REVIEW OF RECENT OBSERVATIONS OF CLUSTER X-RAY SOURCES USING THE EINSTEIN OBSERVATORY

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1. INTRODUCTION

In this contribution I shall review briefly some of the recent research being carried out at the Harvard-Smithsonian Center for Astrophysics in the study of X-ray emission from clusters of galaxies. This work is being done by several of us at CFA, and I particularly wish to thank Drs. Christine Jones, William Forman, and J. Patrick Henry for permission to discuss their results. The data have been obtained from the Einstein X-ray Observatory (HEAO-2) using the imaging instruments, and in particular the Imaging Proportional Counter (IPC). This gives X-ray images with about $1\frac{1}{2}$ arc minute resolution over a field of view of $\frac{1}{2}^{\circ} \times \frac{1}{2}^{\circ}$ and moderate energy resolution over a band from 0.5 to 3.0 keV. (For further details see Giacconi et al. 1979).

2. THE VIRGO CLUSTER

The Virgo cluster has been recognized as an X-ray source since 1966 (Byram, Chubb, and Friedman) and in the time since then our understanding of its spatial and spectral structure has increased substantially (cf. Davison 1978, Serlemitsos et al. 1977, Gorenstein et al. 1977 and Fabricant et al. 1978). The X-ray emission from Virgo consists of several components: that associated with M87, an extended diffuse hot gas pervading the entire cluster, and emission associated with individual galaxies which are relatively normal.

The Einstein Observatory is being used to survey the Virgo cluster to obtain a detailed description of the various components of X-ray emission. Preliminary results are discussed below and are given in more detail by Forman et al. (1979). The data obtained thus far are from the regions shown in Figure 1 which illustrates the IPC field of view. The emission from M87 is discussed by Fabricant et al. (1979), the field containing the galaxies M86 and M84 illustrates the phenomena of X-ray emission from various types of galaxies as shown in Figure 2. Here the X-ray isophotes are plotted on a photograph of the sky (KPNO 4-meter),

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 727–734.

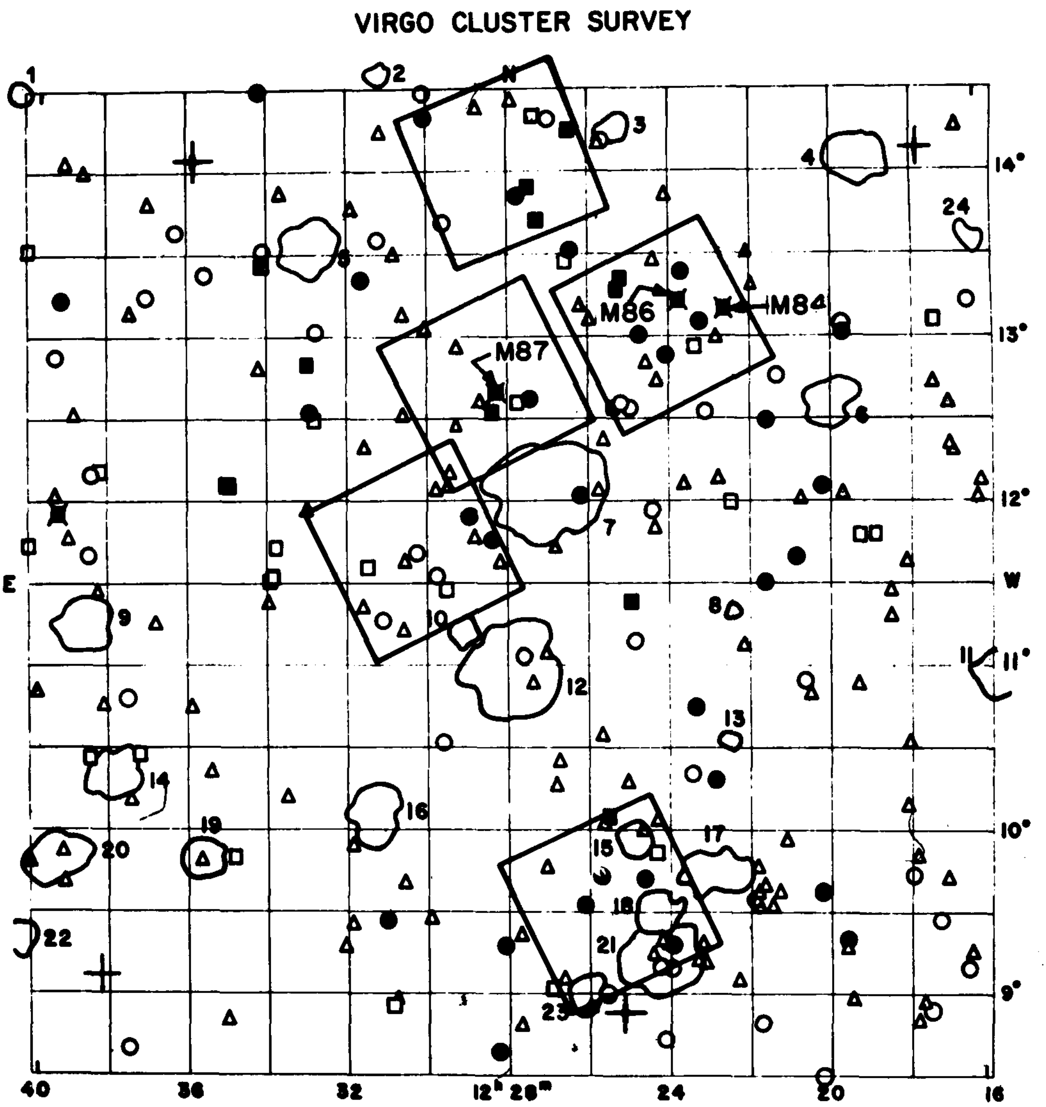

Figure 1. Virgo fields shown in Zwicky catalog.

Figure 2. M86-M84 field KPNO 4-meter plate with X-ray isophotes.

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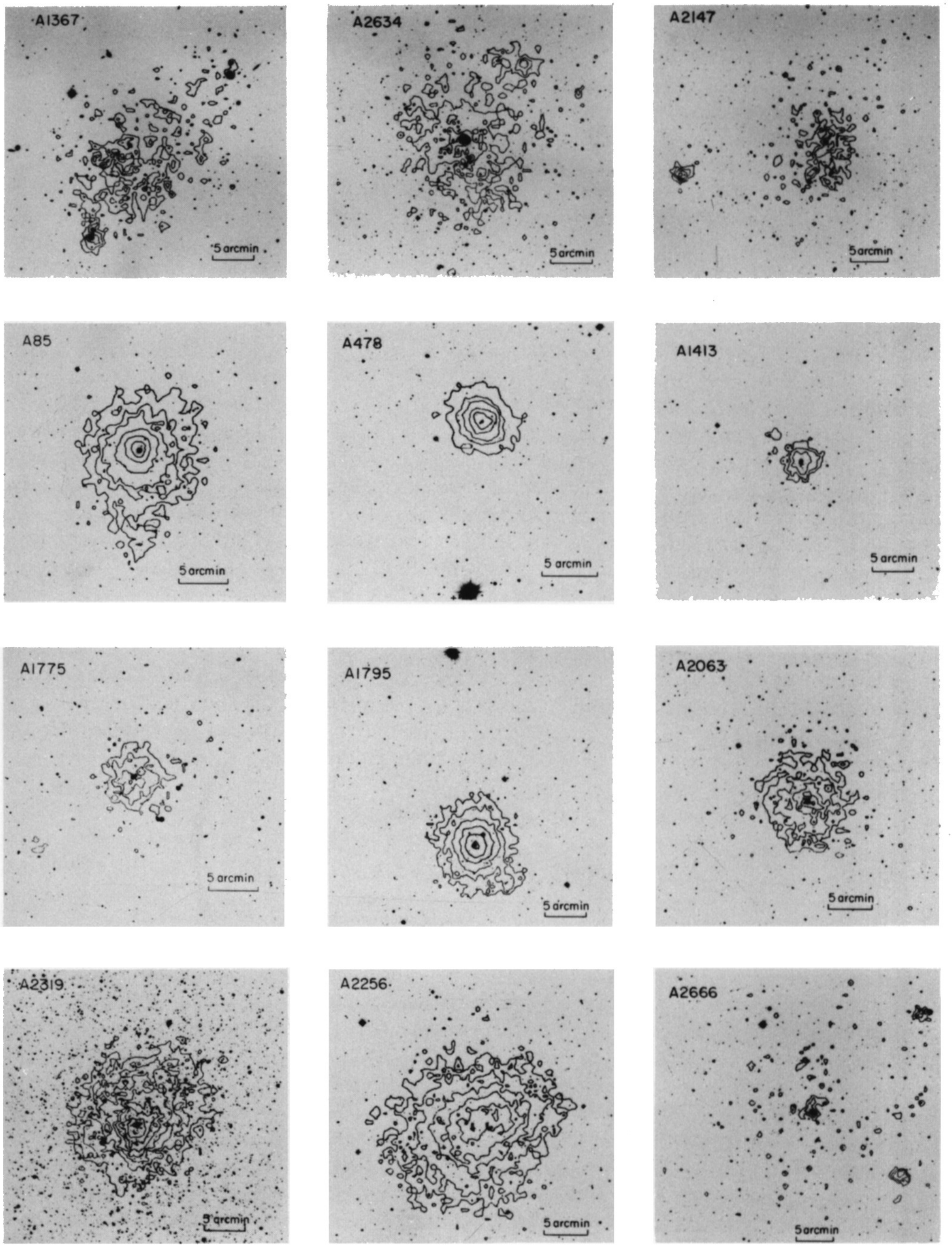

Figure 3. Cluster structure: X-ray isophotes.

four galaxies are seen to be X-ray sources. They are M86, M84, NGC 4388, and NGC 4488. The emission from M86 is extended, and as discussed below (and in more detail by Forman et al. 1979) can be interpreted as evidence for mass flow from the galaxy to the cluster. The galaxy M84 is a 3C radio source. The X-ray luminosity is about 2.6×10^{40} erg s^{-1} in the 0.5 to 3.0 keV band. NGC 4388 has been found to have strong emission lines and a luminosity of 1.6×10^{40} erg s^{-1}. NGC 4488 is a tidally disrupted galaxy and is in Arp's catalogue of interacting galaxies (Arp 120), the luminosity is 4.5×10^{39} erg s^{-1}.

The extended emission around M86 is evident in the map of Figure 2. The asymmetry in the isophote contours is due to the superposition of the very extended emission from M87 which is outside the field of view. Comparing the radial surface brightness distribution of M86 with a simple isothermal sphere model (of Lea et al. 1973), the core radius is about 3 arc minutes (20 kpc) and the total luminosity is 2×10^{41} erg s^{-1}. The X-ray sprectrum from M86 indicates a temperature of about 1 keV (assuming thermal bremsstrahlung). The total mass of X-ray emitting gas is about 6×10^9 $M_\odot$ with a central density of 4×10^{-3} cm^{-3}. Given these source parameters, Formal et al. (1979) show that ram pressure stripping should be an effective mechanism for transferring this gas to the cluster as M86 passes through the Virgo core. The sequence of events these authors present is as follows:

1. M86 spends most of its time outside the 600 kpc Virgo cluster core; in this interval ($\sim 5 \times 10^9$ yrs) it generates gas at a specific mass loss rate of 10^{-12} yr^{-1}. The gas cooling time is long so that it remains heated to $\sim$ 1keV and is rather lossely bound to M86.

2. During the core transit, ram pressure stripping occurs since the ram pressure exceeds the binding energy of the gas

$$\rho_{core} v^2_{M86} > \rho_{gas} \sigma^2_{M86}$$

where $\rho_{core} \sim 5 \times 10^{-4}$ cm^{-3}, $v_{M86} \sim 1500$ km s^{-1}, $\rho_{gas} \sim 4 \times 10^{-3}$ cm^{-3} and $\sigma_{M86} \sim 265$ km s^{-1} is the velocity dispersion of M86.

From this we conclude that M86 is an example of a galaxy which generates hot gas through stellar evolution and that this processed material is transferred to the cluster medium via stripping processes leading to the observed extended cluster emission.

3. OBSERVATION OF CLUSTER STRUCTURE

Several clusters which have been previous known X-ray sources were viewed with the Einstein Observatory to obtain data on their X-ray structure. Jones et al. (1979) describe these observations and give results for twelve clusters. They conclude that the X-ray structure of clusters falls into 3 broad categories which may be correlated with the sequence of dynamical evolution of clusters presented by Peebles

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(1970). This sequence is reviewed by N. Bahcall in this Joint Discussion. From the set of clusters studied by Jones et al., three exhibit broad and highly clumped emission. These are A1367, A2147, and A2634. Another group of 6 clusters (A85, A478, A1413, A1775, A1795, and A2063) are sharply peaked and smoothly distributed in their X-ray emission. The third class is illustrated by the clusters A2256 and A2319 which are smooth but less peaked than the second class. These properties are illustrated in Figures 3 and 4. Figure 3 shows the X-ray isophotes for each of the clusters mentioned, and Figure 4 is a plot of the radial surface brightness distribution.

In terms of the dynamical evolution sequence, the clumped clusters are "late" type clusters where development of a deep cluster potential well has not yet occurred. Stripping of spirals has not proceeded very far and the spiral fraction is expected to be high. Also since the cluster potential is weak, the galaxy velocity dispersion should be low. These properties are found in the case of A1367 as discussed in more detail by Jones et al. (1979).

"Early" type clusters are those which have evolved to develop deep central potential wells often with the formation of a central dominant (cD) galaxy. For these, the X-ray emission is characterized by a sharp central peak and smooth radial distribution. These clusters should have low spiral functions, high galaxy velocity dispersion, and relatively hot X-ray temperature. The properties for A85 are consistent with this interpretation. Once again more detailed discussion can be found in Jones et al.

The conclusion one can reach from these results is that there is a good correlation between the general class of X-ray structure and the dynamical properties of clusters. In particular clusters which appear to have well developed potentials appear in X-rays as smooth extended sources whose radial surface brightness distribution is well described by an isothermal sphere approximation (Lea et al. 1973). For clusters which are not so well developed from optical observations, the X-ray emission appears to be clumpy and the X-ray emission may be primarily from sources around individual galaxies.

4. OBSERVATIONS OF 3C295

The cluster around 3C295 has been observed as part of a CFA program to study clusters at large redshifts. Our data show this object to be an X-ray source of high luminosity L_x (0.5 to 4.5 keV) $\sim 10^{45}$ erg s^{-1}. It is extended with a size of from 0.25 to 0.5 Mpc. High resolution X-ray data indicate that there is strong central peaking in the X-ray emission associated with the cD galaxy and radio source 3C295. In addition, there is extended emission from the surrounding cluster. This result is of great interest since measurements by Butcher and Oemler (1978a, b) indicate that many of the cluster galaxies are blue, sugges-

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ting a large spiral fraction even though a large dominant galaxy has formed. The X-ray data require a sufficiently high hot gas density so that stripping of spirals should have occurred (Henry et al. 1979). Thus there is an apparent contradiction which will require modifications to either the interpretation of the Butcher and Oemler data or the stripping processes in clusters. This in turn may modify the simple sequence of cluster evolution where stripping plays an important role in the transfer of gas from galaxies to the cluster potential well.

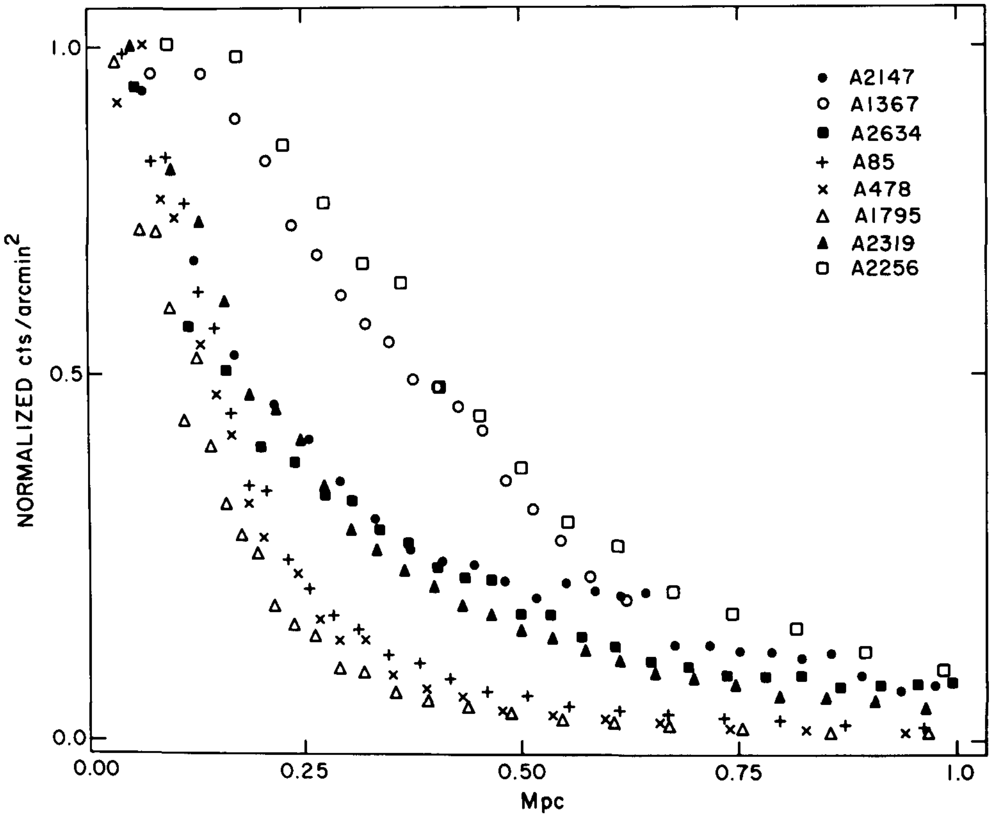

Figure 4. Radial surface brightness distribution of clusters.

5. CONCLUSIONS

Using the image capability of the Einstein Observatory we can investigate X-ray emission properties of clusters of galaxies from nearby objects such as Virgo to clusters which are as distant as z $\lesssim$ 1.0. In the case of relatively nearby clusters we have observed examples of individual galaxies with extended X-ray emission coming from hot gas which can then be stripped by ram pressure processes (Forman et al. 1979)

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as the galaxy travels through the cluster core. There is some correlation between cluster dynamical state and X-ray morphology as illustrated in the sample of clusters studied by Jones et al. (1979). However, in the case of 3C295 which is rather more distant (z = .461) Henry et al. (1979) discuss the apparent discrepancy between the X-ray data and the optical data regarding spiral galaxies in that cluster. The resolution of this problem will lead to a better understanding of the evolutionary development of clusters and the galaxies they contain. More detailed theoretical calculations can be compared with observational data combining the X-ray, optical, and radio properties of clusters, thus allowing us to test the validity of the various models for these objects.

REFERENCES

Butcher, H. and Oemler, A.: 1978a, Ap.J. 219, 18.
Butcher, H. and Oemler, A.: 1978b, Ap.J. 226, 559.
Byram, E.T., Chubb, T.A. and Friedman, H.: 1966, Science 152, 66.
Davison, P.J.N.: 1978, M.N.R.A.S. 183,
Fabricant, D., Topka, K., Harnden Jr., F.R. and Gorenstein, P.: 1978, Ap.J.Lett. 226, L107.
Forman, W., Schwarz, J., Jones, C., Liller, W. and Fabian, A.C.: 1979, Ap.J.Lett. 234, in press.
Giacconi, R. et al.: 1979, Ap.J. 230, 540.
Gorenstein, P., Fabricant, D., Topka, K., Tucker, W. and Harnden Jr., F.R.: 1977, Ap.J.Lett. 216, L95.
Henry, J.P., Branduardi, G., Briel, U., Fabricant, D., Feigelson, E., Murray, S., Soltan, A. and Tanabaum, H.: 1979, Ap.J.Lett. 234, in press.
Jones, C., Mandel, E., Schwarz, J., Forman, W., Murray, S.S. and Harnden Jr., F.R.: 1979, Ap.J.Lett. 234, in press.
Lea, S.M., Silk, J., Kellogg, E. and Murray, S.: 1973, Ap.J.Lett. 184, L105.
Peebles, P.J.E.: 1970, A.J. 75, 13.
Serlemitsos, P.J., Smith, B.W., Boldt, E.A., Holt, S.S. and Swank, J.H.: 1977, Ap.J.Lett. 211, L63.