THE LARGEST KNOWN EINSTEIN RADIUS: MACS J0717.5+3745 (z=0.546)

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Submitted to the Astrophysical Journal Letters

ABSTRACT

We identify 13 sets of multiply-lensed galaxies around MACS J0717.5+3745 (z = 0.546), outlining a very large tangential critical curve of major axis \( \sim 2.8' \), filling the field of HST/ACS. The equivalent circular Einstein radius is \( \theta_e = 55 \pm 3'' \) (at an estimated source redshift of \( z_s \sim 2.5 \)), corresponding to \( r_e \simeq 350 \pm 20 \) kpc at the cluster redshift, nearly three times greater than that of A1689 (\( r_e \simeq 140 \) kpc for \( z_s = 2.5 \)). The mass enclosed by this critical curve is very large, \( 7.4 \pm 0.5 \times 10^{14} M_\odot \), and only weakly model dependent, with a relatively shallow mass profile within \( r < 250 \) kpc, reflecting the unrelaxed appearance of this cluster. This shallow profile generates a much higher level of magnification than the well known relaxed lensing clusters of higher concentration, so that the area of sky exceeding a magnification of \( > 10 \times \), is \( \simeq 3.55' \), for sources with \( z \simeq 8 \), making MACS J0717.5+3745 a compelling target for accessing faint objects at high redshift. We calculate that only one such cluster, with \( \theta_e \geq 55'' \), is predicted within \( \sim 10^5 \) Universes with \( z \geq 0.55 \), corresponding to a virial mass \( \geq 3 \times 10^{15} M_\odot \), for the standard \( \Lambda CDM \) (WMAP5 parameters with 2\( \sigma \) uncertainties).

Subject headings: gravitational lensing , galaxies: clusters: individual: MACS J0717.5+3745 , dark matter

1. INTRODUCTION

Improvements in gravitational-lensing modeling together with the fabulous image quality of the Advanced Camera have led to the identification of increasing numbers of multiply-lensed images and the discovery of some surprisingly large lenses (e.g., Kneib et al., 1996, Broadhurst et al. 2005, Bradac et al., 2008, Halkola et al. 2008, Liesenborgs et al., 2008, Limousin et al., 2008, Zitrin et al. 2009, Zitrin & Broadhurst 2009).

The largest bound structures to form hierarchically are likely to have collapsed recently and hence should be found relatively locally, at low redshifts. The larger masses reliably determined from weak lensing distortion (Kneib et al., 1996, Kneib et al., 1996) and A1689 at \( z = 0.18 \), with \( 1.6 \pm 0.2 \times 10^{15} M_\odot \) (Broadhurst et al., 2005, Umetsu & Broadhurst, 2008), superseded by the most distant Abell cluster, A370 at \( z = 0.37 \) and the most luminous X-ray cluster RXJ1347, \( z = 0.45 \), with masses reliably determined from weak lensing distortion and magnification of \( \simeq 2 \times 10^{15} M_\odot \) (Broadhurst et al. 2008).

Strong lensing is not seen for low redshift clusters \( (z < 0.15) \) because the central projected mass densities do not exceed the critical density required to generate a sizable Einstein radius, which scales inversely with lens distance, diverging at low redshift. Similarly, at high redshift as the lens distance approaches that of the distant sources, thus the critical density is too great for strong lensing. Geometrically, lensing is optimized at intermediate redshifts, where for a given mass the critical density for lensing is minimal, but this is partly offset by the late hierarchical growth of high-mass systems. This trade-off results in estimates of the amplitude of strong lensing to favor the redshift range \( z = 0.2 - 0.4 \), for NFW-like mass profiles (Broadhurst & Barkana, 2008, Oguri & Blandford, 2009). Seemingly, all rich and X-ray luminous clusters at modest redshift are found to have many multiply-lensed images when examined with sufficient depth and resolution, implying that the mass profiles of clusters are in general sufficiently peaked that the critical density for lensing is exceeded.

The Einstein radii of the most massive clusters seem to be larger than predicted by the \( \Lambda CDM \) model (Broadhurst & Barkana, 2008, Puchwein & Hilbert, 2009), based on the “Millenium” simulation (Springel et al., 2005). This discrepancy is empirically supported by the surprisingly concentrated mass profiles measured for such clusters, when combining the inner strong lensing with the outer weak lensing signal (Gavazzi et al., 2003, Broadhurst et al., 2005 & 2008, Limousin et al., 2008, Donnarumma et al., 2009, Oguri et al., 2009, Umetsu et al., 2009, Zitrin et al., 2009).

These largest lensing clusters have proven to be excellent targets for accessing the faint early Universe due to their large magnification consistently providing the highest redshift galaxies (Ebbels et al., 1996, Franx et al., 1997, Frye & Broadhurst, 1998, Bouwens et al., 2004, Kneib et al., 2004, Bradley et al., 2008, Zheng et al. 2009). The larger sizes of lensing images has provided increased spatial detail and the large magnifications permits observations of increased spectral resolution, leading to the discovery that metal enriched material is typically outflowing from galaxies at \( z > 4 \) (Franx et al. 1997, Frye & Broadhurst, 1998, Frye, Broadhurst & Benítez, 2002).

With the goal of discovering high redshift galaxies and to better define the mass profiles of galaxy clusters in general, we have combined data for a sample of
well studied clusters. In this process we have uncovered the extreme lensing properties of MACS J0717.5+3745 \((z=0.546)\), a cluster originally identified in the highly complete sample of the most X-ray luminous clusters in the Universe (Ebeling et al., 2004, 2007). This cluster is thought to be amongst the most massive clusters known, forming part of an intricate DM filamentary structure of \(\sim 4\) Mpc (Ebeling et al., 2004, Ma et al., 2008), whose complex X-ray emission indicates ongoing merging (Ma et al., 2009) accompanied by the most powerful known radio halo (van Weeren et al., 2009, Bonafede et al., 2009).

In §2 we describe the observations; the lensing analysis is described in §3; our results are presented in §4 and in §5 we discuss and conclude them. Throughout the paper we adopt the standard cosmology \((\Omega m_0 = 0.3, \Omega \Lambda_0 = 0.7, h = 0.7)\). Accordingly, one arcsecond corresponds to \(6.42\) kpc/\(h_70\) at the redshift of this cluster. The reference center of our analysis is fixed near the center of the ACS frame at: RA = 07:17:31.65, Dec = +37:45:03.12 (J2000.0).

2. OBSERVATIONS

The very X-ray luminous cluster MACS J0717.5+3745, which is the denser north-western region of the large-scale filament found by Ebeling et al. (2004), was imaged in April 2004 and in October 2005, 2006, with the Wide Field Channel (WFC) of the ACS installed on HST. Integration times of \(\sim 4500\) s were obtained through each of the F555W and the F814W filters in the April 2004 run. We retrieved these images from the Hubble Legacy Archive, along with a subsequent exposure in the F606W band (January 2005, integration time of 1980s) to form a composite high-resolution 3-color image. Several obvious close pairs of multiply-lensed galaxies and giant arcs are immediately visible throughout the full frame, with which we begin our modeling process described below.

3. LENSING ANALYSIS

We apply our well tested approach to lens modeling, which we have applied successfully to A1689, C0024, and MACS J1149.5+2223, uncovering large numbers of multiply-lensed images in several clusters imaged with HST/ACS (Broadhurst et al., 2005, Zitrin et al., 2009, Zitrin & Broadhurst 2009). The full details of this approach can be found in these papers. Briefly, the basic assumption adopted is that mass approximately traces light, so that the photometry of the red cluster member galaxies is the starting point for our model.

Cluster member galaxies are identified as lying close to the cluster sequence by the photometry provided in the Hubble Legacy Archive. We approximate the large scale distribution of matter by assigning a power-law mass profile to each galaxy, the sum of which is then smoothed.

The degree of smoothing and the index of the power-law are the main free parameters. A worthwhile improvement in fitting the location of the lensed images is generally found by expanding to first order the gravitational potential of the smooth component, equivalent to a coherent shear, where the direction of the shear and its amplitude are free, allowing for some flexibility in the relation between the distribution of DM and the distribution of galaxies, which cannot be expected to trace each other in detail. The total deflection field \(\vec{\alpha}(\vec{\theta})\), consists of the galaxy component, \(\vec{\alpha}_g(\vec{\theta})\), scaled by a factor \(K_g\), the cluster DM component \(\vec{\alpha}_{DM}(\vec{\theta})\), scaled by \(1-K_g\), and the external shear component \(\vec{\alpha}_{ex}(\vec{\theta})\):

\[
\vec{\alpha}_T(\vec{\theta}) = K_g \vec{\alpha}_g(\vec{\theta}) + (1-K_g) \vec{\alpha}_{DM}(\vec{\theta}) + \vec{\alpha}_{ex}(\vec{\theta}),
\]

where the deflection field at position \(\vec{\theta}_m\) due to the external shear, \(\vec{\alpha}_{ex}(\vec{\theta}_m) = (\alpha_{ex,x}, \alpha_{ex,y})\), is given by:

\[
\alpha_{ex,x}(\vec{\theta}_m) = |\gamma| \cos(2\phi_\gamma) \Delta x_m + |\gamma| \sin(2\phi_\gamma) \Delta y_m,
\]

\[
\alpha_{ex,y}(\vec{\theta}_m) = |\gamma| \sin(2\phi_\gamma) \Delta x_m - |\gamma| \cos(2\phi_\gamma) \Delta y_m,
\]

where \((\Delta x_m, \Delta y_m)\) is the displacement vector of the position \(\vec{\theta}_m\) with respect to a fiducial reference position, which we take as the lower-left pixel position (1,1), and \(\phi_\gamma\) is the position angle of the spin-2 external gravitational shear measured anti-clockwise from the \(x\)-axis.

We lens candidate galaxies back to the source plane using the derived deflection field, and then relens this source plane to predict the detailed appearance and location of additional counter images, which are then searched for in the data. The fit is assessed by the RMS uncertainty in the image plane:

\[
RMST^2 = \sum \frac{(x_i - x_j)^2 + (y_i - y_j)^2}{N_{images}},
\]

where \(x_i, y_i\) are the locations given by the model, and \(x_j, y_j\) are the real images location, and the sum is over all \(N_{images}\) images.

Importantly, this image-plane minimization does not suffer from the well known bias involved with source plane minimization which biases solutions towards high magnification and hence correspondingly shallower profiles. The model is successively refined as additional sets of multiple images are identified and incorporated to improve the fit (Zitrin et al., 2009). In addition, we find that a bright foreground elliptical galaxy (RA=07:17:37.16, DEC=+37:44:22.54) is important to include in the model as it locally affects lensed images in the eastern to central part of the ACS frame, including their relative lensing distance.

In the above process we uncovered and used 34 multiply-lensed images, corresponding to 13 lensed background galaxies, to constrain the mass distribution and profile of this cluster. A lensed pair of red drop-out objects which are not seen in the F555W band at an estimated redshift of \(z \sim 4\) (system number 5, see Figure 1), helps us pin down accurately the normalization of the deflection field by adopting the lensing distance for this cluster, which is known to be in the process of merging, with disturbed X-ray emission, hot shocked regions (Ma et al., 2008, 2009), and powerful radio halo emission (van Weeren et al., 2009, Bonafede et al., 2009). We find that the elongated central distribution
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Fig. 1.— The cluster MACS J0717.5+3745 ($z = 0.546$) imaged with Hubble/ACS F555W, F606W, and F814W bands. The 34 multiply lensed images identified by our model are numbered here. The white curve overlaid shows the tangential critical curve corresponding to the distance of system 1 at an estimated redshift of $z \sim 2.5$, and which passes through several close pairs of lensed images in this system. The larger critical curve overlaid in red corresponds to the larger source distance for the red dropout galaxy number 5, at the estimated photometric redshift of $z \sim 4$. This large tangential critical curve encloses a very large lensed region equivalent to $\sim 400$ kpc in radius at the redshift of the cluster, $z = 0.546$.

Fig. 2.— A reproduction of system 1 by our model. The observed images are shown in the top row and compared with our model generated images below. Each model image is generated using as input the pixels of image 1.1 (except for the model image of 1.1 which is generated by relensing the observed image 1.2) and delensing these pixels back to the source plane and then relensing the source plane to generate the counter images. It is clear that our model is successful in demonstrating the multiply-lensed relation between the four observed images.

Fig. 3.— Radial surface mass density profile, $\kappa(r)$, in units of the critical surface density, i.e., $\kappa(r) = \Sigma(r)/\Sigma_{\text{crit}}$, derived for the range of radius covered by all sets of multiple images shown in Figure 2. The profile is shallow within $\sim 250$ kpc, at a level close to the critical density for system 1 (black line). The vertical dashed line at $\sim 55''$ is the Einstein radius at the redshift of system 1. This profile was measured circularly while centered on the central pixel of the 2D mass distribution shown in Figure 4.

Fig. 4.— Zoomed-in 2D surface mass distribution ($\kappa$), in units of the critical density. Contours are shown in linear units, derived from the mass model constrained using 34 multiply-lensed images seen in Figure 2. The axes are in ACS pixels. Note that the central mass distribution is rather flat reflecting the unrelaxed appearance of this cluster.

of galaxies is followed by a very extended tangential critical curve, enclosing a large critically lensed region with an equivalent Einstein radius of $\sim 55 \pm 3.0''$ (for an estimated source redshift of $z \sim 2.5$). This corresponds to a physical scale of $350 \pm 20$ kpc/$h_{70}$, substantially larger than in any other known cluster. This very large radius adds to the already uncomfortable discrepancy between the large Einstein radii observed for massive clusters and the predictions based on the standard $\Lambda$CDM cosmology (Broadhurst & Barkana, 2008, Sadeh & Rephaeli, 2008, Puchwein & Hilbert, 2009) for which such large Einstein radii can only be contemplated with mass distributions which are highly prolate and aligned along the line of sight (Corless & King, 2007, Oguri & Blandford, 2009).
Uncertainty in the cosmological parameters \( h, n, \text{and} \sigma_8 \) about the WMAP5 values, and also the \( 1 \sigma \) uncertainty in the measured \( \theta_E \). This number peaks near \( M \sim 4 \times 10^{15} M_\odot \), with \( N_{cl} \sim 2.7 \times 10^{-7} \).

Instead, here this cluster is evidently elongated across the line of sight, traced by the distribution of member galaxies, and by the extended X-ray emission and the tangential curves (see Figure 1).

The mass enclosed within the tangential critical curve, for \( z_s = 2.5 \), is very high \( 7.4 \pm 0.5 \times 10^{14} M_\odot \). The mass enclosed within the larger critical curve for the multiply-lensed dropout galaxy, number 5, at an estimated source redshift of \( z \sim 4 \) is correspondingly larger, \( \sim 1.0 \times 10^{15} M_\odot \) (marked in red, Figure 1). Clearly, the total mass associated with this cluster cannot be smaller than this and is likely to be several times larger, and may soon be reliably estimated from weak lensing. We stress that the scale of the tangential critical curve hardly depends on the mass profile because it is set by the critical density for lensing, which depends only on fundamental constants and the distances involved, so that different profiles explored in the modeling procedure yield very similar critical curves, and hence similarly large Einstein radii and an accurate enclosed mass.

5. DISCUSSION AND CONCLUSIONS

Theoretically, we can make an approximate estimate of the probability of obtaining such a cluster in the context of the tightly proscribed \( \Lambda CDM \) model. Using the probability distribution function (PDF) of halo formation times, calculated within the framework of the extended Press & Schechter (EPS) formalism (Lacey & Cole 1993), we derived a corresponding PDF of halo concentration parameters (Sadah & Rephaeli, 2008) by adopting the formation redshift-concentration scaling, deduced by Wechsler et al. 2002, from N-body simulations.

Solving the equation governing the relation between the concentration parameter and \( \theta_E \) assuming an NFW profile (e.g. Broadhurst & Barkana 2008), leads to a PDF of Einstein radii. Here we adopt the mean source redshift \( z_s = 2.5 \) as described above. The product of the Press & Schechter mass function abundance of clusters within the relevant mass and redshift ranges with the cumulative Einstein radius probabilities multiplied by the volume available at \( z > 0.55 \) provides the number of clusters expected above this redshift for standard \( \Lambda CDM \) where we allow for \( 2 \sigma \) uncertainty in the WMAP5 values of the parameters \([n, h, \sigma_8] \). Extremely low numbers of clusters are predicted peaking at \( M \sim 4 \times 10^{15} M_\odot \) with a maximum probability of only \( 2.7 \times 10^{-7} \) objects per Universe, or approximately half this value when allowing for the area of sky covered by the ROSAT all-sky survey. Clearly it is important to obtain the total mass of the cluster via weak lensing which we are now estimating but it is reasonable to suppose this lies close to the most probable value derived crudely here, given that the mass interior to the critical curve is already 25\% of this value.

MACS J0717.5+3745 is the second strong-lensing analyzed cluster (along the recent critically convergent lens MACS J1149.5+2223, Zitrin & Broadhurst 2009) out of several other very luminous X-ray clusters uncovered by Ebeling et al. (2007) in the ROSAT all-sky survey. Both these clusters have unconcentrated central galaxy distributions reflecting their unrelaxed state and for which we have shown that the central mass distribution is likewise very unconcentrated. A relatively shallow mass profile boosts the gravitational lens magnification and we calculate that the total area of sky exceeding a magnification, \( \mu > 10 \), is \( \sim 3.5 \) square arcminutes, corresponding to the current high redshift limit of \( z \sim 8 \), which is far higher than the equivalent area calculated for other massive clusters (Broadhurst et al., 2005, Zitrin et al., 2009).

Such unrelaxed and massive clusters opens a potentially new regime of highly magnifying lenses for accessing the faint distant Universe.

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Fig. 5.— The number of clusters per universe with masses exceeding \( M \), lying at redshift \( z > 0.55 \), for which the predicted Einstein radius is \( \theta > 55 \pm 3^\prime \). The shaded area reflects the variance generated by incorporating into the the \( \Lambda CDM \) model the \( 2\sigma \) uncertainty in the cosmological parameters \( h, n, \text{and} \sigma_8 \) about the WMAP5 values, and also the \( 1 \sigma \) uncertainty in the measured \( \theta_E \). This number peaks near \( M \sim 4 \times 10^{15} M_\odot \), with \( N_{cl} \sim 2.7 \times 10^{-7} \).
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