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Letter to the Editor

A ring galaxy at $z = 1$ lensed by the cluster Abell 370[*]

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Abstract. We present a study of a very peculiar object found in the field of the cluster-lens Abell 370. This object displays, in *HST* imaging, a spectacular morphology comparable to nearby ring-galaxies. From spectroscopic observations at the CFHT, we measured a redshift of $z = 1.062$ based on the identification of [OII] 3727Å and [NeV] 3426Å emission lines. These emission lines are typical of starburst galaxies hosting a central active nucleus and are in good agreement with the assumption that this object is a ring galaxy. This object is also detected with *ISO* in the LW2 and LW3 filters, and the mid Infra-Red (MIR) flux ratio favors a Seyfert 1 type. The shape of the ring is gravitationally distorted by the cluster-lens, and in particular by a nearby cluster elliptical galaxy. Using our cluster mass model, we can compute its intrinsic shape. Requiring that the outer ring follows an ellipse we constrain the M/L ratio of the nearby galaxy and derive a magnification factor of 2.5 ± 0.2. The absolute luminosities of the source are then $L_B = 1.3\ 10^{12} L_{B\odot}$ and ν $L_\nu \simeq 4.10^{10}$ L$_\odot$ in the mid-IR.

Key words: galaxies: individual: LRG J0239–0134 – galaxies: evolution – galaxies: interactions – galaxies: Seyfert – cosmology: observations – cosmology: gravitational lensing

1. Introduction

A useful property of gravitational lensing is the magnification of background objects: the gain in spatial resolution allows the morphological properties of distant and resolved objects to be probed in greater detail and the gain in apparent flux allows fainter sources than would otherwise either be detected or studied to be probed statistically. Massive clusters of galaxies can then be used as natural "gravitational telescopes" to address sev-

eral astrophysical problems related to the properties and nature of high redshift galaxies. Morphological properties of distant lensed sources were first addressed by Smail et al. (1996) who estimated the intrinsic linear sizes of the galaxies and showed them to be compatible with a significant size evolution with redshift. More recently, several detailed morphological analysis of high-z arcs were proposed using lens modeling. Most of them appear knotty with a more complex morphology than their local counterparts (Colley et al. 1996; Franx et al. 1997; Pelló et al. 1999) although there may be some biases due to observations in the UV restframe.

In this letter, we study a peculiar object detected in the field of the galaxy cluster A370. On the *HST*/*WFPC2* images, it displays an unusual morphology similar to nearby ring-galaxies, although gravitationally distorted by the cluster. Sect. 2 summarises the various observations relating to this source: *HST* imaging, spectroscopic and photometric data including mid-IR photometry obtained with ESA's *ISO* spacecraft (Kessler et al. 1996). The source reconstruction of the ring and a morphological analysis is presented in Sect. 3 with a robust estimate of the lens amplification. Sect. 4 discusses the spectral energy distribution (SED) of the object. Discussion and conclusions are given in the last section.

Throughout the paper, we consider a Hubble constant of H$_0 = 50\ h_{50}$ km s^{-1} Mpc^{-1}, with $\Lambda = 0$ and $\Omega = 1$.

2. Observations

2.1. HST imaging

In the deep F675W *WFPC2* image described in Bézecourt et al. (1999a, hereafter Paper I), a spectacular distorted ring is detected close to a bright cluster elliptical (#32 in the numbering scheme of Mellier et al. (1988) with $z = 0.370$). The object displays a clearly resolved central bulge surrounded by a ~4.8″-diameter distorted ring and a secondary 1.5″-diameter inner ring (Fig. 1). This object is very similar in aspect to the Cartwheel galaxy (Struck et al. 1996), with similar ratio between the two ring radii. We used the APM catalogue to measure the astrometry of the field. The absolute coordinates of the lensed ring galaxy are: $\alpha_{J2000} = $ 2h 39m 56.51s, $\delta_{J2000} = -1°$ 34′ 25.66″
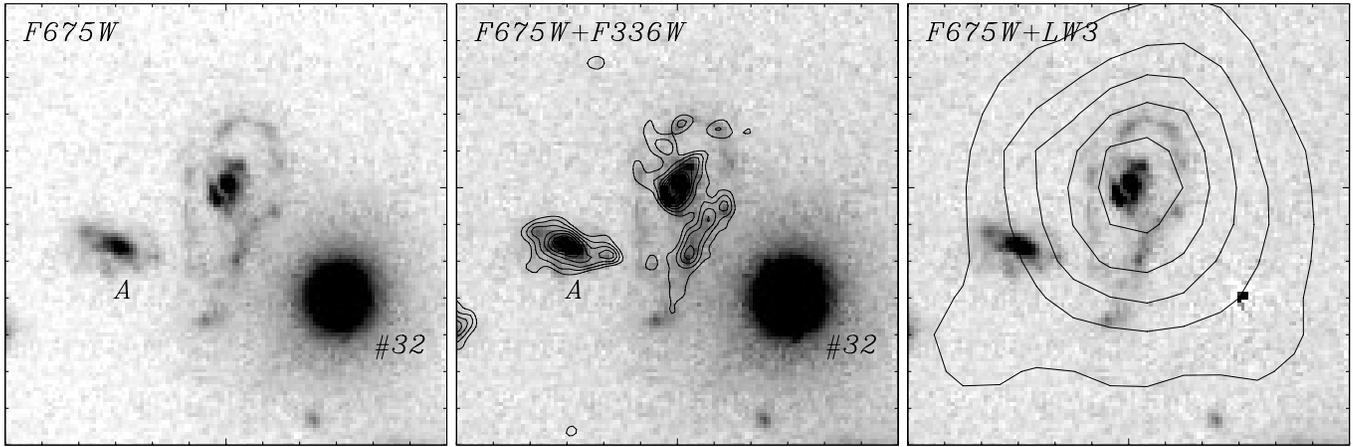

Fig. 1. Multi-colour images of the ring galaxy and its surroundings: *Left: HSTWFPC2* F675W image (with a $12''$ size) – *Center:* isocontours of the *HST* F336W (U-band) image overplotted on the F675W image – *Right: ISO* LW3 contours overplotted on the F675W image. Galaxy # 32 has been subtracted for clarity. Note the accurate matching of the *ISO* source with the nucleus. North is top, East is left.

(with a $0.2''$ rms accuracy). Therefore we reference hereafter this object as: LRG J0239–0134.

A photometric analysis was performed on the F675W *HST* image. First, the nearby galaxy # 32 was subtracted after a radial fit of the isophotes with the "ELLIPSE" package in the IRAF/STSDAS environment. The total integrated flux for LRG J0239–0134 gives a magnitude $R_{675W} = 20.7 \pm 0.1$ that can be separated into the emission of the central part $R_{675W} = 21.5 \pm 0.1$ and the outer ring contribution $R_{675W} = 21.4 \pm 0.2$ (less accurate due to larger uncertainties in the local sky background). In the *HST/WFPC2* U-Band image (see Bézecourt et al. 1999b) the ring-like object is also detected and appears less centrally concentrated than in F675W. However the lower signal-to-noise prevents a detailed morphological analysis of the extended emission (Fig. 1) although there may be some inhomogeneities in the ring due to hot spots similar to that seen in the Cartwheel.

2.2. Spectroscopic and photometric observations

Spectroscopic data were obtained during a CFHT run with the OSIS-V instrument (Le Fèvre et al. 1994) in August 1997. A $1''$-wide long-slit was positioned through the central bulge and the ring (slit orientation was East-West limiting the contamination by the envelope of galaxy #32). We used the 2K×2K Loral thinned CCD and the grism R150 which gives a dispersion of 6Å/pixel, with a resolution of 18Å across the wavelength range 5000 to 9000Å. Two 1.8 ksec exposures were obtained just before morning twilight. The data were reduced with standard procedures for flat-fielding, wavelength and flux calibration. Sky subtraction was performed on the 2D image (Fig. 2). Several features are detected: a strong emission line at $\lambda = 7685 \pm 3$Å, a weaker one at $\lambda = 7064 \pm 9$Å and an absorption line at $\lambda = 5773 \pm 3$Å, all visible on the 2D spectrum. We unambiguously identify those lines as: [OII] 3727Å ,[NeV] 3426Å and MgII 2800Å giving a redshift of $z = 1.062 \pm 0.001$ for the source. Moreover, a tentative identification at this redshift
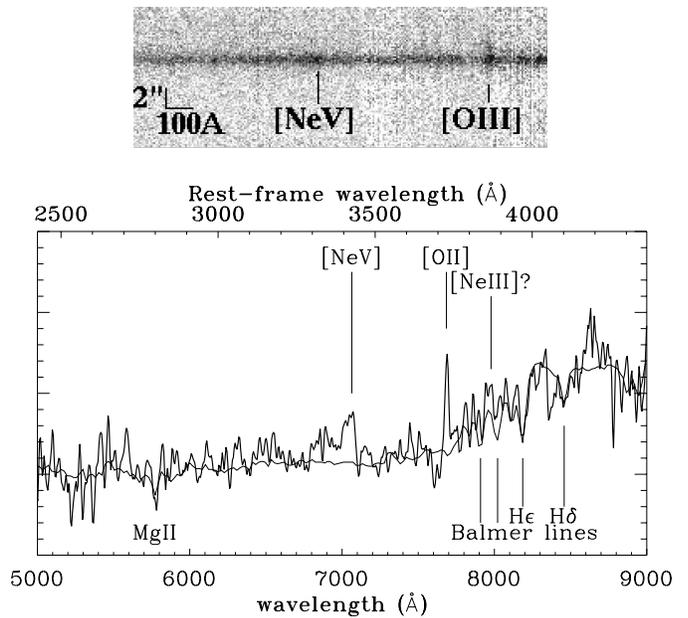
Fig. 2. The spectrum of the ring galaxy superimposed on a synthetic spectrum of a late-type spiral redshifted to $z = 1.062$. The data were smoothed to fit the resolution of the spectrograph and the most prominent lines are identified. Above is the original 2D spectrum after sky subtraction, showing in particular the spatial extent of the emission line at 7685Å.

suggests weak emission from the [NeIII] 3869Å line though the spectrum is contaminated by sky residuals and Hδ and Hε absorption lines. Redder lines fall outside the visible range and unluckily, Hα lies at 1.353μm, a wavelength domain hardly detectable from the ground (outside the J-band). Furthermore, the fit of the continuum with a typical late-type spiral galaxy is satisfactory. Finally, the [OII] line is more spatially extended than the underlying stellar continuum, and a contribution from the ring itself is likely, which is not the case for the [NeV] line. Un-

Table 1. Multi-wavelength fluxes of the ring galaxy (see text for more details). These fluxes are not corrected for the gravitational magnification of the source.

Filter	λ (μm)	Magnitude	Flux (μJy)	Resolution
U_{336W}	0.336	21.00 ±0.2	4.45 ± 0.9	0.1 ″
B_j	0.450	21.81 ±0.2	6.36 ± 1.2	1.1 ″
R	0.646	20.38 ±0.4	21.3 ± 9.4	1.1 ″
R_{675W}	0.673	20.66 ±0.1	15.8 ± 1.5	0.1 ″
I	0.813	19.31 ±0.2	45 ± 9	0.7 ″
J	1.237	17.82 ±0.2	118 ± 24	1.2 ″
K'	2.103	16.34 ±0.2	212 ± 42	1.2 ″
LW2	6.7		750 ± 225	6 ″
LW3	14.3		1800 ± 540	6 ″

fortunately, no information on any velocity field can be provided with this low S/N ratio spectrum.

Multi-band photometry of this galaxy is available from a large set of data existing on the cluster Abell 370. In addition to the *HST* U and R images, we used B, R and I magnitudes from deep CFHT images (Kneib et al. 1994). Near-IR data were obtained with the Redeye camera at CFHT in August 1994. The final near-IR images correspond to deep exposures with integration times of 3.4 ksec in J and 7.2 ksec in K′ in good observing conditions. The details of this photometric setup will be published elsewhere. The photometry of the ring galaxy is summarised in Table 1. From this multi-band photometry, a photometric redshift of 0.95 ± 0.1 was found (R. Pelló, private communication) confirming the spectroscopic identification through a fit to the continuum shape. In addition, the fainter object close to the ring (labelled A in Fig. 1) has a photometric redshift $z_{phot} = 0.4 \pm 0.1$ and is therefore not related to the ring galaxy.

2.3. ISO data

The ring galaxy was detected with the *ISO* camera (*ISOCAM*, Césarsky et al., 1996), as part of a programme of imaging through gravitational lensing clusters (Metcalfe et al. 1999). A370 was deeply imaged on a wide $7' \times 7'$ field, in microscanning mode, with the $3''$ pixel-field-of-view, and using two broad-band, high-sensitivity filters: LW2 (5–8.5μm) and LW3 (12–18μm) with a total exposure time of 16.1 ksec in the deepest part of the image. The data were reduced following two substantially independent methods: a Multi-resolution Median Transform method (PRETI, Starck et al. 1998), and the Vilspa method described in Altieri et al. (1998). The centering of *ISO* maps on optical data was obtained by correlating the positions of 7 sources, giving a final astrometric accuracy of $1''$. The correspondance between the ring galaxy and the *ISO* source is quite secure (Fig. 1). The photometric accuracy achievable for such faint mid-IR sources, allowing for all the uncertainties in the data reduction, is around 30%. In both *ISO* bandpasses, the ring galaxy is the brightest extragalactic source in the field covered by *ISOCAM*, apart from the giant arc.
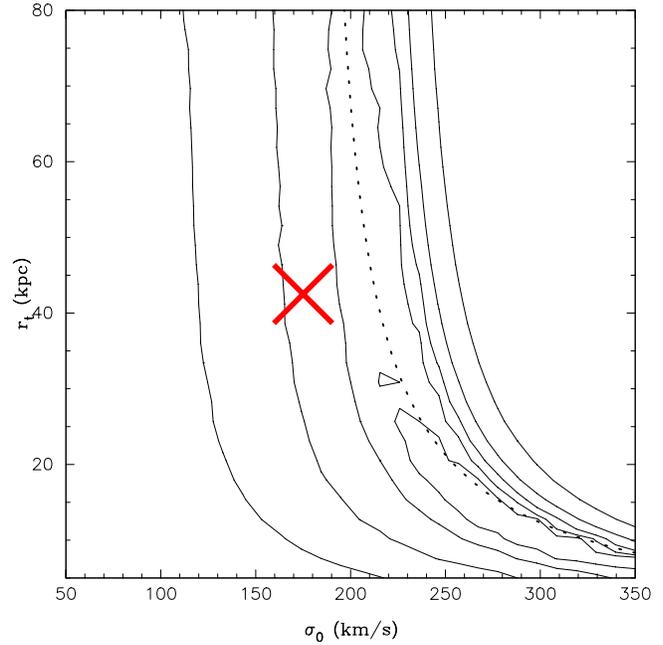
Fig. 3. Contour plot of the estimator E for the galaxy #32 when fitting the outer ring to be projected as an ellipse in the source plane. The dotted line correponds to models with constant M($< a_{32}$)/L.

3. Source reconstruction of the lensed ring galaxy

This ring galaxy is magnified and distorted by the gravitational shear induced by the cluster and the nearby elliptical cluster galaxy #32. This is particularly visible in the distorted shape of the outer ring. In order to reconstruct its true intrinsic size, shape and determine its total amplification, we traced the rays back through the lens into the source plane, using the model proposed in Paper I. This model was optimised from the identification of several multiple images detected on the *HST* images and takes into account the massive halos of the brightest galaxies using standard scaling laws (e.g. Kneib et al. 1996) related to their luminosities with scaling dependance similar to the properties of the Fundamental Plane:

$$\sigma_0 = \sigma_{0*} \left(\frac{L}{L_*} \right)^{\frac{1}{4}} ; \quad r_t = r_{t*} \left(\frac{L}{L_*} \right)^{0.8} ; \quad r_0 = r_{0*} \left(\frac{L}{L_*} \right)^{\frac{1}{2}} .$$

In particular for the elliptical galaxy #32 ($R_{675W} = 18.47$) this means that $L_R = 2.2 \, 10^{11} \, h_{50}^{-2} \, L_\odot$ which translates to $\sigma_0 = 173$ km/s, $r_t = 42.5 \, h_{50}^{-1}$ kpc (or $6.8''$ at the cluster redshift) and a total M/L ratio of 6.4 h_{50} (M/L)$_\odot$ for this galaxy and its halo. Within the aperture $a_{32} = 26.8 \, h_{50}^{-1}$ kpc defined by the distance from #32 to the ring galaxy nucleus we have M($< a_{32}$)/L = 5.7 h_{50} (M/L)$_\odot$.

We then examined the influence of the parameters (σ_0, r_t) in the source reconstruction. In order to quantify this we identified in the image plane 20 points (x_i, y_i) describing the outer ring. We then tuned the two parameters (σ_0, r_t) to check how close to an ellipse the corresponding source points (xs_i, ys_i) are. For this purpose we defined the following estimator:

$$E(\sigma_0, r_t) = \frac{1}{N} \Sigma_{i=1}^N |f_{\sigma_0, r_t}(i)|$$

with

$$f_{\sigma_0, r_t}(i) = \frac{[(xs_i - x_c)\cos\theta - (ys_i - y_c)\cos\theta]^2}{a^2}$$
$$+ \frac{[(xs_i - x_c)\sin\theta + (ys_i - y_c)\sin\theta]^2}{b^2} - 1$$

where (x_c, y_c, a, b, θ) are the parameters of the ellipse that minimise, for each set of (σ_0, r_t), the estimator E. For a set of points belonging to an ellipse, E is zero. Furthermore, by definition, E is scale-invariant and does not depend on the intrinsic size of the ring. Fig. 4 shows iso-contours of the estimator $E(\sigma_0, r_t)$. The original point of the model of paper I is indicated as a cross. Not surprisingly, the shape of the ring does depend strongly on the M/L ratio within the aperture a_{32}. Fixing r_t=42.5 h_{50}^{-1}kpc, the best value for the velocity dispersion is $\sigma_0 = 220 \pm 20$ km/s, which corresponds to a correction factor of 1.4 for the aperture mass leading to $M(< a_{32})/L = 8.0 \pm 1.5$ (M/L)$_\odot$.

The magnification factor of the source has a mean value of 2.5±0.2 but ranges from 3.6 to 2.1 depending on the distance to galaxy #32 (Fig. 4). The intrinsic radius for the outer ring found is $7.7 \pm 0.4\, h_{50}^{-1}$ kpc, a value comparable with the characteristics of nearby similar objects. The axis ratio of the ellipse is $\cos i = b/a = 0.76$ that translates in a inclination angle of $i =40$ degree assuming an intrinsic circular ring. The B-band absolute luminosity of the source, corrected from the magnification and measured directly from the I magnitude, is $L_B = 1.3\,10^{12} L_{B\odot}$, about 10 times brighter than the Cartwheel galaxy (Appleton & Marston 1997).

4. Spectral Energy Distribution

Joining together all the multi-wavelength photometric measurements, we can construct the SED of the ring galaxy over a large wavelength range (Fig. 5). This range covers both the rest-frame stellar emission and the IR flux emitted by the warm component of the interstellar medium. The significant excess of light emitted in the mid-IR with respect to the stellar contribution can originate from three possible sources: either a central active nucleus heats the dust torus around it, or the warm dust is heated by a violent starburst induced by the merger that produced the ring, or we are witnessing a combination of the two phenomena. A strong argument in favour of an active nucleus is the detection in the optical spectrum of the [NeV] emission line typical of Seyfert galaxies. Moreover, the bulk of the optical emission is clearly stellar, with Balmer absorption lines and a typical stellar continuum. This suggests that a starburst is occurring and may dominate the optical light. For this target in the mid-IR it is difficult to differentiate between the contribution from the nuclear emission and that from the starburst (see the discussion of the Cartwheel galaxy in Charmandaris et al. 1998). The flux ratio LW3/LW2 is about 2.4, or equivalently the spectral index is about -1.15 for LRG J0239–1034. Taking into account the fact that we observe the rest-frame fluxes at 3.3μm and 7μm, this can be compared easily with the mid-IR spectra shown by Schultz et al. (1998) for different types of AGN. Our results clearly favour a Seyfert 1 type, in accordance with the weak detection of the [NeV] emission line in the optical spectrum.
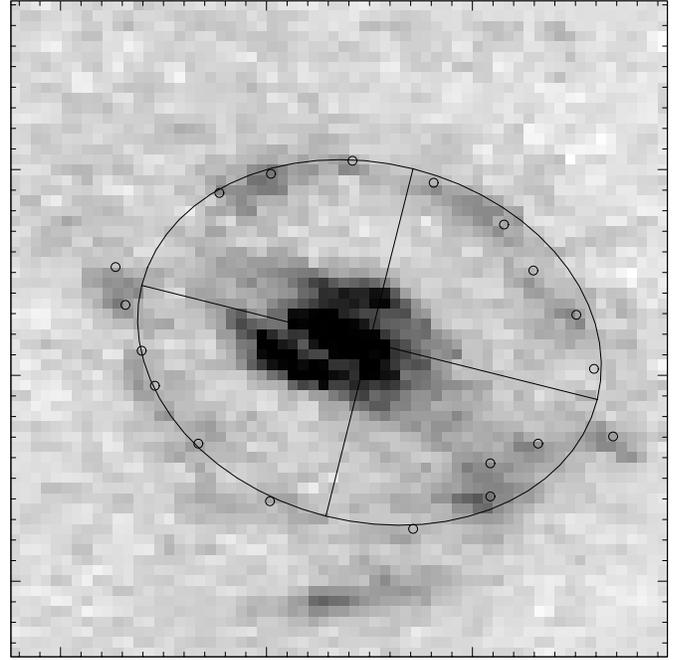
Fig. 4. Image-reconstruction of the ring galaxy in the source plane using the best fit model parameters. The bottom part of the ring was not included in the fitting. This reconstruction suggests that this object does not belong to the outer ring.
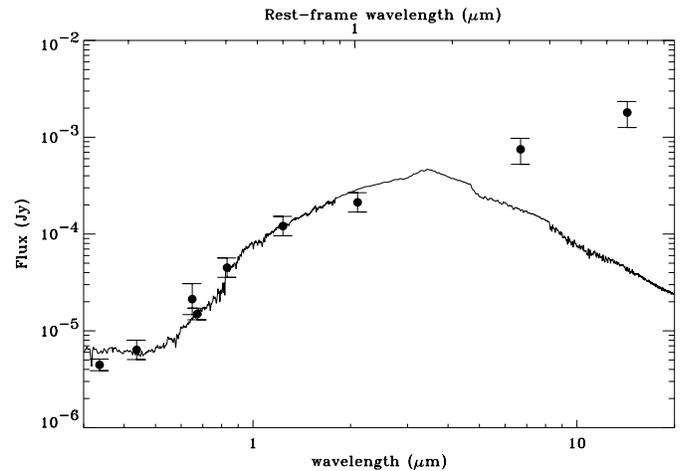
Fig. 5. The spectral energy distribution of the ring galaxy. The data correspond to the observed photometry from 0.3 μm to 15 μm. The curve shows the synthetic SED of an Sc galaxy from Fioc and Rocca-Volmerange (1996). The mid-IR excess is clearly non-stellar.

5. Discussion

In this letter we analyse in details the nature of a peculiar galaxy based on multiwavelength observations. Firstly, the outer ring of the galaxy constitutes good morphological evidence for a starburst induced by a recent gravitational interaction, although the progenitor is not yet identified. The presence of an extended [OII] 3727Å emission line in the 2D spectrum demonstrates the occurrence of star formation in the ring. In addition, the galaxy hosts an active nucleus in its centre, probably triggered by the

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interaction, as shown both by the detection of the [NeV] line in the optical and by the properties of the mid-IR fluxes. This ring galaxy also corresponds to the source L3 detected in the sub-millimeter domain with SCUBA by Smail et al. (1998). This shows that emission arises from cold dust in the source, but without adequate spatial information no conclusion can be drawn about the preferred location of this cold dust (in the ring or nucleus). We can also compute its intrinsic mid-IR luminosity, after correction for both the gravitational magnification and a k-correction estimated from a power-law fit to the spectrum. This gives $F(3.3\mu m) = 1.7\,10^{23}$ W/Hz and $F(7\mu m) = 3.7\,10^{23}$ W/Hz, or equivalently in solar luminosity: $\nu\,L_\nu \simeq 4.10^{10}$ L$_\odot$. In comparison, the total mid-IR luminosity of the Cartwheel at similar wavelengths is only $\nu\,L_\nu \simeq 2.10^8$ L$_\odot$. The difference in luminosity comes most probably by the nucleus emission, relatively weak in the Cartwheel. LRG J0239–0134 belongs more specifically to the sample of high redshift galaxies for which the mid-IR and sub-mm fluxes emissions are powered by a strong and obscured active nucleus (Ivison et al. 1998), possibly triggered by galaxy interactions.

In conclusion, we have shown in this letter that gravitational magnification can be used to give a detailed analysis of the nature of a few peculiar distant galaxies. Clearly cluster-lenses are and will be useful in the future to observe and study the nature of the most distant galaxies in a wide domain of wavelengths and emission processes.

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