV band for a 7 keV temperature is L_x (0.5, 4.5) = $5.37 \times 10^{-24} n_0^2 a^3$ ergs s^{-1}, where n_0 is the central particle (ion plus electron) density in cm^{-3} and a is the core radius in cm of a King (1972) approximation to an isothermal sphere. With $L = 1.3 \times 10^{45}$ ergs s^{-1} and $a = 0.5$ Mpc, $n_0 = 8.1 \times 10^{-3}$ cm^{-3}. The average value of the ion density in the core is then $n_a = 2 \times 10^{-3}$ cm^{-3}.

This is a sufficiently high density that the spirals in the core should be stripped by either of the two mechanisms outlined in the introduction. Stripping by the ram pressure of the intergalactic medium of density n will occur if (Gunn and Gott 1972) $nm_pV^2 > 2\pi G\sigma_s\sigma_g$, where σ_s and σ_g are the stellar and interstellar medium surface densities and V is the velocity of the galaxy with respect to the cluster. For a $10^{11} M_\odot$ galaxy with a radius of 10 kpc, an interstellar medium of 1 cm^{-3}, and a thickness of 200 pc, this criterion becomes $n > 1.5 \times 10^{-3} (V_3)^{-2}$ cm^{-3}, where V_3 is the velocity dispersion of the cluster galaxies in units of 10^3 km s^{-1}. Since $V_3 \approx 1.5$ for centrally condensed clusters like Coma, there should be no late-type spirals in the core of the centrally condensed 3C 295 cluster. Evaporation of the interstellar material by the hot intergalactic medium will take place at a rate of about 100 $M_\odot$ yr^{-1} (Cowie and Songaila 1977) for $n_a = 2 \times 10^{-3}$ cm^{-3} and $T = 7$ keV. Since this is much higher than any reasonable replenishment rate by stars in spiral galaxies, we again expect that there should be no late-type spirals in the core of the 3C 295 cluster.

Thus, for nominal values of the parameters, there is sufficient intergalactic medium to cause stripping of the cluster spirals. It is possible that we are observing the

TABLE 2

Sizes of Objects

Object	$R(1', 2')$	Image σ (arcmin)	Object σ (arcmin)	Linear σ (Mpc)
4U 1658−48..........	2.469±0.019	0.639±0.001	point	...
QSO 1635+119........	2.24±0.47	0.66(+0.05, −0.04)	point	...
A 348................	0.91±0.42	0.95(+0.65, −0.16)	0.71(+0.65, −0.16)	0.24(+0.22, −0.05)
3C 295...............	1.08±0.36	0.87(+0.22, −0.10)	0.59(+0.22, −0.10)	0.27(+0.10, −0.05)
PKS 0116+08.........	1.80±1.07	0.71(+0.38, −0.10)	<0.69	<0.36
3C 343.1[a]............	...	...	...	...

[a] Not detected in the 1′–2′ annulus.

3C 295 cluster just after the spirals have been stripped, but before their colors change.

Alternatively, Gisler (1979) has pointed out that the rate of gas removal due to ram-pressure stripping depends strongly and nonlinearly on the rate of gas injection from the stars. If the stellar injection rate is sufficiently high, the momentum flux of the intergalactic medium, after being shared with all the replenishing gas, yields velocities less than the escape velocity and no gas is stripped. This can be expressed as $nm_pV^2 > \dot{\sigma}V_e$ for stripping to occur, where $\dot{\sigma}$ is the mass injection rate per unit surface area and V_e is the escape velocity. This becomes $\dot{M} < 78\,n_{-3}\,(V_{e2})^{-1}\,(V_3)^2\,M_\odot\,\mathrm{yr}^{-1}$ for a spiral galaxy of 10 kpc radius, where n_{-3} is the intergalactic medium density in units of 10^{-3} cm^{-3} and V_{e2} is the escape velocity in 10^2 km s^{-1}. For $n_{-3} = 2$, $V_{e2} = 3$, and $V_3 = 1.5$, values which should be typical of spiral galaxies in the 3C 295 cluster, we find that if $\dot{M}$ is greater than 120 $M_\odot$ yr^{-1} then the spirals will not be stripped. Although this calculation is only approximate, the size of the necessary mass loss is so large that it is doubtful if this can be a large effect.

IV. LUMINOSITY EVOLUTION OF X-RAY CLUSTERS

The data in Table 1 show that the range of X-ray luminosities in the distant clusters is greater than a factor of 100 from $<1 \times 10^{43}$ to almost 2×10^{45} ergs s^{-1}. In addition, the Bautz-Morgan type I (BM I) clusters tend to be more luminous than those of types II and III. These two properties are similar to those found in nearby clusters (McHardy 1978).

In searching for luminosity evolution we find it convenient to plot the data as shown in Figure 2. Included in the figure are data from Table 1, from the sample of Murray *et al.* (1979) at low redshifts, and from the sample of Mushotzky *et al.* (1978). The Murray *et al.* sample is based on *Einstein* Observatory data. The Mushotzky *et al.* sample comprises clusters with measured spectra observed from *OSO 8*. We have used the spectral parameters of Mushotzky *et al.* (1978) to evaluate F_E for their data.

Since the spread in luminosity for the nearby clusters is more than a factor of 100, we will restrict ourselves to the BM I and I-II clusters in order to achieve a more homogeneous sample. Using the statistically complete *Ariel 5* sample of McHardy (1978), with the sky coverage of Warwick and Pye (1978), we have determined the X-ray luminosity function for BM I and I-II clusters. From it we have found that the average luminosity of a BM I and I-II cluster is L_x (2, 10) = 6.7×10^{44} ergs s^{-1}, or L_x (0.5, 4.5) = 7.1×10^{44} ergs s^{-1} using the conversion given in § II.

The curves in Figure 2 are evolutionary tracks for several of the models discussed in the introduction, normalized at $z = 0.1$ to the average luminosity for a BM I and I-II cluster. The curves labeled 0.0 and 0.5 correspond to no luminosity evolution (i.e., constant luminosity) for the indicated q_0. These curves approximately indicate the track of a model which assumes no cluster potential evolution and moderately efficient galaxy formation (Cowie and Perrenod 1978). The curve labeled M2 shows the track for Perrenod's (1978) model M2 which assumes mass injection from the galaxies in the cluster, an evolving cluster potential, and $q_0 = 0.12$. The curves labeled "all gas" and "no gas" refer to very inefficient galaxy formation (Silk 1976) and very efficient galaxy formation (Sarazin 1979) models. These tracks have been calculated for clusters which form at 6×10^9 years ($z = 1.5$) (Aarseth, Gott, and Turner 1979) and assume $q_0 = 0.05$.

The data shown in Figure 2 are consistent with the curve labeled M2. While this is a suggestive result, it does not prove that Perrenod's models are correct, or that the other models are not, since there are observational selection effects and variation in model parameters to be considered. The clusters we have observed need not be average for their class. In fact, given the exposures we have used we can only detect the most

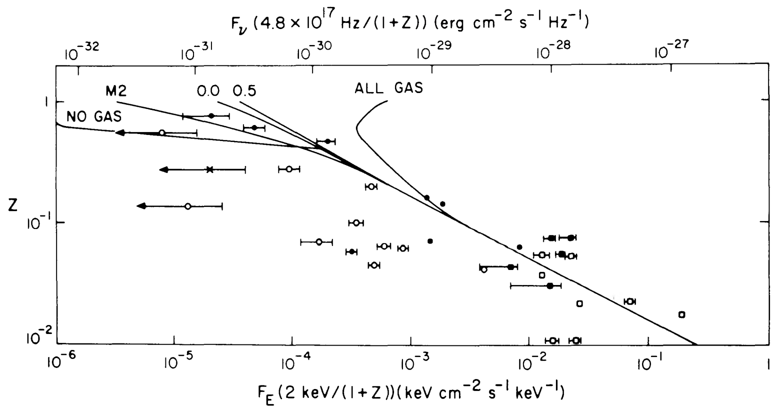

FIG. 2.—Received spectral density at an emitted energy of 2 keV as a function of redshift for cluster X-ray sources. The boxes are *OSO 8* data and the circles are *Einstein* data; closed symbols refer to Bautz-Morgan types I and I-II; open symbols, types II, II-III, and III; the cross refers to an unknown type. The curves are for a source of 7.1×10^{44} ergs s^{-1} at low redshift which undergoes no evolution (with a q_0 of 0 and 0.5) or which evolves according to the Perrenod (1978) model M2, the Sarazin (1979) model with no intracluster gas (no gas), or the Silk (1976) model where at formation most of the mass of the cluster is in intracluster gas (all gas).

luminous clusters at redshifts near 1. This would bias the data away from the "no gas" model. Furthermore, if the clusters we observe actually form earlier than the nominal time given above, then the extreme behavior of the "all gas" and "no gas" models would be shifted beyond the observed range of redshifts. For example, if clusters form at 3×10^9 yr then the "no gas" model would be consistent with the two BM I clusters at $z > 0.5$; the observed data would still lie about a factor of 10 below the "all gas" model.

To make further progress, a sample of about 10 clusters at redshifts near 0.5 and 1.0 is needed. It would then be possible to determine observationally where a given object lies with respect to the mean for clusters at its redshift. Present optical data can provide the required sample at a z near 0.5 (Gunn 1979), and the *Einstein* deep surveys (Giacconi *et al.* 1979*b*) may provide the sample at a z near 1.0.

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