ON THE ORIGIN OF FANAROFF-RILEY CLASSIFICATION OF RADIO GALAXIES: DECELERATION OF SUPERSONIC RADIO LOBES

Nozomu Kawakatu[1]
National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

Motoki Kino
National Astronomical Observatory of Japan, 2-21-1, Osawa, Mitaka, Tokyo 181-8588, Japan

Hiroshi Nagai
National Astronomical Observatory of Japan, 2-21-1, Osawa, Mitaka, Tokyo 181-8588, Japan
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ABSTRACT

We argue that the origin of 'FRI/FRII dichotomy' — the division between Fanaroff-Riley class I (FRI) with subsonic lobes and class II (FRII) radio sources with supersonic lobes is sharp in the radio-optical luminosity plane (Owen-White diagram) — can be explained by the deceleration of advancing radio lobes. The deceleration is caused by the growth of the effective cross-sectional area of radio lobes. We derive the condition in which an initially supersonic lobe turns into a subsonic lobe, combining the ram-pressure equilibrium between the hot spots and the ambient medium with the relation between "the hot spot radius" and "the linear size of radio sources" obtained from the radio observations. We find that the dividing line between the supersonic lobes and subsonic ones is determined by the ratio of the jet power L_{j} to the number density of the ambient matter at the core radius of the host galaxy $\bar{n}_{\mathrm{a}}$. It is also found that there exists the maximal ratio of $(L_{\mathrm{j}}/\bar{n}_{\mathrm{a}})$ and its value resides in $(L_{\mathrm{j}}/\bar{n}_{\mathrm{a}})_{\mathrm{max}} \approx 10^{44-47}\,\mathrm{erg\,s^{-1}\,cm^3}$, taking account of considerable uncertainties. This suggests that the maximal value $(L_{\mathrm{j}}/\bar{n}_{\mathrm{a}})_{\mathrm{max}}$ separates between FRIs and FRIIs.

Subject headings: galaxies: active—galaxies: evolution—galaxies: jets— galaxies: ISM

1. INTRODUCTION

Fanaroff & Riley (1974) discovered that the radio galaxies whose linear size l is $l \geq 10\,\mathrm{kpc}$ exhibit a change in morphology from edge-darkened to edge-brightened at a monochromatic power $\sim 10^{24.5}\,\mathrm{W\,Hz^{-1}}$ at a rest frame frequency of 1.4 GHz. The Fanaroff-Riley type I radio galaxies (FRIs) have the edge-darkened morphology and the subsonic advance speed of their lobes (hereafter subsonic lobes), while the Fanaroff-Riley type II radio galaxies (FRIIs) possess the edge-brightened morphology and the supersonic advance speed of their lobes (hereafter supersonic lobes). Owen & White (1991) and Ledlow & Owen (1996) found a striking separation between the FRIs and FRIIs in the radio-optical luminosity plane. At given optical luminosity of host galaxies, FRIIs are located on the side of brighter radio luminosity, while FRIs tend to fall on the side of fainter radio luminosity.

The origin of the 'FRI/FRII dichotomy', which is an outstanding issue in the astrophysics of extragalactic radio sources, has long been debated. Two promising interpretations for the dichotomy have been proposed; One is that the dividing line can be understood by "the intrinsic differences of the jet's kinetic power" between FRIs and FRIIs (e.g., Meier et al. 1997; Ghisellini & Celotti 2001; Marchesini, Celotti, & Ferrarese 2004). The other is that "the deceleration process of the jets" can determine the dividing line, supposing that FRIs are initially supersonic (e.g., Falle 1991; Bicknell 1994; Kaiser & Alexander 1997; Nakamura et al. 2008). The deceleration scenario are also supported by the following two observational facts; One is the observations of relativistic sub-kpc jets in nearby FRIs

such as M87 (Biretta et al. 1995) and relativistic sub-pc ones in BL Lac objects (e.g., Gabuzda et al. 1994), whose parent populations are FRIs in AGN unified model (e.g., Urry & Padovani 1995). On the other hand, the subsonic lobes at $l > 10\,\mathrm{kpc}$ are observed in FRIs. The second is the existence of a new class of double radio sources in which the two lobes have clearly different FR morphologies at both sides called 'HYbrid MOrphology Radio Sources (HYMORS)' (e.g., Gopal-Krishna & Wiita 2000). However, the deceleration process have been unclear.

In this paper, we especially focus on the deceleration process of lobes to explore the origin of 'FRI/FRII dichotomy'. *How does the supersonic flow decelerate in the first few kpc ?* As a plausible deceleration process, the entrainment through mixing in a turbulent layer between the jets and the ambient medium has been considered (e.g., De Young 1993a, b; Bicknell 1994; Perucho & Marti 2007; Rossi et al. 2008). De Young (1993a, b) suggested that the deceleration of the advancing lobes due to the entrainment is important for the special cases, i.e., both relatively low kinetic power of jets and sufficiently dense ambient medium. In this paper, we elucidate another process of deceleration of radio lobe's advance speed. As a possible deceleration process, Cioffi & Blondin (1992) showed the importance of the jet's head growth by using hydrodynamic simulations. Interestingly, recent observation has suggested that the cross-sectional area of reverse shocked region of jets (hot spots) grows faster in the host galaxy than outside the galaxy. By comparing the dynamical model of radio lobes and hot spots including their head growth, Kawakatu, Nagai & Kino (2008; hereafter

KNK08) suggested that this trend that hot spot radius changes with distance can be explained by the strong deceleration of radio lobes.

The goal of this paper is to elucidate the condition in which initially supersonic lobes become subsonic lobes, which can be closely linked to the origin of 'FRI/FRII dichotomy', *by considering that the deceleration of radio lobes and hot spots controlled by the growth of radio lobes' head.* In §2, we provide a simple treatment for the dynamical evolution of radio lobes, in order to derive the dividing line between FRIs and FRIIs. In §3, we show the ratio of the jet power and the constant number density of the ambient matter is maximal at the core radius. Then, it is newly predicted that the division between FRIs and FRI Is is determined by the maximal ratio of the jet power L_j to the number density of the ambient matter at the core radius of the host galaxy $\bar{n}_a$. In §4, we suggest an evolutionary sequence of variously sized radio galaxies based on our findings. Summary is given in §5.

2. MODEL AND OBSERVATION

In order to obtain the requirement for an initially supersonic lobe to turn into a subsonic lobe, we combine the ram-pressure equilibrium between the hot spots and ambient medium with the observed relation between "the hot spot radius" and "the linear size of radio sources" (Figure 1 in KNK08).

We consider here a pair of relativistic jets propagating in an ambient medium $\rho_a(l_h)$ where l_h is the distance from the jet apex. The equation of motion along the jet axis, i.e., the momentum flux of a relativistic jet is balanced to the ram pressure of the ambient medium spread over the effective cross-sectional area of the cocoon head, $A_h(l_h)$,

$$L_j/c = \rho_a(l_h)v_{HS}^2(l_h)A_h(l_h), \qquad (1)$$

where L_j and $v_{HS}(l_h)$ are the total kinetic energy of jets and the hot spot velocity, respectively. Here, we assume that L_j is constant in time during the activity period $t \approx 10^{6-8}$ yr, which is a typical age of FRIs and FRIIs (e.g., Carilli et al. 1991; Parma et al. 1999; O'Dea et al. 2009; Machalski et al. 2009). Hereafter, we do not consider the entrainment effect of the ambient medium. This is justified for higher L_j (e.g., Scheck et al. 2002) but we will discuss this later on. At the hot spots, the flow of shocked matter is spread out by the oblique shocks (e.g., Lind et al. 1989) and the vortex via shocks (e.g., Smith et al. 1985). Thus, the effective "working surface" for the advancing jet is larger than the cross-sectional area of hot spots (Begelman & Cioffi 1989; Kino & Kawakatu 2005:hereafter KK05; Kawakatu & Kino 2006). The evolution of $A_h(l_h)$ could be determined by the density profile of ambient medium and the growth rate of cross-section of cocoons (e.g., Begelman & Cioffi 1989; Loken et al. 1992; KK05). However, it is difficult to obtain $A_h(l_h)$ analytically because this is determined by the non-linear effects (Smith et al. 1985; Lind et al. 1989; Scheck et al. 2002; Mizuta et al. 2004; Perucho & Marti 2007). Then, we assume $A_h(l_h)$ as being proportional to $r_{HS}^2(l_h)$ as follows;

$$A_h(l_h) \equiv f\pi r_{HS}^2(l_h), \qquad (2)$$

where $r_{HS}(l_h)$ is the hot spot size. Although the parameter f (> 1) is determined by the non-linear effects (e.g., the vortex and oblique shock) at the hot spots (e.g., Mizuta et

al. 2004), the 2D relativistic numerical simulations show $f = const.$ (e.g., Scheck et al. 2002; Perucho & Marti 2007). Thus, we here suppose $f = const.$.

For the ambient density profile $\rho_a(l_h)$, we assume a double power-law distribution obtained from X-ray observations (e.g., Trinchieri et al. 1986; Mathews & Brighenti 2003; Allen et al. 2006; Fukazawa et al. 2006) as

$$\rho_a(l_h) = \begin{cases} \bar{\rho}_a(l_h/l_c)^{-\alpha_{inner}} & \text{for } l_h < l_c, \\ \\ \bar{\rho}_a(l_h/l_c)^{-\alpha_{outer}} & \text{for } l_h > l_c, \end{cases} \qquad (3)$$

where $\bar{\rho}_a$ is the mass density of the ambient matter at l_c where the slope index of $\rho_a(l_h)$ changes and $\alpha \geq 0$ is the slope index of $\rho_a(l_h)$. Here $\bar{\rho}_a = \bar{n}_a m_p$ where m_p is the proton mass. Based on the observed temperature profile of elliptical galaxies from X-ray observations (e.g., Allen et al. 2001; Fukazawa et al. 2006), we assume the ambient temperature profile $T_a(l_h)$ as follows;

$$T_a(l_h) = \begin{cases} T_{a,c} & \text{for } l_h < l_c, \\ \\ T_{a,c}(l_h/l_c)^\beta & \text{for } l_c < l_h < l_g, \\ \\ T_{a,g} & \text{for } l_h > l_g, \end{cases} \qquad (4)$$

where $T_{a,g} = T_{a,c}(l_g/l_c)^\beta$ with $\beta \geq 0$ and l_g is the distance where $T_a(l_h) = T_{a,g}$.

From the radio observations (Jeyakumar & Saikia 2000; KNK08), the evolution of $r_{HS}(l_h)$ can be assumed to be a broken power-law distribution as

$$r_{HS}(l_h) = \begin{cases} \bar{r}_{HS}(l_h/l_c)^{\gamma_{inner}} & \text{for } l_h < l_c, \\ \\ \bar{r}_{HS}(l_h/l_c)^{\gamma_{outer}} & \text{for } l_h > l_c, \end{cases} \qquad (5)$$

where $\bar{r}_{HS}$ is the hot spot radius at l_c.

3. ON THE ORIGIN OF FRI-FRII DICHOTOMY

Based on simple treatments for the dynamical evolution of radio sources, we will derive the condition in which initially supersonic lobes turn into subsonic lobes. We suppose that the growth of radio sources changes drastically when the advance speed along the jet axis equals to the sound speed of the ambient medium, $c_s(l_h)$ (e.g., Gopal-Krishna & Wiita 1987; Gopal-Krishna & Wiita 1991). This criterion is simply described as

$$v_{HS}(l_h) = c_s(l_h). \qquad (6)$$

Here $c_s(l_h) = (5kT_a(l_h)/3m_p)^{1/2}$ where k is the Boltzman constant. Using eqs. (2) and (6), the eq. (1) can be expressed as follows;

$$L_j/c = f\pi r_{HS}^2(l_h)\rho_a(l_h)c_s^2(l_h). \qquad (7)$$

By substituting eqs. (3), (4) and (5) into eq. (7), the critical line between the supersonic lobes and subsonic ones is expressed as a function of l_h as follows;

$$\left(\frac{L_j}{\bar{n}_a}\right)_{crit} = fcm_p\bar{r}_{HS}^2 \begin{cases} c_{s,c}^2(l_h/l_c)^{(2\gamma-\alpha)_{inner}} & \text{for } l_h < l_c, \\ \\ c_{s,c}^2(l_h/l_c)^{(2\gamma-\alpha)_{outer}+\beta} & \text{for } l_c < l_h < l_g, \\ \\ c_{s,g}^2(l_h/l_c)^{(2\gamma-\alpha)_{outer}} & \text{for } l_h > l_g, \end{cases} \qquad (8)$$

where $c_{s,i}(l_h) = (5kT_{a,i}(l_h)/3m_p)^{1/2}$ with i="c" or "g", $(2\gamma - \alpha)_{inner} \equiv 2\gamma_{inner} - \alpha_{inner}$ and $(2\gamma - \alpha)_{outer} \equiv 2\gamma_{outer} - \alpha_{outer}$.
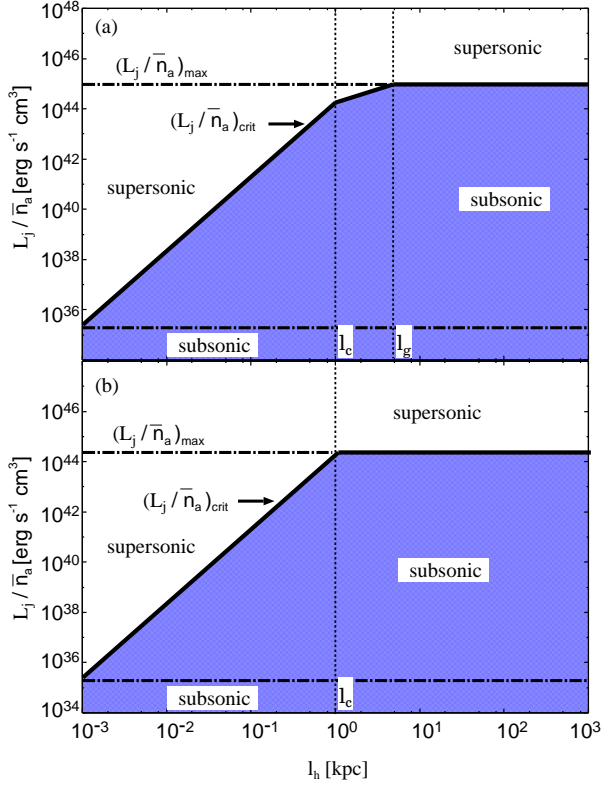
FIG. 1.— (a) The ratio of the jet's kinetic power and the constant number density of the ambient medium in over the core radius (l_c =1 kpc), $L_j/\bar{n}_a$, against the distance from the core, l_h for $f = 10$, $(2\gamma - \alpha)_{inner} = 3$, $(2\gamma - \alpha)_{outer} = 0$ and $l_c = 1$ kpc. We assume $T_{a,c} = 2 \times 10^6$ K and $T_{a,g} = 1 \times 10^7$ K. The solid line [$(L_j/\bar{n}_a)_{crit}$] determined by eq. (10) shows the dividing line between the supersonic lobes and the subsonic ones (the shaded region) for $\beta = 1$ where β is the slope index of $T_a(l_h)$ for $l_c < l_h < l_g$. The two dot-dashed lines divide into three regions which correspond to the evolutionary sequences of variously sized radio galaxies (see §4). (b) Same as (a) but for $\beta = 0$ and $T_{a,c} = T_{a,g} = 2 \times 10^6$ K.

To determine the critical line, the slope index of $(L_j/\bar{n}_a)_{crit}$ is important. Since the slope index depends on the values of α and γ, we can classify the following three cases, i.e., (i) $(2\gamma - \alpha)_{inner} \geq 0$ and $(2\gamma - \alpha)_{outer} \leq 0$, (ii) $(2\gamma - \alpha)_{inner} \geq 0$ and $(2\gamma - \alpha)_{outer} > 0$ and (iii) $(2\gamma - \alpha)_{inner} < 0$ and any $(2\gamma - \alpha)_{outer}$. For the slope of ambient medium α, it is possible to constrain as $0 \leq \alpha_{inner} \leq \alpha_{outer} = 1 - 2$ from X-ray observations (e.g., Trinchieri et al. 1986; Mathews & Brighenti 2003; Allen et al. 2006; Fukazawa et al. 2006). As for $r_{HS}(l_h)$, KNK08 found $\gamma_{inner} = 1 - 1.5$ and $\gamma_{outer} = 0.3 - 0.5$ by using about 120 radio sources. From these values of α and γ, the allowed ranges are given by

$$0 \leq (2\gamma - \alpha)_{inner} \leq 3 \text{ and } -1.5 \leq (2\gamma - \alpha)_{outer} \leq 0. \quad (9)$$

Thus, the cases (ii) and (iii) can be safely ruled out, then hereafter we will consider the case (i). In case (i), there exists the maximal ratio of the jet power and the number density of the ambient medium at l_c, $(L_j/\bar{n}_a)_{max}$ because of $(2\gamma - \alpha)_{inner} \geq 0$ and $(2\gamma - \alpha)_{outer} \leq 0$. Importantly, the presence of $(L_j/\bar{n}_a)_{max}$ is independent of the values of α, β and γ for case (i), except for $(2\gamma - \alpha)_{inner} = 0$ and $\beta = 0$. The existence of $(L_j/\bar{n}_a)_{max}$ is physically understood in terms of the strong deceleration of radio lobes and hot spots in host galaxies due to the growth of the cross-sectional area of radio lobes (see KNK08). The independent observations also imply the deceleration of the

advance speed of hot spots (O'Dea & Baum 1997; Labiano 2008). Note that the maximum of $(L_j/\bar{n}_a)$ disappears only for $\alpha_{inner} = \alpha_{outer} = 2$, $\beta = 0$, $\gamma_{inner} = 1$ and $\gamma_{outer} \leq 1$ because $(L_j/\bar{n}_a)_{crit}$ is independent of l_h. If this is the case, the division between FRIs and FRIIs is determined by T_a and r_{HS} at the distance from nuclei where the A_h growth phase starts, i.e., a few pc.

Figure 1 shows the critical lines (the solid lines) for $\beta = 1$ [case (a)] and for $\beta = 0$ [case (b)], assuming $f = 10$, $(2\gamma - \alpha)_{inner} = 3$, $(2\gamma - \alpha)_{outer} = 0$ and $l_c = 1$ kpc. Concerning β, Fukazawa et al. (2006) found that the temperature slightly increases with l_h, i.e., $0 \leq \beta \leq 1$ ($l_c < l_h < l_g$), for X-ray luminous elliptical galaxies, while for X-ray faint galaxies shows a flat temperature profile against l_h, i.e., $\beta = 0$. For T_a (e.g., Allen et al. 2001; Fukazawa et al. 2006), we assume $T_{a,c} = 2 \times 10^6$ K and $T_{a,g} = 1 \times 10^7$ K for case (a) and $T_{a,c} = T_{a,g} = 2 \times 10^6$ K for case (b). For case (a), $l_g = 5$ kpc because of $l_g/l_c = T_{a,g}/T_{a,c}$. As we mentioned, we see that the maximum of $L_j/\bar{n}_a$ dividing between the supersonic lobes and the subsonic lobes (the shaded region in Figure 1) appears at l_c. From the eq. (8), the maximal ratio of the jet power and the number density at l_c can be described as $(L_j/\bar{n}_a)_{max} = fcm_p\pi r_{HS}^2 c_{s,i}^2$ where i="g" for case (a) and i="c" for case (b). The $(L_j/\bar{n}_a)_{max}$ is expressed as

$$\left(\frac{L_j}{\bar{n}_a}\right)_{max} = 1 \times 10^{45} \left(\frac{f}{10}\right) \left(\frac{c_{s,i}}{10^{-3}c}\right)^2 \left(\frac{\bar{r}_{HS}}{0.3\,\text{kpc}}\right)^2 \text{ erg s}^{-1}\,\text{cm}^3,$$
(10)

where $c_{s,i} = 1 \times 10^{-3}c$ corresponds to $T_{a,i} = 1 \times 10^7$ K and $\bar{r}_{HS} = 0.3$ kpc which is derived from Figure 1 in KNK08. Note that $(L_j/\bar{n}_a)_{max}$ for case (b) is factor 5 smaller than that for case (a) because of $(L_j/\bar{n}_a)_{max} \propto T_a$. The predicted $(L_j/\bar{n}_a)_{max}$ in eq. (10) is about three orders of magnitude higher than the ratio below which the entrainment can work efficiently, i.e., $L_j/\bar{n}_a \leq 10^{42}\,\text{erg s}^{-1}\,\text{cm}^3$ (De Young 1993a, b; hereafter DY93a, b). Thus, by comparing with the future measurements of L_j and $\bar{n}_a$ for the variously sized radio sources, we will be able to reveal which deceleration processes, i.e., the jet's head growth or entrainment, can divide FRIs and FRIIs.

Our results suggests that the supersonic lobes can be maintained up to ~ 1 Mpc when $L_j/\bar{n}_a$ is larger than its maximal value. On the other hand, in the case of below $(L_j/\bar{n}_a)_{max}$, the lobes are initially supersonic but the supersonic lobes decelerate and then turn into subsonic lobes in the core radius of the host galaxy, or the lobes are initially subsonic. The division between FRIs and FRIIs can be determined by $(L_j/\bar{n}_a)_{max}$, because the radio lobes of FRIs and FRIIs can be subsonic and supersonic, respectively. This indicates that FRIs favor the higher $\bar{n}_a$ than FRIIs at given L_j. This is consistent with the observational results showing that FRIs are located at the centers of clusters of galaxies while FRIIs are discovered in the fields or at the edge of clusters of galaxies (e.g., Prestage & Peacock 1988; Miller et al. 2002). The division in the Owen-White diagram has been shown to be much less clear based on the latest Sloan Digital Sky Surveys sample (Best et al. 2009). This may indicate that radio luminosity and optical magnitude of the host galaxy are not the fundamental physical quantities for the demarcation between FRIs and FRIIs. In order to judge whether our prediction is reasonable, it will be essential to compare with the observed L_j

and $\bar{n}_a$ for the variously sized radio galaxies (i.e., CSOs, MSOs, FRIs and FRIIs).

Lastly, we discuss how $(L_j/\bar{n}_a)_{max}$ depends on the different choice of parameters, i.e., f, T_a and $\bar{r}_{HS}$. As for parameter f, A_h must be smaller than πl_h^2 because of the elongated morphology of radio lobes. According to the observed relation between the hot spot size, r_{HS} and the projected linear size, l_h relation (see Figure 1 in KNK08) f can be $10 < f < 10^2$. For four FRIIs, by directly comparing πr_{HS}^2 with A_h, the range of f can be obtained as $10 < f < 10^2$ (e.g., Ito et al. 2008; see Carilli et al. 1991). Thus, we here consider a wide range of f, i.e., $10 < f < 10^2$. As c_s becomes larger, $(L_j/\bar{n}_a)_{max}$ increases at fixed $\bar{r}_{HS}$ and vice versa (see eq. (10)). In order to satisfy $v_{HS} \geq c_s$, the larger $(L_j/\bar{n}_a)_{max}$ is required as c_s increases because of $v_{HS} \propto L_j/\bar{n}_a$ (see eq. (1)). According to the current observations, the ranges of temperature could be narrow, i.e., $2 \times 10^6\,\mathrm{K} \leq T_{a,c} \leq 1 \times 10^7\,\mathrm{K}$ and $1 \times 10^7\,\mathrm{K} \leq T_{a,g} \leq 2 \times 10^7\,\mathrm{K}$ (e.g., Allen et al. 2001; Fukazawa et al. 2006). For the hot spot radius at l_c, the range of $\bar{r}_{HS}$ could be $0.3\,\mathrm{kpc} \leq \bar{r}_{HS} \leq 1\,\mathrm{kpc}$ (see Figure 1 in KNK08) because of $1\,\mathrm{kpc} \leq l_c \leq 10\,\mathrm{kpc}$ (e.g., Fukazawa et al. 2006). Considering all uncertainties, the allowed range of $(L_j/\bar{n}_a)_{max}$ can be $\approx 10^{44} - 10^{47}\,\mathrm{erg\,s^{-1}\,cm^3}$, which is more than 2 orders of magnitude higher than the ratio below which the entrainment would be important (e.g., DY93a, b). To summarize, it will be essential to measure $\rho_a(l_h)$, $T_a(l_h)$ and f more accurately, in order to determine a critical line dividing between FRIs and FRI Is.

4. PREDICTIONS: EVOLUTIONARY TRACKS OF RADIO GALAXIES

In order to evolve into the large-scale $[l_h > l_c (\leq 10\,\mathrm{kpc})]$ supersonic lobes, it is necessary to hold the condition which $L_j/\bar{n}_a$ is larger than $(L_j/\bar{n}_a)_{max}$. Moreover, the dividing line between the subsonic and supersonic, $(L_j/\bar{n}_a)_{crit}$ depends on l_h. Thus, the evolutionary path of radio sources can be divided by $(L_j/\bar{n}_a)_{crit}$ (see eq. (8)). Observationally, several authors have discovered young and compact radio sources such as compact symmetric objects (CSOs; $l_h < 1\mathrm{kpc}$) and medium-size symmetric objects (MSOs; $l_h = 1 - 10$ kpc) (e.g., Wilkinson et al. 1994; Fanti et al. 1995; Readhead et al. 1996).

On the basis of our findings (see Figure 1), we can predict the fate of compact and young radio galaxies as follows;

(i) If $L_j/\bar{n}_a > (L_j/\bar{n}_a)_{max} = 10^{44-45}\,\mathrm{erg\,s^{-1}\,cm^3}$, the evolutionary sequence appears as CSOs → MSOs → FRIIs.

(ii) When $L_j/\bar{n}_a < (L_j/\bar{n}_a)_{max} = 10^{44-45}\,\mathrm{erg\,s^{-1}\,cm^3}$, the evolutionary track is as follows; CSOs → distorted MSOs → FRIs.

(iii) If $(L_j/\bar{n}_a) < 10^{36}\,\mathrm{erg\,s^{-1}\,cm^3}$ at $l_h = 1\,\mathrm{pc}$, the evolutionary track appears as the FRI-like CSOs → distorted MSOs → FRIs.

For case (iii), the distorted MSOs might correspond to $\sim 1\,\mathrm{kpc}$ low power compact (LPC) radio sources (e.g., Kunert-Bajraszewska et al. 2005; Giroletti et al. 2005) because the radio morphology of LPCs tends to be irregular and some LPCs show FRI-like morphology (e.g., Giroletti et al. 2005). Note that the deceleration of supersonic lobes via the entrainment may be also important for cases (ii) and (iii).

We briefly comment on the number of radio sources with supersonic lobes per bin of projected size, $N(l_h)$. As seen in Figure 1, the region of the supersonic lobes allowed is larger as the size of the AGN jets is smaller. This might imply that the number of CSOs having supersonic lobes is larger than that of MSOs. However, in order to predict $N(l_h)$ we need to consider the luminosity evolution of radio sources, the distribution of L_j and $\bar{n}_a$. This is left as our future work.

5. SUMMARY

We examine the origin of 'FRI/FRII dichotomy' by considering the deceleration of expanding radio lobes. We explored the condition of a supersonic lobe turnng into a subsonic one, comparing the observed $r_{HS} - l_h$ relation with the ram-pressure confinement along the jet axis. We then found that the dividing line between the supersonic lobes and subsonic ones is determined by the single parameter, i.e., the ratio of the jet power (L_j) and the number density of the ambient medium at the core radius of hosts ($\bar{n}_a$). Importantly, there exists the maximal ratio of ($L_j/\bar{n}_a$) and its value is $(L_j/\bar{n}_a)_{max} \approx 10^{44-47}\,\mathrm{erg\,s^{-1}\,cm^3}$, taking account of considerable uncertainties. This is more than 2 orders of magnitude higher than the ratio below which the entrainment would be important (e.g., DY93a, b). Thus, it will be able to test whether the predicted maximal ratio $(L_j/\bar{n}_a)_{max}$ divides the FRIs from the FRI Is, by comparing with the future observation of L_j and $\bar{n}_a$ for the variously sized radio sources.

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