

Dark Galaxies – the Dominant Population?

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Abstract. This paper argues that there is a large population of dark galaxies which reveals its presence by the gravitational lensing of quasars, and outnumbers normal galaxies by around 3:1. There are 8 double quasars with a separation greater than 2 arcseconds which have been classified as probable or certain gravitational lenses. Lensing galaxies have only been found for 2 of these systems, and analysis of the remainder has led in each case to the conclusion that they are best explained by the gravitational lensing effect of a ‘dark galaxy’. Here we examine the ensemble properties of this sample and conclude that there is overwhelming evidence that the systems are indeed being gravitationally lensed by dark galaxies or perhaps dark matter galactic halos. The existence and nature of such objects raises some intriguing questions, as well as having profound implications for large scale structure. Several of the quasar systems show strong evidence for microlensing. It is argued that this implies a substantial component of dark matter in the form of compact bodies, either in the halo of the lensing galaxy or more generally along the line of sight.

Key words: galaxies: fundamental parameters – galaxies: statistics – dark matter – gravitational lensing

1. Introduction

In this paper we examine the small but well-known class of double quasars where a quasar image has apparently been split into two by the gravitational lensing effect of a galaxy mass object along the line of sight. In most cases the lensing galaxy is not detectable, and the tight limits on the mass-to-light ratios suggest that the galaxies may be ‘dark’ in the sense that they have failed to form stars. This could be because they do not contain baryonic material, or more plausibly because the conditions for extensive star formation are not present.

In order to establish the existence of the dark galaxies, it is necessary to make the case that the double quasars are lensed and not binary systems, and that the lensing

galaxy is truly dark and not concealed in some way. For any particular quasar pair it is sometimes possible to argue special circumstances which circumvent the need to invoke a dark galaxy. In this paper we use the statistical properties of the known systems to argue that there is indeed a population of dark galaxies to be explained.

2. The quasar sample

At present there are 8 double quasars known with a separation greater than 2 arcseconds that are plausible lens systems (Walsh et al. 1979; Surdej et al. 1987; Weedman et al. 1982; Djorgovski & Spinrad 1984; Meylan & Djorgovski 1989; Hewett et al. 1989; Wisotski et al. 1993; Hawkins et al. 1997). The properties of these systems are summarised in Table 1, and include the redshift, the separation in arcseconds, the magnitudes of the two components in the R band, and the velocity difference. The last 3 columns refer to the lens and are discussed later. It will be seen that all systems have an

image separation less than 8 arcseconds. The surface density of quasars to a magnitude limit of $B = 21$ is about 30 per square degree (Hawkins & Véron 1995). This implies that the probability of a given quasar having a companion at a distance of 2 – 7 arcseconds is in the range $10^{-4} - 10^{-5}$. Thus in a typical search of 1000 candidates there is a probability of 1% to 10% of finding a close pair by chance, not a particularly unlikely outcome. This will be made more likely by the effects of clustering, and less likely by the additional requirement for the redshifts to be the same in a lensed system. Various selection effects will further change the probability, but it seems unlikely that random associations can be convincingly ruled out on statistical grounds in any particular case (see for example Hawkins et al. 1997).

3. Tests for gravitational lensing

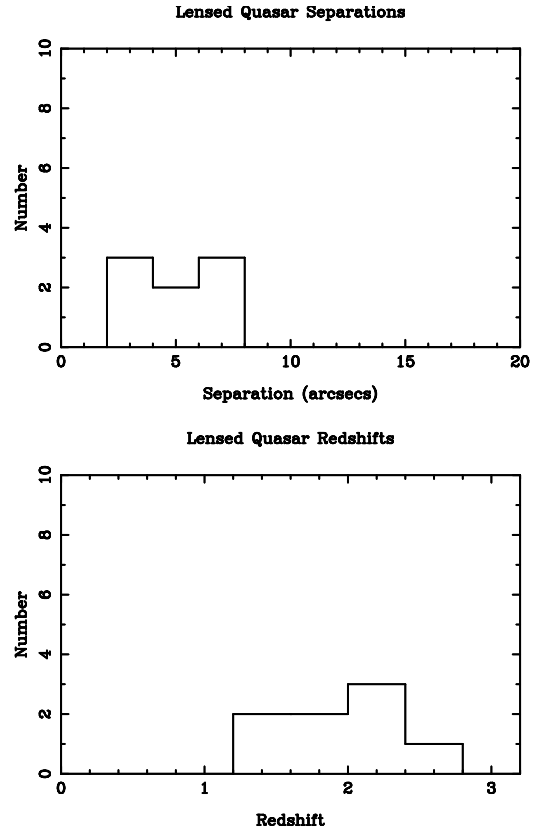
The existence of the small sample of lens candidates in Table 1 makes it possible to carry out a different test. The

Table 1. Parameters for double quasar systems

Name	z	sep (")	m _A	m _B	δm	δv (km sec ⁻¹)	R _g	M _g 10 ¹² M _⊙	M/L
Q0957+561	1.41	6.1	16.6	17.0	0.4	3 ±14	18.5	1.8	26
Q0142−100	2.72	2.2	16.9	19.1	2.2	−24 ±109	19	0.2	4
Q2345+007	2.15	7.0	18.9	20.4	1.5	15 ±20	26	2.6	22000
Q1635+267	1.96	3.8	19.1	20.7	1.6	41 ±54	23.5	0.7	590
Q1120+019	1.46	6.5	16.5	21.2	4.7	200 ±100	23	2.0	1100
Q1429−008	2.08	5.1	17.7	20.8	3.1	260 ±300	24	1.3	1700
Q1104−180	2.30	3.0	16.7	18.6	1.9	0 ±90	24	0.4	540
Q2138−431	1.64	4.5	19.8	21.0	1.2	0 ±115	23.8	1.0	1100

distribution of separations is shown in Fig. 1(a). If the double quasars are chance associations, one would expect the histogram of separations to increase linearly. Selection effects will tend to increase this trend, as close pairs are typically the hardest to find. In fact the distribution falls to zero beyond 8 arcsecs, even though most surveys are aimed at detecting associations to at least 20 arcsecs (Webster et al. 1988; Reimers 1990; Sramek & Weedman 1978). At greater distances the probability of chance coincidences is no longer negligible, although as Schneider (1993) points out it is perhaps surprising that even now very few other quasars with similar redshifts are known with separations less than two arcminutes. If there are indeed no systematic effects in the selection, then the hypothesis that the observed separations are consistent with chance associations can be ruled out as completely negligible by a Kolmogorov-Smirnoff test. If one adopts a correlation function (Collins et al. 1992) of the form $r^{-0.7}$ this flattens the expected relation to $r^{0.3}$ but this is still inconsistent with the data at a very high confidence level. If on the other hand quasars are gravitationally lensed, the separation is basically determined by the mass of the lens. To produce the largest separation of about 7 arcseconds a lensing mass of $3 \times 10^{12} M_{\odot}$ is required, similar to that of the most massive galaxies known. This statistical argument is only modified for binary quasars formed in the same protogalactic environment if there is some sort of mutual triggering mechanism for quasar activity, an idea which is at present of a speculative nature.

Fig. 1(b) shows a histogram of redshifts of the quasars in Table 1. It will be seen that the distribution is highly asymmetric. All 8 quasars have a redshift $z > 1.4$ in contrast to the expected distribution which is almost flat (Hewett et al. 1993). Although a proper statistical test is difficult to carry out as several different search procedures were used (Webster et al. 1988; Reimers 1990; Hawkins et al. 1997; Sramek & Weedman 1978) with possibly different redshift biases, none of them would appear to discriminate significantly against low redshift objects, and there is no lack of single low redshift quasars. On the other hand, the observed redshift distribution agrees well with that ex-

**Fig. 1.** Histograms of the properties of the double quasar systems in Table 1. The top panel shows the distribution of separations of the two components and the bottom shows the distribution of redshifts.

pected on the basis of gravitational lensing probabilities (Turner 1990), which drop sharply below a redshift $z = 1$. The velocity difference between the two components in all the systems in Table 1 is consistent with zero, and in all but two cases has an upper limit of about 100 km sec⁻¹. The observed pairwise velocity dispersion is (Ratcliffe et al. 1996) about 400 km sec⁻¹. This is much larger than the observed limits, but must be reduced to allow for evo-

lutionary effects. This test can be improved considerably when tighter limits can be placed on the velocity differences.

The claims that systems in the bottom part of Table 1 are lensed rest largely on detailed comparisons of the spectra of the two components (Meylan & Djorgovski 1989; Hewett et al. 1989; Turner et al. 1988; Steidel & Sargent 1991; Wisotski et al. 1995). It is generally accepted that small differences in the continuum and absorption line systems can be accommodated within the lensing picture as effects of time delay, microlensing and different light paths for the two components. Nonetheless, spectra of the two components are found to be very similar, and the emission line systems all but identical. This raises the question of how similar one might expect two arbitrary quasars at the same redshift to be. Although it is still difficult to answer this question properly (Turner et al. 1988), one can quite easily compare the colours of the two components with a sample of quasars at the same redshift. There are two systems in Table 1 which have accurate multicolour CCD photometry, and these are plotted in Fig. 2 together with all quasars with a similar redshift from the survey of Hawkins & Véron (1995). Although the two components of the double quasars have identical colours within the measurement errors, there is a wide spread in colour for other quasars at the same redshift.

4. Lensing by dark galaxies?

Taking together the individual analysis of each double quasar with the ensemble properties discussed here, there appears to be an overwhelming case that the systems in Table 1 are gravitationally lensed. This then raises the question of the nature of the lensing objects. For the first two systems, lensing galaxies are clearly visible at $z = 0.39$ and $z = 0.45$, near the most probable value (Turner et al. 1984). The lensing object lies close to the fainter component, as expected for lensed systems. For the remainder, in spite of intense efforts (eg Tyson et al. 1986) no lensing galaxies have been found. Limits of $R > 23$ to $R > 26$ have been put on the magnitude of any possible lens, implying mass-to-light ratios in excess of $500 M_{\odot}/L_{\odot}$. The last 3 columns in Table 1 show the R-band magnitude limit placed on a possible lensing galaxy, the mass of the lens and the resulting mass-to-light ratio, assuming $H_0 = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1}$. The mass of the lens is based on the separation of the two components, and where a lensing galaxy is undetected assumes a lens at $z = 0.5$, the most probable redshift (Turner et al. 1984). The M/L can only be reduced significantly by putting the lens close to the quasar. This is a very unlikely configuration (Turner et al. 1984), and requires a large increase in the mass of the lens. The mass-to-light ratios in Table 1 are at least 10 to 100 times larger than for normal galaxies (White 1990), which can effectively be ruled out as lens candidates.

It has been known for some time (Narayan et al. 1984) that diffuse mass distributions such as galaxy clusters can in principle produce multiple images of quasars. This can be done either by the cluster on its own, or in combination with a galaxy. In the first case fine tuning is required to produce separations of a few arcseconds, but this may be partly offset by the effects of amplification bias. One would also expect the closer quasar pairs to be brighter, a trend which is not evident in the systems in Table 1. The presence of a galaxy between the two images combined with an increase in surface mass density from a cluster can produce a larger separation than would be seen from the galaxy alone, suggesting a larger mass-to-light ratio. This picture has been suggested as an explanation for the wide separation system Q2345+007 where shear has been detected and a candidate cluster is visible (Pelló et al. 1996). There should however be a third fainter quasar image between the two brighter images which has not so far been detected.

It is hard to escape the conclusion that ‘dark galaxies’, or perhaps dark matter galactic halos, are responsible for lensing 6 out of the 8 quasars in Table 1. If we accept that the quasar lenses represent a fair sample of galaxies we must conclude that 3 in 4 galaxies are dark, in the sense that they have a mass-to-light ratio of at least several hundred M_{\odot}/L_{\odot} . A mechanism for formation and evolution of such galaxies has recently been described by Jimenez et al. (1997).

In most of the systems there is evidence for microlensing (Wisotski et al. 1993; Hawkins et al. 1996; Steidel & Sargent 1991; Schild 1996). This could be caused by stars or other compact objects in the lensing galaxy, but would require an optical depth to lensing approaching unity to produce a high probability of variation (Kayser et al. 1986; Schneider & Weiss 1987). Thus the total dark matter content of the galaxy would have to be in the form of microlensing bodies (Kayser et al. 1986), and the stellar population would not be sufficient except perhaps close to the nucleus. Even if the lensing galaxy were entirely composed of microlensing bodies it typically lies close to the fainter of the two quasar images, and is not in a position to lens the brighter image. It is perhaps more plausible that the microlensing arises from a general distribution of dark matter bodies along the line of sight (Hawkins 1996), but either way it supports the idea of dark matter in the form of compact bodies.

5. Conclusions

In this paper we have defined a sample of double quasars which are plausible gravitational lens candidates. In each individual case earlier papers have made strong but not conclusive arguments that they are indeed gravitationally lensed systems. Here we consider the ensemble properties of these candidates from a statistical point of view and conclude that there is an overwhelming case that most if

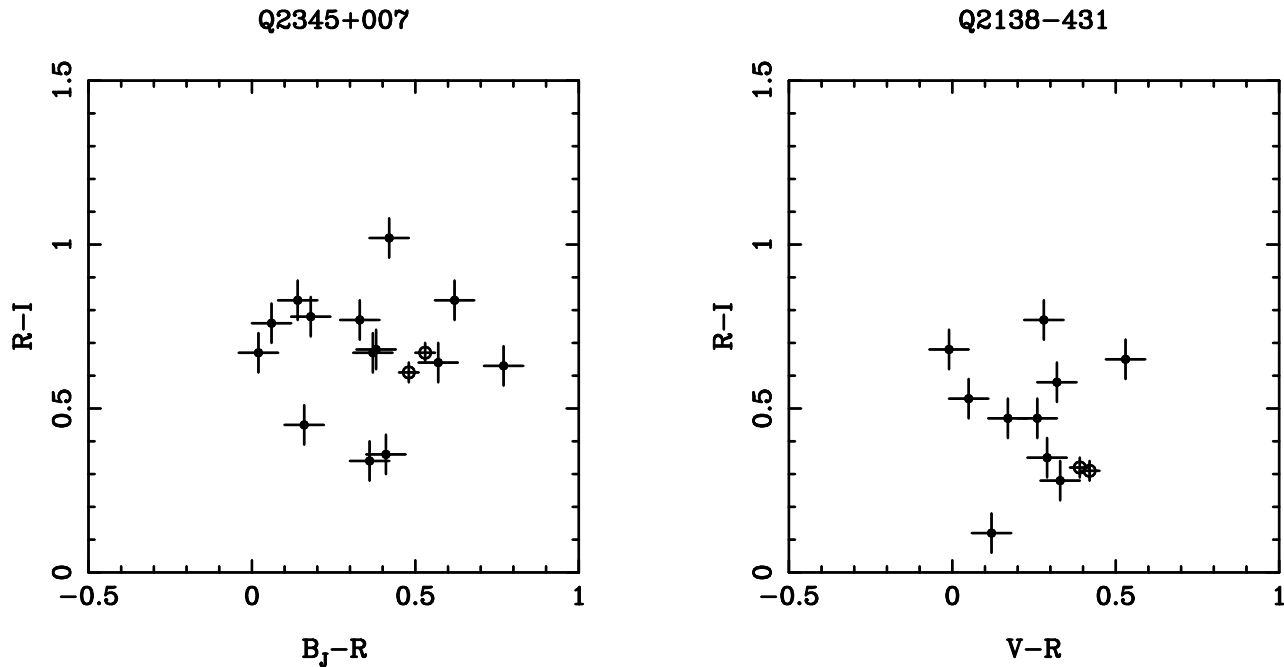


Fig. 2. Two colour diagrams for quasars. The open circles are CCD measures of the two components of double systems, and the filled circles are photographic measures of other quasars with similar redshifts ($\delta z < 0.06$).

not all the quasars are lensed. 6 out of 8 of the systems contain no detectable lensing galaxy, implying a minimum mass-to-light ratio of several hundred, and suggesting that dark galaxies may outnumber normal ones by a substantial amount.

Most of the double quasar systems show evidence for microlensing. If this is caused by compact bodies in the lensing galaxy it would imply that the dark halo was made up almost entirely of substellar compact bodies. A more plausible picture may be one in which the microlensing is taking place all along the line of sight, and double systems are no different from normal quasars in this respect.

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