## Large Kinetic Power in FRII Radio Jets

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Abstract We investigate the total kinetic powers  $(L_j)$  and ages  $(t_{\rm age})$  of powerful jets of four FR II radio sources (Cygnus A, 3C 223, 3C 284, and 3C 219) by the detail comparison of the dynamical model of expanding cocoons with observed ones. It is found that these sources have quite large kinetic powers with the ratio of  $L_j$  to the Eddington luminosity ( $L_{\rm Edd}$ ) resides in  $0.02 < L_j/L_{\rm Edd} < 10$ . Reflecting the large kinetic powers, we also find that the total energy stored in the cocoon ( $E_c$ ) exceed the energy derived from the minimum energy condition ( $E_{\rm min}$ ):  $2 < E_c/E_{\rm min} < 160$ . This implies that a large amount of kinetic power is carried by invisible components such as thermal leptons (electron and positron) and/or protons.

**Keywords** radio galaxies: individual (Cygnus A, 3C 223, 3C 284, 3C 219)

#### 1 Introduction

The total kinetic powers of AGN jets is one of the most basic physical quantities of the jet. It is however difficult to estimate  $L_j$ , since most of the observed emissions from AGN jets are of non-thermal electron origin, and the electromagnetic signals from the thermal

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and/or proton components is hard to detect. Hence, the free parameter describing the amount of the invisible plasma components always lurks in the estimates of  $L_i$  based on the non-thermal emissions.

Recently, Kino and Kawakatu (2005) (hereafter KK05) proposed a new estimate of  $L_{\rm j}$  for FRII radio galaxies based on the dynamical model of cocoon. Jets in powerful radio galaxies are expected inflate a cocoon into the surrounding intra-cluster medium (ICM) which is overpressured against the ICM (Begelman and Cioffi 1989). From their model,  $L_i$  and  $t_{age}$  can be derived by comparing the cocoon model with the actual morphologies of the cocoon based on the radio observations. However, at the moment, this model has been only applied to Cygnus A. The extension of the number of samples are evidently crucial for exploring general characteristics of powerful AGN jets. For this purpose, we apply the method of KK05 (with a slight modification) to four FR II radio galaxies (Cygnus A, 3C 223, 3C 284, and 3C 219).

### 2 Cocoon model

Following KK05, we briefly summarize the dynamics of cocoon in over-pressured regime, namely  $P_{\rm c} > P_{\rm a}$ , where  $P_{\rm c}$  and  $P_{\rm a}$  are the cocoon pressure and the pressure of the ambient ICM, respectively. The basic equations which describe the equation of motion along jet axis, equation of motion of the sideways expansion, and the energy equation are expressed, respectively, as

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

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

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$$\frac{d}{dt} \left( \frac{P_{c}(t)V_{c}(t)}{\hat{\gamma_{c}} - 1} \right) + P_{c}(t) \frac{dV_{c}(t)}{dt} = 2L_{j}, \tag{3}$$

where  $v_{\rm j}$ ,  $\rho_{\rm a}$ ,  $v_{\rm h}$ ,  $v_{\rm c}$ ,  $A_{\rm h}$ , and  $\hat{\gamma}_{\rm c}$  are the velocity of jet, the density of ambient medium, the advance velocity of cocoon head, the velocity of sideways expansion, the cross sectional area of cocoon head, and the specific heat ratio of plasma inside cocoon, respectively. In these equations we also assume that the jet is relativistic, and that  $L_{\rm j}$  is constant in time.  $r_{\rm h}(t) = \int_{t_{\rm min}}^{t} v_{\rm h}(t')dt', \ r_{\rm c}(t) = \int_{t_{\rm min}}^{t} v_{\rm c}(t')dt', \ {\rm and} \ V_{\rm c}(t) = \frac{4}{3}\pi r_{\rm c}(t)^2 r_{\rm h}(t)$  are the distance from the jet apex to the hotspot, the radius of the cocoon body, and the volume of the cocoon where  $t_{\min}$  is the initial time of source evolution. The declining mass density of ICM  $\rho_{\rm a}$  is given by  $\rho_{\rm a}(r) = \bar{\rho}_{\rm a}(r/\bar{r}_{\rm h})^{-\alpha}$  where  $\bar{r}_{\rm h} \equiv r_{\rm h}(t_{\rm age})$ . A cartoon of the cocoon model is illustrated in Fig. 1. We slightly improve the model of KK05 as follows; (i) the geometrical factor of  $V_c$  is more accurate, and (ii) the inclusion of PdV work done by cocoon.

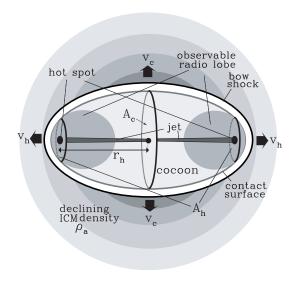


Fig. 1.— A cartoon of interaction of the ICM with declining atmosphere and the relativistic jet.

We further assume the lateral expansion of the cocoon as  $A_{\rm c}(t) = \bar{A}_{\rm c}(t/t_{\rm age})^X$ , where  $A_{\rm c}(t) = \pi r_{\rm c}(t)^2$  is the cross sectional area of cocoon body. By assuming that all physical quantities also have a time-dependence of form  $A = \bar{A} (t/t_{\rm age})^Y$ ,  $v_{\rm c}$  is determined as

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

From this, we obtain the following expressions:

$$\bar{P}_{c} \equiv P_{c}(t_{age}) = \bar{\rho}_{a} \bar{v}_{c}^{2} \mathcal{C}_{pc} \left(\frac{\bar{v}_{c}}{v_{0}}\right)^{-\alpha}, \tag{5}$$

$$\bar{v}_{\rm h} \equiv v_{\rm h}(t_{\rm age}) = \frac{L_j}{\bar{\rho}_{\rm a}\bar{v}_c^2 \bar{A}_{\rm c}} \mathcal{C}_{\rm vh} \left(\frac{\bar{v}_{\rm c}}{v_0}\right)^{\alpha},$$
 (6)

$$\bar{A}_{\rm h} \equiv A_{\rm h}(t_{\rm age}) = \frac{L_{\rm j}}{v_{\rm j}\bar{\rho}_{\rm a}\bar{v}_{\rm h}^2} \mathcal{C}_{\rm ah} \left(\frac{\bar{v}_{\rm h}}{v_0}\right)^{\alpha},$$
 (7)

where  $C_{\rm vh} = \frac{3}{2}(\hat{\gamma}_c - 1)(0.5X)^{-\alpha}[3 - (2 - 0.5\alpha)X]/[4 - (1 - 0.5\alpha)X]$ ,  $C_{\rm vc} = 0.5X/\pi^{1/2}$ ,  $C_{\rm pc} = (0.5X)^{\alpha}$ ,  $C_{\rm ah} = [X(-2 + 0.5\alpha) + 3]^{-\alpha}$ , and  $v_0 \equiv \bar{r}_{\rm h}/t_{\rm age}$ . Note that the only difference from KK05 is  $C_{\rm vh}$ . Although it is not dealt in the present study, the main difference from the previous models (Bicknell et al. 1997; Kaiser and Alexander 1997) is that these solutions can describe non-self-similar evolution. Note that when self-similar condition is imposed, time dependence in the physical quantities becomes identical to these previous models.

Throughout this paper, we assume  $\hat{\gamma}_c = 4/3$  since cocoon is expected to be dominated by relativistic particles (Kino et al. 2007). We also assume that the aspect ratio of the cocoon ( $\mathcal{R} \equiv r_c/r_h$ ) to be constant in time (self-similar evolution). Since  $\mathcal{R}(t) \propto t^{X(2.5-0.5\alpha)-3}$ , this assumption leads to  $X = 6/(5-\alpha)$ .

# 3 Comparison with the observation and the

By substituting the observed values of  $\bar{r}_h$ ,  $\bar{r}_c$  (or  $\mathcal{R}$ ),  $\bar{A}_h$ ,  $\bar{\rho}_a$ , and  $\alpha$  in Eq. (5) - (7),  $L_j$ ,  $t_{\rm age}$ , and also  $\bar{P}_c$  are determined uniquely. In this section, we explain how to extract these quantities from the observations and show the obtained  $L_j$  and  $t_{\rm age}$ 

In the left panels of Fig. 2, we show the VLA radio images of Cygnus A, 3C 223, 3C 284, and 3C 219 in logarithmic scale. Contours in linear scale (green lines) are also displayed for the purpose to determine the position of hotspot accurately. The overlaid straight lines which crosses perpendicular to each others at the hotspot are the lines we used to measure  $r_h$  (black lines) and  $A_h$  (red lines). Here,  $A_h$  is measured as the cross sectional area of the radio lobe at the position of the hotspot. Contrary to  $A_h$ , it is difficult to measure  $r_{\rm c}$  from the VLA radio images since the cocoon emission coming from the cross section perpendicular to the AGN core location is very dim at GHz radio frequency because of the synchrotron cooling. Therefore, we treat  $r_{\rm c} = \mathcal{R}r_{\rm h}$  as a free parameter. In order to take account of large ambiguity, we examine sufficiently wide range of  $0.5 < \mathcal{R} < 1$ . In the present study, we neglect projection effect on  $r_{\rm h}$  for simplicity. Under the assumption of self-similar evolution,  $L_{\rm j}$  and  $t_{\rm age}$  depend on  $r_{\rm h}$  as  $L_{\rm j} \propto r_{\rm h}^{-4}$  and  $t_{\rm age} \propto r_{\rm h}^3$ , respectively. However, since the angle to the line of sight is not expected to deviate largely from  $\pi/2$  in radio galaxies, this effect does not cause significant change in our results.

The adopted values of  $\rho_{\rm a}$ ,  $\alpha$ , and  $P_{\rm a}$  are based on the literatures of Reynolds and Fabian (1996); Smith et al. (2002) for Cygnus A, Croston et al. (2004) for 3C 223 and 3C 284, and Hardcastle and Worrall (1999) for 3C 219, respectively. Note that since most of the radio sources show asymmetries in their shape among the pair of the lobes (Fig. 2), we analyze each side of the lobe independently. However, we only analyze jet in the western side for 3C 219 since the eastern lobe showed severe deformation.

The resultant  $L_{\rm j}$  and  $t_{\rm age}$  are displayed in the right panels of Figs. 2. The red lines displayed in the figure are the resultant range of  $L_{\rm j}$  and  $t_{\rm age}$ , and their ranges reflect the uncertainty in  $\mathcal{R}$ . The age and power depend on the aspect ratio  $\mathcal{R}$  as  $t_{\rm age} \propto \mathcal{R}^{4-\alpha}$  and  $L_{\rm j} \propto \mathcal{R}^{2\alpha-8}$ , and, therefore, satisfy  $L_{\rm j} \propto t_{\rm age}^{-2}$ . Since  $\alpha$  does not exceed 4 in any of four sources, a lower aspect ratio corresponds to a higher power with a lower age. The range included in the shaded region is the forbidden region since the overpressure condition is violated. The Eddington luminosity ( $L_{\rm Edd}$ ) of each source, is also shown (green line) in these figure for comparison. The black hole masses  $(M_{\rm BH})$  are taken from Tadhunter et al. (2003) for Cygnus A, Marchesini et al. (2004) for 3C 223 and 3C 219. For 3C284, we derive  $M_{\rm BH}$  from the B-band magnitude of host galaxy (Shi et al. 2005) by using the empirical correlation of B-band magnitude and black hole mass (Marchesini et al. 2004). In Table 1, we summarize the allowed values of  $L_i$  and  $t_{age}$ and the other relevant physical properties of the cocoon. Reflecting the asymmetries in their shape, the obtained  $L_{\rm j}$  and  $t_{\rm age}$  show discrepancy among the pair of lobes especially in 3C 223 and 3C 284, and 3C 219. Since it seems natural to suppose that the properties of the jets are intrinsically symmetric and equal power and age on both side, we expect that the discrepancy is due to the asymmetry and/or inhomogeneity of ICM density profile. Here we interpret that the actual values of  $L_i$  and  $t_{age}$  is in the range obtained from both lobes.

## 4 Discussions

## $4.1 \text{ On } L_{\rm j}/L_{\rm Edd}$

In Table 1, the total kinetic power of the jet normalized by the corresponding Eddington luminosity,  $2L_{\rm j}/L_{\rm Edd}$ , is displayed. It can be seen that  $2L_{\rm j}/L_{\rm Edd}$  takes quite high value ranging from  $\sim 0.02$  to  $\sim 10$ . Postulating that the relativistic jet emanating from the AGN is

powered by some part of released gravitational energy of the accreting matter (e.g., Marscher et al. 2002), these values give the minimum mass accretion rate normalized by Eddington mass accretion rate. Interestingly, our results indicate that mass accretion rates are super-Eddington ones in some FR IIs (3C 219 and 3C 284) since  $2L_i/L_{\rm Edd} \simeq 1$ .

## 4.2 On the plasma content

It is intriguing to explore how much amount of the internal energy,  $E_{\rm c} = P_{\rm c} V_{\rm c}/(\hat{\gamma}_{\rm c}-1)$ , is deposited in the cocoon compared with the widely-discussed minimum energy,  $E_{\rm min}$ , of the radio lobe obtained from the minimum energy condition for the non-thermal electrons and magnetic fields. Here we calculate  $E_{\rm min}$  based on the observation of 178MHz band radio emission (Hardcastle et al. 1998). In Table 1 we summarize the resultant  $E_{\rm min}$ ,  $E_{\rm c}$ , and  $\eta_{\rm min}$  which we define as the fraction of  $E_{\rm c}$  to  $E_{\rm min}$  ( $\eta_{\rm min} \equiv E_{\rm c}/E_{\rm min}$ ). In all sources  $E_{\rm c}$  exceeds  $E_{\rm min}$ , and the range of the ratio is obtained as  $2 < \eta_{\rm min} < 160$ . This implies that minimum energy condition is unlikely to be realized in these sources.

Using  $\eta_{\min}$ , here we investigate the plasma content in the cocoon. Considering the components of energy,  $E_{\rm c}$  is sum of the energy of the non-thermal leptons (electron/positron) and, if present, the energy of the unobservable particles such as thermal leptons and/or protons. The large excess energy of  $E_{\rm c}$  from  $E_{\min}$  is due to contributions from either of these components.

Let us consider the possibility of large contributions from the non-thermal leptons. In this case  $\eta_{\min}$  is given as  $\eta_{\min} = U_e^{\text{NT}}/U_{\min}$  where  $U_e^{\text{NT}}$  and  $U_{\min}$  are the energy density the nonthermal leptons and the minimum energy density  $(U_{\rm min} \equiv E_{\rm min}/V_{\rm c})$ , respectively. It is useful to express  $U_e^{\rm NT}/U_{\rm min}$  in terms of  $U_e^{\rm NT}/U_{\rm B}$ , where  $U_{\rm B}$  is the energy density the magnetic field since  $U_e^{\rm NT}/U_{\rm B}$  is widely investigated by a lot of authors (e.g., Kataoka and Stawarz; Croston et al. 2005). In the case of power-law distributed leptons, synchrotron luminosity  $(L_{\nu})$  is determined as  $L_{\nu} \propto U_{\rm e}^{NT} U_{\rm B}^{4/3} V_{\rm c}$ . Hence with  $L_{\nu}$  and  $V_{\rm c}$  observed,  $U_{\rm e}$  and  $U_{\rm B}$  are not independent of each other, and  $U_{\rm e}^{\rm NT}/U_{\rm min}$  can be written as  $U_{\rm e}^{\rm NT}/U_{\rm min} = 0.5(U_{\rm e}^{\rm NT}/U_{\rm B})^{3/7}$ . Since recent studies shows that  $1 < U_{\rm e}^{\rm NT}/U_{\rm B} < 10$  on average, the value of  $\eta_{\min}$  is expected to be up to  $\sim 1$  at most. Thus, nonthermal leptons are unlikely to be the main carrier of the energy. We conclude that significant amount of energy is carried by invisible components such as thermal leptons (electron and positron) and/or protons.

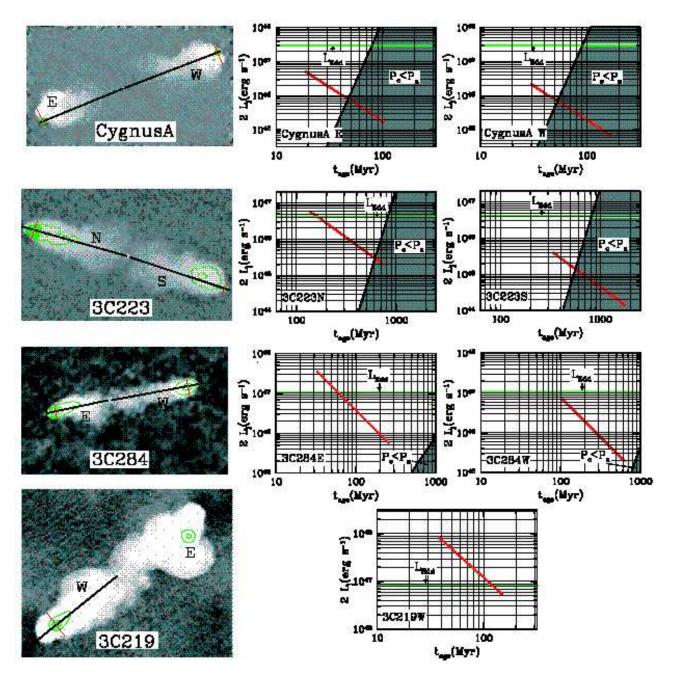


Fig. 2.— left panels: Logarithmic-scaled 5-GHz VLA map of Cygnus A (Perley et al. 1984) and 1.5GHz VLA maps of 3C 223 (Leahy and Perley 1991), 3C 284 (Leahy et al. 1986), and 3C 219 (Clarke et al. 1992) with linearly spaced contours (green lines) are displayed. The straight lines overlaid in each map denote the lines we have used to measure  $r_h$  (black lines) and  $A_h$  (red lines). right panels: The red lines show the obtained range of  $L_j$  and  $t_{\rm age}$ . The shaded regions show forbidden ranges where the overpressure condition ( $P_c > P_a$ ) is not satisfied. Also the Eddington luminosities (green lines) are displayed for comparison.

Source	$(10^{46} \text{ ergs s}^{-1})$	$t_{\rm age} \ ({ m Myr})$	$M_{ m BH} \ ({ m M}_{\odot})$	$2L_{ m j}/L_{ m Edd}$	$E_{\rm c} $ (10 <sup>60</sup> ergs)	$\frac{E_{\min}}{(10^{60} \text{ ergs})}$	$\eta_{ m min}$
Cygnus A E	0.4 - 2.6	19 - 47	$2.5 \times 10^9$	0.025 - 0.16	3.4 - 8.8	1.4	2.3 - 6.1
Cygnus A W	0.35 - 1.1	30 - 53	$2.5 \times 10^9$	0.021 - 0.068	3.2 - 5.7	1.4	2.2 - 4.0
3C 223 N	0.15 - 2.9	140 - 610	$3.2 \times 10^{8}$	0.072 - 1.43	16 - 70	0.88	18 - 79
3C 223 S	0.071 - 0.2	330 - 560	$3.2 \times 10^8$	0.034 - 0.097	6.9 - 12	0.88	7.8 - 13
3C 284 E	0.3 - 18	32 - 260	$8.2 \times 10^8$	0.053 - 3.4	14 - 110	1.8	7.7 - 62
3C 284 W	0.1 - 3.6	100 - 630	$8.2 \times 10^8$	0.018 - 0.67	11 - 68	$\frac{3.0}{1.6}$	3.7 - 23
3C 219 W	2.6 - 43	37 - 150	$6.3 \times 10^8$	0.65 - 10	63 - 250		40 - 160

**Table 1** The obtained properties of the jet and the cocoon together with minimum energy of the radio lobe.

#### 5 Summary

In this paper we have investigated the total kinetic power and the age of the relativistic jet in four FRII radio galaxies (Cygnus A, 3C 223, 3C 284, and 3C 219). Below we summarize our main results.

- (I) A large fraction of Eddington power in the range of 0.02 10 is carried away as a kinetic power of the jets in the FR II sources.
- (II) The energy deposited in the cocoon,  $E_c$ , exceeds the minimum energy,  $E_{\min}$ , by a factor of 2-160.

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