Abell 370 revisited: refurbished *Hubble* imaging of the first strong lensing cluster

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**ABSTRACT**

We present a strong lensing analysis of the galaxy cluster Abell 370 \((z = 0.375)\) based on the recent multicolour images by Advanced Camera for Surveys obtained as part of the Early Release Observation (ERO) that followed the Hubble Service Mission #4. Back in 1987, the giant gravitational arc \((z = 0.725)\) in Abell 370 was one of the first pieces of evidence that massive clusters are dense enough to act as strong gravitational lenses. The new observations reveal in detail its disclike morphology, and we show that it can be interpreted as a complex five-image configuration, with a total magnification factor of 32 \(\pm 4\). Moreover, the high-resolution multicolour information allowed us to identify 10 multiply imaged background galaxies. We derive a mean Einstein radius of \(\theta_E = 39 \pm 2\) arcsec for a source redshift at \(z = 2\), corresponding to a mass of \(M(<\theta_E) = 2.82 \pm 0.15 \times 10^{14} \text{M}_\odot\) and \(M(<250 \text{ kpc}) = 3.8 \pm 0.2 \times 10^{14} \text{M}_\odot\), in good agreement with Subaru weak-lensing measurements. The typical mass model error is smaller than 5 per cent, a factor of 3 of improvement compared to the previous lensing analysis. Abell 370 mass distribution is confirmed to be bimodal with very small offset between the dark matter, the X-ray gas and the stellar mass. Combining this information with the velocity distribution reveals that Abell 370 is likely the merging of two equally massive clusters along the line of sight, explaining the very high-mass density necessary to efficiently produce strong lensing. These new observations stress the importance of multicolour imaging for the identification of multiple images which is key to determining an accurate mass model. The very large Einstein radius makes Abell 370 one of the best clusters to search for high-redshift galaxies through strong magnification in the central region.

**Key words:** gravitational lensing – galaxies: clusters: general – galaxies: clusters: individual (A370).

1 INTRODUCTION

The discovery of the ‘giant luminous arcs’ in rich clusters of galaxies in the mid 1980s (Lynds & Petrosian 1986; Soucail et al. 1987) has opened a new window in research in cosmology: gravitational lensing. This simple geometric tool allows to map out dark matter in the Universe on various angular scales. The strong lensing regime occurs in the densest part of galaxies and massive clusters. When a background source is straddling one or more caustic lines, giant luminous arcs can be produced. The identification of multiple images has remained difficult until deep multicolour space-based imaging has become routinely possible. This has been effectively the case with the installation of the Advanced Camera for Surveys (ACS) aboard *Hubble Space Telescope* (HST) in 2002 March. ACS observations of lensing clusters have led to many discoveries of tens of multiple images (A1689: Broadhurst et al. 2005, Limousin et al. 2007; A1703: Limousin et al. 2008, Richard et al. 2009a; RXJ1347: Bradac et al. 2008a; the bullet cluster: Bradac et al. 2006; A2218: Elsdaleottir et al. 2007; C0024+1654: Zitrin et al. 2009b; MS1358: Swinbank et al. 2009; MACS clusters: Limousin et al. 2009; Zitrin & Broadhurst 2009; Smith et al. 2009). These discoveries have fostered the development of new mass modelling techniques (e.g. Jullo et al. 2007; Coe et al. 2008; Jullo & Kneib 2009) that take advantage of the numerous constraints coming from these many multiple images. The accuracy of the best mass model is now approaching the percent level allowing: (i) the use of massive clusters lenses as probes of cosmography – hence, putting strong geometrical constraints on the cosmological model (Golse & Kneib 2002; Soucail, Kneib & Golse 2004; Jullo & Kneib 2009), (ii) recovering the intrinsic shape of lensed galaxies (Swinbank et al. 2009) and

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(iii) accurate correction of the magnification and dilution effect of massive clusters to constrain the luminosity function of distant galaxies (e.g. Richard et al. 2008; Bouwens et al. 2009).

The ACS failure in 2007 January has stopped the observation and detailed analysis of further massive clusters. The recent recovery of the ACS camera last 2009 May now brings new opportunities to further investigate massive cluster lenses. We present in this letter a strong lensing analysis of the multicolour cluster observations obtained on Abell 370 as part of the Early Release Observation (ERO) validating the performance of the repaired ACS instrument (Section 2). The identification of 10 multiply imaged background galaxies (hereafter called systems of multiple images) totalling 32 images and the lens modelling are presented in Section 3. The results on the nature of the giant arc and the mass distribution and substructure are presented in Section 4.

Throughout the paper, we use magnitudes quoted in the AB system, and a standard Λ CDM dark matter model with Ω_m = 0.3, Ω_Λ = 0.7 and H_0 = 70 km s^{-1} Mpc^{-1}, whenever necessary. 1 arcsec on the sky is equivalent to a physical distance of 5.16 kpc at the redshift z = 0.375 of the galaxy cluster.

2 OBSERVATIONS AND DATA REDUCTION

The (HST)/ACS observations were obtained in 2009 July (PID 11507, PI: Noll), for a total of 6780/2040/3840 s in the F475W/F625W/F814W bands, respectively. We make use of the images provided by STScI, reduced using the package MULTIDRIZZLE, and we measure AB depths (3σ) of 28.39/27.41/27.84 for a point source. The astrometry of these images was checked using the USNO optical catalogues.

We performed a visual inspection of the images to search for multiply lensed background galaxies. We made use of previous strong-lensing work by Kneib (1993), Smail et al. (1996) and Bézecourt et al. (1999) to guide our multiple image identification. Compared to the single Wide Field Planetary Camera 2 observations in F625W, the new multicolour ACS data is deeper and has higher resolution. We identify 10 secure systems of images, including six new confirmed systems compared to previous lensing analyses (e.g. Abdelsalam, Saha & Williams 1998), which we present in Fig. 1 and Table 1. We confirm that all these images are genuine by reproducing their positions and shape using the constructed lens model (Section 3) and by checking that their ACS colours agree within the 1σ error bar (Table 1). We use the notation α · β to design image β of system α. Two of these systems (1 and 2) have spectroscopic redshifts published by Soucail et al. (1988) and Kneib et al. (1993). Seven systems (all except 2, 7 and 10) are tangential systems of three images, while systems 7 and 10 are two radial arcs. We identify five images in total for system 7, but system 10 has a much lower surface brightness, and we can not identify its counter images securely. System 2 is the giant arc first identified by Soucail et al. (1987), and it is a lensed image of a spiral galaxy. Thanks to the new multicolour images, we identify five images of the central red bulge, while individual star-forming regions are recognized as triple images with blue colours (Fig. 1).

An 88 ks Chandra ACIS observation was obtained in 1999 October as part of the program PID 525 (PI: Garmire). We used the adaptively smoothing algorithm COSMOTH in the CIAO package (Ebeling, White & Rangarajan 2006) on the events file with a maximum scale of 15 arcsec. The astrometry of the X-ray data was checked using two bright isolated X-ray point sources located in the ACS image, and is better than 0.5 arcsec.

3 STRONG-LENSING ANALYSIS

We have used Lenstool1 (Kneib 1993; Jullo et al. 2007) to perform a mass reconstruction of the cluster, assuming a parametric model for the distribution of dark matter. This model was constrained using the location of all multiple images identified. This technique builds on the work done in Kneib et al. (1996), Smith et al. (2005) and Richard et al. (2009b), by describing the cluster mass distribution with a superposition of analytic mass components to account for both cluster- and galaxy-scale mass. For each component, we use a dual pseudo-isothermal mass distribution (dPIE, also known as a truncated PIEMD, Eifardt et al. 2007). The dPIE profile is characterized by its central position (α, δ), position angle (θ), ellipticity (e), fiducial velocity dispersion σ_0 and two characteristic radii: a core radius r_{core} and a cut-off radius r_{cut}. Galaxy-scale mass components are added at the location of galaxies colour-selected from the cluster red sequence. In order to limit the number of free parameters, the velocity dispersion, cut-off radius and core radius are scaled to the galaxy luminosity L_g, relative to the luminosity of a L^{*} galaxy (see Jullo et al. 2007, for details). We fix r_{core} = 0.15 kpc and r_{cut} = 45 kpc to prevent degeneracies between the different parameters (see also Limousin et al. 2007 and Richard et al. 2009b for a discussion of these parameters). We kept σ_0 as a free parameter. Finally, the unknown redshifts of systems 3 to 9 are kept as free parameters. The faint surface brightness of the northern radial arc (system 10) and the absence of counter images do not allow us to include it as a constraint.

The model is optimized with the Bayesian Markov Chain Monte Carlo (hereafter MCMC) sampler, described in detail in Jullo et al. (2007). The mass distribution is optimized by minimizing the distance between the positions of the multiple images unlensed back to the source plane. We used the image-plane rms distance σ_i of the images predicted by the model to the observed positions as an accuracy estimator of the model (Limousin et al. 2007).

A model including a single cluster-scale component, such as the one used in the early analysis by Bergmann, Petrosian & Lynds (1990), largely fails in reproducing the multiple constraints (σ_i ~ 3.5 arcsec). This result was already pointed out by Kneib et al. (1993), who showed that the locations and curvature radii of the arcs and multiple images (in particular the systems 1 and 2) can only be reproduced using a bimodal mass distribution. Indeed, we find that a model with two cluster clumps DM1 and DM2 fixed at the locations of the two brightest cluster galaxies gives a much better σ_i (2.2 arcsec). Thanks to the larger number of identified multiple images systems, we can allow the centres (α_1, δ_1) and (α_2, δ_2) of each clump to vary. In addition, the shape and location of the five images previously identified in the giant arc (system 2) are strongly influenced by the nearby cluster galaxies. This is particularly true for the galaxy GAL1 (Fig. 1) which distorts the circular shape of the arc, and the BCG at the south side of the cluster. To better reproduce the giant arc, we choose to model these two galaxies with two independent dPIE potentials. In total, the new model contains 24 free parameters and we have 40 constraints from the multiple images. The resulting σ_i of this model is ~1.76 arcsec, which is good compared to other similar works (Limousin et al. 2007; Richard et al. 2009a). We adopt this model as our best-fitting model for the rest of this letter. The parameters of this model as well as their 1σ errors are

1 Publically available, see http://www.oamp.fr/cosmology/lenstool to download the latest version.
given in Table 2. The predicted redshifts for systems 3 to 9 are presented in Table 1. We note that the large majority of them are about $z \sim 1$. Such a redshift overdensity is often seen when looking at lensed fields.

Although the value of $\sigma_0$ for DM2 is a lot higher than for DM1, $r_{\text{cut},1}$ for DM2 is also much larger, and therefore the total masses of each cluster-scale component are similar. Thanks to the proximity of GAL1 to images 2.3, 2.4 and 2.5 (see Fig. 1), we obtain tight constraints on its parameters $\sigma_1$ and $r_{\text{cut},1}$ (Table 2). Interestingly, we find very little difference between the constrained values ($\sigma_1 = 118$ km s$^{-1}$, $r_{\text{cut},1} = 20$ kpc) and the values it would have had if scaled according to its luminosity $0.17L^*$ ($\sigma'_1 = 123$ km s$^{-1}$, $r'_{\text{cut}} = 18$ kpc).

4 RESULTS

We use the best-fitting model to unlens the giant arc to the source plane. Fig. 1 shows that the source morphology resembles a local spiral galaxy with a red bulge, blue spiral arms containing individual knots of star formation. We also overlay the location of the cluster-scale and GAL1 caustic lines at the giant arc redshift $z = 0.725$. They part the source into three regions of different multiplicity. The eastern part of the source lies outside of both caustics and is singly imaged, the western part inside the cluster caustic is triply imaged, while the central red bulge inside both caustics is a system of five images, as we identified earlier from the HST image. The reconstruction of each part of the giant arc agrees with this source-plane morphology. Intrinsically, the source extends 10.0/2.5 kpc along its major/minor axis, and assuming a disc-like morphology it is observed with an inclination of 75°. By comparing the overall fluxes in the image and the source plane, we derive a total magnification of $32 \pm 4$ for the entire arc. The largest linear magnification is obtained for image 2.2, where the centre is resolved at $<50$ pc.

The reconstructed mass distribution (Fig. 2) shows two main peaks located over the two brightest cluster galaxies. The centre
is fully consistent with the location of DM2, rather than with the  
not
observe that the orientation of the northern radial arc (system 10),  
and the stellar light is not unusual, as a similar value of  
∼ directions. Such a large offset between the dark matter component  
from the second BCG to the north. This offset is well constrained  
1.1 39.966 857  
1.2 39.976 088  
1.3 39.968 466  
2.1 39.973 639  
2.2 39.970 772  
2.3 39.968 546  
2.4 39.969 185  
2.5 39.969 421  
3.1 39.965 457  
3.2 39.968 333  
3.3 39.977 084  
4.1 39.979 437  
4.2 39.970 545  
4.3 39.961 736  
5.1 39.973 275  
5.2 39.970 954  
5.3 39.968 620  
6.1 39.969 266  
6.2 39.964 320  
6.3 39.979 437  
7.1 39.969 579  
7.2 39.969 673  
7.3 39.968 606  
7.4 39.961 367  
7.5 39.983 602  
8.1 39.964 292  
8.2 39.961 680  
8.3 39.983 911  
9.1 39.962 215  
9.2 39.969 287  
9.3 39.981 833  
10.1 39.968 189  

Note. Redshift values quoted with brackets are predictions from the lensing model.

Table 2. Best-fitting parameters of the mass models.

| Comp. | α (arcsec) | δ (arcsec) | ε | θ | σ_0 (km s^{-1}) | r_{core} (kpc) | r_{cut} (kpc) |
|-------|------------|------------|---|---|----------------|----------------|--------------|
| DM1   | 1.2 ± 0.2  | −0.6 ± 0.6 | 0.26\^{+0.10}_{-0.06} | −11 ± 4.0 | 596 ± 30 | 30.2_{+3.3}^{−3.2} | [800] |
| DM2   | 1.5 ± 0.2  | 27.3 ± 1.0 | 0.31\^{+0.02}_{-0.03} | −6.1 ± 0.6 | 1316 ± 55 | 123_{+8}^{−8} | [800] |
| BCG   | [0.0]      | [0.0]      | [0.30] | [−81.9] | 194 ± 30 | [0.14] | 43 ± 5 |
| GAL1  | [7.9]      | [−9.8]     | [0.26] | [25.7] | 118 ± 13 | [0.06] | 20 ± 6 |
| L*    |            |            | 193 ± 9 | [0.15] | [45] |

Note. Values in brackets are not optimized.

of DM1 is located within 1 arcsec of the BCG, while a significant  
offset (about 10 arcsec, or 50 kpc) separates the centre of DM2  
from the second BCG to the north. This offset is well constrained  
by the presence of multiple systems on both northern and southern  
directions. Such a large offset between the dark matter component  
and the stellar light is not unusual, as a similar value of ∼9 arcsec  
was found in the case of Abell 1689 (Limousin et al. 2007). We also  
observe that the orientation of the northern radial arc (system 10),  
which was not explicitly included as a strong lensing constraint,  
is fully consistent with the location of DM2, rather than with the  
centre of the northern BCG (Fig. 2). Finally, we note that the model  
in which the centres of DM1 and DM2 are fixed at the positions  
of the respective BCGs (see Section 3) requires a very large and  
unrealistic ellipticity for the secondary clump (ε ∼ 0.6–0.7).

The mass enclosed within a radius of 250 kpc from the barycentre  
of the mass distribution (located halfway between the centres  
of DM1 and DM2) is 3.8 ± 0.2 \times 10^{14} M_\odot. We find a good  
agreement (within 3σ) when deriving the same mass using the NFW  
fit of the Subaru weak-lensing measurements from Broadhurst et al. (2008):  
\( M_{WL} = 4.3 \times 10^{14} M_\odot \). The statistical error on the enclosed mass is  
always better than 5 per cent within a radius of 100 arcsec, which  
is a significant improvement compared to the model of Kneib et al.  
(1993) who found typical errors of ∼15 per cent. Then, we estimated  
the effective Einstein radius \( \theta_E \), defined for a source at \( z = 2.0 \), as
the radius at which the averaged convergence $\kappa(<\theta_E) = 1$ (see Broadhurst & Barkana 2008; Richard et al. 2009a). By computing it from the barycentre of the mass distribution, we find $\theta_E = 39 \pm 2$ arcsec. The enclosed mass within $\theta_E$ is $2.82 \pm 0.15 \times 10^{14} M_\odot$. This large Einstein radius makes Abell 370 one of the best clusters to be used as a gravitational telescope to search for very distant galaxies, similar to other clusters such as A1689 (Broadhurst et al. 2005), A1703 (Richard et al. 2009a) or MACS0717 (Zitrin et al. 2009a). Indeed, we outline in Fig. 1 the boundary of the region where multiple images happen for a source at very high redshift ($z = 6$), and show that it can assimilate to a circular region of $\sim 50$ arcsec radius.

In Fig. 2, we overlay the X-ray luminosity contours on top of the mass distribution contours, and observe a very good match. In particular, the contours share a similar elliptical shape and the same orientation. We use the ELLIPSE IRAF task to quantify the typical ellipticity $\epsilon$ and position angle $\theta$ of these contours, and measure ($\epsilon = 0.60, \theta = -6^\circ$) and ($\epsilon = 0.62, \theta = -5^\circ$) for the dark matter and X-ray maps, respectively, confirming the very good morphological agreement. Like the mass distribution, the X-ray luminosity map shows evidence for two prominent maxima, located near the dark matter clumps, with an offset smaller than 10 arcsec.

Overall, the galaxy distribution, the mass distribution and the X-ray luminosity map each present two consistent peaks, and suggest that we are witnessing a massive cluster during a phase of merging. Only two other clusters have shown such a bimodality with two peaks of dark matter and X-ray; the bullet cluster (Bradač et al. 2006, 2009) and MACS0025 (also known as the baby bullet, Bradač et al. 2008b). The main difference between these two clusters and Abell 370 is that both show much larger offsets (of the order of 200–350 kpc) between the X-ray and dark matter centres on each peak. Therefore, it seems that the smaller offsets in Abell 370 are due to a projection effect, or due to the fact that the cluster is seen in an earlier stage of the merging process, at a time when the merging process has not yet affected much the baryons in the ICM.

Looking at the dynamical information on Abell 370, de Filippis, Sereno & Bautz (2005) have measured the redshift distribution of cluster galaxies, and shown that the redshift distribution has two redshift peaks separated by $\sim 3000\ km\ s^{-1}$ in velocity, with each of the two brightest galaxies belonging to a different redshift group. This suggests that contrary to the case of the bullet cluster and MACS0025, the merging of the two cluster components has a large projected velocity along the line of sight, which partly explains the smaller offsets observed between the X-ray and dark matter peaks.

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