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THE CONNECTION BETWEEN LINE EMISSION AND RADIO POWER IN DISTANT RADIO GALAXIES

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ABSTRACT

Distant radio galaxies are powerful radio sources and have strong emission lines. The emission-line regions are quite extended, often 100 kpc along the major axis, and are clumpy, elongated, and aligned with the radio axis. In addition, the emission-line luminosity is roughly proportional to the radio power.

Energy transferred from relatively low-energy relativistic electrons to the ambient gas may contribute significantly to the emission-line luminosity of the galaxy. Interactions between relativistic electrons and ambient gas heats the gas, which then radiates line emission. The line luminosity is expected to be proportional to the radio power in this model, in agreement with the observations. The observed normalization requires that cold gas with an average density between about $5 \times (10^{-3}$ to $10^{-1})$ cm^{-3} be present along the radio bridge of the radio source, indicating a total gas mass within a spherical volume with a 50 kpc radius about the radio galaxy of about $5 \times (10^{10}$ to $10^{12})$ $M_{\odot}$.

Relativistic electrons lose energy and cool down as they heat the ambient gas. Relatively cool relativistic electrons inverse Compton scatter microwave background photons to optical and ultraviolet energies, while higher energy relativistic electrons inverse Compton scatter microwave photons to X-ray energies. Thus, when interactions between relativistic electrons and ambient gas are an important source of power for the line emission, interactions between relatively cool relativistic electrons and microwave photons are likely to produce a local source of ultraviolet radiation that will affect the emission-line ratios.

Subject headings: galaxies: peculiar — radiation mechanisms: miscellaneous — radio continuum: galaxies

1. INTRODUCTION

Distant powerful radio galaxies have strong emission lines (e.g., Spinrad et al. 1977; Spinrad & Djorgovski 1984). Both the emission-line and optical continuum morphologies of distant radio galaxies are quite peculiar. The emission-line and optical continuum regions are generally quite extended (~ 100 kpc), clumpy, and aligned with the radio axis, which is referred to as the alignment effect (McCarthy 1988; Chambers 1989; McCarthy et al. 1987; Chambers, Miley, & van Breugel 1987). In addition, the emission-line luminosity is roughly proportional to the radio power (e.g., McCarthy 1991; McCarthy et al. 1991).

The emission lines may be powered by ultraviolet radiation. In this case, the correlation between the emission-line luminosity and the radio power results if the ultraviolet luminosity that powers the emission lines is proportional to the radio power, as is the case for the inverse Compton scattering model (Daly 1992a, b).

Another energy source that may contribute significantly to the emission-line luminosity is that associated with the relativistic electrons that produce the radio emission. This energy source is discussed by Ferland & Mushotzky (1984), who show that energy from the relativistic electrons can contribute significantly to the emission-line luminosity of the radio source. Ferland & Mushotzky (1984) consider relativistic electrons as an energy source in broad- and narrow-line regions of active galactic nuclei (AGNs), and in extended radio lobes. The results they report for extended radio lobes (Ferland & Mushotzky 1984, § IIIc) are directly applicable to sources of the type considered here. Ferland & Mushotzky (1984) conclude that in extended radio sources where the number density of relativistic electrons is relatively low, $\sim 10^{-6}$ cm^{-3}, the total luminosity of the lines increases when gas heated by relativistic electrons is included because of the added heat and ionization, while the relative line strengths are not significantly affected, though there is a tendency for a higher level of ionization. Ferland & Mushotzky (1984) do not include ultraviolet and X-ray radiation produced by inverse Compton scattering of microwave background photons with relativistic electrons; this process will produce a local source of ultraviolet and X-ray radiation if the relativistic electron energy distribution extends to relatively low Lorentz factors, as discussed in § 2.4. Ultraviolet and X-ray radiation may also be produced by thermal bremsstrahlung from hot gas along the radio axis, by stars, or, as discussed in this context by van Breugel & McCarthy (1990), by the AGN.

The possibility that relativistic electrons are a primary energy source to power line emission in distant radio galaxies is considered here. Interactions between relativistic electrons and ambient gas transfers energy from the relativistic electrons to the gas, as discussed in § 2.1; the effect of including a small volume filling factor for the relativistic electrons and magnetic field is discussed in § 2.2. The relationship between the rate at which the gas is heated and the total line luminosity is discussed in § 2.3. Optical, ultraviolet, and X-ray radiation produced in the vicinity of the emission-line clouds by inverse Compton scattering of microwave background photons with relativistic electrons is discussed in § 2.4. Conclusions are drawn in § 3.

2. THE MODEL

Interactions between relativistic electrons and ambient gas transfers energy from the relativistic electrons to the gas. These interactions occur in regions where the gas and relativistic electrons are mixed. The magnetic field may thread the gas, in which case interactions occur throughout the volume that contains the field and relativistic electrons, or the ambient gas may be outside magnetic flux tubes that confine the relativistic electrons, in which case the interactions occur in the boundary layer between the magnetic flux tubes and the ambient gas.

Cold gas in contact with relativistic electrons is heated to a temperature of about 10^4 K in about 10^5 yr (§ 2.3). When the gas reaches this temperature the energy-loss rate due to line emission is on the order of the rate of energy input, so the gas will remain at a temperature of about 10^4 K, and the energy from relativistic electrons input to the gas will be radiated as line emission. Thus, the total line luminosity will be equal to the rate at which energy is input to the gas, discussed in § 2.1. Both the line luminosity and the radio power are proportional to the total number of relativistic electrons, so, in this model, the line luminosity is expected to be proportional to the radio power.

2.1. *Energy Transfer from Relativistic Electrons to Ambient Gas*

Relativistic electrons will interact with ambient nonrelativistic gas, as discussed, for example, by Ginzburg (1989) in § 16 and Pacholczyk (1970) in § 6.3. Interactions that cause the relativistic electrons to lose energy at a rate independent of the Lorentz factor of the electron include ionization losses and Cherenkov emission of plasma waves. This is the dominant energy loss mechanism for relativistic electrons with Lorentz factors $\gamma \lesssim 10^4 \sqrt{n_g}(1+z)^{-2} \min(1, \epsilon^{-1})$ (Daly 1992b), where the ambient gas density n_g is in units of cm^{-3}, and $\min(1, \epsilon^{-1}) = 1$ when inverse Compton losses dominate and $\min(1, \epsilon^{-1}) = \epsilon^{-1}$ when synchrotron losses dominate, where the magnetic field $B_\perp$ is parameterized in terms of ϵ and the energy density $u_{\rm mb}$ of the microwave background radiation, $B_\perp^2/(8\pi) \equiv \epsilon^2 u_{\rm mb}$, as described below.

The energy loss rate per relativistic electron is about $(dE/dt)_{\rm re} \simeq 9 \times 10^{-19}\, n_g$ ergs s^{-1} for interactions with ionized gas, and is about a factor of 2 smaller for interactions with neutral gas; again n_g is the ambient gas density in units of cm^{-3} (e.g., Ginzburg 1989, § 16). Interactions with ionized gas cause an electron with an initial Lorentz factor γ_i to cool to a final Lorentz factor γ_f in a time $t = 10^7\, t_7$ yr: $\gamma_f \simeq \gamma_i - 350\, n_g t_7$; for interactions with neutral gas this expression becomes $\gamma_f \simeq \gamma_i - 170\, n_g t_7$. The time scale for a relativistic electron with an initial Lorentz factor γ_i to lose half of its energy is $t_{\rm re} \simeq (5\text{–}10) \times 10^6\, n_g^{-1}\, (\gamma_i/350)$ yr; the first factor is relevant for interactions with ionized gas and the second for interactions with neutral gas. Synchrotron and inverse Compton cooling of relativistic electrons with Lorentz factors of $\sim 10^3$ indicate that the radio sources in distant radio galaxies have been active for about (5×10^6)–10^7 yr (Leahy, Muxlow, & Stephens 1989).

The rate at which energy is transferred to the ambient gas is $L_{\rm gas} \simeq f_g N_{\rm tot}\, (dE/dt)_{\rm re}$, where f_g is the volume filling factor of regions with gas density n_g in contact with the relativistic electrons. The total number of relativistic electrons $N_{\rm tot}$ can be estimated by extrapolating the power-law energy distribution of the relativistic electrons (inferred from the observed radio power) to low energies. As discussed below, the total number of relativistic electrons can be written as a function of the radio power $P_r \equiv dE/(dt\, d\nu)$ or the radio lumunosity $L_r \simeq \nu_r P_r$ and the low-energy cutoff $\gamma_{\rm co}(t_i)$ of the relativistic electron energy distribution set before cooling has affected the relativistic electrons. When the magnetic field strength is roughly constant over the radio-emitting region, the total number of relativistic electrons inferred from the radio power does not depend directly on the volume filling factor of the magnetic field and relativistic electrons, though it does depend on the strength of the magnetic field. And, as discussed in § 2.2, the minimum energy magnetic field strength is weakly dependent on the volume filling factor of the radio-emitting plasma.

The relativistic electron population is well approximated by a power-law energy distribution where the total number of relativistic electrons with energies in the range from γ to $\gamma + d\gamma$ is $N(\gamma)d\gamma = N\gamma^{-s}\, d\gamma$ (see, for example, Moffet 1975). The total energy of the relativistic electrons is $E_{\rm tot} = m_e c^2 \int \gamma N(\gamma) d\gamma$, where $\gamma \equiv E/(m_e c^2)$ is the Lorentz factor of a relativistic electron with energy E. The relativistic electrons spiral about the magnetic field and produce synchrotron radiation with a radio spectral index $\alpha = (s-1)/2$, where the radio flux density $f_{\nu_r} \propto \nu_r^{-\alpha}$. Thus, for $\alpha > 0.5$, as is the case for the high-redshift radio galaxies, the total energy of the relativistic electrons is concentrated at the low-energy cutoff $\gamma_{\rm co}$ of the energy distribution $E_{\rm tot} \simeq m_e c^2 (2\alpha - 1)^{-1} N \gamma_{\rm co}^{-(2\alpha-1)}$. The low-energy cutoff is probably more of a slow rollover, hence $\gamma_{\rm co}$ should be considered to be the energy at which the relativistic electron energy distribution begins to flatten and deviate from the power-law form. The total number of relativistic electrons is $N_{\rm tot} = \int N(\gamma) d\gamma$, so $N_{\rm tot} \simeq N(2\alpha)^{-1} \gamma_{\rm co}^{-2\alpha}(t_i)$ for $\alpha > 0$; $\gamma_{\rm co}(t_i)$ is the low-energy rollover or cutoff of the relativistic electron energy distribution before cooling affects the energy distribution.

The radio luminosity L_r produced at a frequency ν_1 by relativistic electrons with an energy E_1 via synchrotron radiation is $L_r(\nu_1) = N(E_1)(dE_1/dt)_s$ where the total number of relativistic electrons with energy E_1 is $N(E_1) = N(2\alpha)^{-1} \gamma_1^{-2\alpha}$ for $\alpha > 0$ and where $\nu_1 \simeq c_1 B_\perp E_1^2$ with $c_1 \simeq 6.3 \times 10^{18}$ in cgs units (Moffet 1975). The rate $(dE_1/dt)_s$ at which an electron with energy E_1 produces synchrotron radiation is $(dE_1/dt)_s \simeq 1.7 \times 10^{-26} \epsilon^2 \gamma_1^2 (1+z)^4$ ergs s^{-1} when the magnetic field $B_\perp$ perpendicular to the direction of propagation of the electron is parameterized in terms of ϵ and the energy density $u_{\rm mb}$ of the microwave background radiation $B_\perp^2/(8\pi) \equiv \epsilon^2 u_{\rm mb}$; when the magnetic field is parameterized by $B_\perp = 10^{-5}\, b$ G then $(dE_1/dt)_s \simeq 1.6 \times 10^{-25} b^2 \gamma_1^2$ ergs s^{-1} (Moffet 1975). Both parameterizations of the magnetic field give a reasonable fit to equipartition field strengths of high-redshift ($z \sim 1$) radio galaxies (Leahy et al. 1989). The equipartition field strengths given by Leahy et al. (1989) are estimated assuming that the radio-emitting plasma fills the available volume; the effect of allowing for a small volume filling factor is discussed in § 2.2.

Combining these expressions, the rate $L_{\rm gas}$ at which relativistic electrons transfer energy to neutral ambient gas relative to the radio luminosity $L_r(\nu_1)$ at the frequency ν_1 where $L_r(\nu_1) \simeq \nu_1 P_r(\nu_1)$, is

$$\frac{L_{\rm gas}}{L_r(\nu_1)} \simeq 3 \times 10^6 n_g f_g b^{-2} \gamma_{\rm co}(t_i)^{-2\alpha} \gamma_1^{2\alpha-2}\,, \qquad (1a)$$

which may also be written

$$\frac{L_{\rm gas}}{L_r(\nu_1)} \simeq 3 \times 10^7 n_g f_g \epsilon^{-2} (1+z)^{-4} \gamma_{\rm co}(t_i)^{-2\alpha} \gamma_1^{2\alpha-2}\,. \qquad (1b)$$

For $\alpha \sim 1$, and $\epsilon \sim 1$, $z \sim 1$ (in eq. [1b]), or $b \sim 1$ (in eq. [1a]), and $\gamma_{\rm co}(t_i) \sim 100$ equations (1) imply $L_{\rm gas}/L_r \sim 250 f_g n_g$. As discussed in § 2.3, after about 10^5 yr, energy input to ambient gas will be radiated as line emission, and the total line luminosity $L_{\rm lines}$ is comparable to the rate of energy input: $L_{\rm lines} \sim L_{\rm gas}$.

The observed relationship between the [O II] line luminosity $L_{\rm [O\,II]}$ and the 1.4 GHz radio power $P_{1.4}$ is $L_{\rm [O\,II]} \sim 10^8 P_{1.4}$

(McCarthy 1991; McCarthy et al. 1991). The total line luminosity is about $L_{\rm lines} \sim 10 L_{\rm [O\,III]}$ (McCarthy 1988). The 1.4 GHz radio luminosity is $L_r \simeq (1.4\ {\rm GHz}) P_{1.4}$; hence the observations suggest that $L_{\rm lines} \sim L_r$ (Daly 1992b).

Thus, the normalization of the observed relationship is obtained when the right-hand side of equation (1a) or (1b) is on the order of unity, that is, when $f_g n_g \sim 4 \times 10^{-3}$ to 4×10^{-2} for $\gamma_{\rm co}(t_i) \sim 100$–300 and a magnetic field strength of about 10^{-5} G; these requisite average densities decrease if the field strength is less than the equipartition value. The average densities quoted above imply gas masses between about 5×10^{10} $M_\odot$ and 5×10^{11} $M_\odot$ if the gas is in a roughly spherical volume with a 50 kpc radius about the radio galaxy.

Observations by Carilli et al. (1991) suggest a magnetic field strength of about 1/3 the equipartition value for the lobes of Cygnus A. The low-frequency turnover of the radio spectrum has been interpreted (Carilli et al. 1991) as a low-energy cutoff at a Lorentz factor of about 400 in the hot spots of Cygnus A, and the observations indicate expansion by about a factor of 2 from the hot spots to the lobes, suggesting $\gamma_{\rm co}(t_i) \sim 200$ in the lobes of Cygnus A. High-redshift radio galaxies may be similar to Cygnus A, in which case $\gamma_{\rm co}(t_i) \sim 200$ and $\epsilon \sim 1/3$ should be used in equation (1b).

It is interesting to note that another interpretation of the low-frequency turnover of the radio spectrum of the hotspots of Cygnus A is the cooling discussed here. Interactions between relativistic electrons in the hot spot and dense ambient gas will cool the relativistic electrons and cause the low-energy radio spectrum to flatten (Daly 1992b), though cooling on a relatively short time scale, $\lesssim 10^5$ yr, would require fairly large ambient gas densities, $\gtrsim 10^2\ {\rm cm^{-3}}$. This cooling will eventually cause the low-frequency radio spectrum to turn over, which occurs when the lower energy relativistic electrons have lost most of their energy.

2.2. *Effects of a Small Volume Filling Factor for the Radio-Emitting Plasma*

The radio luminosity may be used to estimate the total number of relativistic electrons, as discussed in § 2.1. When the magnetic field strength is roughly constant over the radio-emitting region, the total number of relativistic electrons determined in this way does not depend directly on the volume filling factor of the relativistic electrons and magnetic fields. It does depend on this quantity indirectly because minimum energy field strengths are assumed, and the minimum energy field strength increases as the volume filling factor of the fields and relativistic particles decreases.

Consider a radio emitting region with energy density in relativistic electrons and magnetic fields of roughly $u_r \simeq [B^2/(8\pi) + \gamma_{\rm co}(t_i) n_{\rm re} (m_e c^2)]$ for $\alpha > 0.5$. The number density of relativistic electrons is $n_{\rm re} \simeq N_{\rm tot}/(f_{\rm re} V_T)$, $N_{\rm tot}$ is the total number of relativistic electrons that occupy a fraction $f_{\rm re}$ of the available volume V_T.

As in § 2.1, the radio luminosity produced by electrons with energy $E_1 \equiv \gamma_1 (m_e c^2)$ is $L(\nu_1) \simeq c_3 B_\perp^2 \gamma_1^2 (m_e c^2)^2 N_{\rm tot} (\gamma_{\rm co}(t_i)/\gamma_1)^{2\alpha}$ valid for $\alpha > 0$, where $\gamma_1 = (m_e c^2)^{-1} (\nu_1)^{0.5} (c_1 B_\perp)^{-0.5}$, and both c_1 and c_3 are in cgs units: $c_1 \simeq 6.3 \times 10^{18}$ and $c_3 \simeq 2.4 \times 10^{-3}$ (Moffet 1975). Using the expression for $L(\nu_1)$ to eliminate $N_{\rm tot}$ from the expression for the energy density u_r, noting that the ratio $\gamma_{\rm co}/\gamma_1$ is independent of B, assuming $B \simeq B_\perp$, neglecting the possible contribution by relativistic protons to the energy density, and minimizing u_r with respect to the magnetic field strength, the field that minimizes the total energy density for $\alpha > 0.5$ is

$$B_{\rm min} \sim \left\{ \frac{6\pi c_1^{0.5} L(\nu_1)}{c_3 f_{\rm re} V_T \nu_1^{0.5}} \left[\frac{\gamma_1}{\gamma_{\rm co}(t_i)} \right]^{(2\alpha - 1)} \right\}^{2/7} . \tag{2a}$$

Consider a radio galaxy at a redshift of 1 with a 178 MHz flux density of 10 Jy, indicating a 178 $(1 + z)$ MHz radio luminosity of about $5 \times 10^{43}\ h^{-2}$ ergs s^{-1} for a deceleration parameter $q_o = 0$ and Hubble constant $H_o = 100\ h$ km s^{-1} Mpc^{-1}, and with a radio-emitting volume $V_T \sim \pi (15\ h^{-1}\ {\rm kpc})^2$ $(150\ h^{-1}$ kpc), which is typical for the radio bridges observed by Leahy et al. (1989). Assuming a radio spectral index $\alpha = 1$, the magnetic field strength that minimizes the energy or energy density of the field and relativistic electrons is

$$B_{\rm min} \sim 3 \times 10^{-5}\ {\rm G} \left\{ h f_{\rm re}^{-1} \left[\frac{\gamma_{\rm co}(t_i)}{100} \right]^{-1} \right\}^{2/7} . \tag{2b}$$

Thus the minimum-energy magnetic field has a very weak dependence on the volume filling factor of the relativistic electrons: $B \propto f_{\rm re}^{-2/7}$.

The Lorentz factor γ_1 of relativistic electrons that produce radio emission primarily at a frequency ν_1 can be estimated once the magnetic field strength has been estimated since $\gamma_1(\nu_1) \propto B^{-0.5}$. If the radio-emitting plasma occupies a fraction $f_{\rm re}$ of the available volume V_T, then $\gamma_1(\nu_1) \propto f_{\rm re}^{1/7}$. This dependence is extremely weak, which implies that the Lorentz factors estimated for relativistic electrons assuming $f_{\rm re} \sim 1$ is probably a good rough approximation. The relativistic electrons inverse Compton scatter microwave background photons to ultraviolet and X-ray energies; the energy to which a microwave photon is inverse Compton scattered depends on the Lorentz factor of the relativistic electron (as discussed in detail by Daly 1992a, b). Thus it is quite interesting and fortuitous that the estimated Lorentz factors of the relativistic electrons are very weakly dependent on the volume filling factor of the radio-emitting plasma.

As in § 2.1, the relationship between the rate $L_{\rm gas}$ at which energy is transferred from relativistic electrons to neutral ambient gas relative to the radio luminosity $L_r(\nu_1)$ at a frequency ν_1 produced by electrons with Lorentz factor γ_1 is

$$\frac{L_{\rm gas}}{L_r(\nu_1)} \simeq \left[\frac{4 \times 10^{-19} f_g n_g}{c_3 (m_e c^2)^2 \gamma_{\rm co}(t_i)^{2\alpha} \gamma_1^{2-2\alpha} B_\perp^2} \right] . \tag{3}$$

Using the minimum energy field given by equation (2b), equation (3) implies

$$\frac{L_{\rm gas}}{L_r(\nu_1)} \simeq 20 f_g n_g f_{\rm re}^{0.57} h^{-0.57} \left[\frac{\gamma_{\rm co}(t_i)}{100} \right]^{-1.43} \left(\frac{B_\perp}{B_{\rm min}} \right)^{-2} . \tag{4}$$

The observations suggest $L_{\rm lines} \sim L_r$, and in the model under consideration $L_{\rm lines} \sim L_{\rm gas}$, so the normalization of the observed relationship is obtained when the right-hand side of equation (4) is close to unity.

Observations of filamentary structure across the lobes of Cygnus A suggest a volume filling factor for the lobe material of between about 0.3 and 0.03 (Perley, Dreher, & Cowan 1984). When a volume filling factor close to unity is assumed, detailed observations of Cygnus A suggest that $B \simeq 0.3 B_{\rm min}$ (Carilli et al. 1991).

The radio lobes and bridges of high-redshift radio galaxies may be similar to the radio lobes of Cygnus A. Let us consider reasonable cases that tend to minimize and maximize the requisite average gas density. Equation (4) with $f_{\rm re} \sim 1$ and

$B \simeq 0.3B_{\min}$ implies $f_g n_g \sim (1/200)$, and equation (4) with $f_{re} \sim 10^{-2}$ and $B \simeq B_{\min}$ implies $f_g n_g \sim 0.6$. The minimum gas masses in a spherical volume with a 50 kpc radius about the radio galaxy implied by these average gas densities are about $6 \times 10^{10}\ M_{\odot}$ and $6 \times 10^{12}\ M_{\odot}$. This range of gas masses does not seem exceedingly large considering that the stellar masses of the high-redshift radio galaxies are estimated to be about $10^{12}\ M_{\odot}$ (Lilly 1990).

2.3. *Properties of the Gas*

Gas in the vicinity of the radio bridge may have been heated as the shock associated with the jet passed. If the gas in the radio bridge is in pressure equilibrium with the relativistic particles and magnetic field, then $nT \sim 10^5 f_{re}^{-0.57}$ K cm^{-3} (Daly 1992b). The gas within the radio bridge is likely to have a distribution of densities and temperatures since it is likely that the ambient medium is clumpy and the shocks associated with the propagation of the radio bridge interact with the low-density gas between higher density gas clumps (see Rees 1989 and Daly 1992b). It seems likely that in the postshock region (i.e., in the radio bridge) some regions will be in pressure equilibrium with the magnetic field and relativistic electrons while others will be out of pressure equilibrium.

The characteristic time scale for gas with density n_g and temperature T to cool due to thermal bremsstrahlung emission is $t \simeq 2 \times 10^3 n_g^{-1} T^{0.5}$ yr; cgs units are used. Thus, the cooling time is $t \lesssim 5 \times 10^5 f_{re}^{0.57}$ yr when $T \lesssim 10^5$ K for $nT \sim 10^5 f_{re}^{-0.57}$ K cm^{-3}, and in this case the cooling time is decreased by at least a factor of 10 due to line emission. It is the high-density gas ($n_g \gtrsim 0.1$ cm^{-3}) that will cool to relatively low temperatures ($T \lesssim 10^4$ K) in a relatively short time scale ($t \lesssim 5 \times 10^5$ yr), and it is the high-density gas that efficiently absorbs energy from relativistic electrons (see eqs. [1]) for a time on the order of the age of the radio source $\sim 10^6$–10^7 yr, or until most of the energy carried by the relatively low-energy relativistic electrons $\gamma \lesssim 500$ has been depleted.

Interactions between relativistic electrons and ambient gas heats the gas. When the gas temperature is low, less than about 10^4 K, the gas does not radiate efficiently and the total energy of the gas is $\sim L_{gas}\, t$. This implies a gas temperature of about $T \sim (2 \times 10^{-3}\ n_{re}\ t)$ K where n_{re} is the number density of relativistic electrons in units of cm^{-3}, and t is the time in seconds. The mean number density of relativistic electrons in the radio bridge is about $(10^{-6}$–$10^{-7}) f_{re}^{-1}$ cm^{-3} (Daly 1992b), suggesting the gas will reach a temperature of 10^4 K in about $(10^5$–$10^6) f_{re}$ yr. Whether the gas temperature continues to rise above this value depends on the rate of energy input to the gas L_{gas} relative to the rate at which energy is radiated in the form of line emission and thermal bremsstrahlung radiation. For $T \sim 10^4$ K, the energy emission rate exceeds the energy input rate when $n_g \gtrsim 5 \times 10^{-3} f_{re}^{-1}$ cm^{-3} for $n_{re} \sim 5 \times 10^{-7} f_{re}^{-1}$ cm^{-3}, assuming a standard cooling curve (e.g., Raymond, Cox, & Smith 1976). Thus, high-density gas, which may have been heated by the shocks associated with the propagation of the jet and radio lobe through the ambient medium, will cool rapidly to relatively low temperatures, will be heated to about 10^4 K by relativistic electrons in about $(10^5$–$10^6) f_{re}$ yr, and will not be heated to temperatures much greater than about 10^4 K because high-density gas radiates very efficiently via line emission. When the gas temperature reaches $\sim 10^4$ K, energy input to ambient gas by relativistic electrons will be radiated by the gas as line emission, with a total line luminosity about equal to the rate of energy input: $L_{lines} \sim L_{gas}$.

2.4. *Ultraviolet Radiation Fields*

The ratios of the equivalent widths of different emission lines is determined by the chemical composition of the gas, local ultraviolet and X-ray radiation fields, and local processes such as charge exchange (Osterbrock 1989). The emission-line regions of high-redshift radio galaxies are often quite extended, with sizes up to ~ 100 kpc, and the radio bridges and hence relativistic electrons are generally at least as extended as the emission-line regions.

Inverse Compton (IC) scattering of microwave background photons to ultraviolet energies will occur when the relativistic electron energy distribution extends to relatively low Lorentz factors: $\sim 150/\sqrt{1+z}$ (Daly 1992a, b). Microwave photons IC scattered by relativistic electrons with Lorentz factors of about 10^3 will be observed at an energy of about 1 keV independent of the redshift of the source, and the 178 $(1 + z)$ MHz radio emission by which many galaxies have been selected is produced by relativistic electrons with Lorentz factors of about 10^3 assuming a redshift of 1 for the source and a magnetic field strength on the order of the equipartition value. Other local sources of ultraviolet and X-ray radiation include thermal bremsstrahlung from gas heated by the shock associated with the propagation of the radio bridge through the medium, ultraviolet radiation from hot stars, and, as discussed by van Breugel & McCarthy (1990), anisotropic radiation from the AGN.

Interactions between relativistic electrons and ambient gas heats the gas and cools the relativistic electrons. These interactions will produce a population of relatively low-energy relativistic electrons if such a population is not present initially. This suggests that when interactions between relativistic electrons and the ambient gas transfer a significant amount of energy to the gas, a local ultraviolet radiation field will be produced as a result of IC scattering of microwave background photons by the relatively low-energy relativistic electrons.

The luminosity of IC scattered microwave background photons by relativistic electrons with total number $N(E)$ and Lorentz factor $\gamma \equiv E/(m_e c^2)$ is $L_{IC} \simeq 1.2 \times 10^{-26}\ \gamma^2\ (1+z)^4\ N(E)$ ergs s^{-1} (Moffet 1975); hence

$$\frac{L_{gas}}{L_{IC}} \sim 3 \times 10^7 f_g n_g \gamma^{(2\alpha-2)} \gamma_{co}(t_i)^{-2\alpha} (1+z)^{-4} \text{ ergs s}^{-1} . \quad (5)$$

Equation (5) is identical to equation (1b) when $\epsilon \sim 1$, that is, when the energy density of the magnetic field and relativistic electrons of the radio source is comparable to the energy density of the microwave background radiation at the redshift of the source, in which case $L_{IC} \simeq L_r$. It is a peculiar fact that equipartition field strengths of high-redshift ($z \gtrsim 1$) radio galaxies indicate energy densities comparable to that of the microwave background radiation at the redshift of the galaxy (e.g., Leahy et al. 1989). Thus, high-redshift radio galaxies with $u_r \sim u_{mb}$ will have $L_{IC} \simeq L_r$, and since $L_{lines} \sim L_r$ in many high-redshift radio galaxies, $L_{IC} \sim L_{lines}$ is expected.

The low-energy rollover or cutoff of the relativistic electron energy distribution determines the low-energy rollover or cutoff of the IC scattered light. Relativistic electrons with Lorentz factors of about 10^3 IC scatter microwave photons to an energy of about $(1 + z)$ keV at the source. Optical and ultraviolet continuum in the observer's rest frame will be produced if the relativistic electron energy distribution extends to Lorentz factors of ~ 50–100 (Daly 1992b, § 4). Thus, if the relativistic electron energy distribution extends to these relatively low energies $L_{IC} \sim L_r$ is expected at optical and ultraviolet frequencies, and for the cases where $L_{lines} \sim L_r$, it is expected that $L_{IC} \sim L_{lines}$. Note that the line emission may be powered by ultraviolet radiation produced by IC scattering if the cloud covering factor is on the order of 1 (Daly 1992a, b).

These relationships seem to be supported by observations of high-redshift radio galaxies. For example, 3 CR radio galaxies with redshifts greater than about 0.7 have optical luminosities $L_{opt} \propto L_r$ and $L_{opt} \sim L_r$ (E. J. Groth 1992, private communication), though this may be a redshift effect. It would be very helpful to know whether the optical continuum luminosities are proportional to the line luminosities in distant radio galaxies, whether $L_{opt} \sim L_{lines} \sim L_r$, and whether the correlation between the optical continuum and radio luminosities is an intrinsic effect or a redshift effect.

3. CONCLUSIONS

The optical continuum and emission-line regions of high-redshift radio galaxies are clumpy, elongated, and aligned with the radio axis (Chambers et al. 1987; McCarthy et al. 1987), and the emission-line luminosity is roughly proportional to the radio power (e.g., McCarthy et al. 1991). In addition, the constant of proportionality suggests that $L_{lines} \sim L_r$ where $L_r \simeq \nu_r P_r$ (Daly 1992b).

Radio emission from radio galaxies implies a significant amount of energy in the form of relativistic electrons. Energy will be transferred from relativistic electrons to ambient gas due to the ionization of neutral gas and Cherenkov emission of plasma waves, as discussed in § 2.1. These interactions cool the relativistic electrons and heat the dense ambient gas, which then radiates line emission. Cool, dense gas in contact with relativistic electrons effectively transfers energy from the relativistic electrons to line emission: the relativistic electrons heat the gas to temperatures $\sim 10^4$ K, which then remains at this temperature radiating line emission as it is continually heated by relativistic electrons. When relativistic electrons are the primary energy source powering the line emission, the emission-line luminosity is expected to be proportional to the radio power, as discussed in § 2.1.

The observed normalization between the line luminosity and the radio power is obtained for average gas densities of about $5 \times (10^{-3}$ to $10^{-1})$ cm^{-3}, indicating gas masses within a spherical volume with a 50 kpc radius about the radio galaxy of about $5 \times (10^{10}$ to $10^{12})$ $M_\odot$. These masses do not seem excessively large considering the stellar masses of high-redshift radio galaxies are estimated to be about 10^{12} $M_\odot$ (e.g., Lilly 1990).

It is interesting to note that interactions between relativistic electrons and gas not only heat the gas but also cool the relativistic electrons. Relatively cool relativistic electrons inverse Compton scattering microwave background photons to optical and ultraviolet wavelengths (e.g., Daly 1992a, b). This suggests that when interactions between relativistic electrons and gas are significant, both line emission from the gas and optical and ultraviolet continuum from IC scattered light will be important.

As discussed in § 2.1, interactions between relativistic electrons and dense ambient gas could cause the low-frequency flattening of the radio emission seen in the hotspots of Cygnus A.

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