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Estimate of the total kinetic power and age of an extragalactic jet by its cocoon dynamics: the case of Cygnus A

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ABSTRACT

We examine the constraints imposed on the total kinetic power ($L_{\rm j}$) and the age ($t_{\rm age}$) of relativistic jets in Fanaroff–Riley type II radio sources in a new way. We solve the dynamical expansion of its cocoon embedded in the intracluster medium and obtain the analytical solution of its physical quantities in terms of $L_{\rm j}$ and $t_{\rm age}$. We estimate $L_{\rm j}$ and $t_{\rm age}$ using a comparison of the model and the observed shape of the cocoon. The analysis focuses on Cygnus A and we find that (i) the source age is $3 < t_{\rm age} < 30$ Myr and (ii) the total kinetic power of the jet is estimated as $0.2 \times 10^{46} < L_{\rm j} < 1 \times 10^{48}$ erg s^{-1}, which is larger than 1 per cent of the Eddington luminosity of Cygnus A.

Key words: plasmas – radiation mechanisms: non-thermal – galaxies: active – galaxies: individual: Cygnus A.

1 INTRODUCTION

After the detections of the inverse Compton component in X-ray from Fanaroff–Riley type II (FR II) radio sources, our knowledge of energetics, especially of the kinetic power of non-thermal electrons, has progressed in recent years (e.g. Leahy & Gizani 2001; Hardcastle et al. 2002; Harris & Krawczynski 2002; Kataoka et al. 2003; Croston et al. 2005). When we explore further physical conditions in the jets, we encounter great difficulty in constraining the fraction such as thermal electrons and/or protons coexisting with non-thermal electrons because it is hard to observe these components (e.g. Celotti et al. 1998; Sikora & Madejski 2000). This problem has prevented us from estimating the total mass and energy flux ejected from a central engine. To conquer this, a simple procedure has been proposed in the study of jets in FR II sources in Kino & Takahara (2004, hereafter KT04). In the pressure and mass density of jets, contributions from the invisible components are also involved. Hence the rest-mass density and energy density estimated from the shock dynamics definitely prove the quantities of total plasma. Also, for radio bubbles in cluster cores, a similar dynamical approach has been adopted to constrain their physical state (Fabian et al. 2002; Dunn & Fabian 2004).

In this paper, we explore the cocoon dynamics in FR II radio sources as a robust tool to know the total kinetic power $L_{\rm j}$ and source age $t_{\rm age}$. In Section 2, we discuss our analytical solution of cocoon expansion, which includes the effect of radial dependence of the rest-mass density of the surrounding intracluster medium (ICM). In Section 3, by comparing the analytical solution and observation of the cocoon, we explore the kinetic power of Cygnus A, which is one of the best-studied FR II sources. Conclusions are given in Section 4.

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2 COCOON DYNAMICS

We deal with the cocoon dynamics in FR II radio sources. The adopted basic equations are almost the same as those in Begelman & Cioffi (1989, hereafter BC89). The main differences between BC89 and the present work are the following: (i) we explicitly solve the physical quantities as a function of $L_{\rm j}$ and $t_{\rm age}$; (ii) we take account of the effect of the radial profile of the mass density of the ICM; (iii) as a result, the growth of the cocoon head $A_{\rm h}$ is consistently solved from the basic equations.

2.1 Basic assumptions

Our main assumptions are as follows:

(i) we limit our attention to a jet relativistic speed ($v_{\rm j} = c$);
(ii) the jet supplies a constant $L_{\rm j}$ in time;
(iii) we focus on the overpressured cocoon phase;
(iv) we assume that the magnetic fields are passive and ignore their dynamical effect.

For (i), although it is still under debate, some jets are suggested to be relativistic (e.g. Tavecchio et al. 2000; Celotti, Ghisellini & Chiaberge 2001). Because little is known about the evolution of $L_{\rm j}$, assumption (ii) is adopted as a first-step working hypothesis. The assumption of (iii) is automatically guaranteed by the sideways expansion of the cocoon (e.g. Cioffi & Blondin 1992). The assumption of (iv) is based on the results that a multifrequency analysis of radio galaxies shows that the energy density of a magnetic field tends to be smaller than that of non-thermal electrons (e.g. Leahy & Gizani 2001; Isobe et al. 2002).

2.2 Basic equations

The model parameters are $L_{\rm j}$ and $t_{\rm age}$. The unknown physical quantities are $v_{\rm h}$, $v_{\rm c}$, $P_{\rm c}$ and $A_{\rm h}$ (or $A_{\rm c}$), which are the advance velocity of the cocoon head, the velocity of cocoon sideways expansion, the pressure of the cocoon, the cross-sectional area of the head part of the cocoon (or the cross-sectional area of cocoon body), respectively (see Fig. 1). The equation of motion along the jet axis, and sideways expansion, and energy conservation in the cocoon are given by

$$\frac{L_{\rm j}}{v_{\rm j}} = \rho_{\rm a}(r_{\rm h}) v_{\rm h}^2(t) A_{\rm h}(t), \tag{1}$$

$$P_{\rm c}(t) = \rho_{\rm a}(r_{\rm c})\, v_{\rm c}(t)^2, \tag{2}$$

$$\frac{P_{\rm c}(t) V_{\rm c}(t)}{\hat{\gamma}_{\rm c} - 1} \simeq 2 L_{\rm j} t. \tag{3}$$

Here, $r_{\rm h}(t) = \int_{t_{\rm min}}^{t} v_{\rm h}(t')\,{\rm d}t'$, $r_{\rm c}(t) = \int_{t_{\rm min}}^{t} v_{\rm c}(t')\,{\rm d}t'$, $V_{\rm c}(t) = 2\int_{t_{\rm min}}^{t} A_{\rm c}(t') v_{\rm h}(t')\,{\rm d}t'$, $t_{\rm min}$ and $\hat{\gamma}_{\rm c}$ are the length from the centre of the galaxy to the head of the cocoon, the radius of the cocoon body, the volume of the cocoon, the start time of source evolution and the specific heat ratio of the plasma inside the cocoon, respectively. The declining mass density of the ICM, $\rho_{\rm a}$, is given by $\rho_{\rm a}(r) = \bar{\rho}_{\rm a}(r/r_0)^{-\alpha}$ where r_0 and $\bar{\rho}_{\rm a}$ are the reference position and the ICM mass density at r_0, respectively. We set r_0 as $r_{\rm h}(t_{\rm age})$ throughout this paper. Most of the kinetic energy is deposited in the cocoon, which was initially suggested by Scheuer (1974), and recent studies of hotspots also show that the radiative efficiency is very small (e.g. KT04). Following Cioffi & Blondin (1992), we add the factor of $1/(\hat{\gamma}_{\rm c} - 1)$ in equation (3) to express the amount of the deposited internal energy. In other words, this corresponds to the neglect of the $P\,{\rm d}V$ work because of its smallness.

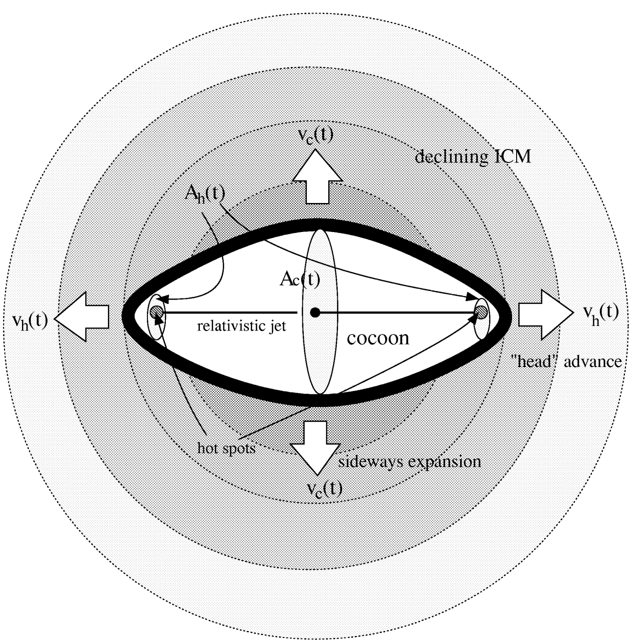

Figure 1. A schematic diagram of the interaction of the ICM with declining atmosphere and the relativistic jet in a FR II radio galaxy. As a result, most of the kinetic energy of the jet is deposited in the cocoon and it is inflated by its internal energy.

The numbers of quantities are four, while those of basic equations are three. Hence, we set $A_{\rm c}(t) \propto t^X$ where X is a free parameter. We can constrain the value of X from observations. A specific case is shown in Section 3. Hence, we obtain $v_{\rm h}$, $v_{\rm c}$, $P_{\rm c}$ and $A_{\rm h}$ by using a free parameter X.

As a subsidiary equation, the area of the cocoon body is given by

$$A_{\rm c}(t) = \pi \left[\int_{t_{\rm min}}^{t} v_{\rm c}(t')\,{\rm d}t' \right]^2 .$$

It is clear that the change of the unknown from $A_{\rm c}$ to $A_{\rm h}$ does not change the result. However, note that when we choose $A_{\rm h}$ as an unknown instead, we cannot obtain the solution for $\alpha = 2$.

2.3 Analytical solution

We assume that the physical quantities have a power-law dependence in time and that the coefficient of each physical quantity is barred quantity. Each quantity has the form of $A = \bar{A}\,(t/t_{\rm age})^Y$ where Y is an arbitrary index. The time evolution of $v_{\rm c}$ is

$$v_{\rm c}(t) = \bar{v}_{\rm c}\left(\frac{t}{t_{\rm age}}\right)^{0.5X-1} = \frac{\bar{A}_{\rm c}^{1/2}}{t_{\rm age}}\mathcal{C}_{\rm vc}\left(\frac{t}{t_{\rm age}}\right)^{0.5X-1}, \tag{4}$$

for a given $A_{\rm c}$. With this, the analytical form of cocoon quantities in the decreasing ICM density is obtained as follows:

$$P_{\rm c}(t) = \bar{\rho}_{\rm a}\bar{v}_{\rm c}^2\mathcal{C}_{\rm pc}\left(\frac{\bar{v}_{\rm c}}{v_0}\right)^{-\alpha}\left(\frac{t}{t_{\rm age}}\right)^{X(1-\alpha/2)-2}, \tag{5}$$

$$v_{\rm h}(L_{\rm j}, t) = \frac{L_j}{\bar{\rho}_{\rm a}\bar{v}_c^2\bar{A}_{\rm c}}\mathcal{C}_{\rm vh}\left(\frac{\bar{v}_{\rm c}}{v_0}\right)^{\alpha}\left(\frac{t}{t_{\rm age}}\right)^{X(-2+0.5\alpha)+2}, \tag{6}$$

$$A_{\rm h}(L_j, t) = \frac{L_{\rm j}}{v_{\rm j}\bar{\rho}_{\rm a}\bar{v}_{\rm h}^2}\mathcal{C}_{\rm ah}\left(\frac{\bar{v}_{\rm h}}{v_0}\right)^{\alpha}\left(\frac{t}{t_{\rm age}}\right)^{X(\alpha-2)(-2+0.5\alpha)+3\alpha-4}. \tag{7}$$

Here, $\mathcal{C}_{\rm vh} = (\hat{\gamma}_c - 1)[3 - (1 - 0.5\alpha)X](0.5X)^{-\alpha}$, $\mathcal{C}_{\rm vc} = 0.5X/\pi^{1/2}$, $\mathcal{C}_{\rm pc} = (0.5X)^{\alpha}$ and $\mathcal{C}_{\rm ah} = [X(-2+0.5\alpha)+3]^{-\alpha}$. $v_0 \equiv r_{\rm h}/t_{\rm age}$ corresponds to the head speed for constant velocity in time.

Here we use the conditions of $0.5X > 0$ and $X(-2 + 0.5\alpha) + 3 > 0$, which make the contribution at $t_{\rm min}$ in the integrations of $r_{\rm h}$ and $r_{\rm c}$ small enough. The case we focus on in Section 3 is that $X = 12/7$ and $\alpha = 1.5$, which clearly satisfies these conditions.

First, let us consider the cocoon evolution. The growth of both $A_{\rm h}$ and $A_{\rm c}$ must be positive. As for the cocoon expansion speeds, three different behaviours are theoretically predicted such as (i) accelerated head $[X(-2 + 0.5\alpha) + 2 > 0]$, (ii) constant head $[X(-2 + 0.5\alpha) + 2 = 0]$ and (iii) decelerated head $[X(-2 + 0.5\alpha) + 2 < 0]$. Cases (i), (ii) and (iii) correspond to $X < 1$, $X = 1$ and $X > 1$ for $\alpha = 0$, while for $\alpha = 2$ cases (i), (ii) and (iii) correspond to $X < 2$, $X = 2$ and $X > 2$, respectively. Related to this, it is useful to express the aspect ratio of the cocoon $r_{\rm c}/r_{\rm h} \equiv \mathcal{R}$ as a function of time. This is written as

$$\mathcal{R}(t) = \frac{X(-2+0.5\alpha)+3}{0.5X}\frac{\bar{v}_{\rm c}}{\bar{v}_{\rm h}}\left(\frac{t}{t_{\rm age}}\right)^{X(2.5-0.5\alpha)-3}. \tag{8}$$

It is worth noting that the solution describes not only the self-similar evolution (e.g. Bicknell, Dopita & O'Dea 1997; Kaiser & Alexander 1997) but also the non-self-similar evolution. Although it is not dealt with in this paper, the evolution of $\mathcal{R}(t)$ may probe the evolution of radio galaxies such as compact symmetric objects (CSOs), which are thought to be the progenitors of FR II sources (e.g. Fanti et al. 1995; Readhead et al. 1996a). Note that, observationally, the large

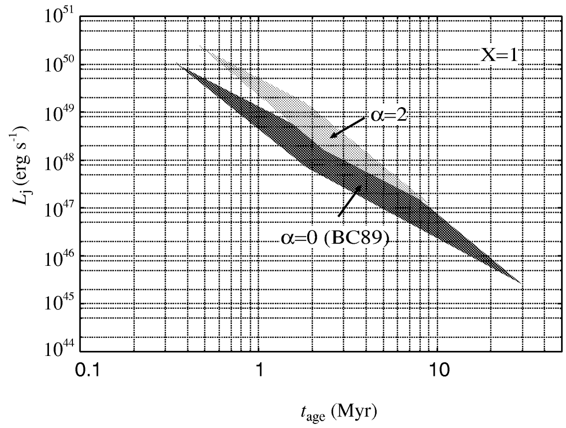

Figure 2. The allowed regions of L_j and t_{age} with the different values of α with $X = 1$. The region is determined by the constraints of $0.5 < \mathcal{R} < 1$ and $30 < A_h < 150\,\mathrm{kpc}^2$. We examine $\alpha = 0$ and 2 here. The case of $\alpha = 0$ and $A_h = 30\,\mathrm{kpc}^2$ by BC89 is shown in the lower-right part of the filled region. Larger α requires significantly larger L_j for ploughing the larger amount of the ICM.

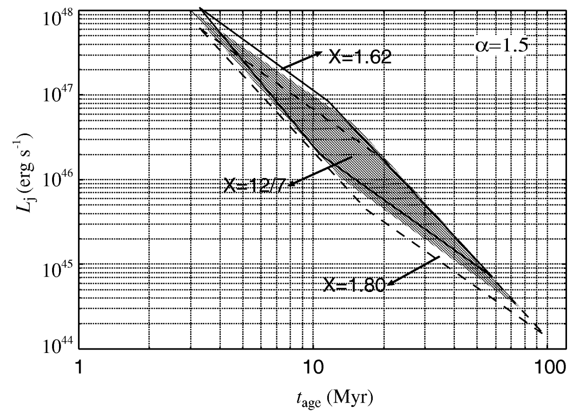

Figure 3. The allowed regions of L_j and t_{age} with the different values of X with $\alpha = 1.5$. As in Fig. 2, we adopt $0.5 < \mathcal{R} < 1$ and $30 < A_h < 150\,\mathrm{kpc}^2$. The cases of $X = 1.62$, 12/7 and 1.80 are shown here. Larger X requires smaller L_j corresponding to the slower velocity of the sideways expansion.

deviation from $\mathcal{R} \sim \mathcal{O}(1)$ does not seem to be unnatural for actual radio sources (e.g. Readhead et al. 1996b).

Next, let us consider the α and X dependences on the quantities based on equations (1), (2) and (3). Here we fix the physical quantities at $t = t_{age}$. With regard to the α dependence in fixed X, larger α leads to larger ρ_a, slower v_h, the same v_c, larger P_c, for $t < t_{age}$. We can understand this as follows. Larger α leads to a stronger deceleration effect on the head speed v_h due to larger ρ_a. Larger α also predicts larger P_c in order to keep the same velocity of sideways expansion v_c. In Fig. 2, we show the effect of varying α when fixing $X = 1$. It shows that larger α requires larger L_j in order to plough the larger amount of the ICM.

Next we consider the X dependence. In fixed α, larger X lead to faster v_h, slower v_c, smaller P_c and smaller A_h for $t < t_{age}$. We can explain this as follows. Larger X leads to slower sideways expansion v_c and smaller A_c by definition. From the equation of motion to the sideways expansion, it is clear that smaller P_c is required. To satisfy the energy equation at the same time, a faster velocity of v_h is needed. This is realized by the smaller area head of the cocoon A_h.

Observationally, little is argued about the emission from the cocoon itself. Recently, Readhead et al. (1996b) have reported on the cocoon emission from the CSO 2352+495. It is visible in the 610-MHz image and the aspect ratio is about $\mathcal{R}(t_{min}) \sim 1/2$. Because of the lack of our knowledge of cocoon emissions, here we examine the cases of $\mathcal{R}(t_{min}) = 1, 1/2$ and $1/4$ for the moment. In Fig. 3, we show the effect of varying X with fixing $\alpha = 1.5$ and $\mathcal{R}(t_{age}) = 1/2$. The cases of $X = 1.62$, 12/7 and 1.80 correspond to $\mathcal{R}(t_{min}) = 1, 1/2$ and $1/4$, respectively. We can verify the shift of L_j to a smaller range as X increases.

Finally, we compare our solution with the previous works. The solution for a flat ICM density by the BC89 model corresponds to the case of $X = 1$ and $\alpha = 0$ and the quantities are written as $v_c \propto t^{-1/2}$, $v_h \propto$ constant, $P_c \propto t^{-1}$ and $A_h \propto$ constant. The absolute values of each physical quantity also agree with those in BC89 when omitting $1/(\hat{\gamma}_c - 1)$ and replacing $\mathcal{C}_{vc} = 1/\pi^{0.5}$, $\mathcal{C}_{vh} = 1$, $\mathcal{C}_{pc} = 1$ and $\mathcal{C}_{ah} = 1$. Fig. 2 includes the case of BC89 with the parameters $\alpha = 0$, $X = 1$ and $A_h = 30\,\mathrm{kpc}^2$. As explained before, the larger (smaller) α predicts smaller (larger) L_j because of the dilute (dense) ICM. The comparison with the analytical model and numerical studies is also an important issue. In Cioffi & Blondin (1992), the issues of 'head cross-section growth' and 'decreasing head velocity' are assessed using hydrodynamic simulations and their result shows $A_h \propto t^{0.4}$. As a good example, our solution of $X \simeq 1.1$ describes the studies of Nath (1995) corresponding to the case of a flat solution above $v_h \propto t^{-0.2}$, $v_c \propto t^{-0.45}$, $P_c \propto t^{-0.9}$ and $A_h \propto t^{0.4}$. Concerning A_c, because most numerical studies have mainly focused on the propagation of cylindrical geometry jets (e.g. Clarke, Harris & Carilli 1997; Marti et al. 1997), this remains an important future work on the time evolution of A_c.

3 TOTAL KINETIC POWER AND SOURCE AGE OF CYGNUS A

Here we explore L_j and t_{age} by matching the observed cross-sectional areas and lengths of a cocoon (i.e. r_h, r_c, A_h and A_c). In this paper, we focus on the archetypal radio galaxy Cygnus A (for reviews, see Carilli & Barthel 1996; Carilli & Harris 1996).

First, we estimate the typical values of physical quantities. Concerning the mass density profile of the ICM, we adopt $\alpha = 1.5$ based on Reynolds & Fabian (1996) and Smith et al. (2002). We examine the case of $X = 12/7$ as a fiducial case, which predicts the constant $\mathcal{R}$ in time. Other observed quantities, $\bar{\rho}_a = 0.5 \times 10^{-2}\, m_p\,\mathrm{g\,cm^{-3}}$ and $r_h = 60\,\mathrm{kpc}$, are based on Carilli et al. (1998), Arnaud et al. (1984) and Smith et al. (2002). Here we assume $\hat{\gamma}_c = 4/3$. Using these quantities, we obtain

$$\beta_h(t) = 8.36 \times 10^{-3}\ L_{j,46} t_{20}^2 \left(\frac{t}{t_{20}}\right)^{-1/7}, \tag{9}$$

$$\beta_c(t) = 6.84 \times 10^{-3}\ t_{20}^{-1} \left(\frac{t}{t_{20}}\right)^{-1/7}, \tag{10}$$

$$P_c(t) = 4.78 \times 10^{-10} t_{20}^{-2} \left(\frac{t}{t_{20}}\right)^{-11/7}\ \mathrm{dyn\,cm^{-2}}, \tag{11}$$

$$A_h(t) = 66.4\ L_{j,46}^{1/2} t_{20}^{1/2} \left(\frac{t}{t_{20}}\right)^{11/7}\ \mathrm{kpc}^2. \tag{12}$$

Here, $\beta_h = v_h/c$, $\beta_c = v_c/c$, $t_{20} = t_{age}/20\,\mathrm{Myr}$, $L_{j,46} = L_j/10^{46}$ erg s^{-1}, with the resultant value of $\mathcal{R}(t_{age}) = 0.815$ for Cygnus A. Note

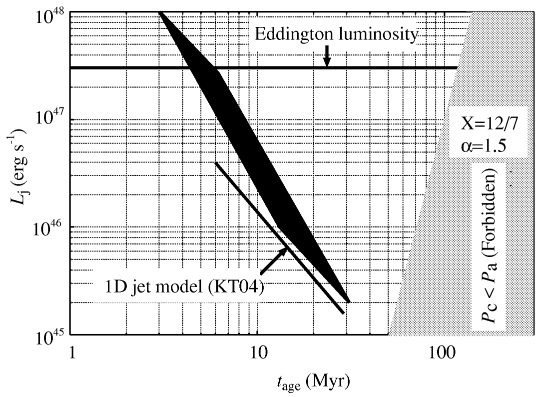

Figure 4. The allowed region of L_j and t_{age} of Cygnus A (shaded black). The underpressured region $P_c < P_a$ is excluded by definition. The case of $0.5 < \mathcal{R} < 0.7$ and $30 < A_h < 150\,\mathrm{kpc}^2$ is examined. As a reference, the Eddington luminosity and the total kinetic power of the jet estimated by KT04 are shown as thick solid and solid lines, respectively.

that $R \propto \bar{\beta}_h/\bar{\beta}_c \propto t_{age}^3$ has a strong dependence on the age such as $\propto t_{age}^3$, the allowed source age is fairly restricted.

Next, to clarify the allowed range of t_{age} and L_j, we impose the following conditions. The conditions which should be satisfied are that (i) $\mathcal{R}(t_{age}) \sim 0.5$–$0.7$, from the *Chandra* image (Wilson, Young & Shopbell 2000), (ii) the cocoon pressure is overpressured, $P_c > P_a = 8 \times 10^{-11}$ dyn cm^{-2} (Arnaud et al. 1984; Smith et al. 2002), (iii) the area size of A_h lies in the range of $30 < A_h < 150$ kpc^2. The minimum value corresponds to that adopted in BC89. From the radio image of Perley, Dreher & Cowan (1984), we employ the maximum value as $A_h = 150$ kpc^2, which corresponds to the cross-sectional area of the radio lobe at the location of the hotspot. In Fig. 4, we show the resultant source age and total kinetic power of the jet. The region of the source age larger than ~30 Myr is not allowed by condition (ii). Larger (smaller) A_h predicts larger (smaller) L_j and younger t_{age}. Obtained values are $3 \times 10^{45} < L_j < 7 \times 10^{48}$ erg s^{-1} and $6 < t_{age} < 30$ Myr.

Let us consider how the uncertainties of L_j and t_{age} are determined. From equations (7) and (8), $A_h \propto L_j t_{age}^2$ and $\mathcal{R} \propto L_j^{-1/(\alpha-4)} t_{age}^{-3/(\alpha-4)}$ are obtained. Because A_h and $\mathcal{R}$ have uncertainties with the factors of 5 and 1.4, respectively, the allowed region is mainly controlled by A_h. In the present work, in view of the comparison of BC89, we took the minimum value as $A_h = 30$ kpc^2. However, from the hydrodynamical point of view, it seems natural to suppose that A_h is the close value to the cross-sectional area of the radio lobe at the head distance, i.e. $A_h = 150$ kpc^2.

3.1 Comparison with previous works

The resultant age agrees well with the independent result of the synchrotron age model by Carilli et al. (1991), which claims that $6 < t_{age} < 30$ Myr. The velocity of the hotspot $\beta_{hs} \sim 0.06$ corresponds to the source age of 6 Myr, while $\beta_{hs} \sim 0.01$ corresponds to the source age of 30 Myr.

As a complementary result, Fig. 4 (solid line) shows L_j estimated in KT04 in the range of $6 < t_{age} < 30$ Myr based on the result of Carilli et al. (1991). KT04 estimate the total kinetic power of the relativistic jet as

$$L_j = A_j c \Gamma_j^2 \beta_j \rho_j c^2 = A_j c \left(\frac{r_{60}}{t_{age}}\right)^2 \rho_a(r_{60}) \propto A_j$$

in the strong relativistic shock limit, where $A_j = \pi R_{hs}^2$, Γ_j, $\beta_j c$, ρ_j and $R_{hs} = 2$ kpc (Wilson et al. 2000) are the cross-sectional area of the jet the Lorentz factor, the velocity and mass density of the jet, and the hotspot radius, respectively. It should be stressed that the cocoon model can predict both L_j and t_{age} at the same time, while the synchrotron ageing model (Carilli et al. 1991) and the one-dimensional jet model (KT04) only determine t_{age} or L_j. Although these three models are independent, they show reasonable agreement with each other for the values of L_j and t_{age}, at least in order of magnitude in the case of Cygnus A. At the same time, it is worth discussing a factor of deviation of the estimate L_j by the cocoon model and one-dimensional jet model. In the same way as KT04, the one-dimensional analysis between the jet and the ICM takes a plane parallel assumption (e.g. Begelman, Blandford & Rees 1984). The approximation means that A_j equals A_h. However, A_h is supposed to be larger than A_j. Hence, the plane parallel approximation would cause an underestimate of L_j in KT04.

Rawlings & Saunders (1991, hereafter RS91) is the pioneering work on the correlation between L_j and the luminosity of the narrow-line regions, which lies close to the central engine. Thus, comparison between the present work and RS91 is an intriguing issue. For the sources where synchrotron spectral ageing is available, it is simply by

$$Q = \frac{E_{eq}}{t_{age}\eta}, \quad \eta = 0.5$$

where Q, η and E_{eq} are, respectively, the kinetic power of the jet, a parameter expressing the fraction of the work done on the ICM and the equipartition energy with the electrons and the magnetic field which makes an equal contribution to the total energy density (e.g. Miley 1980). We focus on the sample sources where t_{age} is independently obtained by the synchrotron ageing method. One difference between the present work and RS91 is that we have solved the equations of motion and the energy equation (three equations in total), while RS91 only employ the energy equation. Because of this, we can eliminate the free parameter η. A more important and essential difference is that Q in RS91 is not a total kinetic power but it is just an equipartition power (even though they insist that it is a total power). We emphasize the advantage of our work in dealing with the total kinetic power whilst RS91 only handle the equipartition power of extragalactic jets.

Kaiser (2000, hereafter K00) independently addressed this quantity by studying some bright radio sources involving Cygnus A. Compared with RS91, the common advantage is that both K00 and the present work can estimate the total kinetic power by directly dealing with the hydrodynamics. The way of comparing the observation with the model by K00 is different from ours. K00 matched the surface brightness distribution of the cocoon along the jet axis. The main difference between the present work and K00 is the derived cocoon pressure during the matching of the observations and the models. In the example of Cygnus A, compared with our estimate of $P_c \sim 5 \times 10^{-10}$ erg cm^{-3}, they tend to estimate smaller P_c of the order of $P_c \sim 10^{-12}$–10^{-11} erg cm^{-3} (tables 2, 3 and 4 in K00). This is the main cause of the deviation of the derived total kinetic power of Cygnus A as $L_j \sim$ (a few) $\times 10^{46}$ erg s^{-1}, whilst K00 derive the total kinetic power with an order of $L_j \sim$ (a few) $\times 10^{45}$ erg s^{-1}.

3.2 Efficiency of accretion power to kinetic power

In Tadhunter et al. (2003), the mass of the supermassive black hole (SMBH) of Cygnus A is reported as 2.5×10^9 M$_\odot$, which leads to the Eddington luminosity $L_{\rm Edd} = 3 \times 10^{47}$ erg s^{-1}. From this it follows that $L_{\rm j}/L_{\rm Edd} \sim 0.01$–1. On the basis of the observational evidence for the accretion flow origin for the jet in active galactic nuclei (AGNs; e.g. Marscher et al. 2002), it is clear that the value of $L_{\rm j}/L_{\rm Edd}$ directly shows the required minimum rate of the mass accretion on to the SMBH normalized by the corresponding Eddington mass accretion rate.

Merloni, Heinz & di Matteo (2003) – see also Maccarone, Gallo & Fender (2003) – examine the disc–jet connection by studying the correlation between the radio ($L_{\rm R}$) and the X-ray ($L_{\rm X}$) luminosity and the black hole mass. With large samples of stellar-mass black holes and SMBHs, they claim these sources have the 'fundamental plane' in the three-dimensional space of these quantities. On the way, the quantity of $L_{\rm X}/L_{\rm Edd}$ is brought up to probe the activity of the central engine. For Cygnus A, Young et al. (2002) report $L_{\rm X} \simeq 3.7 \times 10^{44}$ erg s^{-1}, which leads to $L_{\rm X}/L_{\rm Edd} \sim 10^{-3}$. Whereas we recognize the usability of the quantity of $L_{\rm X}/L_{\rm Edd}$ to probe the engine activity, we emphasize that $L_{\rm X}$ largely depends on the accretion flow model and the radiation efficiency at the X-ray band. On the other hand, the quantity of $L_{\rm j}/L_{\rm Edd}$ addressed in the present work does not have the model dependence and directly shows us the engine activity.

Maraschi & Tavecchio (2003) also addressed this quantity by collecting large samples of blazars. They estimated the jet power from the blazar's non-thermal spectrum energy distribution, which are well understood as synchrotron plus inverse Compton (e.g. Maraschi, Ghisellini & Celotti 1992; Sikora, Begelman & Rees 1994; Blandford & Levinson 1995; Kino, Takahara & Kusunose 2002). The upper limit of the accretion power is inferred from the luminosity of observed broad emission lines. They conclude that for flat-spectrum radio quasars (FSRQs) the total power of the jet is of the same order as the accretion power. Note that their estimate of the accretion power from the emission line is putative way and the estimated total power does not include the contribution of protons associated with thermal electrons, which may cause some underestimate of the total power of the jet.

We again emphasize that, as we see above, the value of $L_{\rm j}/L_{\rm Edd}$ for Cygnus A in the present work is obtained with fewer assumptions. Moreover, it makes a fairly robust probe of the central engine activity of AGN jets. The application of our method to a large sample of other AGN jets surely brings about new and important knowledge. This is actually our ongoing project.

4 CONCLUSION

Our main conclusions in the present work are as follows.

(i) A new method to estimate the total kinetic power of the jet $L_{\rm j}$ and source age $t_{\rm age}$ in powerful FR II radio sources is proposed. For this, the study of cocoon dynamics by BC89 is revisited and physical quantities associated with the cocoon are analytically solved as functions of $L_{\rm j}$ and $t_{\rm age}$. A comparison of the analytical solution with the observed cocoon shape leads to $L_{\rm j}$ and $t_{\rm age}$ in general.

(ii) The analysis is focused on Cygnus A, with the conditions of $0.5 \leqslant \mathcal{R} \leqslant 0.7$ and $30 < A_{\rm h} < 150\,{\rm kpc}^2$. The estimated age $6 < t_{\rm age} < 30$ Myr shows good agreement of the independently estimated age using the synchrotron ageing model by Carilli et al. (1991). The estimated total kinetic power $0.2 \times 10^{46} < L_{\rm j} < 1 \times 10^{48}$ erg s^{-1} also has reasonable agreement with the independent one-dimensional jet model of KT04 with the aid of $3 < t_{\rm age} < 30$ Myr.

(iii) For Cygnus A, we find that the total kinetic power lies in the range of $L_{\rm j}/L_{\rm Edd} \sim 0.01$–1, while the X-ray luminosity $L_{\rm X} \simeq 3.7 \times 10^{44}$ erg s^{-1} (Young et al. 2002) satisfies $L_{\rm X}/L_{\rm Edd} \sim 10^{-3}$. The result of $L_{\rm j}/L_{\rm Edd} \sim 0.01$–1 indicates the lower limit of the mass accretion rate, which gives the crucial hint for resolving the jet formation problem.

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