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X-RAY OBSERVATIONS OF GALAXIES IN THE VIRGO CLUSTER

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ABSTRACT

We have detected X-ray emission from individual galaxies (other than M87) in the Virgo cluster using observations from the *Einstein* X-ray Observatory. One of the galaxies, M86, exhibits extended emission which we interpret as thermal bremsstrahlung from hot gas being stripped from the galaxy by the ram pressure of the intracluster medium. The observations are discussed in relation to models for the dynamical evolution of clusters of galaxies.

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

I. INTRODUCTION

X-ray emission from a region centered near M87 was first reported by Byram, Chubb, and Friedman (1966) and by Bradt *et al.* (1967) and, as such, represents one of the first detections of an extragalactic X-ray source. Since the early detections, our understanding of the spatial and spectral structure of the Virgo cluster X-ray source has increased significantly (Davison 1978; Serlemitsos *et al.* 1977; Gorenstein *et al.* 1977; Fabricant *et al.* 1978).

The first X-ray images of the central regions of the Virgo cluster obtained with the *Einstein* Observatory reveal a very complex structure involving M87, diffuse hot intergalactic gas pervading the entire cluster, and hot gas associated with relatively normal galaxies in the cluster.

The observations presented here represent the initial portion of our Virgo cluster survey and cover only the cluster core. Therefore, until our survey is more complete we cannot discuss the hot intergalactic gas component in detail, although we do detect it in the central region. Our most extensive information is on individual galaxies and the X-ray emission associated with them. Fabricant *et al.* (1979) discuss the X-ray emission associated with hot gas centered on M87. In this *Letter* we have concentrated on the X-ray emission from individual galaxies and its implications concerning the evolution of the cluster.

One of the more remarkable X-ray sources we have detected in the Virgo cluster is M86, which appears to be extended by several minutes of arc. The spectrum of this diffuse emission suggests that it is produced by gas ($kT \sim 1$ keV). We discuss the possibility that the outer portion of this gas is being stripped from the galaxy and will become part of the hot gas ($\sim$10 keV) which can be contained only within the cluster potential.

The observations presented here strongly suggest that gas associated with individual galaxies is being stripped by the ram pressure of the hot intergalactic gas. When interpreted in the cluster evolution picture described by Jones *et al.* (1979) this implies that some of the hot ($\sim$10 keV) gas in evolved clusters originates in the galaxies themselves and is lost to the intracluster medium during the dynamical evolution of the clusters.

II. OBSERVATIONS

During the activation phase of the *Einstein* X-ray Observatory, five fields in the Virgo cluster were studied with the imaging proportional counter (see Giacconi *et al.* 1979*a* for a description). All of the data analyzed for these fields were in the energy range 0.5–3.0 keV.

The process of image generation and source detection is described by Giacconi *et al.* (1979*b*). The telescope vignetting and the physical obscuration of the supporting ribs produce a nonuniform effective area in the region beyond the detector rib structure. Therefore, the automatic detection system, which currently uses a background computed in the region interior to the ribs, is not adequate for completely scanning the entire field for possible sources at the limit of sensitivity. We have supplemented the automatic system by using a local background to compute intensities at the optically determined positions of known galaxies. This procedure involved computing the counts within two circles of radii 3′ and 5′ centered on the optical galaxy position and solving for the two unknowns, the local background, and the source intensity (or upper limit).

We have begun a program to study optical counterparts of *Einstein* X-ray sources. This program has included a spectroscopic study of some of the objects detected in the Virgo fields. The optical observations were made with the "*Z*-machine" mounted on the 60 inch (1.5 m) telescope of the Mount Hopkins Observatory (see Davis and Latham 1979).

Figure 1 (Plate L8) illustrates the X-ray observations of the Virgo cluster and shows the complicating effects of the rib structure. Four of the five X-ray sources detected in this field are associated with bright galaxies in the Virgo cluster (the fifth source has not been identified). The brightest source in the field is associated with M86 and, as can be seen from the figure, is extended. The association of the X-ray emission pic-

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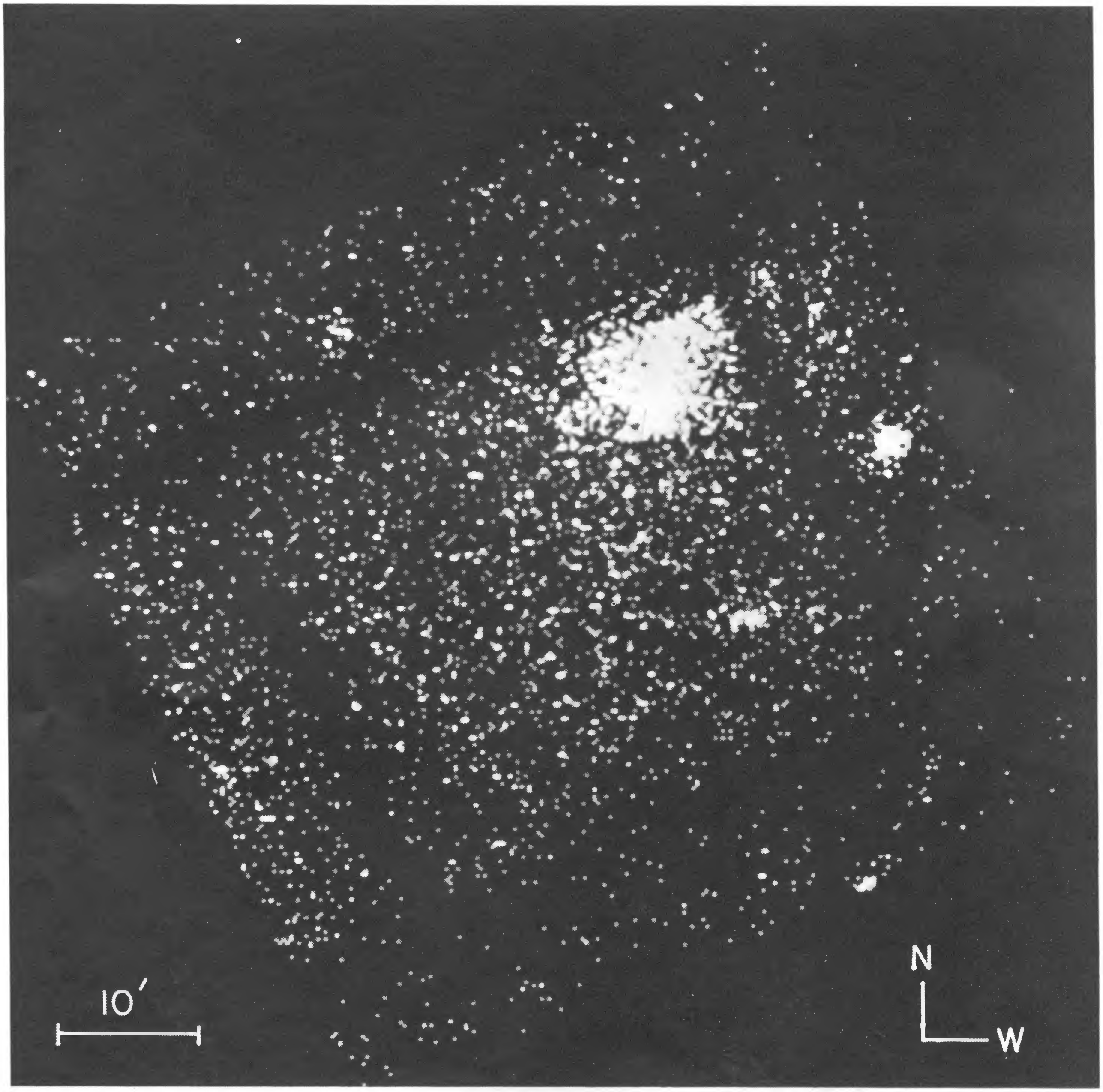

FIG. 1.—Figure shows the X-ray image of field 278 in the energy range 0.5–3.0 keV. The brightest of each pixel (16″ × 16″) is proportional to the number of photons detected in the pixel. The rib pattern (detector supports) is clearly visible. Five sources are visible. The large extended source is associated with M86. The other sources are: *upper left*, NGC 4438; *right*, M34; *lower right*, NGC 4388; and *bottom right*, not identified.

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tured in Figure 1 with galaxies in the Virgo cluster is illustrated in Figure 2 (Plate L9), which shows the X-ray contours superposed on an optical photograph. The galaxies detected as X-ray sources in this particular field exhibit a variety of unusual properties which may account for some of their X-ray emission; M84 is a 3C radio source, NGC 4388 exhibits strong emission lines similar to other X-ray emission-line galaxies (see Ward *et al.* 1978; Griffiths *et al.* 1979), and NGC 4438 appears tidally disrupted by its companion (NGC 4435). In spite of all these peculiarities, many of the galaxies may have a common emission mechanism (similar to that of M86, which we discuss in detail below) since we do observe all the bright galaxies ($m_v < 12.5$) in our limited survey.

During the course of our survey we have detected X-ray sources which are unrelated to the Virgo cluster. The types of objects observed, other than the bright galaxies, are similar to those detected and studied in the deep survey fields (Giacconi *et al.* 1979*b*). For example, in the field with the highest exposure (280) we have detected two normal stars, the cluster Abell 1541, and an uncataloged cluster a few arcmin away which has a similar redshift. A number of sources remain unidentified.

a) *Virgo Cluster Galaxies*

Table 1 lists the galaxies which we have observed that are members of the Virgo cluster, along with their X-ray luminosities and various optical properties.

As mentioned above, the Virgo galaxies which we observe as X-ray sources exhibit a wide range of peculiarities (also see Table 1) which may account for their X-ray emission. However, if the galaxies have an emission mechanism similar to that of M86—thermal bremsstrahlung from hot gas around the galaxy (see below)—then the X-ray luminosity is strongly influenced by the cluster environment. Therefore, even after we accumulate a sufficient number of observations we may not be able to obtain a "normal" galaxy luminosity function using the cluster survey. The Virgo survey, when completed, will provide information for a comparison of cluster galaxies with noncluster galaxies observed in other *Einstein* observing programs.

b) *M86*

We have studied the extended emission from M86 (field 278) in some detail. The surface brightness (well away from any sources) in this field is unusually high, 1.0×10^{-3} counts per arcmin^2 per s, compared to a typical rate of 3×10^{-4} counts per arcmin^2 per s over the energy range 0.5–3.0 keV in most other high-latitude fields. The portion of this emission which can be seen along the eastern edge of Figure 1 is probably associated with M87. An additional component is produced by the diffuse, hot cluster gas.

We have begun a spectral analysis of M86 using the available pulse-height information. However, owing to the unexpected gain changes of the IPC, we have not yet been able to perform a detailed spectral analysis. It is clear, however, that the spectrum is similar to that of M87 (Fabricant *et al.* 1978), although it appears somewhat cooler, with a substantial contribution from the Fe XVII–XXIV line complex. We will assume for our analysis that the temperature is between 0.5 and 3.0 keV.

We have not done detailed modeling of the radial distribution of M86 because of its observed position in the detector (off center and obscured by ribs). A new observation is planned to permit a detailed study for comparison with various models, including that of Bahcall and Sarazin (1978). If we assume the emission around M86 can be described by the isothermal sphere formalism (Lea *et al.* 1973), then we find that the core radius is roughly 3′ (20 kpc). The total luminosity of 2×10^{41} ergs s^{-1} then implies a central particle density of 4×10^{-3} cm^{-3}. The core mass is $2 \times 10^9 M_\odot$ and the mass within 60 kpc is $\sim 6 \times 10^9 M_\odot$. A simple, spherically symmetric de-projection of the radial distribution also gives a central particle density of $\sim 4 \times 10^{-3}$ cm^{-3}. We have assumed an emissivity for thermal bremsstrahlung and line emission given by $(2 \times 10^{-27} T^{1/2} + 10^{-19} T^{-1/2})n^2$ (see, e.g., Raymond, Cox, and Smith 1976), and a uniform gas temperature of $\sim$1 keV. This yields cooling times for the gas in the center of M86 ranging from 4×10^8 years ($T \sim 5 \times 10^6$ K) to 3×10^9 years ($T \sim 3 \times 10^7$ K).

III. DISCUSSION

The proximity of the Virgo cluster provides us with a unique opportunity to investigate the processes which occur during the dynamical evolution of clusters of galaxies. The observations presented here of the Virgo cluster and its member galaxies permit us to place the Virgo cluster into the proper perspective in the general scheme of cluster evolution and to clarify some of the questions concerning clusters and the origin of their X-ray emission.

The discovery of diffuse X-ray emission from clusters and the realization that the bulk of the observed emission from 1 to 10 keV was due to thermal bremsstrahlung, raised the question of the origin of the hot gas. The discovery of emission lines from Fe XXV and Fe XXVI (Mitchell *et al.* 1976; Serlemitsos *et al.* 1977) with roughly solar abundances provided support for the view that the gas responsible for the X-ray cluster emission is produced in stars and then subsequently lost to the intracluster region (Yahil and Ostriker 1973; Cowie and Binney 1977).

Observations have shown that the X-ray emission from the Virgo cluster consists of two components—a 2 keV gas surrounding M87 and a hotter ($\sim$10 keV) gas of lower density contained by the gravitational potential of the entire cluster. The observation of the hot, low-density component has been obscured by the powerful emission from M87. However, Lawrence (1978) and Davison (1978) presented evidence for a large X-ray emitting region ($\sim$600 kpc radius) offset from M87 with a temperature greater than 7 keV. The spectrum of Virgo presented by Mushotzky *et al.* (1978)

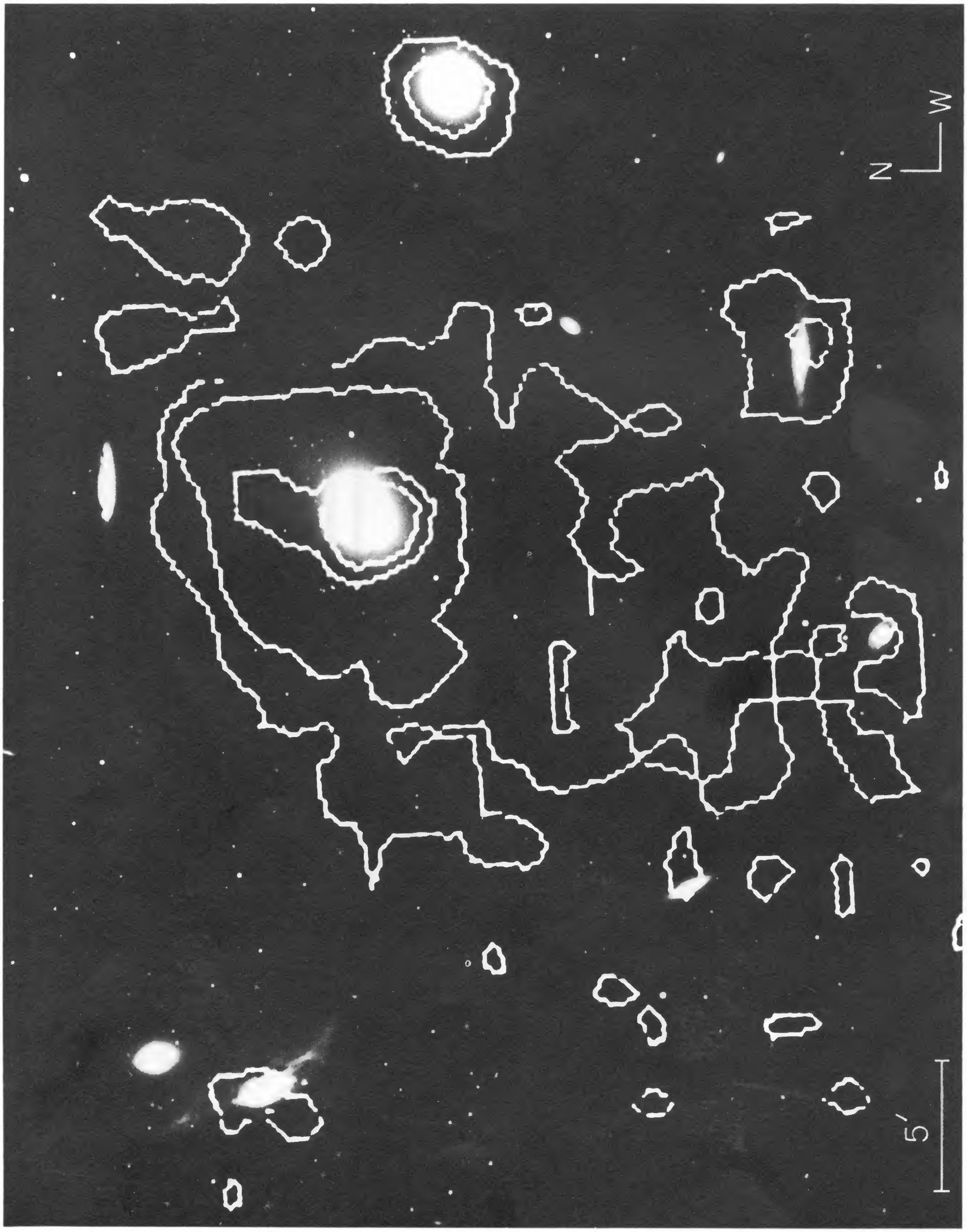

FIG. 2.—Contours (at arbitrary levels) of the X-ray image shown in Figure 1 are superposed on a photograph (from the Kitt Peak 4 m telescope) of the four galaxies observed in this field (NGC 4438, M86, M84, and NGC 4388). The extent of M86 is apparent from this figure.

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also supported this picture. The luminosity of this hard source is roughly 10^{43} ergs s^{-1} and its density is about 5×10^{-4} cm^{-3}. This source is associated not with any individual object in the cluster, but with the cluster as a whole. We can independently confirm the value of the central density using the observed surface brightness in the vicinity of M86 and subtracting both the typical background from other high-latitude fields as well as a component from M87. We find $n_c \sim 6 \times 10^{-4}$ cm^{-3}.

We now consider the evolution of M86 in this environment. The systemic velocity V_s of M86 is -419 km s^{-1} (see Table 1), indicating that the galaxy must be moving through the cluster with a velocity of $v \sim 1500$ km s^{-1}. The direction of motion must be nearly in our line of sight since the cluster velocity dispersion is only 666 km s^{-1} (Tammann 1972) and a substantial transverse velocity component would be very unusual. Gravitational binding of the outer regions of the M86 source requires a galactic mass approaching 10^{13} $M_\odot$ (cf. Mathews 1978). However, a more reasonable galactic mass of 10^{12} $M_\odot$ would bind only the inner 10–15 kpc. The central gas density required to produce the observed surface brightness (assuming an isothermal sphere) is 0.004 cm^{-3}, which produces a pressure comparable to the ram pressure, $\rho_c v^2$, due to the intracluster gas. Any pressure deficit in the trapped gas would have been eliminated by the passage of a shock.

The gas in M86 and the other galaxies detected, if we assume a common origin to their X-ray emission, must have originated within the galaxies themselves. The hot, low-density intracluster gas has a cooling time ($\tau_c = 2 \times 10^3$ $T^{1/2}/n$ yr) much greater than the Hubble time, which eliminates the possibility of pressure-driven accretion of that gas (Cowie and Binney 1977; Fabian and Nulsen 1977). The galaxies cannot significantly enhance the local density, thereby reducing the cooling time. Their internal dispersions are much less than sound speed in the intracluster gas. For M86 the internal velocity dispersion is also much less than the relative speed of the galaxy through the cluster.

Since the gas associated with M86 originated within the galaxy, and since it is not strongly bound gravitationally, we must consider the effects of ram pressure on the gas. To understand the gas stripping from M86 we must take into account the fact that M86 spends most of its time far from the cluster core. The cluster gas density is highest in the core, so the ram-pressure stripping is most effective. In fact, the gas is stripped only when the cluster passes through the high-density core.

In considering the ram-pressure effects, we first compute the maximum radius, $r_{\max}$, to which M86 will rise against the cluster potential. Assuming that the galaxies follow an isothermal sphere distribution and that the velocity dispersion can be used to estimate the cluster mass, we find that $r_{\max} \approx 3$ cluster core radii (taken as $a = 600$ kpc; see above). We also have assumed that M86 is at or near the cluster center, and that its direction of motion is nearly in our line of sight.

The time required for M86 to traverse the cluster from center to $r_{\max}$ and then back to the core is 10 times the crossing time $t_{\rm cross}$ (where $t_{\rm cross} = a/v$, and $v =$ velocity of M86 of 1500 km s^{-1}). Therefore, between each passage through the dense cluster core, M86 spends about 5×10^9 years in the outer regions of the cluster. In this interval of 5×10^9 years M86 will generate on the order of 5×10^9 $M_\odot$ of gas, given a galactic mass of 10^{12} $M_\odot$ and a specific mass-loss rate of 10^{-12} yr^{-1} (Gisler 1976). The cooling time of the gas observed in the core of M86 is larger than the core crossing time and is likely to have been still longer before the galaxy entered the cluster core when the external pressure (and thus the density) was less. Little gas would have accumulated during the initial gas buildup within the galaxy and only small amounts could have undergone cooling.

This large amount of gas generated while the galaxy is outside the cluster core is mostly stripped as M86 crosses the cluster core. The ram-pressure stripping occurs when the ram pressure of the cluster gas exceeds

TABLE 1

SOURCE PARAMETERS

Galaxy	L_x(0.5–3.0 keV) 10^{39} ergs s^{-1}	$m^{(1)}$	Galaxy Type$^{(1)}$	Radial Velocity (km s^{-1})$^{(1)}$	Comments
M86	70.8±3.8[a]	10.1	E3	−419	Extended X-ray source
M84	26.0±2.9	10.4	E1	+854	Radio source 3C 272.1
NGC 4388	16.9±2.5	12.0	SB	+2535	Strong, narrow emission lines
NGC 4438	4.5±1.4	11.0	SA	+182	Interacting galaxy, Arp 120
NGC 4477	11.1±1.3	11.4	SB0	+1190	...
NGC 4459	11.5±2.4	11.6	SA0	+1039	...
NGC 4473	4.6±1.4[b]	11.2	E5	+2205	...
NGC 4424	2.5±0.4	12.3	SB	+358	...
IC 3510	7.0±2.1	15.2$^{(2)}$	...	...	...

REFERENCES.—(1) de Vaucouleurs and de Vaucouleurs 1964. (2) Zwicky, Herzog, and Wild 1961.

[a] Value in a 2′.5 square region. The total luminosity is 2×10^{41} ergs s^{-1}.

[b] Source near rib structure. Observed flux is therefore only a lower limit.

the force holding the gas in the galaxy (see Gunn and Gott 1972). This condition can be expressed as

$$\rho_c v^2 > \rho_{\rm gas}\sigma^2{}_{\rm gal} ,$$

where $\rho_{\rm gas}$ is the gas density in the galaxy and $\sigma_{\rm gal}$ is the galaxy velocity dispersion. As M86 passes through the core of the Virgo cluster this inequality is satisfied (the velocity dispersion of M86 is 265 km $\rm s^{-1}$ as measured by Faber and Jackson 1976). The gas is stripped from the galaxy on a time scale

$$t_s \sim \frac{4}{3}\frac{r}{v}\frac{\rho_{\rm gas}}{\rho_c} ,$$

where r is the size of the galaxy moving with velocity v and containing gas at a density $\rho_{\rm gas}$. The gas will be decelerated in a core crossing time $t_{\rm cross}$ (see above) if $t_s/t_{\rm cross} \lesssim 1$. We find that for stripping to occur we must have $\rho_{\rm gas} \lesssim 8 \times 10^{-3} r_{30}\,\rm cm^{-3}$, where $r_{30} = r/$30 kpc is the galaxy radius in units of 30 kpc.

The value of $\rho_{\rm gas}$ we observe for the central region of M86 is $4 \times 10^{-3}\,\rm cm^{-3}$, and therefore, as M86 passes through the cluster core on its current transit, most of the gas associated with the galaxy will be decelerated by the intergalactic gas. The present association of several times $10^9\,M_\odot$ of gas with M86 implies that M86 could not recently have passed through the cluster core. Therefore, since M86 is moving toward us at a high velocity, the galaxy must be on the far side of the Virgo cluster core, but far down into the potential of the cluster. Alternatively, if the mass-loss rate is much greater than 10^{-12} then M86 could be on the near side of the core and be replenishing its gas supply. This seems unlikely because of the lack of similar extensive gas around the other galaxies we observed.

Our results agree with the usual ram-pressure picture (Gunn and Gott 1972), which predicts that there is less gas associated with galaxies in clusters with denser intergalactic gas (e.g., Coma) since the gas produced by member galaxies is more rapidly stripped, decelerated, and spread through the cluster.

Conduction may also represent a significant stripping mechanism (Cowie and Songaila 1977), depending upon the tangling of the magnetic field. Both a "conduction wake" and a "gravitational wake" in the intracluster medium would have a wide opening angle ($\sim$60°) owing to the high intracluster gas temperature. No real accretion wake (Ruderman and Spiegel 1971; Hunt 1971; Schipper 1974) can exist for M86 since the accretion radius is smaller than the size of the galaxy.

We conclude that M86 represents the first observation of ram-pressure stripping. The material lost by M86 to its parent cluster may be a source of the evolved gas which has been widely observed in clusters. Presumably, other cluster member galaxies contribute their share of material to the intracluster gas.

IV. CONCLUSION

In the dynamical evolutionary scenario studied by Peebles (1970), White (1978), and Perrenod (1978), the Virgo cluster would be in an early phase. The evidence for this includes its irregular shape, high fraction of spiral galaxies, and low velocity dispersion. Jones *et al.* (1979) show that the X-ray properties of other clusters support this same scenario. They show that the X-ray characteristics of the early evolutionary stages include low gas temperatures, emission clumped around individual massive galaxies, low X-ray luminosities, and asymmetrical gas distributions. These properties all characterize the Virgo cluster.

As the cluster evolves and relaxes dynamically, its central potential will grow, as will the density of the gas in the core. This gas will then strip the gas from galaxies passing through the core, thereby decreasing the cluster spiral fraction. In Virgo, our observations of M86 show gas being stripped from the galaxy. This gas then serves to further increase the cluster core density, which enhances still more the cluster's ability to strip gas from its member galaxies.

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