X-RAY STUDIES OF CLUSTERS OF GALAXIES WITH THE EINSTEIN OBSERVATORY

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With the advent of imaging in X-ray astronomy, we can, for the first time, study extended sources with the same detailed spatial and spectral resolution employed by radio and optical astronomers. As in other fields of astronomy, the study of the X-ray emission from clusters of galaxies is beginning to feel the tremendous impact of this advance. The accompanying contributions by Murray and by Grindlay show that the division of clusters into classes based solely on X-ray morphology holds clear implications for the origin of the intracluster medium and the evolution of the cluster as a whole. Comparisons with optical and radio data, along with detailed X-ray studies of nearby objects and the extension of cluster observations to redshifts greater than 0.5, will help connect these ideas to a sound theoretical base. In this report on the cluster observations performed by the Columbia Astrophysics Laboratory with the Einstein Observatory, we restrict ourselves to three brief comments concerning the following areas: (1) The correlation of X-ray brightness with cluster morphology, (2) the detection of a spiral-rich cluster at $z \sim 0.4$, and (3) detailed observations of Coma, the nearest rich cluster.

1. CORRELATION OF X-RAY LUMINOSITY WITH CLUSTER MORPHOLOGY

As noted by N. Bahcall in an accompanying article, the X-ray luminosities of the clusters of galaxies detected in the early surveys of Uhuru and Ariel V tended to show a fairly strong correlation with optical morphological type (e.g., Bautz-Morgan class). Clusters with strong central condensations and/or a dominant central galaxy exhibit a higher 2-10 keV luminosity than the more loosely bound clusters. In Figure 1 we show the initial results of our cluster survey, in which the 0.2-3.0 keV X-ray luminosity is plotted against Bautz-Morgan class for two dozen more or less randomly selected sources. The putative correlation is no longer apparent; each class has members scattered throughout the general luminosity range for clusters of 10^{43} to 10^{45} erg s^{-1}. While selection effects may be important in this small subset of our data, the ultimate Einstein catalogue of several hundred clusters should provide a valuable,

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 747–751.

https://doi.org/10.1017/S1539299600004688 Published online by Cambridge University Press

unbiased sample for such correlation studies. One possible physically significant explanation for the lack of a correlation in these X-ray data lies in the difference in spectral bands employed between this and previous surveys. A relation between morphological type and X-ray temperature was also adduced in the early data (Mushotzky et al. 1978), with the dynamically more advanced systems exhibiting higher temperatures. In the current survey, however, we miss a large fraction of the X-rays from clusters with temperatures kT $\gtrsim$ 4 keV and thus systematically underestimate the X-ray luminosity of these systems. Likewise, the 2-10 keV surveys failed to detect much of the emission from the cooler sources. Thus, an explication of the exact nature of any correlation between

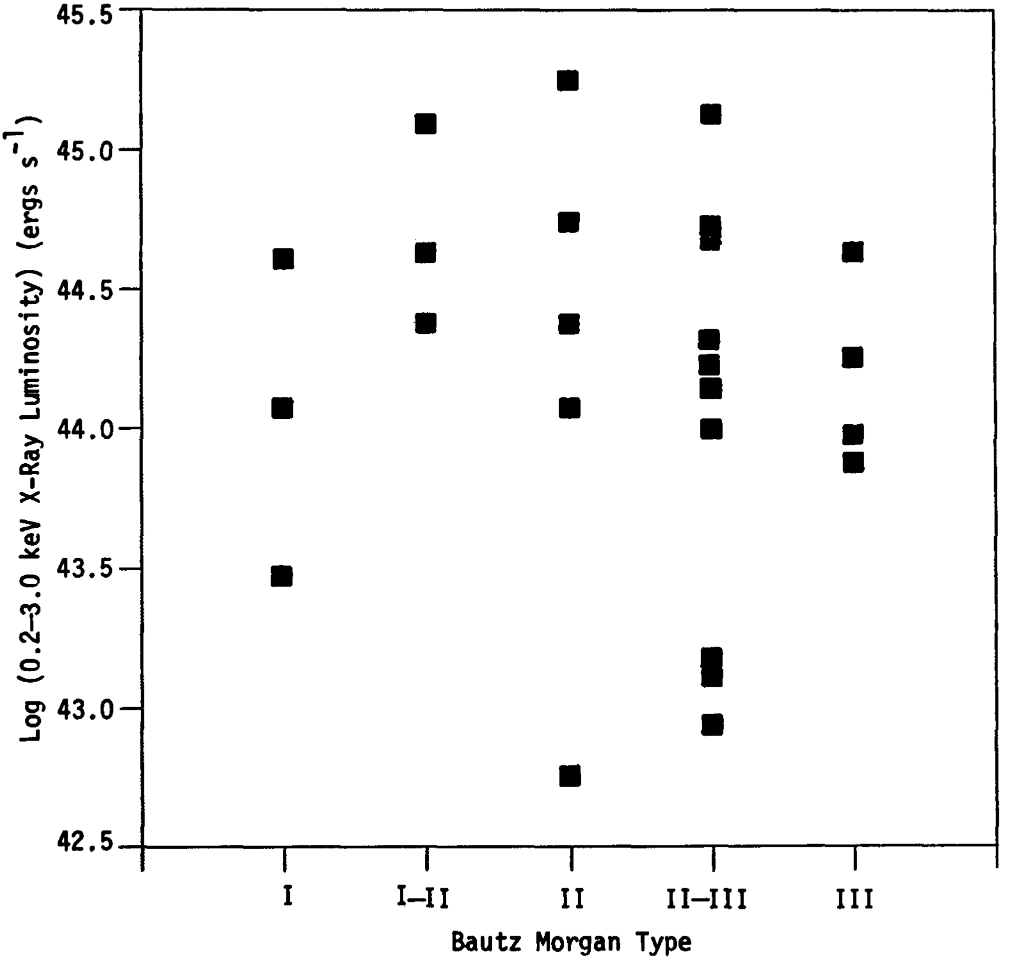

FIG. 1. - The 0.2-3.0 keV X-ray luminosity of the first 25 clusters observed in the Columbia Astrophysics Laboratory's cluster survey with the Einstein Observatory, plotted against Bautz-Morgan morphological type. The reported correlation of X-ray luminosity and cluster type is not apparent in this sample.

optical and X-ray properties must await the improved statistics and spectral data soon to be available from the Einstein observations.

2. SPIRAL-RICH DISTANT CLUSTERS

Recently, evidence has been accumulating that at least some very rich clusters at redshifts around 0.5 have a much larger proportion of blue (presumably spiral) galaxies than similar nearby clusters (Butcher and Oemler 1978; Butcher et al. 1976; Hawkins and Reddish 1975). A clear implication of this result, if it is shown to be general, is that strong evolution of cluster populations is occurring at relatively recent cosmological epochs. The transformation of the observed blue galaxies into the S0's and ellipticals which dominate nearby rich clusters may well be related to a depletion in their reservoir of interstellar material necessary for maintaining a large Population I constituent. If the intracluster material which produces the bright X-ray emission from nearby clusters derives from the gas lost by these blue galaxies, one might expect to find a lower X-ray luminosity for the clusters at large redshifts.

We have observed a field containing the Butcher and Oemler (1978) cluster CL0024+1654 ($z = 0.39$) with the imaging proportional counter (IPC) and have detected a weak source (0.01 counts s^{-1}) coincident with the cluster center. The source shows evidence of extent, with a Gaussian size of $\sigma \sim 0'.66^{+0'.75}_{-0'.33}$, implying a core radius $\sim 2\sigma \sim 0.5$ Mpc. For comparison, the X-ray core radius for Coma is 0.51 Mpc {$H_o = 50$ km (s Mpc)$^{-1}$; $q_o = 0$}. The 0.5-4.5 keV source luminosity for CL0024+1654 is 2.3×10^{44} erg s^{-1}, approximately a factor of three less than the emission in the same band from Coma and an order of magnitude less than that observed from many other rich, centrally condensed, nearby clusters such as A2142 and A754. The study of more such objects at high redshifts may yield information useful in discriminating among the various mechanisms for the production of intracluster media.

3. COMA CLUSTER

The Coma cluster is the nearest and best studied representative of Abell's rich clusters. In Figure 2, we present a contour map of our IPC image of this cluster. The superimposed lines represent the detected window support structure; shadowing by these supports distorts the image within $\sim 2'$ of the center lines shown. Since the data have only just been acquired, no detailed analysis has yet been performed. However, several noteworthy features are already apparent. First, the emission is remarkably smooth, rising to a rather flat central plateau in the vicinity of the giant ellipticals, NGC4874 and NGC4889. Although we begin to see the individual galaxies emerge above the diffuse flux near the edge of the field at the level of 0.1% of the total cluster emission, the central 40' contains no fluctuations on the scale of $\sim 1'$ to the 1% level. From a subsequent pointing with the high resolution imager, we

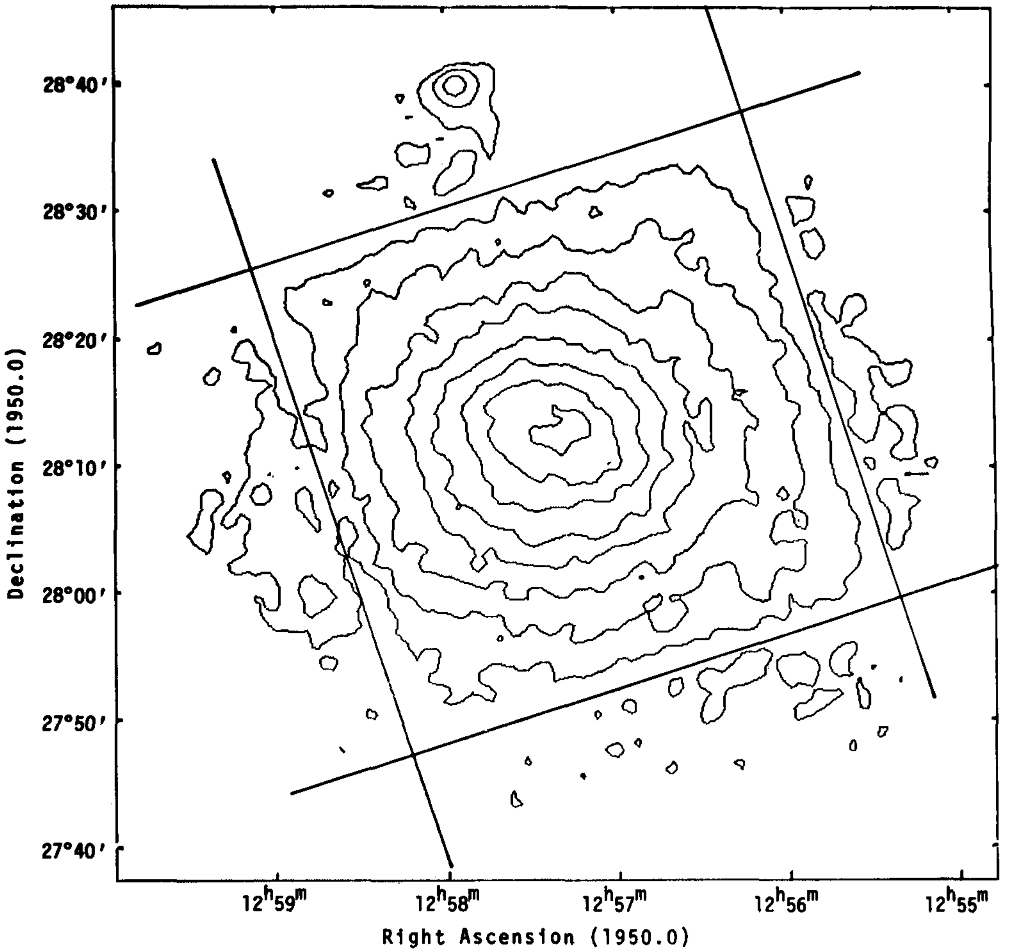

FIG. 2. - A contour plot of the X-ray surface brightness distribution for the Coma cluster observed with the IPC on board the Einstein Observatory. The superimposed lines represent the instrument's window support structure which distorts the image within 2' of the positions shown. The point source to the north of Coma is X Comae, a Seyfert galaxy.

can set a limit of < 0.2% on the contribution of point ($\lesssim$ 12") sources to the diffuse flux in the inner 25' x 25' region. A simple isothermal sphere surface brightness model fits the data well (χ^2 = 12 for 8 degrees of freedom), yielding a core radius of 12!7. The central contours do, however, show a distinct elongation at a position angle of $\sim 70^{\circ}$, the same as that seen in optical galaxy counts by Schipper and King (1978) and Thompson and Gregory (1978). Strimpel and Binney (1979) have recently presented a method by which the three-dimensional gravitational potential of a cluster can be determined from the galaxy positions and line of sight velocity dispersions. Their resulting predictions of the X-ray surface brightness distribution for Coma can be usefully compared with these observations to address such questions as the degree to which the galaxies are good tracers for the matter distribution in the cluster, the importance of cooling at this stage of the cluster's evolution, and, if this test could be extended to several more objects, the origin of such deviations from spherical symmetry, which are of considerable cosmogonic import. Through observations such as those presented here, then, we may use the Einstein Observatory to attack a variety of problems concerning the origin, nature, and evolution of galaxy clusters.

This work was supported by the National Aeronautics and Space Administration under contract NAS8-30753. This paper is Columbia Astrophysics Laboratory Contribution No. 178.

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