Galaxies and clusters around and in front of radio
sources at $0.5 < z < 4.5$

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Abstract

Some recent work on radio source fields at $z \sim 0.7$ and $z \sim 4$ is dis-
cussed. At $z \sim 0.7$ we find that radio-loud quasars are typically found in
moderately rich environments independent of radio luminosity, consistent
with previous results at $z \sim 0.5$. In the field of the $z = 4.41$ radio galaxy
6C0140+326 we find several candidate $z > 4$ galaxies using the Lyman-
break technique, two of which have detectable UV absorption features.
In two $z > 4$ radio galaxies, we find evidence for gravitational lensing
affecting the fluxes by a few tens of percent, although we cannot rule out
unusual lensing events which have larger magnifications associated with
them. A simple calculation suggests lensing of $z > 4$ radio sources should
be very common.

1 Introduction

The discoveries that powerful FRII radio galaxies and radio-loud quasars are
frequently found in moderately rich clusters by $z \sim 0.5$, in contrast to the
situation at low redshifts, represent a large evolutionary change in the relatively
recent past (Hill & Lilly 1991; Ellingson, Yee & Green 1991). Studying the
cluster environments at higher redshifts is clearly important, and is possible in
the optical up to $z \sim 0.8$.

At $z \gtrsim 0.8$ when the 4000Å break redshifts out of the optical window, cluster
galaxies become hard to distinguish from the background. This can be partly
improved by observing in the near-infrared, but even here the slow change of
angular size distance with redshift means that clusters of a given physical size
become no more compact on the sky. At the highest redshifts, spectral methods
of identifying companion galaxies become necessary, for example narrow-band
or, at sufficiently high redshift, Lyman-limit techniques.

Foreground clusters may be important too. Claims of statistical correla-
tions between luminous radio sources and foreground galaxies (Benitez et al.
1997; Hammer & LeFevre 1990) are supported by correlations seen for different
classes of AGN with foreground galaxy and cluster catalogues (e.g. Bartsch,
Barthelmann & Schneider 1997; Rodrigues-Williams & Hogan 1994) and by the
detection of shear fields around a few $z \sim 1$ radio sources (Fort et al. 1996;
Schneider et al. 1997). The nature of the lensing population, and how it is able
to produce these effects whilst retaining a plausible form for the AGN luminos-
ity function remains a mystery, but large (i.e. cluster-sized) lenses could lens
both radio sources, any close companions, and any even higher redshift objects
in the field.

In this paper I begin by describing some early results of optical observa-
tions of the cluster environments of a sample of radio-loud quasars at $z \sim 0.7$
made with the NOT, as part of an on-going programme to study the cluster environ-
ments of radio sources and radio-quiet quasars at $z \sim 0.7$, in collaboration with
Margrethe Wold and Per Lilje. I then discuss some work currently under way
with my student Robin Stevens on $z > 4$ Lyman limit systems, before discussing
weak lensing results on the two most distant radio galaxies.

2 Clusters at $z \sim 0.7$

We have embarked on a programme of imaging the fields of $z \sim 0.7$ AGN using
the Nordic Optical Telescope to measure the richnesses of their environments.
We have taken data on the fields of radio-loud quasars, radio-quiet quasars and
radio galaxies, selected so as to span as large a range in AGN luminosity as
possible ($> 10$ in all cases). The data on the radio-loud quasars has been fully
analysed (Wold 1996) and reveals that the environments of $z \sim 0.7$ radio-loud
quasars are similar to those of the $z \sim 0.5$ quasars studied by Ellingson et al.
(1991), i.e. these objects are frequently found in moderately rich clusters. There
is no strong dependence on the environment with radio luminosity over a range
of $\sim 100$ in radio power, consistent with the results for $z \sim 0.5$ radio galaxies
found by Hill & Lilly (1991). Our results will be discussed in more detail in
Wold et al. (1998, in prep).

These results are an interesting contrast to those of Roche et al. (1997) for 6C
radio galaxies. In these, which are only about four times fainter than 3C radio
galaxies at the same redshift, they find that the scale-sizes and luminosities are
significantly smaller than those measured for 3C radio galaxies by Best et al. (1997). This would suggest that 3C galaxies are more massive than 6C ones and are therefore likely to reside in richer environments. This implies a significant change in the dependence of clustering on radio luminosity over a relatively short period of cosmic time.

3 Lyman break galaxies at $z > 4$

With my PhD student in Oxford, Robin Stevens, I have been working on detecting Lyman-break galaxies in the fields of $z = 3.4 - 4.4$ radio sources. We have imaged the fields of B2 0902+34 ($z = 3.4$), 4C41.17 ($z = 3.8$), 8C1435+635 ($z = 4.25$) and 6C0140+326 ($z = 4.41$) with the WHT prime focus (field area $\approx 40 \text{arcmin}^2$). We have used $U$-band as the short wavelength filter for the two $3.4 < z < 4$ sources and $B$-band for the others. Spectroscopy with LDSS2 on the WHT of the 6C0140+326 field has revealed eight objects with low-dispersion spectra consistent with them being $z > 4$ galaxies, two of which have several plausible absorption features placing them at a redshift of 4.02 and 4.16 respectively (see Spinrad, these proceedings, for a discussion of UV absorption features seen in high-$z$ starbursts). These observations are discussed in more detail in Stevens, Lacy & Rawlings (1997 and in prep).

4 Lensing of high redshift radio galaxies

We have recently investigated the possibility that the two most distant radio galaxies (to which the cross-section to lensing should be highest) may be gravitationally amplified. The questions we wished to address were: could the magnification be high enough to significantly affect estimates of source properties (e.g. stellar content, star formation rate and morphology), and could it distort the radio source luminosity function sufficiently to boost the numbers of luminous radio sources at high-$z$?

4.1 8C1435+635

This $z = 4.25$ radio galaxy has a $z = 0.24$ galaxy projected just beyond the south east radio lobe. This is close to a larger, $\approx L_*$ galaxy at $z = 0.23$, possibly in the same group or cluster (Lacy et al., 1994). Another group of three galaxies was found at $z \approx 0.35$. (All these were found in long-slit spectra designed to measure the radio source redshift, and as yet no systematic redshift survey of
the field has been made.) With a deep $I$-band image from the WHT, we made a weak lensing study of this field, using the technique of Seitz & Schneider (1995). A marginally significant (3.5-$\sigma$) peak is present in the recovered projected mass distribution, offset by about 50 arcsec from the radio galaxy (Fig. 1). Apart from the groups already mentioned there seems to be no obvious optical cluster in the field, and no X-ray emission is seen in this field in a deep ROSAT exposure. This suggests either a high redshift for the cluster providing the bulk of the weak lensing signal, or a “dark cluster” with a high mass:light ratio.

**Figure 1.** The greyscale of our WHT $I$-band image of 8C1435+635 with significance contours of the projected mass distribution superposed, spaced at 0.5$\sigma$ intervals (negative contours shown dashed). The field size is 6 arcmin square, and the approximate position of the radio source is marked with a cross.
4.2 6C0140+326

The evidence for lensing in this source is more secure. Again, a nearby (in projection) galaxy was noted in the discovery paper (Rawlings et al. 1996) at \( z = 0.93 \). This was sufficient to produce significant lensing on its own, revealed in our 5GHz MERLIN image (Fig. 2), where both the hotspots are elongated in the direction expected if they are being lensed by the \( z = 0.93 \) galaxy. Although the exact magnification factor is hard to estimate due to the fact that the source structure is unknown, a simple singular isothermal sphere (SIS) model can be used to obtain a rough magnification if initially circular hotspots are assumed. The maximal magnification from an SIS can be found by placing an isothermal sphere with an Einstein radius of 0.9 arcsec at the nominal lens position (uncertain by \( \approx \pm 0.3 \) arcsec). This is consistent with the galaxy luminosity and at our best estimate distance from the source, and assuming initially circular hotspots produces magnifications of 2 for the eastern hotspot and 1.4 for the west (overall 1.7) (see Fig. 2). Models with elliptical isothermal potentials aligned in the direction of the observed lensing galaxy orientation give higher overall magnifications of \( \approx 2 \).

4.3 Is lensing important?

Some of the best constraints on lensing of AGN come from studies in the radio: with typical lens mass profiles (SISs or the CDM profile of Navarro, Frenk & White 1997) we would expect large numbers of multiple images or radio lobes imaged into rings if overall source magnifications frequently exceed \( A \sim 2 \) [although Kochanek & Lawrence (1990) suggest a large fraction of smaller radio rings are missed due to resolution effects].

An important caveat to this though is that additional sources of magnification which have scale sizes much larger than the size of the radio source could in principle produce significant magnification without image splitting. The effects of a general lensing mass distribution can be broken down into two components, a shear component due to matter distributed inhomogeneously outside the beam with which you observe a distant object (thus a point-mass lens outside the beam is a pure shear lens), and a convergence term due to matter within the beam (thus a uniform mass sheet is a pure convergence lens). Most realistic lensing mass distributions, such as the SIS model described above have contributions of both shear and convergence to the total amplification, but it is possible to conceive of other mass distributions in which either the shear or the convergence term dominates.
Large-scale shear (i.e. shear with a scale size comparable to that of the radio source) should be recognisable in terms of further distortion of the image, and the good match of the SIS model to the image of 6C0140+326 suggests that it must be fairly small in this case. Much harder to deal with is the possibility of a mass sheet associated with a cluster. This could magnify an image without producing distortion. Williams & Lewis (1997) have recently discussed the possibility of highly magnified but unsheared single images which could be formed in the centres of clusters. These depend on the dark-matter profiles having significant core radii (and therefore effectively acting as mass sheets). Weak lensing studies of a large enough field should eventually reach regions where the shear from any lensing cluster is significant though, and we could therefore infer the presence of a lensing cluster from this, as we may indeed have done in the case of 8C1435+635.

If, however, we proceed on the assumption that what we are seeing is indeed only fairly small magnifications, the next question is the frequency with which we expect to see this effect in flux-limited samples of radio sources. The frequency of lensing in a flux-limited sample may be estimated using a model for the lensing population combined with an estimate of the magnification distribution produced by this population and the radio source luminosity function. We will follow Peacock (1982) in assuming a population of singular isothermal lenses. For this population he derives an analytic approximation to the magnification distribution \( F(A) \) which has a tail \( \propto A^{-3} \), and turns over near \( A = 1 \) according to a lognormal distribution with a scatter \( A^\ast - 1 \) which represents the spread in amplifications about unity due to multiple lensing events. Four conditions on this function allow it to be fairly well constrained; \( F(A) = 0 \) at \( A = 0 \); \( \int_0^\infty F(A) dA = 1 \) (normalisation); \( \int_0^\infty AF(A) dA = 1 \) (mean amplification must be unity), and finally the strong lensing tail should give the same number of multiple images of point sources as predicted by models of strong lensing statistics (e.g. Kochanek & Blandford 1987). The other important parameter of this model is the maximum magnification due to lensing, which is proportional to the ratio of the source size to the Einstein ring diameter, and is

\[
A_{\text{max}} = 70(D_s/(c/H_0))(d/\text{kpc})^{-1}
\]

\(^1\)Large-scale shear would be necessary for the alignment effect to be produced via lensing (e.g. Le Fèvre et al. 1988). Although it is possible that in some cases such as 6C0140+326 the alignment could be enhanced by lensing it is highly unlikely that many \( z \sim 1 \) radio sources could be sufficiently distorted by large-scale shear to reproduce the alignment effect without many cases of multiple images being seen, even if the lenses themselves have a high mass/light ratio.
for our model, where $D_s$ is the source angular size distance and $d$ is the source size (Peacock 1982).

Combining this with a power-law luminosity function of the form $\phi(L) \propto L^{-\beta}$, we can estimate the factor $b$ by which lensed sources are overrepresented in a flux-limited sample:

$$b = \int_0^\infty A^{\beta-1} F(A) dA$$

(Peacock 1982). To estimate the mean magnification of a lensed source in a flux-limited sample we need to evaluate

$$< A >= \frac{1}{b} \int_0^\infty A^\beta F(A) dA$$

We also need to allow for the fact that cross-section to lensing of radio sources is significantly higher than that of optical quasars, because the sizes of the regions of highest brightness radio emission are often significant compared to the Einstein radius of the lens (Kochanek & Lawrence 1990). This increases the cross-section to lensing in the strong lensing tail by a factor

$$f_{HS} = \left(1 + g_1 \frac{l_1 + l_2}{r_0} + g_2 \frac{l_1 l_2}{r_0^2}\right)$$

where $l_1$ and $l_2$ are the major and minor axis lengths of the source, $g_1$ and $g_2$ are constants equal to 5/2 and 10 respectively in a spatially flat Universe and $r_0 = 1.4 \sigma_{220}^2$ arcsec where $\sigma_{220}$ is the velocity dispersion in units of 220 km s$^{-1}$ [Kochanek & Lawrence (1990); Kochanek 1993]. Note that the definition of source size here is relative to the Einstein radius $\theta_E$ of the lens. Hence, in the case of FRII sources, if the hotspot separation $\theta_R \gg \theta_E$, lensing events on the two hotspots can be considered independently.

To estimate the importance of lensing on the most distant radio sources, we can take 6C0140+326 as a specific example. At $z = 4.4$ the cross-section to multiple imaging of a point source in an $\Omega = 1$ cosmology is $\approx 2.6 \times 10^{-3}$ (Kochanek & Lawrence 1990). This source is an example where $\theta_R \sim \theta_E$, and the effective source size is debatable. We have decided to consider the two hotspots independently for the purposes of this analysis. Another complication is that the hotspot size used should strictly speaking be the size at the selection frequency, 151 MHz in the case of 6C0140+326. We will make the (probably pessimistic) assumption that the hotspot sizes are no larger than seen in high frequency radio maps, $\approx 0.1$ arcsec in diameter for 6C0140+326, giving $f_{HS} \approx 1.2$. We
Table 1. Lensing enhancement factors and mean magnifications as a function of $\beta$

| $\beta$ | 2.5 | 3.0 | 3.5 | 4.0 |
|-------|-----|-----|-----|-----|
| $b$   | 1.02| 1.09| 1.31| 2.18|
| $< A >$ | 1.29| 2.0 | 4.87| 14.2|

then double the cross-section to allow for both hotspots reaching $\approx 6.2 \times 10^{-3}$. Our hotspot size gives $A_{\text{max}} \approx 24$. Using these values we obtain $b = 1.09$ and $< A >= 2.0$ for $\beta = 3$. Thus the luminosity function is little changed by the effect of lensing, primarily due to the flux conservation condition, but the mean magnification can be comparatively high, basically because the distribution of luminosity-function-weighted amplifications is very flat in the high-$A$ tail, with the areas of the peak about unity and the tail out to $A_{\text{max}}$ comparable. If we take these numbers as typical, we might expect to see about half the $z \approx 4$ sources in a flux-limited sample significantly lensed, with a wide range in magnification factors.

The degree of lensing is very sensitive to the slope of the luminosity function. In Table 1 we list the enhancement factors and $< A >$ as a function of luminosity function slope. It can be seen that $< A >$ increases with $\beta$ too though. In fact the lack of obviously highly-magnified images suggests $\beta$ is probably $\leq 3$ at $z \sim 4$ to keep the mean magnification in the strong lensing tail relatively low.

Including clusters in the analysis will add further to the lensing structures available. A hint that clusters may be important comes from our study of 8C1435+635, and Peacock (1982) estimates that clusters can provide as much as a factor of two in the optical depth. Also, cosmology is potentially very important. A low cosmic density or a significant cosmological constant both increases the cross-section to lensing to point masses and, in the case of non-flat cosmologies, the factor $f_{\text{HS}}$ by which extended sources have larger cross-sections (Kochanek 1993).

Careful studies of both weak and strong lensing of complete samples of distant radio sources should eventually allow studies of lens statistics with a much larger sample of objects than available for conventional lensing studies, besides potentially being able to find new classes of lensing objects. It may also prove possible to use lensing arguments to constrain the luminosity function at redshifts where too few sources are known to measure it directly.

Acknowledgements I thank John Peacock for a helpful discussion which
prompted me to attempt a more in-depth analysis of the effects of lensing, and Lindsay King and Susan Ridgway for both helpful discussions and reading the manuscript.

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Figure 2. Top: MERLIN image of the $z = 4.41$ radio source 6C0140+326, made at 5GHz with 50ms resolution, contours at factors of $\sqrt{2}$ from 0.3mJy.

Below: a model in which two initially circular hotspots are lensed into arcs by an SIS with Einstein radius 0.9 arcsec centered on the position of the lens (indicated by a star in the top and bottom figures). Tangent lines are drawn either side of the two model hotspots, and are repeated in the upper panel to guide the eye.