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Fate of baby radio galaxies: Dead or Alive ?

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In order to reveal the long-term evolution of relativistic jets in active galactic nuclei (AGNs), we examine the dynamical evolution of variously-sized radio galaxies [i.e., compact symmetric objects (CSOs), medium-size symmetric objects (MSOs), Fanaroff-Riley type II radio galaxies (FRIIs)]. By comparing the observed relation between the hot spot size and the linear size of radio source with a coevolution model of hot spot and cocoon, we find that the advance speed of hot spots and lobes inevitably show the deceleration phase (CSO-MSO phase) and the acceleration phase (MSO-FRII phase). The deceleration is caused by the growth of the cross-sectional area of the cocoon head. Moreover, by comparing the hot spot speed with the sound speed of the ambient medium, we predict that only CSOs whose initial advance speed is higher than 0.3-0.5c can evolve into FRIIs.

1 Introduction

According to the standard model for radio-loud AGNs, a pair of relativistic jets transport away the bulk kinetic energy from the central compact region close to a central supermassive black hole (SMBH) to $l_{\rm h} \geq 10\,{\rm kpc}$ scale radio lobes, where $l_{\rm h}$ is the distance from the centre of the galaxies (Blandford & Rees 1974). However, how young radio loud AGNs evolve into powerful extended radio sources (e.g., FRII radio galaxies) is one of the primary problems in astrophysics. In order to clarify this issue, it is important to understand the nature of the small, young progenitors of FR IIs. Young and compact radio sources such as CSOs ($l_{\rm h} <$ 1kpc) and MSOs ($l_{\rm h} = 1-10$ kpc) have been discovered by many authors (e.g., Wikinson et al. 1994; Fanti et al. 1995; Readhead et al. 1996). The bright CSOs and MSOs show the FRII like morphology and possess hot spots (reverse shock) which are the signatures of supersonic expansions. The recent observations of several CSOs and MSOs have indicated that their age ($\sim 10^{2-5}\,{\rm yr}$) is shorter than the typical age of FRIIs (e.g., Parma et al. 1999), which implies that CSOs and MSOs are possible candidates as the progenitors of FRI Is (e.g., Owsianik, Conway & Polatidis 1998; Taylor et al. 2000; Giroletti et al. 2003; Polatidis & Conway 2003; Nagai et al. 2006).

A number of authors have investigated the long-term evolution of extragalactic radio sources in different ways (e.g., Begelman & Cioffi 1989: hereafter BC89; Fanti et al. 1995; Begelman 1996; Readhead et al. 1996; Kaiser & Alexander 1997; Snellen, Schilizzi & van Langevelde 2000; Perucho & Martí 2002; Kawakatu & Kino 2006, hereafter KK06). A constant advance speed of hot spots, or a constant aspect ratio of the cocoon (i.e., a self-similar evolution) have often been assumed for a dynamical evolution of radio-loud AGNs for simplicity. *Do these assumptions reflect the actual evolution of radio sources ?* In order to answer this question, it is essential to build up an appropriate model of radio sources without assuming the constant aspect ratio and the constant advance speed of hot spots such as that presented by KK06.

Recent observations suggested that the power law index for the evolution of hot spot size changes at the transition between the interstellar medium and intergalactic medium, i.e., $l_{\rm h} \sim 1-10\,{\rm kpc}$ (Jeyakumar & Saikia 2000: hereafter J00; Perucho & Martí 2003: hereafter PM03). Since hotspots are identified as the reverse-shocked region of the decelerating jet, the evolution of hot spot size could reflect the dynamical growth of radio sources of various scales. However, it was hard to derive the dynamical evolution of radio sources from previous work (J00 and PM03) because of lack of spatial resolution, the observational bias and small sample of radio sources. In this study, we first compile sample of CSOs, MSOs and FRIIs sources larger than in previous works, by considering the observational bias and being careful about the data quality. Then, from the direct comparison with KK06, we make clear a long-term evolution of advance speed of hot spots (Kawakatu, Nagai & Kino 2008 for details: hereafter KNK08).

2 Observed $r_{\rm HS} - l_{\rm h}$ relation

Following the recent work of Nagai (2007), we compiled 117 variously-sized radio galaxies and examined the physical quantities of the hot spots. Based on these data, we focus

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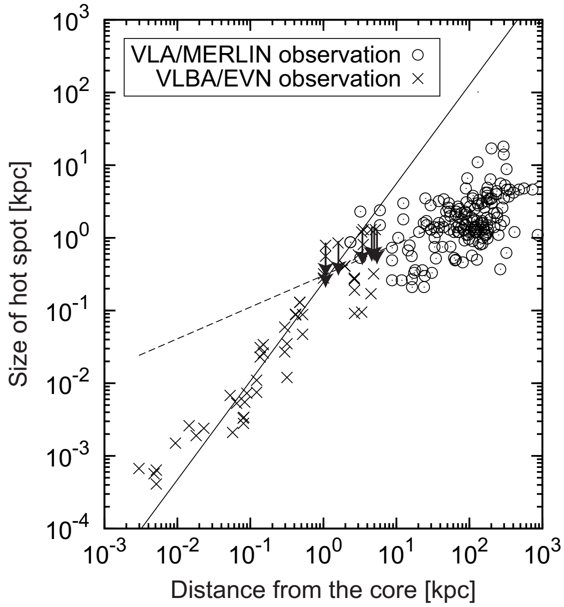

Fig. 1 The relation of hot-spot size ($r_{\rm HS}$) and hot-spot distance from the core ($l_{\rm h}$). Crosses with arrows indicate upper limit. Solid line corresponds to the best-fit for the sources where 10^{-3} kpc$\leq$ $l_{\rm h}$ $\leq$ 1 kpc whereas broken line corresponds to that for the sources where 1 kpc$\leq l_{\rm h} \leq 10^3$ kpc. Note that upper-limit data were not included in the fittings.

on how the size of the hot spot changes with the distance from the core. Figure 1 shows the size of a hot spot, $r_{\rm HS}$ with respect to $l_{\rm h}$, together with the best linear fit on the log-log plane ($\log r_{\rm HS} = a \log l_{\rm h} + b$). We estimated $r_{\rm HS}$ as $(\theta_{\rm maj} + \theta_{\rm min})/2$ where $\theta_{\rm maj}$ and $\theta_{\rm min}$ are full width at half maximum (FWHM) of major and minor axes of the component obtained by Gaussian model fittings, respectively. The slope changes around $\sim$ 1 kpc, and then the best fit value of $a = 1.34 \pm 0.24$ for $l_{\rm h} < 1\,{\rm kpc}$, while $a = 0.44 \pm 0.08$ for $l_{\rm h} > 1\,{\rm kpc}$. This tendency is consistent with PM03, but a large number of sources in our sample allow us to confirm the tendency more clearly. Concerning the possible uncertainties of the estimation of the hot-spot size and the slope change are discussed in KNK08 with more details. As a result, even if we allow for possible uncertainties, the trend of the observed $r_{\rm HS} - l_{\rm h}$ relation would not be changed. It seems reasonable to suppose that the slope change occurs around 1 kpc.

3 Coevolution model of hot spot and cocoon

We briefly review here a dynamical evolution model of radio sources (KK06) which traces the dynamical evolution of advancing hot spots and expanding cocoon (e.g., BC89; see also Kino & Kawakatu 2005). We consider a pair of initially relativistic jets propagating in an ambient medium with matter density ($\rho_{\rm a}$). Here $\rho_{\rm a}$ is given by $\rho_{\rm a}(l_{\rm h}) \propto l_{\rm h}^{-\alpha}$. The basic equations of the cocoon expansion can be obtained as follows:

1. The equation of motion along the jet axis, i.e., the momentum flux of a relativistic jet is balanced by the ram pressure of the ambient medium spread over the effective cross-sectional area of the cocoon head, that is, $A_{\rm h}$, $L_{\rm j}/c = \rho_{\rm a} v_{\rm HS}^2 A_{\rm h}$, where $L_{\rm j}$, c and $v_{\rm HS}$ are the total kinetic energy of jets, the light speed and the hot spot velocity, respectively. Here we assume that $L_{\rm j}$ is constant in time.
2. The equation of motion perpendicular to the jet axis, that is the sideways expansion velocity, $v_{\rm c}$, which is equal to the shock speed driven by the overpressured cocoon with internal pressure ($P_{\rm c}$), $P_{\rm c} = \rho_{\rm a} v_{\rm c}^2$.
3. The energy conservation in the cocoon, namely all of the kinetic energy transported by the jets is deposited as the cocoon's internal pressure, that is, $P_{\rm c} V_{\rm c} = 2(\gamma_{\rm c} - 1) L_{\rm j} t$ where $V_{\rm c}$ is the volume of the cocoon, t is the life time of the source and $\gamma_{\rm c} = 4/3$ is the specific heat ratio of the relativistic plasma in the cocoon.

The cross-sectional area of the cocoon body is given by $A_{\rm c}(t) = \pi l_{\rm c}^2 \propto t^X$, where $l_{\rm c} = \int_{t_{\rm min}}^{t} v_{\rm c}(t')dt'$ is the radius of the cocoon body. Here $t_{\rm min}$ is the time at which the two-dimensional (2D) phase ($A_{\rm h}$ growth phase) starts. Assuming that $A_{\rm h}/r_{\rm HS}^2$ is constant in time, $r_{\rm HS}$ and $v_{\rm HS}$ can be described in terms of the length $l_{\rm h}$.

$$r_{\rm HS} \propto {l_{\rm h}}^{S_{\rm r}}, \quad (1)$$

$$v_{\rm HS} \propto {l_{\rm h}}^{S_{\rm v}}. \quad (2)$$

where $S_{\rm r} \equiv [X(-2+0.5\alpha)(\alpha-2)+3\alpha-4]/[2X(-2+0.5\alpha)+6]$ and $S_{\rm v} \equiv [2-X(2-0.5\alpha)]/[X(-2+0.5\alpha)+3]$. For a free parameter X, we can constrain the value of $1.2 \leq X \leq 1.4$, by comparison with numerical simulations (Scheck et al. 2002; Perucho & Martí 2007).

4 Evolution of the advance speed of hot spots

4.1 Constant velocity evolution ?

In the current models of the evolution of powerful radio sources, the constant velocity of hot spots has often been assumed (e.g., Fanti et al. 1995; Begelman 1996; Readhead et al. 1996; Kaiser & Alexander 1997). But, a deceleration of hot spots may take place via a strong interaction with denser ambient gas in host galaxies since CSOs and MSOs will have a significant interaction with the ambient medium as they propagate through it (e.g., Gelderman & Whittle 1994; de Vries, Barthel & O'Dea 1997 ; Axon et al. 2000; Holt, Tadhunter, & Morganti 2008; Labiano 2008). Thus, it is still unclear whether $v_{\rm HS} = const$ is a reasonable assumption on the evolution of radio sources. In order to test the validity of the $v_{\rm HS} = const.$ model, we will derive the required mass density profile to explain the observed $r_{\rm HS} - l_{\rm h}$ diagram. From eq. (2), the relation of $S_{\rm v} \propto 2 - X(2-0.5\alpha) = 0$ is needed to realize the constant velocity of hot spots. By

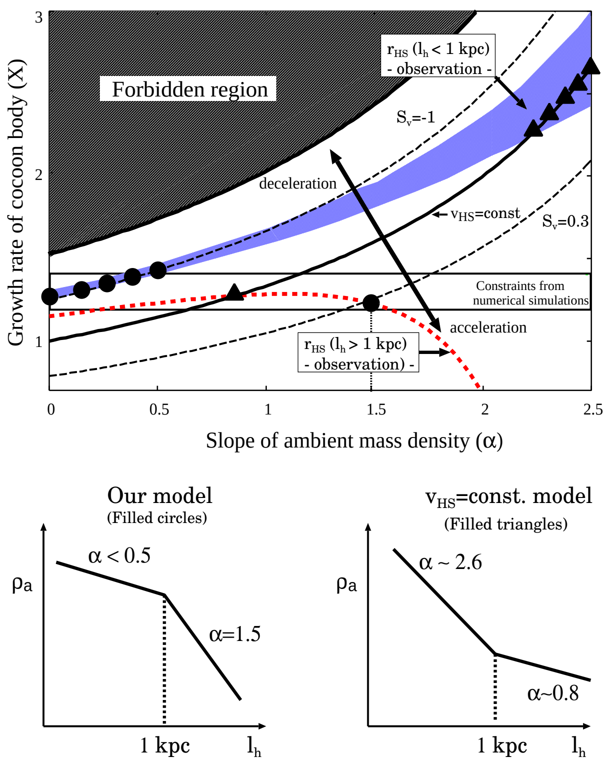

Fig. 2 top) Growth rate of cocoon body ($A_{\rm c} \propto t^X$) against the value of exponents of the ambient matter density profile ($\rho_{\rm a} \propto l_{\rm h}^{-\alpha}$). The dark grey (blue in the on-line version) region shows the allowed region given by the best fit value of the observed $r_{\rm HS} - l_{\rm h}$ relation for the CSO-MSO phase ($l_{\rm h} < 1$ kpc), i.e., $S_{\rm r} = 1.34 \pm 0.24$. The thick dotted line (red thick dotted line in the on-line version) corresponds to the allowed region obtained for the MSO-FRII phase ($l_{\rm h} > 1$ kpc), including the fitting errors, i.e., $S_{\rm r} = 0.44 \pm 0.08$. The black solid line shows $v_{\rm HS}$=const ($S_{\rm v} = 0$). The two black dashed lines are relations for the evolution of hot spot velocity $v_{\rm HS} \propto l_{\rm h}^{S_{\rm v}}$. The filled circles show the solutions for our model. We can constrain the power-law index $\alpha(l_{\rm h} < 1\,{\rm kpc})$ as $0 \leq \alpha < 0.5$. The filled triangles are solutions for the $v_{\rm HS} = const.$. bottom) The predicted ambient mass density profiles are shown in the bottom panel.

eliminating X in eq. (1), one finds $r_{\rm HS} \propto l_{\rm h}^{\alpha/2}$. Comparing this equation with the observed $r_{\rm HS} - l_{\rm h}$ relation, the constant velocity model requires that the slope of the inner part of the density profile (< 1 kpc) must be steeper than that of the outer part (> 1 kpc), i.e., $\alpha \sim 2.6\,(l_{\rm h} < 1\,{\rm kpc})$ and $\alpha \sim 0.8\,(l_{\rm h} > 1\,{\rm kpc})$, as seen in Fig. 2 bottom (filled triangles and also the schematic picture). However, such a density profile of ambient matter is unrealistic because of the slope of the density profile in many clusters of galaxies and groups of galaxies ($l_{\rm h} > 1\,{\rm kpc}$) where $\alpha \approx 1.5$ (e.g., Trinchieri, Fabbiano & Canizares 1986). Thus, the $v_{\rm HS} = const$ model can be rejected.

4.2 Deceleration and acceleration of hot spots velocity

We show an evolutionary track of radio sources that is consistent with the observed evolution of $r_{\rm HS}$ (see Fig. 1). In groups of galaxies and clusters of galaxies ($l_{\rm h} > 1\,{\rm kpc}$), it is well established that the slope of the ambient matter's density profile is $\alpha \approx 1.5$ (e.g., Trinchieri et al.1986). We assume here $\alpha = 1.5$ for $l_{\rm h} > 1\,{\rm kpc}$. Comparing the KK06 model with the observed $r_{\rm HS} - l_{\rm h}$ relation, we can determine (i) the evolution of the advance speed of hot spots and (ii) the slope of mass density distribution for $l_{\rm h} < 1\,{\rm kpc}$. The predicted evolution of hot spots shows that the advance speed of the spots and lobes shows the deceleration phase (CSO-MSO phase) and the acceleration phase (MSO-FRII phase) as follows (see filled circles showing allowed solutions in Fig. 2): In the CSO-MSO phase ($l_{\rm h} < 1\,{\rm kpc}$), the hot spot decelerates as

$$v_{\rm HS} \propto l_{\rm h}^{-1}. \tag{3}$$

In the MSO-FRII phase ($l_{\rm h} > 1\,{\rm kpc}$), the hot spot slightly accelerates as

$$v_{\rm HS} \propto l_{\rm h}^{0.3}. \tag{4}$$

For the CSO-MSO phase ($l_{\rm h} < 1\,{\rm kpc}$), a flatter density profile ($0 < \alpha \leq 0.5$) is predicted in order to satisfy both the observed $r_{\rm HS} - l_{\rm h}$ relation and the constraints from numerical simulations. The mass density profile is quite similar to a King-profile, as indicated by X-ray observations of elliptical galaxies (e.g., Trinchieri et al. 1986). The predicted mass density distribution implies that a significant interaction of the AGN jets with the ambient medium can take place during the CSO-MSO phase, as compared with the MSO-FRII phase. Then, the interaction between the jets and the ambient medium is stronger in the CSO-MSO phase. This leads to the larger velocity of sideways expansion in order to maintain the energy conservation in the cocoon. Thus, $A_{\rm h}$ (or $r_{\rm HS}$) grows faster in the early phase of evolution. From the equation of motion along the jet axis, it is found that the advance speed of hot spots ($v_{\rm HS}$) is determined by the linear density of the effective working surface, $\rho_{\rm a} A_{\rm h}$, i.e., $v_{\rm HS}^2 \propto (\rho_{\rm a} A_{\rm h})^{-1}$. When $\rho_{\rm a} A_{\rm h}$ increases with $l_{\rm h}$ in the CSO-MSO phase ($\rho_{\rm a} A_{\rm h} \propto l_{\rm h}^2$), the hotspot velocity decelerates. On the other hand, the advance speed increases if $\rho_{\rm a} A_{\rm h}$ decreases with $l_{\rm h}$ in the MSO-FRII phase ($\rho_{\rm a} A_{\rm h} \propto l_{\rm h}^{-0.6}$). Summing up, the deceleration and acceleration of hot spot velocity is caused by the deviation from the balance between the deceleration effect via the growth of cocoon head and the acceleration effect due to the decrease of the ambient mass density.

5 Prediction of fate of CSOs: Dead or Alive ?

We further investigate which kind of CSOs can evolve into FRII sources. For this aim, we compare the predicted evolution of $v_{\rm HS}$ with the sound velocity of the ambient medium, $c_{\rm s}$, since the supesonic jets can maintain at $l_{\rm h} > 10\,{\rm kpc}$ only when $v_{\rm HS} > c_{\rm s}$. For the slope of ambient matter density, we assume $\alpha\,(l_{\rm h} < 1\,{\rm kpc}) = 0$ and $\alpha\,(l_{\rm h} > 1\,{\rm kpc})$=1.5 (see §4.2). Correspondingly, the behavior of $v_{\rm HS}$ can be determined as $v_{\rm HS} \propto l_{\rm h}^{-1}$ for $l_{\rm h} < 1\,{\rm kpc}$ and $v_{\rm HS} \propto l_{\rm h}^{0.3}$

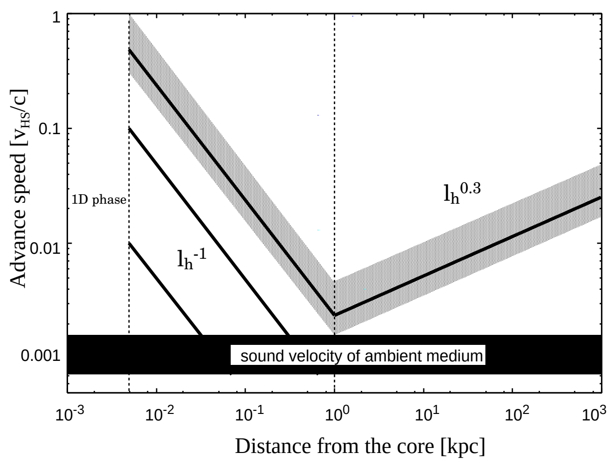

Fig. 3 Our predictions of evolution of $v_{\rm HS}$, i.e., $v_{\rm HS} \propto l_{\rm h}^{-1}$ for $l_{\rm h} < 1\,{\rm kpc}$ and $v_{\rm HS} \propto l_{\rm h}^{0.3}$ for $l_{\rm h} > 1\,{\rm kpc}$. The black solid lines denote the evolution of $v_{\rm HS}$ for $v_{\rm HS}(l_{\rm h,2D}) = 0.01\,c, 0.1\,c, \text{and}\, 0.5\,c$ at $l_{\rm h,2D} = 5\,{\rm pc}$. The light grey shaded region represents the evolutionary path from CSOs into FRIIs. The black shaded region shows the range of sound velocity of the ambient medium, i.e., $7\times10^{-4}c < c_{\rm s} < 1.4\times10^{-3}c\,(5\times10^{6}\,{\rm K} < T_{\rm g} < 2\times10^{7}\,{\rm K})$ where $T_{\rm g}$ is the temperature of the ambient medium.

for $l_{\rm h} > 1\,{\rm kpc}$ (see eqs. (3) and (4)). The hot ambient-gas temperature, $T_{\rm g}$ is measured to be in the range of $T_{\rm g} = 5\times10^{6}\,{\rm K} - 2\times10^{7}\,{\rm K}$, i.e., $c_{\rm s} = (5kT_{\rm g}/3m_{\rm p})^{1/2} \approx 7\times10^{-4}c - 1.4\times10^{-3}c$ (e.g., Trinchieri et al. 1986), k is the Boltzman constant and $m_{\rm p}$ is the proton mass.

Figure 3 shows our predictions of the evolution of hot spot velocity for three initial advance speeds in the ambient medium with $v_{\rm HS}(l_{\rm h,2D}) = 0.01c, 0.1c\,\text{and}\,0.5c$. Here we suppose $l_{\rm h,2D} = 5\,{\rm pc}$ where $l_{\rm h,2D} \equiv v_{\rm HS}(l_{\rm h,2D})t_{\rm min}$ is the distance from the core at which the 2-D phase starts. As seen in Fig. 3, we find that CSOs can evolve into FRII sources, passing through MSOs for any $l_{\rm h}$ when $v_{\rm HS}(l_{\rm h,2D})$ is larger than 0.3-0.5c because of $v_{\rm HS}(l_{\rm h}) > c_{\rm s}$. On the other hand, when $v_{\rm HS}(l_{\rm h,2D})$ is less than 0.3-0.5c, $v_{\rm HS}$ is comparable to the sound velocity during the CSO-MSO phase ($l_{\rm h} < 1\,{\rm kpc}$). Thus, the CSOs can evolve into FRII sources, passing through distorted MSOs. Such distorted MSOs might correspond to low power compact radio sources of sizes of $\sim$ kpc (e.g., Kunert-Bajraszewska et al. 2005; Giroletti 2007).

6 Summary

We have investigated the relation between CSOs, MSOs and FRIIs, by comparing the coevolution model of hot spots and a cocoon (KK06) with the observed $r_{\rm HS} - l_{\rm h}$ relation reflecting the dynamical evolution of radio sources. We find that the advance speed of hot spots and lobes strongly decelerate when the jets pass through the ambient medium in host galaxies (i.e., the CSO-MSO phase), while the jets accelerate outside host galaxies (i.e, the MSO-FRII phase). The reason of deceleration is the growth of the cross-sectional area of cocoon head. The predicted deceleration of hot spots seems to be consistent with the recent observation show that the outflow velocity of the ionized gas around radio lobes may decelerate as $l_{\rm h}$ increaes (Labiano 2008). Furthermore, by comparing the hot spot speed with the sound speed of the ambient medium, we predict that only CSOs whose initial advance speed is higher than 0.3-0.5c can evolve into FRI Is. This indicates that the origin of the FRI/FRII dichotomy could be related to the difference in the initial advance speed (Kawakatu, Kino & Nagai 2008 in preparation).

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