Extended line emission around seven radio-loud quasars at redshift $z \sim 2$

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ABSTRACT

We present near-infrared spectra of seven radio-loud quasars with a median redshift of 2.1, five of which were previously known to have Ly$\alpha$ nebulae. Extended [O$\text{iii}$] $\lambda$5007 and H$\alpha$ emission are evident around six objects, at the level of a few times $10^{-16}$ erg cm$^{-2}$ arcsec$^{-2}$ s$^{-1}$ within $\sim 2$ arcsec of the nucleus (=16 kpc in the adopted cosmology). Nuclear [O$\text{ii}$] $\lambda$3727 is detected in three of the five quasars studied at this wavelength and clearly extended in one of them.

The extended [O$\text{iii}$] tends to be brighter on the side of the nucleus with the stronger, jet-like radio emission, indicating at least that the extranuclear gas is distributed anisotropically. It is also typically redshifted by several hundred km s$^{-1}$ from the nuclear [O$\text{iii}$], perhaps because of the latter being blueshifted from the host galaxy’s systemic velocity. Alternatively, the velocity shifts could be due to infall (which is suggested by linewidths $\sim 1000$ km s$^{-1}$ FWHM) in combination with a suitable dust geometry. Ly$\alpha$/H$\alpha$ ratios well below the case B value suggest that some dust is present.

Photionization modelling of the [O$\text{iii}$]/[O$\text{ii}$] ratios in the extended gas suggests that its pressure is around or less than a few times $10^7$ cm$^{-3}$ K; any confining intracluster medium is thus likely to host a strong cooling flow. A comparison with lower redshift work suggests that there has been little evolution in the nuclear emission-line properties of radio-loud quasars between redshifts 1 and 2.

Key words: quasars: emission lines – quasars: general.

1 INTRODUCTION

The processes which precipitated the steep decline in the comoving density of luminous quasars since the epoch $z \sim 2$ remain poorly understood. One observational approach to the problem proceeds through the study of the emission-line gas extending tens of kpc from the quasar. This material is the only visible tracer of the immediate of the quasar environment and as such its kinematics and ionization state may yield clues to the mechanisms which have driven the cosmological evolution of the population as a whole, as well as the early stages of galaxy formation more generally.

There are numerous indications that at redshift $z > 0.5$ powerful radio sources inhabit environments similar to the rich clusters found locally around the luminous FR II sources Cygnus A and 3C 295. The radio-source properties alone demand a certain type of environment: a confining medium capable of acting as a working surface for the formation of steep-spectrum radio lobes is a basic requirement. Faraday depolarization asymmetry (Garrington & Conway 1991), distorted/compressed radio source morphologies at high redshift (Hintzen, Ulvestad & Owen 1983; Barthel & Miley 1988) and the discovery of sources with very high Faraday rotation measures (Carilli, Owen & Harris 1994, 1997) suggest that the medium is clumpy and dense. Of particular interest is the so-called ‘alignment effect’, whereby the radio and extended optical/UV emission of $z > 0.6$ radio galaxies are seen to be coincident (McCarthy et al. 1987; Chambers, Miley & van Breugal 1987); recent work by Lacy et al. (1999) suggests that different physical mechanisms are responsible for its manifestation on different spatial scales. Similarly, Best, Rottgering & Longair (2000a,b) have studied the emission-line properties of a large sample of $z \sim 1$ radio galaxies: they conclude that in small radio sources ($\leq 150$ kpc in size) the kinematics and ionization state of the line-emitting clouds are dominated by the effects of the bow shock associated with the expansion of the radio source through a confining medium; photoionization of the gas by the nuclear source is more important in larger radio sources.

To study the environments of radio-loud quasars in corresponding detail is technically more difficult, as the bright unresolved nucleus tends to overwhelm surrounding structure. Over the last decade or more, however, we have pioneered the use of optical long-slit spectroscopy to probe the extended emission-line regions around radio-loud quasars out to redshift $z \sim 1$ (Fabian et al. 1988; Crawford & Fabian 1989; Forbes et al. 1990; Bremer et al. 1992). Where the emission line ratio [O$\text{iii}$] $\lambda$5007/[O$\text{ii}$] $\lambda$3727 can be measured for the extended gas, it can be used in...
conjunction with photoionization models to deduce the gas pressure. The latter is found to be consistently high ($nT \sim 5 \times 10^5 - 1 \times 10^7$ cm$^{-3}$ K at tens of kiloparsecs from the nucleus), and an increasing function of redshift (or of quasar luminosity). Pressure equilibrium between the line-emitting gas and any confining X-ray halo restricts the cooling time of the hot gas to be less than the Hubble time, suggesting that the quasars reside in a conﬁning X-ray halo.

Crawford et al. (1999) and by Hardcastle & Worrall (1999).

Beyond $z \sim 1$ the diagnostic lines of [O\textsc{iii}] and [O\textsc{ii}] move into the near IR where differences in the technology and atmospheric properties conspire to make the extension of this technique more difficult. Fortunately, however, there is a narrow redshift window around $z = 2.2$ where the [O\textsc{ii}], [O\textsc{iii}]+H$\beta$ and H$\alpha$+[N\textsc{ii}] complexes fall in the $J$, $H$ and $K$ atmospheric transmission bands, respectively. We have thus obtained near-IR spectra of seven radio-loud quasars near this redshift using the CGS4 spectrograph on the United Kingdom Infrared Telescope (UKIRT). Studies from the ground (Heckman et al. 1991a,b, hereafter H91a,b) and with Hubble Space Telescope (HST) (e.g. Lehnert et al. 1999a, hereafter L99a) have established that 100-kpc-scale Ly$\alpha$ nebulae are common around high-redshift quasars and a weaker analogue of the radio-galaxy alignment effect has been found (Lehnert et al. 1999b). Nevertheless, the spectroscopic elucidation of their properties remains in its infancy (e.g. Lehnert & Becker 1998).

The structure of the paper is as follows: in Section 2 we describe the observations and data reduction and in Section 3 detail the extraction of the extended emission and present the results on an object-by-object basis; in Section 4 we discuss its kinematics, morphology, ionization state and relationship with the radio source; Section 5 comprises a brief analysis of the nuclear emission-line spectra in the light of lower redshift studies and Section 6 a summary of our findings and the conclusions. The cosmological parameters $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$ are adopted throughout, giving a spatial scale of $8$ kpc arcsec$^{-1}$ at $z = 2.2$.

## 2 Observations and data reduction

### 2.1 Target selection

In order to maximize the likelihood of detecting extended emission, the targets were chosen primarily from those with known Ly$\alpha$ nebulae in the narrow-band imaging study of quasars in H91a. For other objects found in a NED search covering the appropriate area of the sky and redshift but not observed by H91a, the presence of strong, narrow nuclear He$\alpha$ $\lambda$1640 was used as a further selection criterion. H91b confirmed the suggestion of Foltz et al. (1988) that this line plausibly originates in the inner parts of such nebulae and that it is thus an indirect indicator of their presence. Other desirable attributes for potential targets were a resolved radio structure (especially one with a depolarization asymmetry) and a well-constrained X-ray–optical spectral energy distribution (SED) for use in photoionization modelling. The sample is thus not in any sense statistically complete.

### 2.2 Data acquisition and reduction

The observations were made using the CGS4 spectrograph on UKIRT on the nights of 1997 November 23–24 and 1999 June 26–27. The $256 \times 256$ InSb array, 40 line mm$^{-1}$ grating and 300 mm focal-length camera were in place, yielding a spatial scale of 0.61 arcsec pixel$^{-1}$ and a spectral resolution of $\sim 850$ km s$^{-1}$ FWHM (in the $H$ band) with a 2-pixel-wide slit.

For each object we acquired a spectrum covering the [O\textsc{iii}] $\lambda$5007, 4959 doublet and the [N\textsc{ii}]+H$\alpha$ complex (i.e. connecting the $H$ and $K$ bands) at at least one position angle, chosen to align with either the axis of greatest extent in published Ly$\alpha$ maps or along/parallel to any extended radio structure. When time permitted, a $J$-band spectrum covering redshifted [O\textsc{ii}] $\lambda$3727 was also obtained. The ND-STARE mode was used along with the conventional object–sky–sky–object nodding pattern, thus

| Object      | Other name | $z$ | spatial scale (kpc/arcsec) | Band$^\dagger$ | Exposure (minutes) | Slit PA (deg. E of N) | Seeing$^*$ (arcsec) | Comments |
|-------------|------------|-----|----------------------------|---------------|-------------------|---------------------|---------------------|----------|
| Q0017+154   | 3C 9       | 2.012 | 8.2                        | $H + K$       | 116               | 0                   | 1.4                 |          |
| Q0225−014   | PKS        | 2.037 | 8.2                        | $H + K$       | 60                | 0                   | 1.4                 |          |
| Q0445+097   | PKS        | 2.11  | 8.1                        | $H + K$       | 60                | 0                   | 1.3                 |          |
| Q0802+103   | 3C 191     | 1.956 | 8.2                        | $H + K$       | 46                | 0                   | 1.3                 |          |
| Q1658+575   | 4C57.29    | 2.173 | 8.0                        | $H + K$       | 52                | 45                  | 1.5                 |          |
| Q1816+475   | 4C47.48    | 2.225 | 8.0                        | $H + K$       | 60                | 146                 | 1.1                 |          |
| Q2338+042   | PKS        | 2.594 | 7.6                        | $H + K$       | 36                | 90                  | 0.9                 |          |

$^\dagger$ $H + K$ covers [O\textsc{iii}] $\lambda$5007, 4959 and [N\textsc{ii}]+H$\alpha$; $J$ covers [O\textsc{ii}] $\lambda$3727.

$^*$ FWHM of standard star spatial profile along the slit.

$^\ddagger$ at start of first night; slit-width changed thereafter to 2-pixel (1.2 arcsec) for rest of run.

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obviating the need for separate bias and dark current frames and permitting the computation of an external error for each pixel; it also reduces the required accuracy of the flat-field frame. Atmospheric absorption features were removed by ratioing with some of the main-sequence F stars tabulated at the telescope which were, in most cases, photometrically calibrated using observations of faint standards.

On- and off-line data reduction was performed using version V1.3-0 of the Portable CGS4 Data Reduction package available through Starlink. Row-by-row spectra were extracted from the fully reduced spectral images and converted to ASCII format for use with the emission-line fitting package qdp/plt (Tennant 1991). For the 1997 data, the FIGARO task sdist was used to correct for spectral curvature prior to splitting into rows, which had the undesirable effect of eliminating the variance array.

The target properties and observation log are shown in Table 1.

3 RESULTS

3.1 Extraction of extended line fluxes

One way to demonstrate the presence of extended line emission is to plot the equivalent width (EW) of the detected line as a function of position along the slit. Extension then manifests itself as an on-nuclear increase in the EW if the underlying continuum originates entirely in the spatially unresolved quasar nucleus. If, however, the continuum is extended – and this can be ascertained by using a suitable point-spread function (psf) from a standard star observation – we use a slightly more complex method: instead of evaluating the EW with respect to the continuum measured locally in each row, we use a so-called psf-scaled nuclear continuum which is obtained by taking the continuum level in the row where it peaks (defined as the nuclear continuum) and scaling it according to the psf. The psf-scaled nuclear continuum for a given row thus represents the continuum which would have been measured in that row if there were no extended continuum. The assumption that at its peak the continuum originates entirely in the unresolved nucleus is conservative, in that this is not the case the method underestimates the true amount of extended line flux. As stated below, Figs 1–7 include for each object the spectrum of the [O iii] doublet integrated along the slit with the nuclear contribution overlaid, the latter being a psf-scaled version of the profile fit to the [O iii] doublet in the nuclear row (and Hβ which is within the range). Also shown are spectra of the extended [O iii] doublet alone, obtained by subtracting a psf-scaled spectrum of the nuclear row from that integrated along the slit.

The above EW procedure was used to search for extended [O iii] λ5007, followed by [O ii] λλ3727 and the narrow component of Hα. Each line complex was fitted with single-component Gaussian profiles atop a linear continuum, with line ratios set to their theoretical values (3:1 for both the [O iii] λ5007, 4959 and [N ii] λλ6584, 6548 doublets) and with the velocity widths of all (narrow) lines within a complex set equal. Except where the continuum was spatially extended, the broad Hα width and the ratio of the broad Hα flux to the local continuum were frozen at the values determined from the fit to the nuclear spectrum. Where nuclear Hβ was within the wavelength range and clearly detected, it was fitted with broad and narrow components having velocity widths equal to those extracted from the Hα and [O iii] fits, respectively; the centroids of both components were constrained to be at the same wavelength, but not tied to the position of [O iii], as the reliability of the estimated wavelength scale is questionable at the end of the wavelength range and there are no arc lines there with which to calibrate it. There was no evidence for any extended Hβ. [O i] λλ7774 was typically very weak and in many cases only an upper limit on its intensity could be extracted; where it was detected, the fitting of nothing more than a single Gaussian was justified at this resolution and signal-to-noise ratio, despite the true doublet nature of this line. Errors on all quantities are the result of propagating the Δχ² = 1 parameter errors from the emission-line fitting.

For each quasar, we give a brief introduction to the literature on the source and describe the results of the EW analysis, which are also illustrated in Figs 1–7. Extended [O iii] λ5007 is found in six of the objects, at the significance levels given in Table 2. The extended surface brightness in this and other lines is computed and listed in Table 3 and comparison made with the Lyα maps of H91a and L99a.

H91a found an oval-shaped Lyα nebula extending =8 arcsec north–south and misaligned with the radio source which lies along a position angle of 150° (Bridge et al. 1994); a faint filament =3.4 arcsec to the south-east coincides with a radio hotspot. We made the first detection of extended [O iii] λ5007 along a north–south slit in 3C 9 during an earlier CGS4 run (Johnstone et al. 1993), prior to a chip upgrade and through thin cirrus cloud; our current value for the redshift of the nuclear [O iii] (z = 2.021 ± 0.0009) accords well with our previous measurement (z = 2.019 ± 0.001). Fig. 1 shows that [O iii] λ5007 is clearly extended in the present data on both sides of the nucleus, especially to the north. Extended narrow Hα is also detected in three rows but [O i] λλ3727 is generally not seen, except for very marginal detections on nucleus (z = 2.019 ± 0.003) and 1.5 arcsec to the south of it (z = 2.025 ± 0.002) (see Fig. 1). The underlying continuum is unresolved.

H91a did not subtract the unresolved nuclear emission from their Lyα map, so a comparison with our results is not straightforward. Nuclear Lyα will contribute to their map at the radii of interest as they report a (spatially extended/total) Lyα flux ratio of 0.2. Their lowest surface brightness contour is at 3.6 × 10⁻¹⁹ erg cm⁻² arcsec⁻² s⁻¹ approximately 4 arcsec north and south of the nucleus, rising to around 4.3 × 10⁻¹⁹ erg cm⁻² arcsec⁻² s⁻¹ 1.8 arcsec to the north. Using the Hα surface brightness in Table 3, we deduce that Lyα/Hα < 3.7 in the extended gas at this position. Comparison with the dust-free case B prediction of Lyα/Hα = 12.3 (Krolik & McKee 1978) suggests that there is at least some dust present in the nebula. We note, however, that very little is needed to quench Lyα because of the effects of resonant transfer in a dust/gas mixture (Fall, Pei & McMahon 1989). Indeed, since [O iii]/Hα = 4 around 1.4 arcsec north of the nucleus it follows that Hα/Hβ = 0.25 × [O iii]/Hβ, so the Balmer decrement may not substantially exceed the case B value if [O iii]/Hβ ~ 10, as found by Boroson, Persson & Oke (1985) for the extended gas around some quasars at z = 0.2–0.5. The upper limit that we can place on any extended Hβ does not constrain the intrinsic reddening.

PKS 0225–014

The Lyα image of H91a is marginally resolved, mostly along a PA of 140°, coinciding roughly with the direction in which the central

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Figure 1. For 3C 9: (a) EW [O\textsc{iii}] $\lambda$5007 versus nuclear distance along the north–south slit (each pixel measures 0.6 arcsec); (b) the integrated spectrum of the [O\textsc{iii}] doublet with the fit to the contribution of the nuclear light overlaid, the latter being the profile fit to the [O\textsc{iii}]+H$\beta$ complex in the nuclear row (defined as that in which the continuum peaks), scaled using the psf to include nuclear light scattered into other rows; (c) the spectrum of the extended [O\textsc{iii}] flux alone, obtained by subtracting from the integrated spectrum of (b) a psf-scaled spectrum of the nuclear row (the resulting line is a 10.2$\sigma$ detection); (d) extended [O\textsc{iii}] $\lambda$5007 surface brightness; (e) identified [O\textsc{ii}] $\lambda$3727 features – the dashed line indicates the fitted position on nucleus.
component of the radio source is extended in the radio map of Barthel et al. (1988). A pair of non-equidistant radio lobes are located at PAs of \(140^\circ\) and \(290^\circ\).

We find no evidence for extended \([\text{[O}\text{III]}] \lambda 5007\) (see Fig. 2) and the underlying continuum is unresolved. There is marginal evidence for extended H\(\alpha\) and comparison with the Ly\(\alpha\) map of H91a (from which the point-source contribution has not been removed) implies that Ly\(\alpha\)/H\(\alpha\) < 5.6 in the extended gas 1.2 arcsec north of the nucleus, suggesting that there is some dust associated with the gas.

**PKS 0445+097**

The Ly\(\alpha\) map of H91a is asymmetrically extended to the south and south-west of the nucleus, with an overall size of 12 arcsec. Much of the radio emission originates in a knotty jet to the west-south-west (Barthel et al. 1988). Lehnert et al. (1992) reported an extended near-IR and optical-continuum ‘fuzz’, with colours similar to those of the central object (which is itself unusually red), thus ruling out the possibility that the fuzz is scattered nuclear light. The SED of the fuzz in fact resembles that of an irregular galaxy, with an inferred star-formation rate of several hundred \(M_\odot\) yr\(^{-1}\). Long-slit spectroscopy by H91b found a linewidth of \(1500 \pm 300\) km s\(^{-1}\) FWHM in the Ly\(\alpha\) nebula, with strong nuclear \(z_{\text{abs}} = z_{\text{em}}\) Ly\(\alpha\) and NV\(\lambda\)1240 absorption. Their claim that the strong, narrow He\(\Pi\) \(\lambda 1640\) arises from the inner part of the nebula would, they say, be supported by the presence of strong \([\text{O}\text{II]}] \lambda 3727\) and \([\text{O}\text{III]}] \lambda 5007\) with widths \(>1000\) km s\(^{-1}\). We do indeed see relatively broad \([\text{O}\text{III]}] \lambda 5007\) both on and off-nucleus (see Section 3.2). Lehnert & Becker (1998) found similarly broad, faint extended He\(\Pi\) \(\lambda 1640\) and C\(\text{III}\) \(\lambda 1909\) from the quasar host galaxy.

The extended continuum complicates the extended line-flux computation as it is impossible to ascertain what fraction of the light is truly nuclear in origin. As explained earlier in this section, we make the assumption that, in its peak row, the continuum is entirely nuclear in origin. The EW([O\text{III}] \lambda 5007 points plotted in Fig. 3 are thus calculated with respect to the *psf-scaled nuclear continuum*, instead of that measured locally in each row. Owing to

![Figure 2](https://example.com/figure2.png)

**Figure 2.** For PKS 0225–014: (a) EW [O\text{III}] \lambda 5007 versus nuclear distance; (b) integrated spectrum of the [O\text{III}] doublet with the fit to the nuclear contribution overlaid; (c) extended flux spectrum.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** For PKS 0445+097: (a) EW [O\text{III}] \lambda 5007 evaluated with respect to the psf-scaled nuclear continuum, because the continuum measured directly in each row is extended beyond the psf (see text for details); (b) integrated spectrum of the [O\text{III}] doublet with the nuclear fit overlaid; (c) extended flux spectrum (the line is detected at the 6.1\(\sigma\) level); (d) extended [O\text{III}] \lambda 5007 surface brightness.
Figure 4. For 3C 191: (a) EW [O\textsc{iii}] $\lambda$5007 versus nuclear distance; (b) integrated spectrum of the [O\textsc{iii}] doublet showing the fit to the nuclear contribution; (c) extended [O\textsc{iii}] spectrum (a 6.7\textsigma detection); (d) extended [O\textsc{iii}] $\lambda$5007 surface brightness; (e) spectra of rows with identified [O\textsc{ii}] $\lambda$3727.
a flux calibration problem with the J-band exposure, upper limits on EW \([\text{O}^{\text{II}}] \lambda 3727\) were converted to surface-brightness limits by extrapolating the continuum from the \(H + K\) band spectra.

The \([\text{O}^{\text{III}}] \lambda 5007\) and \(H\alpha\) are more extended on the southern side of the nucleus, consistent with the appearance of the Ly\(\alpha\) map in H91a. Using the latter, we deduce upper limits on the Ly\(\alpha\)/H\(\alpha\) ratio of 0.6 and 0.8 at distances of 0.9 arcsec north and 1.6 arcsec south of the nucleus, respectively. These values are more than an order of magnitude below the case B prediction, implying that there is some dust associated with the gas.

**3C 191 (Q0802+103)**

Based on a slightly shorter CGS4 exposure, Jackson & Rawlings...
Figure 7. For PKS 2338+042: (a) EW [O\textsc{iii}] λ5007 for slit position angles of 90° and 135°, in the latter case evaluated with respect to the psf-scaled nuclear continuum; (b) the integrated spectrum of the [O\textsc{iii}] doublet with the fit to the nuclear contribution overlaid; (c) extended [O\textsc{iii}] spectrum at PA 135° (an 8.8σ detection); (d) surface brightness of extended [O\textsc{iii}] λ5007 at the two position angles; (e) J-band spectra of the individual rows where [O\textsc{ii}] λ3727 is identified (the dashed vertical line marks the nuclear wavelength); (f) EW [O\textsc{ii}] λ3727 along PA 135°, evaluated with respect to the psf-scaled nuclear continuum; (g) surface brightness of extended [O\textsc{ii}] λ3727.
Extended emission line surface brightnesses in units of $10^{-16} \text{erg cm}^{-2} \text{arcsec}^{-2} \text{s}^{-1}$; a figure in the column $(a,b)$ denotes the value in a 0.6-arcsec-wide pixel lying at some distance $r$ from the quasar nucleus where $a < r < b$ (values in successive columns of a given row correspond to points separated by the 0.6-arcsec-pixel size); the tabulated values should not be understood as average surface brightness levels within the stated range. The slit orientations are as indicated.

**Table 2.** Statistical significance of the extended [O iii] $\lambda$5007 detections.

| Object     | $\sigma$ |
|------------|----------|
| 3C 9       | 10.2     |
| PKS 0225−014 | No detection |
| PKS 0445+097 | 6.1     |
| 3C 191     | 6.7     |
| Q1658+575  | 5.4     |
| Q1816+475 (PA 146°) | 4.6     |
| PKS 2338+042 (PA 135°) | 8.8     |

† The [O iii] $\lambda$5007 detection significance (in units of the standard deviation on the underlying continuum in a 4-pixel-wide extraction box) in the spatially integrated spectrum after subtraction of a psf-scaled nuclear contribution.

**Table 3.** Extended emission line surface brightnesses in units of $10^{-16} \text{erg cm}^{-2} \text{arcsec}^{-2} \text{s}^{-1}$; a figure in the column $(a,b)$ denotes the value in a 0.6-arcsec-wide pixel lying at some distance $r$ from the quasar nucleus where $a < r < b$ (values in successive columns of a given row correspond to points separated by the 0.6-arcsec-pixel size); the tabulated values should not be understood as average surface brightness levels within the stated range. The slit orientations are as indicated.

| Object     | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ |
|------------|------------|------------|------------|------------|------------|------------|------------|------------|
|            | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ |
|            | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ |
|            | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ | $\lambda$ |

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Seven radio-loud quasars at redshift $z \sim 2$

The EW plot of Fig. 4 confirms that [O iii] $\lambda$5007 is extended, especially to the south of the nucleus. [O iii] $\lambda$3727 is seen in the nuclear row and extended in three further rows, the spectra of which are also shown in Fig. 4.

4C57.29 (Q1658+575)

The Ly$\alpha$ map of H91a (from which the point source has been subtracted) reveals a round nebula which is perhaps more extended to the north-north-east, towards the linear radio structure along PA 18° (Barthel et al. 1988). The HST narrow-band Ly$\alpha$ image of L99a shows a broad swath of emission extending 1.5 arcsec north-east of the nucleus, as well as significant extension to the north-west, thus motivating our choice of slit-position angles. Fig. 5 corroborates these results by showing extended [O iii] $\lambda$5007 to the north-east. We see no evidence for extension at the other position angle but this is perhaps due to the much shorter integration time and the less efficient 1-pixel-wide slit which was in use at the start of the first night.

For comparison, the lowest surface-brightness contour in the extended Ly$\alpha$ map of H91a is at $1.1 \times 10^{-17} \text{erg cm}^{-2} \text{arcsec}^{-2} \text{s}^{-1}$ at a radius of about 4 arcsec in the eastern limb of the nuclear row and extended in three further rows, the spectra of which are also shown in Fig. 4.
hemisphere. We thus estimate that Lyα/Hα ∼ 4 in the extended gas around 1 arcsec north-east of the nucleus. Comparison with the dust-free case B prediction that Lyα/Hα = 12.3 suggests that there is some dust present.

4C47.48 (Q1816+475)

This quasar is not in the H91a sample, but we included it on account of its extended radio structure (Barthel et al. 1988), complete with depolarization asymmetry between the jet and counter-jet sides (Garrington, Conway & Leahy 1991). We acquired H + K band spectra along and perpendicular to the radio axis (PA 146° and 56°, respectively) and also along PA 45°. There was only time to do a single PA in [O ii] λ3727.

Extended [O iii] λ5007 and Hα are seen at both PA 146° and 56°, with total [O iii] fluxes of 7.0 ± 3.0 and 1.9 ± 0.8 × 10^{-16} erg cm^{-2} s^{-1}, respectively (i.e. it is brighter along the radio axis). Since the error on the fitted continuum level completely dominates the uncertainty in the EW in some of the rows at large nuclear distances, we do not plot it in Fig. 6. For comparison with the extended [O iii] λ5007 surface-brightness plot, we show a VLA 6-cm radio map of the object, reproduced from Barthel et al. (1988); note that [O iii] is present at the position of the fainter, south-eastern lobe (rows 100 and 101), but absent from that on the north-western side (rows 90 and 91). There is no extended [O iii] λ5007 along PA 45° nor [O ii] λ3727 of any kind.

PKS 2338+042

The Lyα map of H91a has a north-west/south-east orientation, with brighter emission on the south-eastern side. The radio source is a smooth bent triple with lobes to the west and south-east within 2 arcsec of the nucleus (Barthel et al. 1988). L99a interpret the spatial relationship between this distorted structure and the extended Lyα in their HST narrow-band image as evidence for a `jet±cloud’ interaction. The EWs of [O iii] λ5007 along the two position angles listed in Table 3 are shown in Fig. 7. That along PA 135° is computed with respect to the psf-scaled nuclear continuum, owing to the presence of extended continuum at this PA (both H91a and L99a report that the rest-frame UV is well-resolved). There is clear evidence for extended [O iii] λ5007 and Hα, especially to the north-west, south-east and east of the nucleus. There is also strong evidence for extended [O iii] λ3727, as the EW plot of Fig. 7 demonstrates for PA 135° (the continuum beneath [O ii] λ3727 is also extended). Individual spectra of the four rows with [O ii] λ3727 detections are also shown in Fig. 7.

Comparison with the Lyα map of H91a yields upper limits on the extended Lyα/Hα ratio of 7, 0.8, 0.7 and 1.3 at distances of 0.9 arcsec west, 1.5 arcsec east, 1.4 arcsec north-west and 1.0 arcsec south-east of the quasar, respectively, suggesting that there is some dust present.

4 DISCUSSION

Before considering the detailed properties of the extended line emission, we mention the rather obvious point that the mere fact that it is seen from a coolant such as [O iii] implies that the galactic-scale environment of the quasar has undergone some metal enrichment. An episode of star formation has thus occurred, either concurrently with or prior to the quasar phase itself. This is also suggested by the presence of dust associated with the gas, as evidenced by Lyα/Hα ratios well below the case B value.

4.1 Kinematics and morphology of the extended line emission

The noise level of the present data does not permit us to examine the kinematic structure of the gas or its morphological association with the extended radio structure in spatially resolved detail. In fact, nothing more than the extraction of a single, integrated spectrum of the off-nuclear light can really be justified for kinematic purposes. We thus fitted a single kinematic component to the [O iii] doublet of each of the off-nuclear spectra, to determine an average velocity offset (from the nuclear emission) and the velocity dispersion. The results are shown in Table 4.

Whilst the errors for individual objects are large, the extended gas is on average redshifted by a few hundred km s^{-1} relative to the nuclear emission. Furthermore, although the errors are larger still, we found a velocity offset of the same sign on both sides of the nucleus within a given object. This tendency for the extended [O iii] to be redshifted from the nuclear [O iii] can be seen in Figs 1–7, where we show for each quasar an integrated spectrum of the [O iii] doublet with the fit to the spatially unresolved nuclear

Table 4. Kinematic properties of the off-nuclear gas.

| Object      | PA (deg) | ΔV_{ext-nuc} (km s^{-1}) | FWHM (km s^{-1}) |
|-------------|---------|--------------------------|-----------------|
| 3C 9        | 0       | 250 ± 100                | 520 ± 320       |
| PKS 0225−014 | 0       | 100 ± 220                | 1030 ± 520      |
| PKS 0445+097 | 0       | 170 ± 230                | 1020 ± 520      |
| 3C 191      | 0       | 150 ± 220                | 1260 ± 610      |
| Q1658+575   | 45      | 40 ± 240                 | 1260 ± 610      |
| Q1816+475   | 146     | 380 ± 350                | 1260 ± 610      |
| PKS 2338+042 | 90     | 90 ± 130                 | 1180 ± 390      |
|            | 135     | 120 ± 100                | 980 ± 270       |

* Velocity of the extended [O iii] emission with respect to that in the nucleus.
† The extended flux is not visible above the noise.

Figure 8. The extended–nuclear [O iii] λ5007 velocity difference (ΔV_{ext-nuc}) plotted against the nuclear [O iii] A5007-Hα velocity difference (ΔV_{[O iii]-Hα}).
component overlaid: residual emission tends to appear redward of the fit. One possible explanation for this lack of kinematic continuity is that the nuclear [O\textsc{iii}] is blueshifted with respect to the systemic redshift of the galaxy at which the bulk of the extended emission arises.

In this connection, there have been several studies of the velocity shifts between quasar nuclear-emission lines of different ionization; using a sample of 160 quasars, Tytler & Fan (1992) found that each ultraviolet emission line has a well-defined mean velocity with respect to a systemic value defined by H\textsc{\beta}, increasing roughly in the order of increasing ionization to $-454 \pm 37\, \text{km\,s}^{-1}$ for He\textsc{ii} 1640. They also confirmed the result of Gaskell (1982) that in low-z quasars and Seyfert galaxies, the Balmer and narrow-line redshifts agree with one another to within 100 km s$^{-1}$. Wilkes (1986), however, found that the the [O\textsc{iii}] $\lambda$5007, 4959 lines were blueshifted by a mean velocity of 220 $\pm$ 150 km s$^{-1}$ from H\textsc{\beta}. Applied to our sample, the latter result could account for the velocity offsets between the extended and nuclear [O\textsc{iii}] $\lambda$5007. To investigate this hypothesis further, we measured the velocity of nuclear [O\textsc{iii}] $\lambda$5007 relative to H\textsc{\alpha}, for comparison with the $\Delta V_{\text{ext-nuc}}$ values in Table 4, as shown in Fig. 8. Despite the large errors, the sense of the apparent trend is consistent with an interpretation in which the nuclear [O\textsc{iii}] $\lambda$5007 is blueshifted from both the extended [O\textsc{iii}] $\lambda$5007 and the nuclear H\textsc{\alpha} by comparable amounts.

Alternatively, if the nuclear [O\textsc{iii}] $\lambda$5007 is produced at the systemic velocity, the tendency of the extended emission to be redshifted relative to it could instead be due to gaseous infall towards the quasar. In this model, dust between the line-emitting clouds would be invoked to obscure those on the far side which would otherwise appear blueshifted. Evidence for infall is provided by the large linewidths in the extended gas – our values are compatible with those measured by H91b for the off-nuclear Ly\textsc{\alpha} (1000–1500 km s$^{-1}$ FWHM) in some of these quasars and in others near this redshift. Such large linewidths, they argued, result either from infall into the potential well of a very massive galaxy or from interaction with the radio-emitting plasma, but they did not find that the more kinematically disturbed regions of Ly\textsc{\alpha} emission were associated with the strongest radio emission. As we noted earlier, however, L99a found evidence from HST data for a ‘jet–cloud’ interaction in PKS 2338+042: they demonstrated that the cloud responsible for the Ly$\alpha$ emission is massive enough to deflect the radio jet and to survive for long enough after the collision to emit at the observed epoch, several Myr later. Our present data provide little new information on the detailed relation of the extended line emission to the radio structures. The 1997 observations were at a single position angle and the line emission in two of the 1999 objects, Q1658+575 and PKS 2338+042, was already known to align more closely with the radio structure than perpendicular to it (H91a; L99a). Our results on Q1816+475 are qualitatively similar, with the strongest extended emission being along the linear radio axis, as remarked above. Concerning dust, we have noted that while the Ly$\alpha$/H\textsc{\alpha} values in the extended gas are typically well below the case B dust-free prediction, this does not necessarily indicate substantial amounts of reddening. Where H\textsc{\beta} is within the wavelength range, upper limits on its extended flux do not place any constraints on the extinction.

On a global level, where the slit is aligned in the general direction of the extended radio structure, the extended [O\textsc{iii}] tends to be brighter on the side of the nucleus with the stronger, jet-like, radio emission, as in PKS 0445+097, 3C 191, Q1816+475, Q1658+575 and PKS 2338+042. The only exceptions to this are

4.2 The [O\textsc{iii}]/[O\textsc{ii}] ratio and the extended gas pressure

A key objective of this work was to measure the [O\textsc{iii}]/[O\textsc{ii}] ratio in the extended gas as a diagnostic of the pressure, for comparison with the lower redshift studies listed in Section 1. As mentioned in these papers, the frequent occurrence of high-pressure line-emitting gas around radio-loud objects requires that the warm clouds be long-lived; this in turn suggests that they are pressure confined by some hotter medium (otherwise they would disperse rapidly on a sound-crossing time), an obvious candidate being a medium similar to the hot X-ray-emitting gas found in clusters of galaxies (the ICM). In the light of the findings of Section 4.1, it is likely that, in those objects where the slit is aligned essentially along the radio axis (i.e. 3C 191, Q1816+475 and PKS 2338+042), the line-emitting clouds are compressed by passage through shocks associated with the radio jets and the pressures so calculated are not representative of conditions in the surrounding medium (see e.g. Best et al. 2000b). To compute the pressure, we adopt a model in which ionization-bounded (optically thick) clouds are subject to the photoionizing continuum of the central quasar, so the neglect of any in situ sources of ionization (e.g. shocks from the radio jet) results in the derived pressures being lower limits on the actual values. A detailed discussion of the reliability of these assumptions may be found in Bremer (1993). We note that the derived pressures would increase if an extinction correction were applied and decrease if the true nuclear distance to the clouds were used, as opposed to the projected value.

We have information on the [O\textsc{iii}]/[O\textsc{ii}] ratio in the extended gas for four of the seven quasars, although for one of them – PKS 0445+097 – it is wholly in the form of lower limits on the line ratio. The measured [O\textsc{iii}]/[O\textsc{ii}] values are also subject to uncertainty, for the [O\textsc{iii}] and [O\textsc{ii}] fluxes are derived from separate long-slit spectra, which may not sample the same part of the object and between which there may be flux-calibration.
differences. To investigate the latter we have compared the observed $J$ and $H$ band nuclear continua for each quasar and found that for each of 3C 9 and 3C 191, the one matches well the extrapolation of the other; for PKS 2338+042, however, the ‘raw’ [O III]/[O I] values have been increased by a factor of 2.25 as the $J$-band continuum exceeds the extrapolation by this factor (which is not surprising since the ratioing star used for the $J$-band exposure was not flux calibrated against a faint standard). Recall that the $J$-band spectrum of PKS 0445+097 could not be flux calibrated in the usual manner. We are not able to perform a correction for intrinsic dust extinction.

Version 90.05 of the photoionization code cloudy was employed (Ferland 1996), using the ‘AGN’ model continuum therein, which comprises an exponentially cut-off ‘Big Bump’ component and an X-ray power law:

$$f_\nu \approx \nu^{a_{\text{ox}}} \exp(-h\nu/kT_{\text{BB}}) \exp(-kT_{\text{IR}}/h\nu) + a\nu^{-3}. \quad (1)$$

The coefficient $a$ is adjusted by the code to produce the correct X-ray (2 keV) to optical (2500 Å) spectral index, $\alpha_{\text{ox}}$, for the case where the Big Bump does not contribute to the emission at 2 keV. The default parameter values, representative of a ‘typical AGN’, are $T_{\text{BB}} = 1.5 \times 10^5$ K, $\alpha_{\text{ox}} = -1.4$, $\alpha_{\text{UV}} = -0.5$, $\alpha_{\text{c}} = -1$ and $kT_{\text{IR}} = 0.01$ Ryd. The X-ray power law is added only for energies greater than 0.1 Ryd and above 100 keV the continuum is assumed to fall off as $\nu^{-3}$. Where available, literature information on the quasars was used to adjust the parameters $T_{\text{BB}}, \alpha_{\text{ox}}, \alpha_{\text{UV}}$, and $\alpha_{\text{c}}$, to reconstruct the observed portions of the SEDs. The parameters were otherwise left at their default values. For 3C 9 and 3C 191, we take $\alpha_{\text{ox}}$ values (of $-1.478$ and $-1.405$, respectively) and X-ray luminosities from Worrall et al. (1987); for PKS 0445+097, we take $U, B, R$ and $K$ photometry from Lehnert et al. (1992) and H91a, along with a ROSAT X-ray flux (Siebert et al. 1998), to obtain $T_{\text{BB}} = 7.2 \times 10^4$ K, $\alpha_{\text{ox}} = -1.0$, $\alpha_{\text{UV}} = -1$ and $\alpha_{\text{c}} = -1$; similarly, for PKS 2338+042 we find, from B-band photometry (H91a) and an HST flux density at $\lambda_{\text{rest}} = 1520$ Å (L99a), that this narrow portion of the SED is well matched by the default parameter values.

For each object, we ran a grid of constant pressure cloudy models for clouds at various radii from the quasar with different values of the hydrogen density at the exposed cloud face. The results are shown in the plots of Fig. 9, where the cloudy model loci are labelled with the value of the gas pressure ($p_{\text{gas}}$) to which they correspond. With the exception of PKS 2338+042 (where in any case the neglect of in situ ionization associated with the jet–cloud interaction renders the derived pressure a lower limit), our pressure measurements are equal to the maximum possible values that could be maintained at these radii by an isobarically cooling, pressure-confining ICM in an isothermal potential with a line-of-sight velocity dispersion $\sigma_{\text{los}}$ in the range $300 < \sigma_{\text{los}} < 400$ km s$^{-1}$ (see Bremer et al. 1992 for details); the majority of the limits on the pressure are also consistent with such a high-pressure environment, but do not otherwise impose strong constraints on the gas properties. Our values (and limits) are comparable with the pressures measured by Bremer et al. (1992) at slightly larger radii (~20 kpc) around some radio-loud quasars at redshift $z \sim 1$ and thus not obviously inconsistent with their conclusion that the most dramatic pressure evolution seen so far is the strong decrease between redshift $z \sim 1$ and the present day (see their fig. 12).
Seven radio-loud quasars at redshift $z \approx 2$

As the gaseous environment within a projected radius of $\sim 20$ kpc of the quasar.

First, the mere existence of extended [O\textsc{iii}] emission and the dust associated with it implies that the galactic-scale environment of the quasar has already been enriched by an episode of star formation.

Secondly, we found that the extended [O\textsc{iii}] tends to be brighter on the side of the nucleus with the stronger radio emission, indicating that the extended gas is distributed anisotropically and perhaps in some cases also compressed and shock ionized through interaction with the radio plasma.

Thirdly, on a global scale, the extended [O\textsc{iii}] is typically redshifted by a few hundred km s$^{-1}$ from the nuclear [O\textsc{iii}]. By comparison with the measured velocity difference between the nuclear [O\textsc{iii}] and H$\alpha$, we believe that this is probably due to the nuclear [O\textsc{iii}] being blueshifted by comparable amounts from a systemic value defined approximately by both the extended emission and the nuclear H$\alpha$. We cannot, however, rule out an alternative model involving gaseous infall coupled with the effects of selective dust extinction.

Fourthly, for four of the quasars we have information on the [O\textsc{iii}]/[O\textsc{ii}] ratio in the extended gas. This was used in conjunction with cloudy photoionization modelling to place constraints on the gas pressure, assuming that the radiation from the quasar itself is the only source of ionization. We cautioned, however, that such a scenario may not hold in all cases in view of the observed association between the radio plasma and the emission-line gas. With the exception of PKS 2338+042, we measure gas pressures (or limits thereon) which are comparable with the maximum pressure which could be maintained at these radii by any isobarically cooling ICM. This suggests that such an ICM would host a strong cooling flow, with a mass-deposition rate high enough to significantly influence the fuelling of the quasar, as well as the formation of the host galaxy (see Fabian & Crawford 1990). Future observations with Chandra and XMM are expected to reveal such ICMs directly through their X-ray emission. The case of A3581, however, illustrates that emission-line spectroscopy may continue to provide a complementary pressure diagnostic for the environments of high-redshift quasars; X-ray observations by Johnstone, Fabian & Taylor (1998) of this $z = 0.02$ poor cluster (containing the radio galaxy PKS 1404−267) show that despite its low temperature ($\sim 1.5$–$2.0$ keV) and relatively low luminosity ($\sim 2 \times 10^{42}$ erg s$^{-1}$), its mass-deposition rate is as high as $\sim 80 M_\odot$ yr$^{-1}$.

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