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The double quasar Q2138 − 431: lensing by a dark galaxy?

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ABSTRACT

We report the discovery of a new gravitational lens candidate Q2138 − 431AB, comprising two quasar images at a redshift of 1.641, separated by 4.5 arcsec. The spectra of the two images are very similar, and the redshifts agree to better than 115 km s^{-1}. The two images have magnitudes $B_J = 19.8$ and 21.0, and, in spite of a deep search and image subtraction procedure, no lensing galaxy has been found with $R < 23.8$. Modelling of the system configuration implies that the mass-to-light ratio of any lensing galaxy is likely to be around 1000 $M_\odot/L_\odot$, with an absolute lower limit of 200 $M_\odot/L_\odot$ for an Einstein–de Sitter universe. We conclude that the most likely explanation of the observations is gravitational lensing by a dark galaxy, although it is possible we are seeing a binary quasar.

Key words: galaxies: haloes – quasars: individual: Q2138 − 431 – gravitational lensing.

1 INTRODUCTION

The first secure example of a gravitational lens (Q0957 + 561) was discovered by Walsh, Carswell & Weymann (1979), and comprised two images of a quasar at redshift $z = 1.41$ lensed by a bright cluster galaxy at $z = 0.36$. Since then, many manifestations of gravitational lensing have been observed, including multiply lensed quasars, giant arcs around galaxy clusters, and distortions of the distant galaxy distribution. Historically, systems comprising a pair of quasar images have always had a special significance in the catalogue of lensing phenomena because of the simplicity of the geometry, and the plausibility of using them to measure the Hubble constant (Refsdal 1964). There are at present seven wide-separation (> 2 arcsec), two-component lens candidates known, but progress towards finding a value of the Hubble constant has been slow for several reasons. These include the lack of high-quality light curves over a sufficiently long period of time, the uncertainty of the lensing geometry, the effects of microlensing, and the failure to find the lensing galaxy. In this paper we report the discovery of a new gravitational lens candidate which highlights some of these problems.

This eighth wide-separation system was discovered as part of a systematic survey for lens candidates. It has a separation of 4.5 arcsec, and the two components had B magnitudes of 19.8 and 21.0 in 1995. There is extensive archival photometry of the system over 20 yr, and it appears to be clear of any nearby galaxy concentrations. The two images are strongly variable, but, as for all but two of the other known systems, the lensing galaxy has not so far been detected. The large mass-to-light ratios of the order of several hundred to a thousand implied by these non-detections have prompted several authors to speculate about the possibility of 'dark galaxies'. In this paper we report a variety of observations of the new system, and conclude that in this case too the most probable expanation is that the quasar is being gravitationally lensed by a dark galaxy.

2 OBSERVATIONS

2.1 The lens survey

The survey for gravitational lenses was carried out in the ESO/SERC field 287 centred on 21^h28^m, $-45°$ (1950). Extensive plate material from the UK Schmidt telescope exists in this field, which has formed the basis for the large-scale quasar survey and monitoring programme of Hawkins & Véron (1995, 1996) and Hawkins (1996). The selection of subsamples of quasars in different redshift bands typically used colour limits together with variability and compactness criteria, but in all cases the quasar images were required to be round. This was to eliminate overlapping images which might masquerade as quasars, or even quasars merged with stars or galaxies where the photometry would give misleading results. One consequence of this was to reject any gravitationally lensed quasars from consideration, where the split image would appear elongated. To rectify this, a search was designed specifically to look for gravitationally lensed systems. The requirements were that the images should have a major-to-minor axis ratio greater than 1.5, and an ultraviolet excess $U-B<-0.4$. Of the 200 000 objects in the field, 500 have $U-B<-0.4$, of which 23 were elongated. Of these, 12 were variable according to our usual criteria (Hawkins & Véron 1995), with an amplitude greater than 0.35 mag. Four of the sample were quasars with overlapping galaxies previously found by Morris et al. (1991), and so we set about obtaining spectra for the remainder, several of which appeared to be excellent candidates for lensed systems. It also seems possible that some lensed quasars will be found among the non-variable objects.

2.2 The double quasar Q2138 − 431

The first candidate to be studied in detail appeared as two star-like images separated by 4.5 arcsec. Spectra of the two components were obtained on the ESO 3.6-m telescope at La Silla by aligning the slit along the line of centres. The spectra were very similar, and the redshifts appeared to be the same, $z=1.64$. There seemed to be a *prima facie* case for a gravitationally lensed system, and so a few nights later we obtained a second, higher signal-to-noise observation in both blue and red wavelength bands covering a combined spectral range from 3700 to 10 000 Å. The spectra are shown in Fig. 1, and it will be seen that they closely resemble each other. Fig. 2 shows the quotient of the two spectra which is almost flat, implying no significant differences.

The redshifts were first calculated by measuring the emission lines in each spectrum, which gave $z=1.638\pm0.004$ and 1.644 ± 0.005 for the two components, the same within the errors. In order to obtain a more accurate measurement, a cross-correlation routine was applied. This gave identical redshifts within the errors, and a velocity difference of 0 ± 114 km s^{-1}.

Optical photometry of the system was obtained with a CCD camera on the ESO 2.2-m telescope at La Silla in 1995 August. The pixel scale was 0.336 arcsec pixel^{-1}, and the seeing averaged 1.2 arcsec, which allowed a clear separation of the images. The R-band frame is shown in Fig. 3, where the faintest visible objects have magnitude $R>24$. The results are shown in Table 1, where the five columns are the colour passband, the apparent magnitudes of the two components, the flux ratio and the lower limit to the magnitude of any lensing galaxy. It will be seen that at the time of observation the magnitude difference between the two components was $\delta m=1.2$, with no significant dependence on

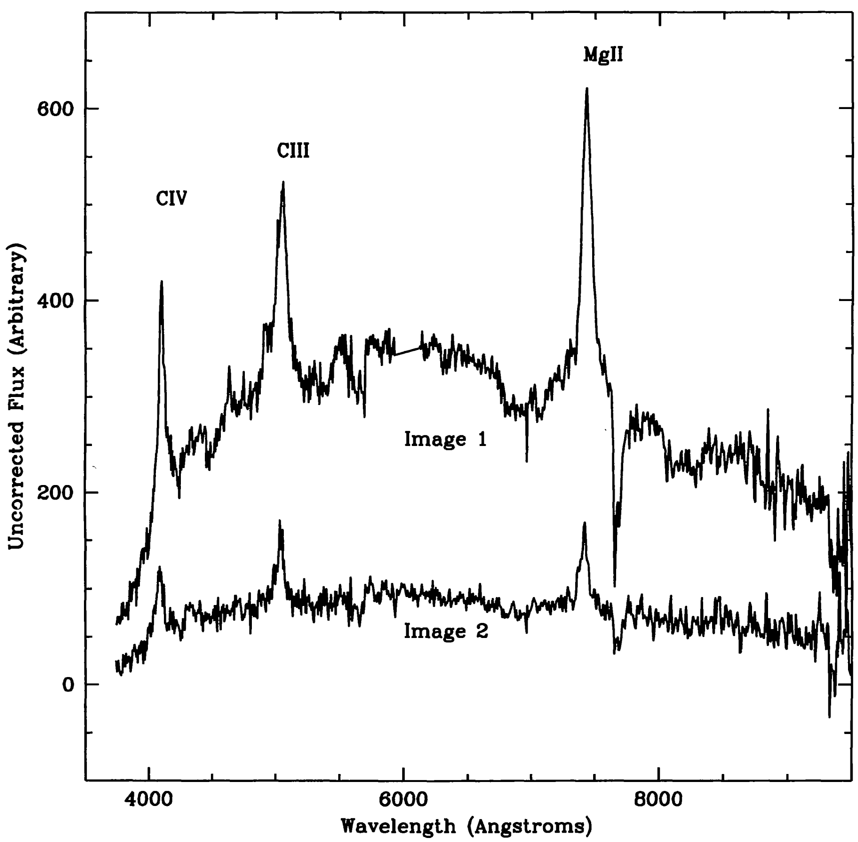

Figure 1. Spectra for the two images of the double quasar Q2138 − 431AB in red and blue passbands.

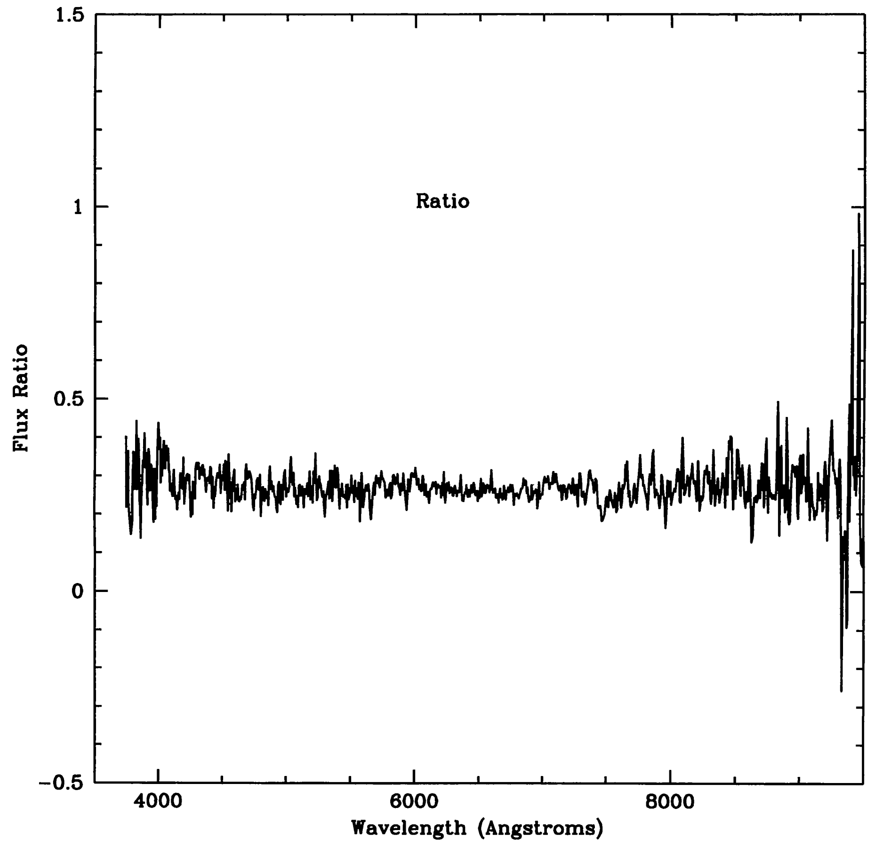

Figure 2. Spectrum of component A divided by that of component B from Fig. 1.

colour. Fig. 4 shows the $V-R$ and $R-I$ colours for the two components of Q2138 – 431, together with photographic measures for 10 other quasars from the sample with very similar redshift. The colours of the double quasar are identical within the errors of the CCD observations, whereas the other 10 quasars in the sample illustrate the wide range of colours which quasars at this redshift can exhibit.

2.3 Search for the lensing galaxy

To understand a gravitational lens system fully, and more specifically to use it to measure the Hubble constant, the lensing galaxy must be located. It is then necessary to measure its redshift, and to estimate the mass distribution relative to the quasar images. In fact, of the seven double quasar systems so far discovered with image separation greater than 2 arcsec, lensing galaxies have been found for only two.

To detect the lensing galaxy for Q2138 – 431, we used the deep CCD frames described above for the photometric measurements. Initial examination of the area around the quasar system showed no objects which might act as gravitational lenses. We obtained a more useful limit by using stars in the vicinity of the quasar images to obtain an accurate measure of the point-spread function (PSF). This was then subtracted from each of the quasar images in the hope of revealing an underlying lensing galaxy. There is an element of uncertainty in the normalization of the PSF in this procedure, but in the event we found that both quasar images subtracted out exactly. To put an upper limit on the magnitude of a possible lensing galaxy, we extracted the faint galaxy visible to the south-east of the quasar in Fig. 3. We then placed it at various points between the two quasar images, varied its brightness and carried out the PSF subtraction procedure. This enabled us to put an upper limit of $R > 23.8$ for a potential lensing galaxy. We also obtained a K-band image of the field with the IRAC2 infrared camera on the ESO 2.2-m telescope. A 5-h integration failed to reveal a lensing galaxy between the two images, although there was evidence for additional K-band flux associated with the brighter component. This observation raises the possibility that a very red lensing galaxy may be lying close to the brighter quasar image, a configuration which requires fine-tuning of the model parameters.

One can now ask what limits can be put on the mass-to-light ratio of a lensing galaxy capable of producing the observed image splitting and flux ratio, but constrained to be fainter than the observed magnitude limit. We have modelled the system assuming both a point mass and a more realistic galaxy profile, and have thus derived a lower limit to the mass-to-light ratio as a function of redshift. If the lens can be modelled as a point mass, the brightness ratio $R > 1$ of the two images and the separation $\Delta\theta$ on the sky can be used to calculate the Einstein radius

$$\theta_E = \sqrt{4GMD_{LS}/(D_{OL}D_{OS}c^2)},$$

where M is the lens mass, and the Ds are the angular diameter distances between observer, lens and source.

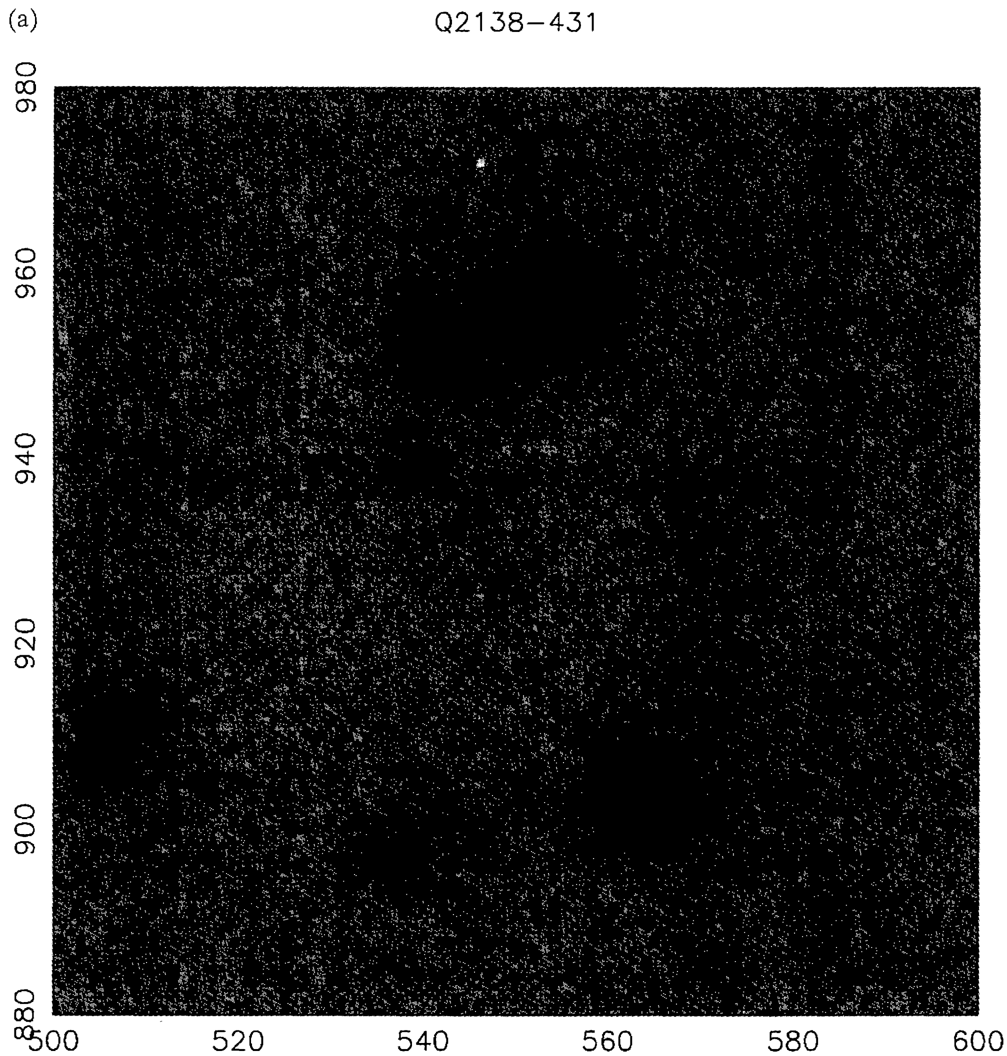

Figure 3. (a) Part of an R-band CCD frame of the field around the double quasar Q2138 − 431. The plot is 50 arcsec on a side, and north is up the page, east to the left. The centroid of the two quasar images is at $21^h38^m6\overset{s}{.}66$, $-44°10'50\overset{''}{.}$ (1950), and they are separated by 4.5 arcsec. The star about 20 arcsec to the south was used for the image subtraction, the effect of which is illustrated in the second panel (b).

It is straightforward to show, from the lensing equations (see, e.g., Schneider, Falco & Ehlers 1992), that $\theta_E = \sqrt{1-f^2}\Delta\theta/2$, where $f \equiv (R+1-\sqrt{4R})/(R-1)$. θ_E is 2.1 arcsec, and the required mass is shown in Fig. 5(a) for two different cosmologies (solid line: Einstein–de Sitter, dashed line: $\Omega_0 = 0.1$). Also shown (dot–dashed) is the mass required in a more realistic Hernquist mass profile (Hernquist 1990), with a density run $\rho(r) = M/[2\pi r_c^2 s(1+s)^3]$, where $s = r/r_c$, and the core radius is taken to be $r_c = 1.7\,h^{-1}$ kpc. An advantage of this profile is that the bending angle may be written in closed form; the enclosed mass within a projected radius rr_c is

$$\frac{M(<rr_c)}{M} = \frac{r^2}{r^2-1} - \frac{r^2}{(r^2-1)^{3/2}}\cos^{-1}\left(\frac{1}{r}\right) \qquad r>1 \qquad (1)$$

$$= \frac{r^2}{r^2-1} - \frac{r^2}{(1-r^2)^{3/2}}\ln\left(\frac{r}{1-\sqrt{1-r^2}}\right) \qquad r<1, \quad (2)$$

with $M(<r_c) = M/3$. Here one needs to search for a solution with the correct brightness ratio and separation, and we see from Fig. 5(a) that for r_c appropriate for galaxies, the required mass is similar to the point-mass calculation. In view of the relatively large masses required if the lens is near the source, it is worth exploring a larger core radius, appropriate for a cluster. However, the only Hernquist profiles which are able to produce split images with the required amplification ratio have core radii less than $7\,h^{-1}$ kpc, so we are restricted to galaxy-like objects (Fig. 5a also shows the mass required for a core radius of $5\,h^{-1}$ kpc). It is also worth noting that it requires an astonishing degree of fine-tuning for the faint third image in the Hernquist model to alter significantly the brightness ratio by merging with another image.

It will be seen from Fig. 5(a) that there is an absolute lower limit of $200\,M_\odot/L_\odot$ when the lens is at a redshift $z = 1.5$ for an Einstein–de Sitter universe, and a slightly lower limit if the Universe is open. In fact, this configuration

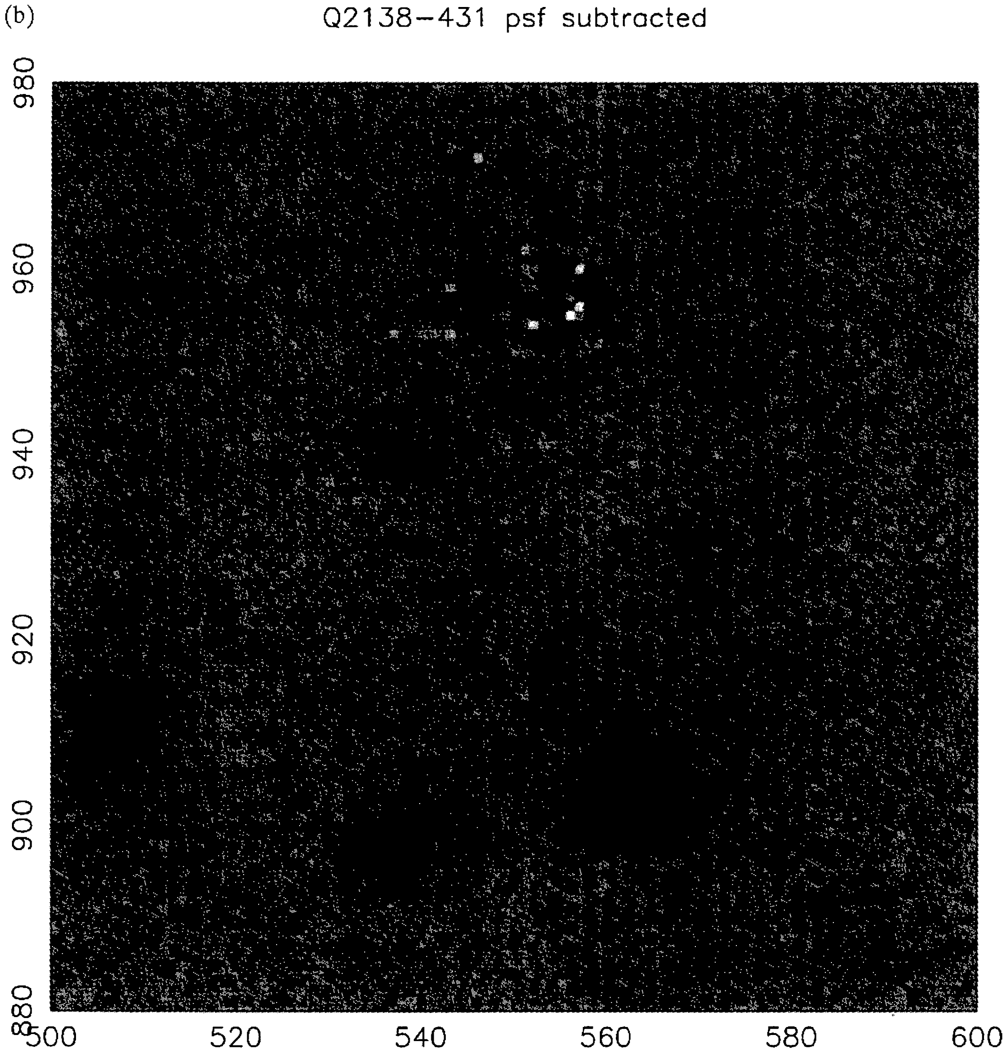

Figure 3 – *continued*

Table 1. CCD photometry for Q2138 − 431AB.

colour	m_A	m_B	f_A/f_B	$m_{gal} >$
B	21.02	19.83	0.33	23.
V	20.85	19.57	0.307	23.5
R	20.43	19.18	0.318	23.8
I	20.12	18.86	0.313	22.8

is highly improbable, and the most likely position for the lens is at around $z = 0.5$ (Turner, Ostriker & Gott 1984), implying a minimum mass-to-light ratio of 1000 $M_{\odot}/L_{\odot}$. In this case the lensing object would presumably be some form of 'dark galaxy', or perhaps a dark matter galactic halo.

Another approach is to consider the possible effect of shear or convergence produced by a nearby group or cluster of galaxies. This is a model which has been used to describe Q0957 + 561 (Bernstein, Tyson & Kochanek 1993), and also for the wide separation lens Q2345 + 007 (Pelló et al. 1996).

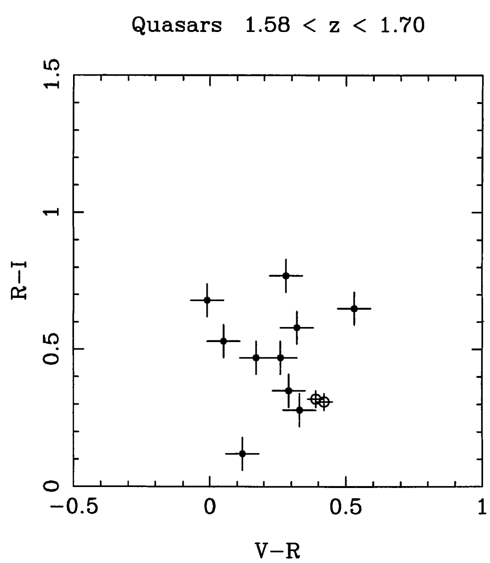

Figure 4. The $V-R$ versus $R-I$ relation for quasars with $z \approx 1.64$. The two components of Q2138 − 431 are shown as open circles, and 10 other quasars from the field 287 sample as closed circles.

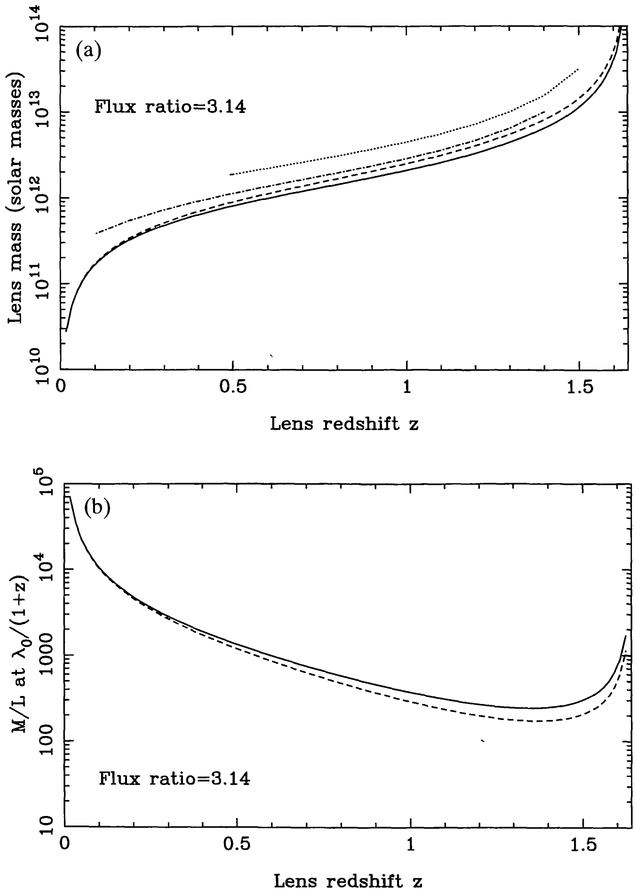

Figure 5. (a) The mass of the postulated lens for the double quasar Q2138 – 431AB as a function of the lens redshift. The solid line assumes a point-mass lens and an Einstein–de Sitter universe; the dotted line assumes that $\Omega_0 = 0.1$ and no vacuum energy. The dot–dashed line shows the required mass if the density distribution follows a Hernquist profile with core radius $1.7\,h^{-1}$ kpc (corresponding with an effective radius of $3\,h^{-1}$ kpc), and the dotted line assumes a core radius of $5\,h^{-1}$ kpc. The last two curves assume $\Omega_0 = 1$. (b) The minimum mass-to-light ratio for a lens for the double quasar Q2138 – 431AB. Lines as in (a).

In both of these cases a group of galaxies is detected close to the quasar images, and the splitting is attributed to the resulting shear field. We are in a much worse position here to model such a situation, as we cannot even establish where the lensing galaxy is (if present). The addition of a uniform screen, representing a smooth cluster, would reduce the mass estimates by a factor $1 - \Sigma/\Sigma_c$, where the critical surface density is $\Sigma_c = c^2 D_{OS}/(4\pi G D_{OL} D_{LS})$. The mass requirement is thus eased if the cluster has a substantial fraction of the critical surface density. Numerical modelling of clusters (Bartelmann & Weiss 1994) indicates that this may be possible, but modelling of observed arcs routinely requires a contribution from a central galaxy (Miralda-Escudé & Babul 1995). Although a significant cluster contribution remains an open possibility, the very small core radius required argues against it, and there is no evidence apparent in the images. Fig. 6 shows an area of approximately 8 arcmin on a side centred on the double quasar. The frame is taken from a digital stack (Hawkins 1994) of 64 UK Schmidt plates in the IIIa-J/GC395 passband with effective wavelength 4500 Å. The limiting magnitude is $B_J \sim 24$, and there is no sign of a cluster within 2 arcmin of the quasar. In fact, judging by the surrounding background, the system lies in a particularly clear region of sky, the nearest cluster being in the top right-hand corner of the field.

3 DISCUSSION

The properties of the double quasar Q2138 – 431AB may be summarized as follows:

Redshift $z = 1.641$.
Velocity difference $\delta v = 0 \pm 115$ km s^{-1}.
Separation = 4.5 arcsec.
B magnitudes: $m_A = 19.8$, $m_B = 21.0$.
Variability amplitudes: $\delta m_A = 1.1$, $\delta m_B = 0.6$.

We now address the question of the underying nature of the system. There seem to be three possibilities:

(1) a chance association of two separate quasars, possibly made more likely by the effects of clustering;
(2) a pair of quasars in a bound orbit, forming a binary system, and
(3) a single quasar gravitationally lensed by a dark galaxy or galactic halo with a mass around 10^{12}–10^{13} M$_\odot$.

The likelihood of a chance coincidence can first be assessed by considering the surface density of the parent population of quasars in the field and asking what is the probability P that two will lie within 4.5 arcsec of each other. The parent population of single quasars with similar characteristics to the lens candidate comprised 310 objects with $U - B < -0.4$ and $B < 21$ in an area of 18.8 deg^2, This gives a surface density of quasars of about 16 per deg^2, which implies a probability of about 1 per cent for any companions within 4.5 arcsec, for the parent sample of ~ 310 quasars. In practice, one would expect this figure to be modified by clustering, which enhances the probability, and by the redshift information, which reduces it. The small-scale clustering of quasars is poorly constrained, but, assuming that it follows the galaxy correlation function $\xi(r) \simeq (r/r_0)^{-\gamma}$, with $r_0 \simeq 5\,h^{-1}$ Mpc and $\gamma \simeq 1.8$ (Collins, Nichol & Lumsden 1992; Vogeley et al. 1992), boosted by a relative bias b_Q^2, we can calculate the probability of a pair within 50 h^{-1} kpc (the comoving separation corresponding to 4.5 arcsec at $z = 1.6$ if $\Omega_0 = 1$). Using the comoving number density of $1.7 \times 10^{-5}\,h^3$ Mpc^{-3} obtained from the redshift distribution in the sample at redshifts around 1 to 1.5, we find this probability to be about 1.5 per cent if $b_Q = 1$ and the clustering does not evolve. This is, however, an underestimate for lensing candidates, since the radial separation can far exceed 50 h^{-1} kpc and still be considered a good lensing candidate. For illustration, a velocity difference of 100 km s^{-1} at a redshift of 1.6 corresponds to a comoving separation of around 600 h^{-1} kpc in an Einstein–de Sitter universe, and this could easily be lost in the uncertainties of redshift determination. If, instead of a radial separation of 50 h^{-1} kpc, we use this larger figure of 600 h^{-1} kpc, the probability would be increased to around 2.5 per cent. Peculiar velocities modify this in a model-dependent manner, reducing the chance of good agreement in the redshifts for virialized systems and increasing it for collapsing systrems, but the point is that the

Field of Q2138−431

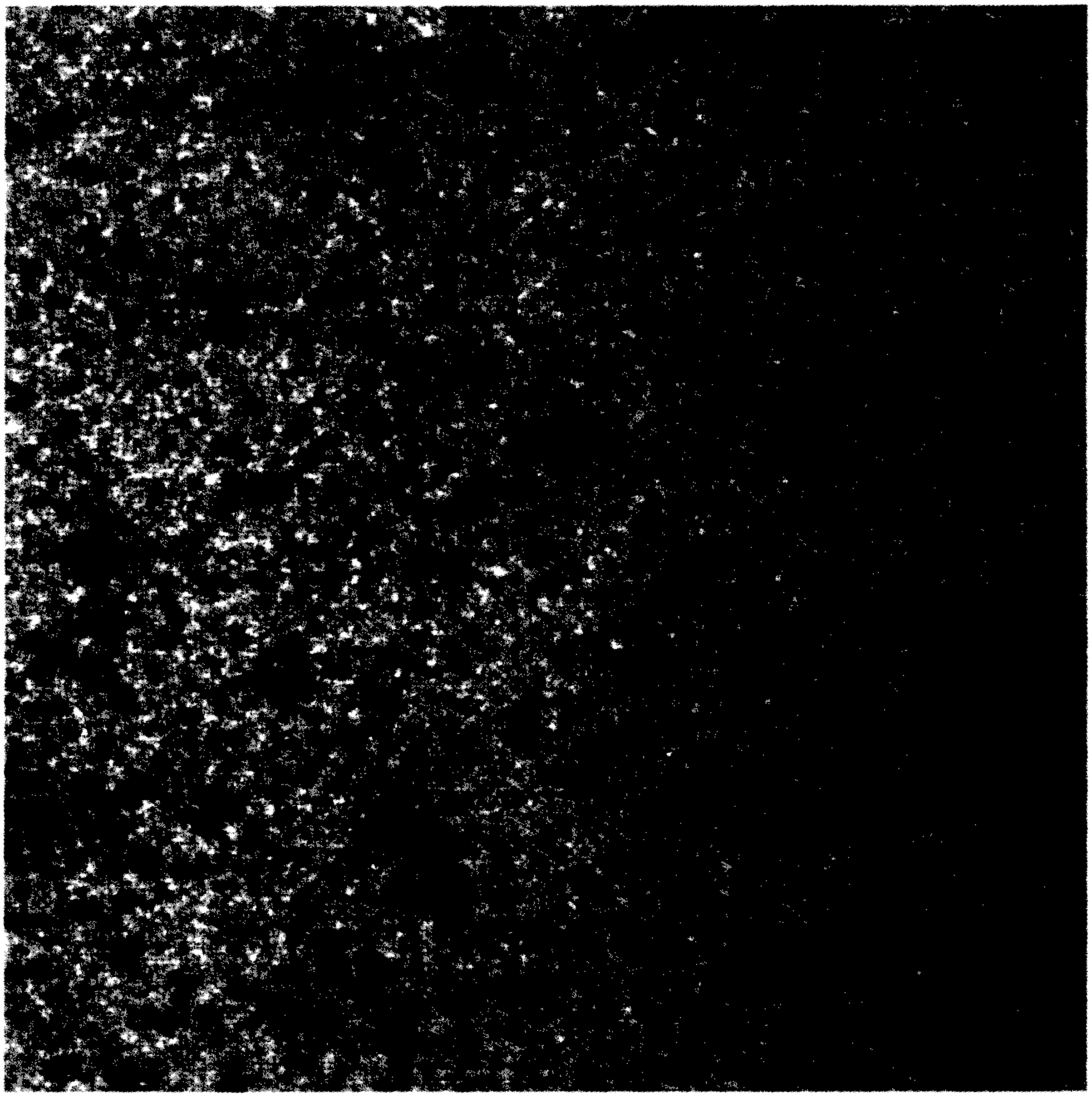

Figure 6. Plot of the area centred on Q2138 − 431. The frame is approximately 8 arcmin^2, and is derived from digitally stacked photographic plates with a limiting magnitude of $B_J \sim 24$. North is up the page, east to the left.

probability of a close separation in angular and redshift terms is small but not negligible.

The idea that the quasars form part of a gravitationally bound binary system is much harder to test, mainly because the circumstances surrounding the formation and evolution of such a system are largely a matter of speculation. There are a number of observations which appear to count against this possibility, such as the extreme similarity of the spectra and colours of the two components and the small differential velocity. It is also clear from the discussion in the previous paragraph that, from a statistical point of view, binary quasars might just be part of a clustering hierarchy. However, none of these arguments is sufficient to rule out the essentially unconstrained concept of binary quasars, and it must remain a possible explanation.

A plausible justification for the binary, or clustered, model is that quasar activity may well be triggered by a close encounter between two galaxies, with a small probability of triggering. The possibility then arises that, in rare cases, quasar activity may be initiated in both galaxies in the encounter. The explanation of the similarity of the spectra, which are not absolutely identical, might then lie in the fact that the quasars would have the same formation epoch, and would be observed at the same time after formation. As part of a common system, their abundances might not significantly differ.

The third possibility, that the system is gravitationally lensed, is well supported by most of the available observations. The similarity of the spectra and colours and the small velocity difference between the two components are to be expected from a gravitationally lensed system. The problem is the failure to find the lensing galaxy. Given the apparent absence of a shear field, this means that to make a case for a gravitationally lensed system one must postulate a dark galaxy as the lens. Although this may seem a radical step, it is, in fact, a position which several other groups have adopted when analysing double quasar systems (e.g. Tyson et al. 1986). An obvious possibility is that the lensing object is a low surface brightness galaxy, which fails not because of the surface brightness limit corresponding with the R limit of 23.8, but rather because known low surface brightness galaxies do not have the very large mass-to-light ratio required (Sprayberry, Bernstein & Impey 1995). We are left with the conclusion that, unpalatable though the idea of dark galaxies may be, it seems to promise the most plausible explanation for the observations.

4 CONCLUSIONS

We have reported the discovery of a new double quasar Q2138 − 431, which we have observed in some detail with a view to establishing whether it is a gravitationally lensed system. It comprises two images with magnitudes $B = 19.8$ and 21.0, separated by 4.5 arcsec. The spectra and colours of the two components are very similar, with a redshift of $z = 1.461$ and velocity diference $\delta v = 0 \pm 115$ km s^{-1}. In spite of an intensive search, we have failed to find a lensing galaxy, which must have a magnitude $R > 23.8$. This has enabled us to put a lower limit on the mass-to-light ratio of any lensing galaxy in the range 200 to 1000 $M_{\odot}/L_{\odot}$, depending on its redshift. We have considered three possible interpretations of the system.

(1) Chance coincidence of the two images, which we rule out on statistical ground.

(2) A gravitationally bound binary quasar. The similarity of the two components and the small velocity difference count against this possibility, but we feel that we cannot rule it out.

(3) A gravitational lens. Most of the observations favour this picture, but the lensing object would have to be a dark galaxy or a dark matter halo. This would clearly require a departure from the conventional idea of the galaxy population.

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