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A cooling flow around the quasar 3C 48

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Summary. Spatially-resolved optical spectra of the nebulosity around the quasar 3C 48 show forbidden oxygen line emission extending to a radius of ~30 kpc. Assuming that the gas is photoionized by the quasar nucleus which has a spectrum unabsorbed shortward of 91.2 nm, we interpret the relative strengths of the [O III] and [O II] lines to indicate a gas density of at least $3\times10^7\,\mathrm{m}^{-3}$. The observed gas is in clumps which are thinner than about 10 pc and is at a pressure consistent with a cooling flow such as that around the central galaxy in the poor cluster MKW3s. The total mass of observed gas is $\sim3\times10^8\,M_\odot$.

The commonly proposed galaxy collision or merger hypothesis for quasar nebulosity leads to the clumps being unconfined so that they rapidly disperse. A much higher total mass of cold gas ($>10^{11}\,M_\odot$) is required so that the nebulosity can last for a collision time-scale and widespread emission can occur. As this far exceeds the mass of gas in normal galaxies, we consider that a galaxy collision is an unlikely explanation for 3C 48.

A cooling flow around 3C 48 and other quasars is consistent with them lying in either poor or rich clusters and, through accretion, provides a direct link between the quasar nucleus and its environment.

1 Introduction

Recent work has shown that quasars are embedded in galaxies. Nearly all quasars with redshifts of less than 0.7 that have been studied carefully are found to be surrounded by diffuse emission – commonly called ‘fuzz’ – that is similar to galactic starlight (Kristian 1973; Gehren *et al.* 1984; Hutchings, Crampton & Campbell 1984; Malkan 1984). The angular resolution of existing observations precludes any general statement about the surroundings of more distant quasars, although some radio-loud objects lie in spectacular and large regions of emission (Spinrad 1986; Spinrad & Djorgovski 1984a, b). Images and spectra of quasar fuzz show it to be irregular in shape (Stockton & MacKenty 1987), often with strong narrow emission lines (Boroson & Oke 1982; Boroson, Persson & Oke 1985).

This discovery has prompted much speculation on the role of galaxy collisions and mergers (van

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Breugel *et al.* 1986; Heckman *et al.* 1986; Stockton 1982; Spinrad & Djorgovski 1984a, b; Stockton & MacKenty 1987), which might also assist in powering the central engine in some way (e.g. Gunn 1979). Alternatively, it is possible that the extensive patches of emission are due to gas deposited by a cooling flow around the quasar (Fabian *et al.* 1986; Sarazin & O'Connell 1983). Hintzen & Romanishin (1986) find good agreement between this explanation and the properties of the nebulosity around the quasar 3C 275.1. Nearby cluster galaxies at the centres of cooling flows, such as M87 and NGC 1275, contain optical emission filaments extending to ~3 and 30 kpc respectively. A luminous quasar at the centre of such nebulosity could illuminate it enough to make it detectable at large redshifts. Furthermore, cooling flows show evidence for continued star formation (Johnstone, Fabian & Nulsen 1987) which can explain the blue continuum in the fuzz of some QSOs.

Here we compare these hypotheses for existing and new data on 3C 48 which was one of the first quasars to show clear evidence of surrounding nebulosity. Deep photographs of the quasar by Sandage & Miller (1966) show features extending ~6 arcsec either side (~40 kpc for $H_0=50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) to the north and south of the nucleus. Strong emission lines of [O II], Hβ and [O III] were found in the fuzz by Wampler *et al.* (1975) in an aperture centred ~4 arcsec NW from the nucleus and interpreted by Bergeron (1976) as due to gas of density $\lesssim 10^5\,\mathrm{m^{-3}}$. Further spectroscopy by Boroson & Oke (1982, 1984) and imaging by Malkan (1984) show that the continuum underlying the nebulosity is blue and probably due to hot young (at least A-type) stars. This has been taken as a signal that the host is a very large spiral galaxy. The extended gas could be similar to the rings of H I seen around some spiral galaxies (e.g. Briggs 1982).

We present in Section 2 data taken with the Isaac Newton Telescope (INT) that resolve the emission line gas and demonstrate that the gas extends to at least 4.5 arcsec (~35 kpc) from the nucleus. Using a photoionization method, similar to the approach of Bergeron (1976) but employing a different nuclear spectrum, consistent with recent observations, we establish in Section 3 that the gas is at a relatively high density and pressure. This favours the cooling flow hypothesis.

2 INT observations

3C 48 and its nebulosity were observed on two nights using the Intermediate Dispersion Spectrograph with a CCD detector on the 235-mm camera on the INT, La Palma (Table 1). The data were reduced using the STARLINK FIGARO system. All images were bias-subtracted, and flat-fielded with a tungsten lamp exposure. Comparison lamp spectra were fitted to a cubic polynomial. The data were then sky subtracted, corrected for atmospheric extinction and approximately flux-calibrated using spectro-photometric standards. Standard reddening corrections were applied.

The spectrum of the nucleus displays the following emission lines; [O III] $\lambda\lambda 500.7, 495.9$, [O II] $\lambda 372.7$, [Ne III] $\lambda 386.9$, [S II] $\lambda 406.9+407.6$, as well as Hδ, Hγ, Hβ and broad Fe II complexes

Table 1. Log of observations.

Observation	Date	Exposure time (s)	Seeing (arcsec)	Slit width (arcsec)	P.A. of slit	Dispersion (nm channel^{-1})
3C48	1986 July 9/10	2000	1.1	1	87°	0.6
3C48	1986 October 1/2	2000	1.0	1	54°	0.6
3″ NW of 3C48	1986 October 1/2	2000	1.0	1	53°.7	0.6
3″ SE of 3C48	1986 October 1/2	2000	1.0	1	53°.7	0.6

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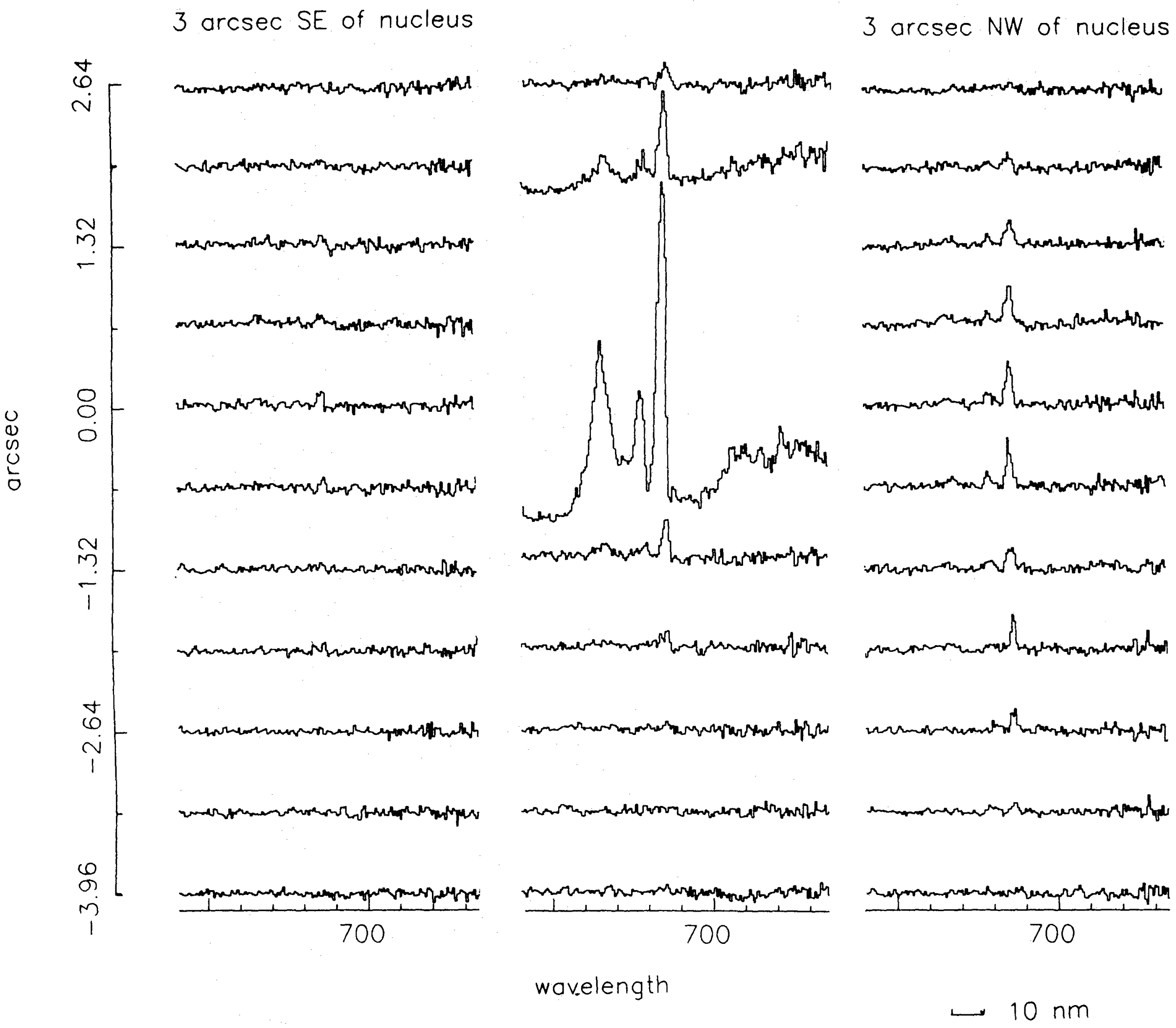

Figure 1. INT spectra of 3C 48 at P.A. 54° over the waveband 640 to 735 nm corresponding to 467 to 536 nm at the rest wavelength of the quasar (z=0.37). Scattered light from the nucleus has not been subtracted. The central column passes through the nucleus where broad Hβ, strong [O III] and the Fe II emission complex are observed. The nucleus spectrum has been rescaled and offset. The [O III] line is clearly extended over eight cross-sections in the right-hand column, which is from a slit centred 3 arcsec NW of the nucleus.

centred at ~453 and ~533 nm. The narrow emission lines of [O II] and [O III] extend well into the nebulosity on either side of the nucleus; [O III] $\lambda\lambda$500.7, 495.9 extend over eight cross-sections ~5 arcsec corresponding to ~35 kpc) in our NW exposure, and over four cross-sections (~2.5 arcsec or 20 kpc) in the SE exposure (Fig. 1). The spectrum of the innermost parts of the nebulosity shows some contamination from scattered light from the nucleus. This was removed by subtracting a spectrum of the nucleus, scaled for each cross-section by an amount matching the broad iron complexes, which are not expected to be present in the nebulosity. The [O III] lines are reduced by about a half for the cross-section nearest the nucleus to the NW whilst those to the SE almost disappear.

In our nucleus-subtracted data we find no stellar absorption features in the nebulosity, and an upper limit to the continuum within a 0.66 arcsec^2 pixel of 0.01 mJy to the NW, and 0.006 mJy to the SE. (This is consistent with the continuum detection by Boroson & Oke 1982.) Little or no Hβ is detected in the nebulosity. The ratio of [O III] λ500.7 to [O II] λ372.7 is measured to be 1.5 in the NW slit (see Fig. 2). The [O III] lines show a definite velocity trend of ~660 km s^{-1} (Fig. 3) and also appear at a slightly higher velocity (+230 km s^{-1}) than those in the nucleus.

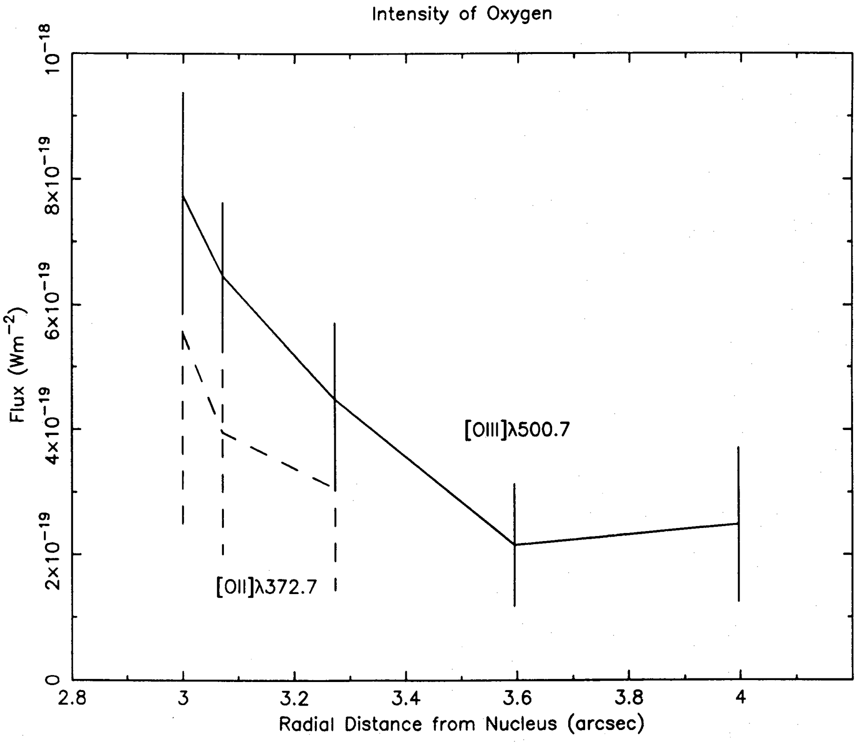

Figure 2. The mean radial distribution of the [O III] λ500.7 and [O II] λ372.7 line strengths from the NW slit. The error bars are $\pm 2\sigma$.

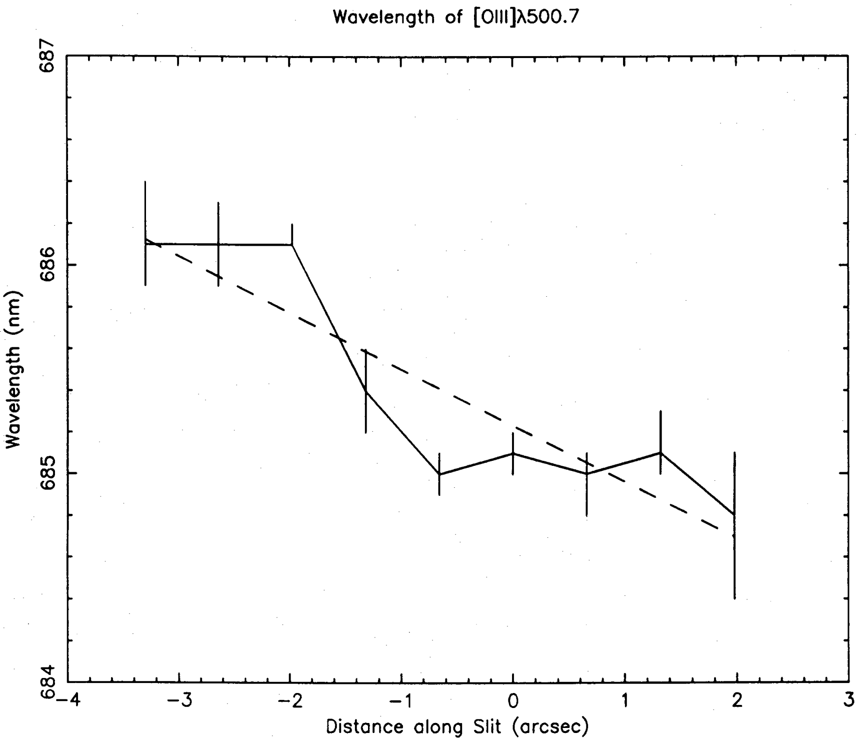

Figure 3. Position of the central wavelength of the [O III] λ500.7 line from the NW slit.

3 Interpretation

3.1 GAS DENSITY

We have no direct estimate of gas pressure or density in the case of 3C 48. The density-dependent [S II] lines are not reliably detected. Instead we use an indirect approach (see also Bergeron 1976) in which the ionization state of the gas inferred from the observed [O III]/[O II] line ratio is compared with model predictions for various ionization parameters (L/nR^2). The emission-line gas density, n, is then found if the ionizing luminosity of the quasar, L, and distance of the gas from the nucleus, R, are known.

The ionizing spectrum of the quasar is crucial to this method of density determination. We begin by noting that the X-ray and optical luminosities of 3C 48 (3×10^{38} W over 0.3–3 keV) are similar to those of 3C 273 (Wilkes & Elvis 1987). Its *IUE* spectrum (*IUE* Low Dispersion Microfiche Plots, 1985) is also similar and flattens towards 91.2 nm, indicating a 'big bump' of excess ultraviolet emission such as found in 3C 273 (Malkan & Sargent 1982). The soft X-ray spectrum of 3C 48 is fitted best by a photoelectric absorbing column of less than the Galactic value in that direction, which suggests that the bump of excess emission extends to the far-ultraviolet and possibly to the softest X-ray waveband (Wilkes & Elvis 1987). Consequently, in the photoionization calculations we use either a power-law spectrum $F_\nu \propto \nu^{-1.3}$ from 0.2–2000 Ryd of total luminosity 10^{39} W (this agrees with the *IUE* short-wavelength spectrum and the X-ray data without allowing for a bump) or a power law with a blackbody bump of equal luminosity (total $L=2\times10^{39}$ W). Bergeron (1976) assumed that the continuum fell off steeply below 91.2 nm and so the *effective L* in the ionization parameter was significantly less than we estimate. There is no evidence that quasar spectra are much absorbed in the Lyman continuum [the Wilkes & Elvis (1987) result corroborates this] and no sign of the reprocessed radiation as line emission. [But see Neugebauer, Soifer & Miley (1985) for observations of a thermal bump probably due to dust emission. This feature is similar to, but ~20 times more luminous than, a bump in the spectrum of the cooling-flow galaxy NGC 1275 (Gear *et al.* 1985).] Absorption will occur, of course, in the fraction of the sky subtended at the nucleus by the broad-line clouds. The covering fraction by these clouds is generally considered to be very small (Baldwin & Netzer 1978).

The calculations are carried out using Ferland's code (Ferland & Truran 1981). The computer code assumes that the ionizing radiation is incident normally on to the gas which lies in a shell at a distance of 30 kpc. The equilibrium temperature and ionization states of the gas are then found in thin radial steps and the total line emission from the ionized and partially-ionized gas tabulated. We plot in Fig. 4 the expected ratio of [O III]/[O II] against density, n, for gas at 30 kpc from the nucleus. This is the outer radial distance of the gas in our slit. The density required at smaller radii increases as r^{-2}. The measured ratio of 1.5 implies that $n\sim3\times10^7\,\mathrm{m}^{-3}$ and it could be $\sim8\times10^7\,\mathrm{m}^{-3}$ if an ultraviolet bump is present. The pressure of the gas is then $nT\sim3\times10^{11}$–$8\times10^{11}\,\mathrm{m}^{-3}$ K which is 100 times larger than the mean value in our interstellar medium. The radial depth of the stable partially-ionized region, where heating balances cooling, is between 10 and 3 pc respectively. Hydrogen is almost fully recombined over the outer two-thirds of this region. We find the predicted emission strength of the other lines to be mostly satisfactory with Hβ:[O III] λ500.7:[O II] λ372.7:[O I] λ630.0:Hα:[S II] $\lambda\lambda$671.8, 673.1 to be 1:13:8:1.1:2.7:4.2. Inspection of the spectra of Boroson & Oke (1982) and Wampler *et al.* (1975) suggests that our prediction for [S II] $\lambda\lambda$661.8–663.1 relative to Hα may be too high, but their spectra have not been properly corrected for nuclear spill-over in that band. Line detections and limits in their, and our, corrected spectra are in agreement with the predictions.

The total mass of emission-line gas detected is estimated from the predicted strength of the [O III] λ500.7 line. The model calculations give $8\times10^{-6}\,\mathrm{W\,m^{-2}}$ in that line at the source. The total detected flux in our slit is $\sim4\times10^{-18}\,\mathrm{W\,m^{-2}}$ so, at a redshift of 0.37, we require an area of

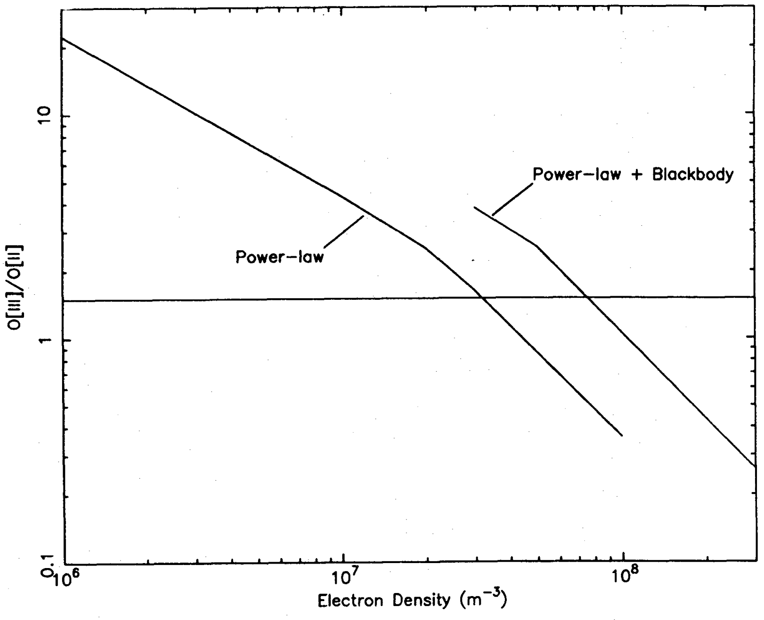

Figure 4. Ratio of [O III] λ5000.7 to [O II] λ3372.7 line strengths predicted by Ferland's code for gas at 30 kpc photoionized by a power-law quasar spectrum (left) and a power law plus a blackbody of equal luminosity (right). The observed ratio of about 1.5 is indicated by the horizontal line.

$\sim 3\times 10^{40}\,m^2$ exposed to the quasar radiation. This represents a covering fraction of ~0.2 per cent at a distance of 30 kpc from the source. The mass of gas is then obtained from the product of the radial depth of the emission-line region, the area and the density. We obtain a mass of $3\times 10^8\,M_\odot$, which is a minimum estimate as there is probably more gas lying undetected outside our slit. The fractional area covered by our slit suggests that there may be 3–6 times more gas.

3.2 COLLISIONS AND MERGERS

If the gas and star formation are fuelled by a collision or merger of two galaxies, we find a serious problem with the lifetime of the emission-line gas. There is no hot confining gas at high pressure so the photoionized gas at temperature $10^4\,T_4$ K expands at its local sound speed, $c_s \sim 10^4\,T_4^{1/2}\,m\,s^{-1}$. As the depth, d, of the ionized region is only about 10 pc, it will dissipate on a sound crossing time $\sim d/c_s$ of $t_{cross} \sim 10^5\,d$ yr, where d is in pc. The dynamical time associated with the collision or merger, assumed to occur at a relative velocity v of $\sim 100\,v_2\,km\,s^{-1}$, is $t_{dyn} \sim l/v \sim 3.5\times 10^8\,v_2^{-1}$ yr where l is length of the nebulosity (~35 kpc). There must then be much more cold gas present in the system than actually observed, in order to compensate for that continually evaporated by the photoionization process. The total mass needed is then $\sim t_{dyn}/t_{cross} \sim 3.5\times 10^2\,v_2^{-1}$ times that observed at any instant, or $\sim 1.1\times 10^{11}\,v_2^{-1}\,M_\odot$. The clumps could be self-gravitating if sufficient (shielded) neutral gas is present. We deduce a similar total mass requirement of $10^{11}\,M_\odot$ in this case. Pre-existing stars could gravitationally bind the gas if $10^{11}\,M_\odot$ of stars are clustered on scales <10 pc. About 3×10^5 globular clusters in the observed region would be needed.

This mass of cold dense gas, presumably molecular gas, is much larger than observed in nearby spiral galaxies and appears to rule out a collision or merger involving normal galaxies. Only if the ionizing radiation from the quasar is absorbed close to the nucleus can a lower pressure and thus longer lifetime and lower mass solution be found. The relative strengths of the broad emission lines in the quasars nucleus are roughly similar to those of the narrow lines in the nebulosity, indicating that there is no drastic change in the ionizing spectrum within the broad-line region.

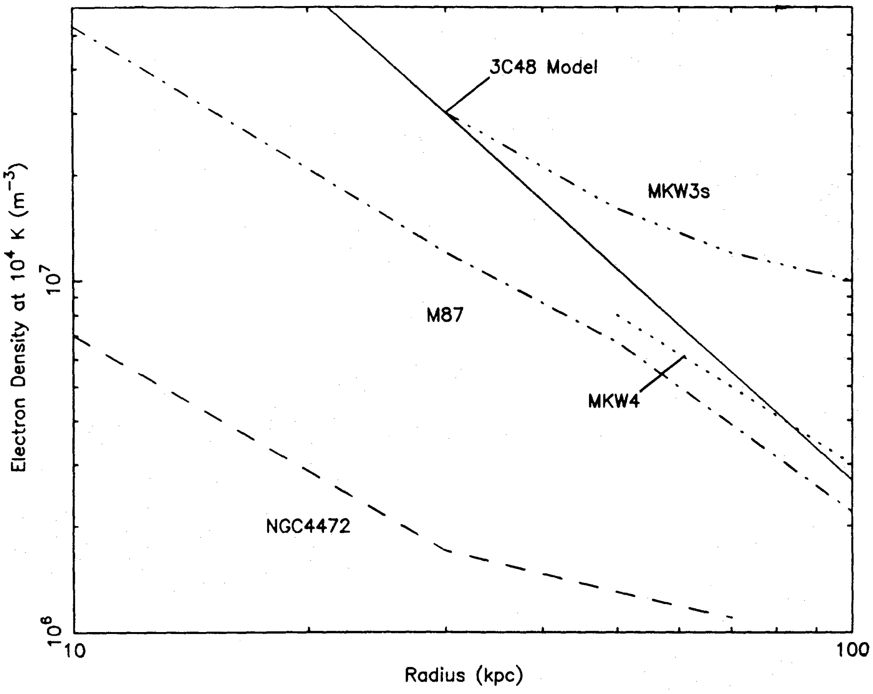

Figure 5. The electron density of gas at 10^4 K in pressure equilibrium with various nearby cooling flows (NGC 4472 has $\sim 1 M_\odot \mathrm{yr}^{-1}$; M87$\sim 10 M_\odot \mathrm{yr}^{-1}$; MKW4, $\sim 30 M_\odot \mathrm{yr}^{-1}$; MKW3s, $\sim 100 M_\odot \mathrm{yr}^{-1}$; see text for references). Our power-law photoionization model for 3C 48 requires that the observed gas lies on the r^{-2} line shown.

3.3 COOLING FLOWS

A cooling flow provides a ready source of cooled gas and a high confining pressure. The gas pressure ranges from about 10–1000 times the pressure of the interstellar medium of our Galaxy as the environment changes from an isolated elliptical galaxy (Thomas *et al.* 1986) to a rich cluster (Stewart *et al.* 1984b). Measurement of the pressure of the emission-line gas (or its density since the temperature must be $\sim 10^4$ K) is a good discriminant of a cooling flow (Fabian *et al.* 1986).

We show in Fig. 5 the expected density profile for gas at 10^4 K in pressure equilibrium with the hot gas around nearby cooling flows. NGC 4472 has a mass deposition rate of $\sim 1 M_\odot \mathrm{yr}^{-1}$ (Thomas *et al.* 1986), M87$\sim 10 M_\odot \mathrm{yr}^{-1}$ (Stewart *et al.* 1984a), MKW4$\sim 30 M_\odot \mathrm{yr}^{-1}$ and MKW3s$\sim 100 M_\odot \mathrm{yr}^{-1}$ (Canizares, Stewart & Fabian 1983). Since many radio-loud quasars are inferred to lie in elliptical galaxies (Malkan 1984) which are in poor clusters (Yee & Green 1984; Hintzen 1984), it is not surprising that the pressure around 3C 48 is comparable with that in nearby poor clusters. We conclude that our, and previous, results for 3C 48 are consistent with a surrounding cooling flow of $\sim 100 M_\odot \mathrm{yr}^{-1}$, similar to that around MKW3s. A larger flow is not excluded if there is a significant blue bump in the nucleus spectrum. Compton cooling of the hot gas by a luminous ultraviolet bump is unimportant provided that $L \lesssim 5 \times 10^{39}$ W.

The young stellar population observed by Boroson & Oke (1982) can be forming from the cooling gas, as may the 15 arcsec long, blue continuum feature observed by Stockton & MacKenty (1987). Gas in clumps that are deeper than a few pc will be shielded from the ionizing radiation and can collapse to low temperatures. The formation of massive stars does appear to be associated with large clumps in cooling flows (Johnstone, Fabian & Nulsen 1987). The blue colour and evidence for A stars in 3C 48 implies that it has an exceptionally large population of massive stars and suggests a link between the activity of the quasar nucleus and the persistence of large clumps.

One unresolved issue in the cooling flow hypothesis is the source of the observed velocity structures. The clumps of gas should have a relative velocity spread of only a few tens of km s^{-1} when suspended in a cooling flow, which is highly subsonic. Instead, relative velocities of up to 500 km s^{-1} are observed in the cooling flow gas of A1795 (van Breugel, Heckman & Miley 1984) and in the above-mentioned 3CR objects. The velocity spread in 3C 48 is $\sim$660 km s^{-1}. It is possible that we observe only large, non-linear clumps that have separated from the flow and are freely-falling (Nulsen 1986). A velocity spread of $\sim$1000 km s^{-1} is obtained from a velocity dispersion of only 430 km s^{-1}, similar to that of the globular cluster system around M87 (Huchra & Brodie 1987). Galaxy interactions may generate turbulence (Nulsen, Stewart & Fabian 1984), or angular momentum leading to Keplerian motion at radii of a few tens of kpc (Cowie, Fabian & Nulsen 1980). Our result for 3C 48 and the rotation curve of 3C 275.1 presented by Hintzen & Stocke (1986) agree best with this last explanation.

4 Discussion and conclusions

We find that the quasar 3C 48 is surrounded by an extensive ($\sim$30 kpc radius) nebulosity of dense ($\sim 3\times10^7\,m^{-3}$) clumps of photoionized gas. If the clumps are unconfined, they will rapidly disperse and an enormous total mass of dense gas ($>10^{11}\,M_\odot$) is required in order that the nebulosity lasts for a dynamical time. The hot diffuse gas commonly observed in central elliptical galaxies in poor clusters can pressure-confine the clumps so that there only need be $3\times10^8\,M_\odot$ of cold gas. The cooling time of the hot gas is less than a Hubble time (unless it is much hotter than can reasonably be gravitationally bound) and so the clumps are simply explained as forming in a cooling flow of $\sim 100\,M_\odot\,yr^{-1}$. The quasar itself may, of course, be fuelled by some of this flow. We do not expect the X-ray image to be obviously extended, as the total X-ray cooling luminosity (*cf.* MKW3s, Canizares *et al.* 1983) is only $\sim$1 per cent of the quasar luminosity.

The hypothesis that the recent evolution of quasars is due to disruption of surrounding cooling flows in hierarchical subcluster mergers and collisions in the build-up of richer clusters (Fabian *et al.* 1986) argues that many quasars lie in *poor* clusters. Yee & Green (1984) and Hintzen (1984) find observational evidence that poor clusters occur around many quasars.

The radio source 3C 48 is of the steep-spectrum core variety (Wilkinson *et al.* 1985) and on a scale of less than 1 arcsec. Radio sources are commonly observed in cooling flows (Jones & Forman 1984; Valentijn & Bijleveld 1984) possibly due to the influence of the high surrounding pressure.

The extensive emission-line nebulosity observed around MR2251 − 178 (Bergeron *et al.* 1983; Norgaard-Nielsen *et al.* 1986) can be reinterpreted along the lines of this paper as indicating a cooling flow if the ionizing radiation is not attenuated in the nucleus. Similar arguments may also be made for the more distant 3CR galaxies (Spinrad 1986; Spinrad & Djorgovski 1984a, b). Further detailed spectroscopy of other objects is required to establish whether the nebulosities and pressures surrounding 3C 48 and 3C 275.1 are exceptional. Figs 4 and 5 show that, for an ionizing flux similar to that in 3C 48, the ratio of [O III]/[O II] must exceed 4 and 12 for the pressure to be less than that around the cooling flow galaxies M87 and NGC 4472, respectively.

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