THE ASTROPHYSICAL JOURNAL, 255:L17–L21, 1982 April 1

ABELL 2069: AN X-RAY CLUSTER OF GALAXIES WITH MULTIPLE SUBCONDENSATIONS[1]

I. M. GIOIA,[2] M. J. GELLER, J. P. HUCHRA, T. MACCACARO,[2] AND J. E. STEINER[3]
Harvard-Smithsonian Center for Astrophysics[1]

AND

J. STOCKE
Steward Observatory, University of Arizona
Received 1981 September 29; accepted 1981 December 21

ABSTRACT

We present X-ray and optical observations of the cluster Abell 2069. The cluster is at a mean redshift of 0.116. The cluster shows multiple condensations in both the X-ray emission and in the galaxy surface density and, thus, does not appear to be relaxed. There is a close correspondence between the gas and galaxy distributions which indicates that the galaxies in this system do map the mass distribution, contrary to what might be expected if low-mass neutrinos dominate the cluster mass.

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

I. INTRODUCTION

Luminous extended X-ray sources associated with clusters of galaxies were first observed with *Uhuru* (Gursky *et al.* 1971; Forman *et al.* 1972; Kellogg *et al.* 1972). More recently, observations using the imaging capabilities of the *Einstein Observatory* (Giacconi *et al.* 1979) revealed a large variety of structures in the X-ray surface brightness distribution of clusters. The structures of the clusters range from highly clumped emission to smooth and centrally peaked emission. In general, these structures reflect the optical characteristics of the clusters and may be interpreted in the context of dynamic cluster evolution (Jones *et al.* 1979; Bechtold *et al.* 1982; Beers, Geller, and Huchra 1982).

In a recent paper, Forman *et al.* (1981) identified a morphologically distinct class of clusters characterized by double or multiple structure in their X-ray emission and suggested that they represent an intermediate phase in the dynamical evolution of the cluster (see Henry *et al.* 1981; Beers, Geller, and Huchra 1982).

In this *Letter* we present X-ray and optical data on a serendipitous X-ray source identified with the cluster of galaxies Abell 2069. The source is characterized by a complex X-ray morphology showing multiple subcondensations in both the optical and X-ray.

[1]Research reported here based on observations at the Multiple Mirror Telescope Observatory, a joint facility of the Smithsonian Institution and the University of Arizona.

[2]Also from Istituto di Radioastronomia del CNR, Bologna, Italy.

[3]On leave of absence from IAG Universidade de São Paulo, C.P. 30627, São Paulo, Brazil.

II. X-RAY OBSERVATIONS

As part of a systematic search for serendipitous X-ray sources to extend the *Einstein Observatory* Medium Sensitivity Survey (Maccacaro *et al.* 1982), we have analyzed an X-ray image of the sky in the region $15^h23, +29°50$.

In the Imaging Proportional Counter (IPC) image, centered on the BL Lac object B2 1523 + 29, a serendipitous X-ray source was detected at about 16′ from the center of the field in a position coincident with the Abell 2069 cluster of galaxies. The X-ray source is clearly extended and has a complex morphology indicating the presence of at least three subcondensations. We designate the two main components as A2069A and A2069B. The optical redshifts (§ III) indicate that these two components are physically associated. A2069A is definitely brighter than A2069B and exhibits three enhancements (A1, A2, and A3, see Fig. 1 [Pl. L2]) in its surface brightness distribution. A High Resolution Imager (HRI) observation centered on the optical cluster shows that the subcondensation A3 coincides with a pointlike source whose position is coincident with a galaxy (No. 7 in Fig. 2 [Pl. L3]) belonging to the cluster. This point source has an X-ray luminosity of $\approx 3 \times 10^{42}$ ergs s^{-1} (assuming a power-law spectrum with photon index of 1.5 and no intrinsic cutoff; C. Jones, private communication) and thus contributes only ≈ 20% of the total flux of A3. If the hydrogen column density is as high as 3×10^{21} cm^{-2}, the point source still contributes only ≈ 40%. A Hubble constant of 100 km s^{-1} Mpc^{-1} has been assumed throughout. We note that using a Hubble constant of 50 km s^{-1} Mpc^{-1} would not substantially affect the conclusions of this *Letter*.

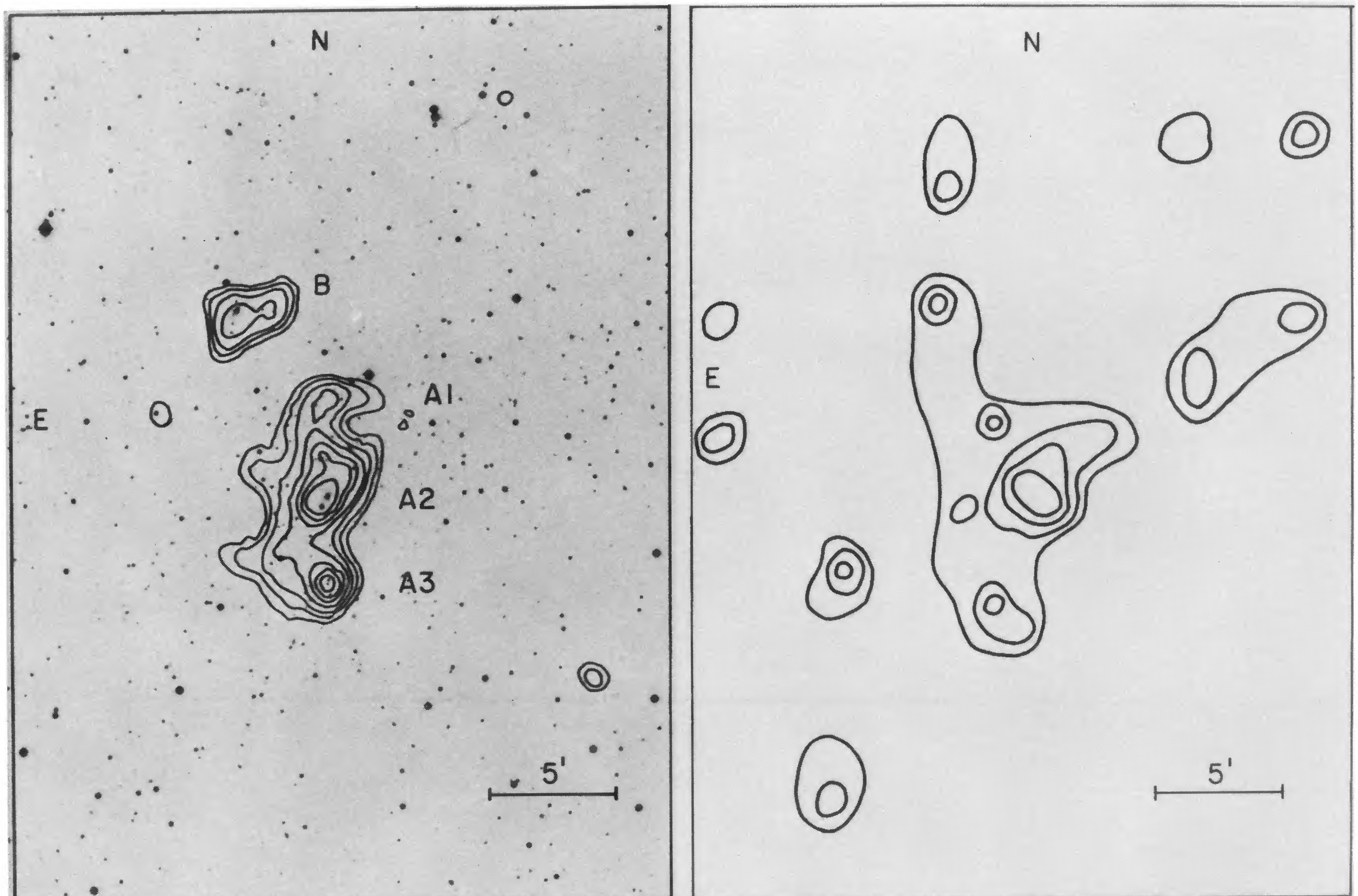

FIG. 1.—(*left*) X-ray contours of A2069 superposed on POSS E print. The background level is 0.24 counts per cell (16″ × 16″). Contours correspond to: 0.18, 0.26, 0.38, 0.55, 0.74, 0.86, and 1.01 counts above the background. (*right*) Galaxy surface number density contours of A2069. Outer optical contour is 3 σ above the background density, and each step is 1 σ.

GIOIA *et al.* (*see* page L17)

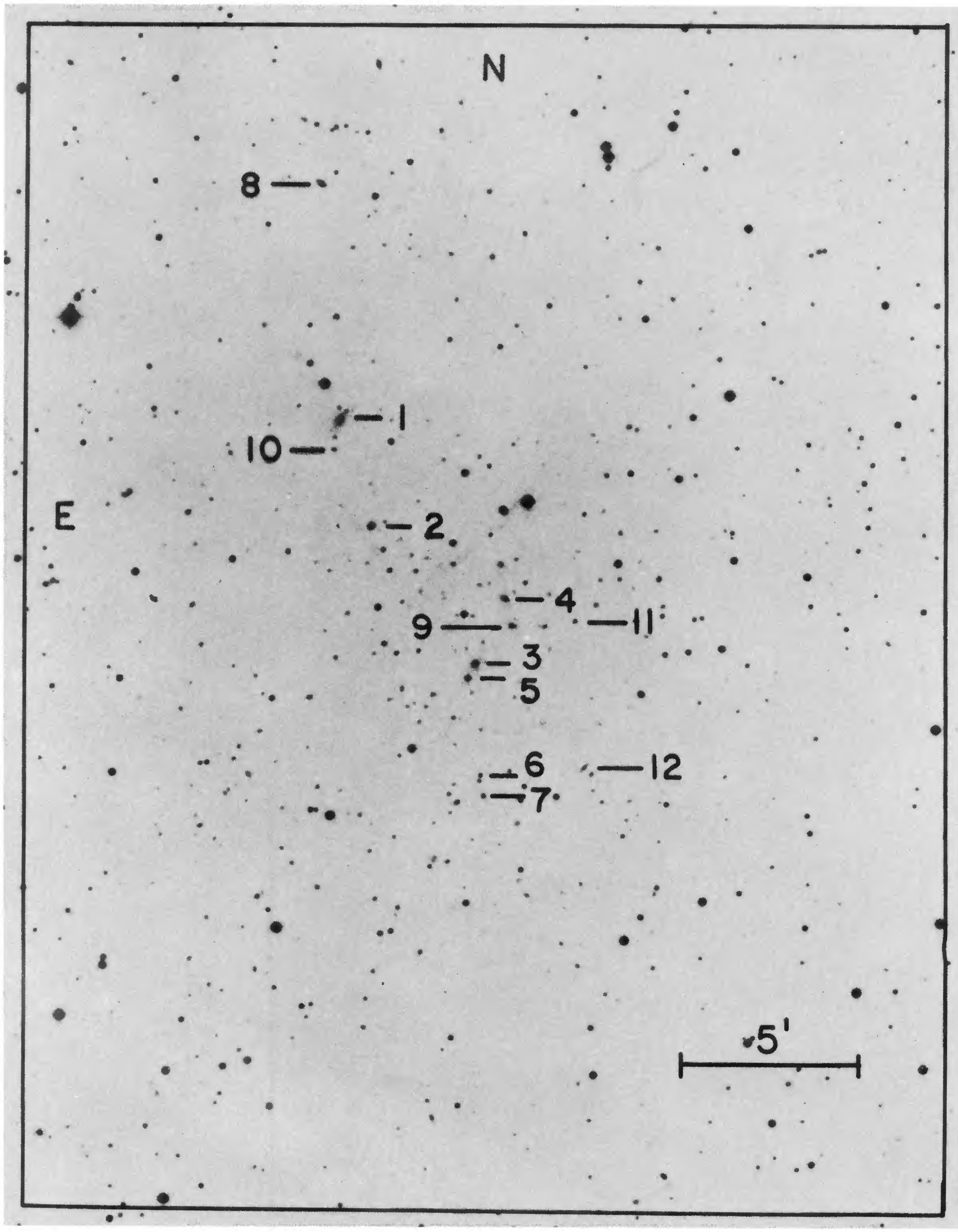

FIG. 2.—POSS E print of A2069 with measured objects marked

GIOIA *et al.* (*see* page L17)

TABLE 1

X-RAY OBSERVATIONS

Source	Position	Flux (ergs cm^{-2} s^{-1})	Luminosity (ergs s^{-1})	Size	Equivalent Core Radius	n_0 (g cm^{-3})
A2069 A1 ...	$15^h22^m03^s$ $+30°07'$ $54''$					
A2 ...	$15^h22^m04^s$ $+30°03'$ $57''$	$(3.9 \pm 0.2) \times 10^{-12}$	0.6×10^{44}	$5'.0 \times 9'.0$ 0.5 × 0.9 Mpc	$4'.6$ 0.45 Mpc	1.1×10^{-26}
A3 ...	$15^h22^m03^s.1$ $+30°00'$ $09''.2$					
A2069 B	$15^h22^m16^s$ $+30°11'$ $00''$	$(6.0 \pm 0.8) \times 10^{-13}$	1.0×10^{43}	$2'.3 \times 4'.0$ 0.23 × 0.4 Mpc	$2'.9$ 0.29 Mpc	1.1×10^{-26}

Figure 1 (Plate L2) shows the X-ray isodensity contours superposed on the Palomar Observatory Sky Survey (POSS) E print. The X-ray contours are obtained by deconvolving the data with the maximum entropy method. This technique is somewhat more powerful than a simple smoothing or a Wiener filter of the X-ray image (see Willingale 1981 and references therein).

Table 1 summarizes the relevant X-ray data. Fluxes are computed in the 0.4–3.0 keV band, assuming a thermal bremsstrahlung spectrum with a temperature of 7 keV for the cluster emission. Assumptions concerning the spectral shape are necessary because calibration problems do not allow one, at present, to derive reliable spectral parameters from the IPC pulse-height analysis. The choice of a temperature of 7 keV is consistent with the spectral information available in the literature (e.g., Mushotzky *et al.* 1978).

To parameterize the properties of the two major components A2069A and A2069B, we have fitted the observed brightness distribution with a King approximation for an isothermal sphere (Lea *et al.* 1973). Because the emission from A2069A is clearly not spherical, it cannot be adequately characterized by this isothermal sphere model. Therefore, the core radius we compute must be regarded as an "equivalent" core radius and used with a grain of salt.

Assuming the X-ray emission to be thermal bremsstrahlung from an isothermal sphere, one may use the central surface brightness and core radius to compute the central particle densities. Following Henry *et al.* (1981), the central particle number density is:

$$n_0 = \left[\frac{I(E,0)\,(1+z)^4\, 8.63 \times 10^{-33}}{g(T,E)\exp(-E/kT)(kT)^{-1/2} r_{\rm core}} \right]^{1/2} \quad ({\rm g\ cm^{-3}}),$$

where $I(E,0)$ is the observed central surface brightness per unit energy at the Earth, $r_{\rm core}$ is the core radius measured in cm, $g(t, E)$ is the Gaunt factor, and kT is in keV. The results are given in Table 1 for $kT = 7$ keV. Since A2069B lies in the vicinity of the area shadowed by the instrumental window supporting structure, the values derived for its parameters (i.e., core radius, X-ray flux, etc.) may have been slightly underestimated.

III. OPTICAL DATA

Spectroscopic observations were made of 11 galaxies and one blue stellar object (BSO) in the field of A2069 using a low dispersion spectrograph at the Multiple Mirror telescope (MMT). The measured objects are marked in Figure 2 (Plate L3). We used a 300 lines mm^{-1} grating with the intensified Reticon detector (Latham 1979) which produces a resolution of approximately 7 Å and covers the wavelength range of 4200 Å–7400 Å. Integration times ranged from 10 to 40 minutes. Redshifts were derived using the cross-correlation technique of Tonry and Davis (1979) for all galaxies except No. 4, whose redshift was determined from measurements of Hα emission and the Ca H and K lines as well as G-band absorption. The BSO has weak Hβ in absorption and is probably a white dwarf or early-type subdwarf.

Two of the six galaxies measured are foreground to A2069. A2069-2 is a foreground emission-line galaxy with strong Hα and weak [N II], [S II], and [O III] lines present in its spectrum. While Hα is somewhat broadened, the galaxy is probably not a Seyfert, and it shows no evidence of X-ray emission—in fact, it lies between the X-ray contours of the two major components of the cluster itself.

Figure 3 shows the spectrum of the galaxy A2069-7 which is associated with the pointlike X-ray source in the subcondensation A3. The spectrum shows only very weak emission at [O III] λ5007 with an equivalent width of ≈ 5 Å, and no Hα emission (although that region of

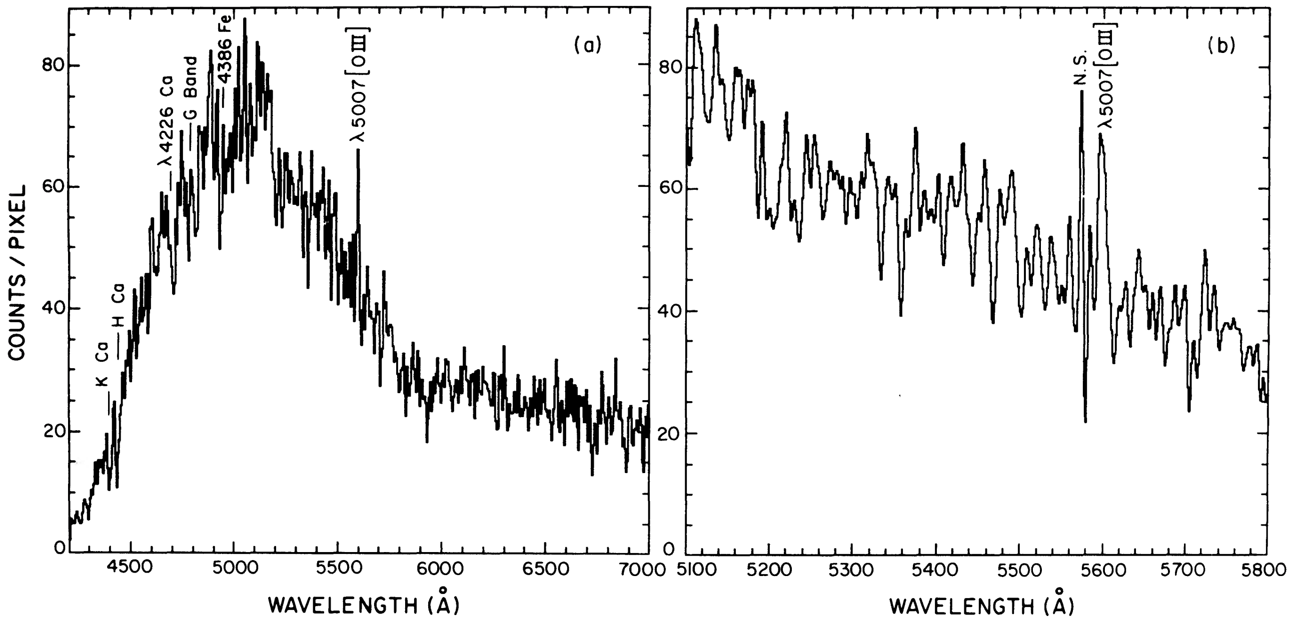

FIG. 3.—(*a*) The spectrum of the galaxy A2069-7. Some strong absorption features and the [O III] λ5007 line are identified. (*b*) An expanded spectrum showing the region around the [O III] λ5007 line.

the spectrum is masked by telluric absorption bands), thus lacking the typical signature of an active galactic nucleus. This galaxy is associated with the pointlike X-ray source in the subcondensation A3 and, although its X-ray luminosity is only a small fraction of the total emission associated with the A3 condensation, it still stands at 3×10^{42} ergs s^{-1}, rather impressive for an optically quiet object. An even higher X-ray luminosity implied by a large hydrogen column density seems unlikely. The combined X-ray and optical properties of this galaxy make it similar to NGC 3862 (Elvis *et al.* 1981). A2069-3 and A2069-5 are the brightest galaxies in the central condensation (A2), and A2069-1 is the brightest galaxy in the northern condensation (B).

The cluster velocity and velocity dispersion are given in Table 2. The mean and errors are calculated according to the procedure of Danese, De Zotti, and Di Tullio (1980). It is of interest to note that A2069 lies behind and is projected near the center of a supercluster of six Abell clusters (A2061, 2065, 2067, 2079, 2089, and 2092) all at redshifts between 20,000 and 23,000 km s^{-1} (Hoessel, Gunn, and Thuan 1980). Both of the foreground galaxies are in this redshift range. The X-ray structure discussed here is not associated with any of the clusters in this supercluster because the centers of these clusters are at least 1° (4 Mpc) from the center of A2069 —in fact, they are not even in the IPC field of view.

We have derived the galaxy surface density from counts of objects on the POSS red print. The contour map based on these counts is presented in Figure 1. The outermost contour corresponds approximately to a surface number density enhancement of 3 σ (the mean background is ≈ 3.8 objects per 2′ × 2′ bin, with a sigma of 2). The background number density was derived from the 4′ perimeter of a 36′ × 34′ region centered on the cluster. This background density of stars plus galaxies corresponds to a limiting apparent magnitude of 19.0–19.5 in R (Kron 1980), which is a limiting absolute red magnitude of −18.5, just brighter than the knee of the galaxy luminosity function. If (as seems likely) all the excess objects above background are

TABLE 2
OPTICAL OBSERVATIONS

Object	Comments	V_{rh}(km s^{-1})
1	...	35,320 ± 49
2	(foreground Hα, Hβ, [N II])	22,594 ± 66
3	...	33,993 ± 62
4	(foreground)	22,657 ± 200
5	...	34,253 ± 57
6	BSO = wd or sd	0
7	[O III] λ5007 (emission)	35,154 ± 64
8	...	35,200 ± 300
9	...	32,518 ± 100
10	...	35,159 ± 75
11	...	33,950 ± 250
12	...	34,784 ± 100
Mean velocity (galactocentric)............		34,778 ± 330
Redshift..................................		0.116
Line of sight dispersion		$831 \left\{ \begin{array}{l} +344 \\ -153 \end{array} \right.$

galaxies in the cluster, we find ≈ 10 galaxies in the northernmost lump and ≈ 70 in the rest of the cluster. This ratio is the same as the ratio of the X-ray luminosities of components A and B. From Table 1, the central gas densities in the two clumps are the same. Therefore, the X-ray luminosities should be in the ratio of the masses of X-ray emitting gas. This result indicates that in the subcondensations of A2069 the gas mass is roughly proportional to the number of bright galaxies. The resolution of both maps is $\approx 1'$ which is ≈ 100 kpc. The separation of A and B is 0.8 Mpc.

In Figure 1 the main 3 σ contour (lowest contour) surrounds the bulk of the cluster and contains both X-ray condensations A and B. Inside the main 3 σ contour, the galaxy surface density contours match the X-ray contours! The redshift of galaxy A2069-8 shows that the northernmost optical clump is also part of the cluster: in the X-ray observation this concentration is completely masked by the ribs of the detector. The other small outlying concentrations in the optical may not be associated with the cluster. All but one have lower surface number density than the regions from which we observe X-ray emission. Note that both parts of Figure 1 are drawn on the same scale.

IV. DISCUSSION

The similarity of the X-ray and optical contours has important implications for cluster dynamics and, thus, cosmology. It is obvious that the system as a whole is not relaxed. In fact, the clumpiness seen is reminiscent of the subclustering apparent in the *n*-body models of White (1976).

One of the nagging problems of cosmology is whether the galaxy distribution marks the actual mass distribution (Davis *et al.* 1980; Schramm and Steigman 1981 and references therein). If the X-ray emission comes from a hot gas not associated with individual galaxies, this gas should follow the potential determined by the overall cluster mass distribution, provided that the gas cooling time is greater than the Hubble time. For the 7 keV gas, the cooling time is $\approx 5 \times 10^{10}$ yr, much greater than the Hubble time (10^{10} yr); the crossing time for galaxies is only $\approx 10^9$ yr. For an assumed temperature of 2 keV, the cooling time decreases to $\approx 2 \times 10^{10}$ yr. In other words, within the temperature range of 2–7 keV of the intracluster medium in other systems, the cooling time for the gas in A2069 is greater than the Hubble time.

If the velocity dispersion for the galaxies in the cluster measures the depth of the cluster potential well, but the cluster mass is dominated by matter more smoothly distributed than the galaxies, the X-ray emission from the intracluster gas (the temperature range 2–7 keV is consistent with the cluster velocity dispersion measured for A2069) should mark the distribution of this dominant matter. The matter which might fill the cluster should have the cluster velocity dispersion. In the picture presented by Schramm and Steigman (1981), low-mass neutrinos dominate the mass in clusters. Following Tremaine and Gunn (1979), we can set a lower limit on the mass of the neutrinos which could be in this cluster. The X-ray and galaxy contours are similar and correspond on a scale $s \approx 100$ kpc; the measured velocity dispersion is $\sigma = 830$ km s^{-1}. The limiting neutrino mass is proportional to $\sigma^{-1/4}\, s^{-1/2}\, g_z^{-1/4}$, where g_z is the number of allowed helicity states. For $g_z = 2$, the lower limit on the neutrino mass is 5 eV. Our velocity dispersion is probably an upper limit because the cluster may well have velocity substructure corresponding to its spatial substructure. Additional evidence that the mass distribution in this system follows the galaxy distribution comes from the correspondence between the bright galaxy counts and the X-ray luminosities in clumps A and B. A weaker limit on the neutrino mass can be obtained from the correspondence of optical and X-ray structures in A98 (Henry *et al.* 1981), where the one-dimensional velocity dispersion is ≈ 900 km s^{-1} (Beers, Geller, and Huchra 1982) and the spatial scale of the clumps is ≈ 250 kpc.

Studies of nearby clusters of galaxies (Forman *et al.* 1979) have shown that individual galaxies—other than Seyfert galaxies—can be X-ray sources. The luminosities of these galaxies are less than 10^{41} ergs s^{-1}. If the X-ray emission from A2069 were provided by individual cluster members brighter than the knee of the optical luminosity function, each of these galaxies would have to be a 10^{42} ergs s^{-1} X-ray source. The X-ray luminosities of "typical" individual cluster members are, therefore, insufficient to account for the emission from A2069.

Combined X-ray and optical mapping of clusters may set important constraints on the "missing mass" problem, because the intracluster medium and the galaxies serve as independent markers of the mass distribution. We also emphasize the importance of detailed structure for the dynamical analyses of clusters and the determination of cluster mass-to-light ratios.

We wish to thank C. Jones for communicating data in advance of publication, and T. Beers for use of a computer program. We thank C. Jones, M. Elvis, and L. Stella for comments on the manuscript. We also wish to thank Bill Wyatt, Bill Kindred, Bill Light, and Phil Evans for their assistance at the MMT. This research has been supported in part by NASA grants NAGW-201, NAS8-30751, NAG8370, and a grant from the Smithsonian Scholarly Studies Program. Typing services were provided by Fang, Ltd.

REFERENCES

Bechtold, J., Forman, W., Giacconi, R., Jones, C., Schwarz, J., Tucker, W., and van Speybroeck, L. 1982, *Ap. J.*, submitted.

Beers, T., Geller, M., and Huchra, J., 1982, *Ap. J.*, **257**, in press.

Danese, L., De Zotti, G., and Di Tullio, G. 1980, *Astr. Ap.*, **82**, 322.
Davis, M., Tonry, J., Huchra, J., and Latham, D. 1980, *Ap. J.* (*Letters*), **238**, L113.
Elvis, M., Schreier, E., Tonry, J., Davis, M., and Huchra, J. 1981, *Ap. J.*, **246**, 20.
Forman, W., Bechtold, J., Blair, W., Giacconi, R., van Speybroeck, L., and Jones, C. 1981, *Ap. J.* (*Letters*), **243**, L133.
Forman, W., Kellogg, E., Gursky, H., Tananbaum, H., and Giacconi, R. 1972, *Ap. J.*, **178**, 309.
Forman, W., Schwarz, J., Jones, C., Liller, W., and Fabian, A. 1979, *Ap. J.* (*Letters*), **234**, L27.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Gursky, H., Kellogg, E., Murray, S., Leong, C., Tananbaum, H., and Giacconi, R. 1971, *Ap. J.* (*Letters*), **167**, L81.
Henry, J. P., Henrikson, M., Charles, P., and Thorstensen, J. 1981, *Ap. J.* (*Letters*), **243**, L137.
Hoessel, J., Gunn, J., and Thuan, T. 1980, *Ap. J.*, **241**, 486.
Jones, C., Mandel, E., Schwarz, J., Forman W., Murray, S., and Harnden, F. 1979, *Ap. J.* (*Letters*), **234**, L21.
Kellogg, E., Tananbaum, H., Giacconi, R., and Pounds, K. 1972, *Ap. J.* (*Letters*), **174**, L65.
Kron, R. 1980, *Ap. J. Suppl.*, **43**, 305.
Latham, D. W. 1979, in *The MMT and the Future of Ground Based Astronomy*, *SAO Special Report 385*, ed. T. C. Weekes (Cambridge:Smithsonian Astrophysical Observatory), p. 119.
Lea, S., Silk, J., Kellogg, E., and Murray, S. 1973, *Ap. J.* (*Letters*), **184**, L105.
Maccacaro, T., *et al.* 1982, *Ap. J.*, **253**, 504.
Mushotzky, R., Serlemitsos, P., Smith, B., Boldt, E., and Holt, S. 1978, *Ap. J.*, **225**, 21.
Schramm, D., and Steigman, G. 1981, *Ap. J.*, **243**, 1.
Tonry, J., and Davis, M. 1979, *A.J.*, **84**, 1511.
Tremaine, S., and Gunn, J. 1979, *Phys. Rev. Letters*, **42**, 407.
White, S. 1976, *M.N.R.A.S.*, **177**, 717.
Willingale, R. 1981, *M.N.R.A.S.*, **194**, 359.

M. J. GELLER, I. M. GIOIA, H. P. HUCHRA, T. MACCACARO, and J. E. STEINER: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

J. STOCKE: Steward Observatory, University of Arizona, Tucson, AZ 85721