MORPHOLOGICAL PECULIARITIES OF HIGH-REDSHIFT RADIO GALAXIES: THE ROLE OF RELATIVISTIC ELECTRONS

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ABSTRACT

High-redshift radio galaxies are very powerful, extended, double radio sources; the radio emission from these systems indicates that the relativistic electrons have a significant amount of energy. The peculiar morphologies of high-redshift radio galaxies appear to be related to the relativistic electron populations since the optical continuum and emission-line regions are elongated and aligned with the radio axes. A close connection with the relativistic electron population is also indicated by the relationships between the radio power and the emission-line luminosity and between the radio spectral index and the optical to near-infrared colors of these systems.

Five models (two new and three previously proposed) to explain the peculiar optical and emission-line morphologies of high-redshift radio galaxies are discussed in detail here: the inverse Compton scattering model, bremsstrahlung and the line emission from clumped hot gas, jet-induced star formation, Thomson scattering of anisotropic light emitted by the AGNs, and optical synchrotron radiation are considered; the models are summarized in § 10. Relativistic electrons are likely to play an important role in the optical and emission-line properties of high-redshift radio galaxies via interactions between the relativistic electrons and the ambient gas, and via inverse Compton scattering of microwave background photons with the relativistic electrons. In addition, the environments of the radio galaxies and constraints on the orientation unified model for radio galaxies and radio-loud quasars are discussed.

Subject headings: galaxies: evolution — radiation mechanisms: Compton and inverse Compton — radiation mechanisms: thermal — radio continuum: galaxies

1. INTRODUCTION

Radio galaxies have been detected out to redshifts of about four; to date optical and emission-line observations of about 200 radio galaxies with redshifts greater than one have been obtained. Radio galaxies with redshifts greater than about 0.7 have peculiar optical and emission-line properties: these regions are quite extended (between about 25 and 100 kpc along the major axis), clumpy, elongated, and tend to be aligned with the axis defined by the positions of the radio hot spots, which straddle the galaxy with typical separations on the order of a hundred kpc; this is referred to as the alignment effect (Chambers, Miley, & van Breugel 1987; McCarthy et al. 1987b; Djorgovski et al. 1987). The optical continuum and emission-line morphologies are generally quite similar.

Inspection of the images suggests that there are two types of alignments. In the first type, local maxima in the radio emission are close to or coincident with local maxima in the optical continuum and emission-line regions. An example of this type of alignment is 3C 368 (see the radio, emission-line, and optical maps of Djorgovski et al. 1987; Chambers, Miley, & Joyce 1988; and Le Fevre, Hammer, & Jones 1988). In the case of 3C 368 the optical continuum and emission-line regions are as extended as the radio hot spots; the primary characteristic of this first type of source is that radio maxima are close to the maxima seen in the optical continuum and emission-line maps, hence there may be other local maxima in the radio map not present in the emission-line and optical continuum maps. The second type of source are those for which the optical continuum and emission-line regions do not track the radio structure; although these regions are elongated and aligned with the radio axis, local maxima in the radio emission are not close to or coincident with the local maxima in the optical continuum

and emission-line maps. These sources are more difficult to identify since detailed radio maps are not available for all of the sources. For example, consider the radio galaxy 3C 68.2 which has a redshift of 1.6. The optical continuum is quite extended, being about 50 h^{-1} kpc along the major axis, clumpy, and aligned with the radio axis (LeFevre & Hammer 1988), while the radio hot spots are separated by about 150 h^{-1} kpc (Leahy, Muxlow, & Stephens 1989). Radio maxima do not appear in the vicinity of the emission-line and optical continuum maxima, and it remains to be determined whether such maxima will appear when radio observations to fainter flux levels are obtained.

The near-infrared morphologies of high-redshift radio galaxies are far less peculiar than the optical and emission-line properties of these systems. The near-infrared morphologies tend to be much more regular than those in the optical in the sense that they are more compact (Rigler et al. 1991; Eisenhardt & Chokshi 1990), and only a small fraction of the near-infrared emission is aligned with the radio axis (Rigler et al. 1992). In addition, the near-infrared magnitudes of the galaxies define a locus of points on the near-infrared Hubble diagram which exhibits remarkably small scatter at a given redshift, and remarkable continuity with redshift (Lilly & Longair 1984; Spinrad & Djorgovski 1987; Lilly 1989, 1990).

There is a simple interpretation of the facts that the galaxies describe a well-defined region on the K-band Hubble diagram, have relatively compact and normal K-band morphologies, yet exhibit a wide range of colors and have markedly peculiar optical and emission-line morphologies: these observations suggest that there is an old underlying galaxy with light superposed upon it associated with the radio activity (e.g., Lilly & Longair 1984; Lilly 1990). The K-band properties suggest that

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most of this light is produced by stars with a well-defined total stellar mass and stellar initial mass function, and that at any given redshift all of the galaxies have basically the same age, as discussed in detail by Lilly (1989, 1990). This indicates that the stellar populations in these systems are old and mature, and most likely formed at redshifts much larger than the redshifts at which the systems are observed.

Therefore, the present data favor the "old galaxy plus burst" model (Lilly 1990; Rigler et al. 1992), where the "burst" is associated with the radio activity. This model is strongly suggested by the properties of the K-band Hubble diagram and is supported by the near-infrared morphologies of these systems.

The extended optical continuum and line emission are likely to be produced by processes associated with the radio activity (or associated optical nuclear activity) since these regions tend to be aligned with the radio axis, and since there is a correlation between the emission-line luminosity and the radio power (McCarthy 1991; McCarthy et al. 1991), and between the radio spectral index and the optical to near-infrared colors of the galaxies (Lilly 1989). Nonstellar processes that are likely to be important in high-redshift radio galaxies include inverse Compton scattering of microwave background photons with relativistic electrons (Daly 1992a), interactions between the relativistic electrons and the ambient gas (this paper; Daly 1992c), thermal bremsstrahlung emission from clumped hot gas (this paper), Thomson scattering of anisotropic radiation from the AGN (Fabian 1989), and optical synchrotron radiation (this paper).

The aligned emission-line regions will result if there is a local source of ultraviolet radiation along the radio axis, since the ultraviolet radiation will ionize the hydrogen and power the emission lines. The gas could also be ionized directly by interactions between the relativistic electrons and the gas in the emission-line clouds, as discussed here in § 2 and by Daly (1992c).

The properties of the relativistic electrons and the effects of interactions between the relativistic electrons and the ambient gas are presented and discussed in § 2. A new model to explain the alignments, discussed in part by Daly (1992c), is presented and discussed in § 3; in this model the alignments are associated with continuum and line emission from clumped hot gas. The details of the inverse Compton scattering model, proposed by Daly (1992a), are discussed in § 4. The jet-induced star formation model, proposed and discussed by several authors (Rees 1989; De Young 1989; Begelman & Cioffi 1989; Daly 1990; Bithell & Rees 1990), is discussed in § 5. The model in which the alignments are associated with Thomson scattering of anisotropic radiation emitted by the AGN, suggested by Fabian (1989) and di Serego Alighieri et al. (1989), is discussed and extended in § 6. The implications of the properties of high-redshift radio galaxies for the orientation unified model for radio galaxies and radio-loud quasars are discussed in § 7. Optical synchrotron radiation is presented and discussed in § 8. The environments of the galaxies and their relation to the formation of clusters of galaxies are discussed in § 9. A discussion of each model follows in § 10, and conclusions are drawn in § 11.

2. THE RELATIVISTIC ELECTRON POPULATION

The properties of the relativistic electron population can be estimated from the radio properties of the radio bridges and hot spots. The total number of relativistic electrons in the radio bridge of a typical radio galaxy at a redshift of 1 is estimated in

§ 2.1. This is used to estimate the characteristic pressure and number density of relativistic electrons in a radio bridge; these numbers are relevant for the transfer of energy from the relativistic electrons to the ambient nonrelativistic gas (discussed in § 2.3), and for the luminosity density of radiation produced by inverse Compton (IC) scattering of microwave background photons by the relativistic electrons.

The total energy and equivalent rest mass carried by the relativistic electrons are discussed in § 2.2. The active nucleus probably increased in mass by at least the equivalent rest mass carried by the relativistic electrons in the radio bridge, since the active nucleus is the ultimate energy source of the large-scale jets that constitute the energy source of the relativistic electrons (as discussed in § 4). The time scale for which the outburst has been ongoing can be estimated from the aging of the relativistic electrons in a radio bridge. The rate at which energy is being input to the relativistic electrons $L_{in,rel}$ can be estimated by dividing the total energy in the relativistic electrons by the time scale for which the outburst has been ongoing; this is done in § 2.2. The large-scale jets carry an energy per unit time L_{dKE} in the form of directed kinetic energy from the nuclear region to the radio hotspots. Some fraction of this energy goes into shock heating and accelerating the ambient gas, and some fraction goes into the relativistic electrons, thus $L_{dKE} > L_{in,rel}$. These luminosities are interestingly close to the limit on the bolometric luminosity L_{phot} emitted in the form of radiation by the AGN (Daly 1992b), suggesting that in these radio galaxies the AGN releases at least as much energy in the form of directed kinetic energy as in the form of radiation. In § 2.2 the relationship between L_{dKE} and the ambient gas density is explored; reasonable upper bounds on L_{dKE} lead to upper bounds on the gas density of the ambient medium. The implications for the properties of the ambient medium are discussed.

Interactions between the relativistic electrons and the ambient gas are discussed in § 2.3; such interactions cool the relativistic electrons and heat and ionize the ambient gas, and may prove to be an interesting energy source to power the emission lines (§ 3 and Daly 1992c). The rate at which energy is transferred from the relativistic electrons to the ambient gas is estimated in § 2.3. The energy is radiated by the gas in the from of continuum and line emission, and the expected continuum and line luminosities are estimated. Interactions between the relativistic electrons and the ambient gas may cool the relativistic electrons to energies where IC scattering with microwave background photons will produce optical and ultraviolet continuum, thus emission from the gas heated by the relativistic electrons (discussed in detail in § 3) may be accompanied by light produced by inverse Compton scattering between microwave background photons and the relatively cool relativistic electrons (discussed in detail in § 4).

2.1. Total Number of Relativistic Electrons

The total number of relativistic electrons with energy $E_1 = \gamma_1 m_e c^2$ is $N(E_1)$. The energy per unit time emitted by an electron with energy γ_1 via synchrotron radiation is $dE_1/dt \simeq 1.6 \times 10^{-25} \gamma_1^2 b^2$ ergs s^{-1} for a magnetic field strength perpendicular to the direction of propagation of the electron $B_\perp \equiv 10^{-5}b$ G, and $dE_1/dt \simeq 1.7 \times 10^{-26} \epsilon^2 \gamma_1^2 (1 + z)^4$ ergs s^{-1} for a magnetic field strength parameterized in terms of ϵ and the energy density u_{mb} of the microwave background radiation, $B_\perp^2/(8\pi) = \epsilon^2 u_{mb}$ (see § 4.1). Both parameterizations give a rea-

sonable fit to typical equipartition fields of high-redshift radio galaxies (e.g., Leahy et al. 1989).

The total luminosity emitted by relativistic electrons with energy E_1 is $L(E_1) = N(E_1)dE_1/dt$. Consider a source at a redshift of 1. The $178(1 + z)$ MHz radiation observed from this source is produced by electrons with Lorentz factor $\gamma_1 \simeq 2.6 \times 10^3 \epsilon^{-0.5}$ (see eq. [4]). In an open universe with deceleration parameter $q_0 = 0$ and Hubble constant $H_0 = 100$ km s^{-1} $M_{\rm pc}^{-1}$ the intrinsic luminosity $L(E_1) \simeq L_\nu \nu$ of a source with an observed flux density of about $10r$ Jy is $L(E_1) \simeq 5 \times 10^{43} rh^{-2}$ ergs s^{-1}. This implies that the total number of relativistic electrons producing the $178(1 + z)$ MHz radiation from a source at a redshift of about 1 is $N(E_1) \simeq 2 \times 10^{61} rh^{-2} \epsilon^{-1}$.

The electron energy distribution extends to lower energies. Suppose that the electron energy distribution extends to an energy $\gamma_{\rm co}$. The total number of relativistic electrons scales as $\gamma_{\rm co}^{-2}$ for $\alpha \sim 1$ because the total number of electrons with energy E_* is $N(E_*) = NV\gamma_*^{-2\alpha}/(2\alpha)$ where N is the normalization of the distribution of Lorentz factors of the electrons (see § 4.3.1).

This implies that, for $\gamma_{\rm co} \sim 100$, the total number of relativistic electrons is $N(\gamma_{\rm co} \sim 100) \sim 2 \times 10^{64} \epsilon^{-2} rh^{-2}$ for $\alpha \sim 1$. The number density of the relativistic electrons can be estimated by dividing by the volume they inhabit. The radio bridges are well approximated by cylinders, with full widths that are remarkably similar and are generally 30 h^{-1} kpc (Leahy et al. 1989), or about 15 h^{-1} kpc in radius. Most of the radio emission contributing to the luminosity estimated above comes from a region that has a volume of about $\pi(15\ h^{-1}$ kpc)^3. This implies a number density of relativistic electrons in this region with $\gamma \sim 100$ of about $5 \times 10^{-5} \epsilon^{-2} hr$ cm^{-3}. An estimate of the number density of relativistic electrons in the radio bridge is obtained by using the full volume of the cylindrical bridge; a volume of about $\pi(15\ h^{-1}$ kpc)^2 (150 h^{-1} kpc) is obtained when the length of the bridge is roughly 150 h^{-1} kpc. This implies a density of electrons with $\gamma \sim 100$ of about $5 \times 10^{-6} \epsilon^{-2} rh$ cm^{-3}.

The total pressure or energy density in relativistic electrons and magnetic field in the radio bridge is $P = \frac{1}{3}(B^2/[8\pi] + \gamma_{\rm co} n[\gamma_{\rm co}][m_e c^2])$. Hence,

$$P \simeq \tfrac{1}{3}\left[7 \times 10^{-12}\epsilon^2 + 4 \times 10^{-10} hr\epsilon^{-2}\left(\frac{\gamma_{\rm co}}{100}\right)^{-1} \right] \text{ergs cm}^{-3} .$$
(1)

With $r \sim 1$ and $h \sim 1$, the total pressure is minimized for $\epsilon \sim 2.7$, in which case the magnetic field strength is about 35 μG, and the number density of relativistic electrons in the radio bridge with $\gamma \simeq 100$ is about $n \sim 7 \times 10^{-7}$ cm^{-3}.

The number and number density of relativistic electrons with $\gamma \sim \gamma_{\rm co}$ are important both for the flux density of the IC scattered light (see § 4) and for heating the gas via interactions between the relativistic electrons and the ambient gas (see § 2.3 and 3), since these processes depend on the number and number densities of relativistic electrons most of which have low energies. As a result, both processes lead to larger luminosities of the optical and ultraviolet continuum and of the line emission when the energy density in relativistic electrons exceeds the magnetic energy density, that is, when $\epsilon \lesssim 2.7$.

2.2. *Energy Input to the Relativistic Electrons*

Large-scale jets carry an energy per unit time $L_{\rm dKE}$ in the form of directed kinetic energy from the active nucleus to the radio hot spots. This energy goes into shock heating and accelerating the ambient nonrelativistic gas, and into the relativistic electrons and magnetic fields. Some fraction of this energy is input to the relativistic electrons; the energy per unit time input to the relativistic electrons is denoted $L_{\rm in, rel}$.

In this section the total energy in the relativistic electrons and the equivalent rest mass are estimated. The bounds on and estimates of the age of the radio source and the total energy carried by the relativistic electrons are used to bound and estimate $L_{\rm in, rel}$, since $L_{\rm in, rel}$ is roughly the total energy in the relativistic electrons divided by the time scale for which the radio activity has been ongoing. The properties of the radio bridges are used to estimate the relationship between the luminosity in directed kinetic energy $L_{\rm dKE}$ and the ambient (nonrelativistic) gas density; upper bounds on the ambient gas density are discussed, and the implications for the properties of the ambient medium are addressed.

The total energy in relativistic electrons with energy E_1 is $E_{\rm tot}(E_1) = m_e c^2 \gamma_1 N(E_1)$, and the total equivalent rest mass is $M_{\rm tot}(E_1) = E_{\rm tot}(E_1)c^{-2} = m_e \gamma_1 N(E_1)$. Since the number of electrons with energy E scales as $\gamma^{-2\alpha}$ (for $\alpha > 0$), the total energy and rest mass in relativistic electrons with Lorentz factor γ scale as $\gamma^{-2\alpha+1}$ (for $\alpha > 0.5$); for $\alpha \sim 1$, characteristic of high-redshift radio galaxies, $M_{\rm tot}(\gamma) \propto E_{\rm tot}(\gamma) \propto \gamma^{-1}$. Hence, the equivalent rest mass associated with electrons with Lorentz factor γ is $M_{\rm tot}(\gamma) = (\gamma_1/\gamma)m_e \gamma_1 N(E_1)$. Using $\gamma_1 \sim 3 \times 10^3 \epsilon^{-0.5}$ relevant for the production of the $178(1 + z)$ MHz emission, the rest mass associated with electrons with $\gamma \sim 100$ is $M_{\rm tot}(\gamma \sim 100) \sim 7 \times 10^5 rh^{-2}\epsilon^{-2}$ $M_\odot$, assuming the radio source is at a redshift of one and has an observed 178 MHz flux density of $10r$ Jy; for $\epsilon \sim 2.7$, $M_{\rm tot}(\gamma \sim 100) \sim 10^5 rh^{-2}$ $M_\odot$.

The total energy in relativistic electrons is $E_{\rm tot} = M_{\rm tot} c^2$, or $E_{\rm tot} \sim 10^{60} rh^{-2}\epsilon^{-2}$ ergs for $\gamma \sim 100$ and $\alpha \sim 1$. The properties of the radio bridges have been used to deduce an age for the radio source and to estimate the velocity of propagation of the hot spot v_h through the ambient medium (Leahy et al. 1989). The radio sources have maximum ages of about 10^7 yr, and estimated-radio-source lifetimes of about 5×10^6 yr; the velocities of propagation through the ambient medium are about $0.1c$ for radio source ages of about 5×10^6 yr; that is, the velocity of propagation through the ambient medium is about $0.05t_7^{-1}c$, for a radio source age of $10^7 t_7$ yr. As discussed by Leahy et al. (1989), these ages are upper bounds; several cooling mechanisms may be operating all of which tend to decrease these estimated ages.

The energy per unit time input to the relativistic electrons $L_{\rm in, rel}$ can be estimated by dividing the total energy in the relativistic electrons by the time scale for which the radio activity has been ongoing. For an age of $t_j = 10^7 t_7$ yr for the current burst of radio activity, the luminosity input to the relativistic electrons must be about $L_{\rm in, rel} \sim E_{\rm tot}/t_j \sim 4 \times 10^{45} rh^{-2} t_7^{-1}\epsilon^{-2}$ ergs s^{-1}, or $L_{\rm in, rel} \sim 10^{45}$ ergs s^{-1} for $t_7 \sim 0.5, \epsilon \sim 2.7, r \sim 1$, and $h \sim 1$.

This is an extremely interesting number. First, this implies that $L_{\rm dKE} \gtrsim 10^{45}$ ergs s^{-1}, the Eddington luminosity of a 10^7 $M_\odot$ black hole, since $L_{\rm dKE} > L_{\rm in, rel}$. Second, this is on the order of the upper bound on the bolometric luminosity of light emitted anisotropically by the AGN (Daly 1992b). The limit on the luminosity of radiation detected directly from the AGN is about 10^{44} ergs s^{-1}. If the light is emitted anisotropically into a cone that does not intersect our line of sight, the properties of the radio bridges can be used to place an upper bound on the bolometric luminosity of the anisotropic radiation since this

light will inverse Compton cool the relativistic electrons in the radio bridge (Daly 1992b); this limit is $L_{phot}(AGN) \lesssim 5 \times 10^{46}$ ergs s^{-1}. This implies that the AGN is putting out a significant fraction of its energy in the form of directed kinetic energy.

The luminosity in directed kinetic energy L_{dKE} goes into shock heating and accelerating the gas and into accelerating the relativistic electrons. Let the pressure of the shock-heated gas be P_g, and the pressure of the relativistic electrons and magnetic field, estimated by using $B_{min}^2/(24\pi)$, be P_{rel}. It is interesting to estimate the relative values of P_{rel} and P_g for given values of the ambient gas density since, very roughly, $P_{rel}/(P_g + P_{rel}) \sim L_{in,rel}/L_{dKE}$.

The minimum energy magnetic field for a radio galaxy with a redshift of about 1 is estimated in § 2.1 and is about 35 μG, indicating a pressure of 10^{-11} ergs cm^{-3} or a density times a temperature of $nT \simeq 10^5$ cm^{-3} K. The mean velocity with which the head of the radio bridge propagates through the ambient medium v_h is typically about $0.1c$ for $t_j \sim 5 \times 10^6$ yr which is indicated by the synchrotron and inverse Compton aging of the relativistic electrons in the radio bridge. This implies a postshock temperature for the protons of about $10^{10}v_{-1}^2$ K, where $v_h \equiv 0.1v_{-1}c$, and a similar temperature for the electrons if the two are in thermal equilibrium. Therefore, if $P_g \sim P_{rel}$, the density of the shock-heated gas is about $10^{-5}v_{-1}^{-2}$ cm^{-3}. Note that the strong shock jump conditions imply that the postshock density will be about 4 times larger than the preshock gas density: to be conservative this factor is not included below. If $P_g \sim P_{rel}$ the ambient gas density is very low $n_a \sim 10^{-5}v_{-1}^{-2}$ cm^{-3}. Observations of the aging of the relativistic electrons suggest that $t_7 \lesssim 1$, which implies that $v_{-1} \gtrsim 0.5$, and $v_{-1} \gtrsim 0.5$ suggests that $n_a \lesssim 4 \times 10^{-5}$ cm^{-3} for $P_g \sim P_{rel}$.

If the luminosity in directed kinetic energy satisfies $L_{dKE} \lesssim 10^{47}$ ergs s^{-1}, then the ambient gas density must be $n_a \lesssim 10^{-3}v_{-1}^{-3}$ cm^{-3} since $P_g/P_{rel} \sim L_{dKE}/L_{rel,in}$ and $L_{rel,in} \sim 10^{45}v_{-1}$ ergs s^{-1}. Thus, if $v_{-1} \sim 0.5$ and $L_{dKE} \lesssim 10^{47}$ ergs s^{-1} then $n_a \lesssim 10^{-2}$ cm^{-3}, while $L_{dKE} \lesssim 10^{46}$ ergs s^{-1} implies that $n_a \lesssim 10^{-3}$ cm^{-3} for $v_{-1} \sim 0.5$, and $n_a \lesssim 10^{-4}$ cm^{-3} for $v_{-1} \sim 1$. This suggests that a fairly firm upper bound on the density of the ambient medium is $n_a \lesssim 10^{-2}$ cm^{-3} with a more likely value of less than about 10^{-3} to 10^{-4} cm^{-3}.

The luminosity in directed kinetic energy L_{dKE} is related to the velocity of propagation of the head of the radio bridge through the ambient medium v_h, the area of the head A_h, and the ambient gas density n_a. It also depends on the jet velocity v_j since it is likely that the interaction region between the jet and the ambient medium is small compared to the width of the head, hence $L_{dKE} \simeq \rho_a A_h v_h^2 v_j$ (Begelman & Cioffi 1989). Several of these variables can be estimated from the observations of Leahy et al. (1989): $A_h \simeq \pi(15\ h^{-1}\ kpc)^2$, $v_h \sim 0.1c$ for $t_7 = 0.5$, and $v_j \sim c$. This implies that $L_{dKE} \sim 3 \times 10^{46}v_{-1}^2 h^{-2} (n_a/10^{-5})$ ergs s^{-1}.

An estimate of the ambient gas density arises by considering the relationship between L_{dKE} and the ambient gas density. It would be surprising if the luminosity in directed kinetic energy is larger than 10^{47} ergs s^{-1}, which implies that the ambient gas density in the vicinity of the radio galaxies is quite low: $n_a \lesssim 3 \times 10^{-5}$ for $v_{-1} \sim 1$ and $n_a \lesssim 10^{-4}$ cm^{-3} for $v_{-1} \sim 0.5$.

The aligned optical continuum and emission-line regions suggest that a significant gas mass is located in the vicinity of the radio galaxy; most of the models to explain the aligned optical continuum require ambient gas, but the gas may be quite clumpy. The low gas densities implied by properties of the radio bridges suggest that the gas in the vicinity of the

radio galaxy is quite clumpy, and the shock (associated with the propagation of the jet through the ambient medium) is interacting with low-density gas between gas clumps, as is the case for the interstellar medium (McKee & Cowie 1975). Therefore, if the high redshift radio galaxies are in clusters or protoclusters of galaxies, the intracluster medium is not yet in place, but is quite clumpy. This is also suggested by depolarization observations of distant radio sources (Pedelty et al. 1989). This leaves open the question of what is confining the radio bridges which have typical minimum pressures equivalent to $nT \simeq 10^5$ K cm^{-3} at a redshift of about 1.

One possibility is that the gas is mixed with the magnetic field and relativistic electrons. In this case the inertia of the gas will confine the radio bridge, since the gas in the bridge (plus the frozen in magnetic field and relativistic particles) will expand at the sound speed of the gas, which may be quite low, $\sim 10^2$–10^3 km s^{-1}. A closely related mechanism for confining the jets is discussed by Begelman & Cioffi (1989).

2.3. Interactions between Relativistic Electrons and the Ambient Gas

Interactions between relativistic electrons and the ambient gas will be important throughout the radio bridge if the two are mixed, or in the boundary layer between the two if they are not mixed. This process is discussed in the context of active galactic nuclei by Ferland & Mushotzky (1984) and Daly (1992c). The Larmor radii of the relativistic electrons are quite small and hence will be mixed with the ambient gas if the magnetic field threads the gas. It will be assumed for the present that the gas and relativistic electrons are mixed; the results are easily generalized if the interaction occurs in a boundary layer between the gas and relativistic electrons. In addition, collective effects, such as those discussed by Scott et al. (1980) and considered by Ferland & Mushotsky (1984), may significantly increase the rate of energy transfer from the relativistic electrons to the gas; the transfer rates discussed here neglect strong collective effects and thus are conservative estimates of the actual transfer rates, being the minimal transfer rates.

The relativistic electrons will interact with the ambient nonrelativistic gas (see, e.g., Pacholczyk 1970 § 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. The energy loss rate per relativistic electron is about $9 \times 10^{-19}n_g$ ergs s^{-1} for interactions with ionized gas and is about a factor of 2 smaller for interactions with neutral gas, where n_g is the ambient gas density in the radio bridge in units of cm^{-3}. Hence, the cooling rate of the electrons due to these interactions with the ambient gas are more important than synchrotron or inverse Compton losses when $\gamma \lesssim 10^4 (n_g)^{1/2}(1+z)^{-2}$ min $(1, \epsilon^{-1})$; when inverse Compton losses dominate min $(1, \epsilon^{-1}) = 1$, and when synchrotron losses dominate min $(1, \epsilon^{-1}) = \epsilon^{-1}$ (see § 2.1 for the relationship between the magnetic field strength and ϵ). The final Lorentz factor γ_f, in terms of the initial Lorentz factor γ_i when the gas is ionized is $\gamma_f \simeq \gamma_i - (3.5 \times 10^{-5}n_g[t/yr])$, hence $\gamma_f \simeq \gamma_i - 350n_g t_7$ yr for interactions with ionized gas, and $\gamma_f \simeq \gamma_i - 170n_g t_7$ for interactions with neutral gas. The cooling time for interactions with ionized gas is about $3 \times 10^4 \gamma_i n_g^{-1}$ yr, and that for interactions with neutral gas is a factor of 2 larger.

Hence, ionization and Cherenkov losses primarily affect the low-energy tail of the electron energy distribution; that is,

$(\delta\gamma)/\gamma \sim 1$ for $\gamma_i \lesssim 700 n_g t_7$. This cooling mechanism flattens the low-energy end of the electron energy distribution. For $n_g \sim$ few, the electrons that begin with $\gamma_i \lesssim 700$ will be cooled and will form a flattened electron energy distribution, with the edge of the plateau moving to lower energies with time. The electrons that have $\gamma_i \gtrsim 700$ will not be significantly affected by this cooling mechanism unless n_g is quite large. When the cooled electrons IC scatter microwave photons to near-infrared, optical, and ultraviolet energies, the spectrum of the upscattered light will be flatter than that of the radio emission produced by the electrons with $\gamma \sim 10^3$, reflecting the flattened electron energy distribution; recall that the spectral index of the IC scattered light is identical to that of the synchrotron emission produced by these same relativistic electrons.

Losses due to interactions with the ambient nuclei, such as those due to free-free radiation, are proportional to the Lorentz factor of the relativistic electron. In this case the energy loss rate is roughly the same for interactions with ionized and neutral ambient gas. The energy loss rate of a relativistic electron with a Lorentz factor γ is about $6 \times 10^{-22} n_g \gamma$ ergs s^{-1}. This energy loss rate exceeds synchrotron and inverse Compton losses for $\gamma \lesssim 3 \times 10^4 n_g (1 + z)^{-4}$ min $(1, \epsilon^{-2})$, where min $(1, \epsilon^{-2}) = 1$ when inverse Compton losses dominate. The final Lorentz factor γ_f, in terms of the initial Lorentz factor γ_i is $\gamma_f \simeq \gamma_i e^{-kt}$, where $kt \simeq 0.2 n_g t_7$.

The energy loss rate per relativistic electron due to ionization losses and Cherenkov emission of plasma waves exceeds that due to free-free radiation for $\gamma \lesssim 2 \times 10^3$. It is expected that the initial electron energy distribution will extend to Lorentz factors of about 100–200; a rough estimate of about 225 is suggested for the lobes of Cygnus A since a cutoff at about 450 is inferred for the hot spots of this source, and it appears that the expansion from the hot spot to the lobe (see § 4.3.1) is about a factor of 2 (Carilli et al. 1991). The electrons near the low-energy cutoff carry most of the energy of the relativistic electron population for $\alpha > 0.5$; since $E_{tot} \propto \gamma^{-2\alpha + 1}$ (see § 2.2), so $E_{tot} \propto \gamma^{-1}$ for $\alpha \sim 1$.

Interactions between the ambient gas and the relativistic electrons near the low-energy cutoff of the electron energy distribution have two important effects. First, it is a mechanism that will cool relativistic electrons from Lorentz factors of ~ 200–300 to Lorentz factors of ~ 50–100 in relatively short time scales $t \sim 5 \times 10^6$ yr for $n_g \sim 1$ cm^{-3}; these electrons will then inverse Compton scatter microwave photons to optical and/or ultraviolet energies, as discussed in § 4. Second, these interactions heat the ambient gas, which will then produce line emission and near-infrared and optical continuum.

The energy loss rate due to ionization losses and Cherenkov emission of plasma waves dominates for $\gamma \lesssim 2 \times 10^3$, hence this energy loss rate is the most interesting for the transfer of energy from the relativistic electrons to the gas, and for the cooling of the relativistic electrons to energies where inverse Compton scattering is important. The total energy transferred to the ambient (ionized) gas per unit time is $dE/dt \simeq 9 \times 10^{-19} n_g fN(E)$ ergs s^{-1}, where $fN(E)$ is the total number of relativistic electrons with an energy E, that is mixed with the gas with density n_g. Using the expression for $N(E)$ obtained in § 2.1, the relativistic electrons will lose energy to the ambient gas at a rate of

$$\frac{dE}{dt} \simeq 1.5 \times 10^{46} n_g f\epsilon^{-2} rh^{-2} \left[\frac{\gamma_{co}(t_i)}{100}\right]^{-2} \text{ ergs s}^{-1}, \quad (2)$$

where f is the volume filling factor of the regions with gas density n_g mixed with the relativistic electrons. Note that this is a lower bound on the energy transfer rate since collective effects could significantly increase this rate.

This energy input to the gas heats the gas to a temperature $T \simeq 10^4 (t/10^5 \text{ yr})$ K, where the relativistic electron density has been assumed to be 7×10^{-7} cm^{-3} that is, $\epsilon \simeq 2.7$ (see § 2.1). The interactions between the relativistic electrons and the ambient gas will heat the gas as long as the rate of energy input exceeds the rate of energy loss. Thus, the gas will be heated to a temperature of about 10^4 K, at which point it will begin to radiate via line emission and thermal bremsstrahlung emission. When the gas reaches a temperature of about 10^4 K, the cooling rate exceeds the rate of energy input for densities $n \gtrsim 10^{-1}$ cm^{-3}, assuming a standard cooling curve (Raymond, Cox, & Smith 1976).

The system will reach a steady state when the rate at which energy is input to the gas is equal to the rate at which it is radiated. This occurs when the temperature reaches $\sim 10^4$ K at which time the energy loss rate is $dE/dt \sim 2 \times 10^{45} n_g f (\gamma_{co}/100)^{-2}$ ergs s^{-1} for $\epsilon \simeq 2.7$, $h \simeq 1$, and $r \simeq 1$. This luminosity is quite large; therefore, radiation from gas heated by interactions with the relativistic electrons could account for the aligned near-infrared, optical, and emission-line regions. For $T \sim 10^5$ K thermal bremsstrahlung radiation will also produce ultraviolet light, which will then ionize the dense emission-line clouds; these clouds may also be ionized directly by interactions between the relativistic electrons and the neutral gas. Thermal bremsstrahlung and line emission as an explanation of the alignment effect is discussed in detail in § 3.

3. EMISSION FROM CLUMPED HOT GAS

3.1. *Emission from Relatively Cool Gas*

Gas within the radio bridge may be shock heated, or may be heated by interactions with relativistic electrons (§ 2.3 and Daly 1992c). Gas with a density $\gtrsim 10^{-1}$ cm^{-3} that is shock heated to temperatures $T \lesssim 10^4$–10^5 K will remain quite cool. Interactions with relativistic electrons will effectively transfer energy from the low-energy tail of the relativistic electrons to line emission (Daly 1992c), and the gas will remain at a temperature of about 10^4 K. In this case the total line luminosity is given by equation (2), and the relative line luminosities are determined by the relative abundance of ions in the emission-line clouds.

It is interesting to note that if the gas is heated by interactions with the relativistic electrons, the rate of energy input to the gas is proportional to the total number of relativistic electrons, which is controlled by the low-energy cutoff of the relativistic electron population since $N_{tot} \propto \gamma^{-2\alpha}$ (see § 2.1). This number increases as the radio power increases for a given radio spectral index, and as the radio spectral index increases, for a given radio power. Therefore, in this model the optical continuum and the emission-line luminosities should increase in proportion with the radio power, and they should increase as the radio spectral index increases. Both of these effects are suggested by the data. The emission-line luminosity is observed to increase with the radio power (McCarthy et al. 1991), which would result in this model due to the increase of the number of relativistic electrons with the radio power. The increase of the optical continuum luminosity with the radio spectral index is also expected in this model, because the

luminosity density of radiation emitted via thermal bremsstrahlung or IC scattering increases as the energy input to the gas increases, which occurs as the radio spectral index increases; this trend is suggested by the data (Lilly 1989).

3.2. Emission from Relatively Hot Gas

If the gas and relativistic electrons are mixed, it is likely that the gas is shock heated as the head of the radio bridge propagates through the ambient medium. Gas that is shock heated to temperatures $T \sim 10^6$ K with densities $n \lesssim 10^{-1}$ cm^{-3} will remain hot for a time $\gtrsim 10^6$ yr since the cooling time due to thermal bremsstrahlung is $t \simeq 2 \times 10^3 n^{-1} T^{0.5}$ yr, although this time scale is decreased if line cooling is included; cgs units are used.

Thermal bremsstrahlung radiation from clumped hot gas could contribute to the aligned optical continuum and could produce ultraviolet radiation which would ionize the neutral gas clouds and power the emission lines. The gas is likely to be shock heated, since it will only be heated to temperatures of $\sim 10^6$ K by interactions with the relativistic electrons if the gas density is quite low, in which case the gas will not radiate efficiently. Optical continuum will be produced by thermal bremsstrahlung emission from gas with temperatures $T \gtrsim 5 \times 10^4$ K, and ultraviolet and optical continuum will be produced by gas with $T \gtrsim (1\text{--}5) \times 10^5$ K.

The shock propagating through the ambient medium due to the energy input L_{dKE} at the hot spot will interact with the low-density medium present (see § 2.2). Clumped gas along the jet axis will be heated subsequently by interactions with the driven shock wave along the jet axis and by interactions with the shock-heated gas and relativistic electrons, in a manner that is analogous to these processes in the interstellar medium (McKee & Cowie 1975).

Gas with a number density n, in units of cm^{-3}, temperature T in units of degrees K, in a roughly spherical cloud with radius R_{10} in units of 10 kpc will produce thermal bremsstrahlung with a luminosity density $L_\nu \equiv dE/(dt \, dv)$ given by

$$L_\nu \simeq 3 \times 10^{31} n^2 c_L R_{10}^3 \, T^{-0.5} \left(\frac{h\nu}{kT}\right)^{-0.4}$$
$$\times e^{(-h\nu/kT)} \text{ ergs s}^{-1} \text{ Hz}^{-1} , \quad (3)$$

where c_L is the clumping factor, $c_L \equiv \langle n^2 \rangle / \langle n \rangle^2$, so $c_L \geq 1$, and the Gaunt factor has been approximated as $(h\nu/kT)^{-0.4}$ valid for $(h\nu \sim kT)$ (Rybicki & Lightman 1979; Blumenthal & Tucker 1974).

The observed optical flux densities of the high-redshift radio galaxies indicate luminosity densities of about $10^{28}\text{--}10^{29}$ ergs s^{-1} Hz^{-1}. For $h\nu \sim kT$ and $\nu \sim 10^{15}$ Hz the luminosity density is nearly independent of the gas temperature and is $L_\nu \sim 10^{29} n^2 c_L R_{10}^3$ ergs s^{-1} Hz^{-1}. The observed luminosity densities could be produced with $n^2 R_{10}^3 \sim 10^{-1}$, allowing $n \sim 10^{-1}$ for $R_{10} \sim (5\text{--}10)$. Note that the total mass of gas in a spherical gas cloud (i.e., galaxy) is about $M \simeq 10^{11} n R_{10}^3 \, M_\odot$. The time scale for a cloud (or galaxy) to cross the radio bridge is relatively large: $t_{cross} \sim 3 \times 10^7 \, h^{-1}$ yr for a width of the radio bridge of about $30 \, h^{-1}$ kpc and a cloud velocity of about 10^3 km s^{-1}, whereas the age of the jet is estimated to be $\lesssim 10^7$ yr. Thus, any companions of the radio galaxy that lie in the relatively large volume occupied by the radio bridge may be shock heated and may then radiate via thermal bremsstrahlung and line emission.

Thermal bremsstrahlung emission from clumped hot gas could produce the aligned optical continuum and could produce ultraviolet radiation to power the emission lines. The flux density of this light is $\propto \nu^{-0.4}$ for $h\nu \sim kT$ and is nearly a flat spectrum for lower frequencies (see Blumenthal & Tucker 1974).

4. THE INVERSE COMPTON SCATTERING MODEL

High-redshift radio galaxies are very powerful radio sources and have a significant amount of energy in the form of relativistic electrons, equivalent to about $10^5\text{--}10^6 \, M_\odot$ of rest mass energy in relativistic electrons with Lorentz factors $\gamma \equiv E/(m_e c^2)$ of $\gamma \sim 10^2$ to 10^3 (see § 2.2).

The radio structure of radio galaxies with redshifts up to 1.7 has been studied in detail by Leahy et al. (1989). The sources typically have hot spots at distances up to a few hundred kpc from the origin of the galaxy and have faint low-surface brightness regions between the hot spots and the galaxy, referred to as radio bridges. The presence of a radio bridge indicates that a reservoir of relativistic electrons lies along the jet axis. These electrons most likely were accelerated by shocks produced by jet-medium interactions.

The jet from the active nucleus in the galaxy impacts the ambient medium in the vicinity of the hot spot, where most of the particle acceleration probably occurs. The position of the hot spot moves away from the galaxy with time, leaving behind the roughly cylindrically symmetric reservoir of relativistic electrons indicated by the observations of radio bridges. This pattern may or may not continue when radio bridges in very high-redshift galaxies ($z \gtrsim 2$ or 3) are observed. In the terminology introduced here, a radio bridge may be considered to be a series of postlobes; the postlobes are regions that were once sites of particle acceleration, but where particle acceleration is no longer occurring, and the postlobes may or may not have expanded significantly since the particle acceleration in the region ceased. The surface brightness distribution of radio bridges in radio galaxies with redshifts $z \lesssim 1.7$ suggest that the postlobes in these systems have not expanded by more than a factor of about 1.5 since acceleration in these regions ceased.

The relativistic electron population that lies along the jet axis may produce the alignment effect in two ways. If the relativistic electron energy distribution extends to relatively low Lorentz factors, $\gamma \sim 50$, inverse Compton (IC) scattering between the electrons and the microwave background photons will produce optical and ultraviolet continuum, as discussed in this section. In addition, interactions between the relativistic electrons and the ambient gas will cool the relativistic electrons and heat the gas. The electrons cooled in this way may then IC scatter microwave photons to the optical and ultraviolet. Meanwhile, the gas heated by the interactions between the relativistic electrons and the ambient gas may reach temperatures of 10^4 K, temperatures sufficient for the gas to produce continuum and line emission, as discussed in § 2.3 and § 3.

4.1. Frequency of the Upscattered Radiation

The relativistic electrons that produce the 178(1 + z) MHz radio emission by which the radio galaxies are selected typically have Lorentz factors $\gamma \equiv E_e/(m_e c^2)$ of about 10^3, since

$$\frac{\nu}{178(1 + z) \text{ MHz}} \simeq 1.5 \times 10^{-7} \gamma^2 \epsilon \left(\frac{1 + z}{2}\right) \quad (4)$$

(see, e.g., Pacholczyk 1970) where v is the frequency at which the radio emission is produced, and the component of the magnetic field perpendicular to the direction of propagation of the electron $B_\perp$ is parameterized in terms of ϵ and the energy density of the microwave background radiation u_{mb}: $B_\perp^2/(8\pi) \equiv \epsilon u_{mb}$. In the radio bridges of the high-redshift radio galaxies, the magnetic field strength that minimizes the energy density of the relativistic electrons and magnetic field in the radio-emitting region (see, e.g., Miley 1980) typically is comparable to that of the microwave background radiation u_{mb}. It is therefore convenient to define the magnetic field strength in terms of the energy density of the microwave background radiation: $B_\perp = 3.3\epsilon(1 + z)^2 \mu G$, for a temperature of the microwave background radiation at the current epoch of 2.75 K. Note that this is a merely a convenient parameterization of the magnetic field strength; ϵ can of course be estimated for each individual radio source.

When a photon with frequency v_b scatters with an electron with Lorentz factor γ, the photon on average will emerge with a frequency $v = 4/3\gamma^2 v_b$. Since the average frequency of a relic photon is $2.7kT\ h^{-1}$, the average frequency of the upscattered radiation is $v \simeq 3.6\gamma^2 kT\ h^{-1}$; here h is Planck's constant. Note that both v and v_b scale as $(1 + z)$, so a relativistic electron with Lorentz factor γ will scatter relic photons into a frequency band that is fixed in our frame; for $T = 2.75(1 + z)$ K, an electron with Lorentz factor $\gamma = 22(v_{14})^{1/2}$ will scatter relic photons into the waveband centered on the frequency v_{14}, where $v_{14} \equiv v(10^{14}\ Hz)^{-1}$; the wavebands K, I, R, V, B, and the ultraviolet (1–4 Ryd) have the following values of v_{14}: 1.4, 3.3, 4.3, 5.5, 6.8, and 33 to 131. Upscattering of relic photons by electrons with Lorentz factors of (125–250), 60, 50, 45, 40, and 25 will produce photons that can be observed in the ultraviolet (1–4 Ryd), B, V, R, I, and K bands, respectively, independent of the redshift at which the scattering occurs. Upscattering to the ultraviolet in the rest frame of the radio galaxy, which may power the emission lines, will result from scattering of relic photons with electrons with $\gamma \sim (125$–$250)/(1 + z)^{1/2}$.

Hence, electrons with $\gamma \sim 25$–100 will upscatter relic photons into the near-infrared and optical continuum (in our rest frame) and can produce the ultraviolet radiation needed to power the emission lines.

The relativistic electrons that produce the radio emission by which the galaxies are selected have Lorentz factors of about 10^3. An order of magnitude estimate indicates that if the power-law distribution of the Lorentz factors γ of the relativistic electrons in the radio lobes extends to low values, the relic photons upscattered to the optical could easily be detected. For example, if the electron distribution extended to $\gamma \sim 50$, upscattering of relic photons would produce light in the V band and wavebands shortward of the V band. For a radio spectral index of $\alpha \simeq 1$, and a 178 MHz flux density of 10 Jy, the flux density in the V band is about 4×10^{-6} Jy for $\epsilon \sim 1$ and is about 3×10^{-5} Jy for $\epsilon \sim \frac{1}{3}$ (see eqs. [8]); these flux densities correspond to V apparent magnitudes of 22.6 and 20.2; 3C radio galaxies with redshifts of about 1 typically have V apparent magnitudes of about 22. Note that a value of $B \simeq B_{min}/3$ for the magnetic field in the radio lobes of Cygnus A is suggested by the data on that radio source, which is consistent with similar findings for other radio sources (Carilli et al. 1991).

When the optical continuum and emission-line regions track the radio structure in the sense that local maxima in the radio emission are close to those in the optical continuum and emis-

sion lines, it is likely that the continuum and line emission are associated with the low-energy tail of the relativistic electron energy distribution. The aligned components could be produced by IC scattering of microwave background photons with the low-energy tail of the electron energy distribution, by emission from gas that has been heated by interactions with the relativistic electrons (see §§ 2 and 3), or by Thomson scattering of anisotropic radiation from the active nucleus with gas along the jet axis that is ionized by the relativistic electrons (see § 6). In some sources the optical continuum and emission-line regions track the radio structure, while in others they do not. Hence, there are actually two types of alignments of the optical continuum and emission-line regions with the radio axis.

For example, the southern lobe in 3C 368 (Djorgovski et al. 1987; Chambers et al. 1988) may have $\gamma_{co} \lesssim 50$ since the optical continuum has a peak near that of the radio emission, which could be produced by IC scattering. The optical continuum and emission-line regions do not extend to and cover the northern lobe in 3C 368. This suggests either that the magnetic field in this region is large (see eq. [8b]), or that the electron energy distribution has a low-energy cutoff $\gamma_{co} \gtrsim 85$; this cutoff is suggested since the ultraviolet radiation would lead to line emission, for $\gamma_{co} \gtrsim 125/(1 + z)^{1/2}$. For cases in which $\gamma_{co} \gtrsim 100$ in the observed lobes, the relativistic electrons in these lobes must cool if they are to upscatter relic photons to optical frequencies (see § 4.3).

4.2. Typical Flux Densities of the Upscattered Radiation

Consider a power-law distribution of electron energies where the number density of electrons with energies between γ and $\gamma + d\gamma$ is $N(\gamma)d\gamma = N\gamma^{-s}d\gamma$. Scattering between these relativistic electrons, which occupy a volume V, and blackbody radiation with a temperature T produces radiation with a power-law spectrum

$$P_{ic} \equiv \frac{dE}{dt\,dv_x} \propto b(s)NV(kT)^3\left(\frac{kT}{hv_x}\right)^\alpha \tag{5}$$

(e.g., Blumenthal & Tucker 1974). The spectral index α is related to the index s of the electrons which were scattered to produce the radiation at frequency v_x, $\alpha = (s - 1)/2$. These same electrons produce synchrotron emission at a frequency v_r with a power-law spectrum

$$P_r \equiv \frac{dE}{dt\,dv_r} \propto a(s)NVB_\perp^{1+\alpha}\left(\frac{3e}{4\pi m_e c v_r}\right)^\alpha \tag{6}$$

(e.g., Pacholczyk 1970; Blumenthal & Tucker 1974); the functions $a(s)$ and $b(s)$ are given in Blumethal & Tucker (1974), and the relevant ratios are listed in Table 1. When the electron energy distribution is described by a single power law that extends from Lorentz factors, $\gamma \sim 10^3$, that produce the 178 MHz radio emission via synchrotron radiation to lower Lorentz factors γ which will IC scatter microwave photons to an observed frequency v_x, the flux density of the IC scattered light relative to the radio flux density may be obtained by taking the ratio of equation (5) to equation (6):

$$\frac{f_{ic}(v_x)}{f_r(v_r)} = \frac{P_{ic}}{P_r} \propto T_r^{3+\alpha}\frac{b(s)}{a(s)}B_\perp^{-(1+\alpha)}\left(\frac{5 \times 10^3 v_r}{v_x}\right)^\alpha. \tag{7}$$

Note that this ratio is independent of the volume filling factor of the relativistic electrons.

TABLE 1

FLUX DENSITY OF IC SCATTERED LIGHT FROM A POSTLOBE[a]

α	$b(s)/a(s)$ $(s = 2\alpha + 1)$	$f_{ic,post}(max)$ $(\epsilon \simeq 1)$ (Jy)	$f_{ic,post}(max)$ $(\epsilon \simeq \frac{1}{3})$ (Jy)
0.7..........	80	$1 \times 10^{-7}r$	$6 \times 10^{-7}r$
1.0..........	160	$9 \times 10^{-7}r$	$8 \times 10^{-6}r$
1.5..........	420	$3 \times 10^{-5}r$	$5 \times 10^{-4}r$

[a] See eq. (17).

Inserting the constants, this may be written

$$\frac{f_{ic}(v_{14})}{f_r(v_r)} \simeq 1.6 \times 10^{-12}\epsilon^{-(1+\alpha)}(1+z)^{1-\alpha}$$

$$\times \frac{b(s)}{a(s)}\left(\frac{7.5 \times 10^3}{v_{14}}\frac{v_r}{178 \text{ MHz}}\right)^\alpha , \quad (8a)$$

where $v_{14} \equiv v/(10^{14} \text{ Hz})$ and the magnetic field is parameterized by $B_\perp \equiv \epsilon 3.3(1+z)^2 \mu G$ (see § 4.1). For a magnetic field strength given by $B_\perp \equiv b \times 10^{-5}$ G, equation (8a) reads

$$\frac{f_{ic}(v_{14})}{f_r(v_r)} \simeq 5.3 \times 10^{-13}b^{-(1+\alpha)}(1+z)^{3+\alpha}$$

$$\times \frac{b(s)}{a(s)}\left(\frac{2.5 \times 10^3}{v_{14}}\frac{v_r}{178 \text{ MHz}}\right)^\alpha . \quad (8b)$$

The observed radio emission is produced by electrons with energies that are about a factor of 50 larger than the electrons that will upscatter radiation to optical and ultraviolet frequencies. Equations (7) and (8) are valid when the observed radio spectral index α continues from $\gamma \sim 10^3$ at which it is observed to $\gamma \sim 50$, since electrons with $\gamma \sim 50$ will inverse Compton scatter microwave photons to the V band (see § 4.1).

As discussed above, there are two types of alignments between the radio axis and the optical continuum and emission-line regions. In some cases the optical continuum and emission-line regions track the radio structure in the sense that the local maxima and surface brightness gradients of the optical continuum and/or emission-line regions track those seen in the radio; of course, the correspondence need not be exact. In these cases it is likely that the aligned component is associated with the low-energy tail of the relativistic electron energy distribution and could be produced by IC scattering.

In other cases the optical continuum and emission-line regions do not track the radio structure. In these cases the aligned optical continuum and emission-line regions can be produced by IC scattering if the relativistic electron population initially had a low-energy cutoff $\gamma_{co}(t_i) \gtrsim 50$, and some process cools the relativistic electrons. For example, the electrons may be cooled by the adiabatic expansion of the radio-emitting region (§§ 4.3.1. and 4.3.2), or the relativistic electrons may be cooled by interactions with the ambient gas, as discussed in § 2.3.

4.2.1. Flattening of the Electron Energy Distribution

If the electron population initially extends to Lorentz factors ~ 50, then these electrons will IC scatter microwave background photons to optical and ultraviolet energies. In this situation, it is possible that the electron energy distribution flattens at a Lorentz factor γ_b that lies between 10^3 and about 10^2, in which case the upscattered flux density will be smaller than

estimated using equations (8). Let the extrapolated spectral index be α_e, and the flattened spectral index be α_f, which are related to the electron energy index in the usual way $\alpha = (s - 1)/2$.

Using equation (5) it can be shown that the ratio $P_{ic}(\alpha_f)/P_{ic}(\alpha_e)$ is

$$\frac{P_{ic}(\alpha_f)}{P_{ic}(\alpha_e)} = \left[\frac{b(s_f)}{b(s_e)}\right]\left(\frac{N_f}{N_e}\right)\left(\frac{kT}{hv}\right)^{\alpha_f - \alpha_e} , \quad (9)$$

where N_e and N_f are the normalizations of the electron energy distributions for the extrapolated and flat indices, respectively. Requiring that the distributions match at the break Lorentz factor γ_b and using the relationship $v \simeq 3.6\gamma^2$ (kT/h) implies that

$$\frac{f_{ic}(\alpha_f)}{f_{ic}(\alpha_e)} = \frac{P_{ic}(\alpha_f)}{P_{ic}(\alpha_e)} \simeq \frac{b(s_f)}{b(s_e)}(3.6)^{\alpha_e - \alpha_f}\left(\frac{\gamma_b}{\gamma}\right)^{-2(\alpha_e - \alpha_f)} . \quad (10)$$

So, for $\alpha_e \sim 1$ and $\alpha_f \sim 0.5$, equation (10) implies that the flux density of upscattered radiation is about $(\gamma_b/\gamma)^{-1}$ less than that estimated assuming that the spectral index extrapolates to low energies. For $\gamma \sim 50$ and $\gamma_b \sim 500$ the estimated flux density of upscattered radiation is decreased by about a factor of 10 from that computed using equation (8).

Inverse Compton scattering will still produce interesting optical and ultraviolet flux densities if the magnetic field strength is less than the equipartition value, or if the redshift of the source is large (see eq. [8b]). Consider the case adopted above: $\alpha_e \sim 1$, $\alpha_f \sim 0.5$. The upscattered flux density is decreased by about 10 from that computed from equations (8) assuming $\alpha \sim 1$. Hence, the upscattered flux density from a single postlobe is about 10^{-7} to about 10^{-6} Jy for $\epsilon \sim 1$ to $\sim \frac{1}{3}$ given that the 178 MHz flux density from the radio lobe prior to its expansion is $f_r \sim 10$ Jy.

If the initial electron energy distribution has a low-energy cutoff $\gamma_{co}(t_i) \gtrsim 50$, the relativistic electrons may cool to interesting energies via adiabatic expansion, or by interactions with the ambient gas. Cooling due to spherical adiabatic expansion is discussed in § 4.3.1 while that due to cylindrical adiabatic expansion is discussed in § 4.3.2; cooling due to interactions between relativistic electrons and ambient gas is discussed in § 2.3.

As discussed in § 4.3, it is unlikely that the electrons will be cooled to $\gamma \sim 10^2$ by synchrotron or inverse Compton cooling.

4.3 Cooling Time Scales

Three cooling time scales are discussed in this section: that for synchrotron cooling, for inverse Compton cooling with the microwave background radiation and with other radiation fields, and for a lobe to expand. The synchrotron and inverse Compton cooling time scales discussed here are the time scales for an electron to cool to a Lorentz factor γ independent of the initial Lorentz factor γ_i for $\gamma_i \gg \gamma$, or the time scales for an electron with a Lorentz factor γ to lose half of its energy. When electrons cool to a Lorentz factor γ, the steepening of the radio spectral index is evident at the frequency v given by equation (4).

The time scale for an electron to cool via synchrotron radiation is

$$t_s \simeq 1.5 \times 10^{12}\gamma^{-1}\epsilon^{-2}(1+z)^{-4} \text{ yr} , \quad (11a)$$

for a magnetic field strength of $B_\perp = 3.3\epsilon(1 + z)^2 \mu$G. If the magnetic field is parameterized in terms of $B_\perp \equiv b \times 10^{-5}$ G, the synchrotron cooling time scale is

$$t_s \simeq 1.6 \times 10^{11} \gamma^{-1} b^{-2} \text{ yr} . \quad (11b)$$

The Lorentz factor of the electron is related to the frequency of the radio emission and the magnetic field strength (see eq. [4]). In terms of the frequency of the radio waves v_r emitted by the electron with Lorentz factor γ, the synchrotron cooling time scale is

$$t_s \simeq 8 \times 10^7 b^{-1.5} (1 + z)^{-0.5} \left[\frac{v_r}{178(1 + z) \text{ MHz}} \right]^{-0.5} \text{ yr} , \quad (11c)$$

which may also be written

$$t_s \simeq 4 \times 10^8 \epsilon^{-1.5} (1 + z)^{-3.5} \left[\frac{v_r}{178(1 + z) \text{ MHz}} \right]^{-0.5} \text{ yr} . \quad (11d)$$

For a source at a redshift of 1, that produces radio emission observed at 178 MHz, the cooling time scales are $t_s \simeq 6 \times 10^7$ yr for $b \simeq 1$, and $t_s \simeq 4 \times 10^7$ yr for $\epsilon \simeq 1$, while the cooling time associated with the 1.4 GHz emission from the same source is about a factor of 3 smaller.

The cooling time scale due to inverse Compton scattering with the microwave background radiation is

$$t_{\text{ic}}(u_{\text{mb}}) \simeq 2 \times 10^{12} \gamma^{-1} (1 + z)^{-4} \text{ yr} . \quad (12a)$$

In terms of the frequency of the radio emission, the time scale for cooling due to interactions with the microwave background radiation is

$$t_{\text{ic}}(u_{\text{mb}}) \simeq 1 \times 10^9 b^{0.5} (1 + z)^{-4.5} \left[\frac{v_r}{178(1 + z) \text{ MHz}} \right]^{-0.5} \text{ yr} , \quad (12b)$$

which may also be written

$$t_{\text{ic}}(u_{\text{mb}}) \simeq 6 \times 10^8 \epsilon^{0.5} (1 + z)^{-3.5} \left[\frac{v_r}{178(1 + z) \text{ MHz}} \right]^{-0.5} \text{ yr} . \quad (12c)$$

For a source at a redshift of 1, that produces radio emission observed at 178 MHz, the cooling time scale is $t_{\text{ic}} \simeq 5 \times 10^7$ yr for $b \simeq 1$ or for $\epsilon \simeq 1$; sources with redshifts of ~ 1 are generally detected at both 178 MHz and 1.4 GHz, and electrons that produce 1.4 GHz emission will cool with a time scale of $t_{\text{ic}} \simeq 2 \times 10^7$ yr.

The synchrotron cooling time scale decreases as the magnetic field strength increases (e.g., eqs. [11]), while the inverse Compton cooling time scale decreases as the magnetic field decreases. Therefore, the maximum age of the electrons that produce radiation at a frequency v_r is obtained from either equation (11c) or equation (12b) with $b \simeq 0.27(1 + z)^2$. That is, for $b > 0.27(1 + z)^2$ synchrotron losses dominate, and for $b < 0.27(1 + z)^2$ inverse Compton losses to the microwave background radiation dominate. When $b \simeq 0.27(1 + z)^2$, the cooling time is about half that for synchrotron or inverse Compton losses to the microwave background since both mechanisms will be operating. In this case the cooling time is $t \simeq 2.9 \times 10^8 (1 + z)^{-3.5} [v_r/178(1 + z) \text{ MHz}]^{-0.5}$ yr; if b is either greater or less than the critical value, the cooling time

scale decreases. Therefore, if radio emission is detected from sources, the relativistic electrons that produce the radio waves must have an age (i.e., time since they were last accelerated)

$$t \lesssim 3 \times 10^8 (1 + z)^{-3.5} \left[\frac{v_r}{178(1 + z) \text{ MHz}} \right]^{-0.5} \text{ yr} . \quad (13)$$

This suggests that the 178 MHz emission from radio sources with $z \simeq 1$ is produced by electrons with ages $t \lesssim 3 \times 10^7$ yr, and the 178 MHz emission detected from sources with $z \simeq 3$ is produced by electrons with ages $t \lesssim 2 \times 10^6$ yr; and the 1.4 GHz emission from radio sources with $z \sim 1$ is produced by electrons with ages $\lesssim 10^7$ yr, while that from sources with $z \sim 3$ is produced by electrons with ages $\lesssim 10^6$ yr.

If, at a given position, another radiation field with energy density $u_{\text{phot}} \gtrsim u_{\text{mb}}$ is present, then the primary cooling mechanism will be Compton cooling with this radiation field. The cooling time scale is $t_{\text{ic}}(u_{\text{phot}}) = t_{\text{ic}}(u_{\text{mb}})(u_{\text{phot}}/u_{\text{mb}})^{-1}$.

Consider an AGN with radiant luminosity $L_{\text{phot}} = 2 \times 10^{45} L_{45}$ ergs s^{-1}, emitted into two oppositely directed cones, each with half-opening angle θ, so that L_{45} is emitted into each cone. This light will inverse Compton cool the relativistic electrons within the emission cone and will be apparent when $u_{\text{phot}}/u_{\text{mb}} \gtrsim 1$. The ratio of the energy densities at a given distance $r = r_{10}$ 10 kpc from the AGN is

$$u_{\text{phot}}/u_{\text{mb}} \simeq 25 L_{45} r_{10}^{-2} \theta^{-2} (1 + z)^{-4} , \quad (14)$$

and the inverse Compton cooling time scale due to this radiation field is

$$t_{\text{ic}}(u_{\text{phot}}) \simeq 9 \times 10^{10} \gamma^{-1} L_{45}^{-1} r_{10}^2 \theta^2 \text{ yr} . \quad (15)$$

If radio galaxies have an anisotropic radiation field with an axis similar to that of the jet, this radiation field will inverse Compton cool the relativistic electrons in the radio bridge, which in turn alters the radio emission from the bridge (see Daly 1992b). This may be detected in low-redshift sources, but is unlikely to be detected in high-redshift sources because of the $(1 + z)^4$ redshift dependence of $u_{\text{ph}}/u_{\text{mb}}$ (see eq. [14]). For example, a source with a redshift of 1 has $u_{\text{phot}}/u_{\text{mb}} \sim 1.6 L_{45} r_{10}^{-2} \theta^{-2}$, so the radiation field will affect the bridge characteristics for $r \lesssim 13 \theta^{-1}$ kpc, and hence could be detected to distances of about 13 kpc from the AGN for $\theta \sim 60°$, or out to larger distances if θ is small or if L_{45} is large, $L_{45} \sim 10$; for example, for $\theta \sim 15°$, the effect could be detected out to $r \sim 50$ kpc even for $L_{45} \sim 1$.

The relativistic electrons in a lobe with an initial magnetic field given by $\epsilon \sim 1$ will cool by both synchrotron emission and inverse Compton scattering with relic photons. If the lobe is overpressured relative to the ambient medium, the lobe will expand (spherical and cylindrical expansion are discussed in §§ 4.3.1 and §§ 4.3.2). In this case the synchrotron cooling time becomes very large because the magnetic field strength decreases, while the time scale for inverse Compton cooling (via scattering with relic photons) to a given electron energy $\gamma m_e c^2$ is not affected by the expansion. Therefore, after a lobe has expanded, the primary cooling mechanism will be inverse Compton cooling with relic photons, assuming that another radiation field with an energy density greater than that of the microwave background radiation is not present.

The time scale for a lobe to expand from its initial size R to its final size χR is $t_{\text{exp}} \sim R(\chi - 1)/c_s$ since the lobe will expand at about the sound speed c_s of the lobe material. The pressure of the lobe may be dominated by relativistic particles and mag-

netic fields, in which case $c_s \simeq c/3^{1/2}$, or the pressure may be dominated by low-density, high-temperature (but nonrelativistic) gas with $c_s \sim 10^2$–10^4 km s^{-1}. The expansion time scale is $t_{exp} \sim 3 \times 10^4 (\chi - 1) R_5$ yr if the radius of the initial lobe is $R = 5R_5$ kpc when $c_s \simeq c/3^{1/2}$; and $t_{exp} \sim 5 \times 10^6 (\chi - 1)R_5$ yr for $c_s \sim 10^3$ km s^{-1}. When the pressure in the postlobe is comparable to that of the ambient medium, the postlobe will no longer expand.

The lobe will cease to expand when it comes into pressure equilibrium with the ambient medium. Compton cooling with relic photons may then continue for a long time. All of the electrons that began with $\gamma > 10^2$ will have cooled to this energy ($E \simeq 10^2 m_e c^2$) via Compton losses in about 10^9 yr for a source at a redshift of 1, and in about 10^8 yr for a source at a redshift of 3 (see eq. [12a]).

4.3.1. Spherical Expansion

Spherical adiabatic expansion of a radio lobe with volume $V = (4\pi/3)R^3$ by the linear factor χ has the following effects: $R \to \chi R$; $\gamma \to \chi^{-1}\gamma$, hence $\gamma_{co} \to \chi^{-1}\gamma_{co}$; $B \to \chi^{-2}B$; $f_r \to \chi^{-4\alpha-2}f_r$; $NV \to \chi^{-2\alpha}NV$; and α remains fixed (see, e.g., Moffet 1975). Here f_r is the radio flux density (produced by synchrotron emission) $f_r \propto \nu^{-\alpha}$, N is the normalization of the electron energy distribution, and V is the volume of the lobe. The number density of electrons with Lorentz factor between γ and $\gamma + d\gamma$ is $N(\gamma)d\gamma = N\gamma^{-s} d\gamma$; the total number of relativistic electrons N_{tot} is $N_{tot} = \int N(\gamma)d\gamma = NV\gamma_{co}^{1-s}/s - 1$ for $\alpha > 0$, that is, $N_{tot} = NV\gamma_{co}^{-2\alpha}/2\alpha$, since $\alpha = (s - 1)/2$. The region containing the relativistic electrons and magnetic field is referred to as a "postlobe" after the acceleration of electrons to relativistic energies ceases.

The expansion of a postlobe cools the electrons. Given that the initial low-energy cutoff of the electrons in the observed radio lobe is γ_{co}, the low-energy cutoff in the postlobe will be γ_{co}/χ. It is assumed that the properties of the lobe prior to its expansion were similar to those of the observed lobe; the radio flux density of the postlobe is decreased by $\chi^{-4\alpha-2}$ from that of the lobe and is therefore unlikely to be detected as a strong radio source.

The minimum expansion χ_{min} needed to allow the relativistic electrons to scatter the relic photons into some particular waveband centered on the frequency ν_x is $\chi_{min} = \gamma_{co}/\gamma_x$ (assuming that $\gamma_x \lesssim \gamma_{co}$), where γ_{co} is the cutoff energy of the electron distribution in the observed radio lobe, and γ_x is the Lorentz factor of the electrons needed to scatter the relic photons into the band centered on ν_x. Hence, the minimum factor by which the radio lobe must be expand for inverse Compton scattering with relic photons to produce radiation at the ($z = 0$) frequency $\nu_{x,14}$ is $\chi_{min} \simeq 4.5\nu_{x,14}^{-0.5}(\gamma_{co}/100)$.

4.3.2. Cylindrical Expansion

If the jet is relatively stable and points in a single direction, then the expansion of the radio lobe should be approximated as cylindrical expansion instead of spherical expansion. Cylindrical expansion is a good approximation for sources in which the jet appears to remain straight, such as 3C 368 (Djorgovski et al. 1987; Chambers et al. 1988), while spherical expansion of the radio lobe is a good approximation if the jet "spatters," as appears to be the case in 4C 41.17 (Chamber et al. 1990).

Consider the radial expansion by the linear factor χ of a cylinder with radius R, length l, and volume $V = \pi R^2 l$: $R \to \chi R$, $\gamma \to \chi^{-2/3}\gamma$; hence $\gamma_{co} \to \chi^{-2/3}\gamma_{co}$, $B \to \chi^{-2}B$ if the magnetic field is parallel to l; $f_r \to \chi^{-10\alpha/3-2}f_r$; $NV \to \chi^{-4\alpha/3}NV$; and α remains fixed.

4.4. Inverse Compton Scattered Radiation from a Postlobe

The flux density of the upscattered radiation from the postlobe which has expanded (spherically) by the factor χ relative to the radio flux density of the observed lobe is

$$\frac{f_{ic,post}(\nu_{14})}{f_{r,lobe}(\nu_r)} \simeq 1.6 \times 10^{-12}\chi^{-2\alpha}\epsilon^{-(1+\alpha)}$$

$$\times (1 + z)^{1-\alpha}\frac{b(s)}{a(s)}\left(\frac{7.5 \times 10^3}{\nu_{14}}\frac{\nu_r}{178 \text{ MHz}}\right)^\alpha, \quad (16)$$

where the magnetic field in equation (16) is that in the observed radio lobe: $B_\perp \simeq 3.3\epsilon(1 + z)^2$ μG(see § 4.1); if the expansion is cylindrical, the factor $\chi^{-2\alpha}$ in equation (16) is replaced by $\chi^{-4\alpha/3}$. Inverse Compton scattered radiation will be detected at the frequency ν_{14} when the power-law electron energy distribution extends down to Lorentz factors of $22(\nu_{14})^{1/2}$ (see § 4.2). The low-energy cutoff of the electron distribution in the postlobe is $\chi^{-1}\gamma_{co}$ for spherical expansion, and $\chi^{-2/3}\gamma_{co}$ for cylindrical expansion, where γ_{co} is the low-energy cutoff of the electron energy distribution in the initial radio lobe, which is assumed to be the same as that in the observed radio lobe.

The expansion of the postlobe will decrease γ_{co} and shift the electron energy distribution to lower energies. For postlobes in which $\gamma_{co} \gtrsim 100$ the electrons must cool if they are to inverse Compton scatter microwave photons to optical and ultraviolet frequencies. The minimum expansion factor χ_{min} which will cause electrons near the low-energy cutoff to be scattered to a particular frequency ν_{14} is $\chi_{min} \simeq 4.5\nu_{14}^{-0.5}(\gamma_{co}/100)$ for spherical expansion, and $\chi_{min} \simeq 10\nu_{14}^{-0.75}(\gamma_{co}/100)^{3/2}$ for cylindrical expansion. For cases in which cooling is required to decrease γ_{co}, the maximum flux density of inverse Compton scattered radiation is obtained from equation (16) with $\chi = \chi_{min}$. For $\chi = \chi_{min}$ the frequency dependence ν_{14} in equation (16) cancels, and the maximum flux density that can be detected in any waveband due to inverse Compton scattering relative to that due to synchrotron emission in the observed radio lobe results. Hence, the maximum optical flux density of a postlobe for cases in which γ_{co} of the initial lobe was $\gamma_{co} \gtrsim 100$ is

$$\frac{f_{ic,post}(max)}{f_{r,lobe}(178 \text{ MHz})} \simeq 1.6 \times 10^{-12}(3.6 \times 10^2)^\alpha$$

$$\times \frac{b(s)}{a(s)}(1 + z)^{1-\alpha}\epsilon^{-(1+\alpha)}\left(\frac{\gamma_{co}}{100}\right)^{-2\alpha}. \quad (17)$$

Equation (17) results for both spherical and cylindrical expansion; the magnetic field strength ϵ is that of the radio lobe prior to expansion. Values of $f_{ic,post}(max)$ are tabulated in Table 1, where the 178 MHz flux density is $10r$ Jy and $\gamma_{co} = 100$ has been assumed; column (4) indicates the maximum flux density when $B \simeq B_{min}/3$ (i.e., $\epsilon \simeq \frac{1}{3}$). A redshift of (1) has been assumed, but the results are very weakly dependent on redshift.

Equation (17) also provides an estimate of the upscattered flux density produced by the cool relativistic electrons that had an initial Lorentz factor γ_{co}, independent of the cooling mechanism. The frequency to which the light will be upscattered by the cool electrons depends on the Lorentz factor to which they have been cooled. Hence, equation (17) provides an estimate of the maximum flux density that can be expected in any waveband, assuming that electrons that began with an initial Lorentz factor γ_{co} cooled to a Lorentz factor that allows scattering to that waveband.

4.5. *The Optical Continuum*

The typical flux densities of the aligned optical components in the high-redshift radio galaxies range from about 10^{-6} to 10^{-5} Jy in *B*, *V*, *R*, and *I* wavebands. Therefore, if the initial electron energy distribution extends to Lorentz factors of about 50, IC scattering could explain the aligned optical continuum and emission-line regions. For f_r (178 MHz) ~ 10 Jy, the upscattered flux density in the *V* band is about 4×10^{-6} to 3×10^{-5} Jy for $\epsilon \sim 1$ to $\frac{1}{3}$.

A postlobe that has cooled via adiabatic expansion has a maximum flux density of about 10^{-6} Jy (for $\epsilon \simeq 1$) to about 10^{-5} Jy (for $\epsilon \simeq \frac{1}{3}$) for a radio spectral index of about 1 that extends to energies of about $\gamma_{co}(t_i) \sim 100$, an expansion factor χ_{min}, and an initial radio flux density of the lobe of about 10 Jy (see Table 1).

A given radio galaxy is likely to have several postlobes, each contributing to the upscattered flux density. If either the cutoff of the Lorentz factors in one of the lobes is less than about 50 or one of the postlobes has expanded by the factor χ_{min}, interesting optical and ultraviolet flux densities result from IC scattering.

Hence, inverse Compton scattering by relatively cool relativistic electrons in the lobes or in postlobes could produce the aligned optical continuum in the high-redshift radio galaxies and provide a local source of ultraviolet continuum to power the emission lines.

4.6. *Morphologies*

Starlight will be produced in the main body of the galaxy by stars that are on the main sequence, while the *K*-band light is produced by stars evolving off of the main sequence. The light produced by stars in the main body of the galaxy may explain the stellar absorption features reported by Chambers & McCarthy (1990), although similar features could be produced by interstellar absorption of optical continuum produced by stellar or nonstellar processes.

The aligned component may be produced by nonstellar processes, such as inverse Compton scattering, as discussed above; this component would be superposed on the starlight produced by the main body of the galaxy. It may sometimes be possible to separate the dynamically relaxed stellar component from that associated with the radio activity by the morphologies and colors of different components, as done by Rigler et al. (1992).

In the inverse Compton scattering model, the morphology of the upscattered component depends on the spatial distribution of relatively low-energy relativistic electrons, electrons with Lorentz factors on the order of 25–100.

In the straight jet model, these electrons should lie in a cylndrical volume between the current position of the lobe and the origin of the jet. Assuming that the radio properties of the lobe are independent of the position of the lobe relative to the origin of the galaxy, the lobe observed in the galaxy can be used to estimate the initial properties of the postlobe. The morphology of the system depends on how much relativistic electrons at different locations along the jet axis have cooled. If the density of the ambient medium is independent of the radial position from the center of the galaxy, then given that enough time has elapsed for the postlobe to expand and come into pressure equilibrium with the ambient medium, the flux density and color of the upscattered radiation should be independent of position along the jet axis. In addition, relativistic electrons may be cooled to low Lorentz factor by interactions

with the ambient gas (see § 2), in which case the cooling rate depends on the local gas density.

Alternatively, the ambient medium may have a radial pressure gradient. Suppose that the ambient pressure decreases as the radial position from the center of the galaxy increases. Then, the regions closest to the body of the galaxy will expand less than those farther out, again assuming that enough time has elapsed for the region to expand and come into pressure equilibrium. In this case, the flux density of the upscattered radiation from the regions near the galaxy will be larger than from those farther away because they will have undergone less expansion; as equation (16) shows, regions which have undergone less expansion have a higher flux density of upscattered radiation. Furthermore, the time scale for relativistic electrons to cool via interactions with the ambient gas is proportional to the ambient gas density. Hence, if there is a gradient of the ambient gas density, relativistic electrons near the main body of the galaxy will be cooled more efficiently than those farther away, as discussed in § 2.3.

The colors of the components depend on the energy distributions of the relativistic electrons that are upscattering the relic photons into observable wavebands, and on the relative contribution of light produced by other processes, such as by stars in the main body of the galaxy and by thermal bremsstrahlung radiation.

4.7. *Colors*

Equivalent to the color of a particular component is the spectral index α of that component, where the flux density of the upscattered component is proportional to $\nu^{-\alpha}$. The spectral index of the IC (inverse Compton) scattered radiation is the same as the radio spectral index of the synchrotron emission produced by the same electrons that are responsible for the upscattering.

The electrons responsible for upscattering to optical and ultraviolet frequencies are much lower energy than those that produce the observed radio emission. The expected spectral index of the optical emission from a given postlobe can be estimated once some assumptions have been adopted. The radio spectra often exhibit high-frequency steepening (e.g., Leahy et al. 1989). Therefore, it seems likely that a postlobe expands, its flux density will decrease, and it will become redder. However, there are many provisos to this statement because cooling mechanisms (e.g., those discussed in § 2.3) may alter the spectrum and because the observed lobe may not always be a good approximation to the initial lobe that expanded to produce the postlobe.

If the low-energy relativistic electrons have been cooled by interactions with the ambient gas, their energy distribution should be flatter than that of the observed radio emission.

Consider the spattering model for the jet. A postlobe in this model might lie adjacent to the current position of the jet and is likely to have expanded to come into pressure equilibrium with the ambient gas. Subsequently the color of this system will evolve with time as the electrons Compton cool (§ 4.3); it will become redder with time. However, if cooling due to interactions between the relativistic electrons and the ambient gas is important, the spectrum of the IC scattered light will flatten with time and could eventually become inverted.

The color of a particular component depends on the initial electron energy distribution, and the cooling and expansion history of the component. Color gradients within a given source are not unexpected, but are difficult to predict. For

components in which cooling has not affected the low-energy electrons, brighter components in general will be bluer, again assuming that the initial lobes had identical properties.

Finally, the integrated color of the upscattered component need not be representative of that of any particular component. And, the integrated color of the galaxy is determined not only by the integrated color of the aligned component, but also by starlight originating from the main body of the galaxy.

4.8. *The Emission-Line Luminosity and the Radio Power*

Ultraviolet continuum is produced by the scattering of relic photons with relativistic electrons. In the rest frame of the radio galaxy, electrons with Lorentz factors of about $(125$ to $250)/(1 + z)^{1/2}$ upscatter the relic photons to energies of about 1–4 Ryd (13.6–54.4 eV). Photons with these energies ionize the gas in the emission-line clouds and provide the energy source for the emission lines, such as Lyα, [O II], and [O III].

The emission-line luminosity is $L_{lines} \sim L_{uv} f_c \tau$, for $\tau \lesssim 1$, where L_{uv} is the total ultraviolet luminosity at the position of the cloud, f_c is the cloud covering factor, and τ is the optical depth of a cloud; typically τ is assumed to be $\gtrsim 1$, in which case $L_{line} \sim L_{uv} f_c$. The ultraviolet luminosity is $L_{uv} \sim P_{uv} \nu_{uv}$ where P_{uv} is the ultraviolet power $P \equiv dE/(d\nu\,dt)$ and $\nu_{uv} \sim 33 \times 10^{14}$ Hz corresponds to an energy of 13.6 eV. The ratio of the ultraviolet power to the radio power may be obtained from equations (8), (16), or (17) depending on γ_{co} of the observed radio lobe.

Assuming a minimum expansion, equation (17) may be used to obtain $P_{uv}/P_r = f_{ic,cool}/f_r$. For $\alpha \sim 1$, f_r (178 MHz) ~ 10 Jy, $\gamma_{CO} \sim 100$, and $\epsilon \sim 1$ the above relations imply L_{line}/P_r(178 MHz) $\sim 3 \times 10^8 f_c$ for $\tau \gtrsim 1$ and L_{line}/P_r(178 MHz) $\sim 3 \times 10^8 f_c \tau$ for $\tau \lesssim 1$.

McCarthy (1991) and McCarthy et al. (1991) report that the ratio of the [O II] line luminosity to the 1.4 GHz radio power is $L_{O II, line}/P_r(1.4$ GHz$) \sim 10^8$ which, for $\alpha \sim 1$, implies $L_{O II, line}/P_r$(178 MHz) $\sim 10^7$. And, McCarthy (1988) suggests that the total line luminosity L_{lines} is ~ 10 times the [O II] line luminosity, which implies that L_{lines}/P_r(178 MHz) $\sim 10^8$. The radio luminosity may be estimated as $L_r \sim P_r \nu_r$. Thus, the observations imply that the ratio of the total line luminosity to the radio luminosity is about one: $L_{lines}/L_r \sim 1$. And, the observed trend could be explained with $f_c \tau \sim 0.1$–1 for $\tau \lesssim 1$, or $f_c \sim 0.1$–1 for $\tau \gtrsim 1$.

Thus the ultraviolet radiation produced by IC scattering of microwave background photons by relatively low-energy relativisitic electrons could contribute significantly to the emission-line luminosities of high-redshift radio galaxies. In addition, the observed relationship between the line luminosity and the radio power is expected in the IC model.

4.9. *Comparison with Observations*

The data are expected to exhibit certain trends if the IC model is correct. The first is that the optical flux density and ultraviolet flux density (and hence emission-line luminosity) should be roughly proportional to the radio flux density for radio sources with a given radio spectral index (see eqs. [8]). The second is that the optical and ultraviolet flux densities should increase as the radio spectral index increases for radio sources with a given radio flux density (see eqs. [8]), assuming that the low-energy ($\gamma \sim 50$) slope of the electron energy distribution steepens when that of the high-energy ($\gamma \sim 10^3$) distribution steepens.

The first expectation is supported by the trend observed between the line luminosity and the radio power: $L_{line} \propto P_r$ (McCarthy et al. 1991; McCarthy 1991; also see § 4.8). The large scatter of the observed trend could result from the distribution of radio spectral indices and the distribution of cloud covering factors if the clouds are optically thick, or the distribution of τf_c if the clouds are optically thin.

The second expectation is supported by the trend between the radio spectral index and f_{5000} (Lilly 1989). This trend implies that the radio galaxies with steep radio spectral indices have a larger fraction of their light originating from a component shortward of the 4000 Å break than galaxies with a less steep radio spectral index. The component contributing most of the light shortward of the 4000 Å break is associated with the aligned blue component, while most of the near-infrared light (longward of the 4000 Å break) is well behaved as evidenced by the properties of the near-infrared Hubble diagram. When the electron energy distribution is quite steep, the radio spectral index is large, and the flux density of upscattered radiation increases (see eqs. [8]), which will increase the optical flux density and hence increase f_{5000}. Thus, a trend between the optical to near-infrared colors and the radio spectral index is expected in the IC model; such a trend is suggested by the data (Lilly 1989).

For a given radio flux density and spectral index, the flux density of the upscattered radiation is only weakly dependent on redshift for $\epsilon \sim 1$. However, the flux density from starlight (in the K band, for example) decreases as the redshift of the source increases. Therefore, the component produced by IC scattering is likely to become more pronouced as the redshift of the radio galaxy increases, for sources with a given radio flux density and radio spectral index.

The upscattered ultraviolet radiation that can power the emission lines results from scattering of relic photons with electrons with Lorentz factors $\gamma \sim 125/(1 + z)^{1/2}$, whereas the optical continuum (the V band, for example) results from scattering with electrons with $\gamma \sim 50$. Therefore, as higher redshift sources are observed, the emission-line regions and the regions from which the optical continuum (such as the V band) originates should be closer together spatially. However, if the emission-line clouds have a large covering factor, then much of the optical continuum (in our rest frame) may be absorbed and reradiated as line emission.

Another prediction of the inverse Compton scattering model is that the radio lobes will be X-ray sources. For an equipartition magnetic field strength, electrons with Lorentz factors of about 10^3 produce the radio emission by which the galaxies are selected. These same electrons will upscatter relic photons to energies of about 1 keV. The upscatter flux density may be estimated from equation (8a) with $\nu_{14} \simeq 2.4 \times 10^3$. For $\alpha \simeq 1$ and $\epsilon \simeq 1$, equation (8a) implies $f_{ic}/f_r \sim 8 \times 10^{-10}$, so for a 178 MHz radio flux density of about 10 Jy, the 1 keV flux density due to inverse Compton scattering is about 8×10^{-9} Jy $\simeq 10^{-5}$ keV keV^{-1} s^{-1} cm^{-2} comparable to the current bounds and detections available for 5 3C sources with redshifts between 0.5 and 1.0 (Henry et al. 1979). The flux density of upscattered radiation is smaller when $\alpha < 1$.

5. JET-INDUCED STAR FORMATION

Jet-induced star formation could explain the alignment effect (Rees 1989; De Young 1989; Begelman & Cioffi 1989; Daly 1990; Bithell & Rees 1990). The stars must be younger than the radio activity, hence $t \lesssim 10^7$ yr. This implies that the stars have

masses $\gtrsim 1.5\ M_\odot$ so that they will reach on the main sequence in the time available. The constraints on the age of the radio source are discussed in detail by Leahy et al. (1989) and Daly (1992a). Older stars may be aligned with the radio axis if the radio source undergoes multiple outbursts. However, the stars are likely to remain aligned for $\lesssim 10^8$ yr since precession of the stellar orbits if the stars are bound, and the random motions of the stars if they are unbound, will wash out the alignment in about 10^8 yr (Daly 1990).

The emission-line and the optical continuum regions often track very similar structures, suggesting a common excitation mechanism. If the stars are to produce ultraviolet light to power the emission lines, they must have surface temperatures in excess of about 2×10^5 K, suggesting stellar masses of about $M \gtrsim 50\ M_\odot$. Such stars evolve onto the main sequence in about 10^4 yr, and remain on the main sequence for about $\sim 10^6$ yr.

The properties of the K-band Hubble diagram indicate that the stellar mass of the parent galaxy is not increasing substantially with time. This suggests that if star formation along the jet axis is occurring, either the stars will not be gravitationally bound to the galaxy, or that the initial mass function of the stars is heavily weighted toward the high-mass end.

In this model it is not clear how the correlations between the radio power and the emission-line luminosity (McCarthy et al. 1991; McCarthy 1991) and between optical to near-infrared color and the radio spectral index (Lilly 1989) might arise. The latter could arise if the radio-emitting electrons are cooled via inverse Compton scattering with the light produced by the stars. However, this would require that the energy density of the starlight u_* exceed both that of the microwave background radiation and that of the light produced by the stars in the main body of the galaxy. For a group of stars with luminosity $L = 10^{44} L_{44}$ ergs s^{-1}, the energy density of the starlight relative to that of the microwave background radiation u_{mb} at a distance $r = 10 r_{10}$ kpc is $u_*/u_{mb} \simeq 0.7 L_{44}\, r_{10}^{-2}\, (1+z)^{-4}$ which is $\ll 1$ for $z \sim 1$; therefore this mechanism cannot explain the observed trend between the radio spectral index and the optical to near-infrared colors of the radio galaxies.

The trend between the radio power and the emission-line luminosity could be understood if the efficiency of star formation increases as the number of relativistic electrons increases. However, the interactions between the relativistic electrons and the ambient gas heat and ionize the gas (see § 2), which seems more likely to inhibit rather than enhance star formation. Perhaps the star formation could be enhanced if the relativistic electrons and the ambient gas are not mixed. This would enhance star formation in the gas if the star formation efficiency increases as the external pressure increases (Rees 1989); the external pressure would increase as the number density of relativistic electrons increases, which causes the radio power to increase.

The radio luminosity is likely to be related to the jet power since the velocity of propagation of the head of the radio-emitting region through the ambient medium increases as the radio power increases (Alexander & Leahy 1987). The observed trend between the radio power and the emission-line luminosity would require that the efficiency of star formation increases as jet power increases. Again, this could be understood in the star formation model if the efficiency of star formation depends on the postshock pressure, although a large postshock pressure might inhibit rather than enhance star formation.

It has been argued that the aligned component is likely to be stellar because the co-added spectra of several high-redshift radio galaxies exhibit stellar absorption features (Chambers & McCarthy 1990). However, each spectrum includes light from the main body of the galaxy which surely is composed of stars, as inferred from the properties of the K-band Hubble diagram (Lilly 1990). In addition, the minimum ages of the stars suggested by Chambers & McCarthy (1990) and Chambers & Charlot (1990) are $\gtrsim 3 \times 10^8$ yr, whereas the aligned component is likely to have an age $\lesssim 10^7$ yr based on the synchrotron aging arguments, and the aligned optical component should have an age $\lesssim 10^8$ yr if it is produced by starlight because the motions of the stars would wash out the alignment over this time scale (Daly 1990). Finally, it should be noted that absorption features similar to those observed could be produced by interstellar absorption. Thus, the conclusion that the aligned component is stellar based on the co-added spectra of the radio galaxies appears to be inconsistent with other observations of these galaxies, as discussed in more detail by Daly (1992a).

6. THOMSON SCATTERING OF ANISOTROPIC RADIATION

Radio galaxies clearly have an active nucleus, which is the source of the large-scale jets that produce the spectacular radio bridges and hot spots seen in radio galaxies. The luminosity in directed kinetic energy is clearly anisotropic, and the radiation emitted by the active galactic nucleus (AGN) may also be emitted anisotropically.

The nuclear activity may be parameterized by the luminosity emitted in the form of directed kinetic energy L_{dKE}, and the luminosity emitted in the form of radiation L_{phot}. The sequence from radio-quiet quasars (RQQs), to radio-loud quasars (RLQs), to radio galaxies (RGs) may be a sequence in the form of the energy released by the AGN: in this case RQQs result when $L_{phot} \gg L_{dKE}$, RLQs result when $L_{phot} \sim L_{dKE}$, and RGs result when $L_{dKE} \gg L_{phot}$.

It is also possible that RQQs fall into one category, and RLQs and RGs fall into a separate category. In this case RLQs and RGs are actually quite similar and emit radiation anisotropically. If the observer lies within the cone of emission, the object is identified as a RLQ; if the observer lies outside the cone of emission, the object is identified as a RG. This is known as the orientation unified model for RGs and RLQs, as discussed, for example, by Antonucci (1989) and Barthel (1989).

If the orientation unified model is correct, and if the symmetry axis of L_{dKE} is similar to that of L_{phot}, then scattering of the anisotropic radiation into the observer's line of sight could explain the alignment effect (di Serego Alighieri et al. 1989; Fabian 1989). The luminosity of the scattered light is $L_{sc} \simeq \tau_T L_{inc}$ where $\tau_T \simeq n\sigma_T R$ is the Thomson optical depth for scattering with a medium with gas number density n, and size R, σ_T is the Thomson scattering cross section; and L_{inc} is the luminosity of light incident on the scattering medium.

Fabian (1989) suggests that the anisotropic radiation from the AGN scatters off of hot gas that comprises a cooling flow about the galaxy; the hot gas has a total mass of about 10^{13} $M_\odot$ and a density of about 10^{-1} cm^{-3}. However, the gas with which a jet from the AGN interacts is likely to have a fairly low density $n \lesssim 10^{-3}$ cm^{-3} (see § 2.2), although cold clumpy material with a much higher density could be embedded in the hotter low-density gas with which the jet interacts. Further, the aligned components do not have a conelike structure, thus Thomson scattering with a smoothly distributed medium

cannot account for the alignments. In addition, it is curious that in many sources continuum and line emission are detected in an elongated region that includes regions near the galaxy and perpendicular to the axis of the jet, so these regions lie outside any conelike emission region.

In any case, if this mechanism is to account for the alignments, the radiation from the AGN must scatter off of a clumpy medium; this is suggested by the clumpy appearance of the aligned components, by the lack of a conelike structure for the aligned components, and by general arguments (§ 2.2) which suggest that the jets are interacting with either a clumpy, or a very low density, medium. The low-density medium will have a very small Thomson optical depth; scattering off of clumpy material embedded in the low-density medium could produce the aligned optical component.

Light from the AGN emitted into a core with half-opening angle θ with luminosity L_{phot} incident on a gas clump with characteristic radius R_c located a distance r from the AGN has a luminosity $L_{\mathrm{inc}} \sim L_{\mathrm{phot}}(R_c/r)^2\theta^{-2}$. The radiant luminosity of the AGN, assuming an orientation unified model, may be estimated from the optical luminosities of the 3CR RLQs with redshifts greater than 1; assuming a deceleration parameter $q_0 = 0$, which maximizes the luminosities, the mean luminosity $L_v v$ of these quasars is $L_{\mathrm{RLQ}} \simeq 3 \times 10^{45}(\theta^2\ h^{-2})$ ergs s^{-1} for a half-opening angle θ in radians; the maximum value for any of the 3CR RLQs is $6 \times 10^{45}(\theta^2\ h^{-2})$ ergs s^{-1}. And the bolometric radiant luminosity of the AGN in the RGs is constrained to be $\lesssim 5 \times 10^{46}$ ergs s^{-1} (Daly 1992b). The half-opening angle must be less than about 60°, so $\theta \lesssim 1$, or the emission is no longer anisotropic.

Let us consider the scattering of the radiation with the gas in a cloud with density $n \sim 1$ cm^{-3}, and size $R \sim 10$ kpc, located about 25 kpc from the quasar; such a cloud (i.e., a galaxy) has a gas mass of about $10^{11}\ M_\odot$. The optical depth to scattering implies that $\tau_T \sim 2 \times 10^{-2}$, and the scattered luminosity is $L_{\mathrm{sc}} \sim 3 \times 10^{-3}\theta^{-2}L_{\mathrm{phot}}$, hence, for $L_{\mathrm{phot}} \simeq 3 \times 10^{45}\theta\ h^{-2}$ ergs s^{-1}, the scattered luminosity is about $L_{\mathrm{sc}} \sim 10^{43}\ h^{-2}$ ergs s^{-1}. Therefore, this mechanism could explain the alignments if the scattering occurs off of clouds that are fairly close to the galaxy. At large distances from the AGN, $r \gtrsim 50$ kpc, it is unlikely that scattering of anisotropic radiation from the AGN will be important.

It is interesting to note that the emission-line regions track the optical continuum regions in many sources. This suggests a common origin of the excitation, and in the Thomson scattering model this could be explained if the ultraviolet light from the AGN was the energy source to power the emission lines, as suggested by van Breugel & McCarthy (1990). The cross section for the absorption of an ultraviolet photon σ_{uv} is quite large relative to the Thomson scattering cross section: $\sigma_{\mathrm{uv}}/\sigma_T \sim 10^7$. Therefore, the optical depth per emission-line cloud, with size R_{elc}, is probably greater than one. In order for the ultraviolet photons from the AGN to escape to distant regions from the AGN the volume filling factor f of the emission-line clouds must satisfy $f \lesssim R_{\mathrm{elc}}/r \sim 10^{-5}$ for $R_{\mathrm{elc}} \sim 0.1$ pc and $r \sim 10$ kpc.

Another possibility is that the primary energy source powering the emission lines is the energy input from the low-energy tail of the relativistic electrons (§ 2.3 and Daly 1992c), which heats and ionizes the gas. The transfer of energy from the relativistic electrons may contribute significantly to the emission-line luminosity, and, if this is the primary source of ionization, the light from the AGN will preferentially scatter off of the ionized gas that permeates the emission-line regions.

Thus, in this model the scattered continuum and the emission-line regions would have very similar morphologies.

A strong prediction of the model in which the aligned optical continuum is produced by Thomson scattering of anisotropic radiation from the AGN is that the aligned optical continuum should be polarized, with the percent polarization independent of wavelength. Let the angle α be that between the incident light and the scattered light. The polarization is $P = (1 - \cos^2 \alpha)(1 + \cos^2 \alpha)^{-1}$. If the emission axis is roughly in the plane of the sky, and the half-opening angle of the cone of emission is about 60°, the polarization of the aligned component should be greater than about 14%. The percent polarization expected in the Thomson scattering model is illustrated by Jannuzi & Elston (1991). Note that the scattered light should have colors independent of position, and the same degree of polarization at all wavelengths. If this is not the case, a second source is likely to be contributing to the aligned optical continuum. Observations of optical polarization in these systems are summarized in §§ 10.4 and 11. To date there is one source for which the extended optical continuum appears to be polarized, 3C 368 (Scarrott, Rolph, & Tadhunter 1990). The variation of the percent polarization through different filters suggest that a second source is contributing significantly to the aligned optical continuum of 3C 368.

The spectral index of the scattered light will be same as that of the incident light. The spectral index of the scattered light should be roughly $\propto v^{-0.7}$ since this is the typical optical spectral index of RLQs.

It is interesting to note that in this model the emission-line luminosity would be correlated with the radio power if the radiant luminosity of RLQs is correlated with their radio luminosity. A glance at the 3C catalog indicates that such a trend is suggested by the RLQs in the 3CR data set. These data are consistent with $L_{\mathrm{phot}} \propto P_{\mathrm{radio}}$, but favor a more shallow relationship $L_{\mathrm{phot}} \propto P_{\mathrm{radio}}^{0.7}$.

7. CONSTRAINTS ON THE ORIENTATION UNIFIED MODEL

Radio galaxies, radio-loud quasars, and radio-quiet quasars are all related since each contains an active nucleus. As discussed in § 6, the sequence from RGs to RLQ to RQQ may be a sequence in the ratio of the luminosity in directed kinetic energy released by the AGN L_{dKE}, and the luminosity released in the form of radiation L_{phot}. In this case, RGs result when $L_{\mathrm{dKE}} \gg L_{\mathrm{phot}}$, RLQs result when $L_{\mathrm{dKE}} \sim L_{\mathrm{phot}}$, and RQQs result when $L_{\mathrm{phot}} \gg L_{\mathrm{dKE}}$.

It is also possible that RLQs and RGs are drawn from a single parent population and form a class separate from RQQs. The AGN in sources with a large luminosity in directed kinetic energy may emit radiation anisotropically; if the observer happens to be inside the cone of emission, the source is identified as a RLQ, and if the observer is outside the cone of emission, the source is identified as an RG. This is known as the orientation unified model for RGs and RLQs (Antonucci 1989; Barthel 1989).

If the orientation unified model were correct, the high-redshift RGs would have emission axes that are roughly in the plane of the sky. In this case, velocities along the radio axis would be difficult to detect since only the component of the velocity along the line of sight is detected. Thus, the observed velocity gradient across the source is expected to be larger in RLQs than it is in radio-loud galaxies if the orientation unified model is correct.

In high-redshift RGs a systematic velocity gradient is exhibited by the emission-line gas. The line-of-sight component

of this gradient is generally about 500 to 10^3 km s^{-1} (Spinrad & Djorgovski 1984a; McCarthy et al. 1987a; McCarthy et al. 1987b; Djorgovski et al. 1987). Since the emission-line regions lie along the radio axis, this is measure of the line-of-sight component of the velocity of the gas aligned with the radio axis. High-redshift RLQs have been studied by Heckman et al. (1992), who place an upper bound on the line-of-sight component of the velocity gradient of the emission-line gas of about 500 km s^{-1}. Thus, the observations suggest that the line-of-sight component of the velocity gradient across the source is larger in the RGs than it is in the RLQs. This is in a sense opposite to that expected in the orientation unified model for RGs and RLQs.

Leahy et al. (1989) have studied and compared the properties of radio bridges of RGs and RLQs. They find that they have different radio morphologies. The radio bridges of RLQs are shorter and wider than the radio bridges seen in RGs, and they conclude that the difference is so large that it cannot be due entirely to projection effects. This suggests that RLQs and RGs are not drawn from a single parent population viewed from different angles.

Both of these observations are inconsistent with the orientation unified model for RGs and RLQs. Both of these observations are consistent with a model in which the velocity of propagation of the shock related to the jet-medium interaction is larger in RGs than it is in RLQs. One explanation of these observations is that the jets from RGs are interacting with a medium with a lower density than the medium that the jets from RLQs are interacting with.

8. OPTICAL SYNCHROTRON RADIATION

Relativistic electrons with large Lorentz factors will produce optical light via synchrotron radiation. For typical equipartition magnetic fields, electrons with $\gamma \sim 10^7$ will produce V-band light. Assuming that the electron energy distribution extends from Lorentz factors of about 10^3, responsible for the radio emission, to Lorentz factors of about 10^7, the optical synchrotron flux density f_s produced at the frequency v_s in terms of the radio flux density f_r produced at the frequency v_r is $f_s = f_r(v_r/v_s)^\alpha$. For $f_r \sim 10$ Jy at 178 MHz, $f_s \sim 3$ μJy at 5×10^{14} Hz (i.e., the V band) for $\alpha \simeq 1$. This value of f_s is typical of the optical continuum flux densities observed in high-redshift RGs. The problem with optical synchrotron as a source of the aligned components is that the lifetime for electrons with Lorentz factors of about 10^7 is only about 10^4 yr for sources at a redshift of about 1 (see § 4.3). Therefore, such a model would require that the electrons be continually reaccelerated. However, the radio spectral index is observed to steepen considerably between the radio hot spots and the inferred origin of the jets (Leahy et al. 1989), which implies that little or no reacceleration to high energies occurs in these regions, so that it is quite unlikely that the electron energy distribution extends to large Lorentz factors, except perhaps in the radio hot spots.

Optical synchrotron radiation is unlikely to play an important role in the radio bridges of high-redshift radio galaxies, but may be operative in some radio hot spots.

9. ENVIRONMENTS OF HIGH-REDSHIFT RADIO GALAXIES

It is interesting to consider whether high-redshift RGs are in protocluster or cluster environments. The evidence does not, however, overwhelmingly suggest that they inhabit rich environments, although this is not precluded by the data.

There are some observations which suggest that high-redshift RGs may be in protoclusters or clusters of galaxies, although none are definitive. First, high-redshift RGs often

have companions. Second, assuming a deceleration parameter $q_0 = 0$ and present age of the universe 10^{10} h^{-1} yr the co-moving number density of high-redshift RGs is about $3 \times (10^{-6}$ to $10^{-7})$ h^2 Mpc^{-3}: this is obtained if there are 100 RGs with redshifts between 1 and 2, each of which is a radio source for a time $t \simeq 10^6$–10^7 yr (see Table 1 of Daly 1991). These numbers are interestingly close to the current comoving number density of rich clusters of galaxies. However, if the radio sources are quite long-lived, or if the radio activity recurs in the same RG, the comoving number density of the sources is much lower: the lower bound on the comoving number density is obtained by considering only the RGs that are directly observed. If there are 100 sources with redshifts between 1 and 2, then the comoving number density of the sources is about 10^{-9} h^3 Mpc^{-3} (see Table 2 of Daly 1991).

Third, high-redshift RGs contain about 10^{12} $M_\odot$ in stars, estimated by assuming that the K-band light is produced by a passively evolving stellar population (Lilly 1990). At low redshift, such massive galaxies are often found in clusters of galaxies. Fourth, the dispersion of the K-band magnitudes is quite small, about 0.4 mag at a given redshift, suggesting that high-redshift RGs may be the precursors to present-day first-ranked giant elliptical galaxies which exhibit a similarly small dispersion in absolute magnitude. In addition, it is possible that the radio activity is related to the formation of the cluster of galaxies.

This evidence is not compelling, and it is possible that, other than undergoing a brief, $\sim 10^6$–10^7 yr radio outburst, these are otherwise unremarkable massive elliptical galaxies. Present-day powerful RGs are not located in rich environments, yet they have a fairly small dispersion in absolute V magnitudes, with $M_V \sim -22$. In addition, the large velocity of the shock propagating through the ambient medium suggests that the medium has a low density $\lesssim 10^{-3}$ cm^{-3} (see § 2.2).

This, however, does not preclude the galaxies from being in clusters of galaxies since there is ample evidence that the intra-cluster medium evolves strongly with redshift. This evidence includes (1) the comoving number density of optically selected clusters appear to be roughly constant out to redshifts of at least 0.5 (Gunn, Hoessel, & Oke 1986); (2) the cluster X-ray luminosity function exhibits strong evolution out to redshifts of about 0.3–0.5 (Edge et al. 1990; Gioia et al. 1990); and (3) powerful RGs that are typically detected in the field at low redshift inhabit both high- and low-density regions at redshifts of about 0.5 (Hill & Lilly 1991), as do RLQs (Yee & Green 1987).

At the present time the data do seem to be consistent with the high-redshift RGs being in clusters or protoclusters of galaxies, or being unremarkable massive galaxies undergoing a burst of radio activity.

10. DISCUSSION: ASSESSMENT OF THE MODELS

Five models to explain the alignment of the optical continuum and emission-line regions with the radio axis in high-redshift radio galaxies have been considered. Some observational facts that should be kept in mind in weighing which of these models are likely to be correct follow: (1) alignment of the optical continuum regions is seen in radio galaxies with redshifts $\gtrsim 0.7$; (2) the optical continuum and emission-line regions generally have very similar morphologies, and they are clumpy, elongated, and aligned with the radio axis; these regions may be quite extended, with sizes up to 100 kpc; (3) there appear to be two distinct types of alignments: (a) the optical continuum and emission-line regions track the radio structure in that local maxima in the continuum and line

emission are accompanied by local radio maxima (such as 3C 368), and (b) those in which the optical continuum and emission-line regions do not track the radio emission, that is, their local maxima are not related to the radio local maxima; (4) the emission-line luminosity is roughly proportional to the radio power, and the observations suggest that the line luminosity is comparable to the radio luminosity (see § 4.8): $L_{\text{lines}} \sim L_r$, where $L_r = L_{\nu_r} \nu_r$; (5) sources with steep radio spectral indices tend to have bluer optical to near-infrared colors; (6) in any given radio source the current phase of radio activity has been ongoing for a relatvely short time, $\sim 10^7$ yr; (7) for a source at a redshift of 1 the typical optical (V-band) luminosity $L_\nu \nu$ is about $\sim 10^{44}$ ergs s^{-1}, and the total emission-line luminosity is about $\sim 10^{44}$ ergs s^{-1}, assuming a Hubble constant of 50 km s^{-1} Mpc^{-1} and deceleration parameter $q_0 = 0$.

10.1. *The Inverse Compton Scattering Model*

The inverse Compton scattering model has several positive features. The alignment effect is expected to set in at redshifts $\gtrsim 1$; this is because the flux density of the IC scattered light is proportional to the energy density of the microwave background radiation, which increases as $(1 + z)^4$ (for a detailed discussion see Daly 1992a). If the relativistic electron energy distribution extends to low energies, the estimated IC scattered flux densities are comparable to the flux densities of the aligned components; IC scattering to the optical would explain the aligned optical continuum, and IC scattering to the ultraviolet would explain the aligned emission-line regions.

The optical and ultraviolet luminosities are expected to increase as the radio power increases and as the radio spectral index increases. These are in the same sense as the trends observed between the emission-line luminosity and the radio power (McCarthy et al. 1991), and between the radio spectral index and the optical to near-infrared color (Lilly 1989).

In this model the ultraviolet light is produced locally. This is a positive feature because the emission-line regions are often detected at significant distances from the AGN and the galaxy, suggesting a local source of excitation for the emission lines, since the cross section for absorption of ultraviolet radiation is quite large. For the sources in which the optical continuum and emission-line regions track the radio structure, it seems likely that the electron energy distribution extends to low energies and that the aligned components are related to the low-energy tail of the relativistic electron energy distribution; thus IC scattering could account for the optical and ultraviolet continuum in sources of this type.

The spectral index of the IC scattered light is identical to that of the radio emission produced by the low-energy electrons that IC scatter microwave photons to the optical and ultraviolet. If interactions between the relativistic electrons and the ambient gas have been negligible for electrons with Lorentz factors of ~ 100, the spectral index should be between about -0.7 and -1.0 which is characteristic of the higher frequency radio emission. If the relativistic electrons have been cooled via interactions with the ambient gas, then, as discussed in § 2.3, the spectral index should flatten and is likely to fall between about zero and -1.0. For the sources in which the optical continuum and emission-line regions do not track the radio structure, the relativistic electrons must cool in order for IC scattering to account for the aligned component. Although IC scattering could explain the alignments in these systems, it may be that a different mechanism is operating in sources of this type.

Light produced by inverse Compton scattering is not expected to be polarized (Blumenthal & Tucker 1974, § 3.3.5).

10.2. *Emission from Clumped Hot Gas*

Continuum and line emission from hot clumped gas along the radio bridge could account for the alignment effect. In this case the redshift dependence of the alignment effect could be explained as evolution of the properties of the ambient medium with redshift, or as a result of the increase of the radio, and hence emission-line, luminosity with redshift, or both. The gas along the radio axis could be shock heated; however, in order to understand the relationships between the radio, optical, and emission-line properties of high-redshift radio galaxies, it seems likely that at least part of the emission is produced by gas that is heated by interactions with the relativistic electrons. This requires that the gas and relativistic electrons be mixed, or that the interactions occur in boundary layers between the gas and magnetic flux tubes; the ambient gas in contact with the relativistic electrons in the radio bridge will be heated by the interactions with the relativistic electrons (Daly 1992c; § 2.3). The hot gas will produce line emission and optical continuum; additional line emission could be produced by the absorption ultraviolet continuum arising from thermal bremsstrahlung radiation from hotter gas $T \gtrsim 5 \times 10^5$ K.

Given that the gas is heated by interactions with the relativistic electrons, this model has the positive feature that the emission-line luminosity is expected to be proportional to the radio power, as observed (McCarthy et al. 1991; McCarthy 1991), and the optical continuum luminosity should increase as the radio spectral index increases as suggested by the trend between the optical to near-infrared color with the radial spectral index (Lilly 1989). The line luminosity should be about a factor of 10 larger than the optical continuum luminosity since at low temperatures the line emissivity is about a factor of 10 greater than the continuum emissivity (e.g., Raymond et al. 1976). The observations suggest that the line luminosity is comparable to the optical continuum luminosity $L_{\text{lines}} \sim L_\nu \nu$; thus the model would require gas with different temperatures and densities to account for the observations.

This mechanism may be operating in sources in which the optical continuum and emission-line regions track the radio structure. It may also be important in sources in which this is not the case since the gas must have a fairly high density $n_g \sim 1$ cm^{-3} to radiate efficiently and so may be more important in the regions along the radio bridge that are close to the galaxy.

The spectral index of the continuum produced by thermal bremsstrahlung is about -0.4 for $h\nu \sim kT$ and is roughly flat for $h\nu \ll kT$ (Blumenthal & Tucker 1974). Light produced via thermal bremsstrahlung is not expected to be polarized.

Note that this mechanism will only be important for a short time, since the energy supply contained in the low-energy population of relativistic electrons will be depleted in about $10^7 n_g$ yr, where n_g is the density of the ambient gas in units of cm^{-3}. It is interesting to note that this mechanism may be operating in conjunction with IC scattering since this mechanism will cool the relativistic electrons that begin with $\gamma \sim$ few 100 to $\gamma \sim 50$ to 100 in about $10^7 n_g$ yr.

10.3. *Jet-induced Star Formation*

The alignments may also be the result of jet-induced star formation. The redshift dependence of the alignment effect could be due to the evolution of the properties of the ambient medium with redshift.

The optical continuum and emission-line regions generally have very similar morphologies. In this model, the ultraviolet radiation to power the emission-line regions would be massive stars, suggesting stellar masses of $\gtrsim 50 M_\odot$.

The negative feature of this model is that it cannot account

for the relationships between the radio, optical, and emission-line properties of the high-redshift RGs in a straightforward way. As discussed in § 5, it is not clear how the observed trend between the optical to near-infrared color and the radio spectral index (Lilly 1989) could result in this model; nor is it clear how the radio power and emission-line luminosities would be related. If the ambient gas and relativistic electrons are mixed, then the interactions between the two are likely to inhibit star formation; if the two are separate, then perhaps the star formation efficiency increases as the external pressure increases (Rees 1989).

The fact that the co-added spectra of several high-redshift RGs exhibit stellar absorption features (Chambers & McCarthy 1990) does not necessarily imply that the aligned component is stellar (see § 5 and Daly 1992a). These absorption features may be produced by stars in the main body of the galaxy or by interstellar absorption. The stellar ages suggested by Chambers & McCarthy (1990) and by Chambers & Charlot (1990) are at least a factor of 30 older than the estimated age of the radio activity. In addition, some of the ages suggested are much larger than 10^8 yr; if the aligned component is stellar, the alignment should persist for $\lesssim 10^8$ yr (see § 5 and Daly 1990).

The starlight is expected to have a flat spectrum, and it is not expected to be polarized.

10.4. *Scattering of Anisotropic Radiation from the AGN*

The AGN in radio galaxies may produce light with a luminosity similar to that released in the form of directed kinetic energy. At the present time it is not known whether this "orientation unified model" for RGs and RLQs is correct. If the RGs have $L_{phot} \sim L_{dKE}$, then the light must be emitted anisotropically, since it is not detected directly. The anisotropic radiation may scatter with clumped ambient gas and lead to the optical continuum alignment and the alignment of the emission-line regions if they are excited by ultraviolet light from the AGN. Independent of whether the gas is clumped, the gas mass required along the radio axis is between about 10^{11} and 10^{13} $M_\odot$. This mechanism could explain the aligned components within about 50 kpc of the AGN. The correlation between the emission-line luminosity and the radio power follows in this model because the optical luminosity is correlated with the radio power in high-redshift RLQs.

Could this model account for the sources in which the maxima in the optical continuum and emission-line regions are accompanied by local maxima in the radio emission? This could be understood in this model if the primary process which ionizes the gas is interactions between the low-energy tail of the relativistic electrons and the ambient gas (see § 2.3 and Daly 1992c). In this case, the regions with a high density of relativistic electrons may show up as local maxima in the radio emission, and it will be in these regions that the gas is most highly ionized; thus these would be the sites where light from the AGN is most efficiently Thomson scattered into the observer's line of sight.

For separations greater than about 50 kpc from the AGN the flux of light from the AGN is decreasing rapidly, and the ultraviolet light from the AGN is likely to have been absorbed. Therefore, the alignment of the emission-line regions at large distances from the galaxy is unlikely to be associated with light from the AGN.

The scattered light is expected to be polarized. Nuclear polarization is detected in some sources but not in others (di Serego Alighieri 1989; Jannuzi & Elston 1991; Antonucci 1992; see the discussion in § 11). The polarized nuclear light

could be produced by optical synchrotron or by Thomson scattering of anisotropic radiation. The polarization of the nuclear light is the strongest argument in favor of this model.

There is one source, 3C 368, in which polarization of the extended optical continuum has been detected (Scarrot et al. 1990). This suggests that the observed light is produced by Thomson scattering of anisotropic radiation from the AGN. However, 3C 368 is a source in which the optical continuum and emission-line morphologies are quite similar to the radio morphology. This suggests that the gas is ionized by interactions with the relativistic electrons, so that the gas is most highly ionized in the regions with a high density of relativistic electrons, and these electrons produce a local maxima in the radio emission. Alternatively, the structure of 3C 368 could be explained as a two-component model: part of the aligned light could result from Thomson or dust scattering of anisotropic radiation, and part could result from inverse Compton scattering of microwave background photons with the low-energy tail of the relativistic electrons, for example, or by heating of the gas by relativistic electrons. A two-component model for the aligned optical continuum in 3C 368 is suggested by polarization observations since the degree of polarization changes with wavelength (Scarrot et al. 1990).

10.5. *Optical Synchrotron Radiation*

If the electron energy distribution extends to very large energies $\gamma \sim 10^7$, optical continuum will be produced by synchrotron radiation. In the typical minimum energy magnetic fields the lifetime of an electron with $\gamma \sim 10^7$ is about 10^4 yr. Therefore, it is unlikely that optical synchrotron plays an important role in the radio bridges of high-redshift RGs.

11. CONCLUSIONS

Both stellar and nonstellar processes are likely to be important in high-redshift RGs. The K-band light is most likely produced by a mature passively evolving stellar population with a well-defined mass and age (at any given redshift) implying that the galaxies are fairly old (Lilly 1990), as discussed in § 1. The relationships between the radio properties and the emission-line and optical continuum properties suggest that the aligned optical continuum and emission-line regions are likely to be produced by nonstellar processes.

All of the models that have been proposed to explain the aligned optical continuum require significant amounts of gas along the radio axis, with gas masses ranging from $\sim 10^{11}$ to 10^{13} $M_\odot$, except for the IC scattering model and the jet-induced star formation model in which the stellar initial mass function is strongly weighted to the high-mass end (Bithell & Rees 1990). The gas in the vicinity of the radio galaxy could be smoothly distributed, or in clumps of various sizes and densities. The radio properties of the galaxies suggest that the jets and associated shocks are interacting with a fairly low density medium $n \lesssim 10^{-2}$ to 10^{-3} cm^{-3} (see § 2.2). Thus, it seems that the gas in the vicinity of the RG is strongly clumped; some of the "clumps" are probably galaxies, companions to the RG that happen to lie along the radio bridge of the galaxy. Hence, if the high-redshift RGs are located in clusters or protoclusters of galaxies, the intracluster medium is not yet in place.

For the RGs in which the optical continuum and emission-line regions have morphologies similar to the radio morphology, the aligned components are probably related to the low-energy tail of the relativistic electron energy distribution. Three processes may account for these alignments: inverse Compton scattering of microwave background photons with

the relativistic electrons, emission from clumpes hot gas that is heated by interactions with relativistic electrons, and Thomson scattering of anisotropic radiation from the AGN by gas along the radio axis that is ionized by interactions with relativistic electrons. In the IC model optical and ultraviolet continuum lead to the alignments; the ultraviolet radiation powers the emission lines. In clumped hot gas model, the relativistic electrons heat and ionize the gas. The hot gas produces continuum and line emission; the emission-line regions may be powered directly via the ionization of the neutral gas by interactions with the relativistic electrons, or the emission lines may be powered by ultraviolet continuum produced via free-free radiation from hotter gas. In the Thomson scattering model, the regions that are most highly ionized have the largest optical depth to Thomson scattering, and these would be the regions where the relativistic electrons have the highest density, and hence are near the maxima in the radio emission.

For the sources in which the optical continuum and emission-line regions do not track the radio morphology, several of the above models are viable. The aligned components could be produced by inverse Compton scattering of electrons that have been cooled since they were accelerated, by free-free and line radiation from gas heated by interactions with the relativistic electrons, by starlight, or by Thomson scattering of anisotropic radiation from the AGN.

The polarization of the aligned component is an important diagnostic for distinguishing between the models. At the present time, the only models that predict that the aligned optical component should be polarized are the dust and Thomson scattering model (see §§ 6 and 10.4). Nuclear optical polarization has been detected in 3C 265 (Jannuzi & Elston 1991; Antonucci 1992) and 3C 277.2 and 3C 368 (di Serego Alighieri et al. 1989), and optical polarization of the nuclear or integrated light has been detected in five RGs, while upper bounds have been obtained for two RGs (Jannuzi & Elston 1992, private communication).

However, the important question for the aligned component of the high-redshift RGs is whether the extended aligned optical continuum is polarized. Scarrott et al. (1990) report that the extended aligned optical continuum in 3C 368 is polarized, which strongly suggests that at least part of the aligned optical continuum is produced by Thomson or dust scattering of anisotropic radiation from the AGN. The wavelength dependence of the polarized component suggests that another source of aligned optical continuum is important in 3C 368.

Important diagnostics for distinguishing between the models include better determinations of the relationships between the radio, optical, and emission-line components, the color of the aligned component, which may be a function of separation from the main body of the galaxy, and whether the aligned components are polarized.

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