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AN ARC SYSTEM WITH A RADIAL GRAVITATIONAL IMAGE IN THE CLUSTER MS 2137−23

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ABSTRACT

This *Letter* presents the first detection of a radial gravitational image candidate in a cluster of galaxies. In addition, the field of the cluster MS 2137−23 ($z = 0.315$) contains a large arc and a few arclets. The radial image is embedded within the halo of the central cD galaxy and can be seen only with high-resolution images. The color and brightness of this image are similar to other arc(let)s and strongly favor the radial gravitational image hypothesis. The radial image implies a small core radius for the cluster.

A geometrical configuration, with both a large arc and a radial image, provides a unique opportunity to model the center of a clusters potential and the dark matter distribution. We also suggest that the very faint diffuse stellar component inside the cluster core may trace the geometrical distribution of the dominant invisible mass. The observational data available for modeling are presented and discussed.

Subject headings: galaxies: clustering — gravitational lensing

1. INTRODUCTION

Since the discovery of the first large arcs in clusters of galaxies (Soucail et al. 1987; Lynds & Petrosian 1986) the Toulouse group has been active in surveying this new class of gravitational images. The initial objectives of our program were to obtain deep imaging under subarcsecond seeing conditions of rich clusters of galaxies with redshifts between 0.2 and 0.7 to a limiting magnitude of $B = 26.5$ and $R = 25$, and to conduct a tentative redshift survey of the cluster members and brightest arcs. The seeing conditions are crucial for detecting arclets formed by the distortion of faint background galaxies because they govern the number of arclets detected, as well as the possible detection of demagnified counterimages of large arcs. From this program, the list of clusters with arc(let)s was recently updated (Fort 1992).

Our discovery that the cluster MS 2137−23 exhibits a very peculiar configuration, with a large arc, a possible radial image, and a few arclets, fully warrants a separate announcement since such a geometrical configuration will allow us to derive strong constraints for the core radius and potential of the cluster from modeling. As the exact distribution of dark matter in clusters is still an open question (Hammer 1991; Blandford & Narayan 1992), MS 2137−23 should mobilize theoreticians for modeling and observers for improved observations.

This *Letter* is organized as follows: § 2 presents the observations, § 3 gives the photometry of the galaxies and arc(let)s, § 4 discusses the arclets and the radial arc, and § 5 describes the overall ellipticity and orientation of the faint stellar diffuse component associated with the cD galaxy.

2. THE OBSERVATIONS

The Toulouse arc survey is mainly based on the selection of rich clusters with a high velocity dispersion or a high X-ray luminosity. In addition, for the most distant clusters, the richness was used to select sample clusters ($z > 0.4$). The cluster MS 2137−23 was selected within the Extended Medium Sensitivity Survey (EMSS) sample (Stocke et al. 1991: $L_x = 7.31 \times 10^{44}$ ergs s^{-1} with $H_0 = 100$ km s^{-1}; $q_0 = 0$). Its coordinates are $\alpha(1950) = 21^h37^m22^s$ and $\delta(1950) = -23°53'05''$.

The first observations were performed with the ESO New Technology Telescope in 1991 August (ESO key program 1-015 "Arc Survey"). The CCD in use was a 2 K Loral CCD (0".34 pixel^{-1}). The seeing was between 1".6 and 2".5 FWHM. Photometry in V, R, and I bands with 30 minute exposure time led to the detection of a large luminous arc and possible arclets of similar brightness. A month later, the large arc detection was confirmed from B, V, R, I images taken again at ESO, with an image quality ranging from 1" to 1".4 FWHM. Finally, during an observing run at the Canada-France-Hawaii telescope in 1991 November, we used FOCAM at the prime focus to obtain a 45 minute blue image with a higher spatial resolution of 0".8 FWHM (0".206 pixel^{-1}). The image displays a "radial" blue feature with about the same surface brightness as the large arc (Fig. 1 [Pl. L13]).

3. PHOTOMETRY

3.1. *Galaxies in the Core of MS 2137−23*

The cluster is dominated by the CD galaxy G1 (Fig. 1 [Pl. L13]). Spectra obtained during the first ESO run gave a red-

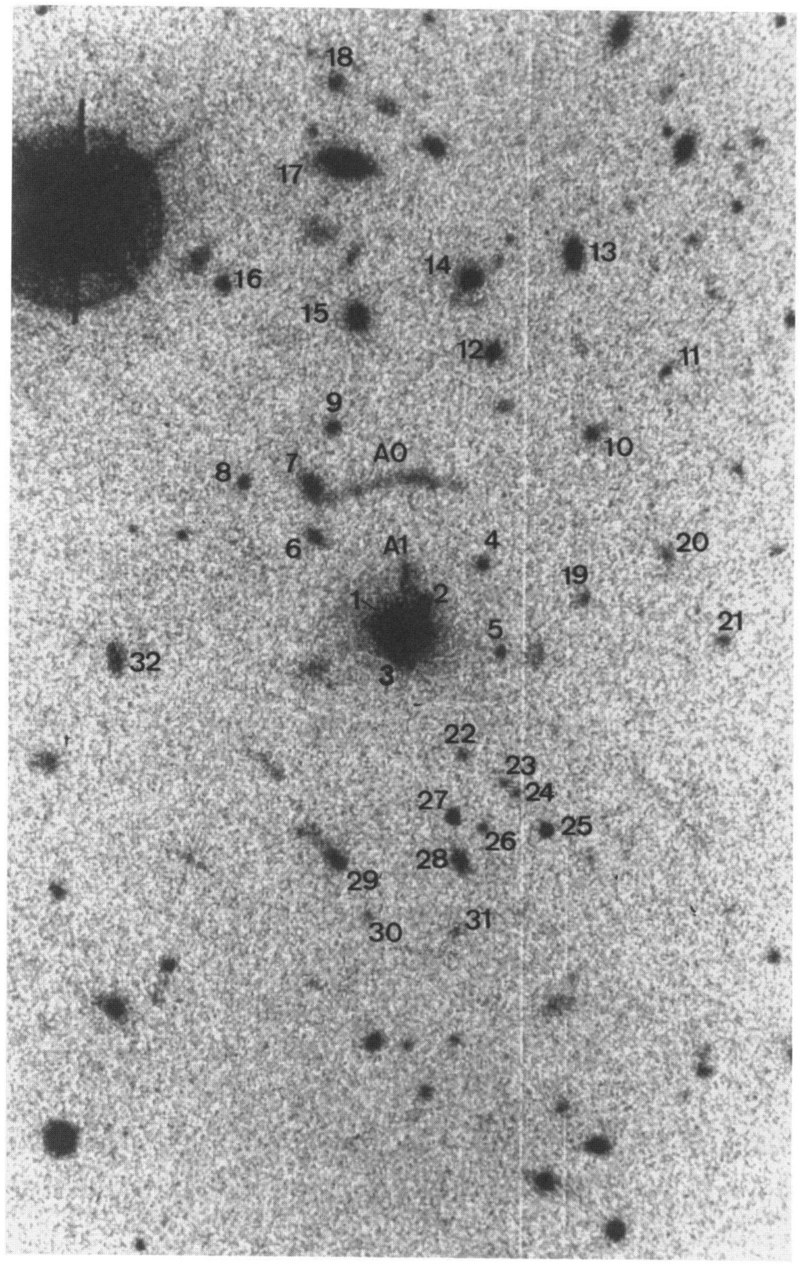

FIG. 1.—Blue CFHT image of the center of MS 2137−23 with the large arc, the radial image, and other arclet candidates (size of the field: 52″.7 × 52″.7; seeing = 0″.8; 0″.206 pixel^{-1}). Probable galaxy members from Table 1 are named Gi.

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TABLE 1

PHOTOMETRY OF THE GALAXIES AND ARCS

No.	*X*	*Y*	*B*	*V*	*R*	*I*
G1	0.0	0.0	20.48	18.28	17.24	16.60
G2	2.1	2.9	...	...	...	...
G3	−0.6	−2.3	...	...	...	...
G4	9.5	−2.1	23.80	...	...	...
G5	7.6	6.8	23.40	22.21	20.99	19.50
G6	−8.9	9.3	23.00	21.90	20.95	20.30
G7	−9.3	14.4	22.05	20.50	19.45	19.05
G8	−16.1	14.8	23.50	22.15	21.05	20.25
G9	−7.4	20.6	23.15	22.12	20.97	20.30
G10	18.3	20.2	23.30	22.25	21.00	19.50
G11	25.8	26.6	24.11	24.00	22.96	22.00
G12	8.4	28.4	22.50	21.17	20.03	19.29
G13	16.3	38.3	21.77	21.33	20.77	20.20
G14	6.2	35.8	21.93	20.41	19.30	18.55
G15	−5.2	31.7	21.70	20.42	19.24	18.55
G16	−18.5	35.0	23.20	...	...	...
G17	−6.6	47.6	20.63	19.50	18.72	18.15
G18	−7.8	56.0	23.30	21.95	20.86	20.15
G19	17.7	3.5	24.35	23.35	21.98	21.05
G20	25.8	8.0	24.00	23.42	22.35	21.06
G21	31.3	−0.4	24.00	23.32	22.29	21.30
G22	6.0	−12.4	24.72	23.78	22.10	21.15
G23	10.1	−14.8	24.65	22.56	21.60	19.80
G24	11.3	−15.9	24.65			
G25	14.0	−19.8	22.50	21.45	20.10	18.95
G26	8.0	−19.6	24.10	23.90	22.60	21.35
G27	4.9	−18.5	22.38	22.00	21.55	20.95
G28	5.8	−23.1	23.00	22.44	21.80	21.10
G29	−6.4	−23.5	22.65	22.45	22.10	21.35
G30	−3.3	−28.6	24.35	24.03	23.22	...
G31	5.4	−29.9	24.33	23.30	22.30	...
G32	−28.4	−3.7	23.17	22.44	21.80	...
A0	−1.0	15.7	22.04	22.00	21.55	21.22
A01	−4.5	14.4	...	...	...	...
A02	1.0	16.1	...	...	...	...
A1	0.2	6.2	23.31	...	...	...
A2	13.0	−2.3	23.63	23.38	23.22	...
A3	−9.1	−3.7	23.00	...	...	...
A4	−13.2	−13.4	23.70	24.33	23.34	...
A5	−8.2	−21.0	...	...	...	...
A6	−20.6	−23.5	23.98	24.23	23.00	...
A7	33.0	16.7	24.13	24.30	23.86	...
A8	42.4	−8.4	23.27	...	...	...
A9	15.4	−37.1	23.25	23.42	22.72	...
A10	10.1	23.3	24.00	24.51	23.40	...

shift of $z = 0.315 \pm 0.002$ for the central cD galaxy. *B*, *V*, *R*, *I* photometry of 26 brightest galaxies in the center of the field is given in Table 1 together with their positions. Two galaxies G2 and G3 are superposed on the core of the central cD galaxy. The twin blue galaxies G23 and G24 are not well resolved in *V*, *R*, and *I*, and we give the total magnitude for these bands. The accuracy of our photometry for objects with a magnitude $B = 23.5$ is about ± 0.25 rms.

A cluster core luminosity $R = 16.99$ was measured within a radius of 15".5 corresponding to the mean radius of the large arc. This luminosity mainly comes from the giant cD galaxy since its surroundings are almost empty of any cluster galaxies! Assuming an Einstein radius equal to the radius of the large arc and a source at a redshift of 1, the mass-to-light ratio (in solar units) can be estimated to be $M/L = 158 \pm 40$ ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$). The uncertainty is mainly from the evaluation of the *k*-correction and luminosity evolution using different models (Bruzual 1983; Guiderdoni & Rocca-Volmerange 1988).

3.2. *The Large Arc*

The large arc A0 has a length of about 14".2 and displays a patchy structure. The distance from the center of the CD galaxy to the "blue" substructures A0-1 and A0-2 is 15".86 and 15".20, respectively (Fig. 2 [Pl. L14]). The arc seems to be embedded in a very faint halo and has a width of 1".8 ± 0".2. However, on the high-resolution blue image the arc is thin, with a width nearly unresolved (Fig. 1 [Pl. L13]). In fact, the width is smaller at each of the extremities ($e < 0''.7$ FWHM after correction from the point-spread function) and larger close to the segment A0-1 ($e = 0''.9 \pm 0''.1$ FWHM). In *R* the structure A0-1 seems to be made of two merging faint knots. Furthermore, the width of the arc A0-2 at its extremity near the cluster galaxy G7 is slightly larger than for A0-1 on the *R* image, and this component is also redder (Fig. 2 [Pl. L14]). A0-2 also possesses a blue knot (diameter: 0".7 ± 0".1) associated with a more diffuse and extended *R* feature and could be a small intervening blue galaxy. However, both the *R* feature and the blue knot seem very well aligned with the general curvature of the arc and therefore may be interpreted as substructures in the source galaxy.

The multiplicity and parity of distinct multiple images coming from a source with substructures are difficult to identify even on images obtained with exceptional seeing conditions (cf. the triple arc in Cl 0024 + 1654; Kassiola, Kovner, & Fort 1992). With the data presently available it is not possible to get a clear understanding of the detailed geometric nature of the large arc A0. The best explanation seems to be that near A0-1, the large arc is a consequence of the merging of two aligned images coming from a source with substructures.

3.3. *The Radial Image and Arclets*

The radial feature A1 is located 5" from the center of the cD galaxy G1. This feature has a length of about 3".5 (and a variable width of 0".85 ± 0".2 FWHM after correction from the point spread function) and is "perfectly" aligned toward the center of the cD galaxy within an accuracy of ±0".2. This radial feature is barely seen on the other *R* and *I* images because of its blue color and merging with the bright red halo of the galaxy G1. Only the *B*-magnitude is given in Table 1.

Several faint blue elongated features named Ai on Figure 2 (Plate L14) are present on the high-resolution *B* image and can also be seen on the best *R* images. The positions and the photometry of these features are given in Table 1 whenever possible. The colors of these arclets are different from the galaxy members Gi. Color information can be used to separate the arclets from cluster members and to derive their rough "color redshift" (Fort 1992). Here, within the photometric uncertainties, their redshifts are probably between 0.7 and 1.5.

The search for arclet candidates was also made with images whereby both the color index and the surface brightness of the objects are used simultaneously for the discrimination between galaxies and arclets (subtracting a scaled *R* frame from a *B* frame). We found that A2, A4, A5, and A6 have a clear tangential elongation in *B* and display color and surface brightness similar to that of A0 and A1. The nature of A3 was more questionable.

4. DISCUSSION OF THE ARCS

Although not yet mentioned by observers, radial arcs should appear when a source falls on the external caustic of a nonsingular elliptical potential (Blandford & Narayan 1992). In

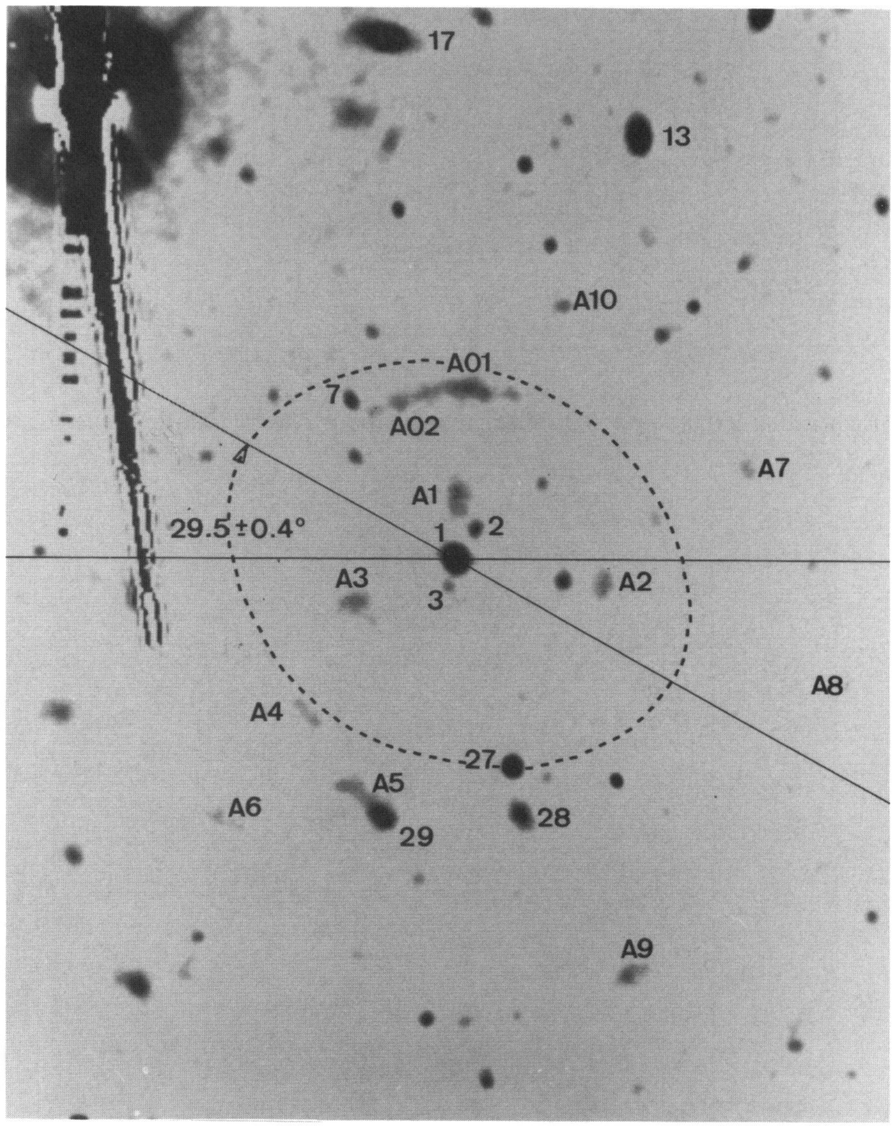

FIG. 2.—$(B-R)$ image of the center of MS 2137−23 after smoothing both the B and R images to an equivalent spread function = 2″ (FWHM). Arc(let)s candidates are named Ai. The dotted line represents the fit of the surface brightness level which has been used to estimate the ellipticity of the extended diffuse component of the cD galaxy G1 ($R = 26$ arcsec^{-2}).

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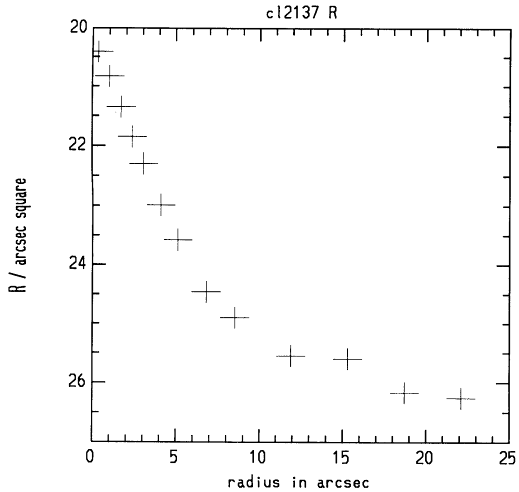

FIG. 3.—Surface brightness of the extended halo of the cD galaxy against the radius in arcseconds.

fact, they are probably difficult to detect because they are expected to form within the large galaxies, close to the center of the cluster. Radial images can only be seen under excellent seeing conditions and when the features are bright and bluer than the cluster galaxies.

It is important to note that a cluster with a strong X-ray emission can occasionally contain a cooling flow of the hot intergalactic gas on to the central galaxy (Donahue, Stocken, & Gioia 1992 and references therein). A cooling flow may result in irregular radial filaments with a strong observable Hα emission line at the redshift of the cluster. Such a line was not detected in spectra of the cD galaxy, but it will be important to obtain the spectrum of the radial image itself before this hypothesis is completely discarded.

An elliptical potential also produces multiple images (Kovner 1990; Kochanek 1992; Blandford & Narayan 1992) from the same source. Therefore, modeling could be made easier with an a priori idea about the possible association of the multiple images. Indeed (cf. § 3.3), some of the arclets Ai may be candidates for counterimages of the large arc A0 and the radial image A1. The colors do not allow us to distinguish which arclets come from the same source, but their geometrical location and relative magnitude can guide modeling.

5. OTHER OBSERVATIONAL CONSTRAINTS FOR MODELING

When modeling a cluster with a two-dimensional elliptical potential, the first step is to find the center of this potential. Here, the radial image is perfectly aligned toward the center of the cD galaxy, which is only expected for a source falling on an external caustic centered on the cD. Therefore, the center of the potential can be considered to be coincident with the center of the cD. A second parameter for the modeling is the ellipticity of the potential. This parameter could be derived from the distribution of numerous arclets (Kochanek 1990; Miralda-Escudé 1991) or from a high-resolution map of the X-ray emission, but none of these observations are available yet. However, in the R band, the central cD galaxy has a very extended and faint halo as shown in Figure 3: the surface brightness profile of the halo was computed for a distance up to 25″ from the cD brightness peak, down to a level 4.2 mag below the sky level background. Halos of cD galaxies are usually believed to be the result of the merging and stripping interactions of galaxies at the cluster centers (Malumuth & Richstone 1984). When galaxies merge within a more massive elliptical galaxy, faint shells extending far away from the galaxy may be created (Prieur 1988). The shell formation process is understood as a phase-wrapping process, and the shells have the property of tracing the dominant potential (Quinn & Goodmann 1986; Dupraz & Combes 1986). If the extended halo of a central cD comes from the superposition of many shells, it can trace the projected mass density of the "dominant" dark matter. In MS 2137−24, an ellipse was fitted on an R isophote of the halo just beyond the radius of the large arc (Fig. 2 [Pl. L14]). This ellipse appears centered on the cD galaxy (Fig. 2 [Pl. L14]). The ellipticity expressed as the ratio of the minor axis to the major axis is $b/a = 0.8 \pm 0.04$. The position angle of the large axis with the east-west orientation of the CCD line is 29°.5 $\pm$ 4° from East to North.

6. CONCLUSIONS

This *Letter* reports the discovery of the first cluster of galaxies with a possible "radial" gravitational image, as well as a large arc and several arclet candidates. A radial arc 5″ from the center of the cluster could be a direct proof of the existence of a small core radius. All the observations available are presented and will allow a subsequent detailed modeling of the arcs. The orientation of the projected two-dimensional mass density of the faint-R diffuse component at the center of the cluster is also given (Fig. 2 [Pl. L14]), since we suggest it can actually map the invisible mass. A few qualitative observational arguments are in favor of this hypothesis (§ 5). The first modeling of this arc system is being published separately (Mellier, Fort, & Kneib 1992) and supports the radial arc hypothesis and the importance of the faint stellar diffuse component to map the geometry of the potential.

Indeed, this new gravitational lens needs an observational follow-up. The spectroscopic identification of the redshifts of the large and radial arcs is essential. A spectrum of the radial "arc" with high spatial resolution is also desirable to definitely exclude a cooling flow filament.

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