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Discovery of a blue arc near the BL Lacertae object RGB 1745+398*,**

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Abstract. We have made a serendipitous discovery of a blue arclike structure 8″ southeast of RGB 1745+398 (z = 0.267) during deep imaging of X-ray and radio selected BL Lacertae candidates. The spectrum of the arc resembles that of a late-type galaxy with three spectral features ([O II] emission, Mg II absorption and 4000 Å break) that indicate z = 1.057. We interpret the arc as a gravitationally enhanced image of a background galaxy and the observed velocity splitting of the [O II] line (350 km s^{-1}) as due to its rotation, although we cannot rule out the possibility that the source consists of a pair of background galaxies. We find the host galaxy of RGB 1745+398 to be the brightest cluster member (M_R = -24.9) of a moderately massive cluster that most likely provides the lensing mass. From simple considerations we obtain M $\sim 1.3 \times 10^{13}$ $M_\odot$ and M/L_B $\sim$ 60 for the central part (r $< 40\ h_{50}^{-1}$ kpc) of the cluster.

Key words: galaxies: BL Lacertae objects: individual: RGB 1745+398 – galaxies: clusters: general – cosmology: gravitational lensing

1. Introduction

The faint wisps and arcs discovered in galaxy clusters during the last decade have provided a new tool for observational cosmology. Their identification as gravitationally distorted images of faint background galaxies makes it possible to obtain an independent estimate of the mass distribution and mass to light ratio in the cluster by combining deep imaging and modeling of the cluster potential (e.g. Saraniti et al. 1996; Kneib et al. 1996). The foreground cluster also acts like a giant gravitational telescope that magnifies the images of faint background galaxies and thus provides us with an opportunity to study an otherwise unobservable faint galaxy population (e.g. Bézecourt & Soucail 1997; Smail et al. 1996). In fact, the pair of galaxies with one of the highest redshifts known today (z = 4.92) was first identified as a gravitational arc (Franx et al. 1997). The review by Fort & Mellier (1994) lists 47 clusters with detected arcs or arclets, but the redshift of the background system is known in only about a third of them. Selecting X-ray bright clusters seems to be an efficient way to detect arc systems as high X-ray luminosity usually implies a deep potential well (e.g. Luppino et al. 1993). For this reason the optical followup programs of the ROSAT All Sky Survey (RASS) studying X-ray clusters are likely to detect more arc systems in the near future (see e.g. Schindler et al. 1995).

We are currently engaged in a project to study the polarization, optical morphology and environments of the ROSAT - Green Bank (RGB) sample of BL Lacertae objects (Laurent-Muehleisen 1996). This sample has been formed by crosscorrelating the ROSAT All Sky Survey with the Green Bank 5 GHz radio survey to produce an intermediate catalog of 2127 sources (Brinkmann et al. 1995). Of this catalog 171 bright objects were classified spectroscopically and the resulting BL Lacertae objects were combined with previously identified objects to produce a sample of 124 radio and X-ray bright BL Lacertae objects (BL Lacs), of which 38 were previously unknown (Laurent-Muehleisen et al. 1998).

One of the new BL Lacs, RGB 1745+398 (α_{2000} = $17^h45^m37\overset{s}{.}76$, $\delta_{2000} = 39°51'30\overset{''}{.}8$), appears to lie in a highly interesting optical environment (Fig. 1). The radio source is identified with an elliptical galaxy at z = 0.267 (Laurent-Muehleisen et al. 1998). The X-ray source lies within 6″ of the radio source and has a 0.1–2.4 keV flux = 1.6 $\times$ 10^{-12} erg s^{-1} cm^{-2}. About 8″ SE of the galaxy a conspicuous arc that bears a striking resemblance to giant gravitational arcs in some galaxy clusters can be seen (compare e.g. with A370; Soucail et al. 1988). The filamentary structure of the arc

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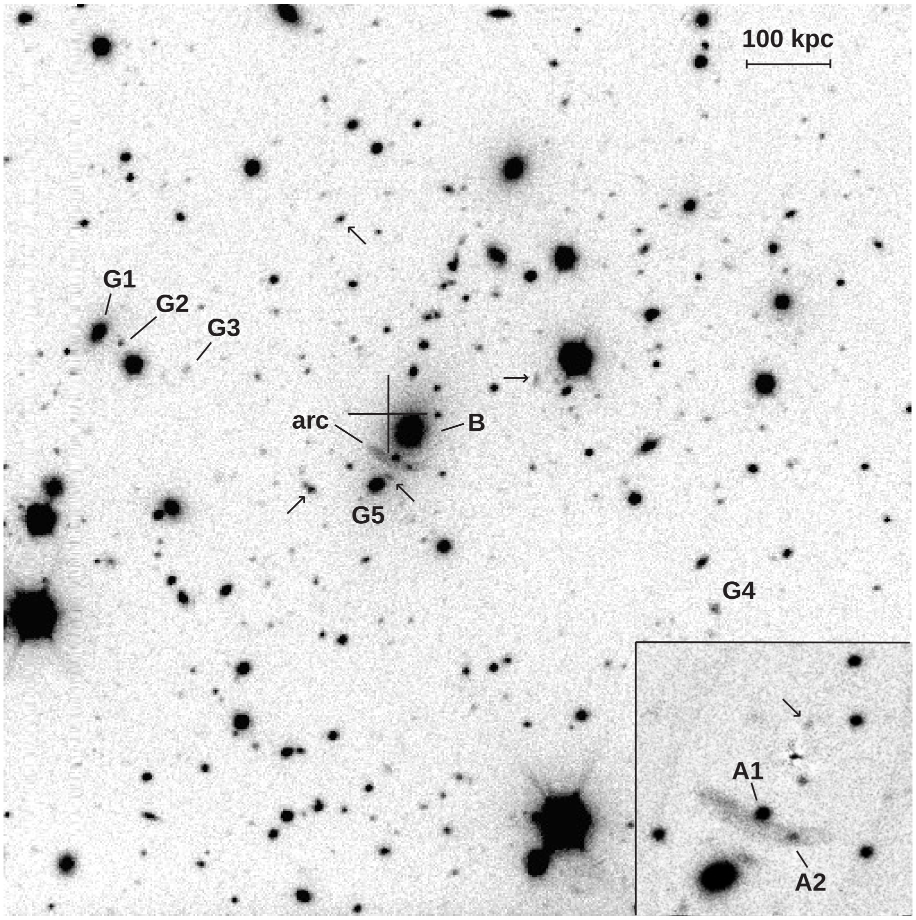

Fig. 1. A 1800 s R-band exposure of RGB 1745+398 obtained at the NOT with 0.″7 seeing. Object B is the brightest cluster galaxy containing the BL Lacertae nucleus. For other objects in the field, see the text. A cross marks the position of the X-ray source, the size of the cross corresponds to the typical positional uncertainty of 18″ (68% level) for ROSAT Survey sources. Small arrows mark the brightest arclet candidates (except for the insert, where it shows a possible counterimage). Field size is 207″ × 209″, north is up and east is to the left. The horizontal bar indicates the linear scale at z = 0.267 in the adopted cosmology. The insert at lower right shows a 15″ × 15″ field around the arc after subtraction of the BL Lac host galaxy and nucleus.

and other arclike structures in the field are further indications of a gravitational lensing phenomenon. Due to this highly interesting possibility we made a more detailed study of RGB 1745+398 and report the results here.

2. Observations

The observations were made at the 2.56 m Nordic Optical Telescope (NOT), La Palma, Canary Islands and at the 2.2m Calar Alto (CA 2.2m) telescope in Spain. At the NOT we obtained BVR_CI_C images with exposure times and field sizes of 1800 s, 1800 s, 1800 s, 600 s and 3.7′, 3.0′, 3.7′, 6.5′, respectively. At the CA 2.2m a wide field (11.5′ × 11.5′) R-band image with a 2100 s exposure time was taken. The observing conditions were photometric during all imaging sessions and seeing varied from subarcsecond (0.6–0.7″ FWHM for B, V and R-band NOT images) to mediocre (∼1.5″ FWHM for the NOT I-band and CA R-band). The direct images were bias-subtracted and flat-fielded with twilight flats in the usual manner and registered and co-added in each filter. Photometric calibration of the field was obtained via standard stars from Landolt (1983, 1992).

A longslit spectrum of the arc was obtained with the ALFOSC instrument at the NOT using grism #5 that covers the spectral range $\lambda\lambda$ 4850–10250 Å with 3.1 Å pix^{-1}. The instrumental resolution with the 1″ slit was 16 Å. The slit was oriented along the arc at PA = 65° and three 3600 s exposures were obtained. The spectra were first bias-subtracted, flat-fielded and corrected for geometric distortion, after which the night sky background was subtracted. The three images were then combined with median and a one-dimensional spectrum was extracted and wavelength-calibrated using calibration lamp exposures. The last reduction steps were to correct the telluric absorption lines and to flux calibrate the spectrum using a spectrophotometric standard star (BD+33°2642).

3. Results and discussion

Fig. 1 shows the surroundings of the arc in the R-band. The arc lies 8″ SE of the BL Lac object and has a length of ∼ 14″ and a width of ∼ 2.5″. It is clearly resolved (the deconvolved width and length are 2.2″ and 14″, respectively), and has a filamentary structure with two compact features, labeled A1 and A2 in Fig. 1. It also shows color changes along its extent, but these may partly be caused by the halos of the two nearby galaxies. The field also contains many arclet candidates, most of which are extremely faint. The brightest candidates have been marked with an arrow in Fig. 1, fainter arclets are visible in the Northern part of the image. From Fig. 1 it would also appear that the host galaxy of RGB 1745+398 is a bright galaxy in a cluster. A closer examination reveals that it is the brightest galaxy even in our wide field image. Our two component fit (nuclear point source + underlying galaxy) implies that this galaxy is an early-

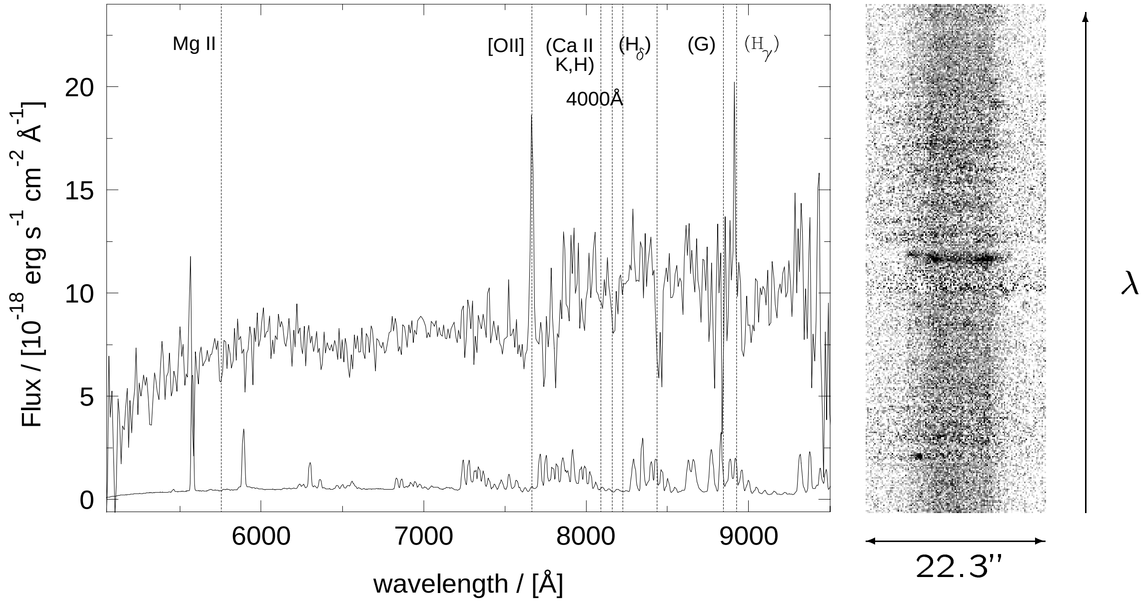

Fig. 2. The spectrum of the arc near RGB 1745+398. The upper part of the *left panel* shows the 1-d spectrum with corresponding night sky spectrum at the lower part. The spectrum has been smoothed by averaging three adjacent pixels. Several spectral features expected at z = 1.057 have been labeled (the undetected features are in parenthesis). The *right panel* shows a portion of the 2-d spectrum from 7120 Å (*bottom*) to 8220 Å (*top*) near the emission line at 7665 Å (the dark band at the center of image). Note the change of redshift at the eastern (*left*) end of the spectrum.

type galaxy with M_R = -24.9, r_e = 27 kpc [1] and $\epsilon = 0.2$. It is thus one of the brightest host galaxies observed in BL Lacs (compare e.g. with Wurtz et al. 1996). From the same fit we obtain M_R = -23.4 for the nuclear point source.

The total magnitude of the arc is difficult to measure because it is embedded in the halos of two nearby galaxies. To overcome this problem we used the ellipse fitting task ELLIPSE in IRAF to model galaxy B and the BL Lac nucleus. After subtracting the resulting model we could obtain a suitably flat background for the arc (see insert of Fig. 1). Table 1 gives the results of the photometry made with a polygonal aperture that includes the arc but excludes A1. The compact feature A1 is redder than rest of the arc and due to its color and morphology we consider it to be a separate object from the arc. There is also a small contribution from G5, but we have incorporated the uncertainty resulting from this contribution to the error estimates. The surface brightness limits were estimated by adding a $3'' \times 3''$ square region with increasing flux to the images and determining the level at which this region became detectable. Due to the relatively subjective nature of this measure, the surface brightness limits in Table 1 have been rounded to the nearest 0.5 mag. The total fluxes have been corrected for galactic extinction assuming A_V = 0.11, which was estimated by searching UGC galaxies within a few degrees from RGB 1745+398 and averaging their extinction estimates from Burstein & Heiles (1982). The scatter in deduced A_V values is very small ($\sim$ 0.01). The arc appears to be fairly blue (B – R = 1.1) compared to the bright galaxies in the field, for which we measure B – R $\sim$ 2.6. The colors of the arc are more similar to those of the faint blue objects in the field (for instance, G3 has B – R = 0.6 and R – I = 0.7).

[1] $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, q_0 = 0.5 is assumed throughout the paper.

Table 1. Photometry of the arc.

	B	V	R	I
Total magnitude	21.6 ± 0.2	21.1 ± 0.1	20.5 ± 0.2	19.6 ± 0.3
Surface brightness[a]	25.5	24.8	24.1	22.9
Surface brightness limit[b]	28.5	27.0	27.5	25.0
Total flux[c]	1.6 ± 0.3	1.4 ± 0.1	1.5 ± 0.3	1.7 ± 0.5

[a] mag/square arcsec, measured at the center of the arc.
[b] See the text.
[c] in $10^{-17}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,Å^{-1}}$

Fig. 2 shows the spectrum obtained by aligning the slit with the arc. The spectrum resembles that of a late type galaxy (Sb-Sc), and it shows three spectral features that allow a fairly secure redshift determination to be made: a conspicuous emission line at λ = 7665 Å (width = 18 Å) that we identify as λ3727 [O II], the λ4000 Å break at $\lambda \sim$ 8000 Å and λ2798 Mg II absorption line at λ = 5754 Å. The two lines yield z = 1.057 for the arc. There are other possible features redwards of 8000 Å (e.g. Ca II K,H), but due to the high number of sky lines and fringing of the detector in this part of the spectrum, we consider them unreliable.

The eastern end of the 7665 Å line seems to have a slightly higher redshift than the rest of the system (see the right panel of Fig. 2). The difference is $\sim$ 9 Å or $\sim 350\,\mathrm{km\,s^{-1}}$, which could correspond to the rotation of the background galaxy. A rotational velocity of $350\,\mathrm{km\,s^{-1}}$ would be quite high, but not unprece-

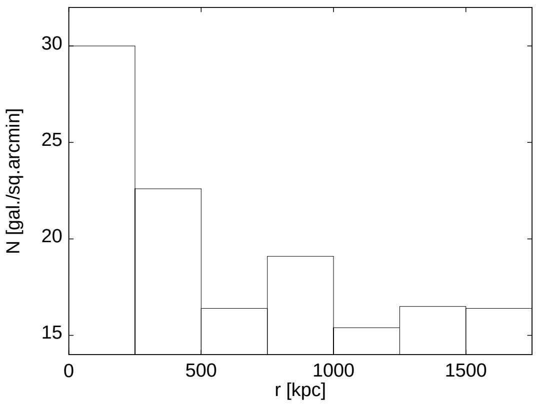

Fig. 3. Galaxy density as a function of distance from RGB1745+398.

dented, for a spiral galaxy of type Sb or Sc (see e.g. Theureau et al. 1997). Another possibility is that we are observing a pair of background galaxies lensed by the foreground system and merged together by seeing.

Giant gravitational arcs are produced by galaxy clusters with deep potential wells that are manifested by X-ray emission from the infalling gas. The RGB 1745+398 field contains a fairly strong X-ray source associated with both the BL Lac object and the cooling flow of the cluster. A first analysis of our pointed HRI data indicates that the BL Lac contributes only about 10% to the X-ray flux in the HRI. The extended emission appears complex with embedded point sources and requires a more detailed analysis (Brinkmann, in preparation). The presence of a cluster is better visible in our optical wide field image (not shown here) obtained at the CA 2.2m telescope and covering 3.5 $\times$ 3.5 Mpc^2 at z = 0.267. We used the FOCAS package to classify the objects into stars and galaxies and counted the number of galaxies brighter than R = 23.5 (the estimated completeness limit from differential counts) in a grid with a cell size of 250 $\times$ 250 kpc^2 (49$''$ $\times$ 49$''$). These counts show an increase in the number of galaxies around RGB 1745+398 with the highest number of galaxies in the central cell containing the AGN. To get an idea of the size of the cluster we counted the galaxies in co-centric annuli with a width of 250 kpc (49$''$) centered on RGB 1745+398 out to a projected distance of 2 Mpc (390$''$). This analysis shows a clear overdensity of galaxies within $\sim$ 1 Mpc (195$''$) from RGB 1745+398 with respect to the region outside this radius (Fig. 3). The galaxy density peaks at the center with 30 galaxies/arcmin^2 and decreases steadily with distance until the $\sim$ 1 Mpc radius, whereafter it remains constant at $\sim$ 16 galaxies/arcmin^2. The galaxy counts thus show that there appears to be a cluster in the field with RGB 1745+398 lying close to the center. This contrasts well with the morphology of the arc and the arclet candidates, that lie perpendicular to a circle centered on RGB 1745+398 or perhaps on a point slightly north of it.

The present data are not deep enough to attempt detailed modeling of the cluster potential. Thus we restrict ourselves to crude estimates only, especially because we do not know 1) the location of the cluster center with sufficient accuracy, 2) if the arc is produced by one or more sources and 3) how the RGB 1745+398 host galaxy and G5 influence the arc morphology. If we make the assumptions that the cluster is centered on RGB 1745+398 and that the arc lies on the Einstein radius of the cluster, we obtain M $\sim 1.3 \times 10^{13}$ $M_\odot$ for the mass enclosed by the arc. The corresponding mass to light ratio M/L_B is $\sim$ 60 (excluding the highly beamed light from the BL Lac nucleus). Both values are within the range observed in galaxy clusters (Fort & Mellier 1994).

We have studied the lensing mass further by modeling it with a softened isothermal potential that is parametrized by the core radius r_c and velocity dispersion σ_v. We assumed that the cluster potential is circular and centered on RGB 1745+398, and used the equations in Schneider & Seitz (1995) and Seitz et al. (1998) to calculate the ellipticity χ induced to an originally circular source. The calculations were done in a two-dimensional grid bound by $0 \leq r_c \leq 50''$ and $0 \leq \sigma_v \leq 1500\,\mathrm{km\,s^{-1}}$. In general, we cannot constrain both r_c and σ_v by considering the ellipticity of a single arc: for every r_c one can always find corresponding σ_v that produces the observed ellipticity χ. The total mass inside the arc, however, *is* well constrained in the models to (0.8–1.7) $\times 10^{13}$ $M_\odot$ for any combination of r_c and σ_v with $\chi > 0.88$. From our deconvolved R-band image we measure the axial ratio a/b of the arc to be $\sim$ 6. Allowing for some error in a/b, e.g. $4 \leq a/b \leq 8$, we are thus confined in the part of r_c - σ_v space for which $0.88 \leq \chi \leq 0.97$. We narrow the allowed region further by assuming that the arc lies close to the Einstein radius of the cluster, i.e. $\theta_\mathrm{E} \sim 8''$, which is equivalent to assuming σ_v $\sim 660\,\mathrm{km\,s^{-1}}$. With this σ_v the core radius is confined to $3\farcs5 \leq r_c \leq 5\farcs5$ (18 kpc $\leq r_c \leq$ 28 kpc) and corresponding flux magnification to $14 \geq \mu \geq 8$. Note that with these values the cluster is subcritical, i.e. we do not expect to see multiple images of the background source. There is a faint object $3\farcs8$ from RGB 1745+398 and on the opposite side of the arc (arrowed in the insert of Fig. 1), that could represent a weak counterimage, but due to its faintness we do not have a spectrum or color for it and thus its nature remains unclear.

The magnification range indicates that the background galaxy must be fairly bright, $-23.0 \leq M_\mathrm{R} \leq -22.4$ (assuming K-correction $\sim$ 1.3 for Sbc type from Fukugita et al. 1995). From the average rotational velocity (v_r) - absolute magnitude relation for spiral galaxies (Theureau et al. 1997) we would expect its total luminosity to be $\sim$ 1 mag brighter than this if the observed velocity difference $350\,\mathrm{km\,s^{-1}}$ really corresponds to rotation. Given the overall uncertainty of our assumptions and the large scatter in the (v_r - M) -relation this difference may not be significant. In any case, it is clear that due to the large amount of assumptions the above discussion should be regarded only as an attempt to find a self-consistent solution and not a rigorous determination of cluster parameters.

The fact that we see a BL Lac lying in a cluster is not a new discovery. The cluster environment of BL Lacs has been studied by e.g. Wurtz et al. (1993, 1997), who found that the BL Lacs in their sample (mostly low redshift objects) were found in relatively poor clusters with Abell richness class < 0. What makes RGB 1745+398 interesting is that for the first time it is

Table 2. Spectroscopy of the arc and nearby objects

object	line	λ_{obs} (Å)	z
arc	λ2798 Mg II	5754	1.056
	λ3727 [O II]	7665	1.057
G1	λ4300 CH	5443	0.266
	λ5175 Mg b	6549	0.266
	λ5893 Na D	7459	0.266
G3	λ3727 [O II]?	7671	1.058?
G4	λ4861 H_β	5894	0.212
	λ4959 [O III]	6012	0.212
	λ5007 [O III]	6069	0.212
	λ6563 H_α	7954	0.212

possible to determine the mass and M/L of a cluster containing a BL Lac via gravitational lensing. If more such lensed systems could be identified at different redshifts, one would be able to study the evolution of gas density with epoch in manner independent from other indicators such as X-ray luminosity (which is hard to do anyway due to the presence of nonthermal X-ray emission in these objects). This would enable a comparison of evolution rates between the cluster environments of BL Lacs and other types of AGN (see e.g. Ellingson et al. 1991), which has direct relevance to the question of the "parent population" of BL Lacs. It remains to be seen, however, if sufficient number of similar systems can be identified from the rather sparse collection of known BL Lacs.

We finally mention the spectra of four additional objects in the field that were obtained simultaneously with the arc spectrum (objects G1-G4 in Fig. 1). Table 2 summarizes their line identifications and redshifts. Galaxy G1 is a member of the foreground cluster and G3 is likely to be part of the same background system as the arc. Galaxy G4 lies in the foreground of the z=0.267 cluster. No lines were seen in the spectrum of object G2. The presence of at least three redshift systems is thus indicated and a further spectroscopic study would be most desirable. This would also enable us to improve the modeling by measuring the cluster velocity dispersion.

4. Summary

We have presented images and spectra of a blue arc near the BL Lac object RGB 1745+398. In our data we find all the elements usually present in giant arc systems: a blue filamentary arc lying close to a bright galaxy that appears to be located in the center of a moderately massive galaxy cluster. Furthermore, the spectrum of the arc is consistent with a late-type galaxy at z = 1.057, which places it behind RGB 1745+398 and its associated cluster a z = 0.267. These redshifts are fairly typical for giant arc systems (Fort & Mellier 1994). Taking all the evidence together we conclude that we have very likely observed the first case of a gravitational arc near a BL Lac object.

Assuming that the arc lies on the Einstein ring of the cluster we obtain M $\sim 1.3 \times 10^{13}$ $M_\odot$ and $M/L_B \sim 60$ for the central part (r $< 40\, h_{50}^{-1}$ kpc) of the cluster. With the same assumption we also find the core radius of the cluster to be $\sim$ (20–30) h_{50}^{-1} kpc by studying simple models. The latter estimate, however, depends on several assumptions that need to be tested using deeper images and a measurement of the cluster velocity dispersion. With improved modeling one could also determine if the velocity gradient of 350 km s^{-1} we observe in the z = 1.057 [O II] line really corresponds to the rotation of a single galaxy or to a velocity difference between two interacting galaxies.

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