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# THE OPHIUCHUS CLUSTER: A BRIGHT X-RAY CLUSTER OF GALAXIES AT LOW GALACTIC LATITUDE

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## ABSTRACT

We report the discovery of an extended X-ray source near 4U 1708 − 23 ($l = 0\overset{\circ}{.}5$, $b = 9\overset{\circ}{.}4$) with the *HEAO 1* Scanning Modulation Collimator, which we identify with an anonymous $z = 0.03$ cluster of galaxies visible on the ESO/SRC (J) plate of the region. The extended source has a 2–10 keV X-ray flux density of $\sim 25$ μJy, about half that of the Perseus cluster ($z = 0.018$) in this energy range. Its X-ray luminosity is $1.6 \times 10^{45}$ ergs s$^{-1}$. We measure an X-ray core radius of $\sim 4'$ (0.2 Mpc) for an assumed isothermal sphere surface-brightness distribution. This is consistent with the observed distribution of galaxies in the vicinity. The X-ray spectrum (2–10 keV), obtained with the *HEAO 1* A-2 instrument, is well fit by a thermal bremsstrahlung model with $kT = 8$ keV and a 6.7 keV iron line of equivalent width 450 eV. We suggest that the steep-spectrum radio source MSH 17 − 203 is associated with the cluster. The cluster, which we designate the Ophiuchus cluster, is the nearest and brightest representative of the class of X-ray clusters with a dominant central galaxy.

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

## I. INTRODUCTION

Clusters of galaxies constitute an important class of high galactic latitude ($|b| > 10°$) X-ray sources, accounting for $\sim 35\%$ of the sources in the *Ariel 5* catalog (Cooke *et al.* 1978). Nearer to the galactic plane, however, only a few cluster sources have been identified, usually on the basis of radio emission or extended X-ray emission [e.g., 3C 129 (Schwartz *et al.* 1979) and Cyg A (Fabbiano *et al.* 1979)]. Based on their distribution at $|b| > 10°$, one would expect that $\sim 10$ of the fainter (3–25 μJy) low galactic latitude sources in the *Uhuru* (Forman *et al.* 1978) and other catalogs are in fact obscured clusters of galaxies.

In this paper we report the discovery, with the *HEAO 1* Scanning Modulation Collimator, of what is probably the brightest such source. 4U 1708 − 23 has been assumed to be a galactic source because of its low galactic latitude ($l = 0\overset{\circ}{.}5$, $b = 9\overset{\circ}{.}4$), brightness (30 *Uhuru* counts s$^{-1}$), and reported variability (Forman *et al.* 1978; Jones 1977). We find it to be extended and positionally coincident with the center of a cluster of galaxies visible through a "window" in the obscuring clouds which lace the region. We discuss in turn the X-ray, optical, and radio properties of the cluster, and conclude with a comparison (see Table 1) of the Ophiuchus cluster with other well-studied X-ray emitting clusters of galaxies.

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## II. X-RAY LOCATION AND OPTICAL IDENTIFICATION

The *HEAO 1* Scanning Modulation Collimator (MC) consists of two four-grid collimators of FWHM 30″ (MC1) and 120″ (MC2) with overall fields of view limited by square coarse collimators to 4° × 4° FWHM (Gursky *et al.* 1978). The region of 4U 1708 − 23 was scanned three times during the *HEAO 1* mission: MC data taken during the first scan were confused with Nova Ophiuchi 1977 (Griffiths *et al.* 1978) and were therefore omitted from the analysis. The superposed data from the second and third scans are shown in Figure 1. Data taken when GX 1 + 4 was nearer than 4° to the center of the collimator have been excluded from the superposition. The MC1 data place a 3 σ upper limit of 2.6 μJy on the average flux density between 1.5 and 13.5 keV of any pointlike source in the vicinity of the *Uhuru* error region (1 μJy ≡ $0.242 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ keV$^{-1}$). The MC2 data (Fig. 1*a*) clearly indicate the presence of a source (7.4 σ), but show a count rate distribution considerably broadened from the expected point source response. Although source confusion can mimic the appearance of source extent, in this case there are no sources near enough or bright enough for this to be the explanation of our results.

Simultaneous observations with the *HEAO 1* A-2 instrument[5] yield a line of position consistent with the *Uhuru* error region (Fig. 2). No variability is observed during three scans over the source at six-month intervals: the average flux density in the 2–10 keV energy band is 25

[5] The *HEAO 1* A-2 experiment is a collaboration led by E. Boldt (GSFC) and G. Garmire (CIT) with collaborators at GSFC, CIT, UCB, and JPL.

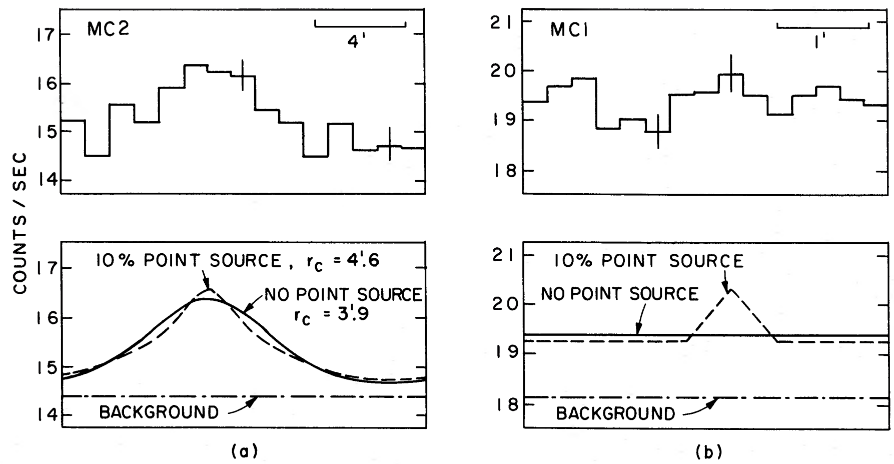


FIG. 1.—Superposed X-ray data (1.5–13.5 keV) for the Ophiuchus cluster (4U 1708−23) from the *HEAO 1* Scanning Modulation Collimator. Models consistent with the MC2 data (*a*) are indicated: an isothermal sphere of core radius 3'.9 (*solid line*) or a 10% point source plus 4'.6 isothermal sphere (*dashed line*) are both allowed. The extended source is almost completely demodulated in MC1 (*b*), which allows at most ~ 10% of the total flux to originate in a pointlike component.

μJy, corresponding to ~ 20 *Uhuru* counts $s^{-1}$. This is consistent with the ~ 600 day *OSO 7* light curve of 3U 1709−23 in which no variability is evident (Markert *et al.* 1979). 4U 1708−23 is listed as variable by a factor of 3 in the *4U* catalog, with a maximum counting rate of 30 counts $s^{-1}$. Since the *Uhuru* collimators have significantly larger fields of view than those of the *OSO 7* and A-2 instruments, we suggest that the variability observed with *Uhuru* is due to confusion with other nearby sources. The region is a crowded one: GX 1 + 4, A1707−27, and the transient sources 4U 1730−22 and Nova Oph 1977 are all located within 6° of 4U 1708−23. One of these sources is probably responsible for the detection of Oph XR-2 in an early Naval Research Laboratory rocket flight (Friedman, Byram, and Chubb 1967) at an intensity of ~ 20% that of the Crab.

The 3U 1709−23 field was searched for optical candidates by Bahcall and Bahcall (1975), who pointed out a conspicuously blue star near the edge of the error region (star BB of Fig. 2), and by Davidsen, Malina, and Bowyer (1976), who confirmed its unusually blue color. Since our data exclude the star as the X-ray source during our observations, we have examined prints of the Palomar Observatory Sky Survey (POSS) E and O plates and second negatives of the ESO Quick Blue and ESO/SRC (J) plates for other possible candidates. A finding chart of the region, prepared from the ESO/SRC (J) negative, is shown in Figure 2 (Plate 7). Our best estimate of the location of the centroid of the X-ray emission is the intersection of the MC2 and *HEAO 1* A-2 lines of position which falls just outside the *Uhuru* error region.

There are unusually many galaxies for this galactic latitude in the vicinity of the X-ray centroid; these are especially apparent on the ESO/SRC (J) negative (Fig. 2). To ascertain their distribution on a larger scale, we have marked off a 2°.1 x 2°.6 region on the negative, centered on the *Uhuru* error region, and have measured the locations of all visible galaxies (Fig. 3). Similar measurements elsewhere on the negative yield an estimate of the background galaxy density of ~ 5 $deg^{-2}$. The density enhancement over background near the X-ray centroid is a factor of ~ 100 and clearly indicates the presence of a cluster of galaxies. We designate it the Ophiuchus cluster, CL 1709−233. The relatively uniform extinction within ~ 0°.5 of the X-ray centroid (see Fig. 3) indicates that the apparent position of the cluster center is close to the true position. We therefore identify the cluster with the X-ray source 4U 1708−23 on the basis of extended X-ray size and positional coincidence.

### III. X-RAY SIZE AND SPECTRUM

We have fit the X-ray data of Figure 1 to an approximate (King) isothermal sphere surface-brightness distribution in order to estimate the X-ray angular core radius $\theta_c^x$. Since the background counting rate is not well determined by the data, we constrained the fit by requiring that the total source intensity be equal to that measured with the A-2 instrument. We allow for a possible ±20% systematic uncertainty in converting from the A-2 energy flux to the expected MC counting rate.

For a source which is entirely extended (i.e., no component of size ≲ 20″), the best fit is obtained for $\theta_c^x$ = 3'.9 (+ 1'.2, − 1'.4; $\chi^2$ = 52.5 for 59 degrees of freedom). The quoted uncertainties are 90% confidence, and include both statistical errors and the ±20% calibration uncertainty mentioned above. The expected counting rate distribution for this model is shown in Figure 1 (solid line). The source profile in MC1 is almost completely demodulated.

The data also admit a more centrally peaked brightness distribution than the isothermal sphere model, which we approximate by including a pointlike component. The MC1 data allow up to ~ 10% of the total flux to originate from a compact region (Fig. 1, dashed line). In this case, the MC2 data require a slightly larger core radius for an acceptable fit: $\theta_c^x = 4'.6$ $(+2'.2, -1'.8$; $\chi^2 = 51.8$ for 59 degrees of freedom). Since the present data do not allow us to distinguish between these models, we adopt an estimated X-ray core radius of 4'.2 for the remainder of the present discussion.

We have searched for a possible energy dependence of the cluster size by fitting separately the data from each of the three MC pulse-height channels (0.9–2.6, 2.6–5.4, and 5.4–13.3 keV). These data are of poorer statistical quality and are consistent at the 90% confidence level with the models which best describe the source profile when all three energy channels are combined.

The X-ray spectrum (2–10 keV) of 4U 1708−23 has been determined with the *HEAO 1* A-2 instrument. It is best described by a thermal bremsstrahlung model with $kT = 8 \pm 2$ keV and a 6.7 keV iron line of equivalent width $450 \pm 150$ eV. No significant low-energy absorption is observed: the upper limit (90% confidence) on the hydrogen column density is $N_H < 2 \times 10^{22}$ cm$^{-2}$. This is consistent with that expected from the estimated visual extinction of 1–2 mag based on the measured $E_{B-V}$ of the nearby globular clusters NGC 6284, NGC 6287, and NGC 6325 (Kron and Mayall 1960) and with the optical extinction estimates of § IV.

## IV. THE DOMINANT CENTRAL GALAXY

The most conspicuous nonstellar object near the X-ray centroid is indicated (No. 1) in Figure 2. It is by no means obvious that it is a galaxy on the basis of its image on the POSS E and O prints: it was described by Bahcall and Bahcall (1975) as a "red diffuse nebulosity" just north of the 3U error region. Its structure is most clearly seen on the ESO/SRC (J) negative: there is an apparent nonstellar nucleus, surrounded by a lower surface-brightness envelope of ~ 1' diameter. The envelope appears to be nearly circularly symmetric. The coordinates ($\pm 5''$) of the nucleus are: $\alpha$ (1950.0) $17^h09^m25^s.6$, $\delta$ $-23°18'35''$.

Spectrophotometry of this object has been obtained (by B. M.) with the Hale 5 m reflector, using the digital spectrograph and SIT Vidicon detector, over the 3600–6800 Å range. The spectrum (of exposure 1500 s) exhibits a noisy continuum with no obvious emission, but with absorption features at 6046 Å and 5333 Å as well as a break in the continuum at 4111 Å. A spectrum with the Lick 3 m Shane reflector and Robinson-Wampler Image Tube Scanner, covering the 5500–7000 Å range, confirms the red absorption feature. We identify these features as NaD, Mgb, and the 4000 Å blanketing break, respectively, and derive a mean galactocentric redshift $z = 0.028 \pm 0.003$. The inordinately large uncertainty in the redshift is due simply to the faintness of the object and the resulting difficulty in fixing the absorption wavelengths. The modest quality of the spectra implies that the redshift must be regarded as tentative until confirmed by more extensive observations. We estimate from the SIT observations that the maximum surface-brightness of the object in the $V$ band is 20.4 mag per square arcsec, again with large uncertainty, $\pm 0.5$ mag. The integrated color is approximately $(B-V) = 1.4 \pm 0.4$. At the Cassegrain acquisition television of both the Hale and Shane telescopes, the object appears as a very low surface-brightness elliptical galaxy.

At the implied distance of 170 Mpc ($H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$), the linear size of the central galaxy is ~ 50 kpc, a factor of ~ 3 greater than any other galaxy in the vicinity. This size would be too small for a cD galaxy; however, it is possible that a more extended envelope is simply undetectable due to galactic absorption. We thus tentatively classify it as type D. The cluster itself may therefore be assigned Type I in the Bautz-Morgan classification scheme, and Type cD in the Rood-Sastry scheme. Detailed surface photometry of the central galaxy will be difficult to perform because of its low surface-brightness and the juxtaposition of many foreground stars, but it would be very useful for confirmation of the classification and for comparison with surface-brightness profiles of dominant galaxies in other clusters (see, e.g., Oemler 1976). If we assign to this galaxy the color of the prototypical cD, NGC 6166, $(B-V) = 1.1$, we derive a (highly uncertain) color excess for the Ophiuchus cluster of 0.3, consistent with the previously mentioned extinction estimates (§ III).

## V. THE GALAXY DISTRIBUTION

To describe the cluster surface density profile, we have fit the observed galaxy distribution to the bounded isothermal sphere model of Bahcall (1975) with $C = 0.1$. We have used a modified form of the maximum likelihood estimation method of Sarazin (1980), since this method does not require binning the galaxy position data and can be used to fit for the cluster center, size, and density parameters simultaneously. We do not, however, assume that the errors in the parameter estimates are normally distributed, since we find by Monte Carlo calculations that this assumption is not justified in our case. Instead we use the method described by Cash (1979) to generate confidence intervals for the parameter estimates. We also fit for a core concentration parameter (the ratio of background to core density) rather than for the core density, $\sigma_c$, or background density, $\sigma_b$, separately. This has the advantage that $\sigma_b$ may be determined either directly from the fit or from measurements elsewhere on the plate without making any changes in the fitting procedure.

The positions of 108 galaxies within a $2°.1 \times 2°.6$ rectangle centered on the *Uhuru* error region were measured to a precision of ~ 30''. Preliminary fits for the cluster center, size, and concentration yield a center location of $\alpha$ (1950.0) $17^h09^m.4 \pm 0^m.1$, $\delta$ $-23°16'.6 \pm 1'.0$, consistent with the X-ray centroid and 2' north of galaxy No. 1 of Figure 2. In this case, however, the size, concentration, and cluster center estimates are clearly biased by areas of heavy extinction ~ 1° from the cluster (Fig. 3 [Plate 8]). We therefore constrained the fit by (i) fixing the cluster center at the location of the dominant galaxy, (ii) including only those galaxies which fall within 0°.5 of the center, and (iii) fixing the background galaxy density at $\sigma_b = 5$ deg$^{-2}$, based on measurements made nearby.

This procedure yields an optical core radius of $\theta_c^{\rm opt} = 6'.5$ $(+5', -3')$, where the 90% confidence interval includes formal statistical errors only. The core density is very uncertain: $\sigma_c = 500$ (+700, −200) deg$^{-2}$. We find that the additional uncertainties caused by errors in the assumed position of the cluster center are negligible, and that a change in the background density by a factor of 2 leads to a change of only 10% in the best-fit values of $\theta_c^{opt}$ and $\sigma_c$. Most of the uncertainty is therefore due to the relatively small number of galaxies which can be readily distinguished from stars on the ESO/SRC (J) negative. The best-fit model is compared in Figure 4 with the actual distribution to a distance of ~ 1° from the cluster center.

The optical core radius corresponds to a linear size of 0.30 (+0.23, −0.14) Mpc at 170 Mpc, and is consistent with the X-ray core radius of ~ 0.20 Mpc. Both are consistent with Bahcall's (1975) measurement of the average optical core radius of a sample of rich clusters: 0.25 ± 0.04 Mpc.

### VI. ASSOCIATION WITH MSH 17−203

MSH 17−203 is located in the direction of the cluster center (Fig. 3) and has a reported 86 Mhz flux density of 42 Jy (Mills, Slee, and Hill 1960). It was also observed in the Culgoora surveys at 80 and 160 Mhz [$S = 23 \pm 2$ and $6.4 \pm 0.1$ Jy, respectively (Slee and Higgins 1975; Slee 1977)], the Jones and Finlay (1974) 29.9 Mhz survey of the galactic plane ($S = 215 \pm 16$ Jy), and the Ohio survey at 1415 Mhz [$S = 0.8 \pm 0.2$ Jy (Ehman, Dixon, and Kraus 1970)]. The observations at frequencies below 1415 Mhz yield a very steep spectral index: $\alpha \approx -2$ (where $S \propto \nu^{\alpha}$). No high resolution maps of the source are available.

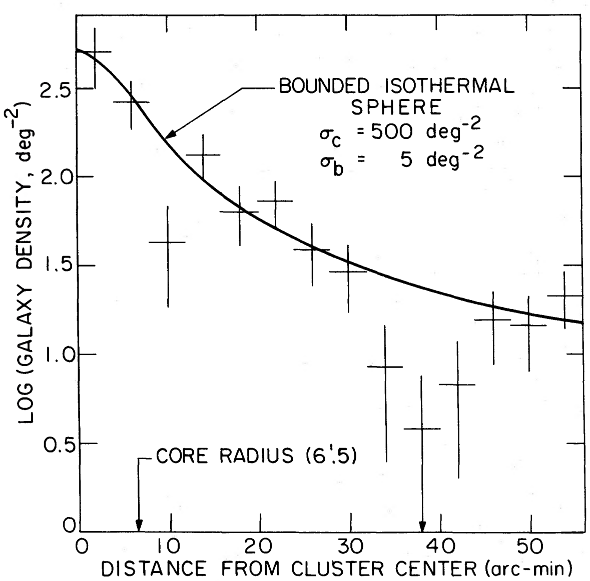


FIG. 4.—The surface density of galaxies to a distance of ~ 1° from the cluster center (*crosses*), compared with the maximum likelihood estimate of their distribution (*solid line*). The bounded isothermal sphere model of Bahcall (1975) has been assumed and fit to galaxies within 0°.5 of the cluster center (§ V). The core and background densities are $\sigma_c$ and $\sigma_b$, respectively.

Steep-spectrum low-frequency radio sources have been found to be associated with many X-ray clusters of galaxies. Erickson, Matthews, and Viner (1978) have carried out a detailed study of the correlation of X-ray luminosity with radio spectral index and 26.3 Mhz luminosity. If we extrapolate the low-frequency spectrum of MSH 17−203 from 29.9 to 26.3 Mhz, we obtain a flux density of 270 Jy and a luminosity of $P_{26.3} = 9.1 \times 10^{33}$ ergs s$^{-1}$ Hz$^{-1}$. This is at the high end of the $P_{26.3}$ distribution and corresponds to a 2–6 keV luminosity of ~ $10^{45}$ ergs s$^{-1}$. The spectral index of −2 is among the steepest known and also correlates with high X-ray luminosity.

We conclude with high confidence that MSH 17−203 is associated with the Ophiuchus cluster. High resolution observations at several wavelengths are suggested in order to correlate the radio, optical, and X-ray structure of the cluster.

### VII. DISCUSSION AND CONCLUSIONS

We summarize in Table 1 the known optical and X-ray properties of the Ophiuchus cluster, along with selected other bright or luminous X-ray clusters with which it may be compared. The high X-ray temperature and luminosity of the Ophiuchus cluster place it in the class of smoothly extended cluster sources, which Jones *et al.* (1979) have subdivided further based on the size of the X-ray emitting region: one class includes clusters with sharply peaked X-ray emission and core radii of ~ 0.25 Mpc; the other includes those with less peaked X-ray emission and core radii of ~ 0.50 Mpc. All clusters known to belong to the former category are Bautz-Morgan Type I, i.e., with a dominant central galaxy.

The X-ray properties of the Ophiuchus cluster (Table 1) place it in the subclass of clusters with sharply peaked X-ray emission and small core radii, adding further support to its tentative classification as Bautz-Morgan Type I. It is of particular interest because it is the nearest and by far the brightest representative of this class and thus an ideal subject for detailed comparison with theories of cluster evolution.

Based on the correlations discussed by Bahcall (1974, 1977*a*, *b*) and Mushotzky *et al.* (1978), we may make several predictions of the expected optical properties of the Ophiuchus cluster. The observed X-ray luminosity ($1.6 \times 10^{45}$ ergs s$^{-1}$, 2–10 keV) and temperature (8 keV) are correlated with high velocity dispersion (~ 1500 km s$^{-1}$), low spiral fraction ($\lesssim 10\%$), and high central galaxy density (~ 40 gal Mpc$^{-2}$ averaged over a circle of radius 0.5 Mpc). Only a few possible spirals are discernible on the ESO/SRC (J) negative, but this is not surprising in view of the high density of foreground stars and the estimated extinction of 1–2 mag (see §§ III and IV). We estimate the central galaxy surface density (within 0.5 Mpc of the cluster center) to be 25 Mpc$^{-2}$, a factor of ~ 2 below the expected value. This apparent discrepancy could also be due to confusion with stars in this crowded region. The need for deep plates of the vicinity of the cluster is evident, especially in the red region of the spectrum where extinction is less serious.

TABLE 1

X-RAY AND OPTICAL PROPERTIES OF THE OPHIUCHUS AND SELECTED OTHER X-RAY CLUSTERS OF GALAXIES

| Name (4U Name) | $z$ | $L_x$ $10^{44}$ ergs $s^{-1}$ (2–10 keV) | $kT$ (keV) | 6.7 keV Fe line E.W. | $\theta_c^{opt}$ ($r_c^{opt}$, Mpc) | $\theta_c^{opt}$ ($r_c^{opt}$, Mpc) | Rood-Sastry Type | Bautz-Morgan Type | References |
|---|---|---|---|---|---|---|---|---|---|
| Ophiuchus ........... (1708−23) | 0.028 | 16 | 8 | 450 | 4'.2 (0.20) | 6'.5 (0.30) | cD | I | present work |
| Perseus ............... (0316+41) | 0.0184 | 12.4 | 6.4 | 400 | 15' (0.47) | 7'.2 (0.22) | L | II–III | 1,2,3,4 |
| Coma ................. (1257+28) | 0.0230 | 8.5 | 7.9 | 200 | 16' (0.62) | 6'.6 (0.25) | B | II | 2,3,4,5 |
| Abell 85 .............. (0037−10) | 0.050 | 6.7 | 6.8 | 300 | 3'.25 (0.26) | ... | cD | I | 2,5,6 |
| Abell 478 .............. (0410+10) | 0.09 | 22 | 7.3 | 360 | 2'.0 (0.27) | 1'.5 (0.20) | cD | I | 2,6,7 |
| Abell 1795 ........... (1348+25) | 0.0630 | 10.1 | 5.8 | 360 | 2'.2 (0.21) | 2'.6 (0.25) | cD | I | 2,5,6 |

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Naive application of the thermal bremsstrahlung formalism to the gas distribution in the Ophiuchus cluster leads to an estimate of the central proton density of 1.5 ($\pm 0.7$) $\times 10^{-2}$ $cm^{-3}$. This is comparable to the values obtained for some other Bautz-Morgan Type I clusters, but is a factor of 4 or 8 larger than obtained for Perseus or Coma, respectively. The relatively short core cooling times (compared to the Hubble time) inferred for Type I clusters indicates that significant departures from hydrostatic equilibrium should be observable. Multiple components (with different temperatures) have been observed in a number of clusters (Mushotzky 1979), but the spatial resolution of these components in cD clusters has been hampered by their distance (see, e.g., Jones *et al.* 1979). The proximity (and thus large angular size) of the Ophiuchus cluster will allow this effect to be studied on smaller linear scales ($\sim 50$ kpc) than has been possible to date. Observations with the Imaging Proportional Counter on the *Einstein* Observatory are planned in order to map the spatial and temperature distribution of the cluster gas, and with the High Resolution Imager to study the surface-brightness distribution in the core.

Another possibility raised by the large angular size and high surface-brightness of the Ophiuchus cluster is spatially resolved X-ray spectroscopy. Efforts to date in this direction have been restricted to nearby bright clusters of relatively large angular size, none of which, however, are dominated by a central cD galaxy (see, e.g., Mushotzky 1979; Canizares *et al.* 1979). Present instruments may be able to map abundance gradients in the Ophiuchus cluster and thus contribute to our understanding of the origin of the cluster gas and of its dynamical history during the later stages of cluster evolution.

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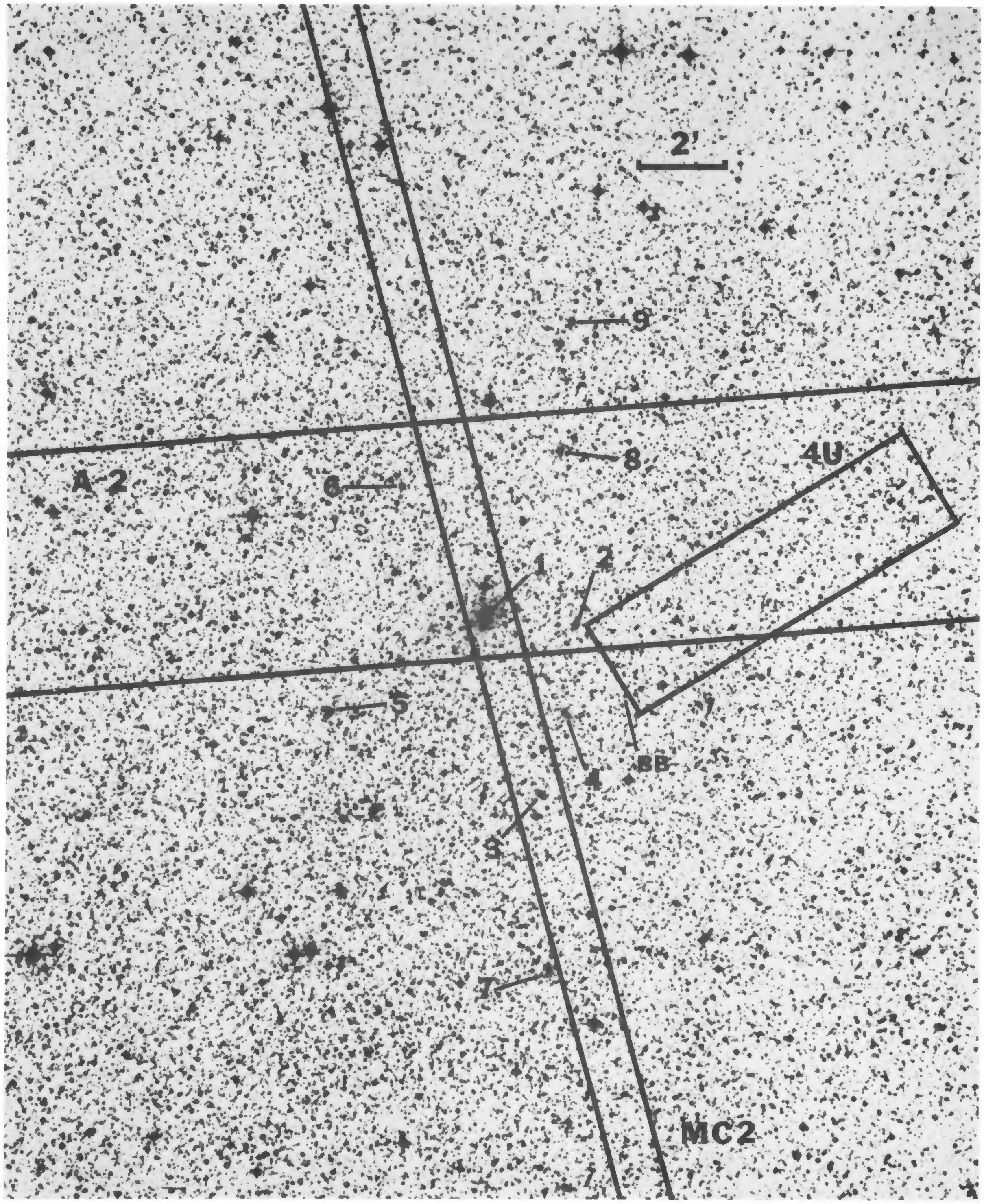


FIG. 2.—X-ray lines of position for the centroid of the Ophiuchus cluster (4U 1708 − 23), superposed on a print of the ESO/SRC (J) negative. The *HEAO 1* MC2 and A-2 lines of position are indicated, as well as the *Uhuru* error region. Some of the brighter galaxies are numbered: No. 1 is the dominant central galaxy, of probable Type D. The stellar candidate (BB) of Bahcall and Bahcall (1975) for 3U 1709 − 23 is excluded. North is up and east is to the left.

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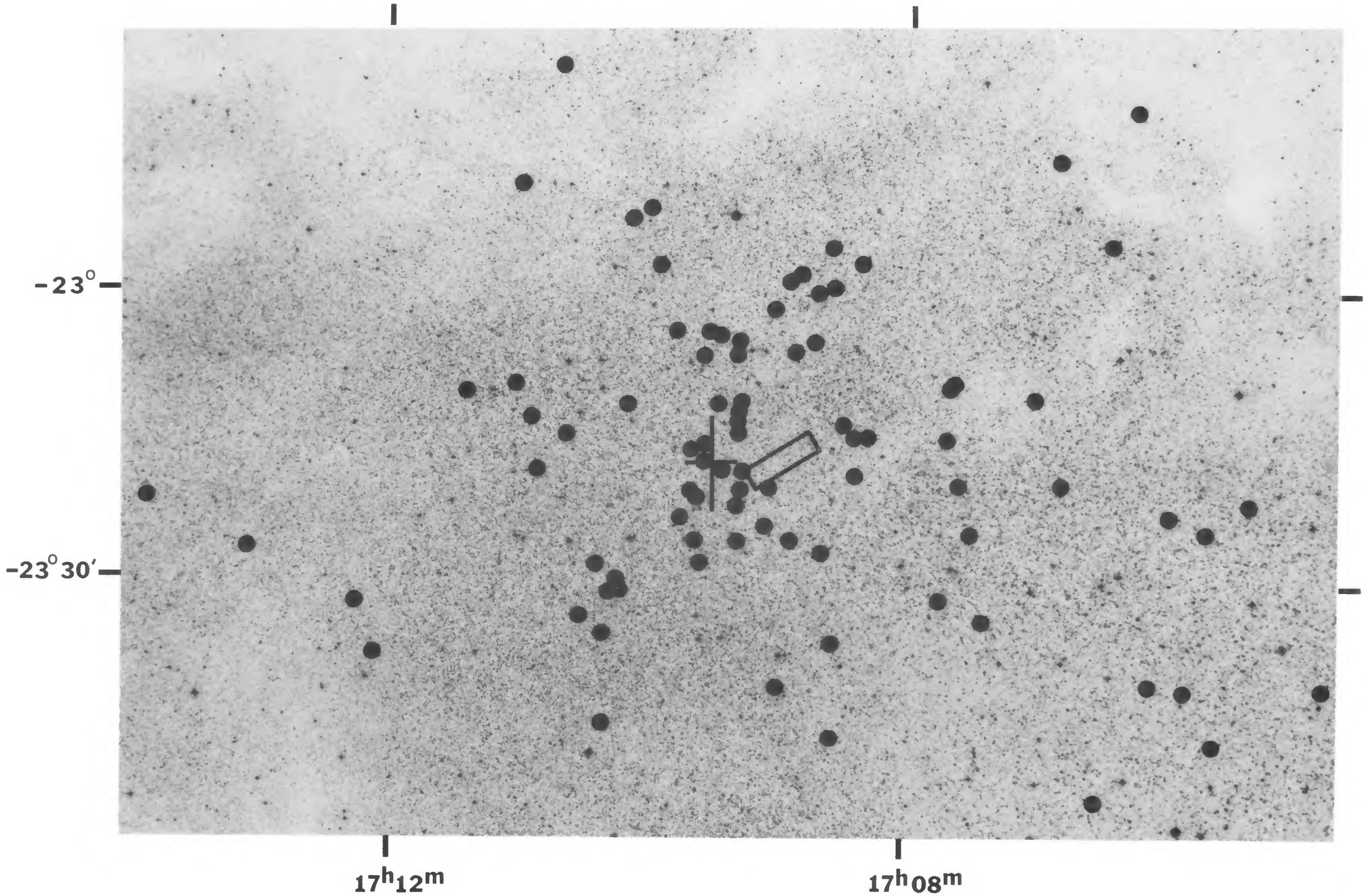


FIG. 3.—The large-scale distribution of galaxies (*dots*) in the vicinity of the Ophiuchus cluster. The central galaxy density is $\sim 500$ deg$^{-2}$, a factor of $\sim 100$ enhancement over the background density as measured elsewhere on the ESO/SRC (J) negative. The *Uhuru* error region (*rectangle*) and the location of the associated radio source MSH 17–203 (*cross*) are indicated. Regions of heavy obscuration are especially evident to the north and east of the cluster center, but the change in extinction within $\sim 0\overset{\circ}{.}5$ of the X-ray centroid is not sufficient to seriously bias the observed galaxy distribution (see Fig. 4).

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