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Extragalactic Radio Sources and the Role of Relativistic Jets*

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Abstract

This paper summarises some of the ideas surrounding the role of relativistic jets in radio galaxies and quasars and describes work presented in two recent papers (Bicknell 1994*a*,*b*) relating relativistic jets to the Fanaroff–Riley classification of radio galaxies. I conclude with some speculation on the evolutionary connection between Fanaroff–Riley Class I and Class II radio galaxies and the relationship between mergers and radio galaxies, an idea which was discussed at the time of the discovery of Cygnus A and Centaurus A.

1. Introduction

I did not have the pleasure of knowing John Bolton well personally, having only met him once, briefly, at a meeting at the Australian Academy of Science. However, it is clear (as other papers in this volume will testify) that the subject of radio galaxies and quasars, to which I have been privileged to make a professional contribution, owes a great deal to John Bolton and his collaborators. It is fascinating to read the early papers by Bolton and Stanley (1948), Bolton (1948) and Bolton, Stanley and Slee (1949) relating to the identification of some of the most famous radio galaxies (Cygnus A, M87, Centaurus A, Coma A and Hercules A) and to imagine the excitement and puzzlement that must have been generated in that group as they grappled with an explanation for these mysterious sources of radio emission. They could not have imagined, of course, the new ideas that would be generated by their work—relativistic jets, accretion discs, black holes—and the present paper reflects, in part, the growth in the study of radio galaxies that has taken place since the pioneering work of the group centred around John Bolton. I therefore respectfully dedicate this paper to his memory.

2. Fanaroff–Riley Class I and II Radio Galaxies

When interferometer observations of extragalactic radio sources started to reveal interesting structure, Fanaroff and Riley (1974) showed that a fundamental change in radio morphology occurs within a decade of monochromatic power $P_{1.4}^{\rm tot} \approx 10^{25}\,{\rm W\,Hz^{-1}}$. Fanaroff and Riley showed that the higher-powered radio sources generally have bright hot spots at their extreme edges (so-called 'edge-

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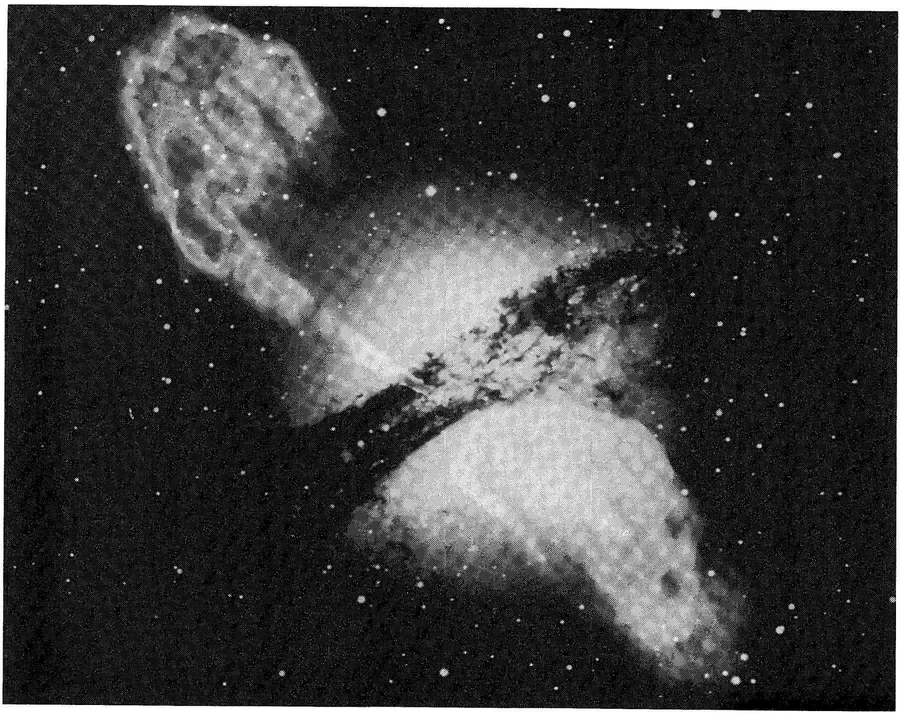

Fig. 1. An overlay of the VLA radio image of Cen A on the an optical CTIO image. [This overlay was kindly provided by Dr. J. O. Burns.]

brightened' structure); the lower-powered sources are 'edge-darkened', and since their discovery radio galaxies have been classified either as Fanaroff–Riley Class I (for the low-powered sources) or Class II (for the high-powered ones). Fig. 1 shows one of the classical FRI sources, Centaurus A, identified by Bolton, Stanley and Slee (1949) with the optical galaxy NGC 5128. Fig. 2, on the other hand, is a radio image (Dreher *et al* 1987; Carilli *et al.* 1994) of the archetypical class II radio galaxy Cygnus A whose position was ascertained by Bolton and Stanley (1948). As well as showing the kiloparsec-scale structure in exquisite detail, Fig. 2 shows an image of the VLBI jet on the parsec scale. Cygnus A is typical of almost all radio galaxies and quasars in that the parsec-scale jet is one-sided and points in the direction of the asymmetric jet structure on the kiloparsec scale. It is well known that this asymmetry is often interpreted in terms of a relativistic beaming model in which nonthermal emission is beamed forward due to the relativistic motion of the emitting plasma. The opposing idea is that the one-sided jet structure is somehow 'intrinsic'. It can safely be said however, that intrinsic models have not been developed to the point of a testable theory.

One observational fact that has led some workers to doubt the relativistic interpretation of radio source motion has been the detection of *subluminal* motions in some jets, e.g. M87 (Reid *et al.* 1989), NGC 315 (Venturi *et al.* 1993) and Cygnus A itself (Carilli *et al.* 1994). This is somewhat ironic since it was the detection of superluminal motions in a large number of quasars that was in large

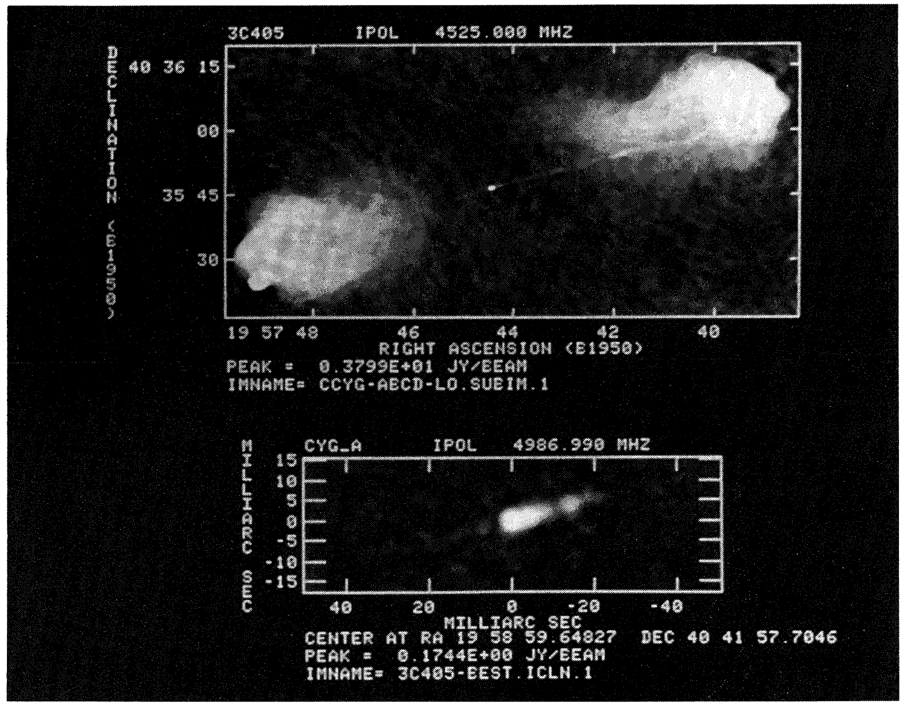

Fig. 2. VLA and VLBI images of the prototype FRII radio galaxy, Cygnus A. [Images kindly provided by Dr C. Carilli.]

part responsible for the adoption of the relativistic jet model: the apparent velocity of a relativistically moving feature is

$$\beta_{\rm app} = \frac{\beta \sin\theta}{1 - \beta\cos\theta}\,, \tag{1}$$

where $\beta = v/c$. However, there is no guarantee that the observed features are moving at or near the jet velocity, especially when it is realised that they are most likely shock waves embedded in the moving jet plasma (Lind and Blandford 1985). Indeed, there is no reason why such shocks should be moving away from the nucleus in the jet frame, and *reverse* shocks, caused by variations in the jet flow velocity, can reconcile jet to counter-jet surface brightness differences whilst at the same time being consistent with subluminal knot velocities (Bicknell 1944*a*). A reverse shock is more likely to significantly affect the jet velocity in a low-γ jet than in a high-γ jet (γ = Lorentz factor). In the latter, the shock is more likely to be advected at near the jet velocity. Hence the appearance of superluminal motions in powerful quasar jets, the detection of subluminal motions in lower-powered sources, and sources thought to be near the plane of the sky (e.g. Cygnus A) are all consistent with relativistic motion of the underlying plasma.

Despite the consistency of relativistic motion in different types of sources the question still remains: are all jets relativistic? Consideration of source dynamics on the kpc scale generally shows that there is no problem with the idea that in quasars and class II radio galaxies, the jets are moving relativistically. This is one of the linchpins of current *Unified Schemes* linking radio galaxies and quasars (see, for example, Barthel 1994; Laing 1994), in which quasars are FRII radio galaxies viewed at a small angle to the line of sight. Matters are not quite so straightforward with class I radio galaxies. The energy budget in these sources on the large scale indicates that the jet velocities are subrelativistic. However, there are good arguments (e.g. Ulrich 1989; Ulvestad and Antonucci 1986; Padovani and Urry 1990) that BL Lac objects are relativistically beamed FRI radio galaxies. If this is true, then the relativistic parsec-scale jets of FRI galaxies must decelerate to subrelativistic velocities on the kpc scale. This has been shown to be dynamically plausible (Bicknell 1994*a*) and is especially appealling since deceleration explains a lot of the features of the kpc-scale properties of radio galaxies (see Bicknell *et al.* 1990).

Another important paper which (as it turns out) has an important bearing on whether jets are relativistic or not, is that of Owen and Ledlow (1994) in which they present the results of a large amount of work on the classification of radio galaxies as class I or class II, and plot them as points in the radio–optical plane. The results of their labours are shown in Fig. 5. The compelling and interesting feature of their compilation is that the dividing line between class I and class II sources is extremely sharp and is approximately of the form $L_{\rm radio} \propto L_{\rm opt}^2$. When projected onto the radio axis, this diagram exhibits

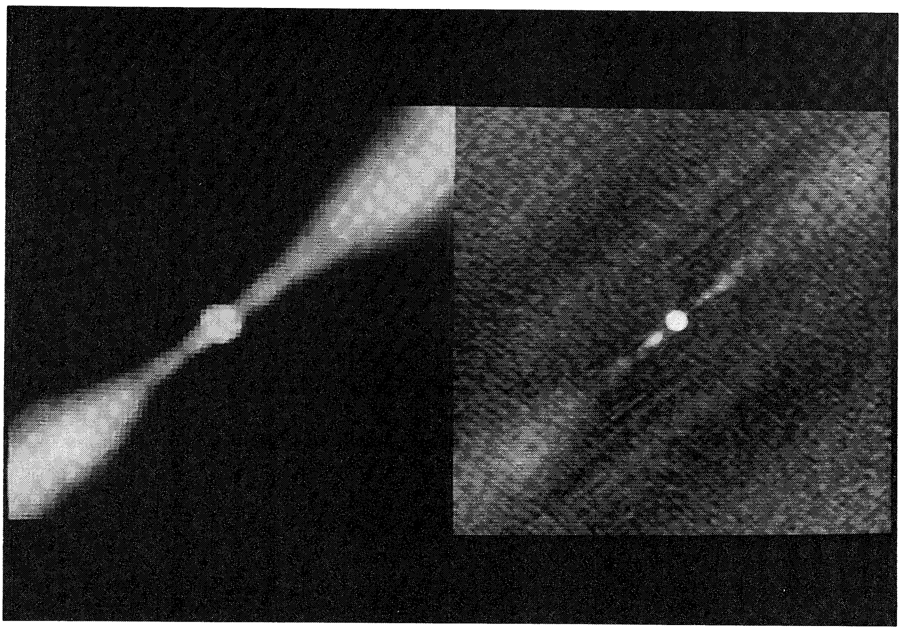

Fig. 3. The inner part of the radio galaxy IC 4296, imaged by the VLA. The left-hand image is a 20 cm, 3″ resolution image; the right-hand image is a 6 cm, 1″ resolution image. Both images are from unpublished work of N. Killeen. The combined information from both images is that an initially knotty, well collimated jet starts to expand rapidly at approximately 3 kpc from the nucleus.

the change from class I to class II morphology over the decade or so in radio power that we have become used to since Fanaroff and Riley (1974).

The relationship between the Fanaroff–Riley classification and relativistic jets arises in the following way. Let us begin with the following premises:

- All jets initially have relativistic velocities.
- The distinction between class I and class II jets is that class I jets which are borderline class I/II are decelerated to transonic, turbulent flows near the optical core radius of the parent galaxy. (Lower-powered class I jets will be decelerated to subrelativistic velocities within a core radius.)

These simple assumptions can then be used to derive a theoretical expression for the dividing line whose slope is well determined and in good agreement with the Owen–Ledlow data. The intercept of the dividing line is within an order of magnitude of the observed value. The significance of the optical core radius in the second of the above assumptions is that it is near the core radius of the parent galaxy that the density is highest and the pressure gradient is lowest, so that entrainment will have the greatest effect.

Part of the motivation for this idea came from observations of the southern radio galaxy PKS 1333−33 (IC 4296) which was studied by Neil Killeen in his PhD thesis (Killeen *et al.* 1986*a*, 1986*b*; Killeen and Bicknell 1988). (The suggestion of IC4296 as a thesis topic was made by a former Bolton student, Ron Ekers.) Fig. 3 shows the inner few kpc of IC 4296 which shows the emergence of a thin knotty jet emanating from the core. This starts to expand rapidly at approximately 3.6 kpc from the centre of the galaxy. In the theory which I am about to summarise, the thin jet is relativistic and the rapidly spreading part is where it is starting to entrain significantly and is entering the mildly relativistic regime.

3. Deceleration of Relativistic Jets

Clearly, from the above discussion, the proposed physics relating to class I sources involves deceleration of a relativistic jet. Much insight into the behaviour of a decelerating relativistic jet can be gained by use of the relevant equations for conservation of energy and momentum, which provide an incomplete, but nevertheless useful, description of the process.

It can be shown on quite general grounds (Bicknell 1994*a*) that the jet energy flux is conserved, to a very good approximation, and that the momentum flux is conserved when either the Mach number is high, or the background pressure is low compared to the external pressure or when the background pressure has a low gradient. Utilising energy and momentum conservation, it is a straightforward matter to determine, for a given initial Lorentz factor, the velocity of the jet as a function of Mach number. A series of these plots is given in Fig. 4 for different values of the ratio, $\mathcal{R} = \rho c^2/4p$, of cold matter rest energy density to relativistic enthalpy (p is the pressure). Now, naively, one would expect that when a relativistic jet decelerates to a Mach number of unity, then its speed would be $c/\sqrt{3}$. However, this does not allow for the decrease of the sound speed due to the addition of thermal matter. In fact, as the curves show, the jet

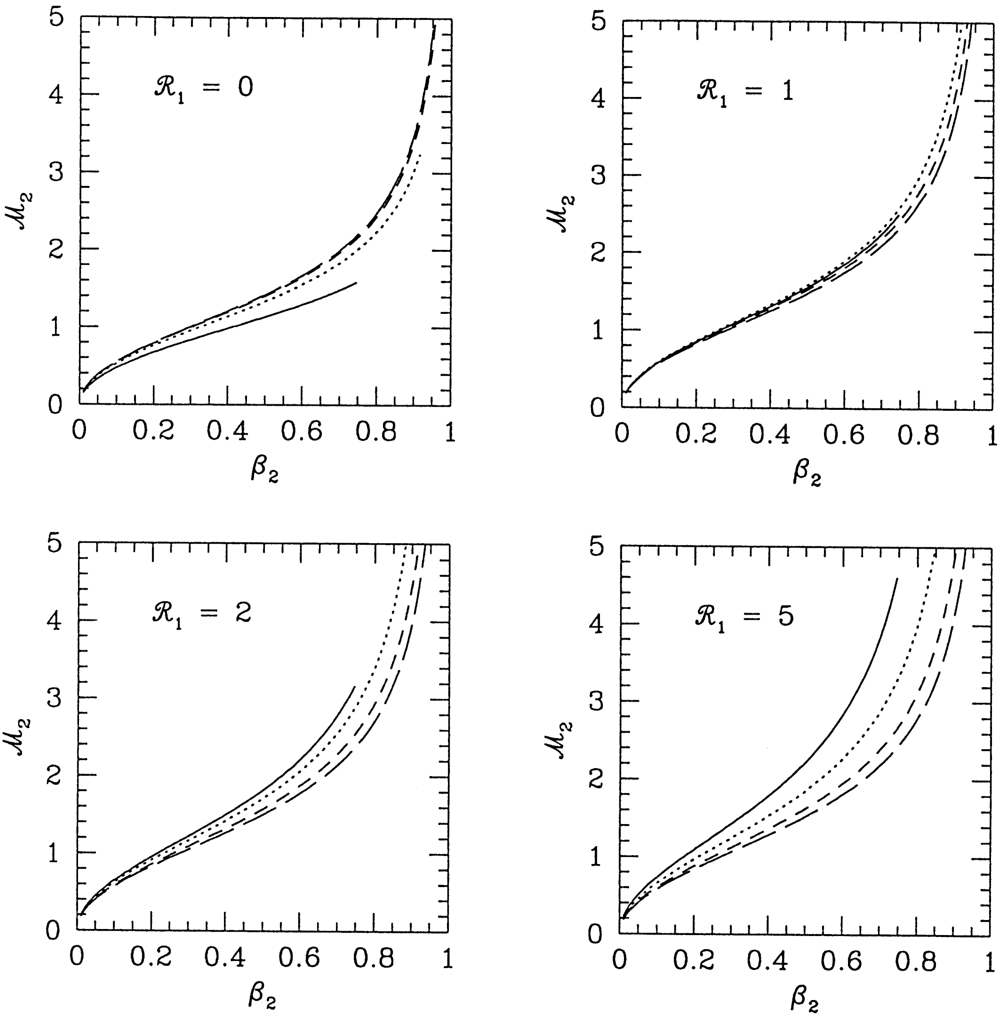

Fig. 4. Velocity–Mach number curves for decelerating initially relativistic jets (from Bicknell 1994*a*). The different panels correspond to different values of the ratio $\mathcal{R}$ of cold matter energy density to enthalpy. The initial Lorentz factors are 1·5 (solid), 2·5 (short dash), 5·0 (medium dash) and 10·0 (long dash).

speed is approximately $0.3c$ when the Mach number $\mathcal{M} \approx 1$. The jet enters the transonic regime $\mathcal{M} \leq 2$ when $v_{\rm jet} \approx 0.6 - 0.8\,c$, provided that there is not too much contribution to the jet inertia from cold matter. This would be the case in electron–positron jets or in electron–proton jets in which the energy density of cold protons is not overwhelming.

The existence of a more or less unique velocity at which a jet becomes relativistic is quite important, as we see in the following section.

4. Energy Flux

It is the energy flux in a jet which is responsible for the radio luminosity of the source. Energy is transported from the core to the lobes and the radiation from the lobes is proportional to the amount of energy which accumulates there. The energy flux F_{E} of a relativistic jet is given by

$$\log F_{\mathrm{E}} = \log(4\pi c) + \left[\log\left\{\left(1 + \frac{\gamma - 1}{\gamma}\mathcal{R}\right)\gamma_{\mathrm{jet}}^2\right\}\right] + 2\log r_{\mathrm{jet}} + \log p_{\mathrm{jet}}\,. \qquad (2)$$

One can see from this that the jet energy flux separates into a number of components (apart from fixed constants):

- A part corresponding to intrinsic jet parameters ($v/c = \beta$, Lorentz factor, γ, and $\mathcal{R} = \rho c^2/4p$).
- The radius of the jet which could, in principle, be determined from the physics of jets as they emerge from the core. However, this physics is uncertain at present and for the time being I use observational data for this quantity (more precisely, $r_{\mathrm{jet}}/r_{\mathrm{t}}$, the ratio of the jet radius to the radial distance from the core where the jet makes a transition to turbulent flow).
- A part which is determined by the environment, namely p_{jet}. Eventually, it is this component which determines the dependence of the radio luminosity on the absolute magnitude of the galaxy. The assumption involved in relating p_{jet} to the environment is that when the jet starts to interact with the interstellar medium, it is in approximate pressure equilibrium with the pressure of the elliptical galaxy atmosphere.

5. Relationship of Jet Pressure to Absolute Magnitude

The *central* interstellar medium (ISM) pressure is related to the optical absolute magnitude through a series of relations between electron number density, temperature, velocity dispersion, optical core radius and absolute magnitude. The relationships between the last three are well known empirical relationships between the parameters of elliptical galaxies (Kormendy 1987; Terlevich *et al.* 1981). This series of relationships is mediated by the following empirical expression for the electron number density, n_{e} (central value $n_{\mathrm{e,c}}$ in an X-ray emitting atmosphere:

$$\frac{n_{\mathrm{e}}}{n_{\mathrm{e,c}}} = \left(1 + \frac{r^2}{r_{\mathrm{c}}^2}\right)^{-\beta\mathrm{at}}, \qquad (3)$$

where r_{c} is the optical core radius, $\beta_{\mathrm{at}} = \mu m_{\mathrm{p}}\sigma^2/kT_{\mathrm{ISM}}$ (σ is the line-of-sight velocity dispersion far from the core), $\mu \approx 0{\cdot}62$ is the mean molecular weight and $T_{\mathrm{ISM}} \sim 10^7$ K is the temperature of the ISM (assumed isothermal). This empirical model has often been used to fit Einstein IPC data which has fairly low resolution ($\sim 90''$), so that using it to determine the central density should give indicative, although not entirely accurate, numbers. In particular, it can be shown on quite general grounds that cooling will *increase* the central pressure above the estimate obtained using this model.

The central pressure estimated from this atmosphere model and the various empirical relations is:

$$\log p_{\mathrm{c}} = -8{\cdot}2 + 0{\cdot}03\, M_B - \tfrac{1}{2}\log\left(\frac{I_{\mathrm{X}}}{5}\right), \qquad (4)$$

where M_{B} is the absolute blue magnitude, and $I_{\mathrm{X}} \sim 5$ is a dimensionless integral derived from the X-ray emissivity of the above model and is a function of the parameter $\beta_{\rm at}$ and the cutoff in radius. I selected an average value of $\beta_{\rm at} = 0.75$ and 100 core radii for the cutoff. This is not of great importance since the integral is only logarithmically divergent for $\beta_{\rm at} = 0.75$.

The resultant expression for the energy flux is

$$\log F_{\rm E} = 24\cdot 1 - 0\cdot 85\, M_{\rm B} - \tfrac{1}{2}\left(\frac{Ix}{5}\right)$$
$$+\left[2\log\left(\frac{r_{\rm jet}/r_{\rm t}}{0\cdot 1}\right) + \log\left(\frac{P_{\rm t} r_{\rm t}^2}{p_{\rm c} r_{\rm c}^2}\right) + \log\left\{\left(1 + \frac{\gamma - 1}{\gamma}\mathcal{R}\right)\gamma_{\rm jet}^2 \beta_{\rm jet}\right\}\right]. \quad (5)$$

The subscript 't' is used to denote values at the transition point to transonic, fully developed turbulence; $r_{\rm t}$ is the galactocentric radius at the transition point. One advantage of expressing the energy flux in this way is that the factor $p_{\rm t} r_{\rm t}^2/p_{\rm c} r_{\rm c}^2$ is constant in an atmosphere in which $p \propto r^{-2}$, and does not vary greatly in other atmospheres for typical values of $\beta_{\rm at}$.

One can already perceive a glimmer of success in the above equation. All others things being constant, the energy flux is proportional to $L_{\rm B}^{2\cdot 1}$, where $L_{\rm B}$ is the blue optical luminosity. This dependence is very close to the observed dependence of the slope of the dividing line.

6. Monochromatic Radio Power

The derivation of the radio power corresponding to a given energy flux necessitates consideration of the source energy budget (Bicknell 1986*a*). The energy budget of a jet-fed lobe is governed by the equation

$$\frac{dE_{\rm L}}{dt} = F_{\rm E} - p_{\rm L}\frac{dV}{dt} - \mathcal{L}\,. \quad (6)$$

where $E_{\rm L}$ is the lobe energy, $p_{\rm L}$ the lobe pressure, V the volume and the lobe luminosity $\mathcal{L} = t_{\rm rad}^{-1}\, E_{\rm L}$, where the radiative time scale

$$t_{\rm rad} = 5\cdot 5 \times 10^7\ {\rm yr}\ f^{-1}\left(\frac{c_{12}}{10^7}\right)\left(\frac{B_{\rm IC}}{3\cdot 2\mu{\rm G}}\right)^{-3/2}\left(\frac{B}{B_{IC}}\right)^{1/2}\left[1 + \left(\frac{B}{B_{\rm IC}}\right)^2\right]^{-1} \quad (7)$$

is a function of the magnetic field, the upper electron cutoff (through the dependence of the parameter c_{12} on this quantity) and the fraction f of the internal energy in electrons and/or positrons.

The conclusions from consideration of the energy budget is that if $t >> t_{\rm rad}$ then the ratio,

$$\kappa = \frac{\text{Nonthermal luminosity}}{\text{Jet energy flux}} \quad (8)$$

approaches 0.75. If $t << t_{\rm rad}$ then $\kappa \approx 0.75\, t/t_{\rm rad}$. The small amount of data that there is relating to this parameter suggests that $\kappa \sim 0.1$. Whether or not κ

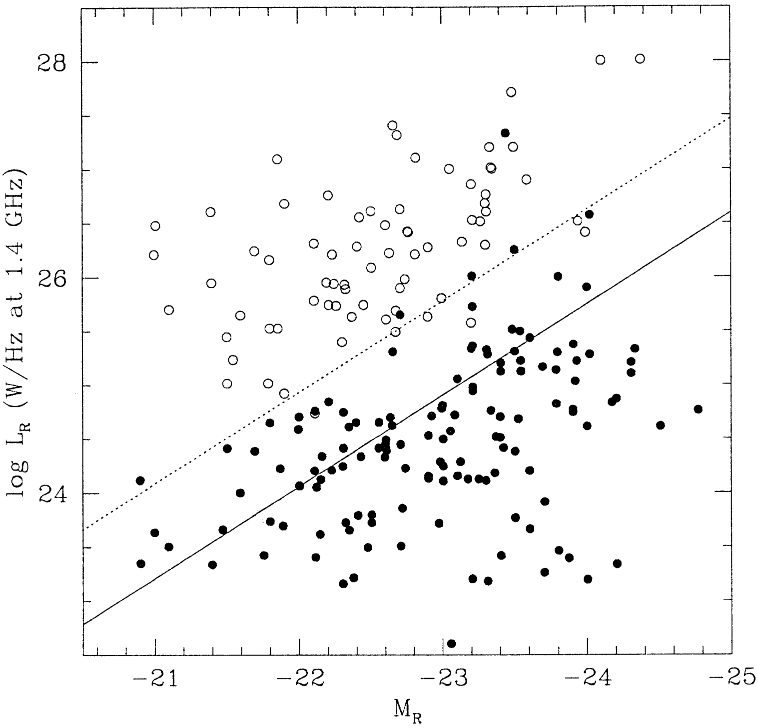

Fig. 5. Data of Owen and Ledlow (1994) showing the distribution of FRI and FRII sources in the radio–optical plane. The solid circles refer to FRI sources and the open circles to FRII sources. The solid line is the theoretical dividing line corresponding to the parameter $\kappa = 0.75$, the dashed line corresponds to $\kappa = 0.1$.

can approach the theoretical upper limit of 0.75 depends upon whether turbulence can keep the high-energy electrons alive to maintain $t_{\rm rad}$ approximately constant as t increases. This is a subject which could bear further investigation.

The *monochromatic* radio power P_{ν_0} at $\nu_0 = 1.4\,$GHz is related to the total radio power through the spectral index and upper frequency cutoff $\nu_{\rm u}$. Putting

$$P_{\nu 0} = C_{\rm S}(\nu_{\rm u}/{\rm n}_{0,\alpha})\nu_0^{-1}\, L_{\rm S}\,, \tag{9}$$

then we get $C_{\rm S}(\nu_{\rm u}/\nu_0, \alpha) \approx 0.15$ for $\nu_{\rm u} = 10\,$GHz and $\alpha \approx 0.7$.

7. Comparison with Owen–Ledlow Data

The above relationships can be combined into the following relation for class I sources at the class I/class II boundary:

$$\log\left[\frac{P_{\nu_0}}{\rm W\ Hz^{-1}}\right] = (\log A + 5{\cdot}7) - 0{\cdot}85\, M_{\rm R}\,, \tag{10}$$

where

$$\log A = 2\log\left(\frac{r_{\rm jet}/r_{\rm t}}{0\cdot 1}\right) + \log\left(\frac{p_{\rm t}r_{\rm t}^2}{p_{\rm c}r_{\rm c}^2}\right) + \log\left[\left(1+\frac{\gamma-1}{\gamma}\mathcal{R}\right)\gamma_{\rm jet}^2\beta_{\rm jet}\right]$$
$$+\log\kappa + \log\left(\frac{C_{\rm S}}{0\cdot 1}\right) - \tfrac{1}{2}\log\left(\frac{Ix}{5}\right) - \log\left(1+\frac{L_{\rm IC}}{L_{\rm S}}\right), \tag{11}$$

$M_{\rm R}$ is the red optical luminosity ($\langle M_{\rm B} - M_{\rm R}\rangle = 1\cdot 9$, Persson *et al.* 1990) and $L_{\rm IC}$ is the inverse Compton luminosity. Here the inverse Compton luminosity is taken to be negligible in comparison to the synchrotron luminosity.

Fig. 5 shows two theoretical dividing lines overlaid on the Owen–Ledlow data. Table 1 lists the values of the parameters used for these lines. The only difference between them is the value of $\kappa = 0.1$ for the solid line and 0.75 for the dashed line. As indicated earlier, the observed slope of the Fanaroff–Riley division is well described by the theoretical expression. This is satisfying since, theoretically, the slope is very tightly constrained. The intercept of the dividing line is not so well determined since, as can be seen from the expression for $\log A$ above, it depends upon a number of quantities that perhaps are not known to within a factor of a few. Moreover, as pointed out earlier, there is probably some error in the estimation of the central pressure from the Einstein model fits to the surface brightnesses of X-ray emitting atmospheres. (In particular, cooling will increase the central pressure and increase the predicted radio power.) Nevertheless, the intercept agrees with the data to within an order of magnitude (perhaps less if $\kappa > 0.1$).

Table 1. Parameters used to calculate the theoretical ClassI/II dividing line

Parameter	Value
$r_{\rm jet}/r_{\rm t}$	$0\cdot 1$
$p_{\rm t}r_{\rm t}^2/p_{\rm c}r_{\rm c}^2$	$0\cdot 1$
β, γ	$0\cdot 6$, $1\cdot 25$
$I_{\rm X}$	$5\cdot 0$
κ	$0\cdot 1$, $0\cdot 75$
$C_{\rm S}$	$0\cdot 15$
$L_{\rm IC}/L_{\rm S}$	$0\cdot 0$

It is important to note the strong dependence of this result on the deduction of mildly relativistic flow near the transition point. If the flow were subrelativistic there (say $\beta < 0.1$), the radio luminosity would be at least an order of magnitude less and the theoretical line would not be on the diagram! Moreover, it is the more or less unique velocity implied by the deceleration of a relativistic jet that ensures that the slope of the dividing line has a value which depends upon environmental parameters only.

8. Discussion

In this paper I have reviewed some of the current ideas associated with relativistic jets in FRI and FRII radio sources, and it is apparent that the arguments for relativistic jets on the parsec scale in both types of extragalactic radio source are strong. Let me now turn to an idea that was prevalent at the time of the discovery of extragalactic radio sources—namely that they were due to 'collisions' of galaxies. A similar idea is now prevalent—although we usually refer to 'mergers' and the physics envisaged is somewhat different.

There is a certain amount of circumstantial evidence that FRII sources are indeed related to mergers—distorted isophotes and considerable amounts of high-excitation ionised gas are prevalent in FRII radio galaxies. FRIs, on the other hand, as a general rule, tend to be more dynamically relaxed, with considerably less ionised gas. Prior to the Owen and Ledlow result, it had been supposed that FRI and FRII radio galaxies are actually quite different galaxies: FRIs tend to be large galaxies in the centres of clusters; FRIIs are smaller galaxies in the outer parts of clusters. Therefore the characterisation of FRIs as evolved FRIIs, and hence an association of the entire population with mergers, was rather difficult. However, with the complete Owen–Ledlow sample, it is now apparent that an evolutionary connection between FRIIs and FRIs is indeed possible since, at a given absolute magnitude, radio galaxies of both types exist (with a range of radio powers). It is the *slope* of the FRI/II dividing line that has been responsible for the previous notion. At low optical brightness, FRIIs dominate, and at high optical brightness, FRIs dominate. Nevertheless, there *are* optically bright FRIIs which may be the (short-lived?) precursors of FRIs.

Hence, it now seems possible that mergers could initiate radio galaxy activity, and that this may result in an evolutionary sequence from FRII to FRI galaxies. Thus we could be in the situation of returning to ideas being discussed in 1948, with the qualification that the physical ideas relating to the effect of galaxy collisions on radio source properties are probably different. It is apposite to remark that Cygnus A and Centaurus A, two of the galaxies that occupied much of John Bolton's attention in the early days of extragalactic radio astronomy, are both good examples of galaxies which appear to have undergone a merger.

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