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A New Evolution Scenario of Compact Symmetric Objects

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Abstract. We elucidate the physical meanings of the observed relation between the hot spot radius and the linear size of radio sources, in order to reveal how compact symmetric objects (CSOs) evolve into Fanaroff-Riley type II (FRII) radio sources, passing through medium-size symmetric objects (MSOs). Comparing with a dynamical model taking into account of the head growth of radio lobes, we predict that the advance speed of hot spots and lobes inevitably show a deceleration phase (CSO-MSO phase) and an acceleration phase (MSO-FRII phase). This is ascribed to the sharp change of ambient matter density in the MSO phase (~ 1 kpc). Based on our findings, we finally discuss the fate of CSOs.

1. Introduction

The bulk kinetic energy of relativistic jets in powerful AGNs is dissipated by the strong terminal shocks which are identified as hot spots. Then, shocked relativistic plasma expands sideways and envelopes the whole jet system and this is so-called a cocoon. Recently, a large number of compact, bright double lobe radio sources so called "compact symmetric objects (CSOs)" has been discovered (Wilkinson et al. 1994; Fanti et al. 1995). Recent observations of the advance speed of hot spots of several CSOs (e.g., Owaiank, Conway & Polatidis 1998), show that the separation velocity is typically $\sim 0.1\,c$, indicating a dynamical age of $\sim 10^3$ yr, showing that CSOs are indeed young radio sources. Thus, these works have identified CSOs as the most likely candidates for the progenitor of FR IIs. Moreover, it has been found the power law index for the evolution of hot spot radius changes at $\sim 1 - 10$ kpc (Jeyakumar & Saikia 2000: hereafter J00; Perucho & Martí 2003: hereafter PM03). Since the evolution of hot spot radius reflects the dynamical growth of radio sources with various scales, it is essential to elucidate the physical meanings of this observational trend, in order to reveal the relation between CSOs and FRIIs. Our main goal is to clarify this issue (Kawakatu, Nagai & Kino 2008), by using a dynamical model of hot spots with the aid of cocoon dynamics (Kawakatu & Kino 2006: hereafter KK06).

2. Evolution of Hot Spot Radius

We examine whether the power-law index change at ~ 1 kpc is a solid result for the evolution of hot spot size by compiling a total number of 106 radio sources. Figure 1 shows the radius of hot spots, $r_{\rm HS}$ with respect to the linear size of radio sources, $l_{\rm h}$, together with the best linear fit on the log-log plane ($\log y = a \log x + b$). The slope is seemed to be changed around ~ 1 kpc, and then the best fit value of a for $l_{\rm h} < 1\,{\rm kpc}$ is $a = 1.34 \pm 0.24$, while $a = 0.43 \pm 0.08$ for $l_{\rm h} > 1\,{\rm kpc}$ (Nagai 2006, Ph. D. thesis). This is consistent with the previous works (PM03, J00), but a large number of sources in our sample allows us to confirm the tendency more clearly.

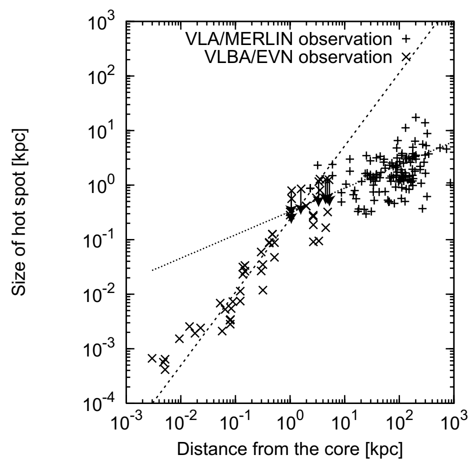

Figure 1. The relation of hot-spot size ($r_{\rm HS}$) and hot-spot distance from the core ($l_{\rm h}$). The dashed line corresponds to the best-fit for the sources where 10^{-3} kpc $\leq l_{\rm h} \leq 1$ kpc, while the dotted line corresponds to that for the sources where 1 kpc $\leq l_{\rm h} \leq 10^3$ kpc.

3. A Dynamical Model

We review a dynamical evolution model of radio sources (KK06) which traces the dynamical evolution of hot spots combined with cocoon dynamics (e.g., Begelman & Cioffi 1989; see also Kino & Kawakatu 2005). According to KK06, the physical quantities of hot spots and the cocoon can be determined by the mass density of the ambient medium, $\rho_{\rm a} \propto l_{\rm h}^{-\alpha}$ and the cross section area of the cocoon body, $A_{\rm c} = \pi l_{\rm c}^2 \propto t^X$, where $l_{\rm h}$ is the distance from the core and $l_{\rm c}$ is the radius of the cocoon body. Concerning a free parameter X, we can constrain the value of X as $1.2 \leq X \leq 1.4$, comparing with numerical simulations (Scheck et al. 2002; Perucho & Marti 2007). The advance speed and radius of hot spots ($v_{\rm HS}$ and $r_{\rm HS}$) can be described in terms of $l_{\rm h}$ as follows:

$$r_{\rm HS} = r_{\rm HS,0} \left(\frac{l_{\rm h}}{l_{\rm h0}}\right)^{\frac{X(-2+0.5\alpha)(\alpha-2)+3\alpha-4}{2X(-2+0.5\alpha)+6}} \propto {l_{\rm h}}^{S_{\rm r}}, \tag{1}$$

$$v_{\rm HS} = v_{\rm HS,0} \left(\frac{l_{\rm h}}{l_{\rm h0}}\right)^{\frac{2-X(2-0.5\alpha)}{X(-2+0.5\alpha)+3}} \propto {l_{\rm h}}^{S_{\rm v}}, \tag{2}$$

where $S_{\rm r}$ and $S_{\rm v}$ represent the values of the exponents of the hot spot radius and advance velocity, respectively.

4. What Can We Learn from $r_{\rm HS} - l_{\rm h}$ Diagram ?

We here elucidate physical reasons and meanings of the change of power-law index in the $r_{\rm HS} - l_{\rm h}$ diagram, by comparing with the theoretical model (KK06). Figure 2 displays the growth rate of the cocoon body ($A_{\rm c} \propto t^X$) plotted versus α (slope of the ambient mass density profile, i.e., $\rho_{\rm a} \propto l_{\rm h}^{-\alpha}$). The dark gray shaded region shows the the solution 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). The dot-dashed line corresponds to the solution obtained for the MSO-FRII phase ($l_{\rm h} > 1$ kpc). The light gray shaded region represents the allowed range of X-parameter ($1.2 \leq X \leq 1.4$).

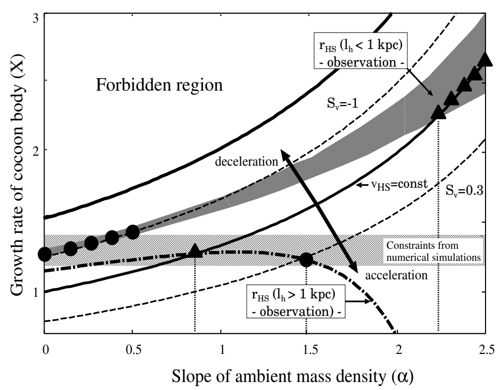

Figure 2. Growth rate of cocoon body ($A_{\rm c} \propto t^X$) against α (slope of the ambient mass density profile).

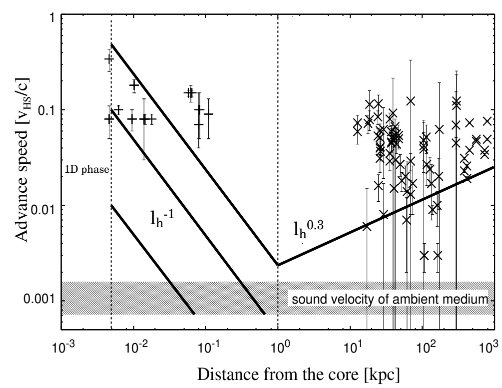

Figure 3. Hot-spot velocity ($v_{\rm HS}$) against hot-spot distance from the core ($l_{\rm h}$).

As seen in Fig. 2, the constant velocity model (solid line) can reproduce the observed correlation between $r_{\rm HS}$ and $l_{\rm h}$, only when the slope of the inner part of the ambient medium ($l_{\rm h} < 1$ kpc) is steeper than that of the outer part of the ambient medium ($l_{\rm h} > 1$ kpc) , i.e., $\alpha > 2.2$ ($l_{\rm h} < 1$ kpc) and $\alpha < 0.7$ ($l_{\rm h} > 1$ kpc); see filled triangles in Fig. 2. However, such a density profile of ambient medium is unrealistic because of $\alpha \approx 1.5$ in lots of clusters of galaxies (e.g., Mulochaey & Zabludoff 1998). Therefore, a simple evolutionary model with $v_{\rm HS} = const.$ can be ruled out.

Next, let us consider a possible evolution scenario of radio sources in a realistic density profile. Provided that the slope of ambient medium is $\alpha = 1.5$ for the MSO-FRII phase ($l_{\rm h} > 1$ kpc), it is requested that the advance speed of hot spots slightly accelerates when MSOs evolve into FRII sources, i.e., $S_{\rm v} = 0.3$. With respect to the CSO-MSO phase ($l_{\rm h} < 1$ kpc), we find that the hot spot velocity decelerates in the evolution from CSOs to MSOs, i.e., $S_{\rm v} = -1$. In addition, the flatter density profile ($\alpha \leq 0.5$) is needed for $l_{\rm h} < 1$ kpc. The filled circles in Fig. 2 show the allowed solutions to reproduce the observed $r_{\rm HS} - l_{\rm h}$ relation. On the basis of these results, we predict that the advance speed of the spots and lobes inevitably show the deceleration phase (CSO-MSO phase) and the acceleration phase (MSO-FRII phase). The stronger interaction with the ambient medium leads to the larger velocity of sideways expansion, in order to keep the energy conservation in the cocoon. From the equation of motion along the jet axis ($L_{\rm j}/c = \rho_{\rm a} v_{\rm HS}^2 A_{\rm h}$), $v_{\rm HS}$ is determined by $\rho_{\rm a} A_{\rm h}$, where $L_{\rm j}$ and $A_{\rm h}$ are the total kinetic energy of jets and the cross section area of cocoon head, respectively. Thus, the deceleration and acceleration of $v_{\rm HS}$ can be ascribed to the sharp change of the ambient matter profile in the MSO phase (~ 1 kpc).

Finally, we discuss the fate of CSOs by comparing $v_{\rm HS}$ with the sound velocity of ambient medium, $c_{\rm s}$, because the overpressure cocoon expansion is possible only when $v_{\rm HS} > c_{\rm s}$. The range of $c_{\rm s}$ (the light gray shaded region in Fig. 3) is assumed to be $\approx 7 \times 10^{-4} c - 1.4 \times 10^{-3} c$ (Trinchieri et al. 1986). Figure 3 shows the evolution of hot spot velocity for $v_{\rm HS}(l_{\rm h,2D}) = 0.01\,c, 0.1\,c$ and $0.5\,c$, where $l_{\rm h,2D} = 5\,{\rm pc}$ is the distance from the core at which the 2-D phase (i.e, head growth phase) starts. As seen in Fig. 3, we find that CSOs can evolve into FRII sources, only when $v_{\rm HS}(l_{\rm h,2D})$ is larger than about 0.1 c.

5. Summary

By comparing the observed $r_{\rm HS} - l_{\rm h}$ relation with the theoretical model (KK06), we find that $v_{\rm HS}$ decelerates in the CSO-MSO phase and it accelerates in the MSO-FRII phase. Moreover, it is predicted that only CSOs, whose initial advance speed is higher than about 0.1 c, are progenitor of powerful FRIIs. In order to test these predictions, it is essential to evaluate $v_{\rm HS}$ of MSOs stage by future VLBI observations.

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