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IMAGING OF 16 DISTANT EMSS CLUSTERS WITH $z \geq 0.2$ AND $L_{X,44} \geq 4$: NEW ARCS AND FIRST CONSEQUENCES[1]

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ABSTRACT

Medium-deep V, R, and I observations of a subsample of 16 clusters of galaxies in the EMSS sample defined from the *Einstein* satellite data are presented. Three new cases of clusters with giant luminous arcs (length/width > 10, $V < 22$) have been discovered together with six new arcs ($4 < l/w < 10$, $V < 22$), and we propose that these arcs are new examples of gravitational lensing of background galaxies by the rich clusters. Combined with giant luminous arcs already observed in the EMSS sample, there is a total of six giant luminous arcs observed in the sample of 16 clusters. This high rate of success in finding arcs added to their axis ratio distribution is consistent with very small core radii (<100 kpc) for the dark matter distribution in rich clusters, and rules out models in which dark matter follows the X-ray gas.

Subject headings: dark matter — galaxies: clustering galaxies: clusters of — gravitation — gravitational lensing

1. INTRODUCTION

The giant luminous arcs, lensed images of background galaxies observed in clusters of galaxies, represent a unique mean to get direct information on the deflecting cluster mass distribution. They provide an independent mass estimation which can be compared to other estimations, for example, from dynamical analysis and X-ray data. Furthermore, while these methods have to assume nontrivial conditions for the cluster medium, like virialization of the galaxies or hydrostatic equilibrium of the hot gas, the estimation of the lensing mass generally comes out simply from the arc geometry. Deep photometry of rich cluster fields has been proposed by Tyson, Valdes, & Wrenk (1990) to map the gravitational potential of these clusters using the statistics of the background galaxy distortions. These deep images have strikingly shown that most of the rich clusters have very smooth and regular potentials, with either spherical or elliptical shapes, and hence provide accurate barycentric position and elliptical axis ratio of the mass distribution. However, this method is not well suited for deriving the cluster density profile, since the mass estimation depends on the redshifts of the arc sources, most of which are too faint to be measured spectroscopically yet, and also because faint arclets are subjected to complex flux selection biases when combined with detection limits (Hammer 1991).

Giant luminous arcs can provide adequate S/N for low-resolution spectroscopy to allow a redshift measurement (Pello & Soucail 1993 and references therein), and their surface brightness prevents the number statistics from being affected by detection limits. The number occurrence, the distribution of the axis ratio, and locations for giant arcs in rich distant clusters have been found to be critically dependent on the cluster mass density profile (Hammer 1991; Wu & Hammer 1993). For instance, one giant luminous arc is expected for every three or four rich distant clusters observed ($L_X > 5 \times 10^{44}$ ergs s^{-1} and $z > 0.15$) if the cluster density profiles follow a $r^{1/4}$ law, while this should be 10 times lower if cluster mass profiles follow the X-ray hot gas profile.

In order to search for lensing and investigate the cluster mass density distribution in rich clusters, we are conducting a photometric survey of a complete sample of rich distant clusters of galaxies, selected from the *Einstein Observatory* EMSS (Gioia et al. 1990a; Stocke et al. 1991), and with L_X(0.3–3.5 keV) $> 2 \times 10^{44}$ ergs s^{-1} ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$) and $z > 0.15$. We describe in this *Letter* the preliminary results of our survey, based on the observations of a complete sample of 16 clusters with L_X(0.3–3.5 keV) $> 4 \times 10^{44}$ ergs s^{-1}($H_0 = 50$, $q_0 = 0.5$) and $z > 0.2$.

2. OBSERVATIONS

The clusters were observed with a variety of instruments providing direct imaging capabilities at the Canada-France-Hawaii Telescope (FOCAM and MOS/SIS) and the University of Hawaii 88 inch (2.2 m) telescope. Conditions were photometric and the seeing range from $0''.6$ to $1''.2$. Images were processed in a standard way with IRAF, including bias and flat field correction as well as cosmic-ray identification and removal. The photometric calibration was performed using fields from Christian et al. (1985) observed in the same conditions as the cluster fields. Images have different depths due to the variety of detectors and sampling pixel sizes used. From the photometric calibration coefficients, all objects with surface brightness brighter than $\mu_I = 25.2$ mag arcsec^{-2} or $\mu_V = 25.3$ mag arcsec^{-2} would have been detected at the 1 σ level, in any of our images (Table 1).

3. DEFINITION OF THE ARC SAMPLE

3.1. *Identification of New Gravitational Arc Candidates*

To identify arclike structures, each final image was visually examined with the SAOIMAGE display under various intensity ranges and contrast in order not to miss either objects very

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[1] Observations obtained with the Canada-France-Hawaii Telescope operated by the CNR of Canada, the CNRS of France, and the University of Hawaii and the 88 inch telescope operated by the University of Hawaii on Mauna Kea.

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close to the detection limit or in cD galaxy halos. When available, images obtained with different filters were similarly explored. When an arclike object was found, we tried to confirm the detection from a different bandpass image.

Three new giant luminous arcs (defined as having a length to width ratio larger than 10 and $V \lesssim 22$) and more than eight other new arcs either fainter than $V = 22$ or with $4 \leq l/w \leq 10$ have been found in our images. New arc candidates are identified in Table 1. We give here a description of the new arc candidates:

MS 0451.5+0250.— This object has a complex X-ray structure and may be a composite source. The field is rich with galaxies in a very irregular distribution. The candidate arc is near a bright elliptical galaxy to the NE of the densest region of galaxies.

MS 1006.0+1202.—Three new gravitational arcs are observed in this field (Fig. 1 [Pls. L1–L4]). They all show a linear structure, that is, no curvature is observed. The orientation of the arcs major axis may be an indication of some irregularity in the cluster potential.

MS 1008.1−1224.—A thin arc is seen to the north and a bright arc to the east (Fig. 1). A large radial arc is possibly observed and looks resolved.

MS 1455.0+2232.—An arclike structure is observed 19.″4 from the giant cD galaxy (Fig. 1). It breaks into two peaks in R that might represent source structures or two images association.

MS 1910.5+6736.—A straight structure is observed 67″ from the central galaxy and is 6.″1 in length (Fig. 1). It can be classified as a giant luminous arc ($l/w > 10$) since it is not resolved in width (see Table 1). Another straight object is observed in R 48″ from the central galaxy, but the V image shows a very definite central core that indicates that this is probably an edge-on spiral galaxy.

3.2. *Completeness of the Sample*

All the 16 clusters discussed in the present sample have been observed by us or by others (MS 0302.7+1658: Mathez et al. 1992; MS 1621.5+2640 and MS 2053.7−0449: Luppino & Gioia 1992; MS 2137.3−2353, Fort et al. 1993, see Table 1) among the EMSS clusters in the Gioia et al. (1990a) sample, which was used to investigate the X-ray luminosity function and its evolution (Gioia et al. 1990b). This forms a complete sample of rich distant clusters of galaxies with $L_X > 4 \times 10^{44}$ ergs s^{-1} and $z > 0.2$.

The field of view (minimum 3′ × 3′) ensures that we have indeed detected all of the giant arcs associated with one cluster (see also Table 1). All our images have a surface-brightness limit, $\mu_V > 25.3$, $\mu_I > 25.2$ mag arcsec^{-2} (1 σ), which ensures that we are able to detect securely any gravitational images ("arcs") having $V \lesssim 22.5$ or $I \lesssim 21.5$. One could wonder about the possible bias which favors the detection of thin arcs that present a better contrast than thicker and well-resolved arcs. $I < 21.5$ (or $V < 22.5$) arcs should be detected above the 1 σ level for sizes (length × width) lower than 20 arcsec^2 (14 arcsec^2 in V). There is no indication that extremely large arcs (with extremely low surface brightness) are present in our sample, although this will be checked when deeper images are available.

3.3. *Arc Sample and the Arc Identification Criteria*

To define a sample of relatively bright gravitational images, one should carefully account for the contamination by foreground galaxies, and especially of the cluster galaxies. Indeed some of these images present no curvature, which could be either due to the flatness of the lensing cluster potential or, more likely, to the presence of a secondary deflector near the line of sight. These images could be difficult to distinguish from (unlensed) edge-on spiral galaxies.

Moreover, we have to consider possible arclike structures belonging to the cluster or background/foreground objects: cooling flows, projected spiral galaxies, and galaxies interactions. One such occurrence was found by us in the cluster Cl 0018−20 where the spectroscopy of the supposed arc (Giraud, Triay and Infante, 1991) indicated it is likely to belong to the "lensing" cluster and might be the result of two interacting galaxies. Infrared observations would help to eliminate the undesirable cases ($I-K$, $V-I$ color-color diagram; see Rigler et al. 1992). Since these observations are not yet available, we can estimate the rate of projected spiral galaxies in our fields in the following way. Since the clusters we are studying are very rich, we can use well-known rich clusters to get an estimate of the fraction of spiral galaxies in the core: Mac Laren, Ellis, & Couch (1988) and Mellier et al. (1988) have found nearly 50% of spiral galaxies in Abell 370 and in other rich Abell clusters. Only Sa, Sb, Sc, or Sd galaxies have a disk contribution providing axis ratio larger than 4, and MacLaren et al. (1988) have found 25% of such galaxies. In each field we have around 60 galaxies ($I < 22$), and we therefore expect 15 to be spirals. For the sake of simplicity, if we suppose that these galaxies are only composed of a thin disk and that the angles of the planes of the spirals disks from the line of sight are homogeneously spread in all directions, 0.5% will have an axis ratio larger than 10 and 1% larger than 4. In the current sample of 16 clusters, we then expect that 2.4 spiral galaxies will present an axis ratio larger than 4 and only 0.5 with an axis ratio of more than 10. Contamination by field spiral galaxies is expected to be about 0.5 galaxies from galaxy counts up to $I = 22$ (Lilly, Cowie, & Gardner 1991).

In order to check for the possible contribution from elongated objects other than gravitational arcs, we searched for all objects with a ratio = major axis/minor axis larger than 4 in an area 3′ × 3′ on all the cluster fields. We found a total number of 13 objects verifying this criterion, which is by far more than what can be expected from the random projection of cluster/field galaxies (>7 σ excess). Two of them are likely to be edge-on spiral galaxies, easily recognizable from their high surface brightness, the presence of a well-defined nucleus, and the absence of any curvature. This number of unlensed galaxies with a (projected) axis ratio larger than four is then in good agreement with what one can expect from a rich cluster and superposed field galaxies (two against three), although infrared colors will be required to identify the nature of a possible ambiguous case. The 11 other elongated images are likely to be gravitational images of background galaxies either because their widths are not spatially resolved, or because they present a well-defined curvature.

4. DISCUSSION AND CONCLUSION

The sample of 11 gravitationally imaged galaxies should then be representative of the lensing properties of our complete sample of highly X-ray luminous clusters. Six of them are not spatially resolved in width (intrinsic width <0.″6) which suggests a compact mass distribution for the lensing clusters (Hammer 1991). Out of the 11 arcs, six are reaching the criterion defined by Wu & Hammer (1993) for giant luminous

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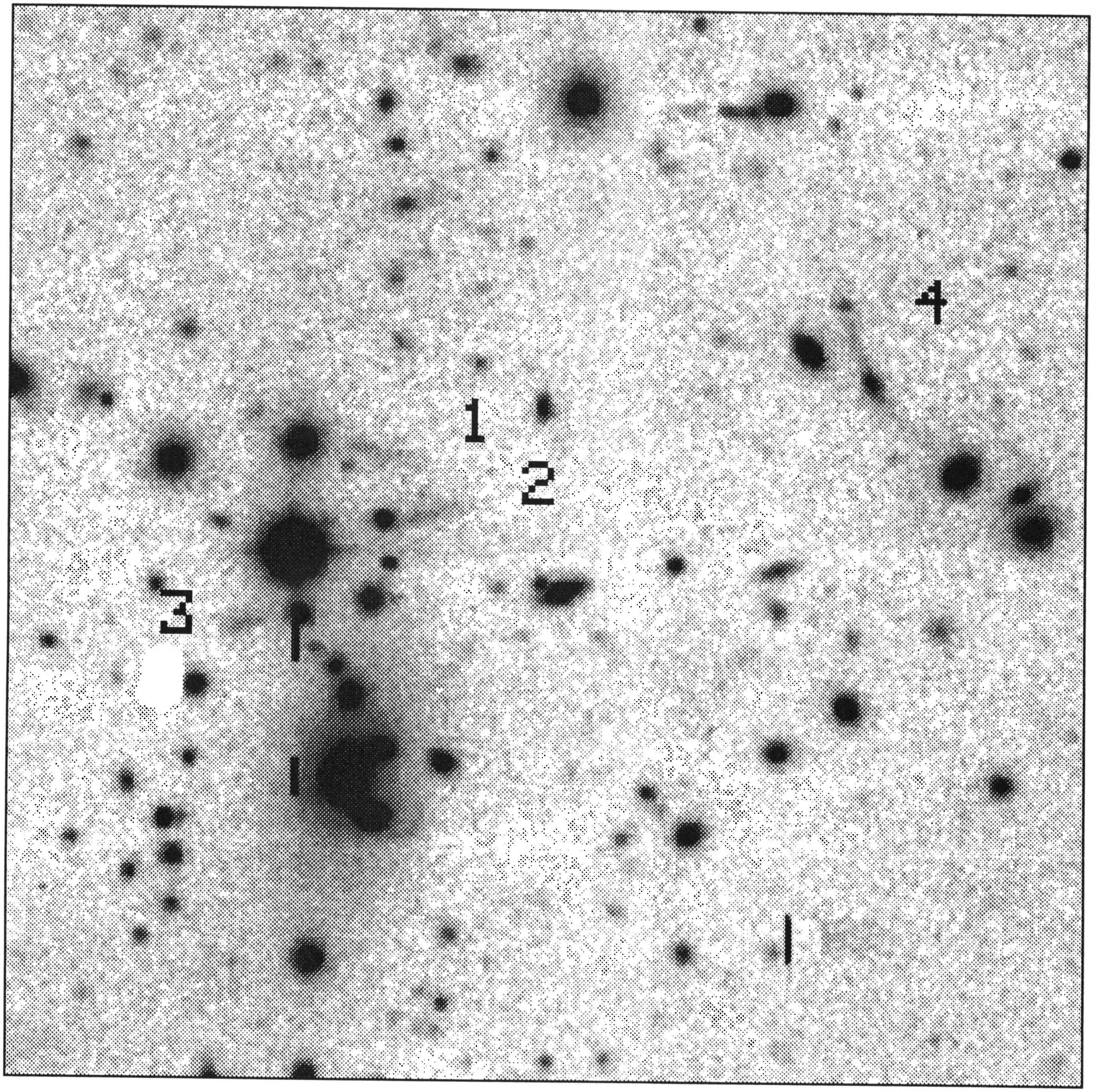

FIG. 1*a*

FIG. 1.—(*a*) Cluster MS 1006+1202. Sum of 20 minute integration in *V* and 20 minute integration in *I*, seeing 0."9 FWHM, CFHT/SIS. North is up, east to the left; the image is 100" on a side. (*b*) Cluster MS 1008−1224. 20 minute integration in *I*, seeing 1" FWHM, CFHT/SIS. North is up, east to the left; the image is 100" on a side. (*c*) Cluster MS 1455+2232. 10 minute integration in *V*, seeing 1."1 FWHM, CFHT/MOS. North is up, east to the left; the image is 100" on a side. (*d*) Cluster MS 1910.5+6736, 15 minute integration in *R*, seeing 0."95 FWHM, CFHT/SIS. North is at the bottom, east to the right; the image is 100" on a side.

LE FÈVRE et al. (see 422, L6)

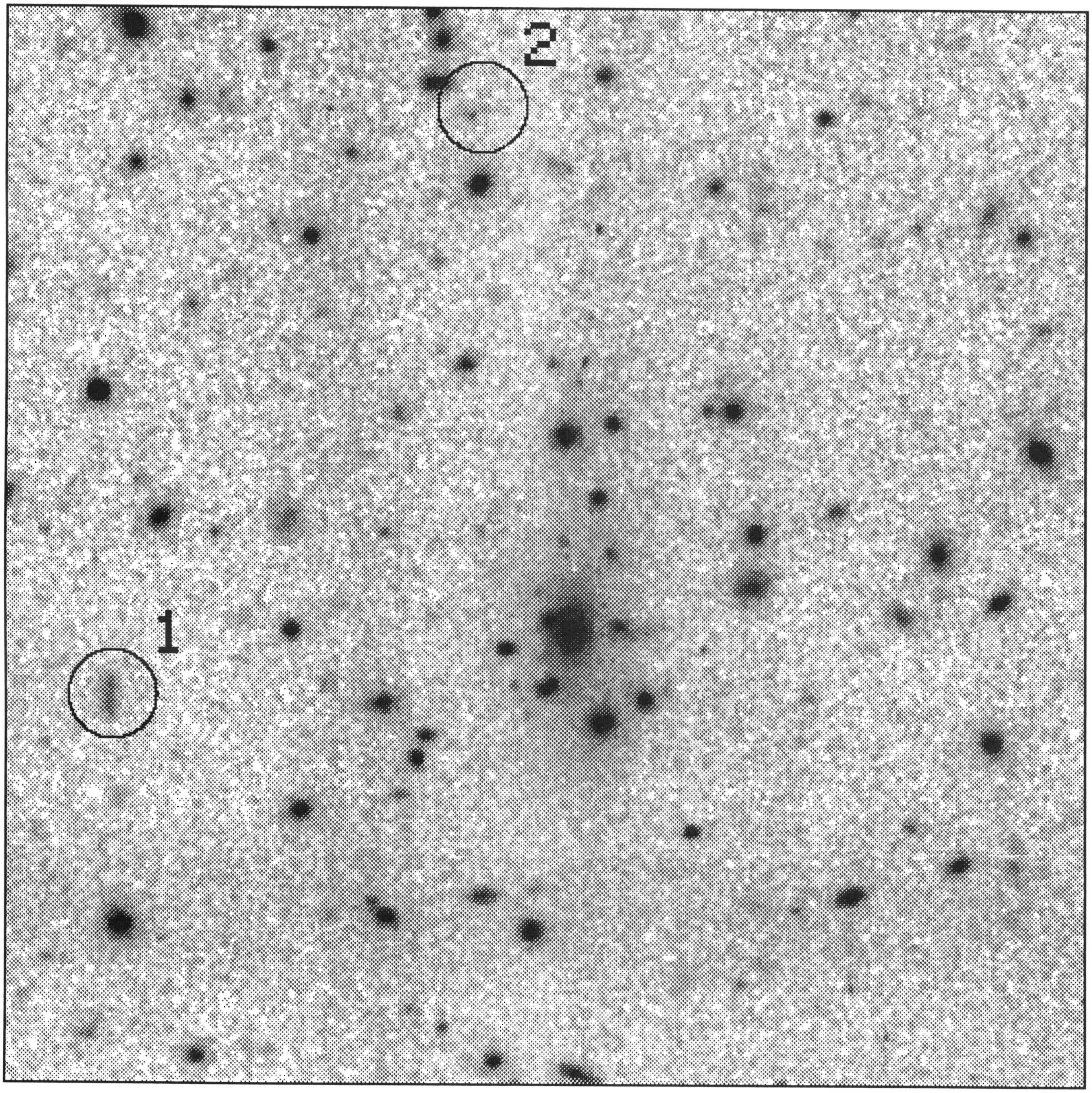

FIG. 1*b*

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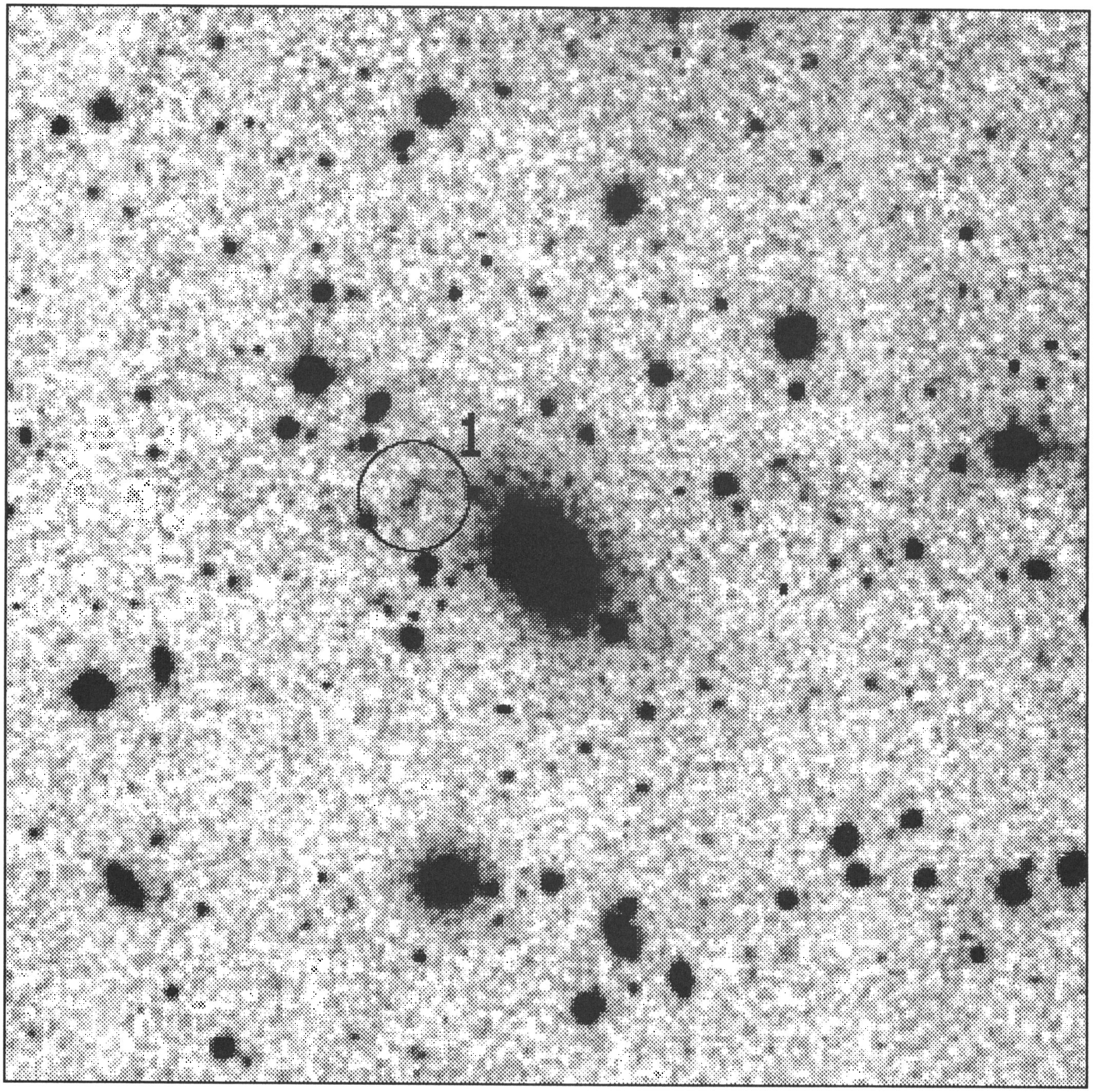

FIG. 1c

LE FÈVRE et al. (see 422, L6)

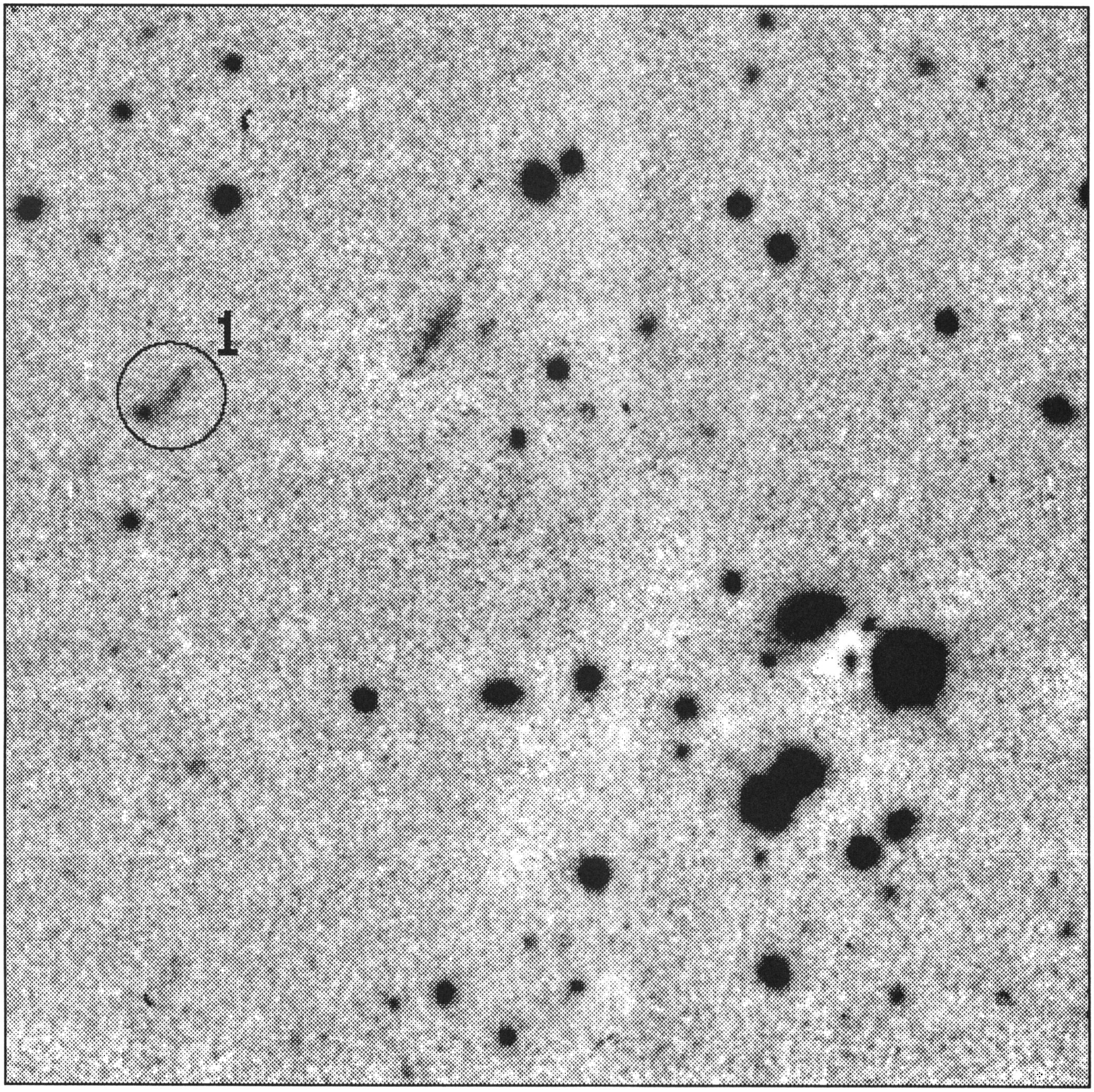

FIG. 1*d*

LE FÈVRE et al. (see 422, L6)

TABLE 1

LIST OF EMSS CLUSTERS AND ARCS IDENTIFIED IN THE PRESENT SAMPLE

Cluster	z $L_{X,44}$	1 σ Isophote of Current Observations (mag arcsec^{-2})	Magnitudes of the Arcs	Morphology: Length l/w d (center)	Notes
MS 0015.9+1609	0.54 14.32	$\mu_R = 24.75$ $\mu_V = 26.4$	...	...	...
MS 0302.7+1658	0.424 4.99	...	$B = 23.83$ $R = 22.35$ $I = 21.71$	10″ 11.1	Mathez et al. 1992 ...
MS 0353.6−3642	0.32 5.23	$\mu_V = 26.2$	...		...
MS 0451+0250	0.202 9.96	$\mu_R = 26.55$	$R = 23.32$	5 5.5 25	New arcs
MS 0735.6+7421	0.216 6.10	$\mu_V = 26.2$ $\mu_I = 26.2$	...	...	...
MS 1006+1202	0.221 4.80	$\mu_V = 26.2$ $\mu_I = 26.2$	Arc 1: $V = 22.18$ $I = 20.47$ Arc 2: $V = 21.92$ $I = 21.47$ Arc 3: $V = 20.05$ $I = 20.91$ Arc 4: $V = 22.34$ $I = 21.49$	Arc 1: 5.8 6.0 31 Arc 2: 5.9 10.5 26 Arc 3: 3.7 3.1 17.5 Arc 4: 4.9 7.0 62	New arcs
MS 1008−1224	0.301 4.48	$\mu_V = 26.20$ $\mu_I = 26.2$	Arc 1: $V = 21.53$ $I = 19.72$ Arc 2: $V = 22.28$	Arc 1: 4.5 10 47 Arc 2: 4.0 6.5 51	New arcs
MS 1224+2007	0.327 4.59	...	...	...	...
MS 1333.3+1725	0.460 5.39	$\mu_I = 25.2$	...	...	...
MS 1358.4+6245	0.328 10.65	$\mu_V = 25.71$ $\mu_I = 25.16$	...	...	...
MS 1455+2232	0.259 15.98	$\mu_R = 25.81$ $\mu_V = 26.24$	$V = 23.24$ $R = 22.91$	8.7 6.7 19.4	New arc
MS 1512+3647	0.372 4.8	$\mu_R = 25.81$ $\mu_V = 26.24$	...	...	...
MS 1621.5+2640	0.426 4.52	$\mu_I = 25.00$ $\mu_R = 26.36$ $\mu_V = 26.70$	$V = 21.16$ $R = 21.08$	9.8 19.6	Luppino & Gioia 1992
MS 1910.5+6736	0.246 4.38	$\mu_R = 25.16$ $\mu_V = 25.38$	$V = 22.29$ $R = 20.63$	6.1 10.5 67	New arc
MS 2053.7−0449	0.583 5.76	$\mu_R = 25.55$	$R = 21.91$	10.5 17.5 15.8	Luppino & Gioia 1992
MS 2137.3−2328	0.313 15.58	...	$B = 22.04$ $V = 22.00$ $R = 21.55$ $I = 21.22$	14.2 17.8 15.5 ...	Fort et al. 1993

arcs ($l/w > 10$ and $B < 22.5$ or $R < 21.5$). This rate, of six giant luminous arcs among 16 highly luminous X-ray clusters, is expected by lensing statistics if clusters have compact density profile, such as $r^{1/4}$ law. However, this is by far much larger than the rate predicted by the lensing model if the dark matter is following the X-ray gas with a typical core radius of 250 kpc ($H_0 = 50$), in which case one would expect less than one giant luminous arc in this sample of 16 clusters (see Wu & Hammer 1993, Table 3). Moreover, all the observed arcs but one have an axis ratio larger than 10. This is again highly suggestive that the dark matter in rich clusters has a smaller core radius than the X-ray gas, since with $r_c = 250$ kpc, less than one-third of the arcs would have an axis ratio larger than 10.

In this *Letter*, we have presented the preliminary results from a survey of a sample of X-ray luminous clusters from the EMSS sample (Gioia et al. 1990a), aimed at searching for gravitational images of background galaxies. These clusters characterize the high end of the X-ray cluster luminosity function, and because of the high rate in finding luminous arcs in this sample, one can reasonably assume that clusters with gravitational arcs adequately represent the X-ray luminous clusters. We have added three new cases of giant luminous arcs ($l/w < 10$, $V < 22$) to the ~20 already known, as well as six other arcs ($4 < l/w$, and/or $V > 22$), and therefore the success rate of finding arcs in this sample is extremely high (11 arcs in 16 clusters). This, combined with the distribution of the arcs axis ratio is highly incompatible with a distribution of dark matter following the X-ray gas. A more detailed discussion can be found in Hammer et al. (1993) who test the validity of several models for the cluster density profile by comparing the predicted values to the observed one. Observations of the complete sample of 42 EMSS clusters [$L_X(0.3\text{–}3.5 \text{ keV}) > 2 \times 10^{44}$ ergs s^{-1} ($H_0 = 50$) and $z > 0.15$] are being finalized and are expected to provide unprecedented constraints on the dynamics of rich clusters of galaxies and their evolution (Luppino et al., in preparation).

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