Identification of a Gravitationally Lensed z=2.515 Star-Forming Galaxy *

T.M.D. Ebbels¹, J.-F. Le Borgne², R. Pelló², R.S. Ellis¹, J.-P. Kneib¹, I. Smail³ & B. Sanahuja⁴

¹Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, U.K.
²Observatoire Midi-Pyrénées, 14 Av. E. Belin, 31400 Toulouse, France.
³The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara St., Pasadena, CA 91101-1292.
⁴Departament d’Astronomia i Meteorologia, Universitat de Barcelona, Diagonal 648, 08028 Barcelona, Spain.

Accepted 1996 Received 1996 ; in original form

ABSTRACT
We discuss the optical spectrum of a multiply-imaged arc resolved by HST in the z=0.175 cluster A2218. The spectrum, obtained with LDSS-2 on the 4.2m William Herschel telescope, reveals the source to be a galaxy at a redshift z=2.515 in excellent agreement with the value predicted by Kneib et al. (1996) on the basis of their inversion of a highly-constrained mass model for the lensing cluster. The source is extremely blue in its optical-infrared colours, consistent with active star formation, and the spectrum reveals absorption lines characteristic of a young stellar population. Of particular significance is the absence of Lyman-α emission but the presence of a broad Lyman-α absorption. The spectrum is similar to that of other, much fainter, galaxies found at high redshift by various techniques and illustrates the important role that lensing can play in detailed studies of the properties of distant galaxies.

Key words: cosmology: observations – galaxies: evolution – gravitational lensing

1 INTRODUCTION

Considerable progress has been made recently from systematic redshift surveys of faint galaxies in understanding the evolutionary properties of galaxies out to redshifts z=1. (Colless 1995, Lilly et al., 1996, Ellis et al.,1996). Beyond this strategic barrier, a variety of new techniques promise to extend our understanding to higher redshift. Cowie et al. (1995) have extended the direct spectroscopic approach for K-limited samples to z ≥1.6 and shown a number have sufficiently strong star formation to account for a high fraction of the present-day stellar density. A drawback of this approach, as a way of finding representative distant galaxies is that only a minority of a magnitude-limited sample, even at the faint limits now reachable with 10-m class telescopes, lie beyond z ≥1. Presumably even fainter surveys would be required to uncover significant numbers of z >2 galaxies. Although systematic, this method may not be the most efficient way to locate high redshift galaxies.

In contrast, Steidel et al. (1996) have shown that very high redshift sources can be effectively isolated from multi-band photometry using the the Lyman limit as a discriminator. However, the Lyman limit (λrest=912 Å ) only becomes amenable to optical detection at redshifts z ≥2.8 and thus, although undoubtedly a very powerful technique, any comparison of such a distant sample with one similarly selected at a lower redshift will remain an observational challenge for the UV capabilities of HST (e.g. Conti et al 1995). Finally, one must consider the searches for damped Lyman-α absorbers (e.g. Wolfe et al. 1995.) The main disadvantage here is contamination of the spectrum by the QSO light which inevitably hampers detailed investigation of the absorbing galaxy. Secondly, one has to contend with an uneven selection function in redshift produced by the varying detectability of the absorption.

In this article we illustrate the important role that gravitational lensing can play in selecting distant galaxies over a large redshift range, spanning those covered by the methods discussed above. The principal advantage of lensing in this context is, of course, the boosting of the apparent magnitude of the faint galaxy. Early work in this direction was begun by Smail et al. (1993) who discussed the photometric properties of giant arcs of known redshift in the context of various evolutionary models. The unlensed magnitudes of the arcs in their sample are estimated to be fainter than

* Based on observations obtained on the William Herschel Telescope at the Observatorio del Roque de los Muchachos, La Palma.
the galaxies studied in the deepest current conventional 10m samples (e.g. Cowie et al. 1995). Although it is well known that lensing conserves surface brightness, parts of the source smaller than the seeing disk do undergo a real surface brightness gain (see Ebbels et al. 1996b). Although this may not be as large as the formal lensing magnification, the spectroscopic gain in depth can be significant. Additionally, the spatial magnification enables distant sources to be resolved into their individual components using HST (Smail et al. 1996).

The data from HST has enabled the construction of very precise mass models for selected lensing clusters. A good example is the recent analysis of Abell 2218 (\(z = 0.175\)) where the ground-based mass model of Kneib et al (1995) was confirmed in exquisite detail from as many as 7 multiply-imaged sources resolved by HST in a 3-orbit exposure (Kneib et. al. 1996, KESCS). The highly-constrained mass model allowed KESCS to invert the lensing equations and predict redshifts for individual arclets readily recognised in the HST images. A number of the arclets were predicted to have redshifts \(z > 1\) and, as a way of isolating high redshift sources, the technique will become more effective as higher redshift lenses are employed. As the inversion is a purely geometric technique, selection effects are less troublesome than with the alternative approaches. Some of the difficulties inherent in the optical detection of lensed galaxies are discussed in KESCS. Clearly it is important to verify the lensing inversion, where possible, and in this article we illustrate the potential of the method via the spectrum of a spectacular multiply-imaged arc in Abell 2218 (#384 in the numbering scheme of Le Borgne et al, 1992.) The large magnification (almost 3 magnitudes for this image) allows us to obtain the spectrum of a normal galaxy at high redshift. The redshift obtained, \(z = 2.515\), is in very good agreement with that predicted by the lensing model of KESCS.

A plan of the paper follows. In §2 we present the spectroscopic observations that lead to the redshift determination and discuss its implications with respect to the inversion method discussed by KESCS. In §3 we discuss the broadband photometric properties of the distant galaxy and estimate the ongoing star formation rate and rest-frame luminosities. In §4 we return to the spectrum and interpret the various features in the context of the photometric data and UV spectra of nearby galaxies and recent spectra of high redshift sources. §5 summarises the main conclusions of the paper.

2 SPECTROSCOPIC OBSERVATIONS AND REDSHIFT DETERMINATION

As part of a major effort to verify the lensing inversion method for Abell 2218 discussed by KESCS, we have secured spectra for a large sample of faint arclets using the LDSS-2 multi-slit spectrograph at the William Herschel Telescope (WHT). A more complete description of these observations will be presented elsewhere (Ebbels et al., 1996b). The arclets were selected to be those with lensed magnitudes \(B < 25\) for which the inversion gave estimated redshifts \(z_{\text{lensing}} > 0.4\). Although a colour selection was imposed to increase the chance of detecting [O II] emission in the spec-

\[ Figure 1. \text{(top) WFPC-2 F702W image of arc #384 (after KESCS), (bottom) WFPC-2 F702W image of arc #468 considered by KESCS to be a the counter-image of #384.} \]
Identification of a Gravitationally Lensed $z=2.515$ Star-Forming Galaxy

Pelló et al. (1992) and Kneib et al. (1995). (3700-5300 Å. 

developed, the source is predicted to lie within the range 

proximity to the critical line. On the basis of the mass model 

represents a crucial constraint because of the arc’s 

magnification of #384 on the other side of the central cD (object #468, Fig-

The mass model discussed by KESCS, which is highly con-

the arc represents the merging of two images across a crit-

data verifies the earlier suggestion (Kneib et al. 1995) that 

most spectacular in appearance in the HST image presented 

librated using the standard LDSS-2 throughput curves. 

extracting the faint spectra, the light profile along the slit 

correct for variations in transmission along the slit, while 

∼0.5 arcsec pixel$^{-1}$). This grism allows us to survey the 

L HST image presented in Ebbels et al. (1996b), where the spectro-

Figure 2. (bottom) LDSS-2 spectrum of the arc #384. Both 

strong and more tentative identifications of features indicating a redshift of $z = 2.515 \pm 0.001$ are marked. Sky residuals near 

spectral lines of #384 are visible here, including the Lyman-α transition. 

The arc in question, #384 (Figure 1(top)) in the pho-

The location and orientations of the two images allowed 

KESCS to predict the inverted redshift and magnification of the source to reasonably high precision. Indeed, the redshift 

represent the merging of two images across a critical line whose location can now be precisely determined. 

The mass model discussed by KESCS, which is highly con-

computed using the standard LDSS-2 throughput curves.

The arc in question, #384 (Figure 1(top)) in the pho-

The observations were conducted on the nights of May 

28 to June 1 1995. LDSS-2 was used in a conventional multi-

a total exposure of 29.9ksec was obtained with the medium 

blue grism, (5.3Å pixel$^{-1}$, $R \simeq 12$ Å) in conditions with see-

Figure 1. A) Inverted parallel morphology, albeit less distorted by the gravi-

tical shear. Since the source lies so close to a caustic in the source plane, any bright parts of it lying outside this 

caustic would be imaged only in #468. The absence of any 

such extra bright knots in #468 leads us to conclude that 

all high surface brightness parts of the source lie inside the 

caustic line.

The LDSS-2 spectrum for #384 is shown in Figure 2 

and has a very satisfactory signal/noise. Although the in-

tegrated photometry indicates $R_{tot}=21.2$, the mean surface brightness is only $\mu_R=23.4$ ($\simeq7$ per cent of the La Palma night sky). Thus the observation represents a considerable challenge. The spectrum shows a number of strong ultravi-

ela features consistent with a redshift $z=2.515$, close to the 

predicted value. Most noticeable is the prominent feature at 

$\approx4250$ Å which arises from strong Lyman-α absorption. No 

emission lines are seen in the optical spectrum. With our 

new data, we find that multiple image hypothesis is rein-

forced by comparing the spectra of all three images. The 

two halves of #384 show no difference in spectral features, 

while the spectrum of #468 (figure 3), although noisy, is cer-

tainly compatible with that of #384. We return to a detailed 

discussion of the spectral features in the next section.

The verification of the inverted redshift, to within the 

estimated precision, illustrates the power of the lensing tech-

nique for isolating high redshift galaxies as well as for de-

termining the statistical redshift distribution of very faint 

sources. It also shows that the mass model for the cluster 

core is very well determined, and in fact, further constrains 

it. The implications of the comparison of the lensing pre-

dicted redshifts and spectroscopically determined ones will 

be presented in Ebbels et al. (1996b), where the spectro-

Figure 2. (bottom) LDSS-2 spectrum of the arc #384. Both 

strong and more tentative identifications of features indicating a redshift of $z = 2.515 \pm 0.001$ are marked. Sky residuals near 

spectral lines of #384 are visible here, including the Lyman-α transition. 

The arc in question, #384 (Figure 1(top)) in the pho-

The observations were conducted on the nights of May 

28 to June 1 1995. LDSS-2 was used in a conventional multi-

a total exposure of 29.9ksec was obtained with the medium 

blue grism, (5.3Å pixel$^{-1}$, $R \simeq 12$ Å) in conditions with see-

Figure 1. A) Inverted parallel morphology, albeit less distorted by the gravi-

tical shear. Since the source lies so close to a caustic in the source plane, any bright parts of it lying outside this 

caustic would be imaged only in #468. The absence of any 

such extra bright knots in #468 leads us to conclude that 

all high surface brightness parts of the source lie inside the 

caustic line.

The LDSS-2 spectrum for #384 is shown in Figure 2 

and has a very satisfactory signal/noise. Although the in-

tegrated photometry indicates $R_{tot}=21.2$, the mean surface brightness is only $\mu_R=23.4$ ($\simeq7$ per cent of the La Palma night sky). Thus the observation represents a considerable challenge. The spectrum shows a number of strong ultravi-

ela features consistent with a redshift $z=2.515$, close to the 

predicted value. Most noticeable is the prominent feature at 

$\approx4250$ Å which arises from strong Lyman-α absorption. No 

emission lines are seen in the optical spectrum. With our 

new data, we find that multiple image hypothesis is rein-

forced by comparing the spectra of all three images. The 

two halves of #384 show no difference in spectral features, 

while the spectrum of #468 (figure 3), although noisy, is cer-

tainly compatible with that of #384. We return to a detailed 

discussion of the spectral features in the next section.

The verification of the inverted redshift, to within the 

estimated precision, illustrates the power of the lensing tech-

nique for isolating high redshift galaxies as well as for de-

termining the statistical redshift distribution of very faint 

sources. It also shows that the mass model for the cluster 

core is very well determined, and in fact, further constrains 

it. The implications of the comparison of the lensing pre-

dicted redshifts and spectroscopically determined ones will 

be presented in Ebbels et al. (1996b), where the spectro-

Figure 2. (bottom) LDSS-2 spectrum of the arc #384. Both 

strong and more tentative identifications of features indicating a redshift of $z = 2.515 \pm 0.001$ are marked. Sky residuals near 

spectral lines of #384 are visible here, including the Lyman-α transition. 

The arc in question, #384 (Figure 1(top)) in the pho-

The observations were conducted on the nights of May 

28 to June 1 1995. LDSS-2 was used in a conventional multi-

a total exposure of 29.9ksec was obtained with the medium 

blue grism, (5.3Å pixel$^{-1}$, $R \simeq 12$ Å) in conditions with see-

Figure 1. A) Inverted parallel morphology, albeit less distorted by the gravi-

tical shear. Since the source lies so close to a caustic in the source plane, any bright parts of it lying outside this 

caustic would be imaged only in #468. The absence of any 

such extra bright knots in #468 leads us to conclude that 

all high surface brightness parts of the source lie inside the 

caustic line.

The LDSS-2 spectrum for #384 is shown in Figure 2 

and has a very satisfactory signal/noise. Although the in-

(tegrated photometry indicates $R_{tot}=21.2$, the mean surface brightness is only $\mu_R=23.4$ ($\simeq7$ per cent of the La Palma night sky). Thus the observation represents a considerable challenge. The spectrum shows a number of strong ultravi-

ela features consistent with a redshift $z=2.515$, close to the 

predicted value. Most noticeable is the prominent feature at 

$\approx4250$ Å which arises from strong Lyman-α absorption. No 

emission lines are seen in the optical spectrum. With our 

new data, we find that multiple image hypothesis is rein-

forced by comparing the spectra of all three images. The 

two halves of #384 show no difference in spectral features, 

while the spectrum of #468 (figure 3), although noisy, is cer-

tainly compatible with that of #384. We return to a detailed 

discussion of the spectral features in the next section.

The verification of the inverted redshift, to within the 

estimated precision, illustrates the power of the lensing tech-

nique for isolating high redshift galaxies as well as for de-

ing the statistical redshift distribution of very faint 

sources. It also shows that the mass model for the cluster 

core is very well determined, and in fact, further constrains 

it. The implications of the comparison of the lensing pre-

predicted redshifts and spectroscopically determined ones will 

be presented in Ebbels et al. (1996b), where the spectro-
scopic results from all the arclets secured in the WHT run are collated and analysed.

3 PHOTOMETRIC PROPERTIES

Although there are now several examples of non-active galaxies with redshifts above 2, most can only be seen by virtue of their abnormal luminosities. The significant boosting of the source responsible for the arcs #384+#468, together with the serendipitous way in which background galaxies are lensed makes a useful probe of normal galaxies at hitherto unexplored epochs, particularly if, as seems clear, further examples can be found in this way. We now illustrate, using this source as an example, what can be learnt from the photometric and spectroscopic properties of lensed high redshift galaxies.

Multiband photometry from U to K′ is presented for both #384 and #468 in Table 1 where the revised magnification is also given. The most reliable method to estimate the source luminosity is to use the infrared photometry to estimate the rest-frame optical luminosity. This is most suitably done with the (J − K′) rest luminosity of the source, a colour correction from [U − R] rest to J rest is required and this yields M_{bol} = -22.2 (-23.0) ± 0.5 corresponding to a galaxy z ≲ 8-20 (16-40) h^{−2} M_{⊙} L^{−1} for q_{0} = 0.5 (0.1). (Loveday et al, 1992.) However, the blue magnitude is much influenced by star formation and, given its blue colours ((U − R) rest ≈ (J − K′) bol = 2.1), it is possible that the rest frame K luminosity of our galaxy could be closer to L′ than suggested by the above M_{bol} value.

The spectral energy distribution (SED) delineated by the broad-band photometry is plotted in Figure 4 where we compare it to a synthetic spectrum produced by Bruzual & Charlot’s (1993) code and to the smoothed SED of a nearby star forming galaxy, NGC 4449 (Ellis 1984). These both show the SED to be consistent with that of an actively star forming galaxy. Although the best model fit obtained was that of a burst (of age ≥ 3 × 10^{8} yr, no reddening), other models (including those with constant star formation) can also reproduce the gross features of the photometry, particularly given the freedom to invoke reddening, which has sizable effects at UV wavelengths (the exact nature of which is little known at these redshifts). At this redshift, the Lyman limit only just reaches the edge of the U band. Thus the drop in the photometry, although influenced by the Lyman break, cannot easily be compared with the (U − G) cut from Steidel et al. (1996). Following Steidel et al, the UV flux can be used to derive an approximate ongoing star formation rate. In the case of a Salpeter initial mass function, (slope α = 2.35, with 1M_{⊙} ≤ M ≤ 80M_{⊙}), this amounts to z ≲ 7-11 (15-24) h^{−2} M_{⊙} yr^{−1} for q_{0} = 0.5 (0.1), which is similar to the range seen in the Steidel sample and comparable to that in NGC 4449 when allowance for luminosity differences is made (≈ 8M_{⊙} yr^{−1}. (Thronson, 1987))

As only the HST has the spatial resolution to adequately detect internal structures, and the WFPC-2 data is only available in a single band (F702W), no colour variations along arc #384 can be seen. However, the presence of ‘knots’ in Fig. 1 is suggestive of luminous HII regions consistent with a galaxy undergoing strong star formation.

4 SPECTROSCOPIC PROPERTIES

The conclusions based on multiband photometry are also supported by analysis of the spectrum of #384 (Figure 2). The most striking features are the broad Lyman-α absorption and the presence of several ultraviolet metal absorption lines. The latter features are typical of UV lines seen with IUE in the spectra of hot stars and nearby star forming
Identification of a Gravitationally Lensed z=2.515 Star-Forming Galaxy

We have secured the redshift, z=2.515, of a multiply-imaged arc in the rich cluster Abell 2218 which we believe to be the first confirmation of a redshift predicted by a cluster lensing model. The result strongly vindicates the precision of the lensing inversion technique developed by KESCS and further illustrates how gravitational lensing through well-constrained clusters can locate samples of high redshift galaxies. The efficiency of this selection technique may be relatively low, given the surface density of high redshift galaxies found by Steidel et al. and the cluster cross section, coupled with the need for high resolution imaging. However, this method is less susceptible to luminosity biases and redshift selection effects than other techniques.

The source responsible for the lensed images appears to be a blue 8-20 L⊙ galaxy whose on-going star formation rate of 7-11 M⊙ yr⁻¹ is similar to that of similar sources found at higher redshift by Steidel and collaborators using the Lyman limit cutoff as a high z locator. The spectrum reveals UV absorption lines which are consistent with the photometric properties. In particular, the Lyman α line is particularly broad suggesting neutral gas is abundant within the galaxy. In conclusion, we believe that the spectral and photometric properties of this source are consistent with those expected of the objects responsible for high redshift absorption along lines of sight to distant quasars.

Acknowledgments

We thank Claus Leitherer, Howard Yee and Chuck Steidel for sharing their results with us prior to their publication. We acknowledge valuable discussions on the interpretation of ultraviolet spectra and photometry with Bob Carswell,

<table>
<thead>
<tr>
<th>#</th>
<th>μR</th>
<th>U</th>
<th>B</th>
<th>g</th>
<th>V</th>
<th>R</th>
<th>r</th>
<th>i</th>
<th>z</th>
<th>J</th>
<th>K'</th>
</tr>
</thead>
<tbody>
<tr>
<td>384</td>
<td>23.4</td>
<td>22.2</td>
<td>22.2</td>
<td>22.1</td>
<td>21.4</td>
<td>21.2</td>
<td>21.6</td>
<td>20.6</td>
<td>21.5</td>
<td>20.0</td>
<td>17.9</td>
</tr>
<tr>
<td>468</td>
<td>23.5</td>
<td>23.8</td>
<td>23.8</td>
<td>23.6</td>
<td>23.1</td>
<td>22.6</td>
<td>23.1</td>
<td>22.3</td>
<td>22.9</td>
<td>20.9</td>
<td>19.1</td>
</tr>
<tr>
<td>δm</td>
<td>1.6</td>
<td>1.6</td>
<td>1.5</td>
<td>1.7</td>
<td>1.4</td>
<td>1.5</td>
<td>1.7</td>
<td>1.4</td>
<td>0.9</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Optical and Infra-red photometry of #384 and #468. Values for μR & R are taken from KESCS, those for J & K' from Kneib et al. (1995) and those for grz from Le Borgne et al. (1992), where the likely errors are ±0.1, ±0.4 and ±0.3 respectively. Values for UBVλ are taken from new photometry obtained at the 5m Palomar telescope (TEK CCD, seeing 1-1.5 arcsec, exposures of 2.5, 16.5, 5.8, 21.7 ksec respectively). Estimated errors are ±0.1 in BVI and ±0.3 / ±0.6 in U for #384 / #468 respectively. Also listed is the relative magnification, δm = (m384 - m468) of the two images. The unlensed magnitude of the source may be obtained by adding the magnification M to the values in the table, where M384 = 2.9±0.3 and M468 = 1.5±0.1.

5 CONCLUSIONS

of Lyman-α emission in a source with demonstrably active star formation confirms earlier suspicions that such emission can be attenuated by a number of processes (Charlot & Fall 1991,1993). It is important to distinguish the configuration of our system with the QSO absorption scenario. In the QSO case, Lyman-α photons are scattered out of the beam by the absorber. In our case, the sources are embedded within the scattering medium and (as highlighted by Charlot & Fall), the extent of the attenuation depends on the relative abundances and geometry of the mixture of stars, gas and dust.
Max Pettini and Alfonso Aragón-Salamanca. We especially note the help Karl Glazebrook provided as a regular user of LDSS-2, which operates successfully thanks to the dedicated efforts of La Palma support staff and, in particular, Mike Breare. We are grateful to G. Bruzual for allowing the use of his code for the spectral evolution of galaxies. We also acknowledge financial support from the Particle Physics and Astronomy Research Council (TMDE & IS), European Commission (JPK) and the DGICYT (Ministerio de Educacion y Ciencia, Spain) (BS).

REFERENCES