

Large Kinetic Power in FRII Radio Jets

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Abstract We investigate the total kinetic powers (L_j) and ages (t_{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_{Edd}) resides in $0.02 < L_j/L_{\text{Edd}} < 10$. 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_{min}): $2 < E_c/E_{\text{min}} < 160$. 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

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_j based on the non-thermal emissions.

Recently, Kino and Kawakatu (2005) (hereafter KK05) proposed a new estimate of L_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 over-pressured against the ICM (Begelman and Cioffi 1989). From their model, L_j 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 $P_c > P_a$, where P_c and P_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

$$\frac{L_j}{v_j} = \rho_a(r_h) v_h^2(t) A_h(t), \quad (1)$$

$$P_c(t) = \rho_a(r_c) v_c(t)^2, \quad (2)$$

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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 ρ_a , α , and P_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_j and t_{age} are displayed in the right panels of Figs. 2. The red lines displayed in the figure are the resultant range of L_j and t_{age} , and their ranges reflect the uncertainty in \mathcal{R} . The age and power depend on the aspect ratio \mathcal{R} as $t_{\text{age}} \propto \mathcal{R}^{4-\alpha}$ and $L_j \propto \mathcal{R}^{2\alpha-8}$, and, therefore, satisfy $L_j \propto t_{\text{age}}^{-2}$. Since α 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_{Edd}) of each source, is also shown (green line) in these figure for comparison. The black hole masses (M_{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_{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_j and t_{age} and the other relevant physical properties of the cocoon. Reflecting the asymmetries in their shape, the obtained L_j and t_{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_j and t_{age} is in the range obtained from both lobes.

4 Discussions

4.1 On L_j/L_{Edd}

In Table 1, the total kinetic power of the jet normalized by the corresponding Eddington luminosity, $2L_j/L_{\text{Edd}}$, is displayed. It can be seen that $2L_j/L_{\text{Edd}}$ takes quite high value ranging from ~ 0.02 to ~ 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 $2L_j/L_{\text{Edd}} \simeq 1$.

4.2 On the plasma content

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

Using η_{min} , here we investigate the plasma content in the cocoon. Considering the components of energy, E_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_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 η_{min} is given as $\eta_{\text{min}} = U_e^{\text{NT}}/U_{\text{min}}$ where U_e^{NT} and U_{min} are the energy density the nonthermal leptons and the minimum energy density ($U_{\text{min}} \equiv E_{\text{min}}/V_c$), respectively. It is useful to express $U_e^{\text{NT}}/U_{\text{min}}$ in terms of U_e^{NT}/U_B , where U_B is the energy density the magnetic field since U_e^{NT}/U_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_ν) is determined as $L_\nu \propto U_e^{\text{NT}} U_B^{4/3} V_c$. Hence with L_ν and V_c observed, U_e and U_B are not independent of each other, and $U_e^{\text{NT}}/U_{\text{min}}$ can be written as $U_e^{\text{NT}}/U_{\text{min}} = 0.5(U_e^{\text{NT}}/U_B)^{3/7}$. Since recent studies shows that $1 < U_e^{\text{NT}}/U_B < 10$ on average, the value of η_{min} is expected to be up to ~ 1 at most. Thus, non-thermal 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.

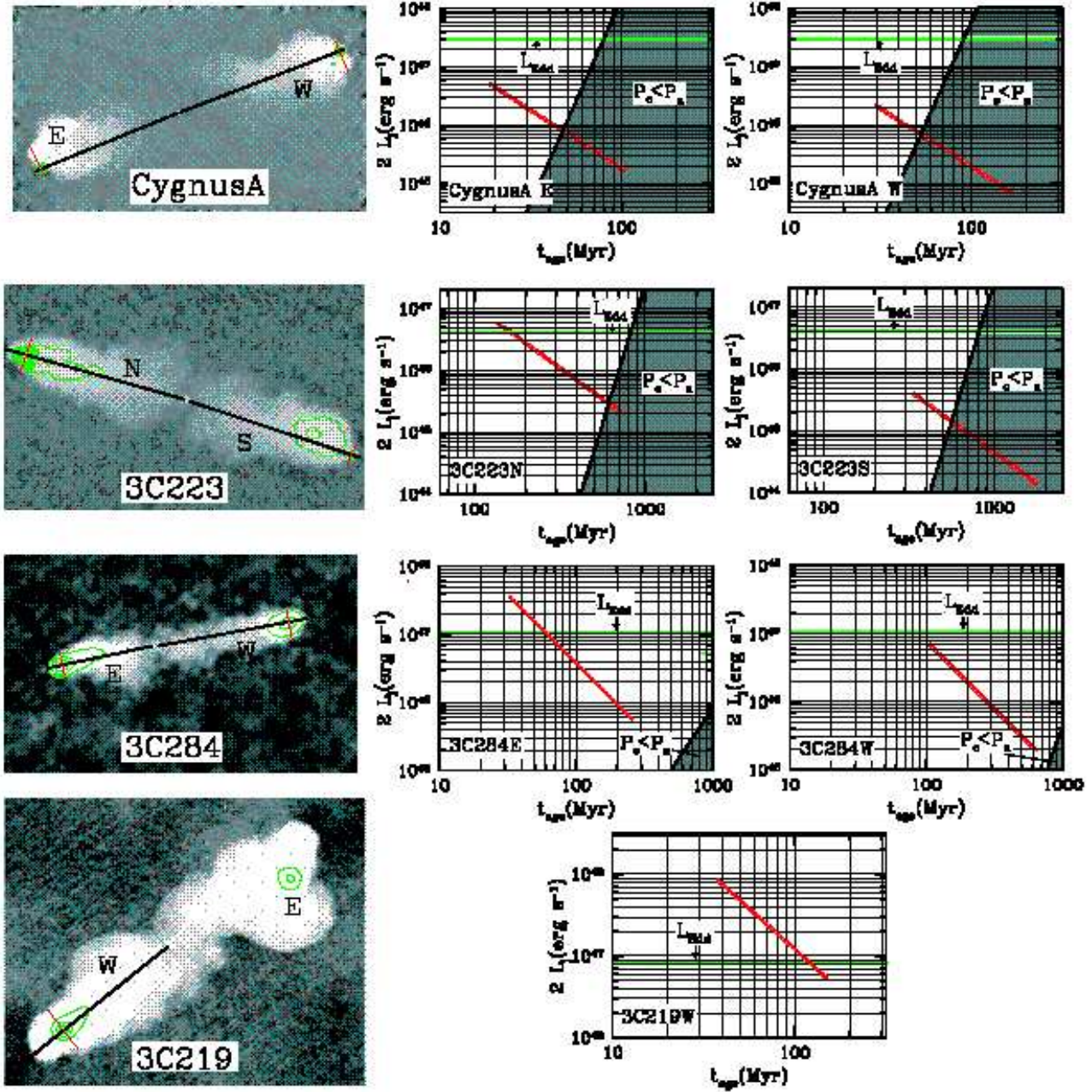


Fig. 2.— *left panels*: Logarithmic-scaled 5-GHz VLA map of Cygnus A (Perley et al. 1984) and 1.5GHz VLA maps of 3C 223 (Leahy and Perley 1991), 3C 284 (Leahy et al. 1986), and 3C 219 (Clarke et al. 1992) with linearly spaced contours (green lines) are displayed. The straight lines overlaid in each map 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_{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.

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

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

5 Summary

In this paper we have investigated the total kinetic power and the age of the relativistic jet in four FR II 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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