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

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We examine the constraints imposed on the total kinetic power \( L_j \) and the age \( t_{\text{age}} \) of relativistic jets in FR II radio sources in a new way. We solve the dynamical expansion of its cocoon embedded in the intra-cluster medium (ICM) and obtain the analytic solution of its physical quantities in terms of \( L_j \) and \( t_{\text{age}} \). The estimate of \( L_j \) and \( t_{\text{age}} \) is done by the comparison of the model and the observed shape of the cocoon. The analysis is focused on Cygnus A and we find that (i) the source age is \( 3 \, \text{Myr} < t_{\text{age}} < 30 \, \text{Myr} \) and (ii) the total kinetic power of the jet is estimated as \( 0.2 \times 10^{46} \, \text{erg s}^{-1} < L_j < 1 \times 10^{48} \, \text{erg s}^{-1} \) which is larger than 1% 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 inverse Compton component in X-ray from FR II radio sources, our knowledge of energetics, especially on the kinetic power of non-thermal electrons, is progressed in recent years (e.g., Leahy and Gizani 2001; Harris and Krawczynski 2002; Hardcastle et al. 2002; Kataoka et al. 2003; Croston et al. 2005). When we explore further physical conditions in the jets, we encounter a big difficulty to constrain on the fraction such as thermal electrons and/or protons co-existing with non-thermal electrons because it is hard to observe these component (e.g., Celotti et al. 1998; Sikora and Madejski 2002). This problem prevented us from estimating the total mass and energy flux ejected from a central engine. To conquer this, a simple procedure is proposed in the study of jets in FR II sources in Kino and Takahara (2004) (hereafter KT04). In the pressure and mass density of jet, the 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, the similar dynamical approach has been adopted to constrain on their physical state (Fabian et al. 2002; Dunn and Fabian 2004).

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

2 DYNAMICS OF COCOON

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

2.1 Basic Assumptions

Our main assumptions are as follows; (1) We limit our attention a jet relativistic speed \((v_j = c)\), (2) The jet supplies a constant \( L_j \) in time, (3) We focus on the over-pressured cocoon phase, and (4) We assume that the magnetic fields are passive and ignore their dynamical effect. For (1), although it is still under debate, some jets are suggested to be relativistic (e.g., Tavecchio et al. 2000; Celotti, Ghisellini, & Chiaberge 2001). Since little is known about the evolution of \( L_j \), the assumption (2) is adopted as a first-step working hypothesis. The assumption of (3) is automatically guaranteed by the sideways expansion of the cocoon (e.g., Cioffi
section and Blondin 1992). The assumption of (4) is based on the results that a multi-frequency analysis of radio galaxies show that the energy density of magnetic field tend to be smaller than that of non-thermal electrons (e.g., Leahy and Giani 2001; Isobe et al. 2002).

2.2 Basic Equations

Model parameters are $L_1$ and $t_{\text{age}}$. Unknown physical quantities are $v_h$, $v_c$, $P_c$, and $A_h$ (or $A_c$) 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). Equation of motion along the jet axis, and sideways expansion, and energy conservation in the cocoon are given by

$$L_1 \frac{dv_h}{dt} = \rho_a v_h^2 (t) A_h(t),$$

$$P_v(t) = \rho_a(v_c(t)) v_c(t)^2,$$

$$\gamma_c \frac{P_v(t)}{A_c(t)} \simeq 2L_1 t,$$

where $r_h(t) = \int_{t_{\text{min}}}^{t} v_h(t^{'}) dt'$, $r_c(t) = \int_{t_{\text{min}}}^{t} v_c(t^{'}) dt'$, $V_c(t) = 2 \int_{t_{\text{min}}}^{t} A_c(t^{'}) v_h(t^{'}) dt'$, $t_{\text{min}}$, and $\gamma_c$ are the length from the center 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 specific heat ratio of the plasma inside the cocoon, respectively. The declining mass density of ICM $\rho_a$ is given by $\rho_a(r) = \rho_a(r/r_0)^{-\alpha}$ where $r_0$ and $\rho_a$ are reference position and the ICM mass density at $r_0$, respectively. We set $r_0 = r_h(t_{\text{age}})$ in throughout this paper. Most of the kinetic energy is deposited in the cocoon, which is initially suggested by Scheuer (1974) and recent studies of hot spots also shows the radiative efficiency is very small (e.g., K004). Following to Cioffi and Blondin (1992), we add the factor of $1/(\gamma_c - 1)$ in Eq. 3 to express the amount of the deposited internal energy. In other words, this corresponds to the neglect of the $PdV$ work because of its smallness.

The numbers of quantities are 4, while those of basic Eqs. are 3. Hence, we set $A_c(t) \propto t^X$ where $X$ as a free parameter. We can constrain on the value of $X$ from observations. A specific case is shown in §3. Hence, we obtain $v_h$, $v_c$, $P_c$, and $A_h$ by using a free parameter $X$.

As a subsidiary equation, the area of the cocoon body is given by $A_c(t) = \pi \left( \int_{t_{\text{min}}}^{t} v_c(t^{'}) dt' \right)^2$. It is clear that the change of the unknown from $A_c$ to $A_h$ does not change the result. However note that when we choose $A_h$ as an unknown instead, we cannot obtain the solution for $\alpha = 2$.

2.3 Analytic Solution

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

$$v_c(t) = \bar{v}_c \left( \frac{t}{t_{\text{age}}} \right)^{0.5X-1/2} = \bar{v}_c \gamma_c^{0.5X-1}(t_{\text{age}})^{-0.5X-1},$$

for a given $A_c$. With this, the analytic form of cocoon quantities in decreasing ICM density is obtained as follows;

$$P_v(t) = \bar{\rho}_a \bar{v}_c^2 C_p \left( \frac{\bar{v}_c}{v_0} \right)^{-\alpha} \left( \frac{t}{t_{\text{age}}} \right)^{X(1-\alpha/2)}$$

$$v_h(L_j, t) = \frac{L_j}{\bar{\rho}_a \bar{v}_c^2 A_c} C_{v_h} \left( \frac{\bar{v}_c}{v_0} \right)^{\alpha} \left( \frac{t}{t_{\text{age}}} \right)^{X(-2+0.5\alpha)}$$

$$A_h(L_j, t) = \frac{L_j}{v_h L_j \bar{\rho}_a A_c} C_{v_h} \left( \frac{\bar{v}_c}{v_0} \right)^{\alpha} \left( \frac{t}{t_{\text{age}}} \right)^{X(\alpha-2)-2+0.5\alpha+3\alpha-4}$$

where $C_{v_h} = (\gamma_c - 1)(3 - (1 - 0.5\alpha)X)(0.5X)^{-\alpha}$, $C_p = 0.5X/\pi^{1/2}$, $C_{v_h} = (0.5X)^{\alpha}$, and $C_{v_h} = [X(2 + 0.5\alpha)]^{3-\alpha}$, respectively. $v_0 \equiv r_h/t_{\text{age}}$ 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 $t_{\text{min}}$ in the integrations of $r_h$ and $r_c$ small enough. The case we focus on $\alpha < 3$ is that $X = 12/7$ and $\alpha = 1.5$, which clearly satisfies these conditions.

First, we consider the evolution of cocoon. The growth of both $A_h$ and $A_c$ must be positive. As for the cocoon expansion speeds, three different behaviors 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 ($X(2 + 0.5\alpha) + 2 < 0$). The case of (I), (II), and (III) correspond to $X < 1$, $X = 1$, and $X > 1$ for $\alpha = 0$, while in the case of $\alpha = 2$ (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 $\frac{r_c}{r_h} \equiv R$ as a function of time. This is written as

$$R(t) = \frac{X(2 + 0.5\alpha) + 3}{0.5X} \frac{v_h}{v_0} \left( \frac{t}{t_{\text{age}}} \right)^{X(2.5 - 0.5\alpha)-3}.$$
3 TOTAL KINETIC POWER AND SOURCE AGE OF CYGNUS A

Here we explore \(L_1\) and \(t_{age}\) by matching the observed cross-sectional areas and lengths of a cocoon (i.e., \(r_h\), \(r_e\), \(A_h\), and \(A_e\)). In this paper, we focus on the archetypical radio galaxy Cygnus A (Carilli and Barthel 1996; Carilli and Harris 1996 for reviews).

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

\[
\beta_h(t) = 8.36 \times 10^{-3} L_{1,46}^2 \left( \frac{t}{t_{age}} \right)^{-1/7},
\]

\[
\beta_e(t) = 6.84 \times 10^{-3} L_{1,46} \left( \frac{t}{t_{age}} \right)^{-1/7},
\]

where \(\beta_h = v_h/c\), \(\beta_e = v_e/c\), \(t_{age} = t_{age}/20\) Myr, \(L_{1,46} = L_1/10^{46}\) erg s\(^{-1}\), with the resultant value of \(\beta_h/\beta_e = 0.815\) for Cygnus A. Then, we compare our solution with the previous work, in view of the comparison of BC89, we took the minimum value as \(A_h = 150\) kpc\(^2\), which corresponds to the cross-sectional area of the radio lobe at the location of the hot spot. In Fig. 3, we show the resultant source age and total kinetic power of the jet. The region of the source age larger than \(\sim 30\) Myr is not allowed by the condition (II). Larger (smaller) \(A_h\) predict larger (smaller) \(L_1\) and younger \(t_{age}\). Obtained values are \(2 \times 10^{45}\) erg s\(^{-1}\) < \(L_1 < 1 \times 10^{46}\) erg s\(^{-1}\) and 3 Myr < \(t_{age} < 30\) Myr.

Let us consider how the uncertainties of \(L_1\) and \(t_{age}\) are determined. From Eqs. (9) and (10), \(A_h \propto L_1/t_{age}\) and \(R \propto L_1^{1/(n-4)} t_{age}^{-3/(n-4)}\) are obtained. Since \(A_h\) and \(R\) 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 \(A_h\) to be the close value to the cross-sectional area of the radio lobe at the distance of head, i.e., \(A_h = 150\) kpc\(^2\).

3.1 Comparison with previous works

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

As a complementary result, \(L_1\) estimated in KT04 in the range of 6 Myr < \(t_{age} < 30\) Myr based on the result Carilli et al. (1991) is shown in Fig. 4 (the solid line). KT04 estimate the total kinetic power of the relativistic jet as

\[
L_1 = A_j c \Gamma_0^2 \beta_j \rho_0 c^2 = A_j c \left( \frac{r_{60}}{t_{age}} \right)^2 \rho_0(t_{age}) \propto A_j
\]

in the strong relativistic shock limit, where \(A_j = \pi R_{hs}^2\Gamma_0\), \(\beta_j\), \(\beta\), 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 hot spot radius, respectively. It should be stressed that the cocoon model can predict both \(L_1\) and \(t_{age}\) at the same time, while the synchrotron aging model (Carilli et al. 1991) and the 1D jet model (KT04) only...
determine $t_{\text{age}}$ or $L_j$. Although these three models are independent, they show a reasonable agreement on the values of $L_j$ and $t_{\text{age}}$ with each other at least in order-of-magnitude in the case of Cygnus A. At the same time, it is worth to discuss a factor of deviation of the estimate $L_j$ by the cocoon model and 1D jet model. In the same way as KT04, 1D analysis between the jet and ICM take the plane parallel assumption (e.g., Begelman, Blandford & Rees 1984). The approximation means that $A_j$ equals to $A_h$. However, $A_h$ is supposed to be larger than $A_j$. Hence, the plane parallel approximation would cause the underestimation of the $L_j$ in KT04.

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

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

where $Q$, $\eta$, and $E_{\text{eq}}$ are the kinetic power of jet, a parameter expressing the fraction of the work done on the ICM, and the equipartition energy with the electrons and the magnetic field field make an equal contribution to the total energy density (e.g., Miley (1980)), respectively. We focus on the sample sources where $t_{\text{age}}$ is independently obtained by synchrotron aging method. One difference between the present work and RS91 is that we solved the equations of motion and energy equation (3 Eqs. in total), while the RS91 only employ energy equation. Because of this, we can eliminate the free parameter $\eta$. More important and essential difference is that $Q$ in RS91 is not a total kinetic power but it is just a equipartition power (even though they insist that it as a total power). We emphasize the advantage of our work of dealing with the total kinetic power whilst RS91 only handles 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 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 $P_c \sim 5 \times 10^{-13}$ erg cm$^{-3}$, they tend to estimate smaller $P_c$ of order of $P_c \sim 10^{-12} - 10^{-11}$ erg cm$^{-3}$ (Tables 2, 3 and 4 in K00). This mainly cause the deviation of the derived total kinetic power of Cygnus A as $L_j \sim (a \text{ few}) \times 10^{46}$ erg s$^{-1}$, whilst K00 derive the total kinetic power with order of $L_j \sim (a \text{ few}) \times 10^{45}$ erg s$^{-1}$.

### 3.2 Efficiency of accretion power to kinetic power

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

Merloni, Heinz and Di Matteo 2003 (see also Macarone, Gallo and Fender 2003) examine the disk-jet connection by studying the correlation between the radio ($L_R$) and the X-ray ($L_X$) luminosity and the black hole mass. With the large samples of the stellar mass black holes and SMBHs, they claim these sources have the “fundamental plane” in the 3 dimensional space of these quantities. On the way, the quantity of $L_j/L_{\text{Edd}}$ is brought up to probe the activity of the central engine. For Cygnus A, Young et al. (2002) reports $L_X \approx 3.7 \times 10^{44}$ erg s$^{-1}$ which leads to $L_X/L_{\text{Edd}} \sim 10^{-3}$. Whereas we recognize the usability of the quantity of $L_X/L_{\text{Edd}}$ to probe the engine activity, we emphasize that the $L_X$ largely depends on the accretion flow model and the radiation efficiency at X-ray band. On the other hand, the quantity of $L_j/L_{\text{Edd}}$ 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 et al. 1992; Sikora et al. 1994; Blandford & Levinson 1995; Kino et al. 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 $L_j/L_{\text{Edd}}$ for Cygnus A in the present work is obtained with fewer assumptions. Moreover it makes us 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 bring 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 $L_j$ and source age $t_{\text{age}}$ in powerful FR II radio sources is proposed. For that, the study of cocoon dynamics by BC89 is revisited and physical quantities associated with the cocoon are analytically solved as functions of $L_j$ and $t_{\text{age}}$.

(ii) The analysis is focused on Cygnus A, with the conditions of $0.5 \lesssim R \lesssim 0.7$ and $30$ kpc$^2 < A_h < 150$ kpc$^2$. The estimated age $3$ Myr $< t_{\text{age}} < 30$ Myr shows a good agreement of the independently estimate age by synchrotron aging model by Carilli et al. (1991). The estimated total kinetic power $0.2 \times 10^{46}$ erg s$^{-1} < L_j < 1 \times 10^{48}$ erg s$^{-1}$ has
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also a reasonable agreement with the independent 1D jet model of KT04 with the aid of 6 Myr < \textit{t}_{\text{age}} < 30 \text{ Myr}.

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

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Figure 1. A cartoon of interaction of the ICM with declining atmosphere and the relativistic jet in FR II radio galaxy. As a result, most of the kinetic energy of jet is deposited in the cocoon and it is inflated by its internal energy.
Figure 2. The allowed regions of $L_j$ and $t_{age}$ with the different values of $\alpha$ with $X = 1$. The region is determined by the constraints of $0.5 < R < 1$ and $30\text{kpc}^2 < A_h < 150\text{kpc}^2$. We examine $\alpha = 0$ and 2 here. The case of $\alpha = 0$, and $A_h = 30\text{kpc}^2$ by Begelman and Cioffi (1989) is involved in the right-lower part of the filled region. Larger $\alpha$ requires significantly larger $L_j$ for plowing the larger amount of ICM.

Figure 3. The allowed regions of $L_j$ and $t_{age}$ with the different values of $X$ with $\alpha = 1.5$. Likewise Fig. 2, we adopt $0.5 < R < 1$ and $30\text{kpc}^2 < A_h < 150\text{kpc}^2$. The case 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 expand.

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