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Dynamical Evolution of Hot Spots in Radio-loud AGNs

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Abstract. We analytically describe the dynamical evolution of hot spots in radio-loud active galactic nuclei (AGNs). 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 in compact symmetric objects (CSOs) and FR II radio galaxies.

1. Introduction

Relativistic jets in powerful AGNs (e.g., FR II radio galaxies) are slowed down via strong terminal shocks which are identified as hot spots. Then, shocked plasma expands sideways and envelope the whole jet system, in a so-called cocoon. Recently, a new population of radio sources so-called "compact symmetric objects" (CSOs) has been noticed. Concerning the origin of CSOs, two scenarios were 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 et al. 1984). The other is "youth radio source" scenario in which CSOs are the young progenitor of FR II radio galaxies (e.g., Philips & Mutel 1980). Recent observations support the 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., Owaiank et al. 1999). This indicates the possibility of CSOs as the progenitor of FR II sources although their evolutionary tracks are poorly understood. In order to connect CSOs and FR IIs physically, we construct an appropriate dynamical model of hot spots in the radio-loud AGNs (see Kawakatu & Kino 2006, hereafter KK06).

2. Dynamical Evolution of Hot Spots Connected with the Cocoon Expansion

We model the 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 ($v_{\rm HS}$), the hot spot pressure ($P_{\rm HS}$) and the hot spot density ($\rho_{\rm HS}$) 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 always reside at the tip of the radio lobe (e.g., Myers & Spangler 1985). Thus, it is natural to impose the relation of $v_{HS} = v_h$, where v_h is the advance speed of the cocoon head. The velocity v_h is significantly affected by the two-dimensional (2D) effect since at the hot spot the flow of the shocked matter is spread out by some complicated physical processes (e.g., the oblique shocks that then deflect, the vortex occurs via shocks and/or the effect of jittering of the jet). Thus, the effective cross section area of the cocoon head A_h is larger than the cross section area of the hot spot A_j, which was pointed out by BC89. Here we describe the 2D effect by the expanding cocoon process (KK05). Then we determine the reasonable value of v_h. As for P_{HS} and ρ_{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}, ρ_{HS} and ρ_j can be obtained as a function of v_h by combining with $v_{HS} = v_h$. Therefore, the quantities of hot spots and jets can be described in terms of the length from the center of the galaxy to the hot spot (l_h).

In order to test the reliability of our analytical model during over-pressure cocoon phase, we compare with the 2D relativistic hydrodynamic simulations in a uniform ambient medium (Scheck et al. 2002, hereafter S02) in Table 1 (KK06). As seen in Table 1, it is found that our analytic model can well explain the results of multi-dimensional co-evolution of jets and cocoons. Moreover, our model prediction reasonably coincides with the recent observational trends of the velocity, pressure and size of hot spots seen in CSO and FR II sources (KK06).

Table 1. Comparison with 2D hydrodynamic simulations

—	v_{HS}	A_h	P_c	P_{HS}	ρ_j	$\mathcal{R}$
"1D" Phase						
S02	$l_h^{-0.11}$	const	$l_h^{-0.95}$	const	const	$l_h^{-0.45}$
This work	const	const	l_h^{-1}	const	const	$l_h^{-0.5}$
"2D" Phase						
S02	$l_h^{-0.55}$	$l_h^{0.90}$	$l_h^{-1.30}$	$l_h^{-1.1}$	$l_h^{-1.0}$	$l_h^{-0.09}$
This work	$l_h^{-0.56}$	$l_h^{1.1}$	$l_h^{-1.30}$	$l_h^{-1.1}$	$l_h^{-1.1}$	$l_h^{-0.08}$

NOTE.— ρ_j, P_c and $\mathcal{R} \equiv l_c/l_h$ are the mass density of the jet, the cocoon pressure and the aspect ratio of cocoon, respectively.

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