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WHT spectroscopy of emission-line gas around two separate quasars at $z = 0.87$

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Summary. We report observations made with the Faint Object Spectrograph on the 4.2-m William Herschel Telescope (WHT), in which the line emission of the fuzz around two separate quasars, which coincidentally both have redshifts $z = 0.87$, is detected and measured. These represent the most distant quasars for which the spectrum of the fuzz has been obtained. The oxygen line ratios we observe are similar to those of the lower-z quasar 3C48 (to which the present quasars show a strong similarity) and again imply a high gas density. If confined by surrounding hot gas, the pressure is so high that an intracluster medium is required. This suggests that the quasars lie in clusters or groups of galaxies. The emission-line gas and the fuel for the quasar luminosity then derive from a cooling flow in the intracluster gas.

1 Introduction

Optical observations of low-redshift quasars have revealed that they are embedded in faint patches of nebulosity, or 'fuzz'. Continuum images of quasar fuzz show the underlying host galaxies, which tend to be elliptical in the case of radio-loud quasars and spiral in the case of radio-quiet ones (Hutchings, Crampton & Campbell 1984; Malkan 1984). Narrow-band images (Smith *et al.* 1986; Stockton & MacKenty 1987) sometimes show patches of line emission from gas clouds that may extend to many tens of kpc from the quasar itself. Such emission-line gas can be diagnostic of the environment of a quasar, as its ionization state will depend mainly upon the ratio of the ionizing flux (dependent on the luminosity of the quasar and the radial distance of the gas) to its density. If the ionization state of the gas is measured at some radius and the ionizing luminosity of the quasar is known, or can be inferred from X-ray and ultraviolet observations, then the density of the gas can be determined. Evidence for a high-density, and thus high-pressure gas ($nT > 10^5$ cm^{-3} K), suggests pressure confinement from surrounding intracluster gas (Fabian *et al.* 1986). This is to be expected in the case of radio-loud quasars which, at least out to redshifts of 0.6, are preferentially found (Yee & Green

1984, 1987; Hintzen 1984) in clusters, albeit poor ones. Extended emission-line gas around radio-loud quasars can thus be diagnostic of distant clusters and groups.

The ionization state of the gas is best studied by spectroscopy. Relatively few spectra have been published so far (Wampler *et al.* 1975; Boroson, Persson & Oke 1985; Hickson & Hutchings 1987; Hintzen & Stocke 1986; Hintzen & Romanishin 1986; Fabian *et al.* 1987), mostly of low-redshift ($z<0.5$) objects. These spectra are consistent with the hypothesis that the radio-loud quasars are in clusters and groups (Crawford, Fabian & Johnstone 1989). In order to test this hypothesis at higher redshifts and to search for distant cooling flows, we have taken long-slit spectra of a sample of radio-loud quasars covering a wide redshift range. The quasars were selected from the list of Worrall *et al.* (1987), which means that they are detected in X-rays and so their ionizing luminosity is known. Here, we present observations of the two most distant quasars in our sample in which extended line emission is obvious. Results from the rest of the sample, in which several more quasars were found to have extended line emission, will be reported elsewhere.

2 The observations

Our observations were made with the WHT on La Palma during 1988 April in conditions of good seeing (~1 arcsec). The Faint Object Spectrograph (FOS) is a highly efficient fixed-format spectrograph (Allington-Smith *et al.* 1987), cross-dispersed to give a spectral range of 3500–9500 Å in two orders. Its peak efficiency, including that of the telescope and atmosphere, of ~16 per cent occurs around 7000 Å where the [O II] line is observed from an object at a redshift of 0.87. The spectral resolution there is about 15 Å.

The quasars of interest here, 3C196 (0809+483) and 4C20.33 (1422+202), both have $z=0.87$ and are steep-spectrum extended radio sources. Long-slit spectra with a spatial pixel size of 0.8 arcsec and slit-width 1.25 arcsec were taken across the nucleus of each quasar. The spectra of the central cross-sections are shown in Fig. 1, together with spectra from cross-sections ~2–3 arcsec away. The equivalent width of the [O II] doublet is clearly greater in the off-nucleus spectra. We have presented the spectra in this 'raw' form so that (i) the extent of the O II] lines and (ii) the good signal-to-noise ratio of the data are obvious. These spectra have then been sky-subtracted and flux-calibrated against standard stars. Atmospheric extinction corrections were also made before the flux ratios of the oxygen lines were determined. We have subtracted the nuclear contributions to the off-nucleus spectra by scaling from the continuum intensity near to the emission lines (there is no evidence that the continuum is more extended than a point source such as a star) and so estimated values for the [O III]λ5007/[Ou II]$\lambda\lambda$3727,3729 flux ratios. We obtain values of 3 ± 1 and <2.6 (90 per cent confidence region) in 3C196 and 4C20.33, respectively. The main source of uncertainty arises in the sky subtraction around the [Ou III]λ5007 line. These flux ratios indicate that the gas is of relatively low ionization, which in turn means that it is of high density if the incident ionizing flux is large.

3 Interpretation and discussion

We have followed the procedure used in our work on 3C48 to determine the gas density. Ferland's (1987) CLOUDY photoionization code is used to calculate the oxygen line ratios as a function of ionization parameter ($L_{\rm ion}/nR^2$, where $L_{\rm ion}$ is the ionizing luminosity of each quasar, n is the gas density and R is the radial distance of the gas cloud). The ionizing luminosity is assumed to be isotropic, since there is no evidence for strongly anisotropic radiation in quasars, and is estimated from a power-law interpolation between the measured ultraviolet and X-ray fluxes of the quasar (Worrall *et al.* 1987). The radial distance is assumed to be

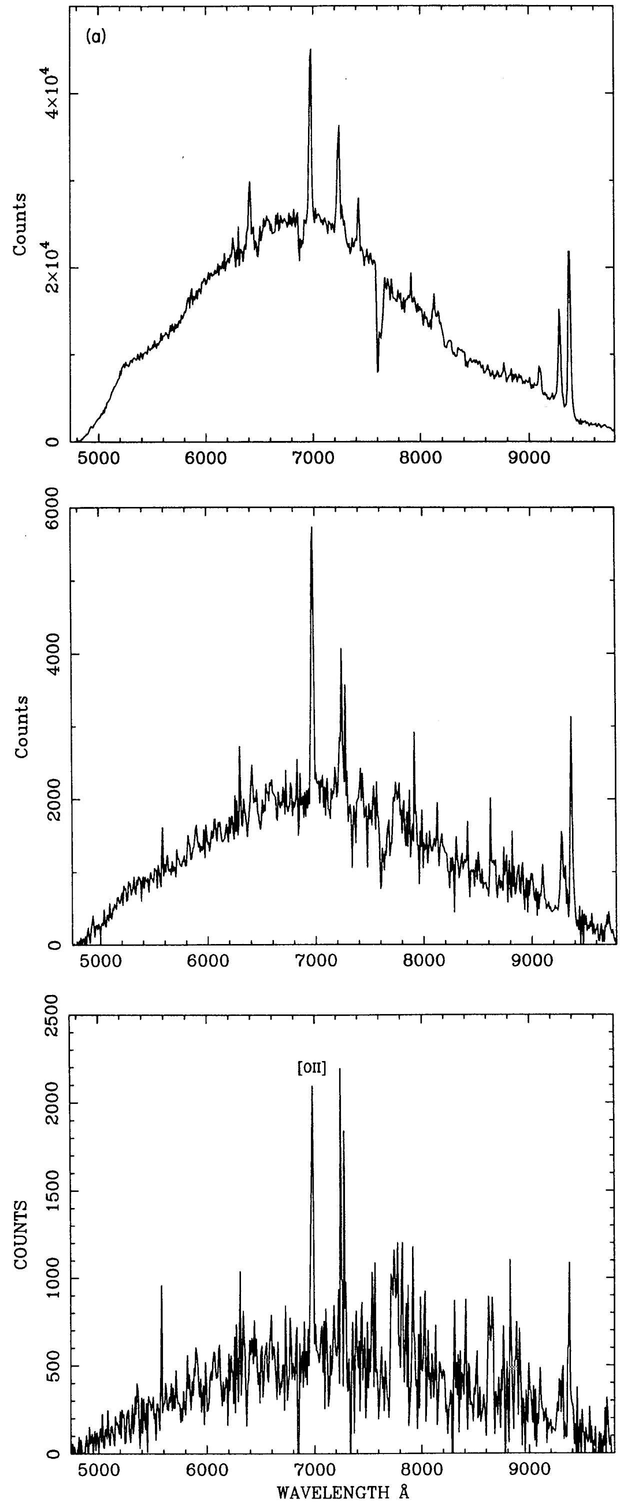

Figure 1. (a) FOS first-order counts spectra of 4×1000 s observations of 3C196. The three panels from top to bottom show spectra from cross-sections 16 and 17 (on-nucleus), 13, 14, 19 and 20 (a mean of 2.4 arcsec off-nucleus), and finally 12, 13, 20 and 21 (a mean of 3.2 arcsec off-nucleus). The position angle of the slit was 163°, chosen to be roughly parallactic for the observation. Atmospheric dispersion over the 7000–10 000 Å-band of interest is much less than 1 arcsec. The equivalent width of the [O II] doublet clearly increases away from the nucleus. No correction for atmospheric absorption has been made in this figure. (b) As (a) for 4C20.33. The panels show cross-sections 12 and 13 (top), 14 and 15 (middle), and 15 and 16 (centre). The emission lines are not obviously extended on the other side. The position angle was again chosen to be roughly parallactic at 37°. CR indicates a cosmic ray event.

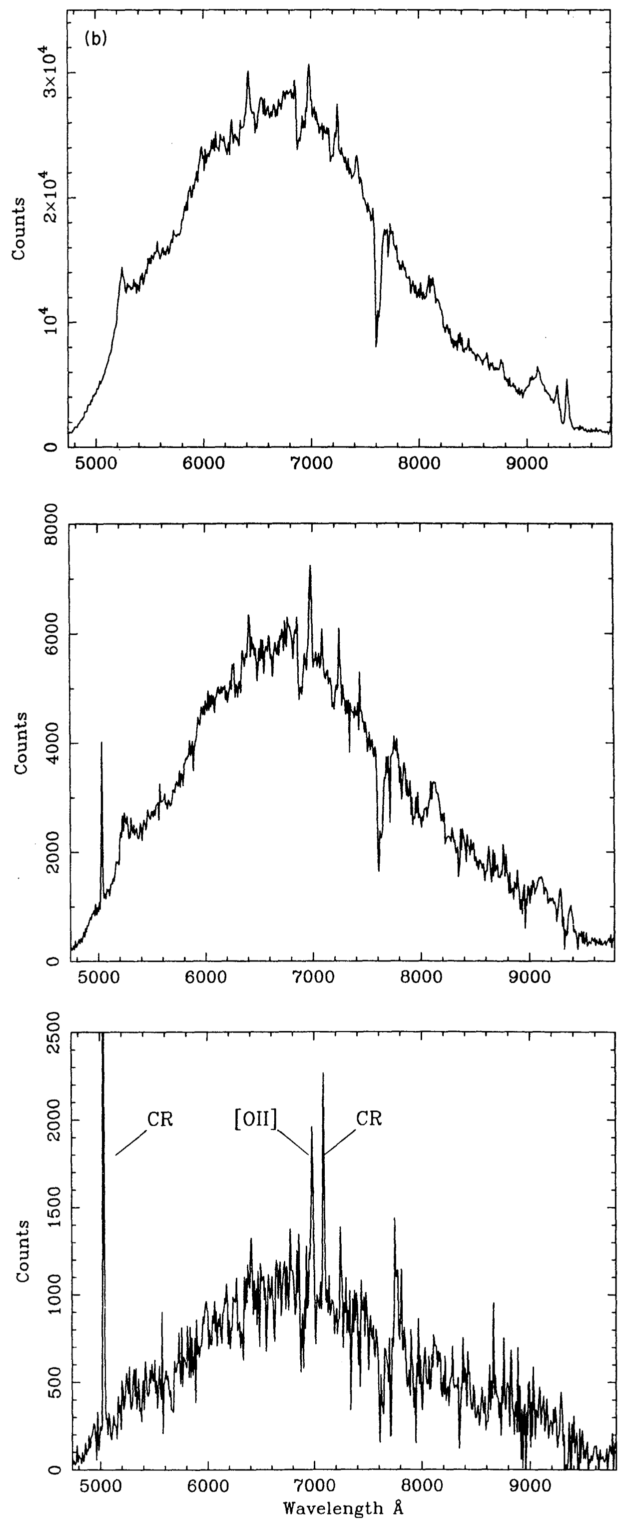

Figure 1 – *continued*

the projected separation of the emission-line gas. We find that gas densities of 25^{+10}_{-8} and >55 $\mathrm{cm^{-3}}$ at distances of 32 and 24 kpc around 3C196 and 4C20.33, respectively, are required to explain the line ratios. (We use $H_0 = 50$ km $\mathrm{s^{-1}}$ $\mathrm{Mpc^{-1}}$ and $q_0 = 0$; 1 arcsec ≈ 10 kpc.)

The assumed spectral interpolation for the ionizing luminosity is similar to that used in models of the broad-line region of quasars and minimizes the resulting gas density. A 'blue bump' in the EUV (as observed in many quasars) would increase the density estimates by a factor of 2 or more (Fabian *et al.* 1987).

The pressures of the emission-line clouds are so high that they would disperse very quickly (in $<10^6$ yr) if not confined in some way (Fabian *et al.* 1987), or they may represent a very small fraction of a large mass of dense colder gas which is being 'burnt' away by the quasar flux. As we have previously argued (Fabian *et al.* 1987) in the case of 3C48, thermal-pressure confinement by an intracluster gas provides the simplest and most straightforward interpretation for the continued existence of warm ($\sim 10^4$ K) gas. Such gas also occurs in poor clusters (Schwartz, Schwarz & Tucker 1980; Canizares, Stewart & Fabian 1983) and need not imply that the quasars must lie in rich clusters. Indeed, most elliptical galaxies have an extensive hot interstellar medium (Forman, Jones & Tucker 1985), so many, if not all, radio-loud quasars are expected to be surrounded by hot gas.

Unless the surrounding clusters are particularly rich, in which case the intracluster gas temperature can be high ($>10^8$ K), the radiative cooling time of the gas will be less than a Hubble time in the centre and so a cooling flow (Fabian, Nulsen & Canizares 1984) will have developed. This then explains the presence of extensive clouds of warm gas which appear similar to those seen around nearby cluster cooling-flows. Some of the cooling gas can of course help to fuel the quasar nucleus and the high pressure will help to confine the radio source. By comparison with the gas pressures in nearby cooling-flows (Fabian *et al.* 1987), we estimate that the mass-deposition rates in 3C196 and 4C20.33 are ~ 100 (similar to that in the poor cluster MKW3s, Canizares *et al.* 1983) and $>150\ M_\odot\ \mathrm{yr}^{-1}$ (similar to that in many rich clusters, Fabian *et al.* 1984), respectively.

Further evidence for dense gas clouds surrounding our quasars is provided by radio observations. 3C196 has a pronounced bent jet (Brown, Broderick & Mitchell 1986) on a scale of 2 arcsec, and 4C20.33 shows similar, but much weaker, evidence (Saikia, Kulkarni & Porcas 1986) on a scale of 5 arcsec. A sharp bend in a jet is explained by its collision with a gas cloud (see, for example, van Breugel *et al.* 1985). The jet–cloud interaction can provide a further source of ionization which means that our estimates of gas density are both lower limits. The position angles of our spectrograph slit do not coincide with those of the bends in the radio jet, so we are not directly sampling any shock ionization.

The conditions may be similar to those around the higher redshift radio galaxies observed by Spinrad & Djorgovski (1984a, b) and one of us (Allington-Smith, Lilly & Longair 1985). There are not, however, any measurements of the photoionizing continua in those cases (they are not quasars), so we cannot apply our diagnostic technique. Perhaps the most interesting example will be provided by detailed spectroscopy of the neighbourhood of the quasar PKS1614+051 at $z=3.2$, which has been imaged in Ly α and found to have a companion emission-line galaxy or cloud (Djorgovski *et al.* 1985; Hu & Cowie 1987).

Our spectra are consistent with the hypothesis (Fabian *et al.* 1986) that clusters, intracluster gas and cooling flows occur around radio-loud quasars at moderate redshift.

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