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INVERSE COMPTON SCATTERING AND THE ALIGNMENTS OBSERVED IN HIGH-REDSHIFT RADIO GALAXIES

RUTH A. DALY
Joseph Henry Laboratories, Department of Physics, Princeton University, Princeton, NJ 08544
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ABSTRACT

A new model to explain the alignments of the optical continuum and emission-line regions with the radio axes in high-redshift radio galaxies is presented. Inverse Compton scattering of microwave background photons with relatively cool relativistic electrons will produce near-infrared, optical, and ultraviolet continuum. Radio bridges detected in high-redshift radio galaxies provide direct evidence for a reservoir of relativistic electrons along the radio axes, hence the upscattered radiation will be aligned with the radio axes.

The constraints on the jet-induced star formation model implied by the properties of the radio bridges are discussed, and the inverse Compton scattering model is presented.
Subject headings: galaxies: evolution — galaxies: jets — radio continuum: galaxies

1. INTRODUCTION

Radio-selected galaxies have been detected out to redshifts of about 4. High-redshift radio galaxies are very powerful, classical double radio sources. Most of the observed radio emission is produced in the radio lobes and hot spots, which straddle the galaxy with typical lobe-lobe separations on the order of 100 kpc; the radio lobes, and core if it is detected, define the radio axis. The radio, emission-line, and optical continuum properties of the galaxies are very closely related: the emission-line regions and the regions of optical continuum are quite extended and lie in the vicinity of the radio axis (Chambers, Miley, & van Breugel 1987; McCarthy et al. 1987); in some cases near-infrared continuum is also aligned with the radio axis (Eisenhardt & Chokshi 1990; Rigler et al. 1992).

The morphologies, luminosities, and inferred star formation rates of the high-redshift radio galaxies indicate whether these systems are young or old, and whether their evolution is fairly complete. A key discriminant is whether the aligned component is stellar or nonstellar, and the age of the stars if this component is stellar. If the aligned optical component is stellar and rather old, $\sim 5 \times 10^8$ yr (see, for example, Chambers & Charlot 1990), the inferred star formation rates are quite large and the incorporation of these stars into the main body of the galaxy may alter the morphology and luminosity of the galaxy: the galaxy might be considered to be in the process of forming.

Chambers & McCarthy (1990) argue that the aligned component is likely to be stellar and therefore associated with the radio activity because the combined spectrum of the galaxies exhibits stellar absorption features, though similar features could be produced by interstellar absorption. The combined spectrum presented by Chambers & McCarthy (1990) is dominated by two galaxies, 3C 256 and 3C 239. The spectrum includes light from all regions of the galaxies, and such a spectrum could be produced by ongoing star formation in the main body of the galaxy: the spectrum does not necessarily imply that the aligned component is stellar. It is interesting to note that the separation of the radio lobes in 3C 256 and 3C 239, and the typical properties of the radio bridges (discussed below), indicate that the current episode of radio activity in these systems began less than about 10^7 yr ago, while the combined spectrum indicates that the stars are about 5×10^8 yr old (Chambers & McCarthy 1990).

If the alignments are caused by jet-induced star formation, then the star formation rates are substantial, about 100 $M_\odot$ yr^{-1}, and were even larger in the recent past (e.g., Chambers & McCarthy 1990). If the alignments are due to nonstellar processes such as scattering of anisotropic radiation from the active galactic nucleus (AGN) (Fabian 1989), optical synchrotron radiation (Daly 1992), or inverse Compton scattering of microwave photons with relativistic electrons (as discussed here and by Daly 1992), then the star formation rates in these systems are not large and the alignments do not necessarily imply that these galaxies are young or in the process of forming. One might go further and consider the implications of the properties of the K-band Hubble diagram and the near-infrared morphologies of the high-redshift radio galaxies. The continuity and small dispersion of the K-band Hubble diagram has been taken to imply that most of the near-infrared emission is produced by a passively evolving stellar population with a well-defined mass (Lilly & Longair 1984; Spinrad & Djorgovski 1987; Lilly 1989, 1990), which is supported by the near-infrared morphologies of the high-redshift radio galaxies (Rigler et al. 1992; Chokshi & Eisenhardt 1991). These characteristics imply that the systems are mature, being dynamically relaxed and having completed most of their star formation.

It is important to keep in mind that the high-redshift radio galaxies may be multicomponent systems, as originally suggested by Lilly & Longair (1984). Star formation may be ongoing in the main body of the galaxy, and this need not be related to the aligned optical and emission-line components. In fact, the radio properties of radio bridges in high-redshift radio galaxies indicate that if the aligned optical component is produced by stars, then it can only be associated with the current episode of radio activity if the stars are quite young, $\sim 10^6$–10^7 yr. If the stars are older, $\sim 10^8$ yr, the system must undergo multiple radio outbursts if the aligned component results from jet-induced star formation, but in this case it is unclear why young systems, systems in their first or second round of jet-induced star formation, have not been detected.

The age of a particular outburst of radio activity is constrained by the properties of the radio bridges (Alexander & Leahy 1987; Leahy, Muxlow, & Stephens 1989); radio bridges are low surface brightness regions, often cylindrical in shape, that have been detected between the radio hot spot and the main body of the galaxy. The 151 MHz to 1.4 GHz radio spectral index as a function of position in the radio bridges can be used to deduce a lower bound on the velocity of propagation of the position of a radio lobe relative to the main body of the galaxy, assuming that the backflow velocity in these systems is less than that of the position of the lobe relative to the galaxy.

The observations of Alexander & Leahy (1987) and Leahy et al. (1989) suggest that the backflow velocities in powerful radio galaxies are small relative to the velocity with which the position of the lobe moves away from the origin of the galaxy. Distortions of the radio bridges in low-redshift, low-power radio galaxies suggest substantial backflow (Leahy & Williams 1984), but such distortions are much less common in powerful radio galaxies, such as the high-redshift radio galaxies. Furthermore, there is a correlation of velocity (which is either that of the lobe or that of the backflow) with radio power. This is expected if the velocity is that of the lobe position relative to the origin of the galaxy, but is rather difficult to interpret if the velocity is that of a backflow, as discussed by Alexander & Leahy (1987). And, if the velocity were that of a backflow, the axial ratio of the radio bridges should increase with radio power; however, the axial ratio decreases (the bridges are thinner) as the radio power increases (Leahy et al. 1989).

The radio spectral index as a function of position in the radio bridges suggests that the position of a radio lobe is moving away from the radio galaxy with a velocity of at least $0.01c$ to $0.1c$ (Leahy et al. 1989); there are many cooling mechanisms that will cause the velocity inferred from the radio data to be an underestimate. For a typical radio lobe separation of about 100 kpc this implies that the current episode of radio activity has been ongoing for less than about 10^6–10^7 yr. Stars with ages as large as 10^8–10^9 yr cannot be related to the current episode of radio activity but may be related to a much earlier episode of radio activity. This, too, seems unlikely because the alignment is expected to last for less than about 10^8 yr if it is due to jet-induced star formation (Daly 1990), and because some systems undergoing a first or second episode of radio activity and jet-induced star formation should have been detected if such a picture were correct. The aligned component could be stellar if the stars are young, as discussed in detail by Bithell & Rees (1990).

The aligned optical continuum could be produced by nonstellar processes. A new model to explain the alignment of the optical continuum regions with the radio axis is presented here: inverse Compton scattering of relatively low energy relativistic electrons with the relic photons that comprise the microwave background radiation. The radio bridges provide direct evidence for a population of relativistic electrons along the jet axis. Rees & Setti (1968) point out that inverse Compton scattering between relativistic electrons and the relic photons is likely to be an important process in high-redshift radio sources because the flux density of the upscattered radiation depends on the energy density of the microwave background, which evolves strongly with redshift. Inverse Compton scattering can also produce steep-spectrum ultraviolet continuum, which could be a significant energy source to power the emission lines. Alternatively, the emission lines could be powered by anisotropic ultraviolet radiation from an (otherwise undetected) AGN (van Breugel & McCarthy 1990; McCarthy 1991). General aspects of the upscattering model are presented in § 2; a more detailed description is given by Daly (1992); and a discussion follows in § 3.

2. THE INVERSE COMPTON SCATTERING MODEL

Scattering between a photon with frequency ν_b and an electron with Lorentz factor γ will on average upscatter the photon to a frequency $\nu = (4/3)\gamma^2\nu_b$. An electron with Lorentz factor γ will upscatter relic photons to an observed frequency (since both ν_b and ν scale as $1 + z$) of $\nu_{14} = \nu \times 10^{14}$ Hz when $\gamma = 22\sqrt{\nu_{14}}$. Scattering between relic photons and relativistic electrons with Lorentz factors of (125–250), 60, 50, 45, 40, and 25 will produce continuum (in the observer's frame) in the following bands, respectively: the ultraviolet (1–4 rydbergs), B, V, R, I, and K. In the rest frame of the galaxy, ultraviolet continuum (1–4 rydbergs) is produced by upscattering of relic photons by electrons with $\gamma \simeq (125\text{–}250)/\sqrt{1 + z}$. In order for inverse Compton scattering to affect the optical and emission-line morphologies of the high-redshift radio galaxies, the electron energy distribution must extend to fairly low energies.

The high-redshift radio galaxies are very powerful radio emitters. The relativistic electrons are the energy source of the radio emission, which is produced via synchrotron radiation as the electrons spiral about the magnetic field. Most of the observed radio emission comes from the hot spots and lobes. The hot spots are the site of the interaction between the jet and the ambient medium; it is here that the particle acceleration most likely occurs, and hence it is here that the electrons are accelerated to Lorentz factors $\gamma = E_e/(m_e c^2)$ which may be quite large ($\gtrsim 10^3$). The radio lobe is the region surrounding the hot spot, and it is thought to be the spillover region into which the relativistic electrons flow from the hot spot. The interaction region between the jet and the ambient medium propagates away from the main body of the galaxy with some velocity, leaving behind a cylindrical volume of relativistic electrons. The radio bridges provide direct evidence that such a reservoir of relativistic electrons lies along the radio axis. This implies that optical and ultraviolet continuum produced by inverse Compton scattering of relic photons with relativistic electrons will be aligned with the radio axis. The expected morphologies are discussed by Daly (1992).

The relativistic electrons that produce the 178 $(1 + z)$ MHz radiation by which the galaxies are selected typically have $\gamma \sim 10^3$. If the electron energy distribution extrapolates down to $\gamma \simeq 22\sqrt{\nu_{14}}$, then the flux density of inverse Compton scattered radiation $f_{\rm ic}$ that would be observed at ν_{14} relative to the flux density of the synchrotron radiation f_r [where $f_r \equiv dE/(dt\, dA\, d\nu) \propto \nu_r^{-\alpha}$] that would be observed at ν_r is (e.g., Pacholczyk 1970; Blumenthal & Tucker 1974)

$$\frac{f_{\rm ic}(\nu_{14})}{f_r(\nu_r)} \simeq 1.6 \times 10^{-12}\epsilon^{-(1+\alpha)}(1 + z)^{1-\alpha} \times \frac{b}{a}\left(\frac{7.5 \times 10^3}{\nu_{14}} \frac{\nu_r}{178\ \text{MHz}}\right)^{\alpha}, \tag{1}$$

where the magnetic field of the lobe has been parameterized in terms of the energy density of the microwave background radiation $u_{\rm mb}$, $B_\perp^2 \equiv \epsilon^2(8\pi u_{\rm mb})$, since this seems to be a valid approximation for the equipartition or minimum-energy magnetic fields of the lobes of the high-redshift radio galaxies (e.g., Miley 1980; for a detailed discussion in this context see Daly 1992); $B_\perp \equiv 3.3\epsilon(1+z)^2$ μG assuming that the current temperature of the microwave background is about 2.75 K; the ratio b/a takes on the values 80, 160, and 420 for α-values of 0.7, 1.0, and 1.5, respectively.

Equation (1) indicates that when the radio spectral index α continues to about 1 MHz (which is produced by electrons with $\gamma \sim 100$) with the same slope as that observed at 178 MHz (which is produced by electrons with $\gamma \sim 10^3$), the flux density of the upscattered radiation is large. For example, if the index of the electron energy distribution extrapolates down to a Lorentz factor of 50 with a radio spectral index of about 1 and a 178 MHz radio flux density of about 10 Jy, the flux density of optical continuum that would be observed in the V band is about 3×10^{-6} Jy for $\epsilon \simeq 1$ and about 2×10^{-5} for $\epsilon \simeq \frac{1}{3}$, corresponding to V apparent magnitudes of about 22.7 and 20.7, respectively.

The optical continuum and emission-line regions generally lie in an elongated region between the two radio hot spots. In some cases the optical continuum and emission-line regions extend to and cover the radio lobes, and they sometimes have local maxima quite close to or coincident with the radio maxima. Clearly, in these cases, the radio, optical, and line emission are strongly linked, and the optical and ultraviolet radiation probably result either from inverse Compton scattering or from optical and ultraviolet synchrotron emission (see Daly 1992); cooling time scales argue that inverse Compton scattering is the likely origin of the optical and ultraviolet photons. For example, in 3C 368 (Djorgovski et al. 1987; Chambers, Miley, & Joyce 1988), the optical continuum and emission-line regions extend to, cover, and have local maxima close to that of the radio emission in the region of the southern radio lobe, but not the northern radio lobe. If the coincidence of these maxima is due to inverse Compton scattering, it implies that the distribution of energies of the electrons in the lobe extends down to fairly low Lorentz factors; upscattering of relic photons by electrons with Lorentz factors of about 50 will produce V-band light. When they do not cover the lobe, it implies that the electron energy distribution has a cutoff at $\gamma_{\rm co} \gtrsim 50$–100 depending on the frequency at which light is no longer observed to originate from the lobe. If the electron energy distribution in the lobes of the high-redshift radio galaxies has a low-energy cutoff that is of order 100 or greater, then the relativistic electrons in the lobes must cool if they are to upscatter radiation to ultraviolet, optical, and near-infrared frequencies.

One way in which the electrons in the lobe may be cooled is by the expansion of the lobe, after which time it is referred to as a postlobe. If the lobe is overpressured relative to the ambient medium, it will expand. Radial cylindrical expansion by a factor χ will cause the initial cutoff $\gamma_{\rm co}$ of the energy distribution in the lobe to decrease by $\chi^{-2/3}$, and the radio flux density to decrease by $\chi^{-10\alpha/3-2}$. Spherical expansion by a factor χ will cause the initial cutoff $\gamma_{\rm co}$ of the electron energy distribution of the lobe to decrease by χ^{-1}, and the radio flux density to decrease by $\chi^{-4\alpha-2}$.

The flux density $f_{\rm ic,post}$ of upscattered relic photons from a postlobe, relative to the flux density of the radio lobe $f_{r,\rm lobe}$, may be estimated assuming that the lobe that expanded to form the postlobe was similar to the lobe that is currently active in the galaxy. This ratio is

$$\frac{f_{\rm ic,post}}{f_r(\nu_r)} \simeq 1.6 \times 10^{-12}\chi^{-2\alpha}\epsilon^{-(1+\alpha)}(1+z)^{1-\alpha} \times \frac{b}{a}\left(\frac{7.5 \times 10^3}{\nu_{14}}\frac{\nu_r}{178\ \rm MHz}\right)^{\alpha} \quad (2)$$

for spherical expansion; for cylindrical expansion the factor $\chi^{-2\alpha}$ is replaced by $\chi^{-4\alpha/3}$ (Daly 1992). The maximum flux density of upscattered radiation is obtained by requiring that the lobe expand by just enough to bring $\gamma_{\rm co}$ down to $22\sqrt{\nu_{14}}$. In this case the frequency dependence in equation (2) cancels, and the maximum flux density that can be detected in any wave band, assuming that upscattering to this wave band requires that the electrons in the lobe cool, is

$$\frac{f_{\rm ic,post}(\rm max)}{f_{r,\rm lobe}(178\ \rm MHz)} \simeq 1.6 \times 10^{-12}(360)^{\alpha}\frac{b}{a}(1+z)^{1-\alpha}\epsilon^{-(1+\alpha)}\left(\frac{\gamma_{\rm co}}{100}\right)^{-2\alpha} . \quad (3)$$

For example, assuming $\gamma_{\rm co} \sim 100$, $f_r(178\ \rm MHz) \simeq 10$, and $\alpha \simeq 1$, the maximum flux density in any wave band that can be produced by upscattering (given that scattering to that wave band required the lobe to expand) is about 9×10^{-7} Jy for $\epsilon \simeq 1$, and about 8×10^{-6} Jy for $\epsilon \simeq \frac{1}{3}$. These flux densities are comparable to those detected in the optical continuum of the high-redshift radio galaxies. Hence, if the radio galaxy has a single postlobe that has expanded by the minimum amount required, or if there are several postlobes each of which has expanded by more than the minimum required, inverse Compton scattering would produce optical flux densities comparable to those observed. Altenatively, the electrons could be cooled to sufficiently low energies to upscatter relic photons to optical frequencies by synchrotron or inverse Compton cooling, as discussed by Daly (1992).

Equations (1), (2), and (3) indicate that, for a single lobe or a postlobe, the upscattered flux density has a bivariate dependence on the radio flux density and the radio spectral index. The flux density of the upscattered radiation increases as the radio spectral index increases for sources with a given radio flux density. This will cause the galaxy to appear bluer, and would explain the trend found by Lilly (1989): galaxies with steep radio spectra tend to have larger values of f_{5000}, that is, they are bluer. And, for radio components with a given radio spectral index, the upscattered flux density increases as the radio flux density of the component increases. This implies that the alignment effect should be less striking for the 1 Jy fields and the 4C radio galaxies than it is for the 3C radio galaxies. In addition, it would explain the correlation between the emission-line strength and the radio power (e.g., McCarthy 1991).

Scattering of relic photons by electrons with Lorentz factors of $\sim(125$–$250)/\sqrt{1+z}$ produces ultraviolet continuum, which will ionize the gas in the emission-line clouds and power the emission lines, as discussed by Daly (1992). The emission-line luminosity $L_{\rm line}$ is related to the cloud covering factor f_c and the optical depth per cloud τ: $L_{\rm line} \simeq L_{\rm uv} f_c$ for $\tau > 1$ (which is generally assumed to be the case), and $L_{\rm line} \simeq L_{\rm uv} f_c \tau$ for $\tau \lesssim 1$. Equation (1), (2), or (3) may be used to estimate $L_{\rm uv}$, since $L_{\rm uv} \simeq P_{\rm uv}\nu_{\rm uv}$ and $P_{\rm uv}/P_r = f_{\rm ic}(\nu_{\rm uv})/f_r$, hence $L_{\rm uv} \simeq (f_{\rm ic}/f_r)\nu_{\rm uv}P_r$, where P_r is the radio power $P_r \equiv dE\,dt^{-1}\,d\nu^{-1}$. Using equation

(3), and assuming $\gamma_{co} \sim 100$, $\epsilon \sim 1$, and $\alpha \sim 1$, $L_{line}/P_r(178\ \mathrm{MHz}) \sim 3 \times 10^8 f_c$ for $\tau > 1$, and $L_{line}/P_r(178\ \mathrm{MHz}) \sim 3 \times 10^8 f_c \tau$ for $\tau \lesssim 1$ result. The observed correlation implies that $L_{line}/P_r(1.4\ \mathrm{GHz}) \sim 10^8$, which for $\alpha \sim 1$ implies that $L_{line}/P_r(178\ \mathrm{MHz}) \sim 10^7$.

In the inverse Compton scattering model the line luminosity is expected to be proportional to the radio power. The normalization of the observed correlation is reproduced for $f_c \sim 10^{-1}$ to 10^{-2} for $\tau > 1$ and with $f_c \tau \sim 10^{-1}$ to 10^{-2} for $\tau \lesssim 1$. Scatter in the observed correlation will result from the distribution of radio spectral indices of the galaxies, from the distribution of cloud covering factors and optical depths, and from the different number of postlobes per system.

3. DISCUSSION

It has been shown that inverse Compton scattering of relic photons (the microwave background radiation) with relatively cool relativistic electrons will produce near-infrared, optical, and ultraviolet continuum with flux densities comparable to those observed, and the upscattering regions will lie along the radio axis because this is where the relativistic electrons are located. The inverse Compton scattering model accounts for the flux densities and alignments with the radio axis of the optical continuum (in some cases near-infrared continuum) and the emission-line regions. The model requires that the electron energy distribution extend to low energies; in some systems the electron energy distribution in the radio lobes appears to extend to low energies, while in others it does not. When the electron energy distribution of the electrons in the radio lobes does not extend to low energies, the electrons in the lobes must cool if they are going to upscatter relic photons to optical and ultraviolet frequencies, as discussed in § 2.

Two expectations of this model are supported by observations. The flux density of upscattered radiation is expected to increase as the radio spectral index increases for sources with a given radio flux density, which is supported by the trend between the radio spectral index and the near-infrared to optical color (Lilly 1989). The flux density of the upscattered radiation is expected to increase as the radio flux density increases for sources with a given radio spectral index, which is supported by the correlation between the emission-line luminosity and the radio power (see § 2).

The alignment effect is expected to become more pronounced in radio galaxies at high redshift (for radio galaxies with a given radio flux density) because the flux density of upscattered radiation is only weakly dependent on redshift (as long as $\epsilon \sim 1$; see § 2), while the optical flux density due to starlight or light from an AGN decreases as the redshift of the source increases.

Inverse Compton scattered radiation from lower redshift radio galaxies is expected to have a lower surface brightness and flux density than that from high-redshift radio galaxies with a similar radio flux density. This is because the flux density of the upscattered radiation is roughly proportional to the energy density of the microwave background radiation which evolves quite strongly with redshift. This is evident in equations (1), (2), and (3) when one considers the behavior of the equipartition magnetic fields, parameterized by ϵ, at low redshifts. The equipartition fields of radio galaxies with redshifts greater than about 1 imply that $\epsilon \sim 1$, but this may not hold for lower redshift systems, in which the lobe minimum magnetic field strengths are typically $\sim 10^{-5}$ G. For example, Cygnus A has an equipartition field of about 5×10^{-5} G (Carilli et al. 1991), implying $\epsilon \simeq 15$, so the upscattered flux density is decreased by about 10^{-2} for $\alpha \sim 0.7$ from that computed assuming $\epsilon \sim 1$. When the field strengths of low-redshift radio sources imply large values of ϵ, the flux density of inverse Compton scattered relic photons will be smaller than the flux density of upscattered radiation from high-redshift radio galaxies in which $\epsilon \sim 1$. In the cases in which the magnetic field of low-redshift radio sources is well approximated by $\epsilon \sim 1$, the surface brightness of the upscattered radiation may be too low to detect.

Several processes may be occurring in each of the high-redshift radio galaxies. The existence of the radio lobes implies the existence of a massive compact central object, and nonstellar radiation from this object must be present at some level, though it remains to be determined whether the central source releases most of its energy in the form of directed kinetic energy or in the form of radiation (which may be isotropic or anisotropic). It may be the case that one mechanism for the alignment effect is operating in most of the high-redshift radio galaxies, or that one process dominates in some systems while another dominates in other systems. Star formation may be ongoing in the main body of the galaxy and along the jet axis. Nonstellar processes such as inverse Compton scattering, optical synchrotron emission, and scattering of an anisotropic radiation field may also have an effect on the near-infrared, optical, and emission-line morphologies of the high-redshift radio galaxies.

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