Dynamical age of FRII-type radio galaxies estimated from their geometry and brightness at different wavelengths

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1. Introduction

According to the standard dynamical models for double FRII-type ([5]) radio sources (e.g. [1], [4], [17]), relativistic jets emanating from an AGN and boring the intergalactic medium (IGM) are not in direct contact with the undisturbed IGM, but rather are surrounded by a "cocoon" consisting of shocked jet material and shocked IGM (cf. Fig. 1). In these models, the lengthening of the cocoon is governed by the balance between the jet's momentum flux (thrust) and the ram pressure of the IGM, while a width of the cocoon is determined by its internal pressure. If the cocoon expands faster than the rate at which the jets deliver their energy, the pressure should decrease until it reaches equilibrium with the pressure of the IGM. These physical conditions would be clarified if the age of the radio structure is known.

The more recent analytical models for the evolution of FRII-type radio sources [8] (hereafter referred to as KDA) and [2] combine the pure dynamical model of [7] (hereafter KA) with expected radio emission from a radio source (its cocoon) incorporating energy losses of the relativistic electrons. In our paper [12], the KDA model has been used to derive two basic physical parameters of FRII-type radio sources with synchrotron age reliable determined from a spectral ageing analysis (e.g. [15]); the jet power $Q_{\rm jet}$ and central density of the galaxy nucleus ρ_0. In that paper we assumed a dynamical age to be approximately twice of the synchrotron age (for arguments after that assumption, cf. [10]).

In this paper, we show an application of the KDA algorithm **to derive a reliable dynamical age** of FRII-type radio galaxies by modelling their observed linear size, volume, redshift, and brightness of the cocoon measured at a number of different wavelengths. Our method is applied to a number of sources from the sample of [12] and, in particular, to two radio galaxies with, so called, "double-double" structure indicating a multiple phase of activity of their AGN. Hereafter we define a dynamical age as follows:

$$\text{if}\quad v_{\rm h}=\frac{dr_{\rm j}}{dt}\qquad\text{then}\qquad t_{\rm dyn}=\int_0^{D_s/2}\frac{dr_{\rm j}}{v_{\rm h}(r)}$$

2. The first approximation of a dynamical age

In the first series of our research papers ([12], [13]), a range of values of the main model's parameters $Q_{\rm jet}$ and ρ_0,

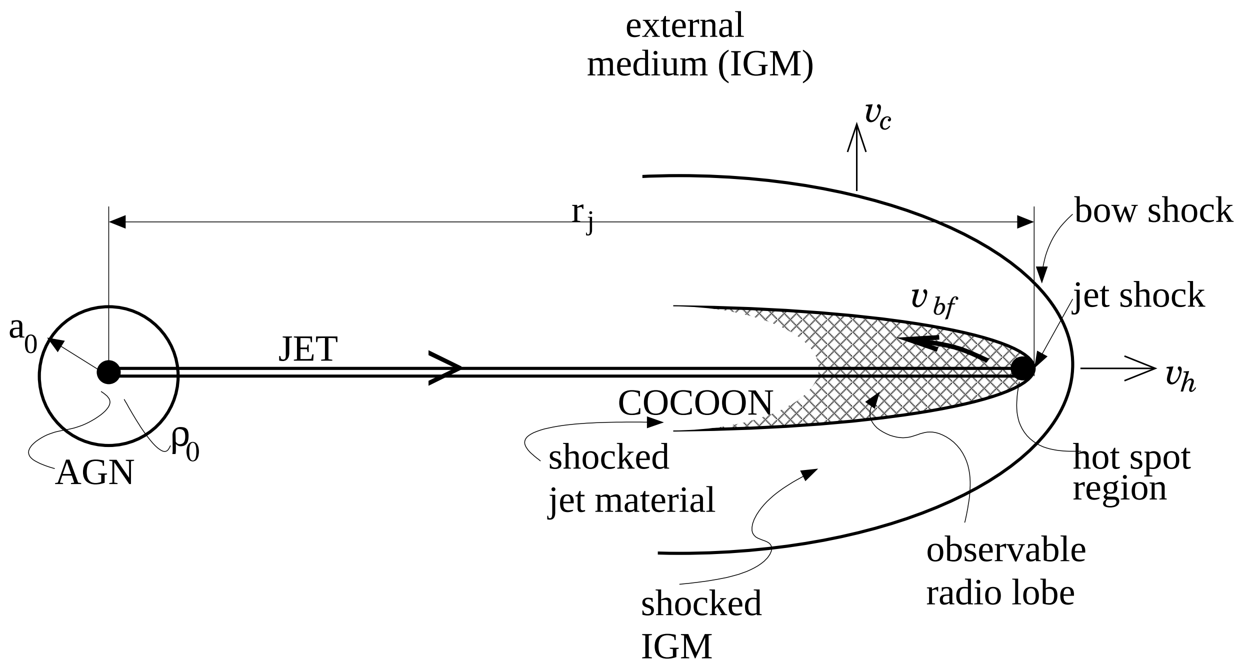

Figure 1: Dynamical model for a radio source of FRII morphological type.

$$Q_{\rm jet} = Q_{\rm jet}(t_{\rm dyn}, D_s, P_{1.4}, AR, z), \qquad \rho_0 = \rho_0(t_{\rm dyn}, D_s, P_{1.4}, AR, z)$$

was approximated for a sample of FRII-type radio sources with known (spectral) age. $D_s, P_{1.4}, AR$, and z are the observational parameters of a source: its linear size, 1.4-GHz luminosity, axial ratio (describing geometry) of the cocoon, and redshift, respectively.

That result was used to confine a range of unknown dynamical age of newly detected "giant" radio galaxies selected from the sample of [11]. Such a confinement of the above parameters is shown in Fig. 2, where large crossed dots mark the "giants" whose age was known prior to our analysis. The numerical modelling indicates that ρ_0 is slightly dependent on $Q_{\rm jet}$, which means that jet of higher power more effectively drill the IGM of higher density. Fitted values of $Q_{\rm jet}$ and ρ_0 for a number of hypothetical ages of a given unknown-age "giant" radio galaxy are connected with the curved lines. For a number of analysed galaxies, the filled small squares mark the values of $Q_{\rm jet}$ and ρ_0 for each hypothetical age. The values of age (in 10^6 years) are marked. An increase of age from the left to the right side of the diagram indicates that, if the source with the observed size and brightness was young, the jet power would be higher and the central density – lower with respect to their relevant values for the same source but much older.

The above results suggest that a dynamical age of actually observed the largest radio sources is likely between 30×10^6 and 200×10^6 years. Now, again basing on the KDA model, we show how a source's dynamical age can be directly determined.

3. Direct determination of the dynamical age

3.1. The method and results

Described above determination of the parameters $Q_{\rm jet}$ and ρ_0 for different hypothetical ages of a given radio galaxy, obtained by fitting the KDA model to the galaxy observed parameters, in particular to its apparent monochromatic brightness (at one frequency), raised the following questions:

– how the curves on the $\log Q_{\rm jet}$–$\log\rho_0$ plane would look like for the same radio source but at another observational frequency?

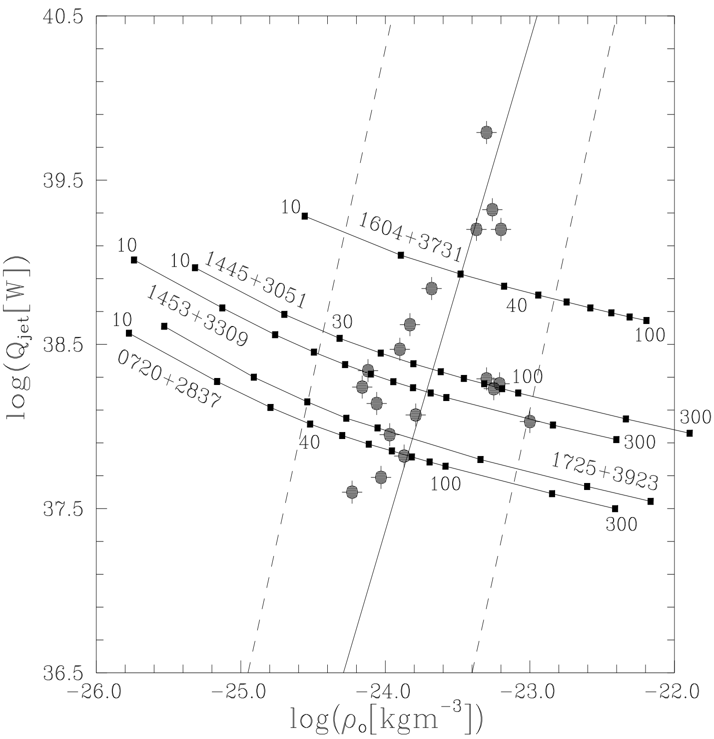

Figure 2: Range of predicted values of the jet power $Q_{\rm jet}$ and dynamical age $t_{\rm dyn}$ vs. central density of the galaxy nucleus ρ_0 for a few exemplary "giant" radio galaxies. The large crossed dots are "giants" with known age used to determine the statistics of ρ_0. The diagonal dashed lines indicate a statistical 0.95 C.I. for this parameter. The age line for each named source begins and ends at the marked age value in Myr.

– whether using the known radio spectrum of a source, i.e. its brightness at a number of different frequencies (wavelengths), one can approximate its age without any assumption about the radio core density ρ_0?

The answer is: Yes! In order of a further confinement of the dynamical age of a source, better than that shown in Fig. 2, its luminosity has been determined at four different frequencies: 151, 408, 1400 and 4800 MHz using the flux density data from the following radio surveys: 6C and 7C (151 MHz), WENSS (325 MHz), B2 and B3 (408 MHz), NVSS (1400 MHz, and GB6 (4850 MHz). Then the calculation algorithm (like in Sect. 2) has been repeated for each of the above frequencies, i.e. the parameters $Q_{\rm jet}$ and ρ_0 are determined for a number of hypothetical age values fitting the source's apparent size and its luminosity at a given frequency P_ν.

Four examples of the resultant $Q_{\rm jet}$–ρ_0 diagrams are shown in Figures 3a and b, where the four curves indicate the $Q_{\rm jet}$ and ρ_0 values expected at different age and different observing frequency for the same radio source. As it is clearly seen, the curves bisected themselves and all intersections are concern - treated in a narrow range of $Q_{\rm jet}$ and ρ_0 values. Indeed, the same values of both parameters are expected for each frequency because different P_ν concern the same source, and should be connected to a unique age. In fact, some spread of these intersections determine an uncertainty of the dynamical age estimated by the fit, however this uncertainty is much smaller than a range of possible age values available from the fitting procedure based on one observing frequency only.

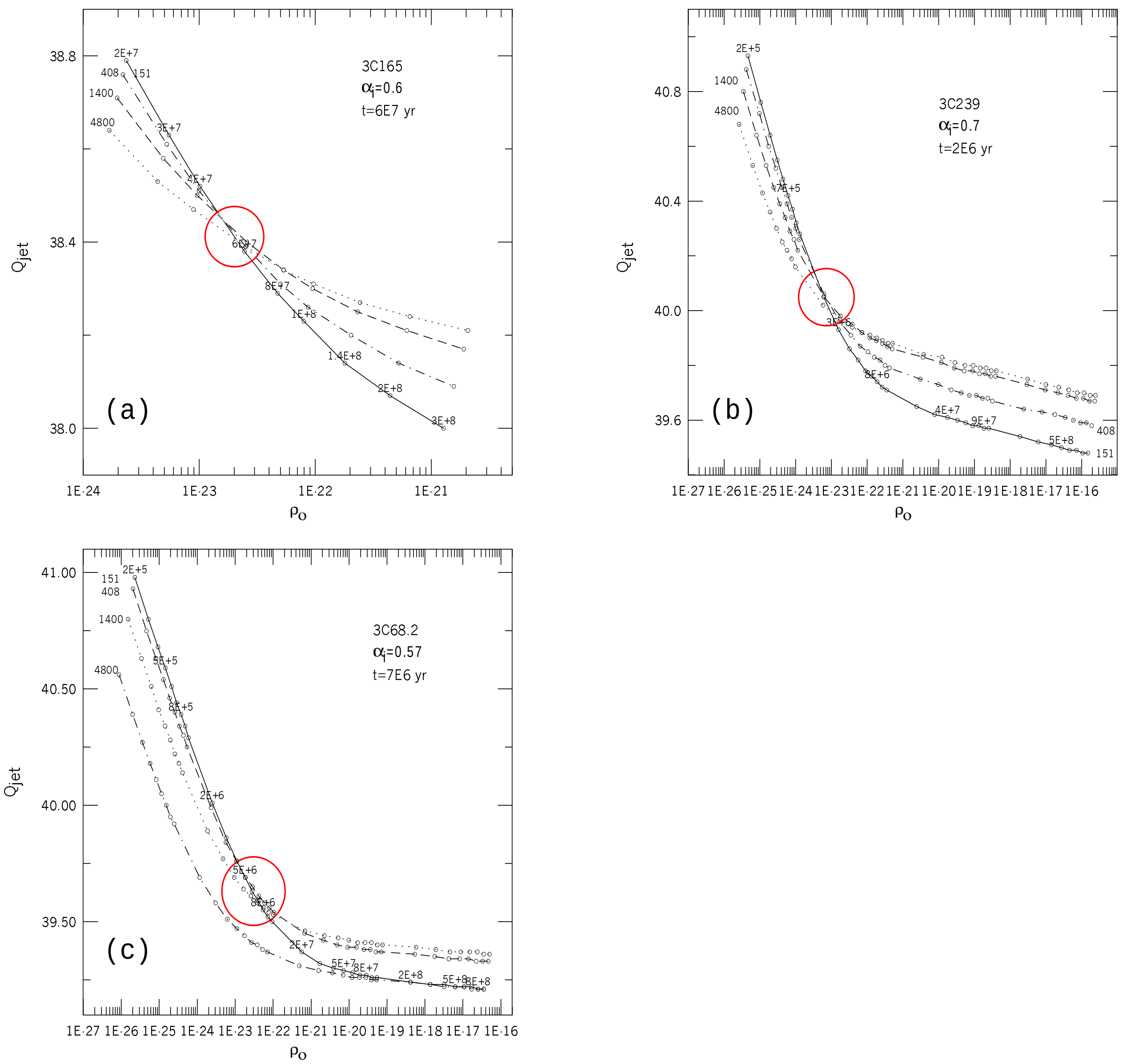

Figure 3: Predicted values of the parameters $Q_{\rm jet}$ and ρ_0 obtained from the fit to the observed source's size and brightness at four different frequencies. The intersections of the curves give the best estimate of the source's age. Panel (c) illustrates the problem described in Sect. 3.2.

Our analysis has revealed that a closer is the source observed radio spectrum to the theoretical spectrum of radiative energy losses described by the model of "continuum injection" of relativistic particles into a region of deceleration (CI model), the intersections of different $Q_{\rm jet}$ vs. ρ_0 curves tend to a common point.

3.2. The problems met

This is worth to emphasize two problems which were met during the above ageing analysis:

(1) In our sample of analysed sources, the spectra of few of them evidently depart from the CI model of energy losses which is basic for the evolutionary KDA model. In such a case, the sources' high-frequency spectrum is strongly steepened, and the resultant $Q_{\rm jet}$ vs. ρ_0 curve (usually at 4.8 GHz) bisects others at an age inconsistent with that implied by the remaining three curves. Fig. 3c illustrates the case of the high-redshift radio galaxy 3C68.2.

In order to determine the best estimate of dynamical age ($t_{\rm dyn}$), we adopt a concentration measure (Δ) of the curves intersections. We define it as the least average value of the mutual separations between [$Q_{\rm jet}$, ρ_0] points found for a given age.

(2) Another difficulty is connected with the initial exponent of the energy distribution at the time the relativistic particles are injected into the source's cocoon. In the original KDA paper, the authors adopted the theoretical value of this parameter drawn from the fluid dynamics consideration of relativistic shock waves by [6]. That value (corresponding to the initial spectrum slope $\alpha_{\rm inj}$= 0.57) is evidently discordant with the observed low-frequency spectra of FRII-type sources many of which show a significant departure from the above canonical value, and are enclosed in a range $0.4< \alpha_{\rm inj} <1.0$.

In this situation, we argue that the best value of $\alpha_{\rm inj}$ (which must be inserted into the model) is that obtained by fitting the theoretical CI model of synchrotron energy losses to the observed spectrum of entire radio source under consideration. Those fits have been performed using the SYNAGE package ([14]).

The dynamical age, $t_{\rm dyn}$, derived with the described above method, is given in Table 1 (in column 4) for a few exemplary radio sources. This age is compared with the radiative (synchrotron) age of the given source, $t_{\rm rad}$, taken from [12] (in column 5). The data in Table 1 show that their ratio, $t_{\rm dyn}/t_{\rm rad}$ (in column 6), is between about 1 to about 3, at least for the sources investigated. The last column 7 gives an average expansion velocity in units of c.

Table 1: Dynamical and radiative ages of exemplary radio sources

Source name	z	D [kpc]	$t_{\rm dyn}$ [10^6 yr]	$t_{\rm rad}$ [10^6 yr]	$t_{\rm dyn}/t_{\rm rad}$	$v_{\rm h}$/c
3C239	1.786	94	2±1	1.4±0.2	1.4±0.7	0.15
1141+354	1.781	97	3.2±1.4	1.7±0.4	1.9±0.9	0.10
3C294	1.779	132	3.8±0.4	1.4±0.2	2.7±0.5	0.11
3C322	1.681	279	4.0±1.8	3.6±0.3	1.1±0.5	0.23
Cyg A	0.564	185	11±1	6.5±1.5	1.6±0.4	0.055
0908+376	0.105	100	14±2	14±3	1.0±0.3	0.023
3C165	0.296	480	64±12	30±5	2.1±0.5	0.024
1209+745	0.107	1090	110±40	55±10	2.0±0.8	0.032

3.3. The case of the "double-double" radio galaxy J1453+3309

The outer and inner radio structures of this very interesting source is shown in Fig. 4. We found that the inner structure is about 7 to 8 times younger than the outer one, depending on a value of the parameter β assumed for the inner source. Such an assumption is related to the physical aspect of how the energy injection via jets has ceased, whether the old jet's power has been switched off completely or not at some moment of time, and what is a time delay between consecutive activity periods? Depending on that, the old cocoon material can or cannot be replaced with the denser IGM (for an extensive discussion of this aspect, cf. [9]). Our calculation shows that a variation of the β value from 1.5 to 0 does not change $t_{\rm dyn}$ of the inner source significantly, and in each case about 10-times weaker jet power as well as 10-times less denser environment within the relic cocoon is found for the second activity period. However, the resultant average expansion velocities of $0.041c$ for both the inner and the outer structures are unexpected; the environmental considerations suggest that the inner source should expand faster (e.g. [16]).

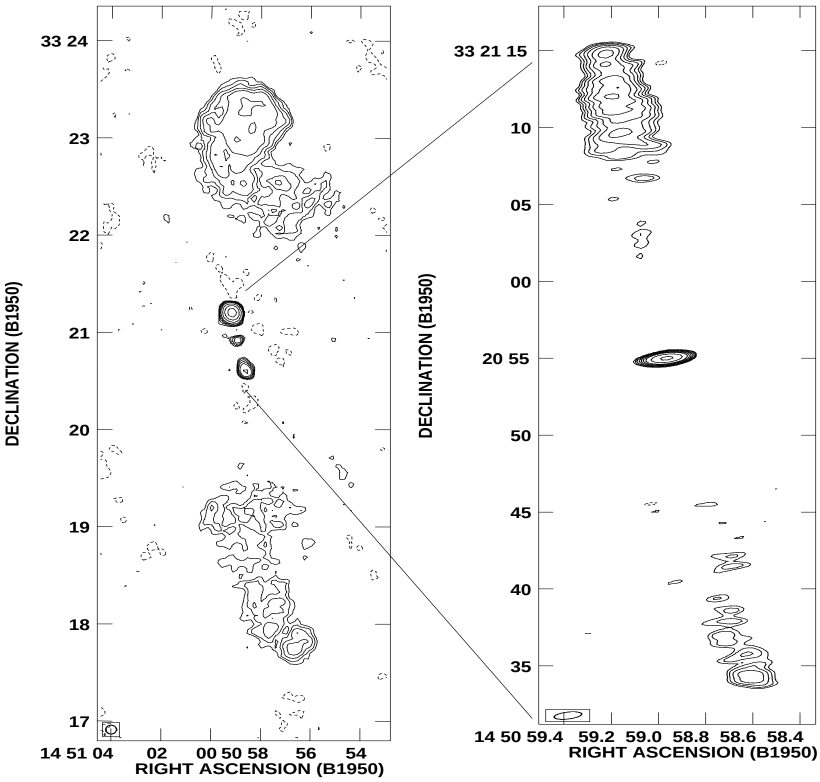

Figure 4: The outer 1.6 Mpc (older) and inner 200 kpc (younger) structure of the "double-double"-type galaxy J1453+3309.

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