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THE COMPLEX, GRAVITATIONALLY LENSED ARC SYSTEM IN THE X-RAY–SELECTED CLUSTER OF GALAXIES MS 0440+0204

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ABSTRACT

We report the discovery of a new, complex, gravitationally lensed arc system in the X-ray luminous cluster of galaxies MS 0440+0204 at $z = 0.190$. This cluster has $L_x = 4.0 \times 10^{44}$ ergs s^{-1} and is one of a sample of 38 high X-ray luminosity ($L_x > 2 \times 10^{44}$ ergs s^{-1}), intermediate-redshift ($z > 0.15$) clusters we are systematically searching for evidence of gravitational lensing. The clusters were selected from the *Einstein Observatory* Extended Medium Sensitivity Survey (EMSS) and form a statistically complete, X-ray luminosity limited sample.

We present CCD images of MS 0440+0204 that show at least 15 blue circular structures surrounding a multiple nucleus cD galaxy in the core of a compact, poor cluster. The largest giant luminous arc has a length $l > 10''$ and remains unresolved in 0\".5 seeing. The three brightest arcs—all of which may be bright enough for spectroscopy—and many of the fainter arcs trace out a 22\" radius circular critical line corresponding to 90 h_{50}^{-1} kpc radius at the cluster redshift ($q_0 = \frac{1}{2}$). The thin arcs provide strong evidence for a compact lensing mass distribution.

The optical morphology of the cluster is remarkable. The core contains six bright galaxies and numerous fainter galaxies embedded in a low surface brightness halo. It appears that we are seeing a poor cluster in the short-lived period when many of the cluster galaxies are merging to form the giant, central cD galaxy. In addition, Donahue, Stocke, & Gioia have observed extended Hα emission coincident with the core of the cluster, suggesting the presence of a large cooling flow—an interpretation supported by the presence of radio emission associated with the cD galaxy.

We measure a total optical luminosity of 9.4×10^{11} $L_\odot$ and compute a lower limit to the total mass enclosed by the arcs of 1.0×10^{14} $M_\odot$ (assuming a source redshift of $z_s \simeq 0.4$), corresponding to a central mass-to-light ratio of 110 $M_\odot/L_\odot$.

This cluster is an ideal target for future X-ray observations with *Astro-D* (*Asuka*) and *ROSAT*, and optical spectroscopy with large telescopes. Furthermore, the bright ($R = 15.9$) foreground star located within a few arcseconds of the cluster center will allow us to obtain very high resolution, ground-based images with a low-order, natural guide star, adaptive optics system.

Subject headings: dark matter — galaxies: clusters: individual (MS 0440+0204) — gravitational lensing — X-rays: galaxies

1. INTRODUCTION

In a recent paper, we reported the discovery of two clusters of galaxies containing new gravitationally lensed images of background galaxies (Luppino & Gioia 1992, hereafter Paper I). Both of these clusters were part of a sample of 21 X-ray–selected clusters we were systematically observing in order to search for gravitational lensing. We chose our sample from the *Einstein Observatory* Extended Medium Sensitivity Survey (EMSS; Gioia et al. 1990; Stocke et al. 1991), where we selected the most X-ray luminous, intermediate-redshift clusters since we believed such objects were true mass concentrations with deep potential wells, and were therefore likely to exhibit lensing. The sample mentioned in Paper I included all clusters in the EMSS with L_x(0.3–3.5 keV) $> 2 \times 10^{44}$ ergs s^{-1} ($H_0 =$ 50; $q_0 = 0$), redshift $z > 0.2$, and at declination $\delta > -40°$, that were observable from Mauna Kea. This original sample of 21 EMSS clusters has now been expanded to 38 clusters by dropping our redshift criterion to $z > 0.15$, and by using the cluster X-ray luminosities listed in Henry et al. (1992), still with L_x(0.3–3.5 keV) $> 2 \times 10^{44}$ ergs s^{-1}, but where $H_0 = 50$ and $q_0 = \frac{1}{2}$. A description of the entire sample will follow in a later paper. In this paper, we report the discovery of a complex arc system in another one of the X-ray–selected clusters in our sample: MS 0440+0204 at $z = 0.190$.

MS 0440+0204 is now the fifth published EMSS cluster (with $z > 0.15$) to exhibit lensed arcs. The others include MS 0302+1658 ($z = 0.424$; Mathez et al. 1992), MS 2137−2353 ($z = 0.313$; Fort et al. 1992), MS 1621+2640 ($z = 0.426$; Paper I), and MS 2053−0449 ($z = 0.583$; Paper I). We have found a number of other arc clusters in our sample, some of which will be described in a forthcoming paper by Le Fèvre et al. (1993), but MS 0440+0204 is one of the more spectacular cases of lensing, with some arcs bright enough for follow-up spectroscopy, and warrants a separate announcement.

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2. OBSERVATIONS

We first observed MS 0440+0204 on the night of 1992 September 25 using a Tektronix 2048 × 2048 CCD at the f/10 focus of the U.H. 2.2 m telescope on Mauna Kea. Each 24 μm pixel subtended 0\".22 on the sky, resulting in a field of view of 7'.5 × 7'.5. The arc system was obvious in a 10 minute R-band exposure during morning twilight. Additional B and R images were acquired two nights later: the total B exposure time was 2700 s and the total R exposure time was 3300 s. The typical seeing for these images was ~0\".8–0\".9 FWHM. In addition to these wide field images, we acquired high-resolution, V and I images using the High Resolution Camera (HR Cam; McClure et al. 1989) on the CFHT. A single 1200 s I exposure was taken on 1992 September 27 and three 900 s V exposures were taken on 1992 November 26. In both cases, HR Cam was equipped with the SAIC-2 1024 × 1024 CCD with 0\".13 pixels. Measurements of stellar profiles on the V and I CCD frames indicate the seeing for the I image was 0\".45 FWHM and the seeing for the combined V image was 0\".6 FWHM.

The data were reduced in the usual way. The I and V images were flattened using dome flats, while the B and R images were flattened using a median-filter stack of night sky exposures. The multiple images in the different colors were combined after they were shifted into registration and cleaned of cosmic rays. Our photometry was calibrated using the new faint CCD standards of Landolt (1992).

3. PROPERTIES OF THE CLUSTER AND THE ARCS

Stocke et al. (1991) identified the optical counterpart to the EMSS source as a compact cluster of galaxies located 41\" east and 8\" north of the X-ray position. A CCD image of this field can be seen in Figure 1. This 1800 s R image is a 1024 × 1024 subarray from the 2048 × 2048 frame, and measures 3'.75 on a side, corresponding to 924 h_{50}^{-1} kpc × 924 h_{50}^{-1} kpc at the cluster redshift (4.1 h_{50}^{-1} kpc arcsec^{-1} at $z = 0.190$ for $q_0 = \frac{1}{2}$). The brightest arcs are visible in this frame, and can be seen even more clearly in the sum of the $BVRI$ images shown in Figure 2. The arcs and galaxies are labeled in the contour plot in Figure 3. One can more easily identify the fainter arcs and arclets by referring to the true color image shown in Figure 4 (Plate 15). This image was generated by using the B and V images for the blue, the R for the green, and the I for the red.

Gioia et al. (1990) measured an X-ray flux for MS 0440+0204 of $f_x = 11.51 \times 10^{-13}$ ergs cm^{-2} s^{-1}, using the observed IPC count rate in the 2'.4 × 2'.4 standard detection cell and the various corrections needed to account for the flux outside the detection cell. A $kT = 6$ keV thermal spectrum was assumed to convert counts into flux, and a corresponding X-ray luminosity of $L_x(0.3\text{–}3.5 \text{ keV}) = 1.95 \times 10^{44}$ ergs s^{-1} was computed. However, the X-ray luminosity listed in Henry et al. (1992), $L_x(0.3\text{–}3.5 \text{ keV}) = 4.00 \times 10^{44}$ ergs s^{-1}, is more appropriate for clusters since it was determined by correcting the observed flux listed in Gioia et al. for the finite size of the IPC detection cell and more importantly for the variation of this correction with redshift. Henry et al. used a β-model for the X-ray surface brightness, $I(\theta) = I_0[1 + (\theta/\theta_c)^2]^{1/2 - 3\beta}$, with $\beta = \frac{2}{3}$ (Jones & Forman 1984), and where $\theta_c(z)$ varies with redshift and is related to the cluster core radius by $r_c = \theta_c(z) D_A(z)$ which was assumed to be 250 kpc in their paper.

The brightest galaxies that make up the core of the cluster have their magnitudes listed in Table 1. Each entry has two

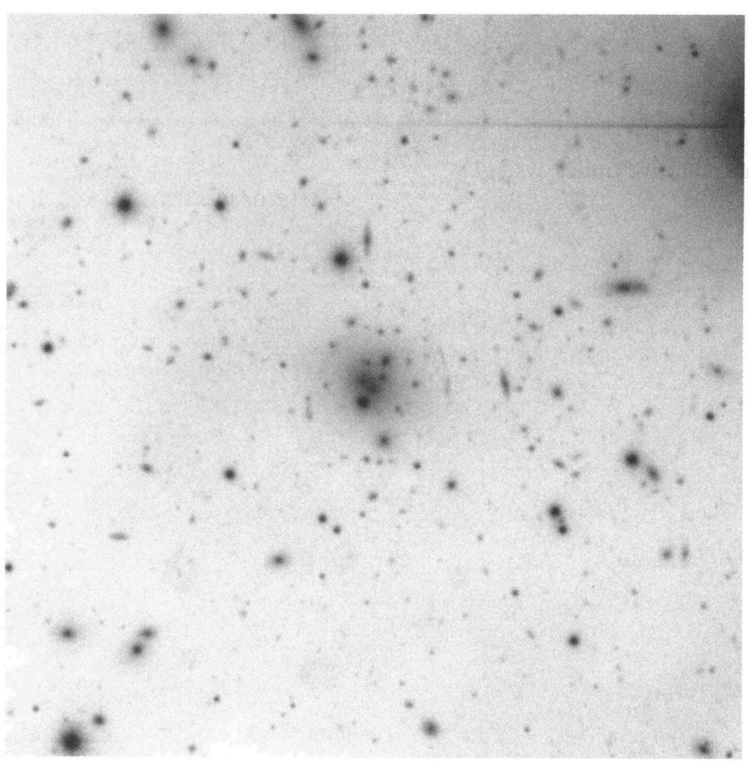

FIG. 1.—Wide field (3'.8 × 3'.8) R-band CCD image of MS 0440+0204. North is up, and east is to the left

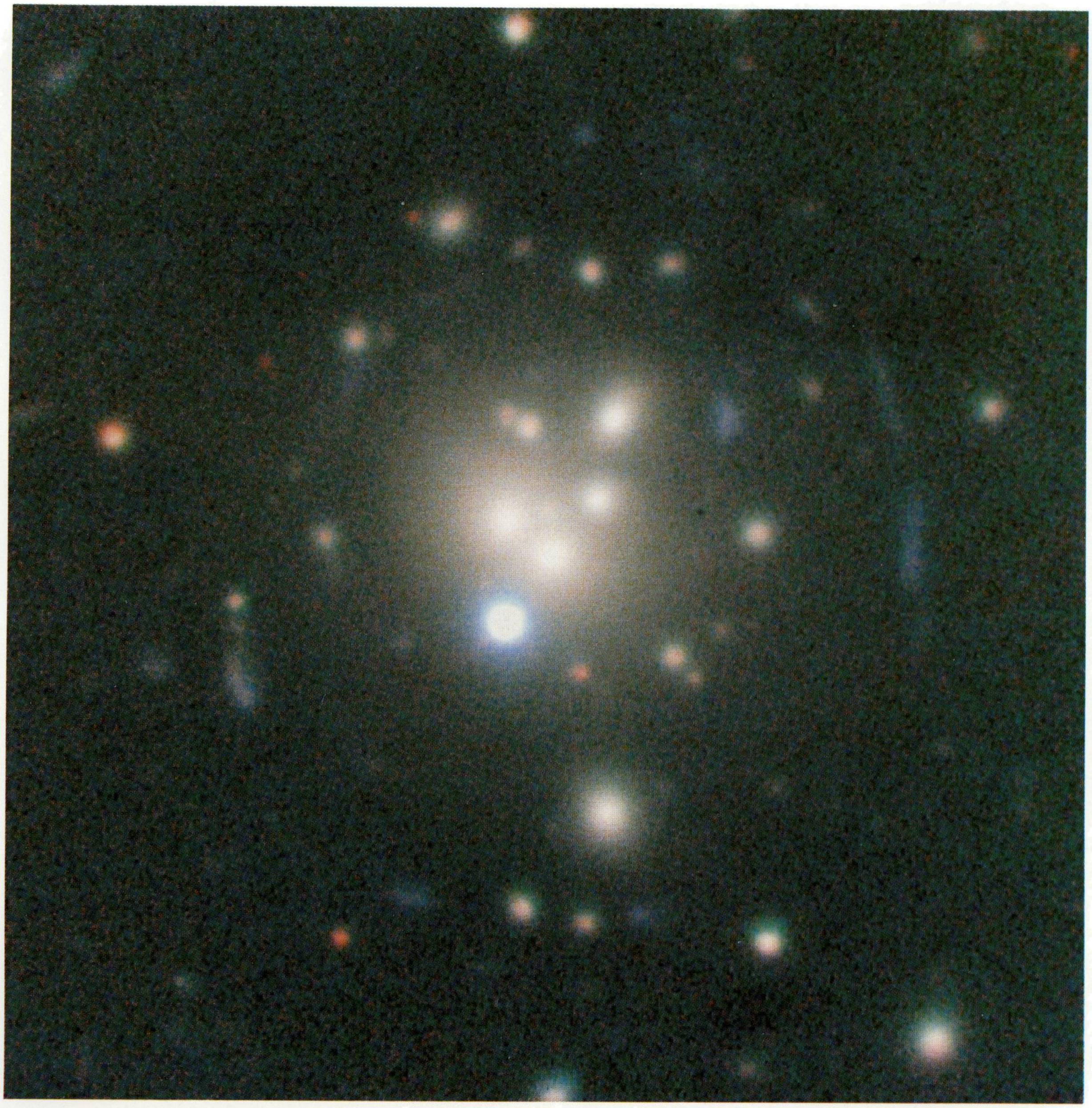

FIG. 4.—True color image of MS 0440+0204. The red image is formed with the *I* CCD image, the green with the *R*, and the blue with the *V* and *B*. The arcs and arclets can be easily seen from their blue color relative to the yellow and red cluster galaxies. North is up, and east is to the left.

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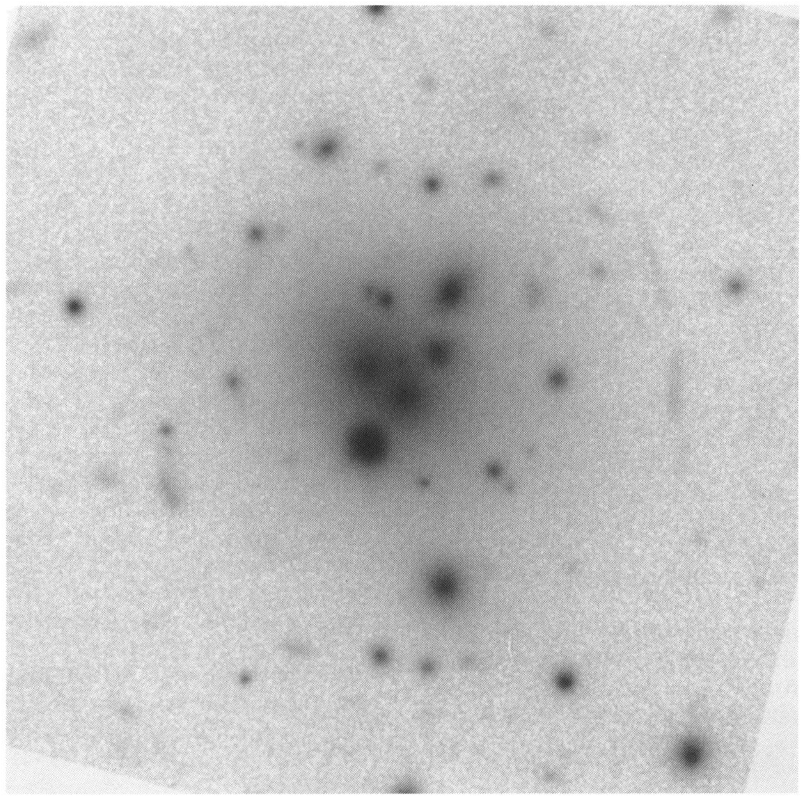

FIG. 2.—Summed *BVRI* CCD images of the central 1′ × 1′ of MS 0440+0204. North is up, and east is to the left. The image is centered on the brightest cluster galaxy. The arc complex is quite evident in this image.

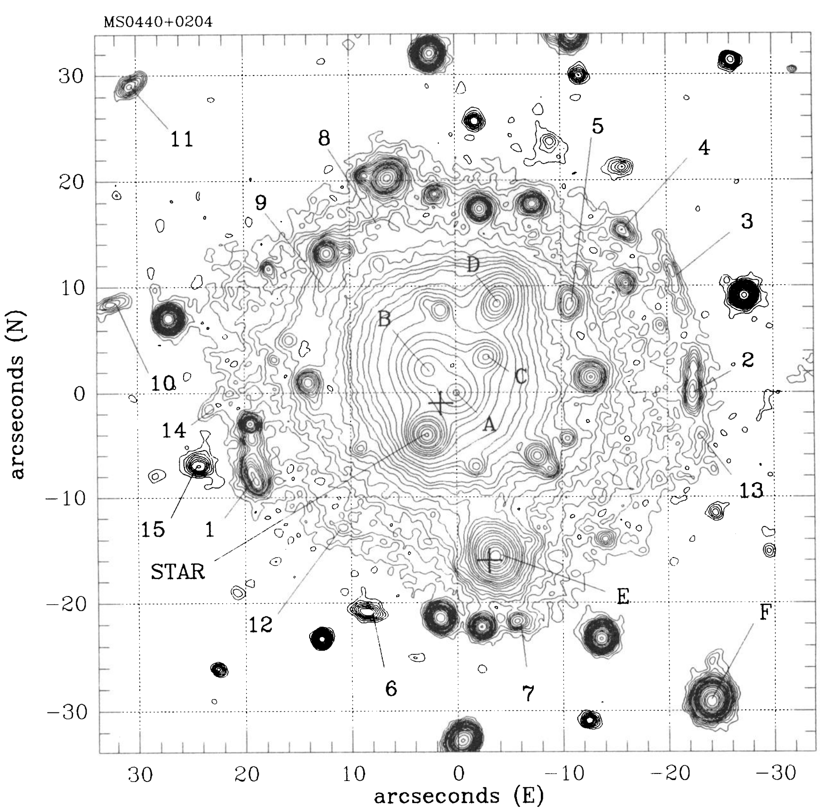

FIG. 3.—Contour plot generated from the summed *BVRI* images. The arc(let)s are labeled with numbers from 1 to 15, and some of the cluster galaxies are labeled from A to F. The image is centered on the brightest cluster galaxy (Galaxy A) at position $\alpha = 04^h40^m33^s.7$ and $\delta = 02°04'44''.7$. The bright object a few arcseconds SE of the center is a foreground star. The image was smoothed with 0″.65 FWHM Gaussian before contouring. Some of the fainter arcs are difficult to see because their contours are embedded in the cluster halo. These are more easily seen in the true color image. The two + signs mark the positions of the VLA radio sources.

TABLE 1

PROPERTIES OF THE GALAXIES IN MS 0440+0204

Galaxy	Position E	Position N	Color B	Color V	Color R	Color I	Color B−R	Notes
A	0″	0″	19.9	18.4	17.5	16.6	2.4	BCG-4.9 mJy radio src
			18.7	17.3	16.4	15.5	2.3	
B	2.6	2.2	20.0	18.5	17.6	16.7	2.4	
			18.7	17.3	16.4	15.6	2.3	
C	−2.9	3.4	20.5	19.1	18.3	17.4	2.2	
			19.3	17.9	17.1	16.1	2.2	
D	−3.9	8.3	20.7	19.2	18.4	17.5	2.3	
			20.0	18.5	17.7	16.8	2.3	
E	−3.6	−15.3	21.1	19.6	18.8	17.9	2.3	1.8 mJy radio src
			20.6	19.2	18.3	17.4	2.3	
F	−23.7	−28.7	22.0	20.5	19.6	18.7	2.4	
			21.8	20.2	19.4	18.5	2.4	
Star	2.7	−3.9	17.2	16.5	15.9	15.6	1.3	AO guide star

NOTES.—Magnitudes on first line of each entry (except for the bright star) were measured in a 16 h_{50}^{-1} kpc diameter aperture; those on the second line were measured in a 32 h_{50-1} kpc diameter aperture.

magnitudes listed for each color, corresponding to either a 16 h_{50}^{-1} kpc or a 32 h_{50}^{-1} kpc diameter aperture. Because of the overlap of the galaxies, the larger aperture magnitude has considerable contamination from the neighbor galaxies.

Extended Hα emission has been detected by Donahue, Stocke, & Gioia (1992) coincident with the center of the cluster, making this object another example of a high-redshift cooling flow cluster. In fact, the luminosity they quote of $L_{\mathrm{H}\alpha+[\mathrm{N\,II}]} = 160(\pm 30) \times 10^{40}$ ergs s^{-1} (for $H_0 = 50$; $q_0 = 0.1$) makes this the fifth brightest cooling flow in their sample (of 23 clusters), even brighter than the cooling flow in MS 0839+2938 ($z = 0.193$; $L_{\mathrm{H}\alpha+[\mathrm{N\,II}]} = 100 \times 10^{40}$ ergs s^{-1}) described by Nesci et al. (1989).

MS 0440+0204 was also observed in 1985 August with the VLA in the C configuration at 6 cm, and two sources were seen near the center of the cluster: a 4.9($\pm$0.13) mJy source (radio luminosity of 9.2×10^{23} W Hz^{-1}) coincident with galaxy A, and 1.8 mJy source coincident with galaxy E. The presence of the radio source adds additional support for the reality of a cooling flow. Burns (1990) has found, for a sample of 27 cD galaxies in rich clusters, that over 70% of the cDs with X-ray cooling cores have central radio emission at 6 cm with typical luminosities of 10^{23-24} W Hz^{-1}.

The X-ray, optical, and radio coordinates (1950.0) are listed below:

$$\text{X-ray:}\quad \alpha = 04^{\mathrm{h}}40^{\mathrm{m}}31^{\mathrm{s}}.0\ ,\quad \delta = 02°04'36''.7\ ,$$

$$\text{optical:}\quad \alpha = 04^{\mathrm{h}}40^{\mathrm{m}}33^{\mathrm{s}}.7\ ,\quad \delta = 02°04'44''.7\ ,$$

$$\text{radio (1):}\quad \alpha = 04^{\mathrm{h}}40^{\mathrm{m}}33.8\ ,\quad \delta = 02°04'43''.7\ ,$$

$$\text{radio (2):}\quad \alpha = 04^{\mathrm{h}}40^{\mathrm{m}}33^{\mathrm{s}}.5\ ,\quad \delta = 02°04'28''.7\ .$$

The positions, magnitudes, colors, and sizes of the arc(let)s are listed in Table 2. Accurate photometry was difficult because of their close proximity to the cluster halo. We measured the magnitude of each arc by adding up all the light enclosed by the lowest isophote. There is undoubtedly some contamination from the cluster halo light. The length and width of each arc were measured from the high-resolution I band frame. The largest arcs have a patchy surface brightness, but they still appear to be unresolved in width, even in 0″.45 seeing. The average color of the arcs, $\langle B-R\rangle \simeq 1.4$, is consistent with that of other known luminous arcs (Soucail 1992).

TABLE 2

PROPERTIES OF THE ARCS IN MS 0440+0204

ARC(let)	Position E	Position N	Length l	Width w	Axis Ratio l/w	B	V	R	I	Color ($B-R$)	Notes
1	19″	−8	5″	0″.5	10	22.9	22.1	21.4	20.4	1.5	Unresolved (I)
2	−22	1	7	<1	>7	23.0	22.1	21.8	21.2	1.2	Unresolved?
3	−20	11	10	0.5	20	24.0	22.8	22.2	21.7	1.8	Unresolved
4	−16	15	3	<1	>3	24.4	23.4	22.6	21.9	1.8	Unresolved?
5	−11	9	4	∼2	2	22.8	22.0	21.5	20.8	1.3	Galaxy?
6	9	−20	4	0.5	8	24.3	23.6	23.2	22.5	1.1	Unresolved
7	−6	−21	2	<1	>2	24.6	24.1	23.6	22.7	1.0	Unresolved?
8	8	16	...	...	...	...	...	...	...	...	Faint-in halo
9	13	10	...	...	...	...	...	...	...	...	Faint-in halo
10	32	9	4	...	...	...	24.5	23.6	22.4	...	Faint
11	30	29	4	<1	>4	24.8	23.4	22.9	22.2	1.9	Unresolved?
12	11	−13	...	...	...	...	...	...	...	...	Faint-in halo
13	−23	−4	4	...	...	25.0	24.0	23.1	22.3	1.9	Faint
14	23	−1	3	...	...	...	...	...	...	...	Faint
15	24	−7	3	∼2	1.5	24.4	23.4	22.9	21.0	1.5	Galaxy?

NOTES.—Values for the arc widths are measured directly from the I-band CCD image without being deconvolved from the seeing.

4. DISCUSSION

MS 0440+0204 is a remarkable object. The cluster is extremely compact and luminous with six bright galaxies and numerous (>15) fainter galaxies all embedded within a low surface brightness halo. The rest frame absolute V magnitude of galaxy A was computed from the observed R magnitude following the procedure outlined in Luppino et al. (1991). We used a rest frame $(V-R)$ color of 0.5 and a K-correction of $K_R(z) \simeq 0.2$ and found $M_V^{(32)} = -23.7$ and $M_V^{(16)} = -22.6$ where the superscripts correspond to the diameter (in kiloparsecs) of the aperture used for the measurement. These absolute magnitudes are consistent with, or slightly more luminous than, that of a first-ranked cluster galaxy in a BM I cluster (Hoessel, Gunn, & Thuan 1980). We measured the total amount of light within a circular aperture defined by the brightest arcs (after first removing the foreground star). The core group of galaxies and halo have a total magnitude of $R = 15.0$, corresponding to $M_V = -25.1$, equivalent to $9.4 \times 10^{11}\ L_\odot$. Although measured within only a 90 kpc radius, this luminosity is roughly twice the total luminosity found within a 0.5 Mpc radius for similar poor clusters with cD galaxies (Kriss, Cioffi, & Canizares 1983; Schneider & Gunn 1982). MS 0440+0204 appears to be quite similar to V Zw 311, a more nearby system ($z \sim 0.05$) interpreted by Schneider & Gunn (1982) as an example of a cD galaxy under construction where the giant central galaxy has simultaneously captured several smaller cluster members. This type of object is quite rare, and Schneider & Gunn estimate the multiple nuclei will merge through dynamical friction on a time scale of order a billion years, and the object will become an isolated cD galaxy. Both MS 0440+0204 and V Zw 311 can be thought of as precursors to the poor clusters with central cD galaxies whose optical properties were studied by Morgan, Kayser, & White (1975; MKW) and whose X-ray properties were studied by Kriss et al. (1983). For the 16 MKW clusters they observed, Kriss et al. found that the low-X-ray temperatures and high central densities were compelling evidence for the presence of cooling flows in these objects. They found a mean core mass-to-light ratio of $\sim$70–100 $M_\odot/L_\odot$ with the M/L rising with increasing radius, indicating the cDs are surrounded by dark massive halos.

We can determine the central mass and mass-to-light ratio in MS 0440+0204 if we assume the multiple arcs trace out a partial Einstein ring, and we make a reasonable guess at the source redshift. For a cluster to form arcs, the central surface mass density must be on the order of, or greater than, the critical surface mass density (Schneider, Ehlers, & Falco 1993)

$$\sum_{\rm cl} \geq \sum_{\rm cr} = \frac{c^2}{4\pi G}\frac{D_S}{D_L D_{LS}}\,.$$

The mass enclosed by an Einstein ring of radius $R_{\rm E}$ is then given by

$$M(R_{\rm E}) \geq \frac{c^2}{4G}\frac{D_S}{D_L D_{LS}} R_{\rm E}^2\,.$$

If we take a source redshift of $z_s \simeq 0.4$, we find a lower limit to the central mass within $R_{\rm E} = 90\ h_{50}^{-1}$ kpc of order 1.0×10^{14} $M_\odot$. The central mass-to-light ratio therefore $M/L \geq 110$ $M_\odot/L_\odot$. The mass enclosed and corresponding M/L drop to $6.7 \times 10^{13}\ M_\odot$ and $M/L \sim 70\ M_\odot/L_\odot$ when we move the source out to a redshift of $z \simeq 1$. These mass-to-light ratios are consistent with the M/L values for the MKW clusters and are similar to the value found by Mellier, Fort, & Kneib (1993) in their detailed model of the lensing X-ray cluster MS 2137−2353.

During the course of our lens survey, we are finding a high frequency of lensing in our X-ray-selected sample. This is in contrast to the findings of Lynds & Petrosian (1989) and Smail et al. (1991) who have attempted to measure the frequency of lensing in samples of clusters selected from various optical catalogs. Lynds & Petrosian found two arc systems in 58 clusters (27 with $0.2 < z < 0.4$), while Smail et al. investigated a "statistically complete" 19 clusters with $\bar{z} = 0.32$ and found only a few giant arcs and some mini-arc candidates. Note that their sample included A370 and was "statistically complete" only in the sense that the images were examined to a fixed surface brightness limit. These results seemed to imply that the frequency of gravitational lensing in rich clusters is only a few percent. However, statistics about the frequency of lensing from such studies are misleading because of severe optical selection effects. For example, Frenk et al. (1990) have shown through numerical modeling and simulations assuming a standard cold dark matter (CDM) cosmology, that $\sim$50% of Abell clusters with richness $R > 0$ correspond to chance superpositions of foreground groups on intrinsically poorer clusters. It is therefore not surprising that many optically selected clusters do not show lensing since they may not be true massive aggregates. Although our results are preliminary, we find that lensing is seen in at least 25% of our X-ray–selected sample (10 secure cases of lensing out of 38 clusters in the complete sample, but not all have been observed yet), and the true frequency may be as high as 50%. Our selection criteria are well defined and will allow us to perform a statistical test of the lensing properties of the high end of the distant, X-ray cluster luminosity function. Indeed, it has been predicted that the lensing properties are strongly dependent on the density profile of the lensing clusters, and hence, that the lensing statistics should provide strong constraints on the mass distribution within rich clusters cores (Hammer 1991). The high frequency of arcs we see in our sample can be explained if the cluster dark matter is much more concentrated in the cluster core (centrally peaked) than the hot X-ray gas (Wu & Hammer 1993). This conclusion is also supported in MS 0440+0204 where the brightest arcs are very thin and often unresolved in width, implying that the core radius of the dark matter should be much smaller than the arc position (Hammer 1991). Furthermore, the circular symmetry of the arcs suggests the dark matter in the cluster is smoothly distributed, rather than clumped into individual galaxies.

We can exploit the lensing geometry in this cluster to say something about the redshifts of the sources. Since the arcs lie on nearly the same radius circle around the cluster center, this implies the arc sources are all at the same redshift, a rather unlikely possibility. If the arc sources were at significantly different redshifts, then the arcs would lie at significantly different angular separations around the cluster. However, it is possible to have arcs of different redshifts lie on nearly the same radius circle if the arc sources are sufficiently far away that the $D_S/D_L D_{LS}$ distance factor in the lensing equation does not change very much with source redshift. For MS 0440+0204 with a low redshift of $z = 0.19$, the distance factor does not change appreciably once the sources are beyond a redshift of one half ($D_S/D_L D_{LS}$ changes by only 20% from $z = 0.5$ to $z = 0.7$, 10% from $z = 0.7$ to $z = 1.0$, and 10% from $z = 1.0$ to

$z = 2.0$). Therefore we argue that a reasonable lower limit to the source redshifts is $z_s > 0.5$.

Future observations will be important in order learn more about this cluster. It may be feasible to obtain redshifts for 2 or 3 of the arcs using the CFHT and Keck telescopes. Redshifts will allow us to determine accurately the mass enclosed by the arcs, as well as provide vital information about the source galaxies. High-resolution X-ray imaging with the *ROSAT* HRI and measurement of the X-ray temperature with *ASTRO-D* will enable us to measure the distribution, mass, and core radius of the X-ray gas, and will potentially provide important clues about a distant cooling flow. Finally, it will soon be possible to obtain ultra high resolution ($< 0\farcs1$ FWHM) optical and near-infrared images of this object using an adaptive optics instrument that uses natural guide stars (see Roddier et al. 1991, 1993). The $R \simeq 15.9$ foreground star near the center of the cluster is bright enough to be used for low-order wavefront correction, and the cluster and arcs are small enough that the entire system will fit within the isoplanatic patch.

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