AGN Jet Power, Formation of X-ray Cavities, and FR I/II Dichotomy in Galaxy Clusters

Yutaka Fujita, Nozomu Kawakatu, and Isaac Shlosman

1Theoretical Astrophysics, Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama-cho, Toyonaka, Osaka 560-0043
2Faculty of Natural Sciences, National Institute of Technology, Kure College, 2-2-11 Agaminami, Kure, Hiroshima, 737-8506
3Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA

*E-mail: fujita@vega.ess.sci.osaka-u.ac.jp

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Abstract

We investigate the ability of jets in active galactic nuclei (AGNs) to break out of the ambient gas with sufficiently large advance velocities. Using observationally estimated jet power, we analyze 28 bright elliptical galaxies in nearby galaxy clusters. Because the gas density profiles in the innermost regions of galaxies have not been resolved so far, we consider two extreme cases for temperature and density profiles. We also follow two types of evolution for the jet cocoons: being driven by the pressure inside the cocoon (Fanaroff-Riley [FR] I type), and being driven by the jet momentum (FR II type). Our main result is that regardless of the assumed form of density profiles, jets with observed powers of $\lesssim 10^{44}$ ergs$^{-1}$ are not powerful enough to evolve as FR II sources. Instead, they evolve as FR I sources and appear to be decelerated below the buoyant velocities of the cocoons when jets were propagating through the central dense regions of the host galaxies. This explains the reason why FR I sources are more frequent than FR II sources in clusters. Furthermore, we predict the sizes of X-ray cavities from the observed jet powers and compare them with the observed ones — they are consistent within a factor of two if the FR I type evolution is realized. Finally, we find that the jets with a power $\gtrsim 10^{44}$ ergs$^{-1}$ are less affected by the ambient medium, and some of them, but not all, could serve as precursors of the FR II sources.

Key words: galaxies: active — galaxies: jets — galaxies: elliptical and lenticular, cD — X-rays: galaxies — X-rays: galaxies: clusters

1 Introduction

Active galactic nuclei (AGNs) in the centers of elliptical galaxies often produce relativistic jets. These jets propagate through the hot interstellar medium (ISM) of host galaxies, and are enveloped by cocoons (e.g., Begelman & Cioffi 1989). Recent X-ray observations have revealed that brightest cluster galaxies (BCGs) are often associated with X-ray cavities that are thought to be relics of these cocoons. Their sizes range from a few kpc to a few hundred kpc (e.g., Birzan et al. 2004; Nulsen et al. 2005; Nulsen et al. 2005; McNamara et al. 2005), and many of them are located at $r \sim 20$ kpc from the galactic centers (Birzan et al. 2004).

The time-averaged jet power can be estimated by measuring the volume of cavities and the timescale of their buoyant rise (e.g., Birzan et al. 2004; Rafferty et al. 2006; Russell et al. 2013). In order to create large cocoons or cavities, the jets have
to break out of the central dense region of the host galaxies. Jet evolution at this breakout phase can affect their subsequent evolution, because they are expected to be decelerated by interaction with the ambient medium (e.g., De Young 1997; O'Dea 1998; Carvalho & O'Dea 2002; Peruch & Martí 2003), and their advance speed can determine whether they evolve into Fanaroff-Riley I (FR I) or FR II types (e.g. Kawakatu et al. 2008).

Previous studies of the relation between AGN jet power and X-ray cavities have not addressed the issue of whether jets are actually capable of forming the observed cavities (e.g., Allen et al. 2006; Rafferty et al. 2006; Balmaverde et al. 2008; McNamara et al. 2011, see also Kawakatu et al. 2008). In this work we investigate whether jets in BCGs have enough power during the breakout phase to form the observed large X-ray cavities using available data on these cavities and the ambient gas. We use the cosmological parameters $\Omega_{\text{m}} = 0.3$, $\Omega_{\Lambda} = 0.7$, and $h = 0.7$. Unless otherwise noted, errors are the 1 $\sigma$ values.

2 Models

2.1 Breakout Jets

We assume that a pair of relativistic jets generated around a supermassive black hole (SMBH) in the galactic center advance into the ambient medium, forming a cocoon that envelopes them (e.g., Begelman & Cioffi 1989). While most of the galaxies in our sample are known as FR I sources, a few are FR II and FR II-like sources (e.g. Cygnus A, see table 1). Moreover, the FR IIs might have evolved as FR IIIs when they were young. Thus, we consider both FR I and II type evolution for the coconos. Figure 1 shows schematic evolution of a cocoon or cavity. Note that while the cocoon evolution is controlled by the jets (phase A $\rightarrow$ B), the cavity evolution is controlled by buoyancy (phase B $\rightarrow$ D). Below, we discuss evolution during phases A and B. Effects of the evolution in phases B and D are addressed in section 4.2 and appendix 2. We do not consider the effects of recurrent jet activities.\footnote{Hydra A in our sample has a cavity-in-cavity structure (Wise et al. 2007). However, the outermost cavity dominates the inner cavities in formation energy and contributes mostly to the average jet power. Thus, we focus on the outermost cavity.}

2.1.1 FR I type evolution

Evolution of young cocoons is driven by the jets inside them (phase A in figure 1). If the cocoon expands due to high pressure inside it, we call the evolution FR I type, which is governed by an energy conservation law:

$$P_j = \frac{1}{\gamma - 1} \frac{dp(r_h)}{dr_h} v_1(r_h) \frac{4\pi r_h^3}{3} + \frac{\gamma_c}{\gamma - 1} 4\pi r_h^2 v_1(r_h) p(r_h),$$

where $r_h$ is the cocoon radius or the distance to the jet head from the galactic center, $\gamma_c(=4/3)$ is the adiabatic index of the relativistic gas in the cocoon, $v_1$ is the advance velocity of the jet or the expansion velocity of the cocoon, $p$ is the pressure of the hot gas outside the cocoon, and $P_j$ is the power of the twin jets. We assume that $P_j$ is constant with time. The first term on the right hand side of equation (1), denoted as $\xi(r)$, is generally much smaller than the second term, because the pressure gradient is modest in the central region of our sample galaxies. Previous studies often ignored it (e.g., Churazov et al. 2000), but it is kept here because we quantitatively consider the pressure profile of the ambient medium.

Jets must have an advance velocity that is larger than the buoyant velocity of the cocoon, in order to create a large cavity whose size is comparable to or larger than that of the host galaxy. This is because when the buoyant velocity is larger, the cocoon detaches from the jet, before it grows substantially. The buoyant velocity is comparable to or a factor of a few smaller than the sound velocity of the ambient hot gas (e.g., Birzan et al. 2004). Thus, the condition for the formation of a large cavity is

$$P_j > \xi(r) + \frac{\gamma_c}{\gamma - 1} 4\pi r^2 f_1 c_s(r) p(r),$$

where $r$ is the distance from the galactic center which must be sufficiently large. The sound speed in the ambient gas, $c_s = \sqrt{\gamma k_B T/\mu m_p}$, is a function of gas temperature $T$, where $\gamma = 5/3$ is the adiabatic index of the gas, $\mu = 0.6$ is the mean molecular weight, and $m_p$ is the proton mass. The buoyant velocity is given by $f_1 c_s$, where $f_1 \leq 1$ — the reduction factor can be constrained from observations (section 3). When the left hand side of equation (2) equals the right hand side, the jets no longer drive the cocoon expansion — the cocoon starts to rise in the hot gas by buoyancy and forms a cavity (phases B $\rightarrow$ C $\rightarrow$ D in figure 1). We assume that AGN activity creates only one cavity. If it creates two cavities (phases B $\rightarrow$ C $\rightarrow$ D$'$ in figure 1), the size of the cavities decreases only by a factor of $2^{1/3} \approx 1.26$ ($L$ and $L'$ in figure 1), which does not affect the following discussion.

2.1.2 FR II type evolution

If a cocoon expansion is driven by the jet momentum, in phase A (figure 1), we call the evolution the FR II type. The momentum flux of the jet is balanced with the ram pressure of the ambient gas over the cross-sectional area at the head of the cocoon, $(A_h)$:

$$P_j/(2c) = \rho(r_h) c_s^2(r_h) A_h(r_h),$$

where $\rho$ is the density of the ambient medium, $v_h$ is the advance velocity of the cocoon head or the velocity of the hot spot at the end of the jet, and $r_h$ is the distance from the galactic center or the SMBH to the hot spot. Note that the velocity of the hot spot $(v_h \ll c)$ decreases gradually with time, while the velocity of the
jet material is $c$. Assuming a constant jet power, the condition for the formation of a large cavity is
\[ P_j / (2c) > \rho(r) f_1 c_0(r)^2 A_h(r) . \]  
(4)

When the left and right hand sides become nearly equal, the evolution is controlled by the buoyancy, as is the case of the FR I type (sequence B→C→D or sequence B→C′→D′ in figure 1). It is difficult to estimate the area of the cocoon head, $A_h$, in the condition (4). However, it can be related to the size of the hot spot, $r_{HS}$, and we use the values obtained by Kawakatu et al. (2008). They compiled observational data for the sizes of the hot spots in 117 radio sources, and found that it is simply represented by a broken power-law of
\[ r_{HS}(r_h) \approx 0.3 (r_h / 1 \text{ kpc})^a \text{kpc} , \]  
(5)

where $a = 1.34 \pm 0.24$ for $r_h < 1 \text{ kpc}$ and $a = 0.44 \pm 0.08$ for $r_h > 1 \text{ kpc}$. Following Kawakatu et al. (2009), we assume that
\[ A_h(r_h) = f_2 \pi r_{HS}^2 (r_h) . \]  
(6)

Although the value of factor $f_2$ can be estimated to lie in the range of $10 < f_2 < 100$ (e.g., Kawakatu et al. 2008; Kawakatu et al. 2009), we fix it conservatively at the lower limit, $f_2 = 10$, allowing the jet to break out with less power. Equation (5) is mainly based on the observations of compact symmetric objects (CSOs) and medium-size symmetric objects (MSOs) for $r_h \lesssim 10 \text{ kpc}$. Most of our sample galaxies are FR Is and we study their jet evolution at $r_h \lesssim 10 \text{ kpc}$. Thus, we implicitly assume that the CSOs and MSOs are the precursors of FR Is as well as of FR IIs (e.g., O’Dea 1998). Note that a jet is not likely to extend substantially beyond the central region of the host galaxy in its lifetime, $\lesssim 10^8 \text{ yr}$ (e.g., Bird et al. 2008), if it is heavily decelerated by the ambient medium as we show below.

### 2.2 Density and Temperature Profiles of Ambient Medium

As a next step, we construct a model for the density and temperature profiles of the hot galactic gas under conditions (2) and (4). We assume that the gas distribution is spherically-symmetric for the sake of simplicity. Even with the superb angular resolution of Chandra X-ray Observatory, it is difficult to resolve the central region of a galaxy on a scale of the Bondi radius $r_B$. Thus, we are required to extrapolate the density and temperature inward from the innermost measurement radius, $r_{\text{in}}$, to the Bondi radius. Previously, the extrapolation was often made by assuming a power-law density profile and a constant temperature (Allen et al. 2006; Balmaverde et al. 2008). However, it is not certain whether such an assumption is justified. Hence, we consider two models for the profiles that are physically motivated, and represent the two extremes that encompass the real density profiles — these are used as test cases.

#### 2.2.1 Low-temperature model

In this model, the hot gas is assumed to be in pressure equilibrium:
\[ \frac{dp}{dr} = \rho g , \]  
(7)

where $g(r)$ is the gravitational acceleration including three components, i.e., $g = g_* + g_{\text{gal}} + g_{\text{cl}}$, where $g_*$ is the SMBH contribution, $g_{\text{gal}}$ is the galaxy contribution, and $g_{\text{cl}}$ is the cluster contribution. The gas temperature around the galaxy center is comparable to the virial temperature of the host galaxy. For given boundary conditions that are consistent with observations, equation (7) can be integrated and the pressure profile $p(r)$ and the density profile $\rho(r)$ can be obtained. Using these profiles, the Bondi accretion rate $\dot{M}_B$ can be estimated. The details are deferred to appendix 1.

#### 2.2.2 Isentropic model

The low-temperature model gives fairly high densities at the center of the galaxies (see figure 2), which results in a short cooling time of the gas, $t_{\text{cool}}$. Recent numerical simulations have shown that thermal instabilities may develop if the condition $t_{\text{cool}} / t_{\text{ff}} \lesssim 10$ is satisfied, where $t_{\text{ff}} = (2r/g)^{1/2}$ is the free-fall time (e.g., Gaspari et al. 2012; McCourt et al. 2012; Sharma et al. 2015).
et al. 2012; Meece et al. 2015). Under these conditions, a substantial fraction of the hot gas may turn into cold gas, and the density of the remaining hot gas, which occupies most of the volume, can decrease significantly. The hot gas creates an entropy core at the center of the galaxy (e.g. Gaspari et al. 2013). In fact, Fujita et al. (2016) have shown that this is plausibly the situation in the center of NGC 1275 in the Perseus cluster — namely, most of the volume in the central region (less than 10 pc) is occupied by tenuous gas (less than 1 cm$^{-3}$; see also figure 3).

However, the evolution of the cold component, which can form as a result of a thermal instability, is expected to differ from that of the hot one. Its accretion rate can be much higher than the Bondi accretion rate (see section 5), but analyzing its properties is beyond the scope of this paper.

Thus, we consider a model in which the density and temperature profiles are the same as those in the low-temperature model for $r > r_s$, where $r_s$ is the radius outside which $t_{cool}/t_B > 10$. For $r < r_s$, the entropy of the remaining hot gas is constant, and thus the relation between the pressure and the density is given by $p \propto \rho^{5/3}$. Moreover, we assume that the hot gas is in pressure equilibrium (equation 7). The cooling time is given by

$$t_{cool} = \frac{1.5 nk_B T}{n_i \Lambda(T, Z)},$$

where $n_i$ is the ion density. The cooling function $\Lambda$ depends on the temperature $T$ and metal abundance $Z$:

$$\Lambda(T, Z) = 2.41 \times 10^{-27} \left[ 0.8 + 0.1 \left( \frac{Z}{Z_\odot} \right) \left( \frac{T}{K} \right)^{0.5} + 1.39 \times 10^{-16} \left[ 0.02 + 0.1 \left( \frac{Z}{Z_\odot} \right)^{0.8} \right] \right] \times \left( \frac{T}{K} \right)^{-1.0} \text{erg cm}^3.$$  

This function approximates the one derived by Sutherland & Dopita (1993) for $T \lesssim 10^5$ K and $Z \lesssim 1 Z_\odot$ (Fujita & Ohira 2013). We fix the abundance at $Z = 0.5 Z_\odot$. In this isentropic model, we do not discuss the Bondi accretion of the hot gas, because the accretion of the cold gas is expected to dominate. In the following, we consider the properties of this model between $r = r_B$ and $r_{in}$, where $r_B$ is the Bondi radius for the low-temperature model. The choice of the inner boundary does not affect the results.

The actual density profiles highly plausibly lie between those predicted by the low-temperature model and those predicted by the isentropic model, because thermal instabilities are ignored in the former and the constant entropy profile is an extreme assumption in the latter. In other words, from the physical point of view, it is unlikely that the actual profiles lie outside the two extreme profiles considered here.

### 3 Data

Accounting for data uniformity and consistency, we study 28 bright elliptical galaxies in clusters, for which the properties of the central gas, the excavated cavity, etc., have been studied by Rafferty et al. (2006; see their table 6). They are BCGs except for M84. We show the parameters for the gravitational potentials in table 1 (see also appendix 1). The masses of the SMBHs were derived by McNamara et al. (2011). They have been estimated using $R$-band absolute magnitudes ($M_R$) obtained by Rafferty et al. (2006). Since McNamara et al. (2011) did not provide the error bars in $M_*$, we take them as 0.5 dex, based on the dispersion around the observed $M_R$–$M_*$ relations (e.g. McClure & Dunlop 2002; see also McConnell & Ma 2013 for massive galaxies). Using the $R$-band absolute magnitudes, the galaxy masses, $M_{gal}$, were estimated by Rafferty et al. (2006) and are consistent with $M_*$. The effective radii of the galaxies, $R_e$, have been derived from the 2MASS All-Sky Extended Source Catalogue (Skrutskie et al. 2006)$^2$. We assume the average of $R_e$ in the $J$, $H$ and $K$-bands, and take their scatter as the error. The galaxy velocity dispersion, $\sigma$, has been obtained from the HyperLeda database (Makarov et al. 2014)$^3$. However, no data have been found for 12 galaxies. For those galaxies, we take the error-weighted average of the remaining 16 galaxies ($290 \text{ km s}^{-1}$) as $\sigma$, and the scatter of these galaxies as the error of $\sigma (36 \text{ km s}^{-1})$.

In addition, the parameters for the clusters are shown in table 1 (see also appendix 1). Most of them are based on recent X-ray observations. If there are no appropriate X-ray data, we adopt the data obtained through lensing observations or kinematics of the member galaxies. We do not consider the contribution of the cluster component to the total gravitational acceleration $g$ for M84, HCG 62, and 3C 388, because M84 is not a BCG and there are no appropriate data for the other two. For Hercules A and Cygnus A, we use the cluster temperatures and the core radii derived by Gizani & Leahy (2004) and Smith et al. (2002), respectively. Using the cluster mass–temperature relation derived by Sun et al. (2009), we convert the temperatures into the cluster masses, $M_{vir}$. The core radii, $r_c$, can be converted into the characteristic radii, $r_s = r_{vir}/c_{vir}$, by using the relation $r_s = r_c/0.22$ (Makino et al. 1998).

The boundary conditions $r_{in}$, $n_{e,in}$ (= $n_e(r_{in})$), and $T_{in}$ are shown in table 2, and are the same as those in table 6 of Rafferty et al. (2006). In their table, $r_{in}$, $n_{e,in}$, and $T_{in}$ are represented by $\alpha$, $n_e$, and $kT$, respectively. Although Rafferty et al. (2006) gave the average densities and temperatures for $r < r_{in}$ excluding the AGN, we expect that most of the emission comes from $r \sim r_{in}$, because the density profiles near the galaxy centers are not very steep, i.e., $\alpha < 1$ for $\rho \propto r^{-\alpha}$, as is shown later (figures 2 and 3). Note that the density and temperature used are

$^2$ http://insa.ipac.caltech.edu/frontpage

$^3$ http://leda.univ-lyon1.fr/
Fig. 2. Most probable density and temperature profiles based on the low-temperature model. The right and left ends of each curve correspond to $r_{\text{in}}$ and $r_{\text{bh}}$, respectively.
Fig. 3. Most probable density and temperature profiles based on the isentropic model. The right and left ends of each curve correspond to \( r_{10} \) and \( r_{10} \) for the low-temperature model, respectively.
Fig. 4. Most probable profiles of $R_{\text{jet}}^I$ for the FR I low-temperature model.

Fig. 5. (a) Relation between the jet power, $P_{j,\text{obs}}$, and $r_{\text{buo}}$ for the FR I low-temperature model with $P_j = P_{j,\text{obs}}$. Filled circles show the most probable values. Arrows indicate that lower or upper limits are not determined. Open circles show upper or lower limits. If $r_{\text{buo}} > r_{\text{in}}$ for all realizations ($r_{\text{buo}} = +\infty$ in Table 4), we show $r_{\text{in}}$ as the lower limit. (b) Same as (a) but for the FR I isentropic model.
Fig. 6. The ratio $L/r_{\text{cav,obs}}$ for galaxies for which $r_{\text{bub}}$ can be determined. Open circles are for the FR I low-temperature model and filled circles are for the FR I isentropic model. Error bars are drawn for the former; they are almost the same for the latter. Some galaxies have multiple cavities, and thus they have multiple values of $L/r_{\text{cav,obs}}$. Galaxies for which only lower or upper limits of $r_{\text{bub}}$ have been obtained are not included.

Fig. 7. Most probable profiles of $R_{\text{jet}}^i$ for the FR I isentropic model.
the deprojected ones. Thus, in general, the density is higher and the temperature is lower than the projected ones because the former increases and the latter decreases toward the galactic center. The deprojected values should be identical to the actual ones as long as the gas is spherically distributed and the density and temperature change smoothly. However, if the gas is strongly disturbed by AGN activities, the results may have some uncertainties. For example, figure 10 of Russell et al. (2013) shows that the density and temperature profiles of some galaxies are somewhat irregular at their centers, which may indicate errors of less than a factor of two.

The jet kinetic power, $P_j$, can be obtained observationally, and we denote it by $P_{j,\text{obs}}$. It has been estimated as the ratio of the enthalpy of cluster X-ray cavities to their buoyancy timescales (McNamara et al. 2011). The enthalpy is given by

$$E_{\text{cav}} = \frac{\gamma c_s}{\gamma - 1} p_s V_c,$$

where $p_s$ is the pressure of the gas surrounding the cavity, and $V_c$ is the cavity’s volume. Note that while equation (10) is appropriate for FR I objects (most of our sample galaxies), it may underestimate the jet power for FR II objects (Cygnus A) by at most a factor of 10 (Ito et al. 2008). Thus, $P_{j,\text{obs}}$ for Cygnus A should be regarded as a lower limit. The jet power can also be estimated from the Bondi accretion rate. The maximal power released from the neighborhood of the SMBH through the Bondi accretion is

$$P_B = \eta M_B c^2,$$

where $\eta$ is the accretion efficiency assumed $\eta = 0.1$. We present $P_{j,\text{obs}}$ and $P_B$ in tables 2 and 3. In general, $P_B$ is much larger than $P_{j,\text{obs}}$.

The reduction factor (see equation 2) is given by $f_z = t_{\text{cs}}/t_{\text{buoy}}$, where $t_{\text{cs}}$ is the migration time of a cavity when the rising velocity is the sound velocity, and $t_{\text{buoy}}$ is the one when the rising velocity is the buoyant velocity (e.g., Birzan et al. 2004). Using X-ray observations, Rafferty et al. (2006) estimated both times for our sample galaxies (see their table 5), and we adopt those values. If multiple values are given per galaxy because there are multiple cavities, we take the average. In general, the reduction factor is $0.5 \lesssim f_z \lesssim 1$.

4 Results

Using input parameters shown in tables 1 and 2, we calculate the evolution of cocoons. Output parameters are summarized in tables 3–5.

4.1 Hot gas profiles

In this subsection, we invoke the Bondi accretion model, for reference purposes only. For the low-temperature model, we calculate the Bondi accretion radii, $r_B$, the density, $n_{e,B} = n_e(r_B)$, and the temperature, $T_B = T(r_B)$, at these radii, and show them in table 3. We also present the Bondi accretion rates. The Bondi radii we obtain are substantially larger than those in Rafferty et al. (2006) because of smaller $T_B$ we adopt. Using Monte Carlo simulations, we estimate the uncertainties in the results. Each input parameter is randomly perturbed with a Gaussian distribution of the perturbations, with an amplitude determined by the error bar of the parameter. We obtain $10^3$ different realizations.

Figure 2 shows the density and the temperature profiles between $r_B$ and $r_{in}$ for the low-temperature model. While the density profiles can be represented by a power-law for most galaxies, some profiles show noticeable bends. In figure 3, we show the density and the temperature profiles for the isentropic model. Sharp bends in the temperature profiles correspond to the radii $r_B$ where $t_{\text{cool}}/t_{\text{ff}} = 10$ inside which the entropy is constant. The galaxies with monotonically increasing temperatures toward the centers have the ratios of $t_{\text{cool}}/t_{\text{ff}} < 10$ at $r = r_{in}$ (e.g., PKS 0745–191). Those with monotonically decreasing temperatures have the ratios of $t_{\text{cool}}/t_{\text{ff}} > 10$ for $r_B < r < r_{in}$ (e.g., MKS 35); their profiles are the same as those in figure 2. Except for the last ones ($t_{\text{cool}}/t_{\text{ff}} > 10$ for $r_B < r < r_{in}$), the central densities derived based on the isentropic model are much smaller than those on the low-temperature model (figures 2 and 3). From conditions (2) and (4), we define

$$R_{\text{jet}}^{i,j}(r) = \frac{1}{P_{j,\text{obs}}^{i,j}} \left[ \frac{\xi(r) + \frac{\gamma c_s}{\gamma - 1} 4\pi r^2 f_1 c_s(r) p(r)}{\rho(r) f_1^2 c_s(r)^2 c_A(r)} \right],$$

$$R_{\text{jet}}^{i,j}(r) = \frac{2\rho(r) f_1^2 c_s(r)^2 c_A(r)}{P_{j,\text{obs}}^{i,j}},$$

Therefore, if $R_{\text{jet}}^{i} < 1$ ($i = I$ or II), a jet with $P_j = P_{j,\text{obs}}$ can progress in the ambient medium with velocities larger than the buoyant velocities (phase A in figure 1). Equations (12) and (13), and (6) show that smaller $f_1$ and $f_2$ give smaller $R_{\text{jet}}^{i,j}$. Using the density and temperature profiles obtained in this subsection, we calculate the profiles of $R_{\text{jet}}^{i,j}$.

4.2 FR I type evolution and cavity ascent

Next, we discuss the results obtained for the case when cocoons expand by the pressure inside them (section 2.1.1). We show the profiles of $R_{\text{jet}}^{i}$ for the low-temperature model in figure 4. In general, they correspond to an increasing function of $r$, because the pressure of the hot gas $p$ decreases slower than $r^{-2}$ (equation 12). However, $R_{\text{jet}}^{I}$ for a number of galaxies decrease in the outer region because $p$ decreases faster than $r^{-2}$. These objects include a single galaxy (M84), or belong to a galaxy group (HCG 62) or a low-temperature cluster (M87), for which the contribution of the cluster component can be ignored. On the contrary, galaxies in massive clusters have monotonically increasing $R_{\text{jet}}^{I}$.

We estimate the size of cavities by deriving the buoyancy radius $r_{\text{buoy}}$ within which $R_{\text{jet}}^{I} < 1$ (figure 5a) for our sample
galaxies (see also table 4). In figure 5a, the radius \( r_{\text{buo}} \) is an increasing function of \( P_{\text{j,obs}} \), and \( r_{\text{buo}} < 10 \) kpc for most of them. The buoyancy radius \( r_{\text{buo}} \) does not necessary show the observed positions of the cavities, because the cavities rise in the ambient medium via buoyancy. We expect that the growth of a cocoon stops at \( r \sim r_{\text{buo}} \) and thus the initial size of the cavity is \( L_0 \sim r_{\text{buo}} \) (phase B in figure 1). The sizes of a significant fraction of cocoons is \( r_{\text{buo}} \lesssim 1 \) kpc (\( P_{\text{j,obs}} \lesssim 10^{44} \) erg \( \cdot \) s\(^{-1} \)) in figure 5a). The radius \( r_{\text{buo}} \) cannot be compared directly with the observed size of the cavities \( r_{\text{cav,obs}} \) because of the evolution in phases B and D (figure 1). The details of the corrections are described in appendix 2. In general, the ratio of the final size of the cavity \( L \) to the initial size \( L_0 \) (figure 1) is less than a factor of a few. In figure 6, we show the ratio \( L/r_{\text{cav,obs}} \). We assume that \( r_{\text{cav,obs}} = \sqrt{ab}/2 \), where \( a \) and \( b \) are the semimajor and semiminor axes obtained by Rafferty et al. (2006), respectively. We did not include galaxies for which only lower or upper limits of \( r_{\text{buo}} \) have been obtained in figure 5. Figure 6 shows that \( L/r_{\text{cav,obs}} \sim 0.5 \) on average and indicates that the predicted radius of the cocoons is consistent with the observed radius within a factor of a few. Note that \( \xi \) in equation (12) affects \( L/r_{\text{cav,obs}} \) by only less than a few percent in most cases.

One may assume that the actual jet power, \( P_{\text{j}} \), is represented by \( P_{\text{B}} \) rather than \( P_{\text{j,obs}} \), if the Bondi accretion is realized and if most of the jet energy has escaped from the cavities. In this case, we replace \( P_{\text{j,obs}} \) in equation (12) by \( P_{\text{B}} \):

\[
R_{\text{ff}}(r) = \frac{1}{P_{\text{B}}} \left[ \xi(r) \frac{\gamma}{\gamma - 1} 4\pi r^2 f_1 c_s(r) P(r) \right],
\]

(14)

In general, \( R_{\text{ff}} \) is smaller than \( R_{\text{jet}} \), because \( P_{\text{B}} > P_{\text{j,obs}} \) (tables 2 and 3). We calculate the buoyancy radius, \( r_{\text{buo}} \), within which \( R_{\text{ff}} \sim 1 \) for our sample galaxies (table 4). The buoyancy radii, \( r_{\text{buo}} \), for \( P_{\text{B}} = P_{\text{j,obs}} \) are much larger than those for \( P_{\text{B}} = P_{\text{j,obs}} \). They can be \( r_{\text{buo}} \gtrsim 5 \) kpc, considering the errors. This means that, if \( P_{\text{B}} \approx P_{\text{j,obs}} \) is realized in actual galaxies, the jet power is large enough or even exceeds the required amount to explain the sizes of the observed cocoons in most of the galaxies.

Next, we show the profiles of \( R_{\text{jet}} \) for the isentropic model in figure 7. For a given radius, \( R_{\text{jet}} \) in figure 7 are smaller than those in figure 4 (see also table 4), because the pressure of the hot gas outside the cocoon (\( p \)) is generally smaller in the isentropic models. This is especially true in the innermost regions of the galaxies where the profiles of the hot gas are different between the isentropic and low-temperature models (figures 2 and 3). However, the overall tendency is not different between figure 4 and figure 7; \( R_{\text{jet}} \) is the increasing function of \( r \) for most galaxies. This means that the expansion of a cocoon stops at a buoyancy radius \( r_{\text{buo}} \). Figure 5b shows the relation between \( P_{\text{j,obs}} \) and \( r_{\text{buo}} \) for the isentropic model. This figure is nearly the same as figure 5a, although \( r_{\text{buo}} \) of the former is slightly smaller (by less than a factor of a few). This happens because the difference in the pressure \( p \) at \( r \sim r_{\text{buo}} \) is not large between the isentropic and low-temperature models. In figure 6, we show the ratios \( L/r_{\text{cav,obs}} \) for this model — they are similar to those for the low-temperature model.

4.3 FR II type evolution

In this subsection, we provide results for the jet momentum-driven expansion of the cocoon (section 2.1.2). We show the profiles of \( R_{\text{jet}}^{\text{FR II}} \) for the low-temperature model in figure 8. Most of them have a bend at \( r \sim 1 \) kpc, where the index of \( T_{\text{HS}} \) changes (equation 5). For larger radii, most galaxies have almost constant values of \( R_{\text{jet}}^{\text{FR II}} \). This suggests that the condition whether the jet can break through the central region or not depends on the values of \( R_{\text{jet}}^{\text{FR II}} \) at \( r \gtrsim 1 \) kpc as long as the ambient medium is in hydrostatic equilibrium.

We show the buoyancy radius \( r_{\text{buo}} \) within which \( R_{\text{jet}}^{\text{FR II}} < 1 \) (figure 9a) for our sample galaxies (see also table 5). While \( r_{\text{buo}} \) is the increasing function of \( P_{\text{j,obs}} \), the absolute values are smaller than those in figure 5a except for these with \( r_{\text{buo}} > r_{\text{in}} \). This is because \( R_{\text{jet}}^{\text{FR II}} \) tends to be larger than \( R_{\text{jet}}^{\text{FR I}} \) at a given radius \( r \gtrsim 1 \) kpc (figures 4 and 8, and tables 4 and 5). Thus, if a cocoon expands following the FR II type evolution, the breakout of the jets from the central region of the galaxy is more difficult compared with the case when it follows the FR I type evolution. This can mean that, if a cocoon starts to expand following the FR II type evolution, its expansion switches to the FR I type evolution around or within the buoyant radius calculated for the FR II type evolution. We shall discuss this issue in section 5.2.

In figure 10, we show the ratios of the predicted cavity size \( L \) to the observed \( r_{\text{cav,obs}} \). The values of \( L/r_{\text{cav,obs}} \sim 0.2 \) are generally smaller than those in figure 6, which indicates that the predicted cavity sizes are less consistent with the observations. This may also indicate that the FR I type evolution is preferable to the FR II type evolution in clusters.

If the jet power is given by the Bondi power (\( P_{\text{B}} = P_{\text{B}} \)), the condition of jet breakout is given by

\[
R_{\text{jet}}^{\text{FR II}}(r) = \frac{2p(r)f_1 c_s(r) A_{\text{HS}}(r)}{P_{\text{B}}}.
\]

(15)

Since \( P_{\text{B}} > P_{\text{j,obs}} \), the buoyancy radii \( r_{\text{buo}} \) for \( R_{\text{jet}}^{\text{FR II}} \) are larger than those for \( R_{\text{jet}}^{\text{FR I}} \) (table 5), which makes the breakout easier. However, \( r_{\text{buo}} \) for \( R_{\text{jet}}^{\text{FR II}} \) are smaller than those for \( R_{\text{B}} \) (tables 4 and 5).

Figure 11 shows the profiles of \( R_{\text{jet}}^{\text{FR II}} \) for the isentropic model. Some galaxies exhibit a bend at \( r \approx 1 \) kpc, which corresponds to the index change of the size of the hot spot (equation 5). Some galaxies (e.g. A85) show another bend at the radius \( r_s \) where \( t_{\text{cool}}/t_{\text{ff}} = 10 \) (see figure 3). Outside this radius, the profile is the same as that in the low-temperature model (figure 8). Some galaxies in figure 11 (e.g. PKS 0745–191) have monotonically, outwardly increasing profiles of \( R_{\text{jet}}^{\text{FR II}} \) for \( r < r_{\text{in}} \), because \( t_{\text{cool}}/t_{\text{ff}}(r_{\text{in}}) < 10 \). However, it is unlikely that they continue to
increase endlessly for \( r > r_{\text{in}} \), because the hot gas is expected to be isentropic only in the innermost region of galaxies, and because the results of the low-temperature model (figure 8) indicate that \( R_{\text{jet}}^{\text{II}} \) does not change much at \( r > 1 \) kpc. Compared with figure 8, the isentropic model gives smaller \( R_{\text{jet}}^{\text{II}} \) in the inner region (figure 11) because of the lower density of the ambient gas (figure 3). The difference of \( R_{\text{jet}}^{\text{II}} \) (equation 13) between the low-temperature and isentropic models is more significant than with \( R_{\text{jet}}^{\text{I}} \) (equation 12), because the difference in the density profiles of the hot gas between the low-temperature and isentropic models is more significant than that in the pressure profiles.

Figure 9b shows the relation between \( P_{\text{jet}} \) and \( r_{\text{obs}} \) for the isentropic model. Although the buoyant radii \( r_{\text{buo}} \) are slightly larger than those shown in figure 9a for many of the galaxies, the difference is small (see also table 5). Therefore, the isentropic model does not allow for the smooth penetration of the FR II type jets in the central dense regions of those galaxies, either (see also figure 10). Since real gas profiles are expected to lie between the low-temperature and the isentropic models, we conclude that the FR II type jets in most galaxies cannot break out of the central region. This result may be closely related to the observations that the morphology of \( \sim 1 \) kpc-scale low power compact radio sources tends to be irregular (e.g. Kunert-Bajraszewska et al. 2005).

5 Discussion

5.1 Summary of the results

We find that, with the jet power estimated from the observations of X-ray cavities (\( P_{\text{obs}} \)), jets have difficulty to progress through the dense central region of the host galaxies faster than the buoyant velocities of the cocoons. This appears to be the case for a significant fraction of our sample galaxies. Such a statement holds even if we assume the FR I type evolution, which makes jet propagation easier than the FR II type evolution. Therefore, the cocoons should have been plausibly broken by the buoyant force before they have grown up. We estimate the sizes of the cavities originated from the broken cocoons, and find that they are consistent with the observations within a factor of two for the FR I type evolution. At the same time, the discrepancy is larger for the FR II type evolution. The resulting “easiness” of jet propagation in the FR I type evolution may explain why FR I sources are more frequent over FR II sources in clusters (Prestage & Peacock 1988; Miller et al. 2002).

5.2 Dichotomy between FR I and II

The advance velocity of a newborn jet, \( v_{\text{h}} \), can be very large (\( v_{\text{h}} \sim c \); Kawakatu et al. 2008). Thus, the cocoon may initially expand by the jet momentum (FR II type evolution) even for galaxies with smaller \( P_{\text{jet}} \) (from point A1 to A2 in figure 12). However, the results in section 4.3 show that this type of evolution does not last for a long time for galaxies with smaller \( P_{\text{jet}} \) because of small buoyant radii, \( r_{\text{buo}} \) (point A2). Since the advance velocity of a jet decreases to the sound velocity at \( r \lesssim r_{\text{buo}} \), the jet momentum can be insufficient to inflate the cocoon further. However, the energy injection by the jet is still substantial at this point because the buoyant radii, \( r_{\text{buo}} \), for the FR I evolution are larger than those for the FR II evolution, for most of our samples (sections 4.2 and 4.3, see also tables 4 and 5). That is, the location of the cocoon jumps from A2 to A3 and then moves toward A4 along the line of the FR I type evolution (thick dashed line in figure 12). Of course, the actual transition could be smooth. Since \( R_{\text{jet}}^{\text{II}} \sim f_{\text{c}} v_{\text{h}} / v_{\text{q}} \) (equations 1 and 12) and \( R_{\text{jet}}^{\text{II}} = (f_{\text{c}} v_{\text{h}} / v_{\text{q}})^{2} \) (equations 3 and 13), the cocoon may track from A2’ and A3’, where \( R_{\text{jet}}^{\text{II}} \sim f_{\text{c}}^{2} / v_{\text{q}}^{2} \), although the detailed discussion on the track is beyond the scope of the paper. The expansion of the cocoon finally stops at point A4. This can explain why most of our objects are known as FR I sources.

The profiles of \( R_{\text{jet}}^{\text{II}} \) bent at \( r = 1 \) kpc (low-temperature and isentropic models) and \( r = r_{\text{c}} \) (isentropic model) show that some cocoons with relatively large \( P_{\text{obs}} \) can continue to evolve as FR II sources, if they start evolving as FR IIs (thin solid line in figure 12). This happens because the profiles of \( R_{\text{jet}}^{\text{II}} \) for the low-temperature model become almost flat at \( r > 1 \) kpc (figure 8) and those for the isentropic model appear to be the same as those for the low-temperature model at \( r > r_{\text{c}} \) (figure 11). Thus, if \( R_{\text{jet}}^{\text{II}} \) of the low-temperature model is less than around unity at \( r \sim 1 \) kpc, it also remains less than around unity at \( r > 1 \) kpc, for both the low-temperature and isentropic models. If this happens, the cocoon can grow as an FR II (point B1 \( \rightarrow \) B2 \( \rightarrow \) B3 in figure 12). Even if a cocoon initially tracks the path of \( R_{\text{jet}}^{\text{II}} \) (thin dashed line in figure 12), it may transfer to the path of \( R_{\text{jet}}^{\text{II}} \) (thin solid line in figure 12) at large radii where \( R_{\text{jet}}^{\text{II}} \ll R_{\text{jet}}^{\text{II}} \).

Figure 13 shows the relation between \( R_{\text{jet}}^{\text{II}} \) (at \( r = 1 \) kpc) for the low-temperature model and \( P_{\text{obs}} \). We observe that \( R_{\text{jet}}^{\text{II}} \) decreases monotonically. This relation can be explained by equation (13), and by the fact that \( P_{\text{obs}} \) varies in a wider range (figure 9) than the profiles of the hot gas (figure 2) among our sample galaxies. We are only interested in the normalization of the correlation and find that \( R_{\text{jet}}^{\text{II}} \lesssim 1 \) at \( P_{\text{obs}} \gtrsim 10^{46} \text{erg s}^{-1} \). Although \( R_{\text{jet}}^{\text{II}} \) of some galaxies with \( 10^{44} \lesssim P_{\text{obs}} \lesssim 10^{46} \text{erg s}^{-1} \) is slightly larger than unity (figure 13), it can be less than unity if \( P_{\text{jet}} \) is underestimated or \( \rho \) is overestimated by only a factor of few. In this case, a significant fraction of galaxies with \( P_{\text{jet}} \gtrsim 10^{44} \text{erg s}^{-1} \) could have evolved as FR II type and created cavities with \( r_{\text{buo}} > 10 \) kpc.

In summary, some of the jets with \( P_{\text{obs}} \gtrsim 10^{44} \text{erg s}^{-1} \) could extend well beyond the galaxies without being much affected by
Fig. 8. Most probable profiles of $R_{\text{II, jet}}$ for the FR II low-temperature model.

Fig. 9. (a) Relation between the jet power, $P_{\text{j, obs}}$, and $r_{\text{bou}}$ for the FR II low-temperature model with $P_j = P_{\text{j, obs}}$. Filled circles show the most probable values. Arrows indicate that lower or upper limits are not determined. Open circles show upper or lower limits. If $r_{\text{bou}} > r_{\text{in}}$ for all realizations ($r_{\text{bou}} = +\infty$ in table 5), we show $r_{\text{in}}$ as the lower limit. (b) Same as (a) but for the FR II isentropic model.
Fig. 10. The ratio $L/r_{cav, obs}$ for galaxies for which $r_{bub}$ can be determined. Open circles are for the FR II low-temperature model and filled circles are for the FR II isentropic model. Error bars are drawn for the former; they are almost the same for the latter. Some galaxies have multiple cavities, and thus they have multiple values of $L/r_{cav, obs}$. The galaxies for which only lower or upper limits of $r_{bub}$ have been obtained are not included.

Fig. 11. Most probable profiles of $R_{jet}^{II}$ for the FR II isentropic model.
Fig. 12. Schematic figure for the relation between $R_{\text{jet}}$ and $r$ (dashed lines) and $R_{\text{jet}}^{\text{II}}$ and $r$ (solid lines). Thick lines (smaller $P_{\text{j,obs}}$) and thin lines (larger $P_{\text{j,obs}}$) show the cases where the cocoon finally becomes FR I and FR II, respectively. The buoyant radii $r_{\text{buo}}$ are the intersections of these lines with $R_{\text{jet}} = 1$.

Fig. 13. Relation between jet power $P_{\text{j,obs}}$ and $R_{\text{jet}}^{\text{II}} (r = 1 \text{kpc})$ for the FR II low-temperature model.

Fig. 14. Relation between $P_{\text{j,obs}}$ and $L_{\text{ICM}}$. 
the friction with the surrounding gas and could turn to be FR II sources. Cygnus A, which is known as FR II, is included in this class of galaxies. Some FR Is with $P_{j,\text{obs}} \gtrsim 10^{44} \text{ erg s}^{-1}$ might have been FR IIs until fairly recently. On the other hand, $R_{\text{jet}}^{11}$ is generally much larger than unity at $P_{j,\text{obs}} \gtrsim 10^{44} \text{ erg s}^{-1}$ (figure 13), and $R_{\text{jet}}^{11} < 1$ may not be achieved even considering uncertainties. Thus, jets with $P_{j,\text{obs}} \lesssim 10^{44} \text{ erg s}^{-1}$ could be strongly decelerated by the ambient medium and might become FR Is soon after their launch. Therefore, $P_{j,\text{obs}} \gtrsim 10^{44} \text{ erg s}^{-1}$ can be a necessary condition to create FR IIs in BCGs. FR II sources appear rare in clusters perhaps because the AGN there are rarely experiencing activity strong enough to break out the central region. Ledlow & Owen (1996) indicated that the FR I/II division is a function of an optical luminosity as well as of a radio luminosity. It would be interesting to study the relation between $P_{j,\text{obs}}$ and optical and radio luminosities for a larger sample.

5.3 ICM heating

The threshold $P_{j,\text{obs}} \sim 10^{44} \text{ erg s}^{-1}$ may have another interesting implication. Figure 14 shows the relation between $P_{j,\text{obs}}$ and the ratio $P_{j,\text{obs}}/L_{\text{ICM}}$, where $L_{\text{ICM}}$ is the X-ray luminosity of the intracluster medium (ICM), inside the cooling radius of the host cluster, which is offset to be consistent with the spectra, $L_{\text{ICM}} = L_{\text{Xc}} - L_{\text{cool}}$. We have adopted the luminosities derived by Rafferty et al. (2006); $L_{\text{Xc}}$ is the X-ray luminosity for which the gas cooling time is less than the look-back time for $z = 1$ ($7.7 \times 10^9$ yr), and $L_{\text{cool}}$ is the associated luminosity of the gas cooling to low temperatures, derived from the X-ray spectrum. We assume $L_{\text{cool}} = 0$ for A1835 because $L_{\text{cool}}$ could not be detected (Rafferty et al. 2006). This assumption will not affect the results strongly, because $L_{\text{cool}} \ll L_{\text{Xc}}$ for most of the other clusters.

Luminosities $L_{\text{ICM}}$ are shown in table 2. In figure 14, $L_{\text{ICM}}/P_{j,\text{obs}} \gtrsim 1$ for most galaxies with $P_{j,\text{obs}} \lesssim 10^{44} \text{ erg s}^{-1}$, while $L_{\text{ICM}}/P_{j,\text{obs}} \lesssim 1$ in general for $P_{j,\text{obs}} \gtrsim 10^{44} \text{ erg s}^{-1}$. Note that, although the distribution appears to peak at $P_{j,\text{obs}} \sim 3 \times 10^{44} \text{ erg s}^{-1}$ (figure 14), we avoid discussing this, because the peak is blurred if we omit the object with the lowest jet power (M84; $P_{j,\text{obs}} = 1 \times 10^{42} \text{ erg s}^{-1}$). If the jet heats up the cool core of the host clusters, the radiative cooling of the hot gas is compensated by the jet power and $L_{\text{ICM}}/P_{j,\text{obs}} \sim 1$ is expected. Since figure 13 shows that the jets with $P_{j,\text{obs}} \gtrsim 10^{46} \text{ erg s}^{-1}$ can evidently break out of the central region ($R_{\text{jet}}^{11} < 1$; see point B3 in figure 12), results shown in figure 14 indicate that the jets with $P_{j,\text{obs}} \gtrsim 10^{46} \text{ erg s}^{-1}$ have broken out of the most dense region in the center, where the radiative cooling is most efficient, and thus the jet power is not used effectively to compensate for the radiative cooling.

For jets with $P_{j,\text{obs}} \lesssim 10^{44} \text{ erg s}^{-1}$ (mostly $L_{\text{ICM}}/P_{j,\text{obs}} > 1$), the energy created around AGN can be conveyed to the ICM in some hidden form, such as a thermal conduction and cosmic rays (e.g., Ruszkowski & Begelman 2002; Guo & Oh 2008; Fujita & Ohira 2012; Fujita et al. 2013). The jets with $10^{44} \lesssim P_{j,\text{obs}} \lesssim 10^{46} \text{ erg s}^{-1}$ can represent the mix of the two populations — a kind of a gray zone. Alternatively, figure 14 can indicate that the jet power fluctuates and $L_{\text{ICM}}/P_{j,\text{obs}} \sim 1$ in a long-time average.

6 Conclusions

We have studied the evolution of AGN jets and associated cocoons in the brightest elliptical galaxies (BCGs) in clusters. Using observational data of the jet power estimated from the size of X-ray cavities and the gas properties of the ambient hot gas, we have analyzed whether these jets can propagate in the host galaxy with sufficiently large velocities. For this purpose, we consider the balance between the pressure inside the cocoon and the thermal pressure outside the cocoon (FR I type evolution), and the balance between the momentum flux of the jet and the ram pressure of the ambient gas (FR II type evolution). Since the hot gas profiles in the innermost region of galaxies are not known, we have extrapolated the observed profiles based on two extreme models. In the low-temperature model, we assume that the gas temperature reflects the virial temperature of the galaxy. In the isentropic model, the entropy of the gas is constant due to the thermal instabilities. The former and the latter give higher and lower central densities, respectively. The actual density is expected to lie in between.

We find that most jets with observed powers of $\lesssim 10^{44} \text{ erg s}^{-1}$ have difficulty to penetrate the dense central regions of their host galaxies with sufficiently high velocities to create large cocoons. If they start evolving as FR IIs, for which the evolution is driven by the jet momentum, the velocity of the jet head quickly falls below the sound speed of the ambient gas. Thus, the cocoons may change into FR Is, for which the evolution is driven by the pressure inside the cocoons. This may be the reason why FR I sources are common in clusters. However, even for the FR I evolution, the expansion velocity gradually decreases down to the buoyant velocity of the cocoons. This indicates that the cocoons could be destroyed by the buoyancy force. From the observed jet powers, we predict the size of cavities, which are the relics of the cocoons, and found that it is consistent with the observed one within a factor of few, if the FR I type evolution is realized.

Our results also indicate that some of the jets with powers of $\gtrsim 10^{44} \text{ erg s}^{-1}$ are less affected by the ambient medium and can serve as FR II sources. Most of the power can be released outside of the most dense region at the galactic center and thus may not efficiently compensate the cooling. On the other hand, jets with powers of $\lesssim 10^{44} \text{ erg s}^{-1}$ are strongly disturbed by the
ambient medium and become FR I sources.

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Appendix 1 Low-temperature model
In this model, we make two assumptions. First, we assume that the hot gas outside the Bondi radius is in a nearly hydrostatic equilibrium:
\[
\frac{dp}{dr} = - \rho g ,
\]  
(A1)
where \( p(r) \) is the thermal gas pressure, and \( g(r) \) is the gravitational acceleration. Second, we assume that the gas temperature near the SMBH (i.e., at \( r \sim r_B \)) reflects the velocity dispersion \( \sigma \) or the virial temperature \( T_{\text{gal, vir}} \) of the host galaxy:
\[
T_0 = \zeta k \frac{\mu m_p \sigma^2}{\rho} \sim T_{\text{gal, vir}} ,
\]  
(A2)
where \( k \) is the Boltzmann constant, and \( \zeta \) is the constant of order of unity. Following Matsushita (2001), we adopt \( \zeta = 0.5 \) for massive elliptical galaxies, including BCGs. The second assumption is based on the first one, because the left-hand side of equation (A1) can be approximated by \( -dp/dr \sim p/r = nkT/r \), where \( n \) is the number density of the gas, and the right-hand side can be approximated by
\[
\rho g = \rho \frac{GM(< r)}{r^2} \sim n k T_{\text{gal, vir}} .
\]  
(A3)
where \( M(< r) \) is the gravitational mass within the radius \( r \). The second assumption (equation A2), is generally consistent with ROSAT X-ray observations (Matsushita 2001).

Assuming that the temperature profile depends on the galaxy size, we interpolate it between \( r = r_B \) and \( r_{\text{in}} \) as
\[
T(r) = T_0 + (T_{\text{in}} - T_0) \frac{\tanh(r/R_e)}{\tanh(r_{\text{in}}/R_e)} ,
\]  
(A4)
where \( T_{\text{in}} = T(r_{\text{in}}) \) and \( R_e \) is the effective radius (half-light radius) of the galaxy. The resulting temperature profile between \( T_{\text{in}} \) and \( T_0 \) nicely mimics the observed profiles (e.g. Churazov et al. 2003). In general, the temperature decreases toward the galaxy center. Once we fix \( T(r) \), the Bondi accretion radius, \( r_B \), can be obtained numerically by solving the equation
\[
r_B = \frac{2GM*}{c_s(T(r_B))^2} ,
\]  
(A5)
for a given SMBH mass \( M_* \) (Bondi 1952). If the angular momentum of the gas can be ignored and the gas is adiabatic, the accretion onto the SMBH can follow the Bondi accretion. Since the direct application of the Bondi accretion model provides a grossly oversimplified picture (e.g., Soker 2006; Pizzolato & Soker 2010; McNamara et al. 2011), we consider the Bondi accretion just as a reference. The Bondi accretion rate is given by
\[
\dot{M}_B = 4\pi \lambda_e (GM_\bullet)^2 \frac{c_s}{\rho_B} = \pi \lambda_e c_s B \rho_B^2 ,
\]  
(A6)
where \( \rho_B = \rho(r_B) \) and \( c_s = c_s(r_B) \) are the density and the sound speed at the Bondi radius (Bondi 1952). The coefficient \( \lambda_e \) depends on the adiabatic index of the accreting gas (\( \gamma \)), and we assume \( \gamma = 5/3 \) and \( \lambda_e = 0.25 \).

The equation of the hydrostatic equilibrium (equation A1) can be written as
\[
\frac{dp}{dr} = - \rho \frac{GM(< r)}{r^2} \left( \frac{dT}{dr} \right) .
\]  
(A7)
In general, the first term on the right hand side dominates over the second term. Since \( T(r) \) has been determined by equation (A4), \( \rho(r) \) can be obtained by numerically integrating the equation (A7) and setting \( \rho_{\text{in}} = \rho(r_{\text{in}}) \) and \( g(r) \). The electron number density is defined as \( n_e = \rho/(1.13 \, m_p) \).

The gravitational acceleration \( g(r) \) is given by three components, i.e., \( g = g_* + g_{\text{gal}} + g_{\text{cl}} \), where \( g_* \) is the SMBH contribution, \( g_{\text{gal}} \) is the galaxy contribution, and \( g_{\text{cl}} \) is the cluster contribution (Mathews et al. 2006; Guo & Mathews 2014). The acceleration from an SMBH is
\[
g_*(r) = \frac{GM_\bullet}{r^2} .
\]  
(A8)
The acceleration from a galaxy with the Hernquist profile (Hernquist 1990) is
\[
g_{\text{gal}}(r) = \frac{GM_{\text{gal}}}{(r + r_B)^2} ,
\]  
(A9)
where \( M_{\text{gal}} \) is the stellar mass of the galaxy, and \( r_{\text{v}} = R_e/1.815 \). Although the Hernquist profile may not be a good approximation for the outer part of BCGs (e.g. Graham et al. 1996), it does not affect our results because we are mostly interested in the inner part. The cluster acceleration for the NFW profile (Navarro et al. 1996) is
\[
g_{\text{cl}}(r) = \frac{GM_{\text{vir}}}{r^2} \left( \frac{\log(1 + y) - y/(1 + y)}{\log(1 + c_{\text{vir}}) - c_{\text{vir}}/(1 + c_{\text{vir}})} \right) ,
\]  
(A10)
where \( y = c_{\text{vir}} v/r_{\text{vir}} \), and \( c_{\text{vir}} \) is the concentration parameter. The cluster virial radius, \( r_{\text{vir}} \), is defined as the radius at which the average cluster density is \( \Delta(z) \) times the critical density \( \rho_{\text{crit}}(z) \) at the cluster redshift \( z \):
\[
r_{\text{vir}} = \left( \frac{3M_{\text{vir}}}{4\pi(\Delta(z)\rho_{\text{crit}}(z))} \right)^{1/3} .
\]  
(A11)
For \( \Delta(z) \), we use the fitting formula of Bryan & Norman (1998): \( \Delta = 18\pi^2 + 82x - 39x^2 \), where \( x = \Omega_\text{m}(z) - 1 \).

To summarize, the required parameters are \( z \), \( M_* \), \( M_{\text{gal}} \), \( R_e \), \( \sigma \), \( c_{\text{vir}} \), and \( M_{\text{vir}} \), and the boundary conditions \( r_{\text{in}} \), \( \rho_{\text{in}} \), and \( T_{\text{in}} \) in order to derive \( r_B \) and \( M_B \). First, \( T(r) \) is determined
by equations (A2) and (A4) for given $\sigma, T_{\text{in}}, R_c$, and $r_{\text{in}}$. The Bondi radius $r_{\text{B}}$ is obtained by solving equation (A5) for given $T(r)$ and $M_*$. Then, $\rho_B = \rho(r_{\text{B}})$ is estimated by integrating equation (A7) from $r = r_{\text{in}}$ to $r_{\text{B}}$ using equations (A8)–(A11) for given $T(r)$, $M_*$, $M_{\text{gal}}$, $R_c$, $M_{\text{vir}}$, $c_{\text{vir}}$ and $z$. Finally, the Bondi accretion rate is given by equation (A6).

**Appendix 2 Correction of the cavity sizes**

We need to consider two corrections associated with the evolution in phases B and D (figure 1), when we compare the predicted cavity size $L$ with the observation $r_{\text{cav,obs}}$. First, the size of a cavity increases as it rises via buoyancy keeping pressure balance with the ambient gas (phase C→D or C′→D′ in figure 1). If the cavity is adiabatic, the size changes with the distance from the galactic center as $L(r) \sim L_c[r(r)/r(r_{\text{bao}})]^{-1/3} = L_c[r(r_{\text{bao}})/r(r)]^{1/3},$ where $r(r)$ is the pressure of the ambient medium.

Second, $P_{\text{obs}}$ in equations (12) and (13) does not involve the effect of the buoyant rise in phases B and D. This leads to an underestimate of jet power. Assuming that the ambient pressure and the volume of a given cavity at phases B and D are $p_B = (p(r_{\text{bao}})/p_B)\rho_B V_B = 4\pi r_{\text{bao}}^2/3$, and $V_B$, respectively, we obtain $V_B = V_B(p_B/p_B)^{1-\gamma/\gamma}$, thus, the enthalpy (equation 10) estimated in phase D is underestimated by a factor of $(p_B/p_B)^{1/4}$, compared with phase B. Since the observed jet power $P_{\text{obs}}$ is proportional to the enthalpy, it is underestimated by the same factor. Hence, combined with the first correction, the cavity radius at the phase D should be $L \sim r_{\text{bao}}(p_B/p_B)^{1/4(1+1/\beta)}$.

We have used the pressure profiles constructed from the density and temperature profiles in figures 2 and 3, and assumed that $p_B = \rho B \sqrt{\gamma p_B} / r_{\text{bao}}$ does not affect the following results and can be ignored. Thus, for given $p_B$, the pressure profile at $r = r_{\text{bao}}$ of a cavity, $R$, obtained by Rafferty et al. (2006). If $R > r_{\text{in}}$, we extrapolate the pressure profile at $r = r_{\text{in}}$ assuming that it is given by a power-law. We find that the correction factor is $1 \lesssim (p_B/p_B)^{1/4(1+1/\beta)} \lesssim 10$, and is $\lesssim 3$ for most galaxies and cavities for both the FR I and II evolutions.

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### Table 1. Parameters for Gravitational Potentials.

| System     | $z$  | $M_\bullet$ (10^9 $M_\odot$) | $M_{gal}$ (10^{11} $M_\odot$) | $R_\bullet$ (kpc) | $\sigma$ (km s^{-1}) | $c_{vir}$ | $M_{vir}$ (10^{14} $M_\odot$) | References\(^a\) |
|------------|------|-------------------------------|-------------------------------|-------------------|----------------------|----------|-------------------------------|------------------|
| A85        | 0.055| 7.0                           | 31.0 ± 1.0                    | 16.3 ± 0.03       | 348 ± 19             | 4.25 ± 0.36 | 12.34 ± 1.24                  | 1                |
| A133       | 0.060| 3.0                           | 17.9 ± 0.4                    | 14.6 ± 0.43       | 236 ± 11             | 6.35 ± 0.93 | 5.64 ± 0.88                   | 2                |
| A262       | 0.016| 6.6                           | 4.9 ± 0.1                     | 10.4 ± 0.58       | 230 ± 10             | 8.84 ± 0.69 | 11.14 ± 0.92                  | 3                |
| Perseus    | 0.018| 3.4                           | 19.2 ± 0.1                    | 11.3 ± 0.43       | 259 ± 13             | 8.08 ± 0.35 | 6.81 ± 0.63                   | 4                |
| 2A 0335+096| 0.035| 3.0                           | 18.0 ± 1.0                    | 15.0 ± 1.4        | 290 ± 36             | 7.44 ± 0.42 | 2.11 ± 0.29                   | 3                |
| A478       | 0.081| 5.8                           | 28.0 ± 1.0                    | 15.8 ± 3.1        | 290 ± 36             | 5.15 ± 0.45 | 16.6 ± 2.0                    | 5                |
| MS 0735.6+7421 | 0.216| 5.0                           | 24.0 ± 1.0                    | 15.1 ± 3.8        | 290 ± 36             | 4.37 ± 0.22 | 9.1 ± 0.40                    | 6                |
| PKS 0745-191| 0.103| 5.5                           | 27.0 ± 1.0                    | 16.1 ± 3.3        | 290 ± 36             | 7.75 ± 0.41 | 14.9 ± 3.7                    | 5                |
| Hydra A    | 0.055| 5.8                           | 28.2 ± 0.7                    | 10.5 ± 0.90       | 302 ± 19             | 15.90 ± 0.23 | 1.15 ± 0.34                   | 7                |
| Zw 2701    | 0.214| 6.5                           | 30.0 ± 1.0                    | 13.4 ± 1.3        | 290 ± 36             | 3.30 ± 0.12 | 10.86 ± 2.57                  | 8                |
| Zw 3146    | 0.291| 9.0                           | 13.5 ± 6.9                    | 17.4 ± 7.6        | 290 ± 36             | 4.19 ± 0.18 | 9.29 ± 1.04                   | 9                |
| M84        | 0.0035| 0.36                          | 4.3 ± 1.3                     | 2.45 ± 0.06       | 282 ± 3              | ...       | ...                           | ...              |
| M87        | 0.0042| 6.4                           | 11.0 ± 3.3                    | 3.67 ± 0.13       | 336 ± 5              | 3.84 ± 0.91 | 5.78 ± 0.59                   | 10               |
| Centaurus  | 0.011| 2.0                           | 11.6 ± 0.1                    | 9.44 ± 0.24       | 254 ± 7              | 7.75 ± 0.78 | 4.09 ± 0.32                   | 4                |
| HCG 62     | 0.014| 0.65                          | 13.5 ± 6.9                    | 6.87 ± 0.04       | 290 ± 36             | ...       | ...                           | ...              |
| A1795      | 0.063| 2.2                           | 13.4 ± 0.6                    | 20.8 ± 0.23       | 302 ± 9              | 6.16 ± 1.14 | 10.8 ± 2.7                    | 5                |
| A1835      | 0.253| 6.7                           | 13.5 ± 6.9                    | 18.4 ± 0.35       | 290 ± 36             | 4.18 ± 0.63 | 24.3 ± 4.4                    | 5                |
| PKS 1404-267| 0.022| 0.7                           | 5.7 ± 0.5                     | 6.03 ± 0.12       | 260 ± 7              | 12.25 ± 1.09 | 1.7 ± 0.43                    | 1                |
| A2029      | 0.077| 4.0                           | 21.9 ± 0.2                    | 24.2 ± 1.6        | 391 ± 10             | 8.64 ± 0.44 | 10.1 ± 0.49                   | 5                |
| A2052      | 0.035| 2.0                           | 11.0 ± 3.3                    | 15.7 ± 0.27       | 216 ± 12             | 6.50 ± 0.71 | 2.86 ± 0.72                   | 3                |
| MKW 3S     | 0.045| 2.0                           | 11.2 ± 0.3                    | 11.6 ± 2.3        | 290 ± 36             | 7.83 ± 0.55 | 2.90 ± 0.27                   | 3                |
| A2199      | 0.030| 2.7                           | 15.7 ± 0.2                    | 10.6 ± 0.20       | 307 ± 7              | 10.40 ± 1.14 | 7.1 ± 1.4                    | 11               |
| Hercules A | 0.154| 2.5                           | 15.0 ± 4.0                    | 20.1 ± 2.0        | 290 ± 36             | 3.51 ± 0.23 | 4.33 ± 0.54                   | 12,13            |
| 3C 388     | 0.092| 4.5                           | 23.0 ± 6.0                    | 11.9 ± 1.2        | 408 ± 26             | ...       | ...                           | ...              |
| Cygnus A   | 0.056| 2.7                           | 9.0 ± 2.0                     | 15.6 ± 0.77       | 290 ± 36             | 16.40 ± 0.25 | 8.33 ± 0.38                   | 13,14            |
| Sersic 15903| 0.058| 2.0                           | 11.0 ± 2.0                    | 20.2 ± 0.95       | 290 ± 36             | 8.57 ± 0.69 | 1.61 ± 0.12                   | 3                |
| A2597      | 0.085| 1.5                           | 9.0 ± 1.0                     | 11.7 ± 1.3        | 210 ± 57             | 7.60 ± 0.63 | 3.55 ± 0.40                   | 15               |
| A4059      | 0.048| 8.7                           | 38.2 ± 0.4                    | 18.7 ± 0.10       | 272 ± 13             | 3.57 ± 0.68 | 4.45 ± 0.63                   | 1                |

\(^a\) References for cluster parameters: (1) Wojtak & Łokas (2010); (2) Vikhlinin et al. (2006); (3) Piffaretti et al. (2005); (4) Ettori et al. (2002); (5) Schmidt & Allen (2007); (6) Gitti et al. (2007); (7) David et al. (2001); (8) Richard et al. (2010); (9) Ettori et al. (2010); (10) McLaughlin (1999); (11) Łokas et al. (2006); (12) Gizani & Leahy (2004), Sun et al. (2009); (14) Smith et al. (2002); (15) Pointecouteau et al. (2005)
| System         | \(r_{\text{ps}}\) (kpc) | \(n_{\text{ps}}\) (cm\(^{-3}\)) | \(T_{\text{in}}\) (keV) | \(F_{\text{ps,obs}}\) (10\(^{42}\) erg s\(^{-1}\)) | \(L_{\text{ICM}}\) (10\(^{42}\) erg s\(^{-1}\)) |
|----------------|--------------------------|----------------------------------|--------------------------|----------------------------------------|----------------------------------------|
| A85            | 5.8                      | 0.107\(^{+0.099}_{-0.008}\)     | 2.1\(^{+0.1}_{-0.2}\)   | 38\(^{+17}_{-11}\)                     | 335\(^{+21}_{-29}\)                    |
| A133           | 8.0                      | 0.048\(^{+0.004}_{-0.008}\)     | 1.8\(^{+0.1}_{-0.2}\)   | 620\(^{+260}_{-20}\)                    | 103\(^{+3}_{-4}\)                     |
| A262           | 3.4                      | 0.065\(^{+0.007}_{-0.008}\)     | 0.86\(^{+0.001}_{-0.001}\)| 9\(^{+7}_{-5}\)                        | 11.10\(^{+0.31}_{-0.46}\)              |
| Perseus        | 8.6                      | 0.150\(^{+0.005}_{-0.005}\)     | 4.4\(^{+0.04}_{-0.05}\)  | 150\(^{+100}_{-30}\)                     | 533\(^{+7}_{-7}\)                     |
| 2A 0335+096    | 5.1                      | 0.056\(^{+0.001}_{-0.002}\)     | 1.4\(^{+0.1}_{-0.1}\)   | 24\(^{+15}_{-6}\)                       | 325\(^{+4}_{-4}\)                     |
| A478           | 5.3                      | 0.20\(^{+0.01}_{-0.002}\)       | 2.7\(^{+0.3}_{-0.3}\)   | 100\(^{+80}_{-20}\)                     | 1400\(^{+22}_{-51}\)                   |
| MS 0735.6+7421 | 23.8                     | 0.067\(^{+0.003}_{-0.003}\)     | 3.2\(^{+0.2}_{-0.2}\)   | 3500                                     | 438\(^{+11}_{-17}\)                    |
| PKS 0745-191   | 11.2                     | 0.14\(^{+0.01}_{-0.01}\)        | 2.6\(^{+0.4}_{-0.4}\)   | 1700\(^{+1400}_{-300}\)                   | 2070\(^{+120}_{-125}\)                  |
| Hydra A        | 4.7                      | 0.15\(^{+0.02}_{-0.002}\)       | 2.6\(^{+0.8}_{-0.5}\)   | 2000\(^{+1500}_{-500}\)                   | 269\(^{+4}_{-4}\)                     |
| Zw 2701        | 37.6                     | 0.024\(^{+0.002}_{-0.002}\)     | 3.3\(^{+0.3}_{-0.3}\)   | 6000\(^{+8900}_{-3500}\)                   | 430\(^{+18}_{-32}\)                    |
| Zw 3146        | 15.0                     | 0.177\(^{+0.007}_{-0.007}\)     | 3.1\(^{+0.2}_{-0.2}\)   | 5800\(^{+6800}_{-1500}\)                   | 2330\(^{+161}_{-196}\)                  |
| M84            | 0.9                      | 0.105\(^{+0.007}_{-0.009}\)     | 0.57\(^{+0.01}_{-0.01}\)| 1.0\(^{+0.4}_{-0.6}\)                     | 0.06\(^{+0.01}_{-0.01}\)                |
| M87            | 1.0                      | 0.191\(^{+0.009}_{-0.009}\)     | 0.94\(^{+0.02}_{-0.02}\)| 6.0\(^{+4.2}_{-0.9}\)                     | 7.29\(^{+0.20}_{-0.11}\)                |
| Centaurus      | 1.3                      | 0.23\(^{+0.01}_{-0.01}\)        | 0.77\(^{+0.01}_{-0.01}\)| 7.4\(^{+5.8}_{-1.8}\)                     | 23.80\(^{+0.35}_{-0.35}\)               |
| HCG 62         | 2.1                      | 0.057\(^{+0.007}_{-0.005}\)     | 0.67\(^{+0.01}_{-0.01}\)| 3.9\(^{+6.1}_{-2.3}\)                     | 1.86\(^{+0.17}_{-0.24}\)               |
| A1795          | 9.5                      | 0.067\(^{+0.005}_{-0.005}\)     | 2.7\(^{+0.4}_{-0.6}\)   | 160\(^{+230}_{-50}\)                      | 615\(^{+19}_{-19}\)                    |
| A1835          | 27.2                     | 0.110\(^{+0.003}_{-0.002}\)     | 4.0\(^{+0.3}_{-0.3}\)   | 1800\(^{+3600}_{-600}\)                   | 3160\(^{+90}_{-90}\)                    |
| PKS 1404-267   | 8.5                      | 0.046\(^{+0.007}_{-0.007}\)     | 1.3\(^{+0.01}_{-0.01}\)| 20\(^{+26}_{-9}\)                        | 24\(^{+1}_{-1}\)                      |
| A2029          | 2.2                      | 0.37\(^{+0.04}_{-0.03}\)        | 2.9\(^{+0.3}_{-0.3}\)   | 87\(^{+49}_{-14}\)                       | 1160\(^{+99}_{-11}\)                   |
| A2052          | 5.5                      | 0.017\(^{+0.002}_{-0.002}\)     | 0.71\(^{+0.04}_{-0.07}\)| 150\(^{+200}_{-100}\)                     | 94\(^{+1}_{-1}\)                      |
| MKW 3S         | 7.8                      | 0.028\(^{+0.006}_{-0.009}\)     | 2.8\(^{+0.8}_{-0.4}\)   | 410\(^{+420}_{-44}\)                      | 99\(^{+3}_{-4}\)                      |
| A2109          | 4.4                      | 0.099\(^{+0.005}_{-0.005}\)     | 2.2\(^{+0.2}_{-0.2}\)   | 270\(^{+250}_{-60}\)                      | 142\(^{+1}_{-1}\)                      |
| Hercules A     | 67.0                     | 0.011\(^{+0.006}_{-0.005}\)     | 2.0\(^{+0.2}_{-0.2}\)   | 16000                                    | 210\(^{+6}_{-6}\)                      |
| 3C 388         | 55.6                     | 0.009\(^{+0.004}_{-0.004}\)     | 3.0\(^{+0.2}_{-0.2}\)   | 200\(^{+280}_{-80}\)                      | 2\(^{+1}_{-1}\)                       |
| Cygnus A       | 5.3                      | 0.132\(^{+0.008}_{-0.009}\)     | 5.2\(^{+0.5}_{-0.6}\)   | 3900                                      | 370\(^{+11}_{-11}\)                   |
| Sersei 159/03  | 12.2                     | 0.056\(^{+0.004}_{-0.004}\)     | 1.8\(^{+0.2}_{-0.1}\)   | 780\(^{+820}_{-260}\)                     | 211\(^{+7}_{-8}\)                      |
| A2597          | 11.0                     | 0.073\(^{+0.005}_{-0.005}\)     | 1.6\(^{+0.2}_{-0.2}\)   | 67\(^{+87}_{-29}\)                       | 440\(^{+37}_{-37}\)                    |
| A4059          | 10.6                     | 0.022\(^{+0.003}_{-0.001}\)     | 2.1\(^{+0.1}_{-0.1}\)   | 96\(^{+35}_{-15}\)                       | 91\(^{+1}_{-1}\)                      |
| System       | rB (kpc)   | nB (cm⁻³)   | TB (keV)   | MB (M☉ yr⁻¹) | PB (10⁴ erg s⁻¹) |
|--------------|------------|-------------|------------|--------------|-----------------|
| A85          | 0.15±0.34  | 2.73±0.68   | 1.56±0.17  | 0.85±1.07    | 48±21           |
| A133         | 0.18±0.29  | 5.68±1.87   | 0.73±0.09  | 1.01±0.16    | 58±13           |
| A262         | 0.029±0.069| 0.76±0.20   | 0.67±0.05  | 0.006±0.002  | 0.35±0.005      |
| Perseus      | 0.037±0.008| 34±12       | 0.86±0.10  | 0.062±0.002  | 3.6±0.3         |
| 2A0335+096   | 0.092±0.222| 1.27±0.94   | 1.07±0.28  | 0.13±0.12    | 7.2±13.3        |
| A478         | 0.17±0.36  | 7.93±10.53  | 1.19±0.31  | 2.78±2.03    | 158±1140        |
| MS0735.6+7421| 0.15±0.34  | 19±60       | 1.09±0.30  | 5.26±4.61    | 298±261         |
| PKS0745-191  | 0.17±0.37  | 25±70       | 1.09±0.29  | 8.23±7.33    | 466±5630        |
| Hydra A      | 0.11±0.25  | 11±7        | 1.69±0.20  | 2.10±1.76    | 119±109         |
| Zw 2701      | 0.19±0.43  | 36±24       | 1.16±0.21  | 16.53±14.52  | 937±6450        |
| Zw 3146      | 0.27±0.55  | 5.72±3.47   | 1.11±0.30  | 4.89±4.25    | 270±3500        |
| MB8          | 0.015±0.027| 9.86±2.35   | 1.01±0.02  | 0.016±0.015  | 0.88±12.20      |
| M87          | 0.15±0.46  | 8.16±1.87   | 1.36±0.24  | 2.60±2.26    | 148±196         |
| Centaurus    | 0.080±0.188| 2.19±0.34   | 0.85±0.09  | 0.15±0.12    | 8.3±55.2        |
| HCG 62       | 0.020±0.050| 4.16±0.21   | 1.00±0.24  | 0.020±0.019  | 1.1±1.1         |
| A1795        | 0.062±0.039| 1.17±0.20   | 1.11±0.06  | 0.053±0.047  | 3.1±2.7         |
| A1835        | 0.20±0.12  | 7.00±3.96   | 1.10±0.21  | 3.36±2.97    | 191±1610        |
| PKS1404-267  | 0.027±0.061| 9.02±4.10   | 0.86±0.05  | 0.068±0.009  | 3.9±31.4        |
| A2029        | 0.067±0.146| 1.72±0.27   | 1.97±0.13  | 0.12±0.10    | 7.0±58.1        |
| A2052        | 0.11±0.26  | 0.53±0.60   | 0.60±0.06  | 0.057±0.050  | 3.2±29.8        |
| MKS 38       | 0.061±0.143| 1.02±1.13   | 1.08±0.29  | 0.045±0.070  | 2.5±26.6        |
| A2199        | 0.073±0.160| 3.81±4.85   | 1.29±0.07  | 0.26±0.26    | 15±151          |
| Hercules A   | 0.077±0.187| 1.28±2.00   | 1.09±0.28  | 0.089±1.125  | 5.1±66.7        |
| 3C388        | 0.069±0.162| 0.65±1.27   | 2.13±0.23  | 0.053±0.062  | 3.0±34.1        |
| Cygnus A     | 0.074±0.145| 3.39±0.71   | 1.13±0.30  | 0.25±0.185   | 14±7.5          |
| Sersic 159/03| 0.061±0.149| 1.02±0.68   | 1.06±0.28  | 0.046±0.014  | 2.6±12.6        |
| A2597        | 0.086±0.226| 13±1.3     | 0.5±0.24   | 0.047±0.040  | 2.6±9.9         |
| A4059        | 0.29±0.062 | 4.28±2.32   | 0.98±0.07  | 4.14±3.43    | 235±194         |
### Table 4. Jet Propagation (FR I type).

| System          | \( \mathcal{R}_{\text{jet}}^1 (r = 1 \text{kpc}) \) | \( \mathcal{R}_{\text{bou}}^1 \) (kpc) | \( \mathcal{R}_{\text{bou}}^2 \) (kpc) | \( \mathcal{R}_{\text{jet}}^0 (r = 1 \text{kpc}) \) | \( \mathcal{R}_{\text{bou}}^0 \) (kpc) |
|-----------------|-----------------------------|--------------------------|--------------------------|-----------------------------|--------------------------|
| A85             | 7.89 ± 0.39                | 0.24 ± 0.13             | 0.060 ± 0.313            | 7.02 ± 0.47                | 0.31 ± 0.14             |
| A133            | 0.25 ± 0.05                | 3.90 ± 1.79             | 0.027 ± 0.13             | 0.14 ± 0.02                | 3.90 ± 1.80             |
| A262            | 2.1 ± 0.95                 | 0.62 ± 0.26             | 0.59 ± 3.54              | 1.82 ± 0.83                | 0.71 ± 0.27             |
| Perseus         | 5.76 ± 0.60                | 0.31 ± 0.12             | 2.48 ± 15.55             | 3.08 ± 0.81                | 0.56 ± 0.07             |
| 2A 0335+096     | 2.94 ± 0.58                | 0.48 ± 0.22             | 0.098 ± 0.088            | 2.93 ± 0.27                | 0.50 ± 0.09             |
| A478            | 5.16 ± 0.38                | 0.31 ± 0.30             | 0.033 ± 0.047            | 3.30 ± 0.13                | 0.52 ± 0.05             |
| MS 0735.6+7421  | 0.031 ± 0.051              | 21.86 ± 3.94            | 0.037 ± 0.17             | 0.006 ± 0.004              | 21.84 ± 1.96            |
| PKS 0745-191    | 0.82 ± 0.14                | 1.18 ± 0.94             | 0.066 ± 0.056            | 0.19 ± 0.12                | 2.56 ± 0.57             |
| Hydra A         | 0.39 ± 0.08                | 3.56 ± 3.60             | 0.017 ± 0.014            | 0.33 ± 0.06                | 3.56 ± 1.07             |
| Zw 2701         | 0.29 ± 0.18                | 6.85 ± 10.97            | 0.020 ± 0.017            | 0.061 ± 0.039              | 6.96 ± 10.87            |
| Zw 3146         | 0.09 ± 0.071               | 4.56 ± 1.75             | 0.060 ± 0.056            | 0.045 ± 0.030              | 5.08 ± 2.58             |
| M8              | 5.33 ± 0.76                | 0.033 ± 0.053           | 0.002 ± 0.001            | 0.000 ± 0.005              | 0.001 ± 0.000           |
| M87             | 4.21 ± 0.78                | < 0.08                  | 0.014 ± 0.004            | 0.072 ± 0.04                | 0.000 ± 0.000           |
| Centaurus       | 5.24 ± 0.176               | 0.23 ± 0.11             | 0.066 ± 0.056            | 0.047 ± 0.024               | 0.000 ± 0.000           |
| HCG 62          | 10.01 ± 35.21              | 0.40 ± 0.28             | 0.033 ± 0.028            | 0.047 ± 0.024               | 0.000 ± 0.000           |
| A1795           | 0.67 ± 0.39                | 1.20 ± 0.28             | 0.034 ± 0.030            | 0.066 ± 0.056               | 0.000 ± 0.000           |
| A1835           | 0.35 ± 0.40                | 1.92 ± 0.73             | 0.017 ± 0.013            | 0.017 ± 0.005               | 0.000 ± 0.000           |
| PKS 1404-267    | 8.23 ± 0.72                | 0.20 ± 0.08             | 0.042 ± 0.038            | 0.420 ± 0.29                | 0.420 ± 0.29            |
| A2029           | 4.35 ± 0.71                | 0.45 ± 0.05             | 0.054 ± 0.048            | 0.431 ± 0.51                | 0.46 ± 0.06             |
| A2052           | 0.078 ± 0.043              | +∞                      | 0.036 ± 0.021            | 0.0073 ± 0.020              | +∞                      |
| MKW 3S          | 0.15 ± 0.09                | 3.50 ± 2.74             | 0.24 ± 1.32              | 0.15 ± 0.07                | 3.50 ± 2.74             |
| A2199           | 0.76 ± 0.71                | 1.25 ± 0.85             | 0.14 ± 0.72              | 0.74 ± 0.55                | 1.25 ± 0.84             |
| Hercules A      | 0.006 ± 0.002              | 42.86 ± 35.78           | 0.11 ± 0.11              | 0.003 ± 0.001              | 42.80 ± 35.89           |
| 3C 388          | 0.50 ± 0.34                | 1.65 ± 2.41             | 0.019 ± 0.013            | 0.050 ± 0.017              | 1.65 ± 2.41             |
| Cygnus A        | 0.08 ± 0.003               | 3.64 ± 0.34             | 0.23 ± 0.20              | 0.083 ± 0.014              | 3.64 ± 0.34             |
| Sersic 15903    | 0.10 ± 0.05                | 4.15 ± 1.11             | 0.30 ± 0.27              | 0.065 ± 0.033              | 4.51 ± 1.10             |
| A2597           | 3.37 ± 1.90                | 0.41 ± 0.40             | 0.047 ± 0.044            | 0.96 ± 0.56                | 1.09 ± 0.07             |
| A4059           | 2.39 ± 1.54                | 0.45 ± 0.44             | 0.010 ± 0.007            | 0.81 ± 0.84                | 0.94 ± 0.38             |
### Table 5. Jet Propagation (FR II type).

| System | Low-Temperature ($P_i = P_{i,\text{obs}}$) | Isentropic ($P_i = P_{i,\text{obs}}$) |
|--------|------------------------------------------|-------------------------------------|
|        | $R_{\text{jet}}^I(r = 1 \text{ kpc})$ | $r_{\text{bueo}}$ | $R_{\text{jet}}^I(r = 1 \text{ kpc})$ | $r_{\text{bueo}}$ | $R_{\text{jet}}^I(r = 1 \text{ kpc})$ | $r_{\text{bueo}}$ |
| A85    | 114.29±15.14 | < 0.17 | 0.88±0.75 | > 0.38 | 71.30±15.25 | 0.18±0.07 |
| A133   | 5.08±1.02    | 0.43±0.12 | 0.55±0.67 | > 0.46 | 1.18±0.11 | 0.94±0.32 |
| A262   | 45.59±20.74  | 0.20±0.08 | 12.77±13.17 | 0.53±0.50 | 25.43±12.90 | 0.29±0.08 |
| Perseus | 93.68±37.71  | 0.19±0.07 | 40.28±44.91 | 0.18±0.28 | 14.87±7.49 | 0.39±0.10 |
| AG37   | 51.24±24.42  | 0.16±0.09 | 1.71±1.91 | 0.77±0.50 | 47.51±12.97 | 0.21±0.20 |
| A478   | 82.17±39.54  | < 0.18 | 0.52±0.40 | > 0.48 | 21.25±9.67 | 0.32±0.31 |
| MS 0735+7421 | 0.53±0.92 | < 0.24 | 0.63±0.47 | > 0.43 | 0.20±0.04 | +∞ |
| PKS 0745-191 | 13.99±7.35 | 0.26±0.16 | 0.51±0.44 | > 0.47 | 0.82±0.48 | 1.25±0.66 |
| Hydra A | 5.49±2.18 | 0.39±0.10 | 0.92±0.87 | > 0.33 | 2.83±0.86 | 0.65±0.66 |
| Zw 2701 | 4.69±3.08 | 0.41±0.32 | 0.30±0.29 | > 0.56 | 0.28±0.17 | 5.07±3.61 |
| Zw 3146 | 1.58±1.12 | 0.81±0.12 | 0.33±0.25 | > 0.68 | 0.21±0.14 | 4.72±3.56 |
| M84    | 152.58±27.85 | 0.02±0.01 | 1.73±1.58 | 0.24±0.19 | 152.58±271.85 | 0.03±0.05 |
| M87    | 101.17±45.33 | < 0.03 | 0.04±0.21 | +∞ | 101.17±19.08 | < 0.06 |
| Centaurus | 114.57±42.52 | 0.08±0.02 | 1.02±0.27 | 0.98±0.69 | 100.06±44.12 | 0.14±0.06 |
| HCG 62 | 216.53±36.95 | 0.05±0.17 | 7.51±6.96 | 0.27±0.19 | 216.53±156.81 | 0.07±0.08 |
| A1795 | 10.50±6.11 | 0.35±0.12 | 5.35±4.66 | 0.50±0.31 | 5.53±3.13 | 0.54±0.11 |
| A1835 | 5.78±3.08 | 0.41±0.21 | 0.55±0.45 | 4.7±0.97 | 0.42±0.23 | 2.22±0.84 |
| PKS 1404-267 | 161.94±101.28 | 0.08±0.19 | 8.34±7.29 | 0.33±0.23 | 36.04±21.24 | 0.25±0.08 |
| A2029 | 51.09±8.91 | 0.20±0.18 | 6.40±5.01 | 0.47±0.29 | 42.12±12.66 | 0.25±0.24 |
| A2052 | 1.87±0.89 | 0.74±0.19 | 0.87±0.73 | > 0.37 | 1.31±0.29 | 0.89±0.08 |
| MKW 3S | 2.43±1.09 | 0.67±0.30 | 3.91±4.13 | 0.54±0.34 | 2.43±0.88 | 0.67±0.32 |
| A2199 | 11.86±5.32 | 0.30±0.11 | 2.21±1.73 | 0.67±0.44 | 9.15±4.96 | 0.42±0.12 |
| Hercules A | 0.10±0.04 | +∞ | 3.20±2.94 | 0.61±0.38 | 0.01±0.01 | +∞ |
| 3C 388 | 6.30±4.18 | 0.44±0.28 | 4.22±3.69 | 0.52±0.93 | 6.30±12.11 | 0.44±0.22 |
| Cygnus A | 1.14±0.10 | 0.90±0.06 | 3.07±2.90 | 0.62±0.34 | 0.80±0.21 | 1.21±0.21 |
| Sensic 159/03 | 1.71±1.11 | 0.88 | 5.16±4.58 | 5.11±3.02 | 0.50±0.26 | 2.23±1.07 |
| A2597 | 76.82±45.35 | 0.19±0.10 | 1.08±0.97 | 0.96±0.67 | 5.38±7.17 | 0.54±0.16 |
| A4059 | 44.18±30.25 | < 0.19 | 0.18±0.12 | > 0.87 | 13.83±8.10 | 0.35±0.34 |