On the dynamical evolution of hot spots in powerful radio loud AGNs

N. Kawakatu$^{1,2}$* and M. Kino$^{1,3}$†

$^1$SISSA, via Beirut 2-4, 34014, Trieste, Italy
$^2$National Observatory of Japan, 181-8588 Mitaka, Japan
$^3$Department of Earth and Space Science, Osaka University, 560-0043 Toyonaka, Japan

ABSTRACT

We describe the dynamical evolution of hot spots velocity, pressure and mass density in radio loud active galactic nuclei (AGNs), taking proper account of (1) the conservations of the mass, momentum, and kinetic energy flux of the unshocked jet, (2) the deceleration process of the jet by shocks, and (3) the cocoon expansion without assuming the constant aspect ratio of the cocoon. By the detailed comparison with two dimensional relativistic hydrodynamic simulations, we show that our model well reproduces the whole evolution of relativistic jets. Our model can explain also the observational trends of the velocity, the pressure, the size, and mass density of hot spots in compact symmetric objects (CSOs) and FR II radio galaxies.

Key words: Radio Galaxies: general—shocks: galaxies: jets—galaxies: active—galaxies

1 INTRODUCTION

Which evolutionary tracks are radio loud AGNs (radio galaxies) passing through? This is one of the primal issues in the study of AGNs (Ryle & Longair 1967; Carvalho 1985; Fanti et al. 1995; De Young 1997). Stimulated by the observational progress (e.g., Turland 1975; Readhead, Cohen & Blandford 1978; Bridle & Perley 1984), a number of hydrodynamic simulations of jet propagations have been performed to examine their physical state of the jet (e.g., Norman et al. 1982; Wilson & Scheuer 1983; Smith et al. 1985; Clarke, Norman & Burns 1986; Lind et al. 1989; Clarke, Harris & Carilli 1997; Marti et al. 1997). These numerical studies have confirmed that the jet is composed of “light” (i.e., lower mass density) materials compared with an ambient medium to reproduce the observed morphology of the expanding cocoon (e.g., Norman et al. 1982). However it is hard to examine the whole duration of powerful radio loud AGNs with sufficiently large dynamical range because of the limitation of computational powers.

A new population of radio sources so-called “compact symmetric objects (CSOs)” has been recently noticed. The CSOs was first identified by Philips & Mutel (1980, 1982) and more complete sample were presented by Wilkinson et al. (1994) and Readhead et al. (1996a, b). Concerning the origin of CSOs, two scenarios were initially proposed. One is so-called “frustrated jet scenario” in which the ambient medium is so dense that jet cannot break its way through, so sources are old and confined (van Breugel, Miley & Heckman 1984). The other is “youth radio source scenario” in which CSOs are the young progenitor of FR II radio galaxies (e.g., Shklovsky 1965; Philips & Mutel 1982; Carvalho 1985; Fanti et al. 1995; Begelman 1996; Readhead et al. 1996a; O’Dea & Baum 1997). Recent observations reveal that their speeds are better understood within youth radio source scenario because of their age with $10^{3-5}$yr, which is much shorter than the age of FR II sources with $10^{6-7}$yr (e.g., Owainik, Conway & Polatidis 1999; Murgia et al. 1999; Taylor et al. 2000). This indicates the possibility of CSOs as the progenitor of FR II sources although their evolutionary tracks are poorly understood.

The hot spot, which is identified as the reverse shocked region of the decelerating jet, is one of the most important ingredients in the whole jet system. The evolution of the hot spot is tightly linked to that of cocoon because the cocoon is consist of the shocked plasma escaped from the hot spot (see Fig. 1). Observationally, the correlations between the hot spot properties (the velocity, the pressure, the size and the mass density) and projected linear size have been reported for CSOs and FR II sources (Readhead et al. 1996a; Jeyakumar & Saikia 2000; Perucho & Martí 2002 ). These observational trends would also reflect the evolutionary tracks of radio loud AGNs. Thus, in order to clarify the physical relation between CSOs and FR II sources, it is inevitable to model the dynamical evolution of hot spots in radio loud AGNs. However, little attention has been paid to this point in spite of lots of theoretical evolutionary models have been
N. Kawakatu and M. Kino

proposed based on cocoon dynamics (e.g., Falle 1991; Begelman 1996; Kaiser & Alexander 1997). Thus, the goal of this paper is to construct an appropriate dynamical model of hot spots in the radio loud AGNs.

The plan of the paper is organized as follows. In §2 we outline and model a dynamical evolution of hot spots connected with the cocoon dynamics. In §3, we compare with previous theoretical and observational works. Conclusions are given in §4.

2 DYNAMICAL EVOLUTION OF HOT SPOTS CONNECTED WITH THE COCOON EXPANSION

2.1 Outline

In this paper, we model a dynamical evolution of hot spots with the aid of cocoon dynamics (Begelman & Cioffi 1989: hereafter BC89; Kino & Kawakatu 2005: hereafter KK05). Specifically, the evolution of the hot spot velocity ($v_{HS}$), the hot spot pressure ($P_{HS}$) and the hot spot density ($\rho_{HS}$) are discussed. These quantities are described in terms of the length from the center of the galaxy to the hot spot ($l_h$).

Concerning $v_{HS}$, radio observations of powerful FR II radio galaxies show us that hot spots are always reside at the tip of the radio lobe (e.g., Myers & Spangler 1985; Readhead et al. 1996b). Thus, it is natural to impose the relation of $v_{HS} = v_h$, (1)

where $v_h$ is the advance speed of the cocoon head. The velocity $v_h$ is significantly affected by the two dimensional (2D) effect. However it can be reasonably handled by the phenomenological description as follows. Consider a pair of jets propagating in an ambient medium (see Fig. 1). At the hot spot, the flow of the shocked matter is spread out by the oblique shocks that then deflects (Lind et al. 1989), the vortex occurs via shocks (e.g., Smith et al. 1985) and/or the effect of jittering of the jet (e.g., Williams & Gull 1985; Cox et al. 1991) which behaves like the “dentist drill” (Scheuer 1982). Thus, the effective “working surface” for the advancing jet is larger than the cross section area of the hot spot $A_h$, which was pointed out by BC89. BC89 introduced the effective cross section area of the cocoon head $A_h$ as that of the effective “working surface”. Thus, we can determine the reasonable value of $v_h$ by the expanding cocoon process.

As for $P_{HS}$ and $\rho_{HS}$, we deal with them through one dimensional (1D) shock junctions. Since the hot spot is identified with the reverse shocked region of the jet, $P_{HS}$ and $\rho_{HS}$ can be obtained as a function of $v_h$ by combining with eq. (1).

2.2 Un-shocked Jet

Here we set up the mass, momentum and energy flux of the jet with three assumptions. Our main assumptions are as follows; (i) We assume that the speed of the jet is relativistic on the large scale ($\sim 100$ kpc) and the jet is consist of the cold medium. Although the jet speed on large scales is still open issue, several jets are suggested to be relativistic ones (e.g., Tavecchio et al. 2000; Celotti, Ghisellini & Chiaberge 2001; Uchiyama et al. 2005), (ii) The mass, energy and momentum of jets are conserved in time. Namely, we do not include the entrainment effect of the ambient medium. This is justified by the numerical simulations for highly relativistic jet flows (e.g., Scheck et al. 2002; Mizuta, Yamada & Takabe 2004) and (iii) We ignore the dynamical effect of magnetic fields because of the kinetic flux dominance in FR II radio galaxies (e.g., Hardcastle & Worrall 2000; Leahy & Giani 2001; Isobe et al. 2002). Then, the mass ($J_{1D}$), energy ($L_{1D}$) and momentum ($Q_{1D}$) flux are given (Blandford & Rees 1974);

$$J_{1D} = \Gamma_j A_j \rho_j c, \quad (2)$$

$$L_{1D} = \Gamma_j^2 A_j \rho_j c^2, \quad (3)$$

$$Q_{1D} = \Gamma_j^2 A_j \rho_j c^2, \quad (4)$$

where $\Gamma_j$ and $\rho_j$ are the Lorentz factor and the mass density of the jet, respectively. Note that the kinetic energy flux $L_{1D}$ denoted here satisfies the relation of $L_j = (A_h/A_j)L_{1D}$, where $L_j$ is the total kinetic power shown in KK05.

From these conditions, the following quantities are conserved for any $l_h$;

$$\Gamma_j = \text{const}, \quad (5)$$

$$\rho_j A_j c = \text{const}. \quad (6)$$

Interestingly, the Lorentz factor $\Gamma_j$ does not depend on $l_h$. In other words, the speed of jet is relativistic even on the large scale.

2.3 Shock junctions between the jet and ambient medium

We briefly review the 1D shock jump conditions which governs the deceleration of the relativistic jet by the surrounding ambient medium (Kino & Takahara 2004 for details).
We can determine $P_a$ and $\rho_a$ from X-ray observations where $P_a$ and $\rho_a$ are the pressure and the mass density of the ambient medium, respectively. The assumption of a cold jet is written as $P_j = 0$. We regard $\Gamma$ as a parameter.

Since $v_{\text{HS}}$ is estimated to be in the range 0.01c to 0.1c both for FR II sources (Liu, Pooley & Riley 1992; Scheuer 1995) and CSOs (Conway 2002 and references therein), the forward shocked (FS) region quantities are determined by the shock jump conditions in non-relativistic limit (Landau & Lifshitz 1959). By using the pressure balance along the contact discontinuity between the hot spot and ambient medium, we can obtain the expression of $P_{\text{HS}}$ as functions of two observable quantities $v_{\text{HS}}$ and $\rho_a$ such as

$$P_{\text{HS}} = \frac{4}{15} \frac{[5 - (1/M^2)]}{[1 - (1/M^2)]} \rho_a v_{\text{HS}}^2,$$

(7)

where $M = v_{\text{FS}}/\sqrt{5P_a/3\rho_a}$ and $v_{\text{FS}}$ are the Mach number and the velocity of the upstream of FS, respectively. We adopted the adiabatic index of the downstream of FS as 5/3. In the reverse shocked (RS) region, we employ the relativistic shock jump conditions in the strong shock limit (Blandford & McKee 1976). Then, the equation of state and the mass continuity in the RS region can be written as

$$\rho_{\text{HS}} = \frac{3P_{\text{HS}}}{(\Gamma - 1)c^2},$$

(8)

$$P_j = \frac{3P_{\text{HS}}}{(4\Gamma + 3)(\Gamma - 1)c^2},$$

(9)

where we set the adiabatic index in the RS region as 4/3. Thus, $\rho_{\text{HS}}$ and $P_j$ also can be given by $\rho_a$ and $v_{\text{HS}}$.

2.4 Dynamical evolution of the cocoon

To determine the velocity of the cocoon head $v_h$, with considering 2D sideways expansion, we prepare the solutions of cocoon dynamics based on KK05. In KK05, by solving the equation of motion along the jet axis, perpendicular to the axis (i.e., sideways expansion), and energy injection into the cocoon, we obtained the $v_c$, $v_h$, $P_c$, and $\Lambda_h$ in terms of $l_h$, where $v_c$ and $P_c$ are the velocity of cocoon sideways expansion and the pressure of cocoon, respectively. The declining mass density of the ambient medium is assumed to be $\rho_a(d) = \rho_{a0}(d/d_0)^{-\alpha}$, where $d$, $d_0$ and $\rho_{a0}$ are the radial distance from the center of the galaxy, the reference position and the mass density of the ambient medium at $d_0$, respectively. In order to convert $d$-dependence of the results of KK05 to $l_h$-dependence, we use the equation $l_h = \int_0^l v_h(t')dt'$ and $\Lambda_h = \int_0^l v_h(t')dt'$ where $l$ is the radius of the cocoon body. The obtained cocoon quantities in KK05 are as follows:

$$v_c = v_{c0} \left( \frac{l_h}{l_{h0}} \right)^{-\frac{0.6X-1}{X-2-0.5(\alpha-2)+3}},$$

(10)

$$P_c = P_{c0} \left( \frac{l_h}{l_{h0}} \right)^{\frac{X(-1-\alpha/2)-2}{X-2-0.5(\alpha-2)+3}},$$

(11)

$$v_h = v_{h0} \left( \frac{l_h}{l_{h0}} \right)^{-\frac{X(2-0.5\alpha)}{X-2-0.5(\alpha-2)+3}},$$

(12)

$$\Lambda_h = \Lambda_{h0} \left( \frac{l_h}{l_{h0}} \right)^{\frac{X(2-0.5)(\alpha-2)+4-3\alpha}{X-2-0.5(\alpha-2)+3}},$$

(13)

where $X$ is the power law index of the effective cross section area of the cocoon head $A_h$ and $A_l$. The same $l_h$-dependence as $A_h^{\lambda/2}$ from eqs. (6) and (10).

2.5 Dynamical evolution of hot spots

Combining with (i) the mass, momentum, and kinetic energy of the jet ([2.2]), (ii) the deceleration process of the jet by shock ([2.3]), and (iii) the cocoon expansion ([2.4]), we can finally obtain the dynamical evolution of hot spots. From eqs. (1), (5), (7), (8) and (12), the quantities $v_{\text{HS}}$, $P_{\text{HS}}$, $\rho_{\text{HS}}$, and $\rho_j$ as follows;

$$v_{\text{HS}} = v_{\text{HS0}} \left( \frac{l_h}{l_{h0}} \right)^{\frac{X(2-0.5\alpha)}{X-2-0.5(\alpha-2)+3}},$$

(15)

$$P_{\text{HS}} = P_{\text{HS0}} \left( \frac{l_h}{l_{h0}} \right)^{\frac{X(2-0.5)(\alpha-2)+4-3\alpha}{X-2-0.5(\alpha-2)+3}},$$

(16)

$$\rho_{\text{HS}} = \rho_{\text{HS0}} \left( \frac{l_h}{l_{h0}} \right)^{\frac{X(2-0.5)(\alpha-2)+4-3\alpha}{X-2-0.5(\alpha-2)+3}},$$

(17)

$$\rho_j = \rho_{j0} \left( \frac{l_h}{l_{h0}} \right)^{\frac{X(2-0.5)(\alpha-2)+4-3\alpha}{X-2-0.5(\alpha-2)+3}},$$

(18)

Note that $P_{\text{HS0}}$, $\rho_{\text{HS0}}$ and $\rho_{j0}$ can be expressed by only observable quantities $\rho_{a0}$ and $v_{\text{HS0}}$ if we assume $\Gamma$ (see eqs. (7), (8) and (9)). Thus, it is possible to know not only $l_h$-dependence but also the absolute quantities of hot spots and jets. The aspect ratio of the cocoon $R \equiv l_h/l_0$ is the intriguing quantity for studying the dynamical evolution of hot spots. The $l_h$-dependence of the aspect ratio of cocoon is then given by

$$R = R_0 \left( \frac{l_h}{l_{h0}} \right)^{\frac{X(2-0.5\alpha)+3}{X-2-0.5(\alpha-2)+3}},$$

(19)

where $R_0 = (v_{c0}/v_{\text{HS0}})[(X(2-0.5\alpha)+3)/(0.5X)]$. As a consistency check of our assumption of constant $A_h/A_l$, we can easily find that hot spot radius $r_{\text{HS}} (\propto A_l^{\lambda/2})$ shows the same $l_h$-dependence as $A_h^{\lambda/2}$ from eqs. (6) and (18). From
above results, we obtain the slope of all physical quantities as functions of two key physical quantities, namely \( \alpha \) (the slope index of the ambient matter density) and \( X \) (the growth rate of cross section of cocoon body). In the case of constant \( \mathcal{R} \), our results agree with self-similar models of cocoon expansions (e.g., Falle 1991; Begelman 1996; Kaiser & Alexander 1997). However, we stress that these self-similar models assume that \( P_{\text{HS}}/P_c \) and \( \mathcal{R} \) are both constant in \( l_h \), whilst we do not impose these assumptions and also predict the dynamical evolution of \( P_{\text{HS}} \) and \( \rho_j \).

The relation between \( P_{\text{HS}} \) and \( P_c \) is also the interesting topic. From eq. (12), the hot spot pressure is written by \( P_{\text{HS}} = 4\rho_a(l_h) v_{\text{HS}}^2/3 \) for \( M \gg 1 \), while the over-pressured cocoon requires \( P_c = \rho_a(l_c) v_c^2 \). Thus, the ratio of \( P_{\text{HS}} \) to \( P_c \) is

\[
\frac{P_{\text{HS}}}{P_c} = \frac{3}{4} \left( \frac{0.5X}{X(2 + 0.5\alpha) + 3} \right)^2 \mathcal{R}_0^2 \mathcal{R}^{-\alpha}. \tag{20}
\]

This implies that \( P_{\text{HS}}/P_c \) is controlled by \( \mathcal{R} \) and \( \alpha \). Since \( \mathcal{R} < 1 \) and \( \mathcal{R}_0 < 1 \) are satisfied by definitions, \( P_{\text{HS}}/P_c \) should less than unity for \( \alpha < 2 \). In the case of \( \mathcal{R} = \mathcal{R}_0 = \text{const} \) or \( \alpha = 2 \), it reduces to the interesting relation of

\[
P_{\text{HS}}/P_c = \frac{3}{4} \mathcal{R}_0^2.
\]

This shows that \( P_{\text{HS}}/P_c \) is determined only by \( \mathcal{R}_0^2 \). We stress that our model predict that \( P_c \) is smaller than \( P_{\text{HS}} \) as long as \( \mathcal{R}_0 < 1 \). Additionally, rewriting of the explicit form of the \( P_c \) in terms of the quantities of the jet may be also stimulating, which is given by \( P_c = \mathcal{R}_0^2 \Gamma_j^2 \rho_j c^3 \) for \( \mathcal{R}_0 = \text{const} \). From this, one can find that the larger \( \Gamma_j \) leads to the larger \( P_c \), which is actually seen in relativistic hydrodynamic simulations (see Fig. 5 in Martí et al. 1997). To comprehend the energy injection process into the cocoon via the hot spot with the duration of \( t_{\text{inj}} \), we rewrite the eq. (20) as

\[
P_{\text{HS}}(v_{\text{c}}) S_{\text{c0}} \equiv P_{\text{HS}}(v_{\text{c0}}) S_{\text{H0}} \equiv L_j(t_{\text{inj}}), \tag{21}
\]

where \( S_{\text{HS0}} \equiv 4\pi r_{\text{HS0}} \), and \( S_{\text{c0}} \equiv 2\pi r_{\text{c0}} l_{\text{h0}}, v_{\text{c0}} \equiv c/(2(0.5X)^{\frac{\alpha}{2}}) \approx (0.5 - 0.7)c \). This describes the continuous energy injection of AGN jets (i.e., \( t_{\text{inj}} = t_{\text{age}} \)). On the contrary, Blandford and Rees (1974) used the relation of \( P_{\text{c0}}(v_{\text{c0}} S_{\text{c0}})^{\frac{\alpha}{2}} \equiv P_{\text{HS}}(v_{\text{c0}} S_{\text{HS0}})^{5/3} \mathcal{R} \), where \( \mathcal{R} \) is the adiabatic index in each region. We claim that this relation is appropriate for the instantaneous (i.e., \( t_{\text{inj}} \ll t_{\text{age}} \)) injection seen in supernovae (SNe) or gamma-ray bursts (GRBs).

### 3 COMPARISON WITH PREVIOUS WORKS

#### 3.1 Comparison with numerical simulations

Scheck et al. (2002; hereafter S02) examined the long term evolution of the powerful jet propagating into a uniform ambient medium (\( \alpha = 0 \)) with “2D” relativistic hydrodynamic simulations. S02 showed that the evolution of the jet proceeds in two different phases appear (they are shown in Table 4 and Fig. 6 in S02). “1D” phase: In the initial phase (\( t < 1.2 \times 10^7 \text{yr} \)), the jet shows ballistic propagation with \( A_h = \text{const} \) and \( v_{\text{HS}} = \text{const} \). “2D” phase: This phase starts when the first large vortices are produced near the tip of the jet. Then, the cross section area of the cocoon head begins to increase. The hot spot then starts decelerating, but the jet speed remains the same relativistic one during whole simulations. Below we compare of the present work with the hydrodynamic simulation of S02 in Table 1.

In the “1D” phase, the results of S02 can be well described by our model with \( \beta = 0 \) and \( \alpha = 0 \). Note that this “1D” phase corresponds to the evolutionary model with constant \( A_h \) (BC98). For \( v_{\text{HS}} \), the power law index is slightly (\( \sim 10\% \)) different from our model (also BC89) and the results of S02. In this case, \( P_c \propto l_h^{-1} \) and \( P_{\text{HS}} = \text{const} \) are predicted by this work and BC98, which coincides with the numerical results of S02 (see Fig. 6(c) for \( P_c \) and \( P_{\text{HS}} \) in S02).

In addition, our model can reproduce the constant \( \rho_j \) (see Fig. 5(a) in S02). For comparisons, let us briefly comment on the self-similar model of expanding cocoons in which the growth of the cocoon head is included (e.g., Begelman 1996; hereafter B96). As already pointed out (e.g., Carvalho & O’Dea 2002), the self similar model of B96 cannot represent the behavior of the “1D” phase. The behavior of \( P_c/P_{\text{HS}} \) is also the intriguing issue. The decrease of \( P_c/P_{\text{HS}} \) with time is reported in Fig. 6 of S02. Using our model, this behavior is clearly explained by the decrease of the cocoon aspect ratio (see eq. (20)).

The “2D” phase of S02 is well described by our model with \( \beta = 1.1 \) and \( \alpha = 0 \). We adopt \( \beta = 1.1 \) to reproduce the evolution of \( P_c \) in Fig. 6(c) of S02 because the other quantities shows much larger fluctuations in Fig. 6 of S02. The present model predicts the evolution of the hot spot pressure and mass density of the jet as \( P_{\text{HS}} \propto l_h^{-1.1} \), \( v_{\text{HS}} \propto l_h^{0.56} \) and \( \rho_j \propto l_h^{-1.1} \). These coincides with the average value of \( P_{\text{HS}}, v_{\text{HS}}, \) and \( \rho_j \) (see Fig. 5(a) and Fig 6 in S02). In the “2D” phase, the cross section area of cocoon head grows as \( A_h \propto l_h^{1.1} \) unlike the “1D” phase (\( A_h = \text{const} \)). Thus, the velocity of hot spot decreases with \( l_h \). Actually, the growth of the cross section area of the cocoon head can be seen in their simulations (Fig. 3 in S02). In this phase, B96 also explains these results of S02. Moreover, the cocoon pressure is proportional to \( P_{\text{HS}} \) in this phase of S02. From eq. (20), it can be understood with a constant \( \mathcal{R} \). From above detailed comparison with “2D” relativistic hydrodynamic simulations, we found that the model represented in this paper can describe the flow and cocoon behaviors seen in the “1D” and “2D” phases very well. It should be stressed that our analytic model is

#### Table 1. Comparison with 2D hydrodynamic simulations and self-similar models

|          | \( P_{\text{HS}} \) | \( A_h \) | \( P_c \) | \( P_{\text{HS}} \) | \( \rho_j \) | \( \mathcal{R} \) |
|----------|-------------------|----------|----------|-------------------|----------|----------|
| “1D” Phase\(^a\) | S02 | \( l_h^{-0.11} \) | const | \( l_h^{-0.95} \) | const | const | \( l_h^{-0.45} \) |
|          | B09 | const | const | \( l_h^{-1} \) | const | — | \( l_h^{-0.5} \) |
| This work | const | const | \( l_h^{-1} \) | const | const | \( l_h^{-0.5} \) |
| “2D” Phase\(^b\) | S02 | \( l_h^{-0.55} \) | \( l_h^{0.9} \) | \( l_h^{-1.30} \) | \( l_h^{-1.1} \) | \( l_h^{-1.0} \) | \( l_h^{-0.09} \) |
|          | B96 | \( l_h^{-2/3} \) | \( l_h^{4/3} \) | \( l_h^{-4/3} \) | \( l_h^{-4/3} \) | — | const |
| This work | \( l_h^{-0.56} \) | \( l_h^{1} \) | \( l_h^{-1.30} \) | \( l_h^{-1.1} \) | \( l_h^{-1.1} \) | \( l_h^{-0.08} \) |

**Note:** \(^a\) The “1D” phase corresponds to our model with \( \beta = 0 \) and \( \alpha = 0 \). \(^b\) The “2D” phase (b) corresponds to our model with \( \beta = 1.1 \) and \( \alpha = 0 \).
more useful than numerical simulations when investigating a longer-term evolution of jets. The length of jets performed by numerical simulations of jets achieves at most the length order of 100 times of a jet beam size, while the spacial sizes of actual jets in AGNs are spread in six order of magnitude (i.e., from parsec to mega-parsec scale).

### 3.2 Comparison with observations

Based on a number of recent reports of indicating that the constant speed of hot spot advance (0.01 < vHS/c < 0.1) (e.g., Readhead et al. 1996b; Carilli et al. 1991; Conway 2002), we here examine the case of vHS = const. Observationally, PHS and ρHS are inferred by using the minimum energy assumption and the neglecting the effect of thermal components (Readhead et al. 1996a; Jeyakumar & Saikia 2000; Perucho & Martí 2002). From eq. (15), the relation of 2 − X(2 − 0.5α) = 0 is required for the constant hot spot velocity. By eliminating the parameter X, our model reduce to the following forms: κc ∝ h05−(α−2)/(α−4), Pc ∝ h04/(α−4), PHS ∝ h0−α, ρHS ∝ h0−α, RHS ∝ h0−α/2, ρl ∝ h0−α, and R ∝ h0−(α−2)/(α−4). Here we used mean density profiles obtained by a large number of sample clusters of galaxies, which is ρα(d) ∝ d−(1.5−2) (e.g., Mulchaey & Zabludoff 1998).

We show the comparison with observational data for CSOs and FR II sources in Table 2. This indicates that our model well reproduce observational trends within the error bars. These agreements are likely to support "youth radio source scenario" basically. At the same time, the large dispersion of the observational data could tell us other possibilities of evolutionary tracks of radio loud AGNs usually discussed. To explore it, it must be valuable to inquire into possibilities of evolutionary tracks of radio loud AGNs usually discussed. To explore it, it must be valuable to inquire into possibilities of evolutionary tracks of radio loud AGNs usually discussed. To explore it, it must be valuable to inquire into possibilities of evolutionary tracks of radio loud AGNs usually discussed.

### Table 2. Comparisons with observations

|         | vHS     | PHS     | rHS     | ρHS     |
|---------|---------|---------|---------|---------|
| Observationsa | const   | 1.3−1.7 | 1.7−1.3 | 1.9−2.9 |
| This workb   | const   | 1.5−2.0 | 0.75−1  | 1.5−2.0 |

NOTE.– a The results are adopted from Readhead et al. (1996a), Jeyakumar & Saikia (2000) and Perucho & Martí (2002). bWe set the slope index of the ambient density α = 1.5−2.

### 4 CONCLUSIONS

In the present work, we model a dynamical evolution of hot spots in radio loud AGNs. In this model, the unshocked flow satisfies the conservations of the mass, momentum, and kinetic energy. We take account of the deceleration process of the jet by shocks, and the cocoon expansion which is identified as the by-product of the exhausted flow. The model describes the evolution of physical quantities (vHS, PHS, and ρHS) in the hot spot in terms of t0. Below we summarize the main results based on this model.

(i) We find that the ratio of Pc/PHS is controlled by the aspect ratio of the cocoon R and slope index of the ambient medium α. If R remains to be constant during the jet propagation, the value Pc/PHS is proportional to R2 with the coefficient of order unity. This naturally explain the basic concept of the elongated cocoon with larger PHS than Pc. Concerning Pc, it is proportional to the bulk kinetic power of the jet in given ρ0. This is originated from our treatment of adiabatic injection of the dissipation energy of the jet into the cocoon. In addition, we suggest a new method to evaluate the velocity of hot spots from the aspect ratio of cocoon and the opening angle of hot spots.

(ii) Our analytic model can well explain the results of 2D co-evolution of jets and cocoons obtained by relativistic hydrodynamic simulations. This clearly guarantees the reliability of our model during the over-pressure cocoon phase. Since the dynamical length of jets obtained by numerical simulations is about a few 100 times of the jet beam size, our analytic model must be an useful tool to explore a longer-term dynamical evolution of jets than this scale.

(iii) Our model prediction reasonably coincides with the recent observational trends of hot spots seen in CSO and FR II sources. Furthermore, we predict R ∝ h05−(0.2−0) and A0 ∝ h01.5−2 although little is done about systematic studies on these quantities.

Lastly we should keep in mind that the present model do not take account of the details of (i) the absolute value of the mass density of the ambient medium, and (ii) radiative cooling effect which may be important for younger radio galaxies. In order to investigate whole story of evolutionary track of the radio loud AGNs, the study of above two points will be inevitably required. We plan investigate both of them in the near future.

### ACKNOWLEDGMENTS

We thank A. Celotti, H. Ito and F. Takahara for useful discussions and comments. We acknowledge the Italian MIUR and INAF financial support. We also thank an anonymous referee for helpful comments to improve this paper.

### REFERENCES

Begelman M. C., 1996, in Cygnus A—Study of a Radio Galaxy, ed. C. L.Carilli & D. E. Harris (Cambridge: Cambridge Univ. Press), 209
Begelman M. C., Cioffi, D. F., 1989, ApJ, 345, L21(BCS89)
Begelman M. C., Blandford R. D., Rees M. J., 1984, RvMP, 56, 255
Blandford R. D., McKee C. F., 1976, Physics of Fluids, 19, 1130
Blandford R. D., Rees M. J., 1974, MNRAS, 169, 395
Bridle A. H., Perley R. A., 1984, ARA&A, 22, 319
Carvalho J. C., O’Dea C. P., 2002a, ApJS, 141, 337
Carvalho J. C., O’Dea C. P., 2002b, ApJS, 141, 371
Carvalho J. C., 1985, MNRAS, 215, 463
Carilli C. L., et al., 1991, ApJ, 383, 554
Celotti A., Ghisellini G., Chiaberge, M., 2001, MNRAS, 321, L1
Clarke D. A., Norman M. L., Burns J. O., 1986, ApJ, 311, L63
Clarke D. A., Harris D. E., Carilli C. L., 1997, MNRAS, 284, 981
Conway J. E., 2002, NewAR, 46, 263
Cox C. I., Gull S. F., Scheuer P. A. G., 1991, MNRAS, 252, 558
De Young D. S., 1997, ApJ, 490, L55
Falle S. A. E. G., 1991, MNRAS, 250, 581
Gilbert G. M., Riley J. M., Hardcastle M. J., Pooley G. G., Alexander P., 2004, MNRAS, 351, 845
Hardcastle M. J., Worrall D. M., 2000, MNRAS, 319, 562
Isobe N., et al., 2002, ApJ, 580, L111
Jeyakumar S., Saikia D. J., 2000, MNRAS, 311, 397
Kaiser C. R., Alexander P., 1997, MNRAS, 286, 215
Kino M., Takahara F., 2004, MNRAS, 349, 336
Kino M., Kawakatu N., 2005, MNRAS, 364, 659 (KK05)
Komissarov S. S., Falle S. A. E. G., 1998, MNRAS, 297, 1087
Landau L. D., Lifshitz E. M., 1959, Fluid Mechanics, Pergamon Press, Oxford
Leahy J. P., Gizani N. A. B., 2001, ApJ, 555, 709
Lind K. R., et al., 1989, ApJ, 344, 89
Liu R., Pooley G., Riley, J. M., 1992, MNRAS, 257, 545
Martí M. A., et al., 1997, ApJ, 479, 151
Mizuta A., Yamada S., Takabe H., 2004, ApJ, 606, 804
Mulchaey J. S., Zabludoff A. I., 1998, ApJ, 496, 73
Murgia M., Fanti C., Fanti R., Gregorini L., Klein U., Mack K.-H., Vigotti M., 1999, A&A, 345, 769
Myers S. T., Spangler S. R., 1985, ApJ, 291, 52
Norman M. L., Smarr L., Winkler K-H. A., Smith M. D., 1982, A&A, 113, 285
O’Dea C. P., 1998, PASP, 110, 493
O’Dea C. P., Baum S. A., 1997, AJ, 113, 148
Owsianik I., Conway J. E., Polatidis A.G., 1999, NewAR, 43, 669
Perucho M., Martí J. M., 2002, ApJ, 568, 639
Phillips R. B., Mutel R. L., 1980, ApJ, 236, 89
—, 1982, A&A, 106, 21
Readhead A. C. S., Cohen M. H., Blandford R. D., 1978, Nature, 272, 131
Readhead A. C. S., et al., 1996a, ApJ, 460, 634
Readhead A. C. S., et al., 1996b, ApJ, 460, 612
Ryle M. S., Longair M. S., 1967, MNRAS, 136, 123
Scheck L., et al., 2002, MNRAS, 331, 615, 2002 (S02)
Scheuer P. A. G., 1995, MNRAS, 277, 331
Scheuer P. A. G., 1982, in Extragalactic Radio Sources, ed. D.S. Heeschen and C. M. Wade, IAU Symp. 97, Reidel Publishing Co., 163
Shklovsky I. S. 1965, Nature, 206, 176
Smith, M. D., et al. 1985, MNRAS, 214, 67
Tavecchio F., et al. 2000, ApJ, 544, L23
Taylor G. B., Marr J. M., Pearson T. J., Readhead A. C. S., 2000, ApJ, 541, 112
Tinti S., de Zotti G., 2006, A&A, 445, 889
Turland B. D., 1975, MNRAS, 172, 181
Uchiyama Y., et al., 2005, ApJ, 63, L113
Wilkinson P. N., et al., 1994, ApJ, 432, L87
Williams A. G., Gull F. G., 1985, Nature, 313, 34
Wilson M. J., Scheuer P. A. G., 1983, MNRAS, 205, 449
Wilson A. S., Young A. J., & Shopbell P. L., 2000, ApJ, 544, L27
van Breugel W. J. M., Miley, G. K., Heckman, T. A. 1984, AJ, 89, 5