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Extended emission-line gas around the quasars 3C 254 and 3C 309.1; very massive cooling flows

D. A. Forbes,[1] C. S. Crawford,[2] A. C. Fabian[1] and R. M. Johnstone[1]

[1] *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
[2] *Department of Astrophysics, Keble Road, Oxford OX1 3RH*

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SUMMARY

We present optical spectra of the radio-loud quasars 3C 254 ($z=0.734$) and 3C 309.1 ($z=0.905$) which show them to be surrounded by extensive emission-line gas. The gas around 3C 254 extends to a radius of at least 80 kpc. The [O III]λ5007/[O II]λ3727 line ratio is used to infer high thermal pressures in the emission-line gas consistent with confinement by an intracluster medium. The pressure profiles imply that the cooling time of the intracluster gas is so short that both quasars must be surrounded by very massive cooling flows; they are the most extreme examples yet found. 3C 309.1 is the most distant quasar for which the spectrum of the surrounding nebulosity has been obtained. The flow around it exceeds 1000 $M_\odot$ yr^{-1} within 21 kpc and can easily form the central galaxy within a Hubble time. A trend of increasing gas pressure with redshift suggests that mass deposition rates were stronger in the past and that cooling flows are a significant galaxy formation process.

Observations of 3C 254 at different position angles are used to study the degree of anisotropy of the quasar continuum radiation. We find that the extended emission-line gas around quasars has several properties in common with that around powerful radio galaxies.

1 INTRODUCTION

Optical spectroscopy of the surrounding emission-line gas (Fabian *et al.* 1987; Crawford, Fabian & Johnstone 1988; Fabian *et al.* 1988; Crawford & Fabian 1989), counts of neighbouring galaxies (Yee & Green 1984, 1987) and colours of the host galaxy (Romanishin & Hintzen 1989) all indicate that powerful radio-loud quasars are in central cluster galaxies. Extended emission-line gas is also observed around radio galaxies (see Baum *et al.* 1988, and references therein) and may have a similar origin to that seen around quasars, i.e. the result of a cooling flow (e.g. Fabian, Nulsen & Canizares 1984; Fabian *et al.* 1986) or tidal interactions (e.g. Stockton & MacKenty 1987). At low redshifts, central cluster galaxies are embedded in hot intracluster gas which is often so dense that it cools rapidly, leading to a cooling flow in which tens of hundreds of solar masses of gas cool and are deposited around the galaxy in some unseen form (for reviews of cooling flows see Fabian *et al.* 1984; Sarazin 1986). Our studies of the ionization state of the extended emission-line gas around radio-loud quasars have shown that they too are surrounded by a hot, dense intracluster gas and therefore are located in cooling flows (Crawford & Fabian 1989, and references therein). Strong radio galaxies such as Perseus A, Hydra A and Cygnus A, occur at the centres of nearby cooling flows and we do not find it surprising that more distant radio sources are also found in this environment. The study of the properties of the gas surrounding radio-loud quasars therefore provides a means with which to discover and probe the evolution of cooling flows.

We report observations of two of the more extreme examples so far discovered – 3C 254 and 3C 309.1. They are surrounded by extensive emission-line gas at high pressure. In the case of 3C 254, the extent of the emission is very large (80 kpc radius) and we can search for spatial variations in the line ratios and investigate the degree of anisotropy of the ionizing quasar radiation. We also comment on the similarity to the extended emission-line gas surrounding distant radio galaxies which may just be quasars observed from a different vantage point (Barthel 1989). 3C 309.1 is the most distant quasar for which extended emission lines have been found and has the most massive cooling flow. We discuss the prospects for discovering extended emission-line gas around quasars with even higher redshifts.

2 OBSERVATIONS AND DATA REDUCTION

Our observations were made using the Faint Object Spectrograph (FOSII) on the 4.2-m William Herschel Telescope

Table 1. Journal of observations.

Quasar	Redshift	Date	Position Angle (degrees)	Exposure (seconds)	Seeing (arcsec)
3C 254	0.734	15/3/89	105	2000	~1.3
		7/3/89	238	1000	~1.0
		7/3/89	350	3400	~1.0
3C 309.1	0.905	15/3/89	165	3000	~1.0

(WHT) in 1989 March. A log of the observations is given in Table 1. Both quasars reported on here are extended, steep-spectrum, radio sources with X-ray detections (Worrall *et al.* 1987). 3C 254 is a highly asymmetric radio source (see e.g. Owen & Puschell 1984, fig. 2), 3C 309.1 is a compact steep spectrum source with triple structure (see e.g. Spencer *et al.* 1989).

The spectra were flat-fielded and corrected for the curvature introduced by the cross-dispersion and by atmospheric dispersion before wavelength calibration and sky subtraction were carried out. Each spectrum was then flux calibrated and corrected for interstellar reddening. The narrow emission lines in the spectrum of 3C 254 are very strong and extended (see Fig. 1a) out to a radius of at least 80 kpc (assuming $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$). In Fig. 1(b) we show an enlarged region of the spectrum near [O II]. A velocity shift of 1.5 pixels (~ 600 km s^{-1}) is seen across the nucleus. Velocity broadening of the extended lines is less than our instrumental resolution, corresponding to a FWHM of < 800 km s^{-1}. Light from the quasar nucleus, scattered by our atmosphere into the off-nucleus spectra, is insignificant beyond the central four cross-sections (a cross-section corresponds to 0.8 arcsec; the seeing was typically ~ 1 arcsec). In Fig. 2, we show flux-calibrated spectra, corrected for interstellar extinction, after a simple scaled-subtraction has been made for the scattered light.

A weak continuum source can be seen in the spectra of 3C 254 taken at position angle 350° at a distance of about 4 arcsec south of the nucleus (Fig. 1a). It is much redder than the quasar nucleus and is visible in each of the four spectra taken at this position angle, which have been combined to form Fig. 1a. Its spectrum is shown in Fig. 3. At the resolution of FOSII, we are unable to distinguish whether it is a red galactic star or a companion galaxy to the quasar. Its colours are consistent with an M0 dwarf star but its magnitude (nothing is apparent on the *Palomar Observatory Sky Survey* plate of this region) would put it several kiloparsecs away in the halo of our Galaxy. If it is a companion galaxy to 3C 254, then its (redshifted) colours indicate that it is intrinsically blue and possibly undergoing star formation. It lies at the (projected) position of the S extension to the E lobe of the radio source and so may be involved in some jet–cloud interaction. The continuum from this object causes the decrease in equivalent width of the emission lines at about 40 kpc from the nucleus at position angle 350°; it is not used when modelling the scattered continuum from the nucleus.

The equivalent widths of the [O II] emission lines, in each cross-section of the slit where the line is detected, are shown in Figs 4 (3C 254) and 5 (3C 309.1). These confirm the extension of the lines in 3C 254 and show that the emission line of [O II] in 3C 309.1 is also extended, but less dramatically so. The [O II] and [O III] lines of 3C 254 are extended by ~ 80 kpc to the south and by ~ 60 kpc to the east (Fig. 2); only [O II] is seen to be extended to the west. [O III] is the more difficult line to detect in these objects since the redshift causes it to occur at the longer wavelengths where the lines and bands of the night sky emission make the background 'noise' much stronger. In order to measure line fluxes, we use the method described by Crawford & Fabian (1989) to

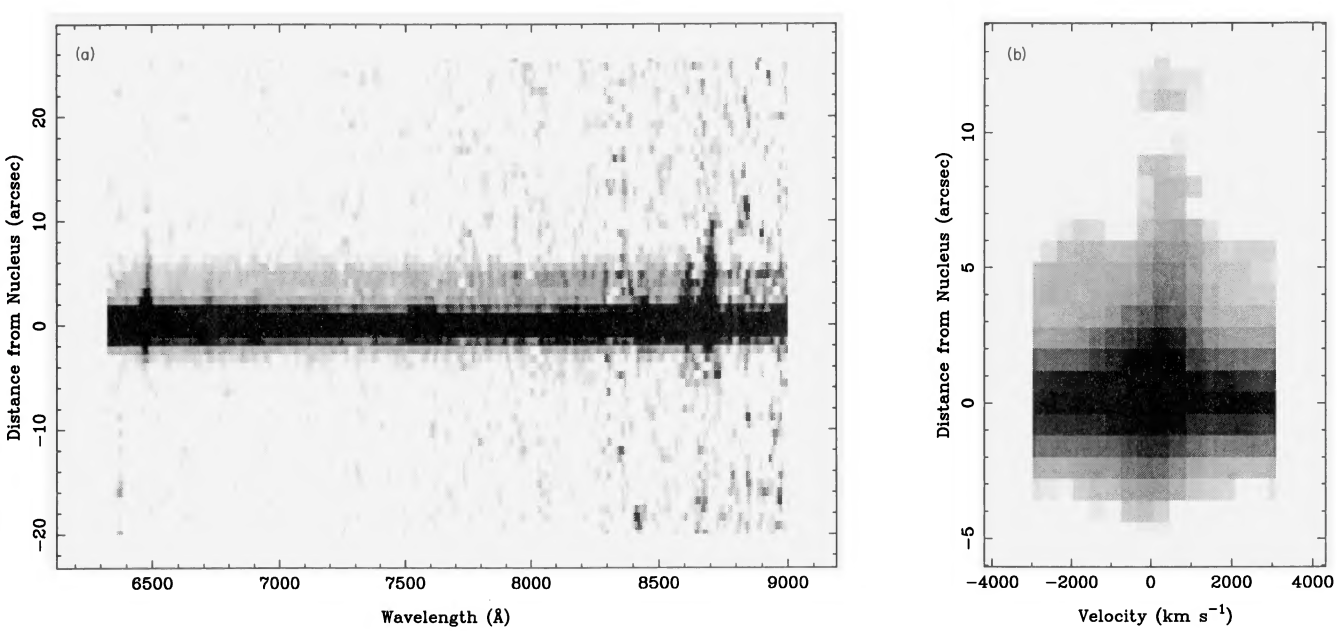


Figure 1. (a) Two-dimensional spectrum of 3C 254 at position angle 350°. [O II]λ3727 is redshifted to 6462 Å and [O III]λ5007 to 8682 Å. Note the large extent of these lines and the weak red continuum source to one side of the quasar nucleus. (b) Enlarged region of (a) centred on [O II]. Note the 600 km s^{-1} velocity shift across the nucleus.

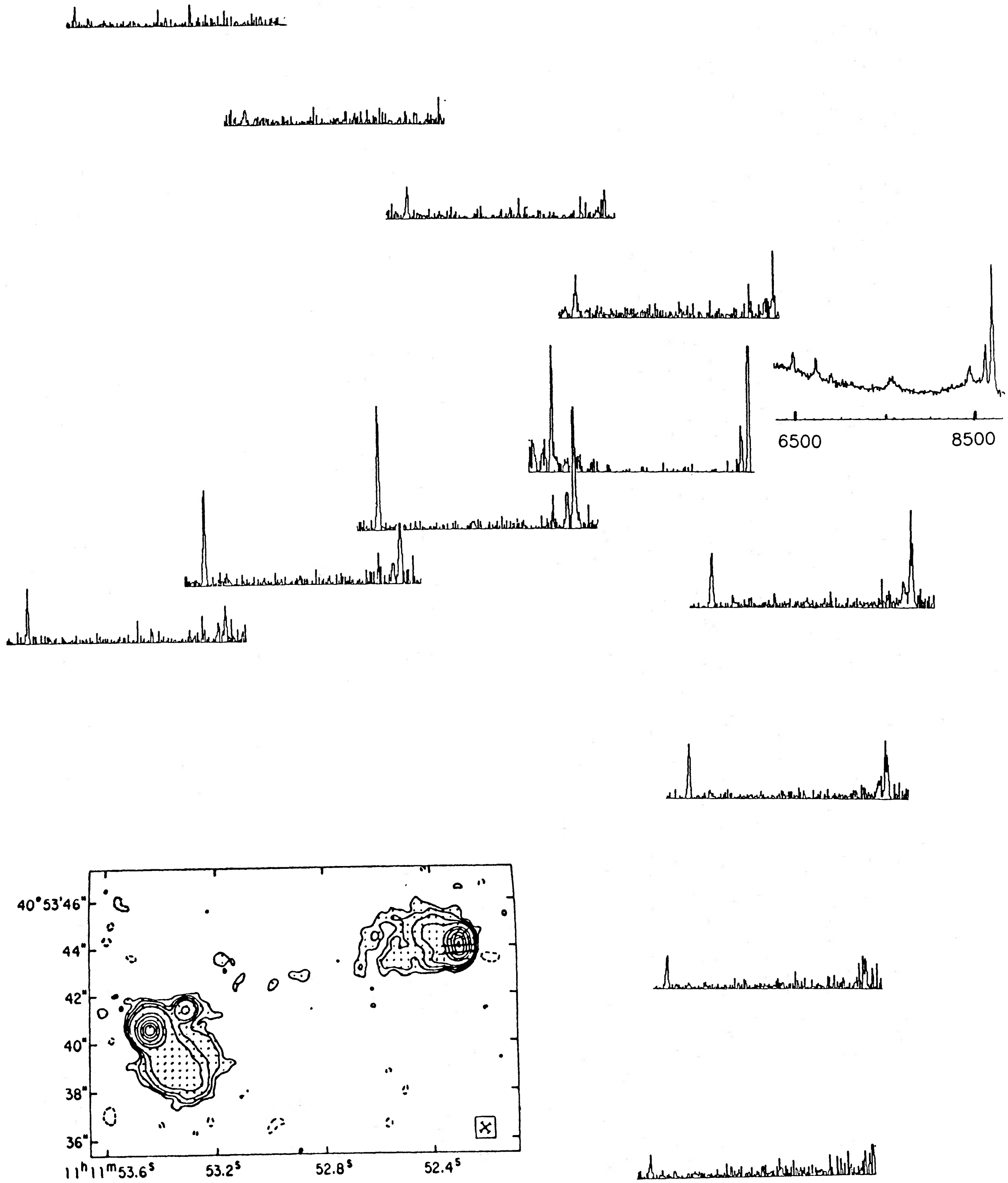


Figure 2. Spectra of 3C 254 taken at three position angles. The spacing between each cross-section is 0.8 arcsec which corresponds to 7.7 kpc at the redshift of the quasar. The intensity scale of the spectrum of the nucleus has been reduced by a factor of 15 relative to that of the off-nucleus spectra; the wavelength scale is the same for all spectra. The insert shows the radio map by Owen & Puschell (1984).

estimate and remove light from the nucleus which the seeing has caused to contaminate the off-nucleus spectra. The method assumes that the quasar continuum is not extended (it does not appear to be significantly extended beyond the seeing profile), and uses the intensity profile of the continuum as a model for the amount of line emission scattered from the nucleus. We have measured the flux in each line to obtain the line ratios given in Table 2. Where

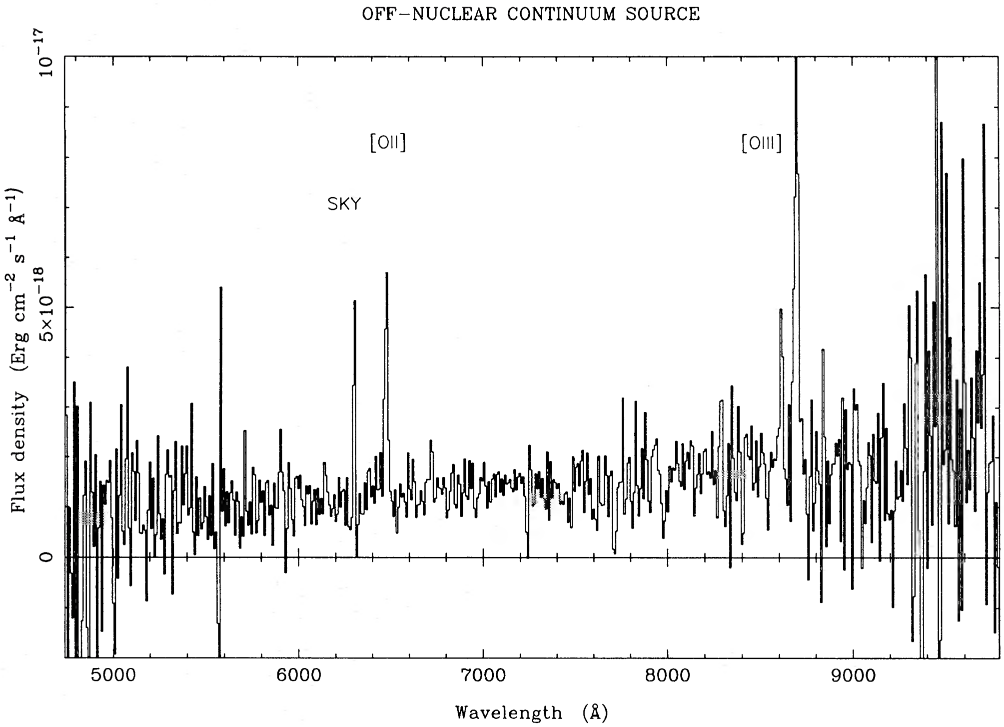


Figure 3. Spectrum of the weak continuum source 4 arcsec from the nucleus of 3C 254 at a position angle of 350°.

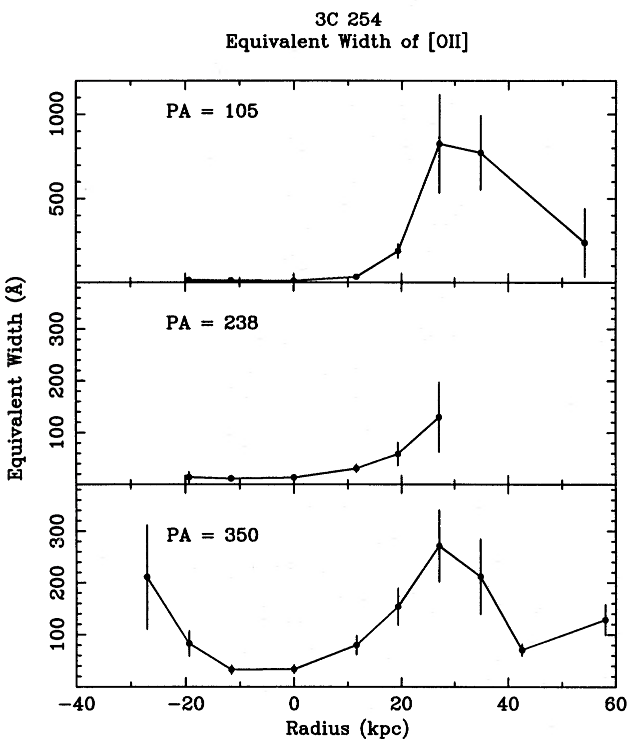


Figure 4. Measured equivalent widths for [O II]λ3727 versus projected radial distance from the nucleus of 3C 254 at three position angles: (a) position angle of 105°, which is aligned with the direction radio axis of the double source (Owen & Puschell 1984), (b) position angle of 238°, (c) position angle of 350°. The weak off-nucleus continuum object affects the equivalent width at radii of 30–50 kpc. The equivalent width shows a dramatic increase off-nucleus indicating that the [O II] emission is clearly extended off the nucleus.

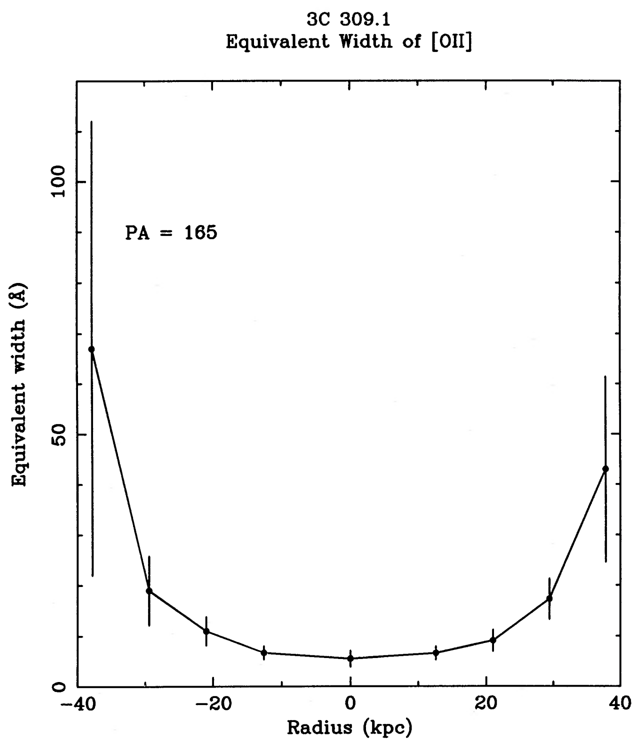


Figure 5. Measured equivalent width of [O II]λ3727 versus projected distance from the nucleus of 3C 309.1 for position angle 165°. The radio emission is extended at position angles of ~120° and ~250° in the 6-cm map by van Breugel, Wiley & Heckman (1984) (see also Wilkinson *et al.* 1986). The [O II] emission is clearly extended on both sides of the nucleus.

Table 2. The [O III]/[O II] line ratio and corresponding pressure in the extended gas around 3C 254 and 3C 309.1.

Quasar	Log(L_{ion}) (erg s^{-1})	Position Angle (degrees)	Radius (kpc)	[OIII]/[OII]	Gas Pressure (10^6 cm^{-3} K)
3C 254	46.45	105	11.61	0.92±0.25	$4.9^{+1.3}_{-0.9}$
			19.35	0.93±0.14	$4.3^{+0.7}_{-0.5}$
			27.09	0.75±0.17	$2.5^{+0.9}_{-0.4}$
			34.85	0.72±0.26	$1.6^{+0.7}_{-0.4}$
			54.18	2.11±0.85	$0.23^{+0.15}_{-0.07}$
		238	11.61	<1.11	>4.2
			19.35	0.65±0.54	$6.1^{+11}_{-2.7}$
			27.09	<1.52	>1.4
		350	11.61	0.88±0.31	$5.2^{+15}_{-1.3}$
			19.35	0.78±0.18	$5.0^{+1.2}_{-0.9}$
			27.09	0.79±0.22	$2.5^{+0.9}_{-0.5}$
			34.85	1.19±0.72	$1.0^{+1.2}_{-0.4}$
			42.57	2.58±0.45	$0.30^{+0.08}_{-0.04}$
			58.05	2.70±0.58	$0.15^{+0.05}_{-0.03}$
			77.40	3.50±1.40	$0.06^{+0.05}_{-0.02}$
3C 309.1	46.80	165	12.60	<3.8	>10
			21.00	1.32±0.89	$9.6^{+17}_{-3.5}$
			29.40	<2.9	>1.9
			37.80	<6.0	>0.6
			12.60	<1.5	>27
			21.00	<2.6	>4.6
			29.40	<5.2	>1.0
			37.80	<5.0	>0.6

[O III] has not been detected we use an upper limit of 2σ to obtain an upper limit on the ratio of [O III] to [O II].

3 ANALYSIS AND RESULTS

We assume that the ionization state of the emission-line gas surrounding the quasars is principally due to the equilibrium between photo-ionization by radiation from the quasar nucleus and recombination occurring within the clouds of gas. Making the further assumption, to which we return later, that the quasar radiation is isotropic so that the cloud sees the same luminosity and spectrum as we do, enables us to model the line ratios as a function of gas pressure and so deduce the pressure of the extended gas by matching the observations. Where we have an upper limit on the ratio of [O III] to [O II], we obtain a lower limit to the gas pressure at that radius.

The ionizing flux is estimated from a power-law interpolation of the X-ray and ultraviolet luminosity of the quasar given by Worrall *et al.* (1987) and the line-ratio calculations are carried out using the photo-ionization code CLOUDY (Ferland 1987). (This code includes many more processes than pure photo-ionization and recombination.) The (total) gas pressures obtained by our method are listed in Table 2 and the radial variations of pressure with radius are shown in Figs 6 and 7 for 3C 254 and 3C 309.1, respectively.

The central gas pressures are high, $nT > 10^6$ cm^{-3} K, and much higher than the mean gas pressure in, say, the disc of a spiral galaxy. The optical emission regions are so thin that the gas would rapidly disperse (in less than 10^5 yr) if not confined in some way. Following the arguments given in our earlier paper (Fabian *et al.* 1987) we propose that the gas is confined by the pressure of a surrounding intracluster medium. The ionization state of the emission-line gas therefore acts as a barometer of the intracluster gas. We infer that the total thermal pressure of the intracluster gas around 3C 254 is 10^6 cm^{-3} K at a projected distance at 35 kpc. A similar value is found in the other position angle to the east of the nucleus and is consistent with the lower limit found to the west.

The increasing gas pressure at smaller radii means that the gravitational potential of the central galaxy is important. For this to occur, the temperature of the diffuse hot gas cannot be much higher than the virial temperature of the galaxy, i.e. $T < 2 \times 10^7$ K (the virial temperature of a large galaxy is $\sim 0.5 - 1 \times 10^7$ K). The cooling time of the intracluster gas is then 5.6×10^8 yr ($T = 2 \times 10^7$ K) or 10^8 yr ($T = 10^7$ K), where we have used the approximation to the cooling function* for gas of metal abundance 0.4 (appropriate for nearby cluster gas) given by Thomas (1988). 3C 254 is therefore situated at the centre of a cooling flow, similar to those in nearby clusters, although within 35 kpc it appears to be at a higher

*We assume that there are no heat sources strong enough to counteract radiative cooling of the hot gas. The quasar radiation will Compton *cool* the hot gas, especially if there is an EUV bump in the spectrum. Mechanical energy has to be supplied at $> 10^{45}$ erg s^{-1} for $\sim 10^8$ yr to heat the gas significantly above the virial temperature of the underlying galaxy. This would then flatten the pressure profile, in contradiction to the form that we observe.

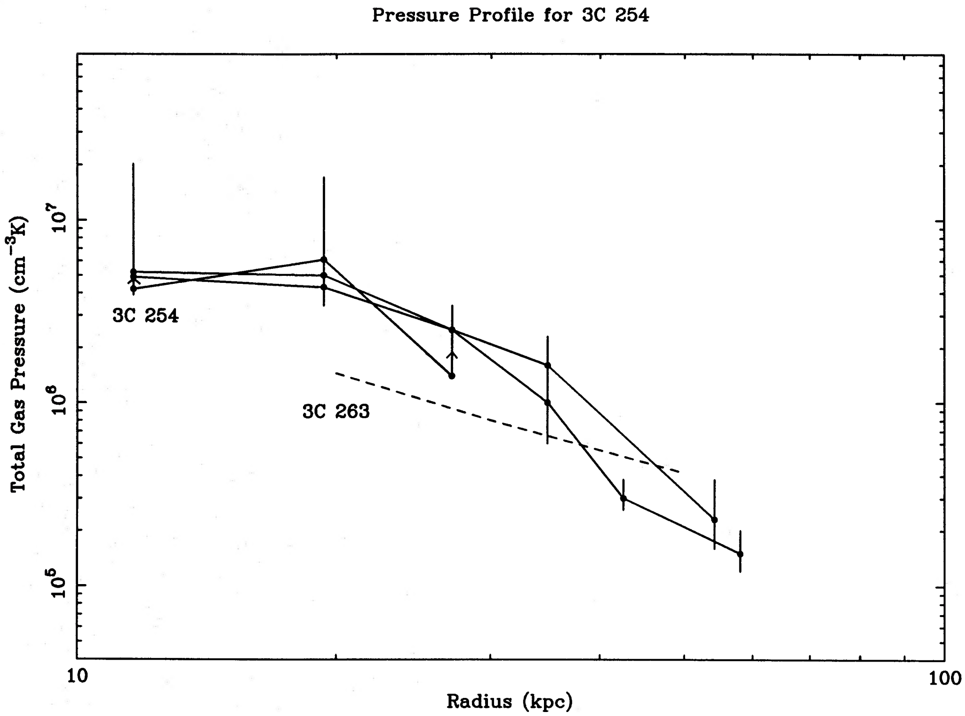


Figure 6. Pressure profiles of the gas to the south and east in 3C 254 [$\dot{M}$(<35 kpc) ~ 900 $M_\odot$ yr^{-1}] plotted with the profile for 3C 263 (>100 $M_\odot$ yr^{-1}; Crawford & Fabian 1989). See text for a discussion of the profile.

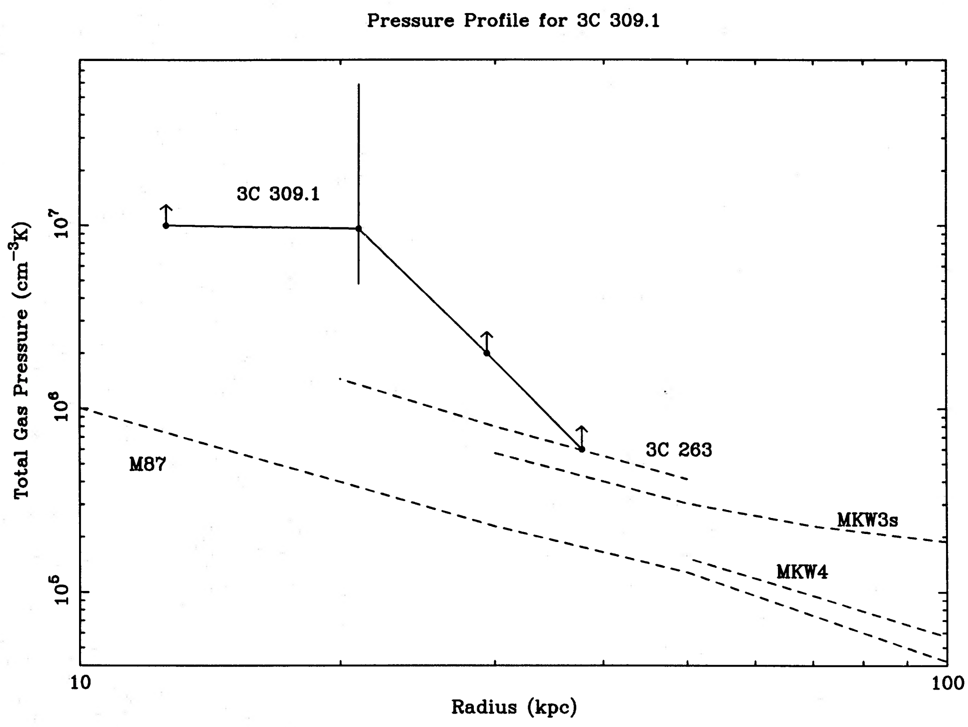


Figure 7. Pressure profiles of the gas to the west of 3C 309.1 [$\dot{M}$(<21 kpc)>1000 $M_\odot$ yr^{-1}] plotted with the profiles for some nearby cooling flows: M87 ~ 10 $M_\odot$ yr^{-1} (Stewart *et al.* 1984b), MKW4 ~ 30 $M_\odot$ yr^{-1} and MKW3s ~ 100 $M_\odot$ yr^{-1} (Canizares *et al.* 1983) and 3C263 > 100 $M_\odot$ yr^{-1} (Crawford & Fabian 1989).

pressure, as the comparison of pressure profiles in Fig. 6 shows. Dividing the mass of intracluster gas within 35 kpc by the cooling time gives an estimate of the mass deposition rate, $\dot{M}$, within that radius of 180 to 1800 $M_\odot$ yr^{-1}, depending upon whether $T=2\times10^7$ K or 10^7 K, respectively. These are enormous rates, the lower of which is comparable with the larger mass deposition rates found for much larger regions around nearby cooling flows.

In the nearby flows we find typically (Thomas, Fabian & Nulsen 1987) that $\dot{M} \propto r$, out to the cooling radius, $r_{\rm cool}$, where the radiative cooling time of the gas equals the age of the cluster ($\sim H_0^{-1}$). Without knowing the properties of the cluster which we infer to surround 3C 254 and the mean temperature of the gas beyond $r_{\rm cool}$ (X-ray observations with high spatial resolution are necessary to disentangle the quasar emission from that of the cluster), we cannot estimate $r_{\rm cool}$. If it is at 100–200 kpc as in nearby clusters, the total mass deposition rate is 500–1000 $M_\odot$ yr^{-1} for $T = 2 \times 10^7$ K and much higher if the temperature is lower. $\dot{M} \propto T^{-2.5}$ if $T > 2 \times 10^7$ K; as a guide, T at 30–40 kpc around nearby large flows is in the range of $1-3 \times 10^7$ K.

We deduce similarly that the mass cooling rate around 3C 309.1 exceeds 1000 $M_\odot$ yr^{-1} within 21 kpc. Unfortunately we can place only a lower limit on the thermal pressure at more distant radii. Nevertheless, at a rate of 1000 $M_\odot$ yr^{-1}, a substantial galaxy of $\sim 10^{12}$ $M_\odot$ is formed within $\sim 10^9$ yr. This makes 3C 309.1 the most extreme object yet found. The host galaxy associated with both of the quasars reported on in this paper is still undergoing significant formation at $z < 1$.

In the case of 3C 254, we note that the pressure profile is *steeper* beyond 35 kpc than is observed for nearby flows. This means that the gas is cooler than the virial temperature of the galaxy at those radii. If the gravitational potential of the 3C 254 host galaxy is comparable with that of M87, which appears to have a dark massive halo (Stewart *et al.* 1984a; Mould, Oke & Nemec 1987), then the virial temperature is nearer 2 keV. The steep pressure profile indicates that the gas must be at 1 keV or less. We discuss this further in the next section, but note that if 3C 254 is surrounded by a massive cooling flow of at least many hundreds and probably many thousands of solar masses per year in which the cooling time approaches the gravitational free-fall time, then the mean gas temperature may remain relatively low throughout the core of the cluster. A very high cooling rate is necessary if the matter deposited from the cooling flow is to form the dark halo. 3C 254 may be the nearest 'cooling flood'.

4 DISCUSSION

The mass deposition rates that we have deduced from our spectra are very high and suggest that both 3C 254 and 3C 309.1 are surrounded by very massive cooling flows. The emission-line region around 3C 254 is extended over a radius of at least 80 kpc. This is similar in extent to only 3C 275.1 (Hintzen & Romanishin 1986) at $z = 0.55$ and to distant radio galaxies such as 3C 326.1 at $z = 1.82$ (McCarthy *et al.* 1987a). In deducing the high pressures and cooling rates of Section 3, we have made several assumptions. In this section we discuss those assumptions in turn in order to assess the strength of our conclusions.

We have assumed that the gas is at the projected radius when it might be further from the nucleus along our line-of-sight. The inferred pressure drops roughly as r^{-2} as the assumed radius distance of the gas from the nucleus is increased (see Fabian *et al.* 1987). It is unlikely that this is a large effect since the ratios that we obtain are similar to each other at each position angle and on both sides of the quasar nucleus. We note that in a given cooling flow the pressure drops off as r^{-1} so that, were the gas to be further away from the nucleus than assumed, the inferred mass-deposition rate would only be reduced by a factor of $r_{\rm true}/r_{\rm projected}$.

This point is relevant to our assumption that the ionizing luminosity is isotropic. If it were grossly anisotropic, we would expect that the line ratios would be very different at different position angles. We do suspect that the radiation has some anisotropy, following the arguments of Barthel (1989). He noted that the redshift distributions of the 3C radio galaxies and quasars, in the redshift range covering our objects, are very similar and that the mean size of the double radio sources of the quasars is smaller than that of the radio galaxies. This can be explained if the quasars are the same population as the radio galaxies and we view them within 45° of the radio axis. Thus the quasars are those objects viewed down the broad emission beam and the radio galaxies are the objects viewed at other angles. The necessary anisotropy is thus of an approximately on–off nature, where we (or the emission-line clouds) either see the full nuclear radiation field or we (or the clouds) do not. Such anisotropy does not seriously affect our assumptions, except that on average the clouds are probably not in the plane of the sky. For an individual object we cannot comment on the geometry. We see no strong change in the line ratio when the slit is placed along the radio axis (a position angle of 105° in Table 2). In the case of distant radio galaxies, the emission lines tend to be extended along the radio axis, to within $\sim 45°$ (McCarthy *et al.* 1987b), so we expect that the emission lines in the quasars are in the full nuclear radiation field.

3C 309.1 has been noted as an object in which the radio jet is interacting strongly with an inhomogeneous environment (on the scale of a kpc or so) and in which the jet may point fairly close to our line-of-sight (Wilkinson *et al.* 1986). If the optical luminosity appears significantly enhanced in our direction, then we have overestimated the luminosity used in our photo-ionization calculations and consequently the gas pressure.

We have attempted to deduce a quantitative measure of the anisotropy in the nuclear radiation field of 3C 254 by estimating the covering fraction of a spatial cross-section of our slit by emission-line clouds. This can be done since the CLOUDY models give the [O II] flux from the surface of a cloud at 20 kpc ($\sim 2 \times 10^{-2}$ erg cm^{-2} s^{-1} for an ionizing luminosity of 2.8×10^{46} erg s^{-1}) and this can be matched to the observed extended flux observed at that radius ($\sim 2.4 \times 10^{-16}$ erg cm^{-2} s^{-1} per 1.25 by 0.8 arcsec pixel). We obtain a covering fraction of ~ 8 per cent. (A similar fraction is obtained if we rework this estimate at 40 kpc.) Including a factor of $\sqrt{2}$ to account for the aspect of the clouds which cannot simultaneously be face on to both us and the quasar, we find that the covering fraction remains below 100 per cent provided that the ionizing luminosity and the pressure exceed one tenth of our assumed luminosity and $\sim 10^5$ cm^{-3} K, respectively. This pressure and the implied mass-deposition rate then still exceed that in a nearby flow such as that around M87. Corrections for seeing will increase this lower limit. The emission-line clouds can also act as absorbers if they lie along the line-of-sight to the quasar nucleus. A covering fraction of ~ 10 per cent is compatible with the fraction of radio-loud quasars that have metal absorption lines at the quasar emission-line redshift, $z_{\rm abs} = z_{\rm em}$ (Crawford *et al.* 1987; Weymann, Carswell & Smith

Table 3. [Ne III]/[O II] and [Ne V]/[O II] line ratios in the extended gas around 3C 254.

Quasar	Log(L_{ion}) ($erg\ s^{-1}$)	Position Angle (degrees)	Radius (kpc)	[NeIII]/[OII]	[NeV]/[OII]
3C 254	46.45	105	11.61	0.30±0.17	0.25±0.19
			19.35	0.10±0.06	0.10±0.09
			27.09	0.10±0.06	-
		350	11.61	0.20±0.08	0.14±0.11
			19.35	0.24±0.06	<0.21
			27.09	0.14±0.10	-
			34.85	0.27±0.24	-

1981). The total [O II] luminosity of the extended emission within a few arcsec of the nucleus of 3C 254 is at least 5×10^{42} erg s^{-1}, making it comparable with the more luminous objects in the (lower redshift) quasar-imaging sample of Stockton & MacKenty (1987).

Evidence in favour of Barthel's (1989) picture is provided by the ionization state of neon, measured from [Ne III]/[O II] and [Ne V]/[O II]. It is clear from Fig. 2 that the neon lines are extended, if not by as much as the oxygen lines. We list the neon to oxygen line ratios in Table 3 and note that they are in very good agreement with those measured for the extended gas around radio galaxies in the redshift range of our quasars (McCarthy *et al.* 1988). We do not, however, find agreement with our photo-ionization models for the [Ne V]/[O II] ratio. Since the ionization potential of Ne^{3+} is 97 eV, it seems that we need some extra source of high-energy ionizing radiation or some other ionizing process. This problem is well known in the nuclear spectra of active galaxies (Binette, Courvoisier & Robinson 1987; Binette, Robinson & Courvoisier 1987) and we do not attempt to solve it here but simply note two possibilities: the first is that an extra source of ionization is required; the second is that some of the emission-line clouds are matter-bounded. We have carried out the photo-ionization calculations assuming that the clouds are radiation-bounded, which means that the photo-ionizing radiation is exhausted before reaching the back of a cloud. Thin clouds through which most of the ionizing flux can pass will have a higher mean ionization and give rise to stronger lines from the more ionized species. Extra ionization or thin clouds both mean that our estimates of the gas pressure and mass deposition rates are *lower* limits. One source of thin clouds is stellar mass loss from the underlying galaxy.

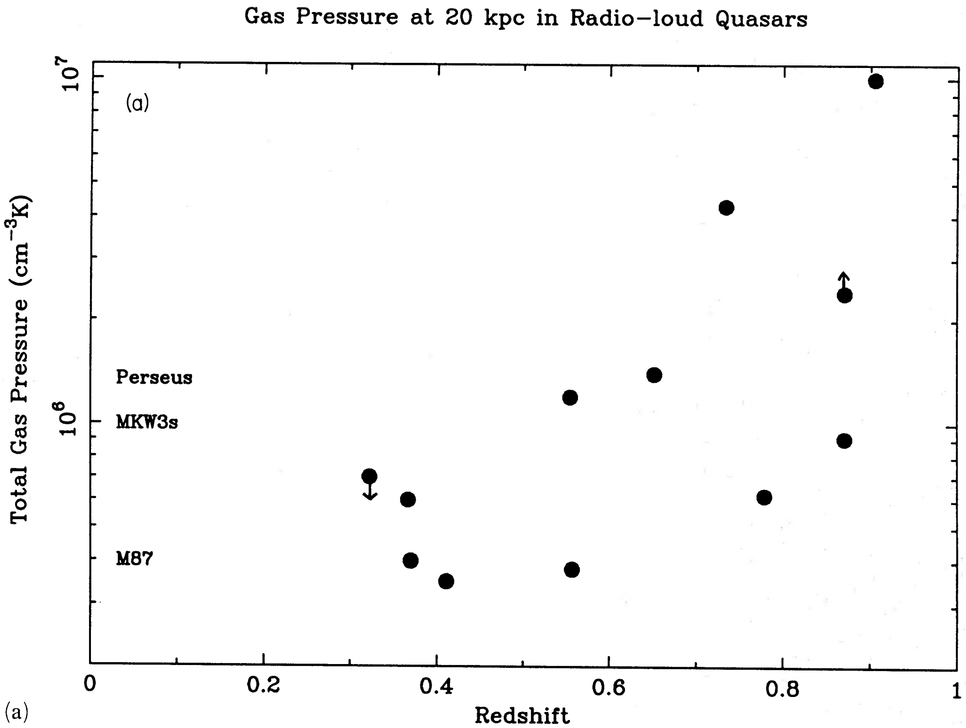
We have already commented on the relatively low pressure found at large radii around 3C 254. This may be a simple consequence of a very massive cooling flow causing the mean gas temperature to be lower than in nearby objects – the flow is 'loaded' with cool clouds. Alternatively it may indicate problems with our interpretation. Extra ionization (or matter-bounded clouds) at such radii may cause the [O III]/[O II] ratio to increase and lead to an apparent drop in pressure. Since both the 350° and 105° position angle results agree with each other, it seems that the radio source is not directly responsible since it should only affect the 105° axis. (The same point can be made for the weak off-nucleus continuum source, which is only observed to the south.) The fact that the results from the two position angles agree and yet are separated by 75 kpc is encouraging for the hot-confining-medium interpretation, since the hot medium provides the common factor over such a distance. Gas pressure should be almost constant at a given radius. Another possible factor which could affect the line ratios at a large radius is variability of the quasar nucleus. If the quasar was about three times brighter 2×10^5 yr ago, then the pressure profile would be consistent with that of nearby flows. Of course, the quasar may have been fainter 3×10^4 yr ago and our pressure profile at 10–30 kpc would then be overestimated.

In summary, a straightforward interpretation of the [O III]/[O II] line ratios as due to photo-ionization by the quasar nucleus indicates that the emission-line regions around both 3C 254 and 3C 309.1 are at very high pressure. The pressure profiles mean that the confining gas is responding to the gravitational potential of the underlying galaxy and so is relatively cool. Our interpretation is dependent on a number of assumptions, the chief of which is the shape and intensity of the ionizing spectrum incident on the emission-line clouds. If the quasar radiation is beamed or variable, then, depending on whether we see more or less radiation than the clouds, the inferred pressure can reduce or increase, respectively. In passing, we note that the extent to which the radiation is beamed has a direct influence on the luminosity function of quasars and on implications for the mass and evolution of their central engines. A direct test of the pressure, and thus of our assumptions, can be made by measuring the doublet ratio of the [O II] line, which is sensitive at the implied densities.

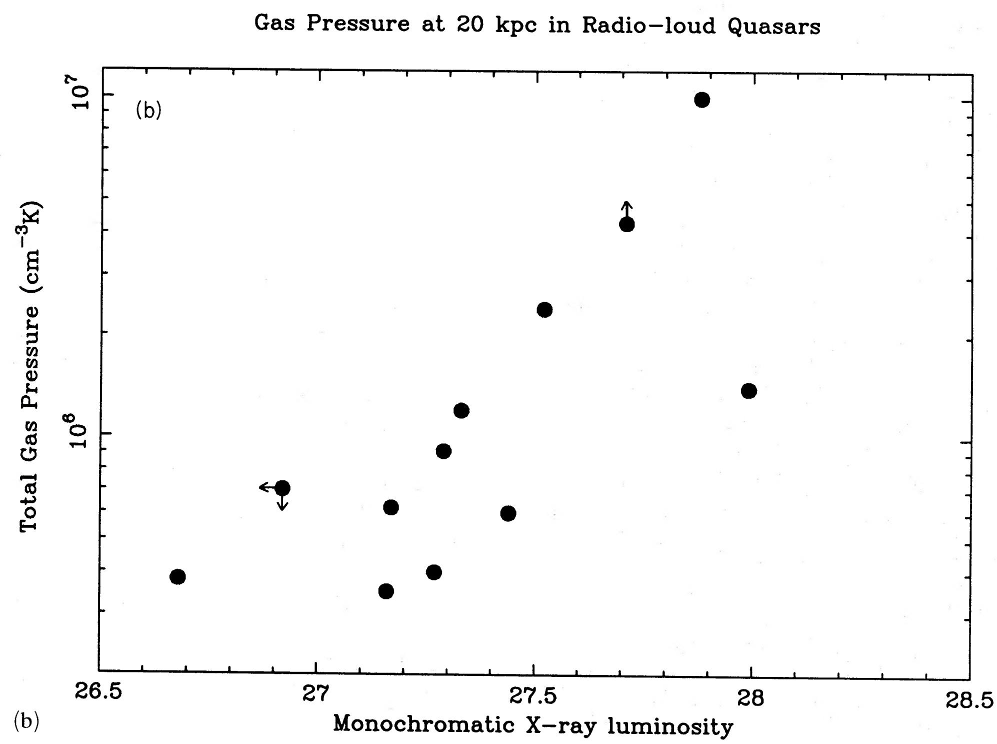
The need for hotter surrounding gas to confine the emission-line clouds is particularly acute in the cases reported here. Following our earlier arguments for 3C 48 (Fabian *et al.* 1987), we note that the emission-line gas will disperse at its internal sound speed in about $t_{dis}\approx5\times10^4$ yr if it is not confined. This would then require that there is $\sim t_{cross}/t_{dis}$ times more cold gas ready to be photo-ionized than observed as emission-line gas. t_{cross} is the lifetime of the emission-line cloud system, which we estimate to be at least the dynamical crossing time of the system ($t_{cross}\approx5\times10^8\ R_{100}/v_{300}$ yr, where the size of the system is 100 R_{100} kpc and the velocity is 300 v_{300} km s^{-1}). Since we already see $\sim10^8\ M_\odot$ in warm emission-line clouds, the total mass of cold gas in the system, if there is no confining medium, is almost $10^{12}\ M_\odot$. This is so large that we can rule out the possibility that the clouds are unconfined.

Corroborative evidence that the quasars are surrounded by gas at high pressure is provided by the radio maps of these sources (Owen & Puschell 1984; Spencer *et al.* 1989). The minimum pressures obtained from their extended radio emission, assuming that it is synchrotron radiation, are $\sim5\times10^6$ cm^{-3} K at 20 kpc in 3C 254 and $\sim10^7$ cm^{-3} K at 12 kpc in 3C 309.1. These values agree remarkably well with those obtained here (Table 2). The much stronger polarization of the western lobe of 3C 254 relative to the eastern lobe may also indicate Faraday depolarization in the intra-cluster gas (see e.g. Garrington *et al.* 1988; Laing 1988). The unusual and distorted radio appearances of the quasars are probably due to interactions with dense clouds of gas.

We note that the higher pressures that we have previously reported for radio-loud quasars (Fabian *et al.* 1987; Crawford *et al.* 1988; Fabian *et al.* 1988; Crawford & Fabian 1989) occur around the higher redshift objects. There appears to be a trend of pressure increasing with redshift (Fig. 8a). This is reminiscent of the trend found for surrounding cluster richness by Yee & Green (1987), out to a redshift



(a)



(b)

Figure 8. (a) Pressure of emission-line gas, at 20 kpc from the nucleus, plotted against redshift for the radio-loud quasars reported by us and by Fabian *et al.* (1987), Crawford *et al.* (1988), Fabian *et al.* (1988) and Crawford & Fabian (1989). The pressures in three nearby cluster cooling flows are indicated. (b) Pressure of emission-line gas, at 20 kpc from the nucleus, plotted against monochromatic X-ray luminosity (erg s^{-1} Hz^{-1}) (taken from Worrall *et al.* 1987) for the radio-loud quasars reported by us and by Fabian *et al.* (1987), Crawford *et al.* (1988), Fabian *et al.* (1988) and Crawford & Fabian (1989).

of about 0.65, where their observations become signal-to-noise limited. Yates, Miller & Peacock (1989) find a similar effect for radio galaxies and Barthel & Miley (1988) found that the jet bending-angle of quasars tends to be larger at higher redshifts. This is taken as an indication of a more dense, or clumpy, environment with redshift. We cannot say whether our trend of increasing pressure is a primary correlation, or due to some selection effect (e.g. selection of the brightest quasars), from our highly selected small sample. In Fig. 8(b) we show the pressure versus the monochromatic X-ray luminosity (from Worrall *et al.* 1987). There is a strong systematic trend in the data which suggests that the luminosity of the quasar is related to its environment and is consistent with the cooling flow helping to power the quasar. (The correlation occurs because of the small observed range of [O III]/[O II] ratios.) These correlations suggest that a dense surrounding medium is relatively common around powerful radio-loud quasars at moderate redshifts. Together with the evidence for radio-loud galaxies being similar objects and for them being surrounded by strong extended emission-line gas with a similar ionization state out to a redshift approaching $z=2$ (Spinrad & Djorgovski 1984a,b and McCarthy *et al.* 1988 find [O II] to be very strong), we see that the possibility of distant radio-loud objects being surrounded by massive cooling flows (Fabian *et al.* 1985, 1986; Fabian 1988) is consistent with observations. Finally, we note that the large observed velocity spreads to the emission lines are comparable with those observed in distant radio galaxies.

If the mass deposition rates above a redshift of $z=1$ exceed 1000 $M_\odot$ yr^{-1} by a factor of a few, then cooling flows may have been sufficiently strong in the past to have built the central cluster galaxies. With this in mind, we have considered the redshift limitation of our method. The major problem is subtraction of night sky emission which becomes much more difficult at redshifts greater than $z=0.93$. In Fig. 9 we show a typical night sky spectrum plotted against the redshift of [O II]. Apart from a small window at $1.17<z<1.22$, we see that it will be difficult to continue the method to much higher redshifts than obtained here unless the line strengths increase considerably. The [O III] line is already in the 'forest' of night-sky emission lines by a redshift of $z=0.69$. This is the major source of uncertainty in our [O III]/[O II] line ratios. At a redshift of $z=1$ the [O III] line has a wavelength of 1 μm where the FOSII has very little response. However, it may be possible to detect it with the new generation of infrared spectrographs. We may also use lines of shorter rest-wavelength, although our CLOUDY models indicate that those lines (e.g. Mg II, C IV etc.) are much weaker than [O II].

5 CONCLUSIONS

The radio-loud quasars 3C 254 and 3C 309.1 are surrounded by extensive optical emission-line gas which is at very high pressure. The gas must be confined by hot intracluster gas which is part of a massive cooling flow around each quasar. In the case of 3C 309.1, the mass deposition rate is the highest yet inferred and may be high enough to form most of the central galaxy. We have found a trend of increasing gas pressure (and thus of mass deposition rate) with redshift, suggesting that cooling flows are an important process of galaxy formation.

There is no evidence for the emission-line ratios being influenced by the radio source or for the quasar radiation being strongly anisotropic. In the inner regions of these objects, the gas pressure is high enough that the density-sensitive doublet ratio of [O II] will be reduced below its low-density limit. A more direct measurement of the electron density – and a test of our interpretation – can be made therefore with higher dispersion spectroscopy. This will also enable us to determine whether the emission-line gas is exposed to the same ionizing luminosity as we are.

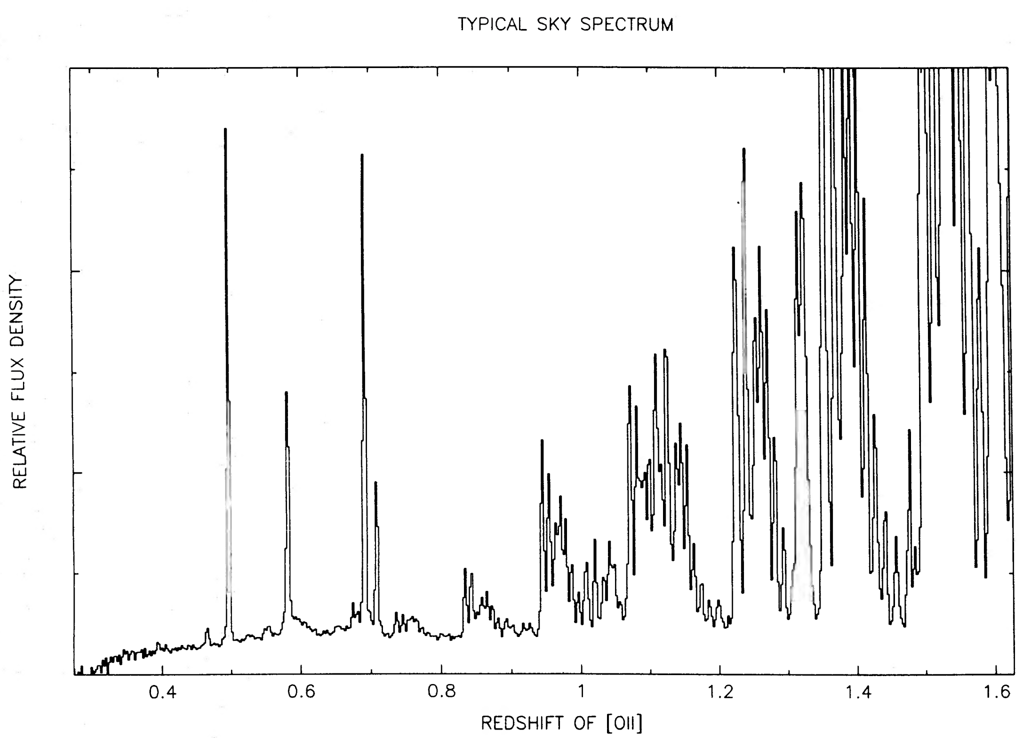


Figure 9. The relative intensity of a typical sky spectrum with the wavelength scale expressed in terms of the redshift of the [O II]λ3727 line. At redshifts greater than $z=0.93$, sky subtraction around the [O II] line becomes rather uncertain. Apart from a small redshift window ($1.17<z<1.22$), it will be difficult to use this line as a diagnostic for more distant quasars.

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