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ON SPECTRAL AGING IN LOBES OF DOUBLE RADIO SOURCES

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ABSTRACT

We stress the sensitivity of the ages derived from the observed spatial gradients of spectral index along the lobes of double radio sources to the presence of small variations of magnetic field. Age variations inconsistent with the simple picture of lobe formation can be inferred if a uniform magnetic field throughout the lobe is assumed, particularly when the magnetic energy density in some regions is comparable to that of the cosmic microwave background. Our reanalysis of the multifrequency radio data of Alexander for the western lobe of 3C 234, incorporating a small magnetic field gradient indicated by the equipartition estimates, provides no clear evidence for the claimed *in situ* acceleration. Our study provides additional support for the assumption of equipartition in the lobes.

Subject headings: galaxies: individual (3C 234) — galaxies: structure — radio sources: galaxies

I. INTRODUCTION

In classical double radio sources the radio spectral index is often found to steepen progressively along the lobe with increasing distance from the hot spot toward the parent galaxy. Such spectral gradients are believed to arise mainly from radiation losses suffered by relativistic plasma left behind by an advancing hot spot in which the particles are accelerated (e.g., Burch 1977)

Studies of such spectral gradients along the lobes have been used extensively for estimating the ages and the expansion velocities of radio galaxies (e.g., Burch 1977; Willis and Strom 1978; van Breugel 1980*a*, *b*; Winter *et al.* 1980; Myers and Spangler 1985; Alexander and Leahy 1987; Leahy, Muxlow, and Stephens 1989).

Some authors have further inferred *in situ* acceleration of relativistic particles within the lobes from such studies (e.g., Willis and Strom 1978; Alexander 1987), although this is not found to be necessary for several equally well observed sources (e.g., Winter *et al.* 1980; Alexander and Leahy 1987). Also, examples of large double sources are known where spectral gradients are not detected (Jenkins and Scheuer 1976; Gopal-Krishna, Joshi, and Ananthakrishnan 1976; Gopal-Krishna 1977; Högbom 1979). Typically, the observed special gradients have yielded ages of (3–60) $\times 10^6$ yr and velocities of advance of the hot spots relative to the lobes in the range 5000–60,000 km s^{-1} (e.g., Myers and Spangler 1985; Alexander and Leahy 1987; Jägers 1986); these velocities may be higher than the true velocities of the hot spots relative to the parent galaxies, in view of the likelihood of a significant plasma backflow in the lobes (Norman *et al.* 1982; Leahy and Williams 1984).

The most detailed analyses of spectral aging incorporate aperture-synthesis maps at four or five frequencies stretching from ≈ 0.1 to above 10 GHz. Such maps should have not just high sensitivity and angular resolution but also similar *u-v* coverage over the entire frequency range; these requirements have been rarely met to date. Aside from Cygnus A (Spinks, Rees, and Duffett-Smith 1986 and references therein), another source for which such high-quality data are available is the powerful radio galaxy 3C 234 with an angular size of 1′.8 and a redshift $z = 0.1848$ (linear size = 460 kpc, based on $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$). For this object, Alexander (1987) has presented high-resolution maps at 1.4 and 1.6 GHz (Leahy, Pooley, and Riley 1986), has reanalyzed data at 2.7 and 5.0 GHz from Burch (1979) and Riley and Pooley (1975), and also has obtained a map at 15.0 GHz. This has enabled him to derive the five-frequency spectra at 35 different locations across the source.

An anomalous feature revealed by the observations of 3C 234 is that, whereas a usual progressive change of age is inferred along the eastern lobe, the aging appears to cease roughly midway between the western hot spot and the nucleus (Alexander 1987). Two possible explanations for this anomaly, discussed by Alexander, are (i) the onset of particle reacceleration and (ii) recompression of the radiating plasma. He convincingly dismisses the second possibility, since the brightening expected at low frequencies at those locations (Scheuer and Williams 1968) is not observed; furthermore, there is no significant enhancement of polarized emission that would have arisen in the event of anisotropic compression (Laing 1980). Reacceleration, on the other hand, would flatten the spectrum without increasing the lobe brightness at low frequencies. Since there is no evidence for shocked flow in the lobe, Alexander favors stochastic reacceleration driven by instabilities in the backflow interacting with the gaseous corona of the parent galaxy. Clearly, any evidence for such an important astrophysical process deserves close scrutiny.

Here we suggest an alternative explanation for the apparent cessation of spectral aging in the western lobe of 3C 234. The explanation derives from the sensitive dependence of the spectral break frequency ν_b upon the ratio of energy densities of the magnetic field, which causes synchrotron losses, and the cosmic microwave background radiation (CMBR), causing inverse Compton losses. If the magnetic field in the lobe slowly decreases away from the hot spot, as actually indicated by the observations, the ratio $\eta = U_B/U_{\rm IC}$, with U_B and $U_{\rm IC}$ the energy densities of the magnetic field and the CMBR, respectively, would also decrease. A small decrease in η near $\eta \simeq 1$ yields a substantial upward shift in ν_b which could arrest the decline of ν_b with time. As the condition $\eta \rightarrow 1$ is met in the relevant part of the western lobe, provided that the equipartition estimates of B given by Alexander (1987) are roughly correct, our simple explanation for the apparent lack of spectral aging furthermore provides indirect support for the quasi-universal assumption of equipartition.

II. THE EVOLUTION OF SPECTRAL CURVATURE

In the canonical picture derived from the spectral studies cited above, the synchrotron plasma is progressively deposited by the advancing hot spot at increasing distances from the nucleus. It is usually assumed that the electrons accelerated within the hot spot have a power-law energy spectrum $[N(E) = N_0 E^{-\gamma}]$, where γ is best determined from the lowest frequency measurements because aging due to both synchrotron and inverse Compton losses leads to a preferential depletion of more energetic electrons, thus causing a downward spectral curvature at higher frequencies. For the conditions prevailing in radio lobes the above losses dominate ionization and free-free losses (Pacholczyk 1970; see also Kardashev 1962). Thus, the loss rate of the electron energy, E, is given by

$$\frac{dE}{dt} = -(\xi_S + \xi_C)E^2 = 2.37 \times 10^{-3}(B_S^2 \sin^2 \theta + B_{IC}^2)E^2 , \quad (1)$$

where B_{IC} is the equivalent magnetic field of the CMBR; θ is the pitch angle of the electron with respect to B_S, the average field in which the electron has suffered synchrotron losses; the constant assumed cgs units; and adiabatic losses are ignored.

Following the detailed discussion by Alexander (1987), the assumed neglect of adiabatic losses over most parts of the lobes of 3C 234 is probably justified, though right behind the hot spots these losses might be significant, and can explain the inferred nonzero ages near the locations of the hot spot. In Alexander's analysis he roughly compensates for some of these adiabatic losses by utilizing a constant value of B_S estimated to be that just outside the hot spot. But a key feature of our approach is to assume that the typical field in which the electrons are radiating is closer to the one in which they are currently situated instead of a higher, preexpansion, value. Given the data available, we see no *a priori* reason to prefer one of these simplifying assumptions over the other. With our approach, the estimated nonzero ages right near the hot spots are smaller, so any need for consideration of adiabatic losses is reduced, and an *a posteriori* consistency check thus agrees with our assumption. We also make the common assumption that at any location much behind the hot spots the magnetic field remains essentially unchanged over most of the time since the injection by the hot spot. This is certainly only an approximation, and more detailed models, incorporating temporal as well as spatial variability, are being considered (Siah, Wiita, and Gopal-Krishna 1990).

If the spectral curvature is quantified by an observed break frequency ν_b at which the flux density falls to one-half the value expected from linear extrapolation of the low-frequency spectrum, where $\alpha = -0.83$ or $\gamma = 2.66$ for 3C 234, then (Kardashev 1962; Pacholczyk 1970; Saunders 1982; Jägers 1986)

$$\nu_b = 1.12 \times 10^{24} B_S t^{-2}(B_S^2 + B_{IC}^2)^{-2}(1 + z)^{-1} , \quad (2)$$

where the losses have been averaged over the pitch angle θ and isotropization of the pitch angle is assumed to be slow compared with the radiation time scale. The constant in equation (2) is ~ 2 times higher if rapid isotropization of the pitch angle is assumed (Jaffe and Perola 1973; Myers and Spangler 1985; Alexander and Leahy 1987).

With $B_S = \eta^{1/2} B_{IC} = \eta^{1/2}[3.18 \ \mu G(1 + z)^2]$, equation (2) becomes

$$\nu_{b,9} = 3.50 \times 10^4 \eta^{1/2} t_6^{-2}(\eta + 1)^{-2}(1 + z)^{-7} , \quad (3)$$

with $\nu_{b,9} \equiv \nu_b/10^9$, i.e., in GHz, and $t_6 \equiv t/3.15 \times 10^{13}$, i.e., in Myr. Substituting $z = 0.1848$ for 3C 234,

$$\nu_{b,9} = 1.07 \times 10^4 \eta^{1/2} t_6^{-2}(\eta + 1)^{-2} . \quad (4)$$

Because ν_b is the observationally determined parameter, we solve equation (4) for the spectral age,

$$t_6 = 103 \nu_{b,9}^{-1/2} \eta^{1/4}(\eta + 1)^{-1} . \quad (5)$$

This relation peaks for $\eta^{1/2} = 3^{-1/2}$ for a fixed ν_b (van der Laan and Perola 1969). Figure 1 shows a plot of the spectral age against $B_S/B_{IC} = \eta^{1/2}$ for five representative values of ν_b. It is clearly seen that in the presence of a magnetic field gradient, a range in age is possible even for the same value of ν_b, and the absolute range broadens as B_S approaches $B_{IC}(\eta \rightarrow \frac{1}{3})$ from a higher initial value. On the other hand, the assumption of a uniform magnetic field throughout the lobe, as made by Alexander for 3C 234, implies the same age for all regions for which the break frequencies are found to be equal. Thus the key point of this paper is that if the magnetic field changes, even by small amounts, in the lobes it is possible for the break frequency to increase with age, which, as we shall see, can explain the "anomalous" spectral gradient in 3C 234.

We now proceed to compute, using equation (5), the ages for the 12 locations in 3C 234 listed in Table 1 of Alexander (1987) and compare them with the corresponding values derived by him on the assumptions that (i) inverse Compton losses are negligible, (ii) the time scale for pitch-angle isotropization is

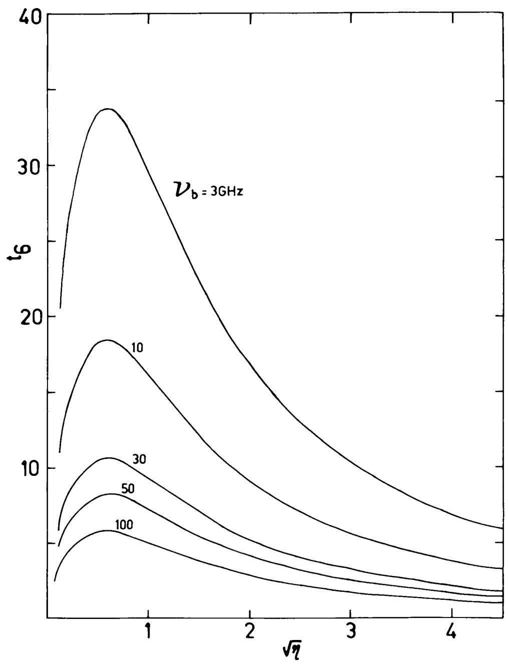

FIG. 1.—Predicted dependence of age of a synchrotron source on $\eta^{1/2} = B/B_{IC}$ is shown for five representative values of spectral break frequencies, ν_b (eq. [4]); t_6 is in units of 10^6 yr.

TABLE 1

PROPERTIES OF REGIONS IN 3C 234

Region[a] (1)	ν_b[b] (GHz) (2)	B_{min}[b] (μG) (3)	d[c] (kpc) (4)	t_A[b] (10^6 yr) (5)	t_6 (10^6 yr) (6)	t'_A (10^6 yr) (7)
1.........	80.3	12.5	10	4.0	2.2	2.5
2.........	49.3	7.5	85	5.1	5.0	3.2
3.........	31.3	7.0	150	6.4	6.7	3.9
4.........	25.4	5	240	7.1	9.6	4.4
5.........	10.2[d]	5	270	9.0	12.1	5.6
6.........	10.1	5	295	1.1[e]	15.2	6.8
7.........	45.0[f]	13.6	25	3.0	1.5	1.9
8.........	48.2	7.6	95	5.2	5.0	3.2
9.........	28.9	6	135	6.7	7.9	4.1
10.........	36.8	6	170	5.9	7.0	3.6
11.........	29.5	6	195	6.6	7.8	4.1
12.........	27.9	5.6	155	7.0	8.5	4.3

[a] Regions 1–6 are in the eastern lobe, 7–12 in the western lobe.

[b] Taken directly from Table 1 of Alexander 1987.

[c] Estimated from Alexander's Fig. 3; see text for details.

[d] For consistency with eq. (6), ν_b is almost certainly 15.9 GHz and is supported by Alexander's Fig. 2.

[e] This must be a misprint; only $t_A = 11$ is consistent.

[f] If t_A is consistent, $\nu_b \approx 145$, also supported by Alexander's Fig. 2.

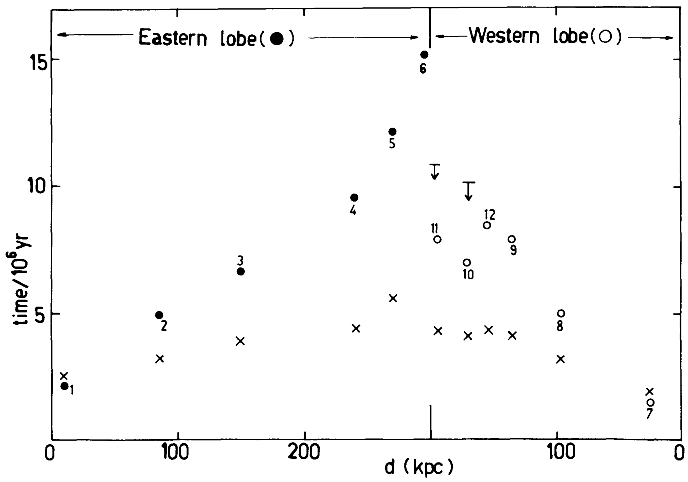

FIG. 2.—Estimated spectral ages of the 12 different regions in the radio lobes of 3C 234 are plotted against their distances from the respective hot spots, estimated as discussed in the text. Open and filled circles are the values of t_6 from eq. (5), and crosses are the values of t'_A, based on Alexander's analysis, which have been appropriately scaled from eq. (6), in order to provide a meaningful illustration of the effect of spatially varying magnetic fields (see text).

much smaller than that of synchrotron losses, and (iii) apparently he has neglected the factor of $(1 + z)$ in equation (2) by which the observed frequency is lower than the emission frequency. In Table 1 we reproduce the values of ν_b given by Alexander and the values of B_{min} he derives from standard equipartition arguments (noting that his values of ν_b for regions 5 and 7 seem to be grossly underestimated). The distances of the 12 regions from their respective hot spots have been read by us from Alexander's Figure 3 and may be uncertain by up to 15%–20%. In light of the uncertain trajectory of the bulk flow within the lobes, these distances represent averages of the direct separation from the hot spot and the sum of the projected distance along the radio axis, plus the offset of that location from the axis. In column (5) we reproduce the spectral ages from Alexander's Table 1 which are consistent with the following equation, equivalent to his equation (4),

$$t_A = 167\eta^{-3/4}\nu_{b,9}^{-1/2}, \tag{6}$$

where t_A is also in Myr and $\eta = 7.8$ throughout the lobes; note that his value for region 6 is a misprint.

The next column gives our estimates of spectral age from equation (5), computed for equipartition magnetic fields. To make explicit the impact of considering mild spatial variations of magnetic field in the vicinity of B_{IC}, we have removed the differences induced by Alexander's assumptions (ii) and (iii) mentioned above by tabulating in the last column $t'_A = 0.62t_A$. Since the microphysics of pitch-angle scattering is so uncertain (Myers and Spangler 1985), a comparison of our age estimates with t'_A is preferred, and we see that except in proximity to the hot spots our estimates are significantly larger.

The results are plotted in Figure 2, where t_6 and t'_A are shown against distances from the hot spots. Also plotted for regions 10 and 11 are the maximum permissible ages, given by the condition $B_S = B_{IC}/3^{1/2}$, making $B_S \simeq 0.43B_{min}$. An overestimation of B_{min} for the western lobe is a distinct possibility if its smaller projected size compared with the eastern lobe arises from its making a larger angle with the plane of the sky; Alexander has also noted that the asymmetry between the lobes could be due to such a projection effect. Considering the uncertainties in the derived spectral ages and the upper limits, there is no real evidence that spectral aging has halted over parts of the western lobe, as claimed by Alexander. We note that the estimated B_S for region 12 is the weakest in the lobe, although it appears to lie nearer to the hot spot than regions 10 or 11. This anomaly could perhaps be understood if the plasma in region 12 was injected earlier but has participated in a backflow which has "rebounded" from the galaxy's corona. Such flow patterns have been observed in recent hydrodynamic simulations (e.g., Wiita, Rosen, and Norman 1990) and, if present in 3C 234, would further weaken the argument for cessation of spectral aging and the need for *in situ* acceleration.

Our analysis thus suggests a comparable age of $\sim 10^7$ yr for the oldest parts of the western and eastern lobes, except for region 6, which lies on a faint extension of the eastern lobe offset from the sources axis by ~ 100 kpc. Because of its low surface brightness the quality of the spectral data is poor, leading to substantially larger uncertainty (see Fig. 3 of Alexander 1987).

Our interpretation rests on the existence of mild gradients of the magnetic field within the lobes. While this is supported by the observations, if the gradients were sufficiently large, the pressure differences would drive bulk flows rapid enough to produce mixing and a concomitant diminution of both spectral and magnetic field gradients. This is unlikely to be a difficulty, however, because the maximum acceleration that could be driven by the pressure gradients is

$$a_{max} \simeq \frac{P_I - P_{II}}{\rho_I r} = \frac{9.0 \times 10^{-9} B_I^2[1 - (B_{II}/B_I)^2]}{n_{-5} r_{10}}, \tag{7}$$

where $P_I > P_{II}$ are the total pressures in the adjacent regions I and II, derived from equipartition magnetic fields B_I and B_{II} given in μG; ρ_I is the mass density and n_{-5} the number density in units of 10^{-5} cm^{-3}; and r_{10} is the separation between the two regions in units of 10 kpc. Consider regions 8 and 9, where $B_{min} = 7.6$ and 6 μG, respectively, and $r_{10} \simeq 4$; then $a_{max} \simeq 5 \times 10^{-8}/n_{-5}$ cm s^{-2} and $V_{max} = a_{max} t = 15 n_{-5}^{-\frac{1}{2}} t_6$ km s^{-1}. This is negligible compared with the typical velocities of the hot spots for any reasonable value of density.

III. CONCLUSIONS

We have argued that the presence of weak spatial gradients of magnetic field in radio lobes can yield particularly large changes in the ages of adjacent regions when the magnetic density is comparable to that of the microwave background. Ignoring plausible field variations can thus lead to patterns of spectral age gradients that are at variance with the canonical picture that the regions located farther behind the hot spot are older. Minimal differences in B are required to produce absolute (though not relative) age shifts if $B < 2B_{IC}$. If this is the case, observations of peculiar spectral gradients can often be easily reinterpreted in terms of the conventional scenario, thus providing a useful hint that the strength of the magnetic field is comparable to B_{IC}, which is an accurately known quantity.

For 3C 234, the equipartition values of the magnetic field are indeed close to B_{IC} over the parts of the western lobe where an anomalous gradient of spectral age has been derived by Alexander (1987) under the assumption of a higher uniform magnetic field. Our reanalysis of his data, assuming slow pitch-angle isotropization, is consistent with ages monotonically increasing from the hot spots to approximately 10^7 yr for both the lobes, keeping in mind the possibility of small deviations from the equipartition estimates and the substantial uncertainty in the cumulative distances actually traversed by the individual regions behind the hot spots. On the assumption that the pitch-angle isotropization is rapid, as considered by Alexander, our ages apparently scale up by a constant factor of ~ 1.5 and would thereby significantly exceed his published estimates. The present analysis thus suggests that *in situ* acceleration of particles in the western lobe of 3C 234 is probably not required, although such a possibility cannot be excluded. Again, the lack of consideration of temporal variations of field strength in any of the extant analyses leaves additional uncertainties.

It would be valuable to obtain similarly high-quality, multifrequency maps for other edge-brightened double radio sources to help discriminate between magnetic field variations and reacceleration as possible explanations for anomalous spectral gradients. Particularly interesting would be the sources for which evidence already exists for atypical spectral gradients, e.g., 3C 136.1 (western lobe) and 3C 285 (eastern lobe), as presented by Alexander and Leahy (1987). While for 3C 285 these authors suspect contamination of the lobe by jet emission, it is interesting to note that for both sources the estimated equipartition lobe magnetic field is 4.5–5 μG, which is within 20%–40% of B_{IC}.

Various recent studies have indicated that the typical lifetime of intense nuclear activity in massive galaxies is of the order of 10^8 yr (e.g., Stockton and MacKenty 1987; Hutchings 1987; Schmidt 1988). Similar lifetimes are also inferred from the modeling of the observed median sizes of typical double radio galaxies (Gopal-Krishna and Wiita 1987; Rosen and Wiita 1988; Gopal-Krishna, Wiita, and Saripalli 1989; Rosen 1989). Part of the discrepancy between these estimates and the derived spectral ages of 3–60 Myr (e.g., Alexander and Leahy 1987; Leahy, Muxlow, and Stephens 1989) can be attributed to the frequent neglect of magnetic field gradients in the radio lobes. Another part of this difference is probably due to the fact that only the most powerful sources have been spectrally mapped, and it is likely that their lifetimes are shorter than those of average sources. In fact, for weak radio galaxies lifetimes as long as 10^9 yr have been suggested (Cordey 1986). Other important effects we hope to take into account in future work are the temporal evolution of the physical conditions in the lobes (e.g., Eilek and Shore 1989) and the role of filamentation and small-scale inhomogeneities (Scheuer 1989; Perley, Dreher, and Cowan 1984; Hines, Owen, and Eilek 1989).

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