Evolutionary tracks of FRII sources through the $P-D$ diagram

Christian R. Kaiser, Jane Dennett-Thorpe and Paul Alexander

MRAO, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE

Accepted 1997 August 6. Received 1997 August 6; in original form 1997 February 6

ABSTRACT
This is the second in a series of papers presenting an analytical model for the evolution of FRII radio sources. In this paper we evaluate the expected radio emission from a radio source incorporating energy-loss processes for the relativistic electrons. By combining these results with our earlier dynamical model we calculate evolutionary tracks through the power–linear size diagram. These tracks are in good agreement with the observed distribution of sources in this diagram. The effects of different forms for the evolution of the magnetic field in the cocoon, the redshift of the source, the environment of the source, and the defining parameters of the jet are investigated. The evolutionary tracks are found to be insensitive to the assumed form of the magnetic field evolution. Some evidence against protons as a major constituent of the jet material is also found.

Key words: radiation mechanisms: non-thermal – galaxies: active – galaxies: jets.

1 INTRODUCTION
This is the second in a series of papers presenting an analytical model for the evolution of FRII radio sources; in the first paper (Kaiser & Alexander 1997, hereafter KA97) we investigated the dynamical evolution of the source, and here we extend this analysis to consider the luminosity evolution of a radio source and the tracks it follows through the power–linear size ($P-D$) diagram. The $P-D$ diagram was introduced by Shklovskii (1963) as a powerful tool for investigating the temporal evolution of FRI and FRII radio sources. By plotting the radio luminosity at a specific frequency, $P_r$, as a function of the linear size of a source, $D$, a diagram analogous to the Hertzsprung–Russell diagram is obtained. The evolution of a radio source through the $P-D$ diagram is, however, not well understood. Some constraints can be placed on these evolutionary tracks by the relative densities of objects in regions of the $P-D$ diagram; specifically, sources with large linear sizes ($D > 1$ Mpc) and high radio luminosities ($P_r > 10^{26}$ W Hz$^{-1}$ sr$^{-1}$ at $\nu = 178$ MHz) seem to be rather rare, suggesting that the luminosity of sources should decrease quickly with linear sizes approaching 1 Mpc. Care must be taken in interpreting the $P-D$ diagram in this way, since selection effects have a strong influence on the observed high-redshift population (e.g. Masson 1980; Macklin 1982); moreover, giant sources are likely to be difficult to detect, since the extended emission of the cocoon will be weak and the hotspots may therefore appear unconnected (e.g. Muxlow & Garrington 1991). Searches specifically for giants have been undertaken by Cotter, Rawlings & Saunders (1996) and Subrahmanyan, Saripalli & Hunstead (1996). Both groups identify a number of radio sources in low-frequency surveys as classical doubles of extreme size, although almost all of these sources have luminosities below $2 \times 10^{26}$ W Hz$^{-1}$ sr$^{-1}$, suggesting that there is a real deficit of powerful giant sources.

Baldwin (1982) used the model for FRII sources of Scheuer (1974) and minimum energy arguments (e.g. Burbidge 1956) to calculate evolutionary tracks through the $P-D$ diagram. In its original form his model predicts $P \propto D^{7/8}$ for a power-law energy spectrum of the relativistic electrons, $N(E) \, dE \propto E^{-2} \, dE$, with $p = 2$ as exponent. This implies that all sources would crowd together in exactly that area of the diagram which is almost empty. Modifications of the model incorporating a density gradient in the external medium surrounding the radio source ($\rho \propto d^{-\delta}$, where $d$ is the distance from the centre of the distribution) predicted tracks with decreasing radio luminosity, in reasonable agreement with observations for $\beta = 1.9$ and $D < 300$ kpc. To explain the rapid decline in luminosity for $D \approx 1$ Mpc, Baldwin suggested that the density of the atmosphere may decrease more steeply with $\beta = 2.9$ for $D > 300$ kpc. However, sources in environments with a density gradient steeper than $1/d^2$ are unlikely to develop the typical FRII morphology (Falle 1991; Kaiser & Alexander 1997).

An alternative hypothesis to account for the decrease in luminosity at large $D$ is that the central engine ceases to supply energy to the jet after a certain period which is...
similar for all sources (for a discussion see Daly 1994). The cocoon will then dim quickly via an adiabatic expansion. Observations indicate that only of order 4 per cent of all radio sources show no signs of ongoing AGN activity (Giovannini et al. 1988) in support of this hypothesis.

The synchrotron radiation of FRIIs demonstrates the presence of highly relativistic electrons in the cocoon (Rees 1971). To achieve charge neutrality in the cocoon, we need some species of positively charged particles. If we assume that there is no entrainment across the contact discontinuity which separating the cocoon from the IGM, the jet must supply these additional particles. The nature of these charge-balancing particles is subject to debate (e.g. Leahy 1991). If they are protons, a significant fraction of the kinetic energy transported by the jet will be stored by these in the cocoon but will not contribute to the radiated power. Alternatively, if the particles providing charge neutrality were positrons, they would behave almost exactly like electrons in a completely tangled magnetic field and will contribute to the observed synchrotron emission. The kinetic power of the jet required to produce a cocoon of given radio power per unit frequency and solid angle is

\[ P_{\nu} = \frac{1}{6\pi} \sigma_T c B_0 \gamma^3 \nu n(\gamma) V. \]

If the relativistic electrons are initially accelerated at time \( t_i \) (for example, via a first-order Fermi process at the jet shock), we expect their energy distribution to be a power-law function of their initial Lorentz factor, \( \gamma_i \), (e.g. Heavens & Drury 1988):

\[ n(\gamma_i, t) \, d\gamma_i = n_0 \gamma_i^{-\Gamma} \, d\gamma_i. \]

This spectrum will then evolve with time as the electron population loses internal energy. The rate of change of the Lorentz factor for the electron population is given by

\[ \frac{d\gamma}{dt} = \frac{a_1}{3} \frac{\gamma^2}{\gamma_i^2} \frac{4}{3} \frac{\sigma_T}{m_e c} \nu^2 (u_B + u_c). \]

The first term on the right-hand side represents adiabatic expansion losses for the case where the volume \( V \) expands as \( V \propto t^n \) (e.g. Longair 1981). The second term is the combined loss rate due to synchrotron radiation and inverse Compton scattering of the cosmic microwave background radiation (CMBR); \( m_e \) is the electron mass, and \( u_c \) is the energy density of the CMBR. Integration of equation (4) gives

\[ \frac{1}{\gamma} - \frac{1}{\gamma_i} = \frac{4}{3} \frac{\sigma_T}{m_e c} \nu \left[ (u_B + u_c)(t')^{-s_{\nu}^3} dt' \right], \]

where for an electron with a Lorentz factor of \( \gamma \) at time \( t \), the Lorentz factor at time \( t_i \), when it was initially accelerated, is \( \gamma_i \), and we may therefore consider \( \gamma_i \) to be a function of \( \gamma \) and \( t \). As mentioned above, we assume the magnetic field to be completely tangled on all relevant scales, allowing us to treat \( u_B \) as a pressure with adiabatic index, \( \Gamma_B \), such that

\[ u_B \propto t^{-s_{\nu}^3}. \]

The energy density of the CMBR, \( u_c \), is a function of redshift \([u_c \propto (z + 1)]\), but since the lifetime of radio sources does not exceed a few times \( 10^8 \) yr (Alexander & Leahy 1987), we take \( u_c \) to be constant during the evolution of a given source. Performing the integral in equation (5),
where

$$\frac{t^{-a(t)}}{\gamma_i - a^{-1}} = a_2(t, t_i),$$

(6)

with

$$a_2(t, t_i) = \frac{4a_1}{3m_e c} [\frac{u_s(t)}{a_3} t_i^{3/2} (t_i^{a_i} - t_i^{a_0}) + \frac{u_c}{a_4} (t_i^{a_i} - t_i^{a_0})],$$

(7)

where $a_3 = 1 - a_1 (\Gamma e + 1/3)$ and $a_4 = 1 - a_1/3$. If $u_s(t_i)$ is the energy density of the relativistic electrons at time $t_i$, we find for $n_0(t_i)$ from equation (3)

$$n_0 = \frac{u_s(t_i)}{m_e c^2} \left[ \frac{\gamma_i - 1}{\gamma_i - 1} \frac{\gamma_i^{3/2} - t_i^{a_0/3}}{t_i^{a_0/3}} \right],$$

(8)

where $\gamma_{i,\text{min}}$ and $\gamma_{i,\text{max}}$ are the low- and high-energy cut-off of the initial energy distribution. The electrons are uniformly distributed over the volume $V$. Because of the expansion of $V$ we have to set $t^{a_0/3}(\gamma_i, t) d\gamma = t_i^{a_0/3} n(\gamma_i, t_i) d\gamma$, Thus the energy distribution of the relativistic electrons at time $t$ can be shown to be

$$n(\gamma_i, t) d\gamma = n_0 \frac{\gamma_i^{3/2} - t_i^{a_0/3}}{t_i^{a_i} - t_i^{a_0}} d\gamma,$$

(9)

where, from equation (6),

$$\gamma_i = \frac{\gamma_{i,\text{min}}^{3/2}}{t_i^{a_i} - t_i^{a_0}} a_2(t, t_i),$$

(10)

and $n_0$ is given by equation (8).

### 2.2 A model for the cocoon

The overall dynamics of the cocoon, and specifically the evolution of the cocoon pressure, $P_c$, were considered in detail in KA97; in this section we review the essentials of this model necessary to calculate the luminosity of the source and to determine also how an element of radio-emitting plasma evolves within the cocoon.

For the calculation of the radio emission of the cocoon we divide its contents into three separate ‘fluids’ with individual energy densities. The first fluid consists of the electrons (and possibly positrons); these are described by the energy spectrum given in equation (3) and contribute an energy density $u_s$ with adiabatic index $\Gamma e$. For a completely tangled magnetic field we have a magnetic ‘fluid’ with energy density $u_b$ and adiabatic index $\Gamma B = 4/3$. Finally, we allow for the possibility that protons and/or electrons with a thermal spectrum are present in the cocoon with an energy density $u_p$ and adiabatic index $\Gamma T$. The overall dynamics are governed by the pressure in the cocoon, $p_c = (\Gamma e - 1)(u_s + u_b + u_p)$, where the adiabatic index of the cocoon as a whole, $\Gamma e$, depends on the relative pressures of each component.

$$P_c = \int_0^t \frac{1}{6\pi v(r + 1)} \left[ \frac{\sigma c T}{6\pi v(r + 1)} Q_s n_0 (4R^2)^{(1 - \Gamma e)/\Gamma e} \right] \frac{1}{\gamma_i - 1} \frac{\gamma_i^{3/2} - t_i^{a_0/3}}{t_i^{a_0/3} - t_i \gamma_i} d\gamma_i.$$

(11)
limits of the radio spectrum of 10 MHz and 100 GHz respectively, implying that there is no thermal material present in the cocoon \(k = 0\). Their frequency cut-offs translate in our model to \(\gamma_{\text{min}} \approx 500\) and \(\gamma_{\text{max}} \approx 10^3\) for a source with \(D = 100\) kpc. Since in our model the power law of the energy distribution extends to \(\gamma_{\text{min}} = \gamma_{\text{max}}\), there is some thermal material present in the cocoon, and for the quoted values we find \(k = 3.6\). We must therefore adjust their values to be consistent with our choice of \(\gamma_{\text{min}}\) and \(\gamma_{\text{max}}\). Rawlings & Saunders (1991) also assumed that half of the energy that is transported by the jet during its life time, \(t\), is lost to the surrounding IGM because of the expansion work of the cocoon. However, from KA97 we find that this work is given by

\[
\int p_c \, dV_c \left[ \frac{5 - \beta}{9[\gamma_c + (\Gamma_c - 1) R_c^2]} - 4 - \beta \right] Q_{\text{tot}},
\]

where \(V_c\) is the volume of the cocoon. We can therefore derive jet kinetic powers from the values given by Rawlings & Saunders (1991) using

\[
Q_0 = \frac{9[\gamma_c + (\Gamma_c - 1) R_c^2] - 4 - \beta}{10 - 2\beta} \left( k + 1 \right)^{\alpha \left( + p \right)} Q_{\text{ns}} \approx 13 Q_{\text{ns}},
\]

where \(R = 2, k = 3.6\) and \(\Gamma_c = 5/3\).

The pressure in the cocoon also depends on its axial ratio, \(R\), and the bulk velocity in the jet, \(v_j\). We adopt \(R = 2\), which is an average value (Leahy & Williams 1984), and \(v_j = 0.87c\), implying a Lorentz factor of the bulk motion of \(\gamma_{\text{jet}} = 2\). This velocity is a rather arbitrary choice, since there are no reliable estimates of \(v_j\) in the literature.

The distribution of sources in the P–D diagram is constructed from the data presented by Laing, Riley & Longair (1983), Cotter et al. (1996) and Subrahmanyan et al. (1996); these authors quote luminosities at or close to an observing frequency of 178 MHz, and we therefore use this frequency in our calculations. Note that the distribution of observed sources presented here cannot be taken as the ‘true’ distribution because of the involved selection effects. The observed linear size of a radio source projected on to the plane of the sky, \(D\), depends, of course, not only on the advance speed of the hot spots but also on \(\sin z\), where \(z\) is the angle between the jet axis and the line of sight. Assuming that the low-frequency LRL sample represents a uniform distribution in \(z\), we adopt the average viewing angle \(z = 39.5\) for the model sources.

### 3.1 Evolution of the magnetic field

To proceed, we need to know the equation of state of the material in the cocoon as a whole, and also how the magnetic field is behaving during the expansion of the volume elements \(dV\). Since there is a mixture of three different fluids in the cocoon, this is not straightforward, and it is also likely that the equation of state varies both within the cocoon and with time. Hence we investigate three limiting cases.

**Case 1.** Both the cocoon and the magnetic field energy density have a relativistic equation of state \(p = \rho c^2\).
Case 2. The cocoon is 'cold' \((\Gamma_c = 5/3)\), but the energy density of the magnetic field is proportional to the one of the relativistic particles and therefore \(\Gamma_B = 4/3\).

Case 3. Cocoon and magnetic field are 'cold' \((\Gamma_c = \Gamma_B = 5/3)\). This implies some energy-dissipation process between the magnetic field and the non-relativistic particles by which the adiabatic index of the energy density of the magnetic field is held constant at 5/3. This effectively keeps the energy of the magnetic field and that of the particles in equipartition.

In cases 1 and 3 the ratio of the energy densities of the magnetic field and of the particles for every volume element \(\delta V\) in the cocoon, \(r = 0.785\) for the value of \(p = 2.14\) adopted here, is not changing with time. In case 2 the value of \(r\) will increase with time, since the adiabatic index of the magnetic field is lower than that of the particles. This implies that after some time the energy density of the magnetic field will start to dominate the total energy density in \(\delta V\), and therefore change the adiabatic index of this part of the cocoon. For a volume element injected into the cocoon at time \(t\), the ratio of energy densities \(r\) becomes equal to 1 at time \(t = 1.9 t_i\). At the same time the total volume of the cocoon, \(V_c\), has increased by a factor 6.4 \([V_c \propto t^{(\Gamma_B - \Gamma_p)}\); see KA97\], implying that in most parts of the cocoon \(r < 1\). We therefore make the approximation that the adiabatic index of the cocoon as a whole is 5/3.

Fig. 1 shows the evolutionary tracks for all three cases (correct for \(\Gamma_c = 5/3\): \(Q_0 = 13 Q_{IS}\)) for two limiting jet powers \(Q_0 = 1.3 \times 10^{38}\) and \(1.3 \times 10^{40}\) W and an intermediate case with \(Q_0 = 1.3 \times 10^{39}\); the redshift \(z\) is 0.2 for the low-power jet, 0.5 for the 'average' jet, and 2 for the high-power jet.

The range of luminosities observed in FRII sources is bounded by the tracks for the two limiting jet powers, and the drop in luminosity caused by the catastrophic energy losses of the relativistic electrons occurs at approximately the correct linear size. The importance of radiative losses in reducing the source luminosity at large linear sizes (even at a low observing frequency) is very significant – the lack of large (Mpc) sources at high luminosity is therefore a direct result of their intrinsic luminosity evolution, and is a strong function of frequency. Most of the observed sources 'crowd' in the region of the diagram between 100 kpc and 1 Mpc. From the time markers on the tracks in Fig. 1 it is clear that the model discussed here predicts exactly this behaviour, since model sources spend the longest part of their life time in this region of the diagram. The difference between cases 2 and 3 is almost negligible. The higher luminosity for case...
1 results from the fact that in this case less of the energy transported by the jet is lost in the expansion of the cocoon. Using the appropriate correction factor for $Q_o$ for this case by setting $\Gamma_c = 4/3$ in equation (18), which yields $Q_o = 2.3 Q^*$, puts this track very close to the other two. Thus we can conclude that the different possibilities for the equation of state of the cocoon and for the evolution of the magnetic field do not have a significant influence on the evolutionary tracks. We will therefore use only case 3 in the following.

Fig. 2 shows a comparison of the effects of the various loss processes. The most luminous track in this figure represents a model where the energy losses of the relativistic electrons are completely neglected, i.e., the right-hand side of equation (4) is set to zero. This curve is equivalent to the results of Baldwin (1982). The two other tracks shown both incorporate adiabatic losses plus one of the radiative loss processes each. Obviously the adiabatic losses lead to a pure luminosity offset, which one would expect from equation (4) if the two radiative terms on the right are set to zero. From the figure it is also clear that synchrotron losses are dominating the shape of the track for small sources, and that inverse Compton losses are responsible for the steep decline of the luminosity of large sources. The decreasing importance of synchrotron losses with increasing linear size is caused by the decreasing energy density of the magnetic field in the cocoon. Once the energy density of the CMBR becomes comparable to the energy density of the magnetic field the inverse Compton losses determine the shape of the track and limit the size of the radio source.

As the source luminosity decreases as the result of inverse Compton losses, so the prominence of the hotspots will increase. A detailed investigation of this effect requires a proper model for the hotspot itself, and this will be investigated in a forthcoming paper.

3.2 Effects of redshift and environment

In Fig. 3 we show evolutionary tracks at an observing frequency of 178 MHz at various redshifts; the other source parameters are given in the figure caption. These tracks are calculated assuming that there is no evolution of the surrounding gas with redshift. Since the energy density of the CMBR increases with redshift, the inverse Compton losses become important earlier and the evolutionary tracks begin to steepen for smaller linear sizes of the source.

The environments of radio sources have a great influence on their appearance. The effects on the radio luminosity of a source caused by a change in the shape of the density profile is shown in Fig. 4, where the exponent, $\beta$, in the density distribution of the IGM is varied. The track for $\beta = 0$ is purely hypothetical, since KA97 have pointed out that a jet with the parameters used here could not reach a linear size greater than about 80 kpc in an uniform environment without being destroyed by turbulence; for this value of $\beta$
Figure 3. The influence of the redshift $z$ on the evolutionary tracks at $v = 178$ MHz. Solid curve: $z = 0$, dashed: $z = 0.5$, dot-dashed: $z = 1$, dotted: $z = 2$ and dot-dot-dot-dashed: $z = 3$. All other model parameters as in the intermediate case in Fig. 1.

Figure 4. The influence of the shape of the density distribution in the IGM. Solid curve: $\beta = 0$, dashed: $\beta = 1$, dot-dashed: $\beta = 1.5$ and dotted: $\beta = 2$. All other model parameters as in the intermediate case in Fig. 1.
the track is increasing in radio luminosity for small sources, a result also found by Baldwin (1982), but the inverse Compton losses are still strong enough to reverse this trend and cause the track to steepen for large linear sizes. The behaviour for $\beta=1$ is close to that of a source with constant radio luminosity in the absence of radiative losses.

The point of intersection is due to the intrinsic characteristic time-scale of the problem $\tau = (a^2 \rho_0 Q_0)^{1/3}$ (see KA97), which is the same for all values of $\beta$. Note also that the point at which inverse Compton losses become important shifts to smaller linear sizes for smaller values of $\beta$ (with the exception of $\beta=0$). This is because the pressure in the cocoon is lower at any given linear size in the case of large values of $\beta$ compared to smaller values. The population of relativistic electrons in these cases has therefore lost less energy when the energy density of the CMBR becomes comparable to the energy density of the magnetic field in the cocoon. The steepening of the track due to inverse Compton losses then occurs at large linear sizes. In the case of $\beta=0$ the luminosity of the source would increase with linear size for all sizes without any radiative losses. However, the synchrotron losses of the electrons in this case are so severe that the luminosity of the source is almost entirely produced by material which has just been injected into the cocoon while older parts are not radiating anymore, leading to almost constant radio luminosity for all linear sizes. Because of this the exact point at which inverse Compton losses become important in this case is difficult to determine and the start of the steepening of the track is less obvious.

The observed distribution of sources in the $P-D$ diagram seems to be fitted best by tracks with $\beta$ just less than 2. This is in agreement with $\beta=1.9$ found by Cotter (1996), who constructed evolutionary tracks through the $P-D$ diagram by comparing the positions of sources with similar observed jet power, and also with X-ray observations of the gas surrounding galaxies at low redshift (Canizares et al. 1987).

Fig. 5 shows the effect of varying the central density of the IGM, $\rho_0$. For a greater central density the pressure in the cocoon is higher; this leads to an increased radio luminosity and also to greater energy losses of the relativistic electrons via synchrotron radiation. This effect ‘flattens’ the tracks of small sources in a high-density environment. Again the steepening of the tracks of large sources occurs at smaller linear sizes for sources in denser environments, since their hotspot advance speeds are smaller.

### 3.3 Effects of jet properties

In Section 3.1 we have already investigated the influence of the jet power, $Q_0$, on the evolutionary tracks. Other jet parameters which have an effect on the radio luminosity of radio sources are the jet half-opening angle $\theta$ (which controls the aspect ratio of the cocoon $R$) and the nature of the jet material.

![Figure 5](https://example.com/figure5.png)
If the expansion of the cocoon perpendicular to the jet axis is confined by the ram pressure of the IGM, we find that the aspect ratio of the cocoon is determined by the ratio of the pressure at the hotspot to the pressure in the cocoon. From KA97 we find that this ratio is proportional to the inverse square of the jet half-opening angle $\theta$. Fig. 6 shows the evolutionary tracks for the range of $R$ observed in sources at constant $Q_0$. The limiting cases $R=1.3$ and 6 correspond to $\theta=47^\circ.8$ and $10^\circ.4$ respectively. The pressure in the cocoon must be high in the sources with wider cocoons to allow the faster expansion perpendicular to the jet axis, leading to higher synchrotron losses and hence giving relatively flat tracks for small linear sizes. Since the energy density at the hotspots is lower relative to that of the cocoons, the hotspot advance speeds are smaller than those for the sources with thinner cocoons, and the steepening of the tracks occurs at smaller linear sizes.

All models considered up to this point have assumed that the jets consist of an electron–positron plasma and that the contribution of the thermal particles to the energy density in the cocoon is negligible. If there are protons in the jet, they are also accelerated to relativistic velocities at the jet shock. Bell (1978) shows that for a proton–electron plasma accelerated in a shock front the protons can store 10 times more energy than the electrons. Other acceleration scenarios predict much higher values (Eilek & Hughes 1991). From Fig. 7 it is clear that an addition of protons to the jet material, even if they contribute only moderately to the energy density in the cocoon ($k'=100$), decreases the luminosity of radio sources severely. Should the jets in FRII sources consist of protons and electrons, they must have much higher energy transport rates than we have assumed so far in order to explain the most luminous sources. This would considerably increase the hotspot advance speeds of these sources, and lead in turn to very large linear sizes for the sources before inverse Compton losses become significant (see Fig. 7). Since we do not observe such large luminous sources, this can be taken as evidence against the presence of protons in the jet.

4 CONCLUSIONS
A model for the cocoon of FRII radio sources based on the model of KA97 is presented. Energy-loss processes for the relativistic electrons producing the radio emission of the cocoon are incorporated into a calculation of the expected radio luminosity. The resulting evolutionary tracks through the $P–D$ diagram are shown to be in good agreement with the observed distribution of sources. The lack of luminous giants in the diagram is reproduced by just the energy losses of the electrons without invoking changes in the density distribution of the IGM or the switching off of the central engine. The exact details of the evolution of the magnetic field in the cocoon are shown to have no significant effect on the evolutionary tracks. The effects of the environment and
The influence of protons in the jet. Tracks are plotted for $\rho_0 = 7.2 \times 10^{-22}$ kg m$^{-3}$, $a_o = 2$ kpc, $\beta = 1.9, z = 2$ and $R = 2$. Solid curve: $Q_o = 1.3 \times 10^{46}$ W and $k' = 0$, dashed: $Q_o = 1.3 \times 10^{46}$ W and $k' = 100$ and dot-dashed: $Q_o = 10^{42}$ W and $k' = 100$.

jet parameters on the tracks are investigated. The requirement of very high jet powers and the associated high hotspot advance speeds for proton-electron jets to account for the most luminous observed sources might rule out large fractions of protons in the jet.

ACKNOWLEDGMENT

We thank the referee, Dr J. P. Leahy, for helpful comments on the manuscript.

REFERENCES

Rees M. J., 1971, Nat, 229, 312
Shklovskii I. S., 1963, SvA, 6, 465

@ 1997 RAS, MNRAS 292, 723–732

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System