THE ASTROPHYSICAL JOURNAL, 336:702–721, 1989 January 15

EXTENDED OPTICAL LINE EMITTING GAS IN POWERFUL RADIO GALAXIES: WHAT IS THE RADIO EMISSION-LINE CONNECTION?

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Received 1988 March 15; accepted 1988 June 21

ABSTRACT

We use the results of the emission-line and radio imaging survey of radio galaxies presented in Baum *et al.* and Baum and Heckman to look for statistical evidence of energetic and spatial relationships between the extended emission-line gas and the radio source in powerful radio galaxies.

We find that the radio luminosity correlates with the optical narrow emission-line luminosity over roughly four orders of magnitude in line luminosity and five in radio luminosity. This correlation most likely points to a common energy source for both the optical line and the radio emission, and suggests that the radio and line luminosities of radio galaxies are determined, to first order, by the properties of their central engines.

The total emission-line luminosity (emitted in the infrared, the optical and the ultraviolet) of the powerful radio galaxies in the representative sample is roughly half of the luminosity of the associated radio source. While there exist a host of active galaxies with much higher ratios of line to radio luminosities than is found in radio galaxies (e.g., Seyfert galaxies and radio-quiet quasars), we find no steep-spectrum radio galaxies with high radio luminosities and low line luminosities. Combined with the strong correlation of the ionizing continuum with the emission-line luminosity, this implies that in powerful radio galaxies: (1) the central engine typically produces at least as much ionizing continuum luminosity as it does radio luminosity, and (2) the host galaxies always have cold gas near their nuclei.

We find that there is a better correlation between the radio and *narrow* line luminosity than between the radio and the *total* (broad plus narrow) emission-line luminosities in radio galaxies. Two possible explanations are (1) there is a much stronger physical link between the radio jets and the narrow-line region than between the radio jets and the broad-line region, and (2) the broad emission lines are aspect angle dependent, while the narrow emission lines are aspect angle independent.

We find statistical evidence of a *spatial* relationship between the very extended emission-line gas and the radio source. In all cases but one, the radio source extent is similar to or greater than the extent of the emission-line nebula. The very extended emission-line gas shows a statistical tendency to align with the radio source axis in both radio galaxies and radio-loud, steep-spectrum quasars, and the luminosity of the very extended emission-line gas comes preferentially, although not exclusively, from the radio quadrants.

If the very extended emission-line gas is photoionized by the active nucleus, there are two possible explanations for the preference of the very extended emission-line gas for the radio quadrants. Some fraction of the ionizing radiation from the nucleus may be emitted, or escape, preferentially along the radio source ejection axis. Alternately, the nuclear ionizing radiation may be emitted isotropically, but the relatively high density gas which we observe in emission lines may be found preferentially along the edges of the radio source. It is also possible that the radio source contributes to the ionization of this gas. Possibilities include shock ionization, ionization by an ultraviolet extension of the radio synchrotron emission, and heating/ionization by cosmic rays associated with the radio source. The former two possibilities are likely to be most important in the few cases where the emission-line gas is found adjacent to regions of bright radio emission. We show that cosmic-ray ionization is energetically feasible; unfortunately, due to the large number of unknowns, we cannot estimate its actual contribution to the ionization of the gas.

We find that small ($d_{\rm radio} < 150$ kpc) radio sources with very extended emission-line gas (1) commonly have distorted radio morphologies and low apparent fractional radio polarizations, (2) often are associated with the dominant galaxies in rich clusters of galaxies where the cooling time of the intracluster gas is shorter than the Hubble time, and (3) commonly have emission-line gas which is cospatial, in projection, with the radio emitting plasma. Thus, in this class of "small" radio galaxies with very extended emission-line gas, the morphology, physical extent, and polarization properties of the radio sources appear to have been affected by the gas-rich environment through which the radio sources propagate.

By contrast, we find that large ($d_{\rm radio} > 150$ kpc) radio sources with very extended emission-line gas (1) have undistorted, FR2 radio morphologies and normal levels of fractional polarization, (2) are either the dominant

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members of small groups of galaxies, or isolated galaxies, and (3) have emission line nebula in which the brightest (off nuclear) regions of line emission are sometimes found along a position angle which is skewed to the radio source axis and are only sometimes found adjacent to bright radio features or directly along the path between the core and the hotspots. In a few sources the emission-line gas appears to be located preferentially along the low surface brightness regions of the radio source, perhaps associated with the regions of the radio source thought to be formed by the backflow of radio plasma from the hotspots toward the galaxy nucleus. Thus, in these "large" radio sources with very extended emission-line gas, there is typically no evidence that the morphologies of the radio sources have been affected by the cold gas in the surrounding medium.

Subject headings: radiation mechanisms — radio sources: galaxies — radio sources: extended

I. INTRODUCTION

It is now well known that some radio galaxies and some radio-loud quasars contain emission-line gas which is extended on scales of tens of kiloparsecs (Fosbury 1986; van Breugel 1986; Stockton and MacKenty 1987; Boroson, Persson, and Oke 1985). In some radio galaxies (e.g., 3C 277.3, van Breugel *et al.* 1985*a*; 3C 171, Heckman, van Breugel, and Miley 1984) there is convincing evidence that the kinematics and excitation of the very extended emission-line gas is governed by its interaction with the outflowing radio plasma. However, in other radio galaxies with very extended emission-line gas (e.g., PKS 0349−278, Danziger *et al.* 1984; PKS 0634−206, Fosbury *et al.* 1984), the evidence for an interaction between the radio source and the emission-line gas is much weaker. In these sources, the ionization of the emission-line gas may be predominantly determined by the nuclear ultraviolet continuum and the kinematics of the gas by the gravitational potential of the host galaxy. It has also been established that extended emission-line gas is more common in steep-spectrum radio-loud QSOs than in flat-spectrum radio-loud QSOs or radio-quiet QSOs (Boroson, Persson, and Oke 1985; Stockton and MacKenty 1987), but it is not yet known whether there is a physical relationship between the emission-line gas and the extended radio emitting plasma in these sources.

In this paper, we use the results of the emission-line and radio imaging survey presented in Baum *et al.* (1988; hereafter Paper I) and Baum and Heckman (1989*a*; hereafter Paper II) to look for statistical evidence of energetic and spatial relationships between the extended emission-line gas and the radio source in radio galaxies. We also use data available in the literature to look for an association between the extended emission-line gas and the radio source structure in steep-spectrum radio-loud quasars.

Throughout this paper, we use a Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1} and a deceleration parameter $q_0 = 0.0$, and adopt the expression $S_\nu \propto \nu^\alpha$ to define the spectral index α.

II. THE DATA

We wished to study, in an unbiased way, the emission-line properties of steep-spectrum radio galaxies and the relationship of the emission-line nebulae to the extended radio sources in these galaxies. Therefore, we conducted a program of radio and optical imaging of a representative sample of radio galaxies. We have obtained narrow-band images isolating redshifted Hα + [N II] or [O III], broad-band (V or R) images and 1″–10″ radio images using the Very Large Array, of 38 galaxies which form a "representative sample" of radio galaxies, chosen primarily on the basis of their flux density at 408 MHz. We also observed five additional galaxies (hereafter the "special sample") specifically because we knew from previous observations that these sources had interesting optical or radio properties. In Paper I, we describe the sample selection, observations, and data reduction, and we present contour maps of the optical broad-band, emission-line, and radio images, as well as detailed descriptions of the individual source properties. In Paper II, we present parameters of the emission-line, radio, and broad-band images, and we discuss the statistical properties of the sample. Thirty-one of the 38 sources in the representative sample and four of the five sources in the special sample have radio luminosities greater than 10^{42} ergs s^{-1} (or, equivalently, powers at 1.4 GHz, $P_{1.4} \gtrsim 10^{24.5} h_0^{-2}$ ergs s^{-1} Hz^{-1}, where $h_0 = H_0/100$). In this sense, the great majority of the sources in our sample are "powerful" radio galaxies. We encourage the reader to refer to Papers I and II prior to reading this paper.

III. THE ENERGETIC RELATIONSHIP

In this section, we consider the relationship between the energy emitted in optical emission lines and in radio synchrotron radiation. We first present the basic results and correlations, then discuss their implications.

a) The Results

i) *Ratio of Optical Line to Radio Continuum Luminosity*

In Figure 1, we show a histogram of the ratio of the Hα + [N II] emission-line luminosity (where we have assumed an [O III] to Hα + [N II] ratio of 2) to the total radio luminosity for the sources in the representative sample (see Paper II for a detailed description of the calculation of the luminosities and the uncertainties inherent in their calculation). If there is any internal extinction within the host radio galaxy, we will have underestimated the emission-line luminosity. The magnitude of the internal reddening in our galaxies is not, in general, known. Ferland and Osterbrock (1985) used line ratios of Lyα, Hβ, and Hα, along with models of the ionization of the nuclear narrow-line region (NLR) by a hard nuclear continuum and the E_{B-V} values of Burstein and Heiles (1958) to deduce the internal reddening in the nuclear narrow-line regions in 3C 192 and 3C 223. They found that the line ratios were consistent with little or no internal reddening in 3C 192 but required an internal reddening of $E_{B-V} \sim 0.25$ in 3C 223, corresponding to an increase by a factor of ~ 1.7 in the intrinsic Hα flux over that observed. For most radio galaxies, there is much less detailed data and modeling available for determination of the extinction. For the 21 cases with published narrow-line Balmer decrements in Koski (1978), Costero and Osterbrock (1977), Grandi and Osterbrock (1978), Osterbrock, Koski, and Phillips (1976), and Cohen and Osterbrock (1981), a typical correction factor of ~ 2 for the Hα luminosities is implied (including the correction for foreground Milky Way extinction).

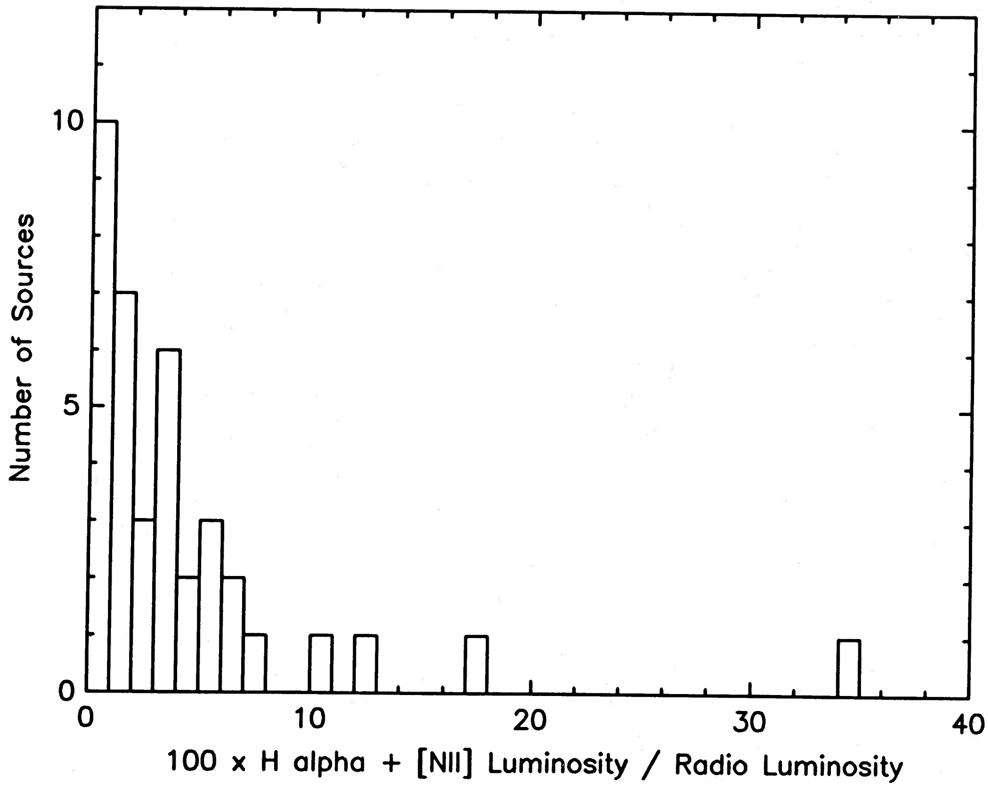


FIG. 1.—Histogram showing the distribution of 100 × ($L_{\rm lines}/L_{\rm radio}$) for the sources from the representative sample, where $L_{\rm lines}$ is the narrow-line luminosity in Hα + [N II], and $L_{\rm radio}$ is the total radio luminosity.

The ratio of the luminosity emitted in Hα + [N II] to the total line luminosity emitted in the infrared, the optical, and the ultraviolet depends on the ionization mechanism (e.g., shock excitation of photoionization), and the physical conditions and metallicity of the emitting gas. We estimate that the Hα + [N II] emission represents between 4% to 8% of the total (IR, optical, and UV) line luminosity (e.g., Shull and McKee 1979; Kramer 1986).

For our sample we find a median value of 0.03 for the Hα + [N II] to total radio luminosity. Thus, typically, the total *line* luminosity is at least *half* of the total *radio* luminosity.

ii) *Correlation of Radio and Emission-Line Luminosity*

As presented in Paper II, the radio and emission-line luminosities of the sources from the representative sample are strongly correlated. Shown in Figure 2*a* is a plot of the log of the narrow emission-line luminosity (in Hα + [N II]) versus the log of the radio luminosity, for the sources from the representative sample. We have assumed that the flux in the [O III] line is twice that in Hα + [N II] to convert the [O III] luminosities. On this same plot, we have also included eight powerful radio galaxies at high redshifts ($z \sim 1.8$) taken from the work of Spinrad (1987). These high-redshift galaxies were observed to have fairly narrow Lyα emission lines. To convert the Lyα emission from these galaxies to the equivalent Hα + [N II] luminosity, we have assumed that the Lyα flux is 4.5 times the Hα + [N II] flux (e.g., Ferland and Mushotzky 1982; Gaskell and Ferland 1984). We correct the one source from their sample with significant Galactic reddening (3C 470) for its effect.

We also show the best-fit (least-squares) line to all of the sources with calibrated emission-line data, including the eight radio galaxies taken from Spinrad (1987). We note that the correlation of the log of the radio and line luminosities appears to extend over four orders of magnitude in line luminosity and five orders of magnitude in radio luminosity. The least-squares fit to the relation $\log_{10} L_{\rm line} = m \times \log_{10} L_{\rm radio} + b$ yields $m = 0.73 \pm 0.06$, $b = 10 \pm 2.5$. This relationship predicts that at higher radio luminosities the ratio of line to radio luminosity declines.

However, we also note the nonlinearity of the relation between radio and line luminosity. For example, at low line and radio luminosities ($L_{\rm radio} < 5 \times 10^{42}$ ergs s^{-1}), almost all of the points lie below the best-fit line, and at intermediate radio luminosities (5×10^{42} ergs s$^{-1} < L_{\rm radio} < 10^{44}$ ergs s^{-1}) most of the points lie above the best-fit line. Thus we find that for radio luminosities between $\sim 10^{40}$ and 10^{44} ergs s^{-1}, the median ratio of line to radio luminosity is roughly constant for the sources from the representative sample, while for $L_{\rm radio} > 10^{44}$ ergs s^{-1}, the ratio drops by roughly one order of magnitude.

We have shown that there is a very strong correlation between the optical *narrow* emission-line luminosity and the radio luminosity for the radio galaxies in our representative sample. There are three broad-line radio galaxies (BLRGs) in our sample. If we plot the total (i.e., *broad plus narrow*) Hα + [N II] emission for these galaxies (using broad-line strengths from the literature) against their radio luminosity, we find that these galaxies are displaced from the region of the graph occupied by the radio flux density selected sample of radio galaxies. This is shown graphically in Figure 2*b*, where we have also included three additional broad-line galaxies for which broad and narrow emission-line fluxes were available from the literature (3C 382, 3C 445, and PKS 2349−01; Osterbrock, Koski, and Phillips 1976; Yee 1980). The BLRGs have a median ratio of *narrow* line to radio luminosity of 0.08, compared to a median ratio of 0.03 for narrow-line radio galaxies (NLRGs) of similar radio luminosities. However, they have a median ratio of *total* (broad plus narrow) line to radio luminosity of 0.72, roughly a factor 25 times higher than the NLRGs.

In Figure 2*c*, we plot the narrow-line luminosity in Hα + [N II] for the radio galaxies from our sample along with the steep-spectrum radio-loud QSOs from the sample of Stockton and MacKenty (1987). Again, we convert from [O III] luminosities to Hα + [N II] by assuming a ratio of [O III] to Hα + [N II] of 2 for the narrow lines. We find that, in the median, for a given radio luminosity, the QSRs have slightly higher narrow-line luminosities than do the radio galaxies (see below), but there is also overlap in the $L_{\rm radio} - L_{\rm narrow\ line}$ plane between the two groups of objects.

It has been shown that P_{1400} (the total radio power at 1400 MHz) correlates with the [O III] λ5007 luminosity in broad-line and narrow-line Seyfert galaxies (de Bruyn and Wilson 1978; Whittle 1985). In Figure 2*c*, we indicate the region of parameter space occupied by the broad-line and narrow-line Seyfert galaxies (adapted from Whittle 1985, assuming a spectral index of $\alpha = -1$ for the radio emission, and an [O III] to Hα + [N II] line ratio of 2). Whittle (1985) has shown that, at a given radio power, the broad-line Seyfert galaxies have a higher median [O III] line luminosity than do the narrow-line Seyferts. The Seyfert galaxies appear to occupy a region of parameter space in the $L_{\rm radio} - L_{\rm narrow\ line}$ plane which is distinct from, but roughly parallel to, that occupied by the radio galaxies from the representative sample.

In Table 1, we list the median ratio of the luminosity in narrow Hα + [N II] to the radio luminosity for (1) radio galaxies with radio luminosities $<10^{44}$ ergs s^{-1}, (2) radio galaxies with radio luminosities greater than 10^{44} ergs s^{-1}, including the high-redshift galaxies from Spinrad (1987), (3) broad-line radio galaxies, (4) radio-loud steep-spectrum QSOs with radio luminosities less than 10^{44} ergs s^{-1}, and (5) radio-loud steep-spectrum QSOs with radio luminosities greater than 10^{44} ergs s^{-1}. We also give the range of ratios found for the narrow- and broad-line Seyfert galaxies. We find that, in

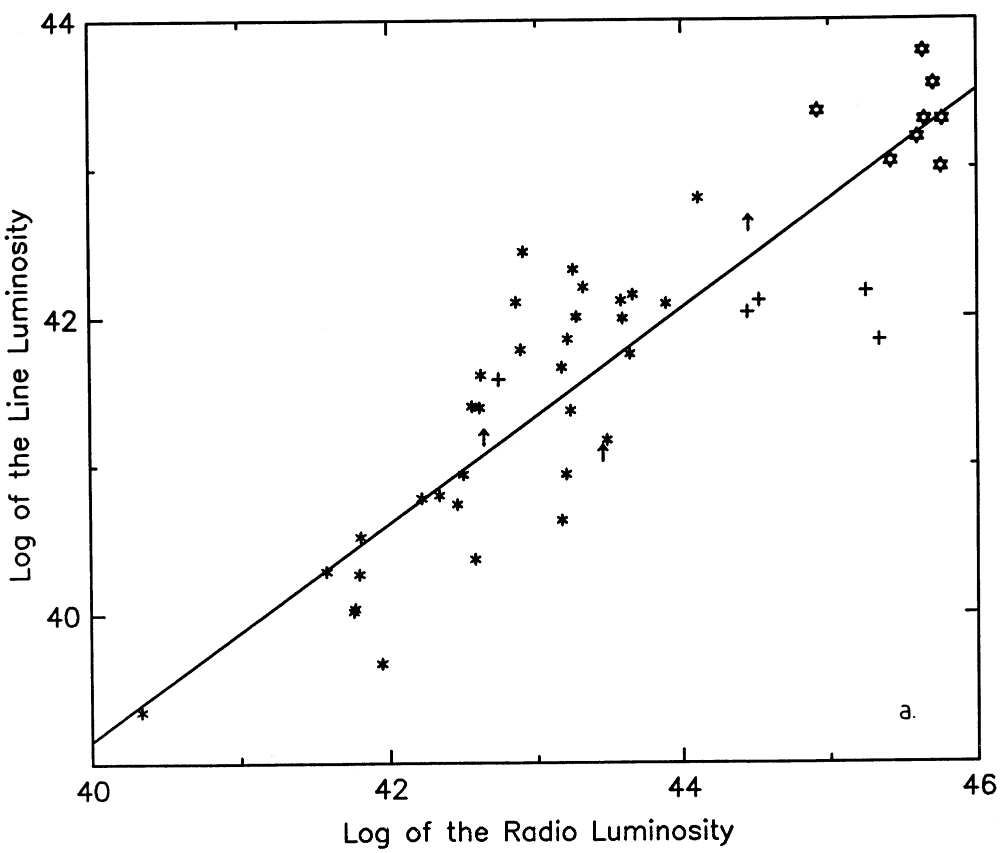
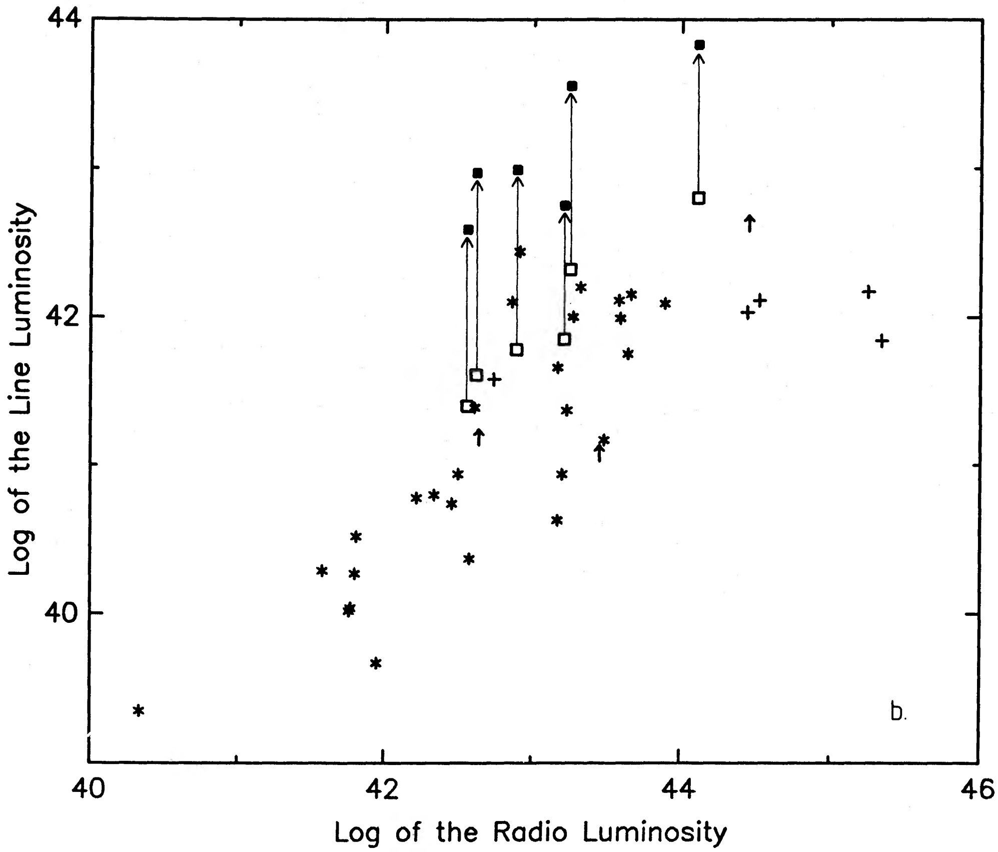


FIG. 2.—(*a*) Plot of $\log_{10} L_{\rm line}$ vs. $\log_{10} L_{\rm radio}$, where $L_{\rm line}$ is the narrow-line luminosity in Hα + [N II] in ergs s^{-1}, and $L_{\rm radio}$ is the total radio luminosity in ergs s^{-1}. Sources from the representative sample observed in Hα + [N II] are indicated as asterisks. Sources from the representative sample for which we have derived the Hα + [N II] luminosity from [O III] observations are indicated as crosses. The three galaxies from the representative sample observed under non-photometric conditions are indicated as lower limits, where the midpoint of the arrow is located at the location of the limit. The high-redshift radio sources taken from Spinrad (1987) are indicated as stars. The line, $\log_{10} L_{\rm line} = 0.73 \log_{10} L_{\rm radio} + 10$, indicates the least-squares linear fit to the data points, excluding the three lower limits. (*b*) Same as (*a*), except the high-redshift galaxies from Spinrad (1987) have been omitted, open squares indicate the narrow Hα + [N II] line luminosity of the broad-line radio galaxies, and filled squares indicate the broad plus narrow Hα + [N II] line luminosity of these same galaxies. See text for details. (*c*) Same as (*a*). In addition, the radio-loud, steep-spectrum QSOs from Stockton and MacKenty (1987) are plotted as crosses, and the region of the graph occupied by the broad- and narrow-line Seyfert galaxies has been shaded. The arrow on the right-hand edge of the region of Seyfert galaxies indicates that the shaded region includes points which have only upper limits to their radio luminosity.



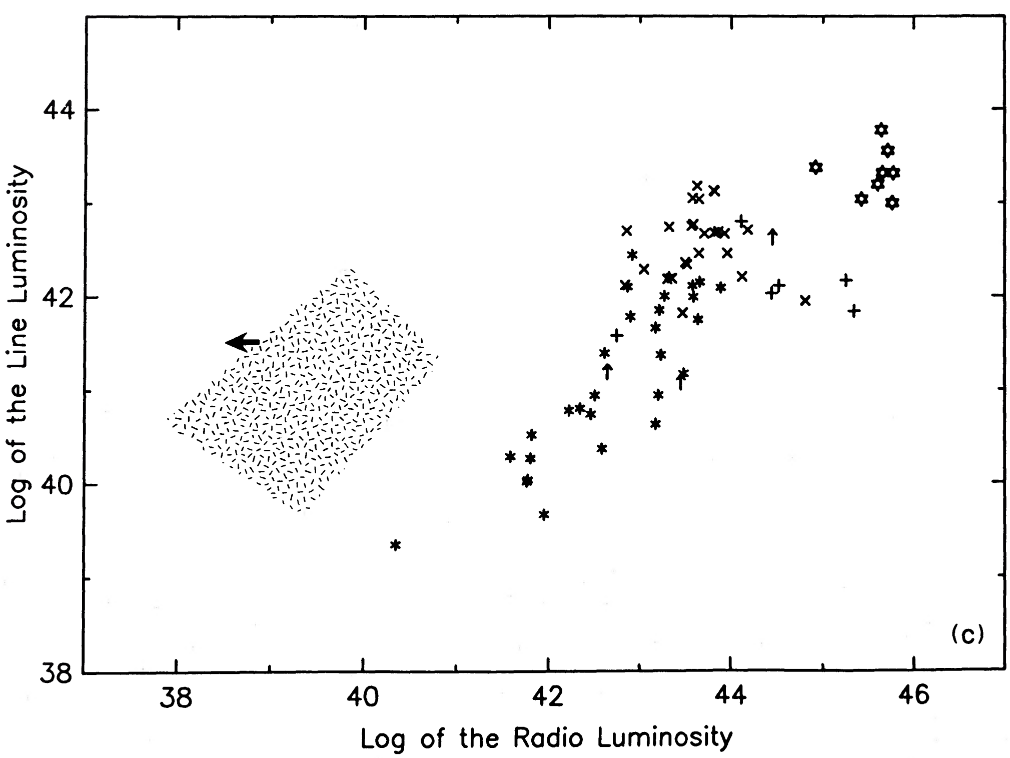


FIG. 2—*Continued*

TABLE 1

RATIOS OF LINE TO RADIO LUMINOSITY

Radio Galaxies		QSOs		Seyfert Galaxies
$L_{rad} < 10^{44}$	$L_{rad} > 10^{44}$	$L_{rad} < 10^{44}$	$L_{rad} > 10^{44}$	
0.04	0.005	0.16	0.017	~30 (1–600)

NOTES.—The median ratio of narrow emission-line (Hα + [N II]) to radio luminosity for different classes of active galaxies. For the Seyfert galaxies we give a typical value as well as the range of observed values in parentheses, estimated from Whittle 1985. See text for details.

the median, the steep-spectrum radio-loud QSOs have narrow-line to radio luminosity ratios ~4 times higher than do the radio galaxies. A typical value for the ratio of narrow Hα + [N II] to radio luminosity for the Seyfert galaxies is ~30 or ~1000 times higher than for the radio galaxies. Finally, we note, that for both the radio galaxies and the steep-spectrum radio-loud QSOs, we find that the ratio of narrow-line to radio luminosity drops by almost a factor of 10 in sources with radio luminosities greater than 10^{44} ergs s^{-1}.

iii) *Line Luminosity versus Core Radio Power*

We have shown that the high radio luminosity sources have high line luminosities and high radio core powers. Thus we expect to find, and do find, a strong correlation of line luminosity with core radio power (see Fig. 3). The correlation of line luminosity with core radio power is weaker than both the correlation of line luminosity with the radio luminosity and the correlation of core radio power with radio luminosity. Hine and Longair (1979) have suggested that the correlation of line luminosity with core radio power may reflect the independent correlations of line luminosity and core radio power with the total radio luminosity.

b) Discussion

i) *Implications of the Luminosity Correlations*

In the section above, we have presented the strong correlation of the narrow emission-line luminosity with the total radio luminosity. This result may have implications for our understanding of the factors which influence the radio and line luminosities of a radio source. We have argued in Paper II that the emission-line luminosity of a powerful radio galaxy is determined, to first order, by the strength of the nuclear ionizing continuum. The correlation of emission-line luminosity with radio luminosity therefore suggests that the radio luminosity of these galaxies is also determined, to first order, by conditions in the galaxy nucleus (e.g., by the properties of the central engine) where the nuclear ionizing (ultraviolet) continuum originates. We note that though the correlation of L_{radio} with L_{line} extends over four orders of magnitude in L_{line} and five in L_{radio}, there is roughly one order of magnitude scatter in

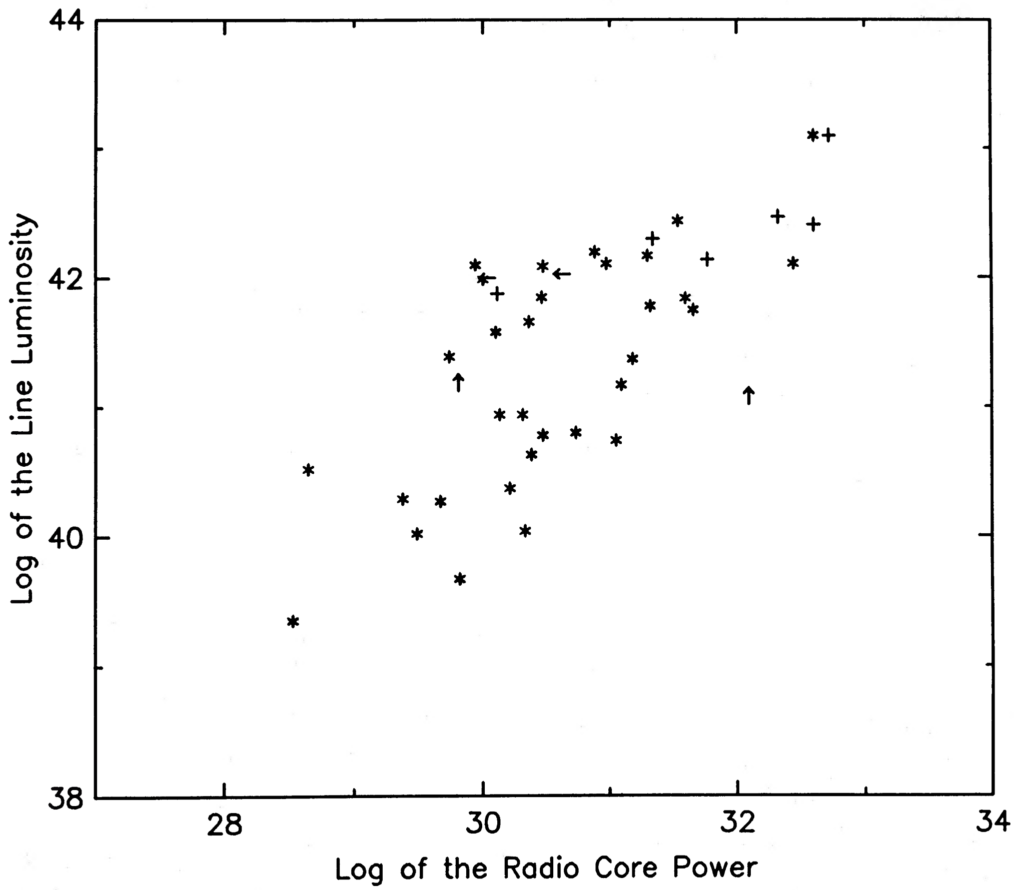


FIG. 3.—(*a*) Plot of $\log_{10} L_{line}$ vs. $\log_{10} P_{radio\,core}$ for the extended radio sources from the representative sample, where L_{line} is the narrow-line luminosity in Hα + [N II] in ergs s^{-1}, and $P_{radio\,core}$ is the radio core power in ergs s^{-1} Hz^{-1}. Crosses indicate sources for which the Hα + [N II] luminosities were derived from [O III] observations, and arrows indicate limits, where the midpoint of the arrow is located at the location of the limit.

L_{radio} for a given L_{line}, suggesting that other factors (e.g., the environment) do play a secondary role in determining the radio and/or emission-line luminosities of these sources. Other explanations of the correlation are, of course, also possible; for instance, the radio source may be directly responsible for ionizing the emission-line gas, or the line luminosity and radio luminosity may be independently correlated with a third parameter (e.g., the amount of cold gas present on the kiloparsec scale).

We also find very strong correlations of the core radio power with the narrow emission-line luminosity and the extended radio luminosity (Paper II). However, we find that these correlations are weaker than the correlation of radio luminosity with emission-line luminosity. One possible explanation is that variability introduces additional scatter into the correlations of core properties with the properties of the more extended emission. The core radio power originates on scales of parsecs, and therefore has a variability time scale of years, while the narrow emission-line luminosity typically originates on size scales of kiloparsecs and therefore has a variability time scale of thousands of years (but see also Clavel and Wamsteker 1987), while the extended radio luminosity represents the output of the central engine integrated over tens of thousands of years or more.

Thus, any short-term variability of the power output of the central engine will introduce scatter into the correlation between the core radio power and the emission-line or extended radio luminosity, but will not introduce scatter into the correlation between total radio and narrow-line luminosity. Additional scatter in the relationships involving radio core power may arise if (1) some fraction of the radio core flux density is beamed (e.g., if we are observing relativistic outflow of plasma in the core; Browne 1983) or (2) synchrotron opacity effects and geometry (e.g., Reynolds 1982, and references therein) cause the $\tau = 1$ surface of the core (and thus the radio core flux density) to vary between sources which have the same intrinsic energy output.

ii) *Broad-Line Radio Galaxies*

As shown graphically in Figure 2*c* and discussed in § III*a*(ii), all six broad-line radio galaxies we examine are, to first order, indistinguishable from narrow-line radio galaxies on a plot of *narrow* line luminosity versus radio luminosity, but are *clearly* distinguishable on a plot of the *total* (broad plus narrow) line luminosity versus radio luminosity. We also know that the "ionizing continuum" correlates with (and is in fact roughly proportional to) the total (broad plus narrow) permitted line luminosity for both narrow- and broad-line radio galaxies (Yee and Oke 1978; Paper II). What are the implications of these results for our understanding of the differences between broad-line and narrow-line radio galaxies?

The fact that (for radio galaxies as a whole) there is a better correlation between the radio and *narrow*-line luminosity than between the radio and the *total* emission-line luminosities has two plausible interpretations. One is that there is a much stronger physical link between the radio jets and the narrow-line region than between the radio jets and the broad-line region (BLR). This has been suggested for Seyfert galaxies (e.g., Wilson and Heckman 1985; Pedlar, Dyson, and Unger 1985) where the radio sources are much smaller and weaker than in the radio galaxies discussed here.

An alternate interpretation is that the extended radio and the narrow-line luminosities in radio galaxies are largely independent of viewing angle (and hence correlate well), while the broad-line region (and the nonstellar optical continuum luminosity) is highly viewing angle dependent. The possibility that the emission-line properties of different classes or subclasses of active galaxies are in part related to the inclination angle at which we observe them has been discussed in the past (e.g., Lawrence and Elvis 1982; Antonucci and Miller 1985; Wills and Browne 1986; Heckman 1983). Consider a model in which there is a nonspherical absorbing or scattering medium between the broad- and narrow-line regions (e.g., in the shape of a torus; Lawrence and Elvis 1982; Antonucci 1984). The radio flux density should be largely aspect-angle independent in the steep-spectrum, extended radio galaxies which comprise our sample, even allowing for some relativistic Doppler boosting of the core and approaching jet. Since the NLR is outside of the obscurer, the narrow emission-line flux will be aspect angle independent. In contrast, both the broad emission-line flux and the full ionizing continuum will be visible only when viewed down the axis of the torus. In this scenario, the NLR would then intercept the same fraction of the ionizing continuum in both NLRGs and BLRGs. Further, we, the observers, would see the same fraction of the central ionizing continuum as does the NLR when we look at a NLRG. Only when we look down the axis of the torus do we see both the BLR and the full ionizing continuum. This scenario is consistent with our results, and with the results of Yee (1980), who found that the ratio of [O III] to the nuclear, nonthermal, optical continuum is roughly a factor of 10 higher in NLRGs than in BLRGs.

iii) *The Ratio of Line to Radio Luminosity*

It appears that roughly *all* powerful radio galaxies have nuclear optical line emission (Paper II). Further, as discussed in § III*a*(i), a typical powerful radio galaxy has a total radio luminosity which is of the order of its total (IR, optical, and UV) line luminosity. There are many classes of active galaxies which have (much) higher ratios of line to radio luminosity than the powerful, extended, steep-spectrum radio galaxies. However, there are no radio galaxies in our sample which have high radio luminosities but low line luminosities. Coupled with the strong correlation of the ionizing continuum with the emission-line luminosity (Yee and Oke 1978; Paper II), this suggests that (1) the amount of energy from the central engine which goes into producing ionizing photons is always roughly at least as great as the amount of energy lost as radio synchrotron emission, (2) there is always cold gas present in the inner few kiloparsecs of the host radio galaxy; and (3) over the lifetime of the radio source, the nuclear ionizing continuum does not vary strongly (i.e., turn on and off) on a time scale which is longer that the recombination time in the emission-line gas. These results are consistent with suggestions that cold gas in the ISM of elliptical galaxies may be related to the fueling of nuclear activity and production of a radio source (e.g., Knapp 1988).

There may not be any galaxies with active nuclei in which the ratio of radio to total line luminosity is appreciably greater than one (i.e., in which there is either a shortage of nuclear ionizing photons or a lack of cold gas). The BL Lac objects have been cited as possible examples of active galaxies in which there is a lack of cold gas (e.g., Miller, French, and Hawley 1978). However, as the dynamic range at which emission lines can be detected improves, emission lines are being detected in more and more BL Lac objects (e.g., Lawrence *et al.* 1987), and the emission-line luminosities of the BL Lac objects (Miller, French, and Hawley 1978; Antonucci *et al.* 1987) are comparable to those detected in our steep-spectrum radio galaxies.

We also find that the ratio of narrow emission-line luminosity to total radio luminosity is roughly an order of magnitude less in steep-spectrum quasars and radio galaxies with very high radio luminosities ($L_{\rm radio} > 10^{44}$ ergs s^{-1}) than in their lower luminosity counterparts. The reason for this is unclear. Possible explanations include the following: (1) the central engines of very luminous radio sources are intrinsically different from the central engines of their lower luminosity counterparts in the ratio of ionizing to radio luminosity which they produce; (2) the radio luminosities of these very luminous sources have been enhanced over that expected from the optical/ultraviolet output of the central engine, due to environmental factors (e.g., the confinement of the radio source by a high-density medium) or to the beaming of the radio emission in plasma moving at velocities near light close to our line of sight; and (3) the observed line luminosities of these very powerful radio galaxies do not reflect the strength of the nuclear ionizing continuum, either because of obscuration or because there is insufficient gas present in the host galaxy to absorb all of the ionizing radiation produced by the central engine (i.e., the interstellar medium is fully ionized by the AGN).

IV. THE SPATIAL RELATIONSHIP BETWEEN THE RADIO SOURCE AND THE VERY EXTENDED EMISSION-LINE GAS

a) Results

In Paper II, we noted the morphological differences between the emission-line nebulae which were kiloparsec-scale in diameter and those which were extended on scales of tens of kiloparsecs. Specifically, in galaxies which have small (kiloparsec scale) emission-line nebula, the emission-line gas tends to be distributed in a smooth appearing region which is roughly centered on and symmetric about the galaxy nucleus. In contrast, in galaxies where the emission-line gas is distributed on scales of tens of kiloparsecs, the emission-line gas is often filamentary in appearance and asymmetrically distributed with respect to the host galaxy nucleus. The emission-line gas which is found within several kiloparsecs of the galaxy nucleus may bear a different relationship to the large-scale radio source structure than the more distant emission-line gas. For instance, it may be distributed in a rotating disk which feeds the central engine and/or influences the collimation of the outflowing radio plasma. Therefore, we wish to consider separately the relationship of the near-nuclear and the very extended emission-line gas (VEELG) to the extended radio source structure. In order to isolate sources which have VEELG, we (arbitrarily) separate out those sources which have emission-line nebula which are greater than 10 kpc in total extent (i.e., for which $d_{\rm neb} > 10$ kpc; see Paper II for a precise definition of $d_{\rm neb}$). In a subsequent paper (Baum and Heckman 1989*b*), we will discuss the morphologies and kinematics of the near-nuclear emission-line gas. In this paper we concentrate on the distribution of the "very extended emission-line gas" and its relation to the radio source.

There are 24 sources in our sample for which $d_{\rm neb} > 10$ kpc. There are 3C 33, 3C 63, PKS 0349−398, 3C 98, 3C 109, PKS 0634−206, PKS 0745−191, 3C 192, 3C 196.1, 3C 218, 3C 223, 3C 227, 3C 274, 3C 275, PKS 1345+125, 3C 295, 3C 313, 3C 317, 3C 403, and 3C 433 from the representative sample, and 3C 171, 3C 285, 3C 305, and 3C 321 from the special sample. A detailed description of the morphologies of the emission-line nebulae and the extended radio sources in these galaxies can be found in Paper I. Here we discuss the global properties of this sample of sources.

i) *Statistical Evidence of a Spatial Relationship*

We use the sample of sources from the *representative sample* for which $d_{\rm neb} > 10$ kpc to determine whether, in a statistical sense, the very extended emission-line gas and the extended radio source structure are related to each other.

In Figure 4, we show a histogram of the ratio of the size of the emission-line nebula ($d_{\rm neb}$) to the size of the extended radio emission ($d_{\rm radio}$) (see Paper II for a precise definition of $d_{\rm radio}$) for all the sources in the representative sample except PKS 1345+125. The radio source associated with PKS 1345+125 is unresolved, even at an angular resolution of 0".1, corresponding to a linear size for the radio source of less than 200 pc, while our emission-line images suggest that the emission-line nebula is greater than 10 kpc in extent. In all of the sources except PKS 1345+125, the extent of the emission-line nebula is of the order of, or less than, the extent of the radio source. The median value of the ratio is ~ 0.2.

In Figure 5*a*, we show a histogram of the position angle differences between the VEELG and the radio source for all of the sources from the representative sample with emission-line nebulae which are greater than 10 kpc in total extent. Table 2 lists the position angle of the extended emission-line gas in these sources and the position angle of the radio sources. In some sources, two position angles were needed to define the extended line emission: if these two angles differ by more than 30°, we treat each position angle independently, if not, we average together the two position angles to define the position

TABLE 2

ORIENTATION OF THE VERY EXTENDED EMISSION-LINE GAS

Source	P.A.	ΔP.A.	% On
3C 33*	56	37	55
3C 63*	64	30	55
PKS 0349−278*	81	26	92
3C 98*	17, 162	9, 44	63
3C 109*	9	44	46
PKS 0634−206*	174	5	57
3C 171	104	5	98
PKS 0745−191*	120	35	58
3C 192*	120, 148	14	75
3C 196.1*	51	9	95
3C 218*	4	1	100
3C 223*	57	73	...
3C 227*	39, 114	47, 28	61
3C 274*	113	2	100
3C 275*	47	3	...
3C 285	96, 152	15, 71	42
3C 295*	134	9	...
3C 305	86	41	73
3C 313*	74	15	...
3C 317*	78, 156	29, 73	55
3C 321	140	4	76
3C 403*	25	62	57
3C 433*	130	36	67

Col. (1).—Source name. An asterisk denotes membership in the representative sample.

Col. (2).—Position angle of the extended emission-line gas.

Col. (3).—Position angle difference between the extended emission-line gas and the radio source.

Col. (4).—Percentage of the total line luminosity (at distances greater than 3 projected kpc from the galaxy nucleus) which comes from the radio quadrants of the sky.

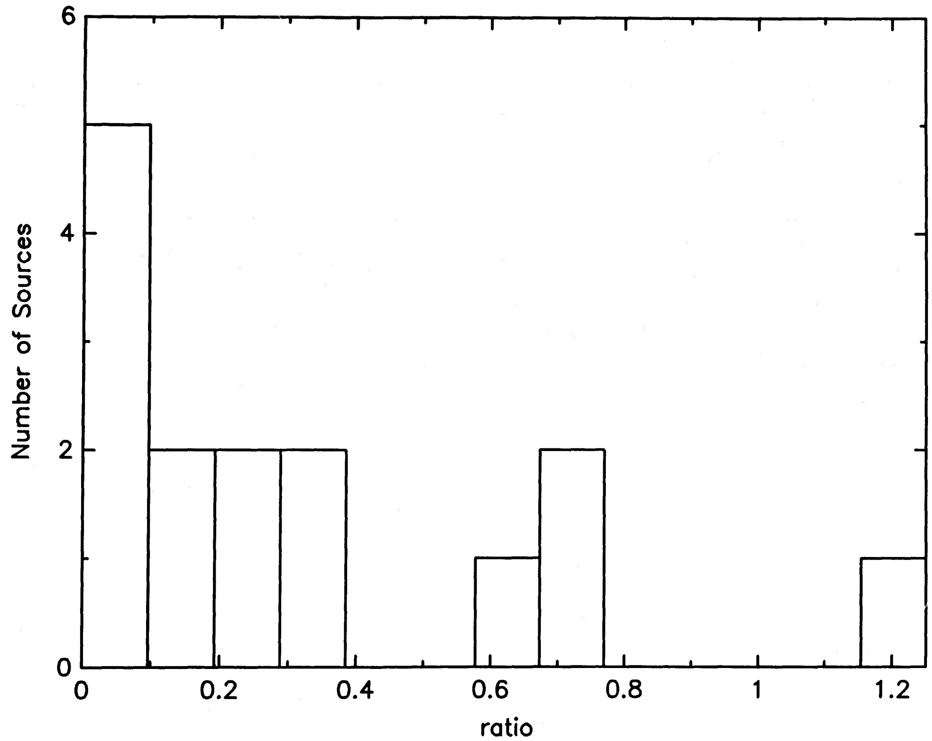


FIG. 4.—Histogram of the ratio (d_{neb}/d_{radio}), for all of the sources from the representative sample except PKS 1345+125, where d_{neb} and d_{radio} are, respectively, the size of the emission-line nebula and the size of the extended radio source, in kiloparsecs.

angle difference between the radio source and the extended emission-line gas. The radio source position angles were taken from Paper II. We find that for the representative sample as a whole, there is a clear tendency for the very extended gas to be found along the radio source axis; in 18 out of 22 cases the position angle difference is less than 45°, and the median position angle difference between the extended radio and line emission is 28°.5. Applying a Kolmogorov goodness of fit test, we find that this result is significant at the 98% confidence level (using a two-sided test) (Conover 1980).

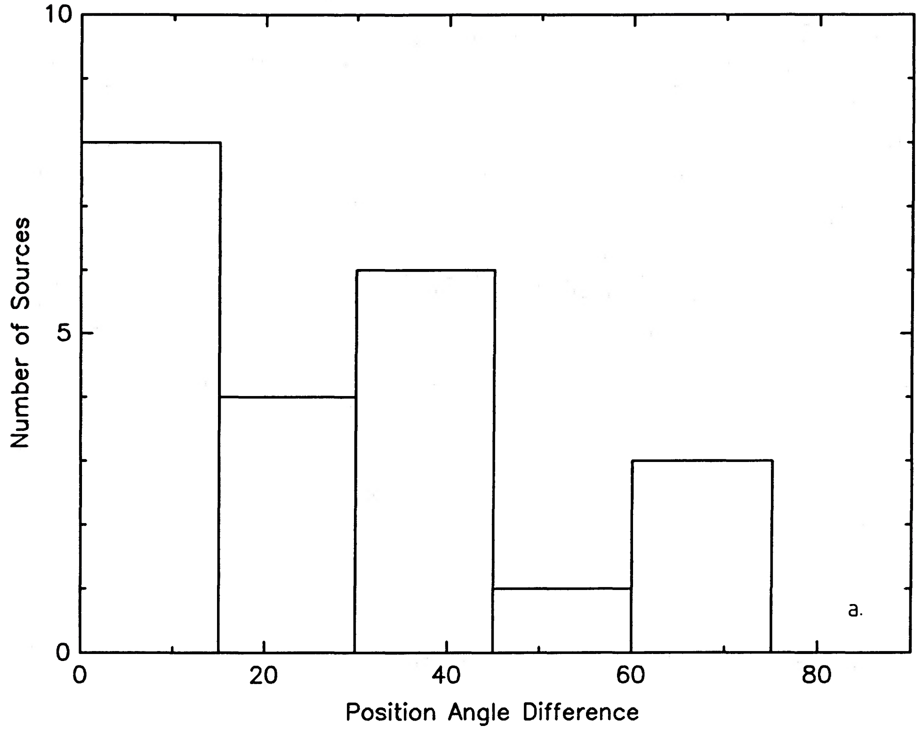
In Figure 5*b*, we show a histogram of the position angle difference betwe n the emission-line gas which is most distant from the galaxy nucleus and the radio source. We note that there is *no* ambiguity in the definition of the position angle of the most distant emission-line gas. Again, we find evidence for an alignment of the radio source and the emission-line gas. The median position angle difference is 30°, and 16 of the 18 sources have position angle differences less than 45°. Applying the Kolmogorov goodness of fit test, we find that this result is significant at greater than 99% confidence level (using a two-sided test).

In Figure 5*c*, we show a histogram of the fraction of the total emission-line flux at distances greater than 3 kpc from the galaxy nucleus for the sources from the representative sample with $d_{neb} > 10$ kpc in which the line emission was sufficiently resolved. To determine this fraction, we have divided the image into four equal angle quadrants, centered on the radio source position angle, and determined the emission-line flux which comes from each quadrant (see Table 2). Again, although there are individual sources in which $\sim 50\%$ of the emission-line flux comes from the nonradio quadrants, there is a clear statistical trend for the emission line flux to come preferentially from the radio quadrants. In only one of the 15 sources does less than 50% of the line emission come from the radio quadrants, and the median fraction of line emission coming from the radio quadrants is 61%.

Recently, Stockton and MacKenty (1987) reported the results of a project of imaging QSOs through narrow-band filters which isolated redshifted [O III]. In a sample of 47 QSOs selected from a redshift ($z \leq 0.45$) and absolute V magnitude limited sample, they detected extended [O III] emission in 19 QSOs. Stockton and MacKenty find that the presence and strength of extended [O III] line emission is correlated with the presence of a steep-spectrum ($\alpha \leq -0.5$) radio source.

To investigate the possibility of a *spatial* relationship between the extended emission-line gas and the extended radio source structure in the steep-spectrum radio-loud QSOs from Stockton and MacKenty's sample, we have compiled a list of the position angles for the extended [O III] emission and the radio source structure (see Table 3). We have each independently measured the position angles of the extended [O III] emission from the plates presented in Stockton and MacKenty, following the same guidelines as outlined for the radio galaxies. The radio source position angles were compiled from radio maps in the literature, under the same prescription used for the radio galaxies.

In Figure 5*d*, we present a histogram of the position angle differences between the extended radio source structure and the extended [O III] emission for these QSOs. We find a tendency for the emission-line gas to be extended in the direction of the radio source; in 10 out of 13 cases the axis of the extended emission-line gas is within 45° of the radio source axis, and the median position angle difference between the two is 20°. Applying Kolmogorov goodness of fit test, we find that



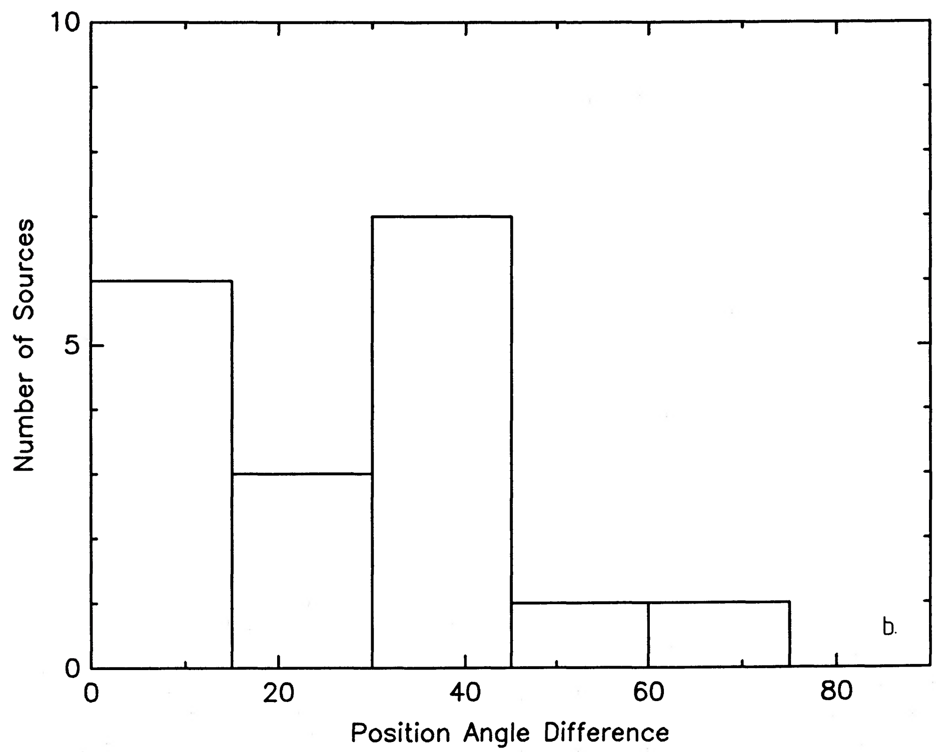
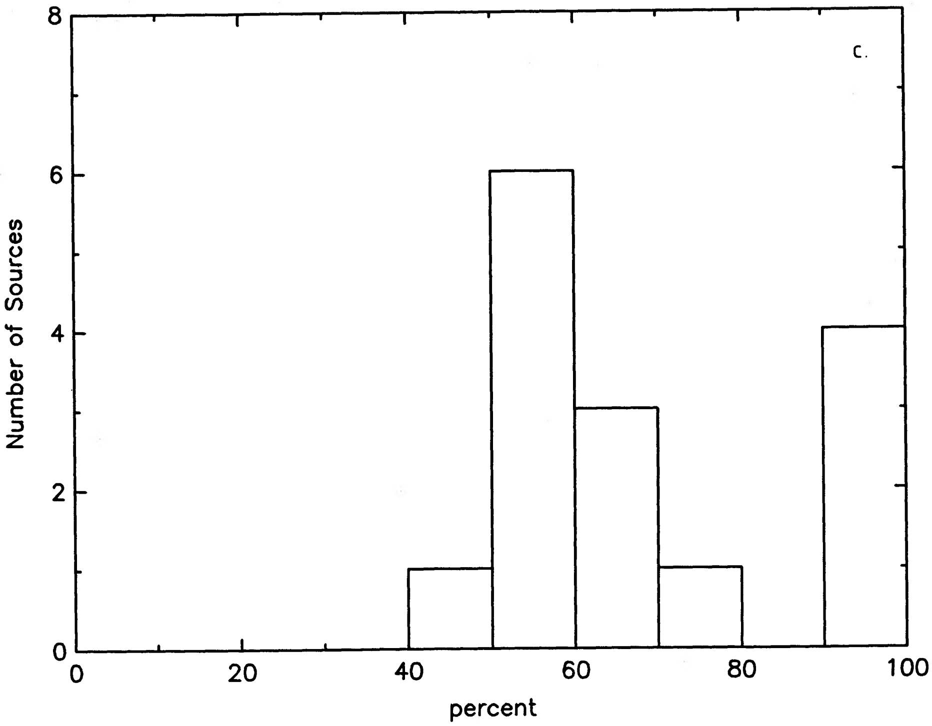


FIG. 5.—(*a*) Histogram of the position angle difference between the emission-line nebula and the radio source axis for the sources from the representative sample with $d_{neb} > 10$ kpc. (*b*) Histogram of the position angle difference between the most distant emission-line gas and the radio source axis for the sources from the representative sample with $d_{neb} > 10$ kpc. (*c*) Histogram of the percent of line emission at distances greater than 3 kpc from the galaxy nucleus within the radio quadrants, for the sources from the representative sample with $d_{neb} > 10$ kpc. (*d*) Histogram of the position angle difference between the *very* extended emission-line gas and the radio source axis for those QSOs from the sample of Stockton and MacKenty (1987) with published radio maps.



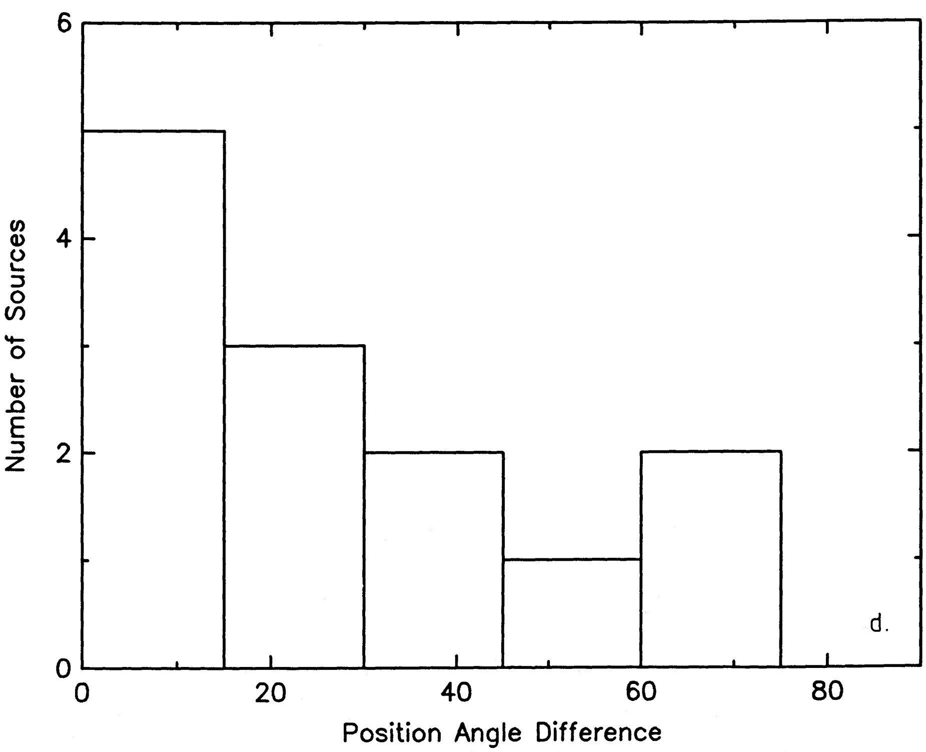


FIG. 2—*Continued*

TABLE 3

POSITION ANGLES FOR QSOs WITH EXTENDED RADIO STRUCTURE

Source	Radio P.A.	Emission-Line P.A.	ΔP.A.
0110+297.......	61	64	3
0134+329.......	17	11	6
1011+282.......	150	127	23
1100+772.......	102	122	20
1223+252.......	54	60	6
		165	69
1512+370.......	110	80	30
1525+227.......	150	148	2
1545+210.......	21	170	31
		90	69
1548+114.......	116	125	9
2135−147.......	103	45	58
2251+113.......	140	125	15

Col. (1).—Source name. All QSRs with extended emission-line nebula from the sample of Stockton and MacKenty 1987 with published maps of their extended radio structure.

Col. (2).—Position angle of the extended radio source. Measured from maps of the extended radio emission taken from Miley and Hartsuijker 1978 for 0110+29; R. Perley, private communication, for 0134+32; Miley and Hartsuijker 1978 and Gower and Hutchings 1984 for 1011−282; Londsdale and Morison 1983 for 1100+77; Miley and Hartsuijker 1978 for 1223+252; Potash and Wardle 1979 for 1512+370; Gower and Hutchings 1984 for 1525+227; Pooley and Henbest 1974, Miley and Harsuijker 1978, and Gower and Hutchings 1984 for 1545+210; Hintzen, Ulvestad, and Owen 1983 for 1548+114; Miley and Hartsuijker and Gower and Hutchings 1984 for 2135−147; Hintzen, Ulvestad, and Owen 1983 for 2251+113.

Col. (3).—Position angle of the extended emission-line nebula, measured from the images presented by Stockton and MacKenty 1987).

Col. (4).—Position angle difference between the radio source axis and the emission-line nebula.

this result is significant at the 93% confidence level (using a two-sided test) (Conover 1980).

Thus, there is statistical evidence that the very extended emission-line gas and the extended radio source structure in steep-spectrum, radio-loud galaxies and QSOs are spatially related.

ii) *The Properties of Radio Galaxies with VEELG*

We divide the radio galaxies with $d_{\rm neb} > 10$ kpc into two groups, those with $d_{\rm radio} < 150$ kpc and those with $d_{\rm radio} > 150$ kpc, where $d_{\rm radio}$ is the diameter of the radio source taken from Paper II. Forman, Jones, and Tucker (1984) reported that most, if not all, elliptical galaxies contain hot ($T \sim 10^7$ K) gaseous halos and that these halos may extend as far as 65 kpc from the galaxy nucleus. Thus, the radio sources in the first group of galaxies are likely to be contained within the ISM of their hosts, while the radio sources in the second group have "escaped" from their host galaxy's ISM. As we show below, when we divide the galaxies with VEELG in this way, we find clear differences in the radio morphologies and environments of the sources in the two groups.

1. *Small* ($d_{\rm radio} < 150$ *kpc*) *radio sources.*—We identify nine sources from the representative sample with $d_{\rm neb} > 10$ kpc and $d_{\rm radio} < 150$ kpc (3C 63, PKS 0745−191, 3C 196.1, 3C 218, 3C 274, 3C 275, 3C 295, 3C 317, and 3C 433), and two such sources from the special sample (3C 171 and 3C 305). The radio sources in these galaxies have sizes ranging from 20 to 125 kpc, while their radio powers span a wide range, from $\sim 6 \times 10^{41}$ ergs s^{-1} in 3C 274 to 2×10^{45} ergs s^{-1} in 3C 295.

Many of the sources in this category possess nonstandard radio morphologies.[3] Only three of these 11 galaxies (3C 63, 3C 275, and 3C 295) can clearly be categorized as having classical double, FR2 radio morphologies and at least two of the four sources which might be classified as having edge-dimmed, FR1 radio morphologies have diffuse halos (3C 274 and 3C 317). In addition, two of the 11 sources (PKS 0745−191, 3C 196.1) have "amorphous" radio morphologies. In these sources, there is no clear evidence, direct or indirect, that the radio emission is the result of a collimated outflow from the galaxy nucleus. Finally, three of the sources (3C 218, 3C 171, and 3C 305) have bright *interior* hotspots with diffuse trails of emission extending away from and well beyond the hotspots.

In these small radio sources with VEELG the emission-line gas is typically cospatial with radio emission. Although in some of these sources emission-line gas is found adjacent to bright radio emission, in many instances there is no detailed morphological relationship between the emission-line gas and the radio source structure.

Seven of the sources (3C 317, M87, 3C 218, PKS 0745−191, 3C 196.1, 3C 171, and 3C 305) show extensive regions of very low fractional polarization at 6 (or 20) cm, even in regions of the source where no emission-line gas is detected. In 3C 218 and 3C 295, there is evidence for Faraday rotation measures of −1850 and +2250 rad m^{-2}, respectively (Kato *et al.* 1987), indicating the presence of a rich magnetoionic medium, most likely in front of the radio source, either in a cocoon around the radio source, or within the interstellar or intergalactic medium (e.g., as documented in detail for 3C 405; Dreher, Carilli, and Perley 1987, and references therein). It is likely that the low fractional polarizations we observe in many of these small sources with VEELG result from structure on angular scales smaller than our resolution in rich magnetoionic (Faraday rotating) media between us and the radio emission. Interestingly, PKS 0745−191, 3C 218, 3C 274 (Virgo), 3C 295, and 3C 317 (Abell 2052) are all known to be associated with central dominant galaxies in clusters, and all of these clusters are thought to have cooling accretion flows in their cores (Sarazin 1986, and references therein; W. Forman and C. Jones 1988, private communication). Thus, both the presence of extended line emission and the low apparent radio polarizations in these sources may be related to their locations at the centers of clusters. 3C 275 and 3C 196.1 also appear to be in galaxy rich environments. 3C 171 and 3C 305, the two sources in this class from our "special" sample, are isolated galaxies.

2. *Large* ($d_{\rm radio} > 150$ *kpc*) *radio sources.*—We now turn to the second category defined above; galaxies with very extended emission-line nebulae and large radio sources ($d_{\rm radio} > 150$ kpc). In this category, we place the sources 3C 33, PKS

[3] In Paper II we describe our classification of radio source morphology for the sources in our sample. The more powerful extended radio sources $L_{\rm radio} > 10^{42.7}$ ergs s^{-1} typically have Fanaroff and Riley (1974) Class II (hereafter FR2) "edge-brightened" radio morphologies with bright hot spots near the most distant parts of the radio source. The hotspots are believed to be shocks at the working surface of the outflowing radio plasma with the surrounding (interstellar or intercluster) medium. Conversely, lower power extended radio sources typically have Fanaroff and Riley Class I (hereafter FR1) edge-dimmed morphologies, where the radio brightness fades (more or less) gradually with distance from the core. In sources with FR1 and FR2 radio morphologies, the radio emission can typically be seen to straddle the galaxy nucleus, and there is sometimes evidence, in the form of "jets" (i.e., narrow regions of radio emission pointing toward the core) for collimated outflow from the host galaxy nucleus (e.g., Bridle and Perley 1984, and references therein).

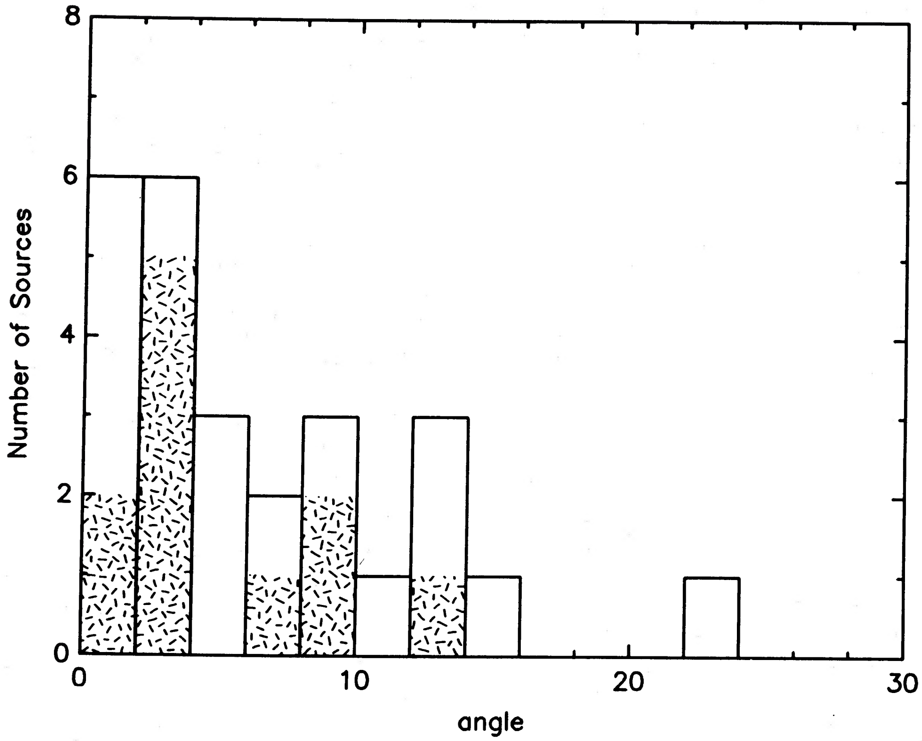


FIG. 6.—Histogram of the bending angle of the FR2 sources from the representative sample. Sources with associated emission-line nebula which are greater than 10 kpc in total extent are indicated by shading.

0349−278, 3C 98, PKS 0634−206, 3C 109, 3C 192, 3C 223, 3C 227, 3C 313, and 3C 403 from the representative sample, and 3C 285 and 3C 321 from the special sample. None of these sources appears to be in a cluster, in several cases the host galaxy appears to be the dominant galaxy in a small group of galaxies, while in the others the host galaxy is isolated.

The radio sources associated with this second class of galaxies have sizes ranging from 175 to 870 kpc, undistorted FR2 morphologies, and intermediate to high radio luminosities. In Figure 6, we show a histogram of bending angles for all of the FR2 sources in the representative sample where we have discriminated between sources with and without VEELG. We find no evidence that the FR2 sources with VEELG have more bent radio structures than their counterparts without such gas.

The apparent fractional polarization of the radio emission from these large sources is, in general, high (typically $\gtrsim 20\%$ averaged over the source at 6 cm).[4] Our snapshot radio images are not of sufficient quality to map the total intensity and polarization structure of the diffuse radio emission near the galaxy nucleus, where the emission-line gas is found. Therefore, we cannot determine whether the radio emission which is coincident (in projection) with the emission-line gas shows a low fractional polarization.

The very extended emission-line gas in the sources in this second category does not, in general, show an obvious association with the bright radio features, the hotspots, or the path from the core to the hotspots in these sources. In some sources, the brightest emission-line features define an axis which is askew to the radio source axis (e.g., 3C 98). In several of these sources (e.g., 3C 98, PKS 0634−206, 3C 192, and 3C 227), there are "tangential" emission-line filaments—filaments whose long axis is positioned perpendicular to the radial from the nucleus. We also note that in some sources (e.g., 3C 98, 3C 192, 3C 227), the emission-line gas appears as if it may be located preferentially near the edges of the low surface brightness regions of the radio source (i.e., the cocoons, or "backflow" regions).

[4] It is difficult to quantify the average polarization of a source in a meaningful manner, since bridges, jets, hotspots, and lobes have systematically different polarization properties and are reproduced at different levels in our snapshot images of different sources.

b) Discussion

i) *Why the Preference of the VEELG for the Radio Quadrants?*

We have shown that, for the galaxies from the representative sample with VEELG, the emission-line gas at distances greater than 3 kpc projected from the galaxy nucleus shows a statistical preference to be found in the radio quadrants of the sky and that this distant emission-line gas shows a statistical tendency to align with the radio source axis. How can we explain this preference of the very extended emission-line gas for the radio quadrants? We consider three possible explanations: (1) the radio source itself plays a role in the ionization of the emission-line gas; (2) the emission-line gas is photoionized by the active nucleus, but the relatively dense gas we observe in emission lines is found preferentially along the radio source axis; and (3) the ionizing radiation from the active nucleus escapes preferentially along the radio source axis. We consider each of these in more detail.

1. *Ionization by the radio source.*—We consider three ways in which the radio source may ionize the emission-line gas (1) through shocks, (2) through photoionization by an ultraviolet synchrotron extension of the radio synchrotron emission, and (3) through cosmic-ray heating and ionization.

The outward motion of the radio jet may result in the passage of shocks through cold clouds that have accumulated in the interstellar medium of the host galaxy, thereby creating emission-line filaments in much the same way that supernova remnants create optical emission-line filaments in the interstellar medium of our Galaxy (e.g., Ford and Butcher 1979). The passage of shocks through cold clouds may also induce star formation in the cold gas with subsequent ionization of the gas by stellar photoionization (e.g., van Breugel *et al.* 1985*b*; Chambers, Miley, and van Breugel 1987; McCarthy *et al* 1987). The most obvious place for shock ionization by the radio source to occur is at the interface between the outflowing plasma and the ambient medium. Similarly, photoionization by a localized source of ultraviolet synchrotron emission can occur only at sites of particle acceleration (e.g., along the jets or adjacent to the hotspots).

Thus, the radio source may contribute to the ionization of the VEELG in sources in which that gas is located adjacent to the jets or hotspots of the radio source. For instance, photoionization by a local source of ultraviolet continuum emission associated with the radio hotspot has been established as the likely means of ionization of the emission-line gas which is found immediately adjacent to the hotspot in the source 3C 277.3 (van Breugel *et al.* 1985*a*). Further, there are several examples in the literature of sources in which both the morphology and the kinematics of the emission-line gas indicate that the outflowing radio plasma and the gas have interacted (e.g., 4C 29.30; van Breugel *et al.* 1986 and van Breugel 1986).

However, in many cases, we find that the very extended emission-line gas does *not* lie adjacent to the regions of brightest radio emission, adjacent to the jets or the path from the nucleus to the hotspots, or adjacent to the hotspots themselves. In these sources it is unlikely that a localized source of ultraviolet synchrotron emission associated with the extended radio structure contributes to the ionization of the gas. Further, if the extended emission-line gas in these sources is shock-ionized by outflowing plasma, then the outflowing plasma must shock the surrounding medium at regions distant from the bright radio emission. One possibility is that the radio emission observed as the "jets" traces only the central region of the outflowing plasma (e.g., van Breugel *et al.* 1986), or that *oblique* shocks propagate away from the jets into the surrounding regions of diffuse radio emission (e.g., Norman *et al.* 1982). Shocks may also occur along the edges of the radio source, if the source expands supersonically into the interstellar or intergalactic medium, or if the plasma which flows back from the hotspots toward the host galaxy moves supersonically with respect to the ISM.

A final possibility is that the very extended emission-line gas may be locally heated via Coulomb interactions with, or directly ionized by, cosmic rays associated with the radio source (e.g., Lea and Holman 1978). Cosmic-ray heating is dominated by the population of low-energy ($\sim$5–10 MeV) relativistic electrons, and so may be effective near the edges and lower surface brightness regions of the radio source where the "oldest" of the electrons from the radio source (i.e., those with the steepest spectral index) are likely to be found.

We can estimate the energy input from cosmic rays associated with the radio source as follows. Ferland and Mushotzky (1984) argue that direct cosmic-ray ionization is less effective at ionizing the gas than is heating by Coulomb interactions with cosmic rays. They give the rate at which energy is passed from energetic particles to cold electrons as

$$\epsilon = 8.5 \times 10^{-19} \beta N_e N^* \text{ ergs cm}^{-3} \text{ s}^{-1} ,$$

where β is the ratio of the total heating rate (including collective effects; e.g., Scott *et al.* 1980) to the heating rate by direct Coulomb interactions and N^* is the density of cosmic-ray electrons. Scott *et al.* (1980) suggested that β may be as high as 10^5, but Rephaeli (1987) argues that collective effects should not dominate in galaxy atmospheres. Assuming a spectral index of -2.4 for the electron distribution ($N_e \propto E^{-2.4}$), and a lower bound to the electron distribution at an energy of 5 MeV, Ferland and Mushotzky (1984) estimate that $N^* = 10^5 P_{\rm rel}$ cm^{-3}, where $P_{\rm rel}$ is the pressure in relativistic particles which are in equipartition with the magnetic field.

The energy input due to relativistic particles can be compared with the radiative losses of the emission-line nebula. Osterbrock (1974) estimates that a nebula at 6000 K will cool at a rate of $L_{\rm cool} \sim 8 \times 10^{-25} N_e N_p$ ergs s^{-1} cm^{-3}, assuming approximately solar abundances, that O, Ne, and N are 80% singly ionized and 20% doubly ionized, and that H is 0.1% neutral. The ratio of heating by cosmic rays to radiative cooling can therefore be written as

$$\frac{\epsilon}{L_{\rm cool}} = \frac{10^6 \beta N^*}{N_p} .$$

For a density in the very extended emission-line gas of 1 cm^{-3} (Paper II), and a temperature of 6000 K, the pressure in the line-emitting gas is $P_{\rm gas} \sim 10^{-12}$ ergs cm^{-3}. This gas pressure is similar to the minimum pressure in relativistic particles and magnetic fields typically found for the diffuse radio emission in the lobes of extragalactic radio sources. We will assume that the pressure in relativistic particles and magnetic fields in the radio plasma is balanced by the pressure in the emission-line gas (i.e., $P_{\rm gas} \sim 2N_p kT = P_{\rm rel}$). Then, for $T = 6000$ K, we find that $N^* \sim 1.7 \times 10^{-7} N_p$, and hence that

$$\frac{\epsilon}{L_{\rm cool}} \sim 0.2\beta .$$

Thus, we find that the radiative losses of the emission-line gas are balanced by cosmic-ray heating, if $\beta \sim 5$, or, if $\beta \sim 1$ but there are a factor of 5 more low-energy relativistic electrons than used in our estimate. This result is somewhat dependent on the temperature in the line-emitting gas; for example, if the temperature in the line emitting gas is 10,000 K, then the ratio $(\epsilon/L_{\rm cool}) \sim 0.1\beta$.

Thus, it may be energetically feasible for cosmic-ray electrons associated with the extended radio source to heat and ionize the very extended emission-line gas. However, the details of the process of cosmic-ray heating and ionization are poorly understood. The calculation of the actual contribution made by cosmic rays to the ionization of the emission-line gas is sensitive to parameters (e.g., the importance of collective plasma effects, the number of low-energy [$\sim$5–100 MeV] relativistic electrons and protons, the low-energy cutoff in the relativistic electron population, and the magnetic field strength and configuration in the emission-line nebula) which cannot be adequately estimated (e.g., Ferland and Mushotzky 1984).

2. *Isotropic nuclear ionizing radiation.*—We assume that the emission-line gas is photoionized by the galaxy nucleus. If the ionizing radiation from the nucleus escapes isotropically, then the tendency for the very extended emission-line gas to be found in the radio source quadrants implies that the relatively high density gas which we observe in emission lines is found predominantly in those quadrants. Gas may accumulate along the radio source axis for any of the following reasons:

1. The jet may entrain gas that has accumulated in the center of the galaxy and transport it outward.

2. Dense gas acquired from either a tidal interaction with a gas-rich companion or from thermal instabilities in a cooling flow may be prevented from falling toward the center of the galaxy in the regions of the sky occupied by the radio source, due to either the ram pressure of the expanding radio source or the magnetic tension in the radio plasma (e.g., van Breugel, Heckman and Miley 1984). Thus, the expanding radio source may "snowplow" (and/or shock heat) filaments from the surrounding medium, causing them to accumulate along the edges of the radio source.

3. The expansion of the radio source into the hot, diffuse interstellar, or intergalactic medium may do *PdV* work on that medium, compressing the ambient gas and triggering the formation of thermal instabilities, thereby causing optical emission-line filaments to appear along the edges of the radio source.

Thus, there are several plausible mechanisms by which cool gas from the interstellar or intergalactic medium may accumulate preferentially along the radio source. Unless the radio source shocks the surrounding gas to sufficiently high temperatures that the cooling time of the gas is longer than the radio source lifetime, it may, in fact, be difficult to prevent cool material from piling up along the edges of a radio source which expands in an environment which contains appreciable amounts of cool gas. For shock velocities in the range 100–1000 km s^{-1}, the postshock cooling times range from $\sim 10^3 n_0^{-1}$ to $10^6 n_0^{-1}$ yr, where n_0 is the preshock density in cm^{-3} (e.g., McKee and Hollenbach 1980). Indeed, unless the gas is heated to temperatures greater than 10^9 K (corresponding to shock velocities $\gtrsim 7000$ km s^{-1}), the gas will cool in less than $\sim 5 \times 10^7 n_0^{-1}$ yr.

3. *Anisotropic escape of the nuclear ionizing radiation.*—Here we assume that the gas is photoionized by radiation from the nucleus, but that the ionizing radiation escapes (or is emitted) preferentially along the radio source axis. If the ionizing radiation is most intense along a wide cone whose axis is centered on the radio source ejection axis, then we might expect to find the most distant emission-line gas preferentially in the radio source quadrants. We would also expect that, in general, more ionizing photons would be available to the gas than we would infer from observations of the nonthermal nuclear flux.

Anisotropic radiation of the nuclear nonstellar continuum in active galaxies has been discussed in the past (Steiner 1981; Boroson, Persson, and Oke 1985; Antonucci 1984; Unger *et al.* 1987; Kinney *et al.* 1984). Two hypotheses for why the nuclear ultraviolet continuum might be emitted anisotropically are that (1) the emission is beamed synchrotron emission in a relativistically moving jet and (2) an optically thick disk surrounds the central source, thereby allowing the escape of ionizing photons only along the axis of the disk. In both of these models, the "collimation" of the nuclear ionizing radiation occurs close to the central engine (i.e., at the parsec or subparsec scale).

For the radio galaxies in our sample a substantial fraction of the ionizing radiation from the nucleus must escape *isotropically*, since a substantial fraction of the total emission-line luminosity in the radio sources in our sample comes from within 2.5 projected kpc of the galaxy nucleus (see Paper II). Morphologically, the gas within 2.5 kpc of the nucleus appears, in general, to be fairly smoothly distributed about the galaxy nucleus and to show a slight preference to be oriented perpendicular to the radio source axis (see Baum and Heckman 1989*b*). In addition, if too great a fraction of the nuclear, nonstellar, optical continuum escapes, or is emitted, anistropically, then the optical nuclear continuum should not be tightly correlated with the narrow emission-line luminosity since the observed nuclear, nonstellar continuum would be viewing angle dependent, but the emission-line luminosity would not be.

Another possible scenario which would account for the observed distribution of the near nuclear emission-line gas, is that the ionizing radiation from the active nucleus is *emitted* isotropically, but the cold gas around the galaxy becomes optically thick to the ionizing radiation in the direction perpendicular to the radio source axis within several kiloparsecs of the galaxy nucleus. The path along the radio axis may be swept clear of gas by the passage of the radio source, or, alternately, gas may preferentially settle out of the galaxy atmosphere into the plane perpendicular to the radio source ejection axis. In either case, the ionizing photons would only be able to escape to large distances from the nucleus in a cone centered on the radio source ejection axis. This model would require a high covering factor for the gas in a direction perpendicular to the radio source axis, but patchiness in the opacity would explain why we do see some very extended emission-line gas in the nonradio quadrants. For "circumnuclear" emission-line gas with a covering factor of unity, a shell of width $\sim 250(Q_{54})(n_{100})^{-2} R_{100}^{-2}$ pc is required to absorb all of the ionizing photons along a given line of sight, where Q_{54} is the number of ionizing photons emitted per second by the nucleus in units of 10^{54}, n_{100} is the density of the gas in units of 100 cm^{-3}, and R_{100} is the distance of the shell from the nucleus in units of 100 pc. The covering factor of optically thick gas in radio galaxies and quasars must be consistent with the observation that radio-loud objects also tend to be X-ray loud (i.e., optically thin to keV radiation) (e.g., Fabbiano *et al.* 1984). The constraint this imposes is dependent on (1) a nuclear origin for the X-ray emission (of particular concern for the radio galaxies; e.g., Feigelson and Berg 1983) and (2) possible directionality of the X-ray emission (of particular importance for quasars).

ii) *The Radio Source Properties of Sources with VEELG*

We have shown that, statistically, there is a spatial connection between the very extended emission-line gas and the extended radio source structure. Is there evidence of a more detailed relationship between the two, and, if so, how has the radio source structure been affected by the relatively cool and dense emission-line gas?

1. *Small ($d_{\rm radio} < 150$ kpc) radio sources.*—In a large fraction of the smaller ($d_{\rm radio} < 150$ kpc) radio sources with extended filamentary emission-line gas, there is evidence that the radio morphology and the apparent fractional polarization of the radio emission have been strongly affected by the media surrounding the radio sources. Most of these sources exhibit unusual radio morphologies and low levels of fractional polarization over large regions of the radio source. In general, the emission-line gas tends to be cospatial with the radio source structure, although an obvious physical connection between the two is in many cases difficult to discern. Since we have chosen these sources to be less than 150 projected kpc in total extent, in all cases the radio source should be contained largely within the ISM of the host galaxy.

Of the nine radio sources from the representative sample which fall in this category, seven appear to be associated with central dominant galaxies in cluster of galaxies, and in five of these clusters the cooling time of the intracluster gas is known to be short compared to the Hubble time. Thus both the forces which shape the radio properties of these sources and the origin of the extended emission-line gas in these sources may be directly related to their rich cluster environments.

The results of O'Dea and Baum (1987) and Baum and Heckman (1987) suggest that, in general, radio sources associated with central dominant galaxies in cluster cooling flows tend to be small and show morphological distortions. These effects may be indicative of confinement of the radio source by a high pressure, possibly turbulent, and clumpy medium. Also of interest is the finding by Dreher, Carilli, and Perley (1987) of extremely high rotation measures and rotation measure gradients in the polarized radio emission from 3C 405 (Cygnus A). They conclude that, most likely, the Faraday rotating medium is associated with the hot cluster gas surrounding 3C 405. Thus, the presence of very extended emission-line gas, the observed low percentage polarization of the radio emission, and the unusual radio morphologies of the small sources in our sample with very extended emission-line gas all signal the presence of dense interstellar media in these galaxies.

We have noted the unusual radio morphologies of PKS 0745−191 and 3C 196.1. These two sources have amorphous radio structures and show no evidence of collimated outflow from the nucleus. We have also noted the existence of several small sources with very extended emission-line gas in rich environments which show evidence of collimated outflow but which also have amorphous radio halos (e.g., 3C 274, 3C 317, and possibly 3C 218). What is the origin of these unusual regions of diffuse, amorphous radio emission?

Silk *et al.* (1986) argued that the unusual halo of diffuse radio emission around 3C 84 (associated with NGC 1275 at the center of the "cooling flow" in the Perseus cluster) can be explained as the combined emission from many supernova remnants; the results of high-mass star formation in gas accreted from the cluster cooling flow. Fabian and Khembavi (1982) proposed that shocks in the accretion flow associated with thermal instabilities will amplify existing magnetic fields and cosmic rays to produce diffuse radio sources in cooling flows. Either or both of these processes may contribute to the amorphous radio halos we observe. It is perhaps more likely that the radio halos are fed by collimated outflow from the central engine. The position angle of the radio jets may change with time, thereby spraying radio luminous plasma over a wide region (e.g., as we have suggested for 3C 317 [Paper I], and has been suggested for 3C 274 [M87] [Rao 1987]). Alternatively, the jets may decollimate due to pressure gradients or turbulence in the external medium (e.g., Sumi and Smarr 1985). The radio jet position angle may change if the host galaxies suffers a tidal interaction (e.g. Wirth, Smarr, and Gallagher 1982), merges with a companion galaxy, or is fed by gas with an angular momentum orientation which differs from that of its central engine (Rees 1978; Begelman, Blandford, and Rees 1980). Alternatively, the diffuse morphology may be the result of the gradual diffusion/expansion of radio-emitting plasma from a radio source in an "equilibrium" configuration in pressure balance with the dense ICM. A final possibility is that we are looking down the radio jet axis and see the radio sources end on. However, there is no reason why we should find this radio source orientation associated preferentially with galaxies at the centers of rich cluster environments.

Two additional small radio sources with extended filamentary emission line gas (3C 171 and 3C 305) deserve special note. The host galaxies of these two radio sources are isolated galaxies which nevertheless appear to have interstellar media which contain large amounts of cold gas. In both cases, the radio source appears to have plowed into this ambient medium. Both sources exhibit unusual radio morphologies, with bright radio hotspots close to the galaxy nucleus and diffuse trails of emission extending laterally from the hotspots. These lateral trails of emission may result from the deflection and decollimation of the radio plasma at the interface with the dense ambient medium, or may represent bouyant plumes rising along the paths of least resistance, away from the high-density, high-pressure gas along the radio source axis. Neither of these sources were members of the representative sample; both were chosen for study because we knew from previous work that they had extensive regions of emission-line gas. We have not encountered any similar examples of small, intermediate to high radio power sources within isolated galaxies which appear to have interacted so strongly with a gas-rich environment within their parent galaxies. However, our source selection process specifically selected against sources of small angular size ($<5''$; Paper I), so we cannot properly evaluate how common such sources are. Van Breugel, Heckman, and Miley (1984) and Fanti *et al.* (1985) have suggested that there may be a strong interaction between the outflowing radio plasma and cold gas within the inner few kiloparsec of the host galaxy in steep-spectrum core radio sources.

2. *Large ($d_{\rm radio} > 150$ kpc) radio sources.*—As discussed above, all of the large ($d_{\rm radio} > 150$ kpc) radio sources in our sample with very extended emission-line gas are very powerful radio sources with undistorted FR2 radio morphologies and normal levels of fractional polarization throughout most of the source structure (at 6 or 20 cm). We can compare the properties of these sources with those of 3C 277.3 (Coma A), the most dramatic example of a radio source which has interacted with cold gas in the ISM of its host galaxy. As reported by van Breugel *et al.* (1985*a*), the radio structure and polarization of 3C 277.3 have clearly been affected by the interaction of the outflowing radio plasma with cold clouds in the ambient medium (see Fig. 7). The radio source appears to bend by $\sim 40°$ at an interface between a bright radio knot in the southern jet and a bright Hα emitting optical knot, giving the source a distinctive C-shape. The fractional polarization of the source at 6 cm is generally low throughout the radio lobes, except in some locations along the edges of the lobes, suggesting the presence of a magnetoionic Faraday depolarizing medium surrounding the radio source. The northern hotspot and southern radio knot show very low fractional polarization at 6 cm ($<3\%$) and are located adjacent to bright optical line emitting filaments.

Thus, the radio source 3C 277.3 shows clear evidence that its morphology and apparent polarization have been altered by its interaction with dense gas in its interstellar medium. 3C 277.3 is a relatively small ($d_{\rm radio} \sim 75$ kpc) source of intermediate radio luminosity. Clearly, in the powerful, large, FR2 radio galaxies with very extended emission-line gas in our sample, the radio sources show none of these obvious signs of having interacted with and having been modified by the presence of dense gas in their interstellar or intergalactic media.

It appears that if the radio jets in these powerful radio sources have encountered cold clouds in their passage through the ISM of their host galaxies (as is likely, given the distribution of the very extended emission-line gas), then (1) the

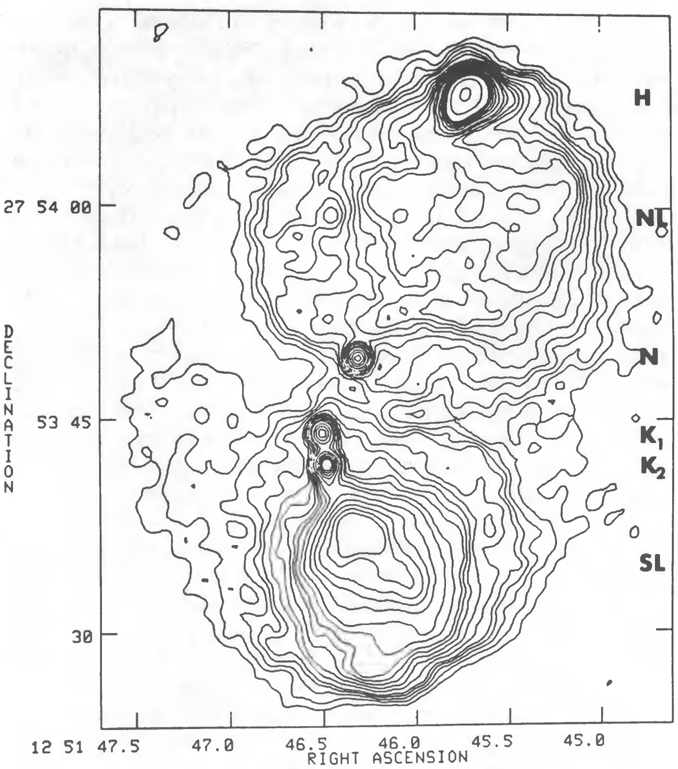
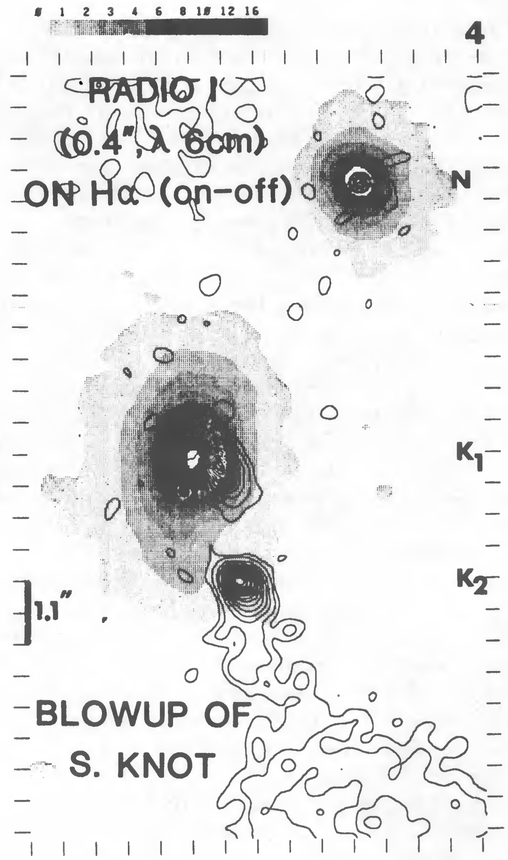


FIG. 7*a*



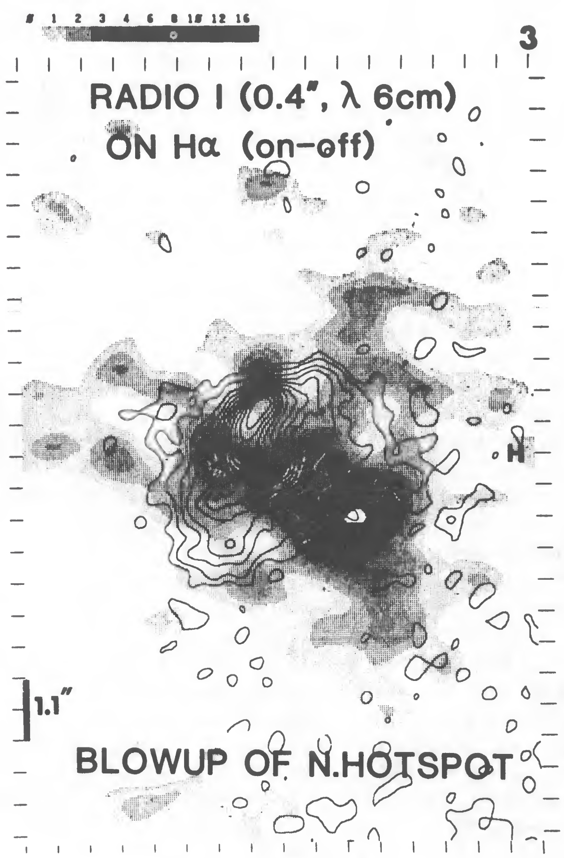


FIG. 7.—Contour maps and overlays of 3C 277.3, reproduced from van Breugel *et al.* (1985*a*). (*a*) Contours of the 21 cm VLA image of 3C 227.3. Levels are 0.57 × (−0.9, 0.9, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 10, 12, 16, 20, 24, 28, 32, 50, 90) mJy per restoring beam (1".2 FWHM circular Gaussian). (*b*) Blowup of the northern hotspot (labeled "H" in *a*) showing the Hα + [N II] emission as a gray scale superposed on contours of the 6 cm radio VLA image at 0".4 resolution. (*c*) Blowup of the southern knot (labeled "K1" in *a*), as in (*b*).

plasma beams have not been redirected through large angles due to the interaction and (2) the plasma beams have not entrained sufficient thermal material to depolarize the radio emission in their hotspots and lobes at 6 cm. The plasma beams in these sources seem to have plowed through any ambient medium relatively undisturbed. Indeed, the sizes of these radio sources indicate that the end of the plasma beams are now well outside the interstellar media of their host galaxies. It is possible that in an earlier stage of their development, these powerful radio sources interacted more strongly with the cold gas in their ISMs (e.g., as in 3C 171 or 3C 305). Conversely, it may be that such a strong interaction between cold gas and the radio source would have *prohibited* the formation of a large radio source.

Although we do not, in general, find an obvious morphological connection between the extended filamentary emission-line gas in these sources and the path from the core to the hotspots, we note that in some of the FR2 sources the emission-line gas appears as if it may lie preferentially along the edges of the low surface brightness regions of the source. Specifically, the gas appears along the relatively diffuse radio emission which forms a bridge or tail from the hotspots back toward the parent galaxy. These bridges have been interpreted as backflowing plasma which has passed through the terminal shocks at the end of the jets (i.e., the hotspots) (Norman, Winkler, and Smarr 1983; Wilson 1983). Leahy and Williams (1984) suggest that the backflowing plasma is deflected when it encounters the pressure of the host galaxy's ISM, thereby forming extensions which run perpendicular to the axis of the radio source. We note that in the two most convincing cases, 3C 227 and 3C 192, the radio sources have an overall X-shape (i.e., the diffuse, "backflow" emission from the lobes "deflects" to opposite sides of the host galaxy). In both cases the emission-line gas is found along the outside of the bend of the radio bridge; that is, on the side facing the radio galaxy where, in this scenario, the backflowing radio plasma would be deflected by the pressure of the galaxy's ISM (see Paper I).

The possible association of filamentary emission-line gas with the edges of these backflow regions may indicate that the backflow compresses the host galaxy ISM, leading to the accumulation of preexisting cold, thermal material along the edges of the radio source. In addition, if the backflow is expanding supersonically with respect to the sound speed in the ambient medium (Miller *et al.* 1985), the ambient medium will be shocked and compressed. This may trigger the formation of thermal instabilities or shock heat cold clouds. Clearly, we require more detailed radio data and kinematic spectroscopic data on the emission-line gas in order to confirm and elucidate the nature of any interaction between the emission-line gas and the backflow region. We note that Wirth, Smarr, and Gallagher (1982) have suggested an alternate interpretation of X-shaped radio sources. In their model the X-shape arises from a change in the radio source ejection axis which is caused by a tidal interaction between the host radio galaxy and a companion galaxy. Thus, in this scenario, both the very extensive nature of the emission-line gas and the X shapes of the radio sources in these two galaxies would originate from a tidal interaction. While 3C 227 has a potential secondary nucleus, 3C 192 shows no signs of having recently undergone an interaction (see Papers I and II).

c) Conclusions

We find a relationship between the *energy* emitted in optical line and radio emission. The radio luminosity correlates with the optical narrow emission-line luminosity over roughly four orders of magnitude in line luminosity and five in radio luminosity. This correlation most likely points to a common energy source for both the optical line and the radio emission. If, as seems likely (e.g., Paper II), the optical emission-line gas is ionized by the nuclear continuum, then this suggests that the radio luminosity of a galaxy is determined, to first order, by the properties of its central engine.

The total emission-line luminosity (emitted in the infrared, the optical, and the ultraviolet) of the powerful radio galaxies in the representative sample is typically at least half of the luminosity of the associated radio source. Comparing the radio galaxies in our sample with the steep-spectrum radio-loud QSOs in the sample of Stockton and MacKenty (1987), we find that the typical ratio of narrow line to radio luminosity in the QSOs is ~ 4 times that in radio galaxies of similar radio luminosity. This suggests that, when taken as a class, extended, steep-spectrum radio galaxies can be separated from extended, steep-spectrum QSOs on the basis of their presumably (although not necessarily) aspect angle independent, narrow-line luminosities. However, we note that there is also overlap of the steep-spectrum radio-loud QSOs with the powerful radio galaxies in the $L_{\text{radio}} - L_{\text{narrow line}}$ plane.

While there exist a host of active galaxies with much higher ratios of line to radio luminosities than are found in radio galaxies (e.g., Seyfert galaxies and radio-quiet quasars), we find no steep-spectrum radio galaxies with high radio luminosities and low line luminosities. Combined with the strong correlation of the ionizing continuum with the emission-line luminosity, this implies that in powerful radio galaxies (1) the central engine typically produces at least as much ionizing continuum luminosity as it does radio luminosity, (2) the host galaxies always have cold gas near their nuclei which "reprocesses" the ionizing radiation into emission lines, and (3) the ultraviolet nuclear continuum cannot be strongly variable on a time scale long compared to the recombination time in the line-emitting gas.

The fact that (for steep-spectrum, extended, radio galaxies as a whole) there is a better correlation between the radio and *narrow* line luminosity than between the radio and the *total* emission-line luminosities has two plausible interpretations. One is that there is a much stronger physical link between the radio jets and the narrow-line regions than between the radio jets and the broad-line region. The other is that the broad emission lines are aspect angle dependent, while the narrow emission lines and most/all of the radio emission are aspect angle independent.

We find the following evidence for a *spatial* relationship between the very extended emission-line gas and the radio source: (1) in all cases but one, the radio source extent is comparable to or greater than the extent of the emission-line nebula; (2) the very extended emission-line gas shows a statistical tendency to align with the radio source axis in both radio galaxies and radio-loud, steep-spectrum quasars; and (3) the luminosity of the very extended emission-line gas comes preferentially, although not exclusively, from the radio quadrants.

If we consider the subset of galaxies which have very extended emission-line gas and whose radio sources are less than 150 kpc in total extent, we find that (1) almost all of these sources have distorted radio morphologies, (2) at least half of these sources are known to be located at the centers of rich clusters of galaxies in which the intracluster gas may be cooling and accreting onto the host galaxy, (3) many of the radio sources show large regions of low fractional polarization and two of the sources show evidence for foreground Faraday rotation of the polarization position angle implying rotation measures of ~ 2000 rad m^{-2}, and (4) the emission-line gas and the radio source are often cospatial, in projection, in these sources; in some cases there is a detailed physical relationship between the two, while in others there is not. Thus, in this class of "small" radio galaxies with VEELG, the morphology, physical extent, and polarization properties of the radio sources appear to have been affected by the gas-rich environment through which the radio sources propagate.

If we consider the galaxies with very extended emission-line gas whose associated radio sources are greater than 150 kpc in total extent, we find (1) all of the sources have undistorted, FR2 radio morphologies and appear to show normal levels of fractional polarization, (2) none of the sources are known to be located at the centers of rich clusters of galaxies, and appear instead to be the dominant members of small groups of galaxies, or to be isolated galaxies, (3) the brightest (off nuclear) regions of line emission do not typically appear adjacent to bright radio features or directly along the path from the nucleus to the hotspots, although the line emission does show a statistical tendency to align with the radio source axis, (4) in several of these sources, the emission-line gas appears as if it may be located preferentially along the low surface brightness regions of the radio source, perhaps associated with the regions of the radio source thought to be formed by the backflow of radio plasma from the hotspots toward the galaxy nucleus (more evidence is needed to determine whether this apparent association is real). In this class of "large" radio sources, there is no evidence that the morphology of the radio source has been affected by the interstellar or intergalactic medium surrounding the radio source. The nature of the relationship between the extended radio source structure and the emission-line gas is unclear for most of these large ($d_{\rm radio} > 150$ kpc) radio sources. It is possible that at an earlier stage in the development of these galaxies the radio source interacted more strongly with cold gas in the ISM of its host galaxy, and that we are selecting out those radio sources which have long since broken out of any confining interstellar medium. Alternatively, these sources may be large and undisturbed *because* they never interacted strongly with a dense, cold, confining medium.

Assuming that the very extended emission-line gas is photoionized by the active nucleus (see Paper I), we consider two possible explanations for the preference of the very extended emission-line gas for the radio quadrants. One possibility is that some fraction of the ionizing radiation from the nucleus is emitted, or escapes, preferentially along the radio source ejection axis. A second possibility is that the nuclear ionizing radiation is emitted isotropically, but the relatively high density gas which we observe in emission lines is found only along the edges of the radio source. This could be because the flow of plasma from the nucleus (i.e., the jets) has entrained higher density matter from the nuclear regions and transported them outward, or because the radio source has compressed the ambient interstellar medium, perhaps running over preexisting cold clouds or inducing turbulence and accompanying thermal instabilities in a hot ($\sim 10^7$ K) interstellar/intergalactic medium.

Alternatively, the very extended emission-line emission gas may come preferentially from the radio quadrants because the radio source contributes to the ionization of this gas. Possibilities include shock ionization, ionization by an ultraviolet extension of the radio synchrotron emission, and heating/ionization by cosmic rays associated with the radio source. The former two possibilities are likely to be most important in the few cases where the emission-line gas is found adjacent to regions of bright radio emission. Conversely, cosmic-ray heating is dominated by the population of relatively low energy relativistic electrons, and so should be effective near the edges, and lower surface brightness regions of the radio source, where the "oldest" population of relativistic electrons are likely to be. We show that cosmic-ray ionization is *energetically* feasible; unfortunately, due to the large number of unknowns, we cannot estimate its actual contribution to the ionization of the gas.

We have presented evidence of spatial and energetic relationships between the radio source and the very extended emission-line gas. In many individual sources the nature, and even the existence, of a relationship between the radio source and the very extended emission-line gas is unclear. Nevertheless, the statistical preference of the most extended emission-line gas for the radio quadrants suggests that the distribution and/or the ionization of this gas is influenced by the radio source. The correlation of emission-line and radio luminosities argues for a common energy source (i.e., the central engine) for the bulk of the radio and emission-line luminosities.

We acknowledge support from NSF grant AST85-15896. We thank Wil van Breugel, Alan Bridle, and George Miley for many scientific discussions and the referee, Gary Ferland, for his comments. S. A. B. thanks NRAO for the award of a predoctoral research associateship, G. Kessler for his careful work on the figures, C. O'Dea for comments on the paper and encouragement, and little C. O'Dea and D. Mint for moral support.

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