

## Lens magnification by CL0024+1654 in the $U$ and $R$ band

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From the detection of  $R$  band background source depletion due to gravitational lens magnification, we present measurements of the distribution of mass and the mass-to-light ratio of the galaxy cluster CL0024+1654. Using this information in combination with our  $U$  band observations of the cluster, we show how flux magnification facilitates the search for a break in the  $U$  band field galaxy number count slope. This leads to the conclusion that a change of slope of  $d \log N/dm = 0.4 \rightarrow 0.15$  can be ruled out up to  $U_{AB} \leq 26.4$  with 95% confidence.

### 1 Introduction

CL0024+1654 ranks as one of the most highly studied lensing clusters to date. Lying at a redshift of  $z = 0.39$ , early measurements of the cluster's velocity dispersion suggested a formidable mass<sup>4</sup>. The discovery of a large gravitationally lensed arc from a blue background galaxy<sup>9</sup> has since provoked a range of studies to estimate the cluster's mass from its lensing properties. Nearly all of these studies have exploited lens shear with only two lens magnification based studies<sup>7, 13</sup> existing to date.

The motivation for the work presented here was driven partly by the current lack of thorough magnification analyses of CL0024+1654 and partly by recent claims<sup>11, 12</sup> that the  $U$  band field galaxy number count slope becomes distinctly more shallow at  $U_{AB} \simeq 25.5 - 26$ . In the presence of lens magnification, this change of slope should manifest itself as a depletion in the surface number density of objects at these faint magnitudes<sup>3</sup>.

In section 2, we describe our magnification analysis of our  $R$  band observations of CL0024+1654 and the mass measurements thus obtained. Using our  $U$  band observations of the cluster in section 3, we test whether depletion is indeed observed, thereby; a) investigating the suitability of  $U$  band observations for future magnification studies b) enabling limits to be placed on the faint  $U$  band field galaxy number counts. We refer the reader to our main paper<sup>6</sup> for further details on all aspects of the analysis summarised here.

## 2 Mass in CL0024+1654

The number count slope of field galaxies observed in the  $R$  band is known to be sufficiently shallow<sup>8</sup> to allow significant detection of lens magnification through measurement of depletion in count density<sup>3</sup>. We therefore used our  $R$  band observations of CL0024+1654 to constrain the mass properties of the cluster before using this information in the search for a change of slope in the  $U$  band counts.

Our  $R$  band background object sample was formed by applying the selection criterion  $R_{AB} > 23.5$  to all objects  $SExtracted$ <sup>1</sup> from our 9ksec,  $6' \times 6'$  Nordic Optical Telescope (NOT) observations. This yielded a total of 1400 objects with an anticipated 300 foreground contaminants estimated from both the known field galaxy LF<sup>10</sup> and the measured cluster LF<sup>6</sup>.

A background population of galaxies whose integrated number counts follow the standard power-law  $n(< m) \propto 10^{0.4\beta m}$  will be observed under a lens magnification factor  $\mu$  to have the number count  $n'(< m)$  given by<sup>3, 14</sup>

$$n' = n\mu^{\beta-1}(1 + \delta_{nl}). \quad (1)$$

The quantity  $\delta_{nl}$  accounts for perturbations in  $n$  due to non-linear clustering. We use a joint lognormal-Poisson distribution to model the uncertainty arising from a combination of these perturbations and shot-noise. Using a maximum likelihood approach, we obtain the magnification in a given binned region of sky from equation (1). Since magnification relates to the surface lens mass density, or convergence,  $\kappa$ , and shear,  $\gamma$ , as

$$\mu = \left| (1 - \kappa)^2 - \gamma^2 \right|^{-1}, \quad (2)$$

a direct route for the determination of  $\kappa$  is immediately available, provided  $\gamma$  can be measured. We use both a 1D<sup>14</sup> and a 2D<sup>5</sup> non-local, self-consistent method which essentially enables  $\gamma$  to be derived from the measured magnification. Applying these to our radially binned and grid binned number counts, respectively yields the mass profile and map shown in Figure 1.

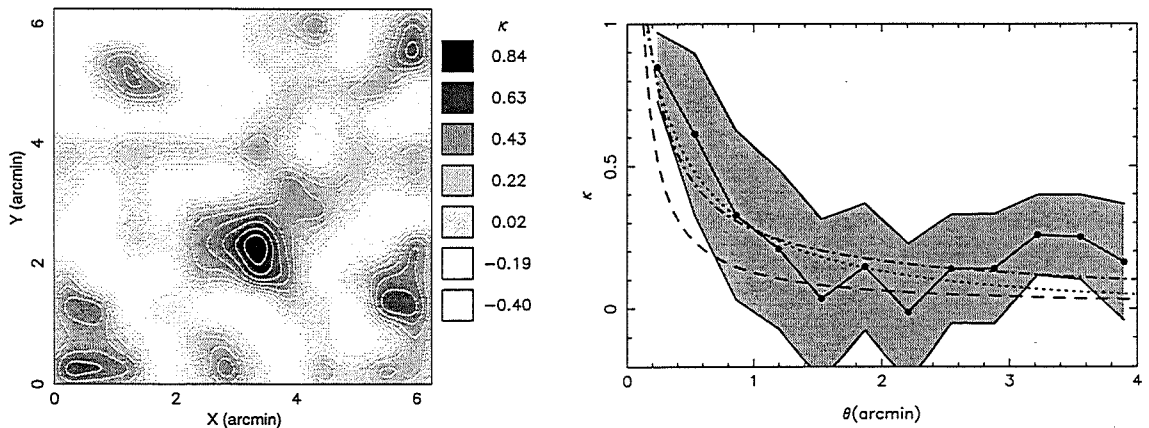


Figure 1: Left: Mass map of CL0024+1654 determined using the non-local, self-consistent method of Dye & Taylor (1998) applied to our  $R$  band background galaxy sample. The peak has  $4\sigma$  significance where errors account for shot-noise, clustering, contamination and uncertainty in number count normalisation. Right: Mass profile derived from the  $R$  band sample using the radial, self-consistent method of Taylor et al. (1998). Shaded region shows  $1\sigma$  errors as listed for mass map. Dashed, dotted and dot-dashed lines show fitted isothermal, power-law and NFW models respectively.

Rather than estimate the redshift distribution of objects in our source sample, we convert our  $\kappa$  profile to a real mass profile by normalising to the mass contained within the Einstein radius. This is accurately known from the redshift of the lensed background galaxy which forms the ring<sup>2</sup>. We find that the cumulative projected mass scales with radius  $R$  as  $M(< R) = 2.9 \times 10^{14} (R/1')^{1.3-0.5 \lg(R/1')} h^{-1} M_{\odot}$ . At a radius of  $0.54 h^{-1}$  Mpc, this corresponds to a mass-to-light ratio of  $M/L_B = 470 \pm 180$ .

### 3 The $U$ band number count slope

Having determined the magnification profile of CL0024+1654 from our  $R$  band observations by knowing the  $R$  band number count slope, we can invert the problem and determine the number count slope of galaxies in the  $U$  band by knowing the cluster's magnification properties. Unlike traditional methods of determining number count slopes, this technique is not affected by completeness at faint magnitudes (see main paper<sup>6</sup> for details). Our  $U$  band background sample used for this purpose was generated using *SExtractor* on our 37ksec  $U$  band NOT observation with the selection  $(U - R)_{AB} < 3$  and  $U_{AB} > 24$ .

We use two number count models, in succession, to search for a change in slope. Firstly, we attempt to fit a model with a bright slope  $\beta_U$ , which at a characteristic cut-off magnitude  $U_0$ , smoothly and completely flattens at faint magnitudes. The number counts corresponding to this model are given by equation (3a) where  $\Delta U = U_{lim} - U_0$  and  $U_{lim}$  is the limiting magnitude of our  $U$  band sample ( $U_{AB} = 25.7$ ). Equation (3a) is thus used to predict the number of objects at a particular radius given the magnification  $\mu$  measured at that radius from the  $R$  band sample. This predicted number is compared with the measured number in each radial bin in a  $\chi^2$  test where  $\beta_U$  and  $U_0$  are allowed to vary. The  $\chi^2$  contours resulting from this fit are plotted on the left hand side in Figure 2 and accommodate all sources of error listed in the previous section. The contours show that a complete flattening of counts can be ruled out with 95% confidence up to  $U_{AB} = 27.3$  and that the bright slope is  $\beta_U = 1.07$ .

$$\text{a) } n'_U = n_U \mu^{\beta_U - 1} \left[ \frac{1 + 10^{0.4\beta_U \Delta U}}{1 + \mu^{\beta_U} 10^{0.4\beta_U \Delta U}} \right] \quad \text{b) } n'_U = n_U \mu^{-1} \left[ 1 + \frac{\beta_U}{\beta_{U2}} (\mu^{\beta_{U2}} - 1) \right] \quad (3)$$

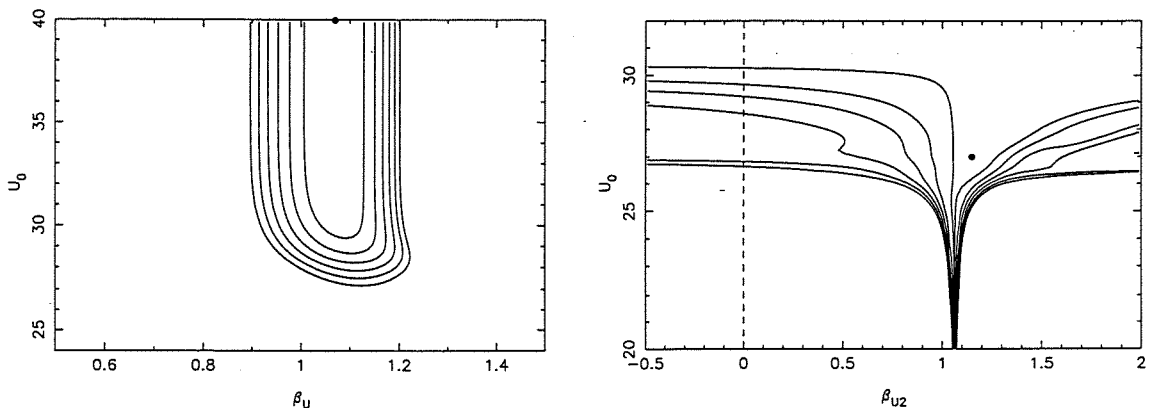


Figure 2: Left:  $\chi^2$  distribution of the  $U$  band number count slope  $\beta_U$  and the break scale  $U_0$  assuming the number counts flatten off completely at faint  $U$ . Right:  $\chi^2$  distribution of the faint number count slope  $\beta_{U2}$  and  $U_0$  holding  $\beta_U = 1.07$ . All contours are separated by  $\Delta\chi^2 = 1$ .

The second number count model we apply is a dual slope model with a change of slope occurring at a magnitude  $U_0$ . The number counts for this model are given by equation (3b),

where again the radial variation in magnification is supplied from the results of the  $R$  band analysis. We use these predicted counts in exactly the same way as with the first model but this time allow the faint magnitude slope  $\beta_{U2}$  and  $U_0$  to vary whilst holding the bright slope fixed at  $\beta_U = 1.07$ . The  $\chi^2$  contours we obtain are illustrated on the right hand side of Figure 2.

Slightly more relaxed than the previous result, the data rule out a complete flattening ( $\beta_{U2} = 0$ ) brighter than  $U_{AB} = 26.6$  at a confidence level of 95%. Furthermore, a slope of  $\beta_{U2} = 0.4$ , the value reported recently<sup>11, 12</sup> as being applicable fainter than  $U_{AB} \simeq 25.5 - 26$ , can be ruled out to  $U_{AB} < 26.4$  with 95% confidence. Pushing this limit further still, we predict that a slope even as steep as  $\beta_{U2} = 0.8$  can be ruled out with 95% confidence to  $U_{AB} < 26.0$ . Finally, at  $\beta_{U2} = \beta_U$ , where the degeneracy between the faint and steep slope is 100%, the break magnitude cannot be constrained at all. Note how flux magnification by CL0024+1654 allows deeper limits than the physical limit imposed on our  $U$  band sample to be placed on all break magnitudes we quote. Given that both models predict a near lensing invariant slope ( $\beta = 1$ ) with no significant change, we conclude that at least up to  $U_{AB} \simeq 27.5$ , the  $U$  band is unsuitable for the measurement of lens magnification.

#### 4 Summary

We have observed CL0024+1654 in  $U$  and  $R$ . Our  $R$  band sample of background objects exhibits a significant depletion in surface number density owing to its shallow number count slope and lens magnification by the cluster. From this, we have determined the cluster's radial magnification and mass profile, in turn allowing limits to be placed on the faint  $U$  band field galaxy number count slope. We conclude that there is a lack of significant flattening up to  $U_{AB} < 26.4$  and that up to at least  $U_{AB} \simeq 27.5$ , the  $U$  band is unsuitable for the measurement of lens magnification. This result is insensitive to completeness effects.

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