ON THE ORIGIN OF X-RAY EMISSION IN SOME FR I GALAXIES: ADAF OR JET?

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ABSTRACT

We investigate the origin of X-ray emission in FR I galaxies using radio, submillimeter, optical, and Chandra X-ray data for a small sample of eight FR I sources. These sources are very dim, with X-ray luminosities $L_X/L_{Edd} \sim 10^{-4}$ to $10^{-8}$ (with $L_X$ the X-ray luminosity between 2 and 10 keV). We try to fit the multi–wave-band spectra using a coupled accretion-jet model. In this model, the accretion is described by an advection-dominated accretion flow (ADAF); in the innermost region of the ADAF, a fraction of the flow is transferred into the vertical direction and forms a jet. We find that X-ray emission in the source with the highest $L_X$ ($\sim 1.8 \times 10^{-4}L_{Edd}$) is from the ADAF. The results for the four sources with moderate $L_X$ ($\lesssim 10^{-6}L_{Edd}$) are more diverse. Two sources are dominated by the ADAF, one by the jet, and the other by the sum of the jet and ADAF. The X-ray emission in the three least luminous sources ($L_X \lesssim 1.0 \times 10^{-6}L_{Edd}$) is mainly from the jet, although for one source it can also be interpreted as the ADAF, since the quality of the X-ray data is low. We conclude that these results roughly support the prediction of Yuan & Cui that when the X-ray luminosity of a system is below some critical value, the X-radiation will not be dominated by the emission from the ADAF any longer, but by the jet. We also investigate the fuel supply in these sources. We find that the accretion rate in four of the five sources for which we have good constraints must be higher than the Bondi rate. This implies that another fuel supply, such as gas released by the stellar population inside the Bondi radius, should be important.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: nuclei — X-rays: galaxies

1. INTRODUCTION

FR I radio galaxies (defined by edge-darkened radio structure) have lower radio power than FR II galaxies (defined by edge-brightened radio structure due to compact jets terminating into hot spots) (Fanaroff & Riley 1974). What causes the morphological difference between FR I and FR II radio galaxies is still unclear. Different explanations for the division between FR I and FR II galaxies invoke either the interaction of the jet with the ambient medium or the intrinsic nuclear properties of accretion and jet formation processes (e.g., Bicknell 1995; Reynolds et al. 1996a; Gopal-Krishna & Wiita 2000). The mode of accretion in low-power FR I’s may be different from that in powerful FR II’s. There is growing evidence (Reynolds et al. 1996b; Donato et al. 2004; Gioiatti et al. 2003; Merloni et al. 2003) to suggest that most FR I–type radio galaxy nuclei, except for a few 3C FR I galaxies with obscured bright nuclei (Cao & Rawlings 2004), possess an advection-dominated accretion flow (ADAF) or “radiatively inefficient accretion flow” (Narayan & Yi 1994; 1995; for reviews, see Narayan et al. 1998; Kato et al. 1998). In fact, we now have strong observational evidence that ADAFs may power various types of low-luminosity AGNs (LLAGNs; e.g., Fabian & Rees 1995; Reynolds et al. 1996a; Quataert et al. 1999; Yuan et al. 2002; Ho et al. 2003; Ptak et al. 2004; Yuan & Narayan 2004; Nemmen et al. 2006; for reviews, see Yuan et al. 2005; Ho 2005; Yuan 2007) and our Galactic center’s Sgr A* (Yuan et al. 2003, 2006), not just FR I sources.

Even so, there are still many details that are unclear and require detailed investigation. One example is the relative contribution of ADAFs and jets at various wave bands in LLAGNs. For FR I’s and LLAGNs more generally, the least controversial nuclear emission is that in the radio band, which is believed to be dominated by the jet (e.g., Wu & Cao 2005). In the optical wave band, Hubble Space Telescope (HST) observations show that the optical luminosities of FR I’s correlate linearly with their radio nuclear luminosities very well, with little scatter. This, together with the high linear polarization from the nuclear optical emission, argues for a synchrotron (jet) origin for the nuclear optical emission (e.g., Chiaberge et al. 1999; Hardcastle & Worrall 1999). The correlation between the optical nuclear luminosity and radio nuclear luminosity suggests a dual population for FR I’s and LINERs (as well as Seyfert galaxies). Chiaberge et al. (2005, 2006) suggest that the optical emission of FR I’s comes from the jet, while the optical emission from LINERs and Seyfert galaxies is dominated by the accretion flow.

While we usually think that the X-ray emission of LLAGNs comes from the ADAF (e.g., Reynolds et al. 1996b; Quataert et al. 1999), recently it has been proposed that in some sources the emission from a jet may be responsible for the observed X-ray emission (e.g., NGC 4258, Yuan et al. 2002; IC 1459, Fabbiani et al. 2003; NGC 821, Pellegrini et al. 2007; M31, Garcia et al. 2005; see references in Yuan & Cui 2005). An important question is then systematically under what kinds of conditions the radiation from the jet will be important in the X-ray band.

There have been several papers aimed at answering this question. Almost all are based on the correlation between the radio and X-ray luminosities of black hole sources: $L_R \propto L_X^{0.6}$, where $L_R$ is the radio luminosity at 8.6 GHz and $L_X$ is the 2–11 keV X-ray luminosity. Such a correlation was originally found in the context of the hard state of black hole X-ray binaries (Corbel et al. 2003; Gallo et al. 2003; but see Xue & Cui 2007 and discussion below) and subsequently extended to include LLAGNs as well (Merloni et al. 2003; Falcke et al. 2004; Wang et al. 2006; Kording et al. 2006; Merloni et al. 2006). This correlation has sometimes been used to argue in favor of a common origin from the jet (e.g., Markoff et al. 2003; but see Heinz 2004). However, the correlation does not necessarily imply a common jet origin, because it is naturally expected if the mass accretion rate in the
ADAF is positively correlated with the mass-loss rate in the jet, as is very likely the case. On the other hand, the quantitative nature of the correlation does provide us with some important information on the physics of the accretion flow and jet and their relationship. For example, Merloni et al. (2003) argued that the X-ray emission from low-luminosity black hole sources, as used to establish the correlation, is most likely dominated by an ADAF rather than a standard thin disk or a jet.

Most sources in the sample of Merloni et al. (2003) have $L_X/L_{Edd} \sim 10^{-7}$ to $10^{-1}$. Based on Merloni et al.’s (2003) correlation result, Yuan & Cui (2005) investigated how the correlation will change at lower luminosities. For this purpose, they first used a coupled ADAF-jet model to explain the observed correlation (within the range $L_X/L_{Edd} \sim 10^{-7}$ to $10^{-1}$). The X-ray emission is modeled as thermal Comptonization in the ADAF, while the radio emission is modeled as being due to synchrotron emission in the jet. To quantitatively explain the correlation, they find that the ratio of the mass-loss rate in the jet to the mass accretion rate in the ADAF, $M_{\text{jet}}/M$, is not (but not far from) a constant with changing $M$. Extrapolating this ratio to lower $M$ or $L_X (< 10^{-7}L_{Edd})$ and assuming that the jet physics remains unchanged at the same time, they find that the X-ray emission of the system should be dominated by the jet when $L_X$ is lower than a critical value $L_{X,\text{crit}}$, determined by

$$\log \left( \frac{L_{X,\text{crit}}}{L_{Edd}} \right) = -5.356 - 0.17 \log \left( \frac{M}{1 M_\odot} \right).$$

The physical reason is that with a decrease in accretion rate, the X-ray radiation from both the ADAF and the jet will decrease. The former decreases faster, since it is roughly proportional to $M^2$, while the latter varies as $M$. Below a certain $M$ that corresponds to $L_{X,\text{crit}}$, the X-ray emission from the jet will dominate over the ADAF. In this low-$M$ regime, both the radio and X-ray emission are due to the jet, and thus the radio–X-ray correlation will change, with the correlation index changing from $\sim 0.6$ to $\sim 1.2$ (see also Heinz 2004). We wish to emphasize that the normalization of the correlation adopted in Yuan & Cui (2005) is based on the data for XTE J1118+480. Because of the large scatter in the correlation (see Merloni et al. 2003), and because of its statistical nature, for individual sources the exact value of $L_{X,\text{crit}}$ could be significantly different from that estimated by equation (1). The prediction thus only has statistical meaning.

Similarly to Yuan & Cui (2005), Fender et al. (2003) pointed out the important role of jets when the X-ray luminosity of the system, $L_X$, is very low. They compared the power of the jets, $P_{\text{jet}}$, and $L_X$. They found that when $L_X$ is lower than a critical value, $P_{\text{jet}}$ is larger than $L_X$. The difference between this work and that of Yuan & Cui (2005) is that the former compared $L_X$ with the total power of the jet $P_{\text{jet}}$ rather than the emitted X-ray luminosity from the jet.

The main aim of the present paper is to check the prediction of Yuan & Cui (2005). For this purpose, we selected a small sample from Donato et al. (2004) with $L_X/L_{Edd}$ ranging from $\sim 10^{-4}$ to $\sim 10^{-8}$. We wish to check whether the dominance of X-ray emission will change from ADAF to jet when the luminosity decreases.

Another reason we choose this sample is that we want to investigate the question of fuel supply. Observationally, we have good estimates of the Bondi accretion rate for all the sources in this sample. On the other hand, when the X-ray spectrum comes from an ADAF, we can obtain the required value of the mass accretion rate based on the accretion disk model. We thus can investigate how good the Bondi accretion rate is as an indicator of the accretion rate.

In §§2 and 3, we introduce the sample and the coupled ADAF-jet model, respectively. The modeling results are presented in §4, and the discussion and summary are in §§5 and 6. Throughout, we adopt $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. SAMPLE

The FR I sample used for the present investigation is selected from Donato et al. (2004). The sources in this sample have estimates of their black hole mass, Bondi accretion rate, and optical, radio, and X-ray nuclear emission. There are nine FR I’s in their sample that have compact core X-ray emission and have been observed by Chandra. We excluded 3C 270, since the optical emission may be obscured by its large intrinsic column density ($N_{HI} \sim 10^{22}$ cm$^{-2}$). Therefore, our final sample includes eight FR I galaxies (see Donato et al. 2004 for more details). We have compiled in Table 1 the nuclear luminosity obtained from the literature in the radio, submillimeter, infrared, optical, UV, and X-ray bands. This sample is ideal for us to check the prediction of Yuan & Cui (2005), since the range of X-ray luminosities is $\sim 10^{-4}L_{Edd}$ to $10^{-8}L_{Edd}$.

3. COUPLED ACCRETION-JET MODEL

We briefly describe the ADAF-jet model here. The reader can refer to Yuan et al. (2005) for details. The accretion flow is described by an ADAF. Over the past few years, both numerical simulations (Stone et al. 1999; Hawley & Balbus 2002; Iguemenchev et al. 2003) and analytical work (Narayan & Yi 1994, 1995; Blandford & Begelman 1999; Narayan et al. 2000; Quataert & Gruzinov 2000) have indicated that probably only a fraction of the gas that is available at large radii actually accretes onto the black hole. The rest is either ejected from the flow or is prevented from being accreted by convective motions. Following the proposal of Blandford & Begelman (1999), we parameterize the radial variation of the accretion rate with the parameter $\rho_w$, as $M = M_{\text{out}}(R/R_{\text{out}})^{\rho_w}$, where $M_{\text{out}}$ is the accretion rate at the outer boundary of the ADAF, $R_{\text{out}}$. We calculate the global solution for the ADAF. The viscosity parameters $\alpha$ and magnetic parameter $\beta$ (defined as the ratio of gas to total pressure in the accretion flow, $\beta = P_g/P_{\text{tot}}$) are fixed at $\alpha = 0.3$ and $\beta = 0.9$. Another parameter is $\delta$, describing the fraction of the turbulent dissipation that directly heats electrons. Following Yuan et al. (2006), we use $\delta = 0.3$ and $\rho_w = 0.25$ in all our calculations.

The radiative processes we consider include synchrotron emission, bremsstrahlung, and Comptonization of the two. We set the outer boundary of the ADAF at the Bondi radius, $R_B = 2GM_B/m_Bc^2$; $c_e = \sqrt{\gamma kT/m_B}$ is the adiabatic sound speed of the gas at the Bondi accretion radius, $T$ is the gas temperature at that radius, $\mu = 0.62$ is the mean atomic weight, $m_p$ is the proton mass, and $\gamma = 4/3$ is the adiabatic index of the X-ray–emitting gas. After the ADAF structure is obtained, the spectrum of the flow can be calculated (see, e.g., Yuan et al. 2003).

The jet model adopted in the present paper is based on the internal shock scenario, widely used in interpreting gamma-ray burst (GRB) afterglows (see Piran 1999; Spada et al. 2001). A fraction of the material in the accretion flow is assumed to be transferred into the vertical direction to form a jet. The jet is assumed to include equal numbers of protons and electrons. Since the velocity of the accretion flow is supersonic near the black hole, a standing shock should occur at the bottom of the jet because of bending. From the shock-jump conditions, we calculate the properties of the postshock flow, such as the electron temperature $T_e$. The jet is assumed to have a conical geometry with half-opening angle $\phi$ and bulk Lorentz factor $\Gamma_j$ that are independent of distance.
from the black hole. The internal shock in the jet should occur as a result of the collision of shells with different $\Gamma_j$. These shocks accelerate a small fraction of the electrons into a power-law energy distribution with index $p$. We assume that the fraction of accelerated electrons in the shock is $c_e$ and fix $\xi_e = 10\%$ in our calculations. Following the widely adopted approach in the study of GRBs, the energy density of accelerated electrons and the amplified magnetic field are described by two free parameters $c_e$ and $\xi_e$. Obviously, $\xi_e$ and $c_e$ are not independent. The half-opening angle of the jet is assumed to be $\phi = 0.1$ radians, which is a typical value for the inner jet in FR I galaxies but does not affect our results (see, e.g., Laing & Bridle 2002). We find that the Lorentz factor has only a modest effect on the best fit to the jet spectrum if it is in the typical range $\Gamma_j \sim 2-5$ (or $v/c < 0.9$) for FR I’s (e.g., Bondi et al. 2000; Verdoes Kleijn et al. 2002; Laing & Bridle 2002). Laing et al. (1999) also concluded that the typical on-axis velocity of the inner jet is $v/c \sim 0.9$ for FR I’s. For simplicity, we set $\Gamma_j = 2.3$ (corresponding to $v/c = 0.9$) in the calculations of the jet spectra if there is no estimate of the Lorentz factor.

We consider only synchrotron emission in the jet spectrum calculation, since Compton scattering is probably not important in these FR I sources, for several reasons. First, our calculations show that the synchrotron self-Compton in the jet is several orders of magnitude less than the synchrotron emission in these FR I’s, since the ratio of the photon energy density to the magnetic field energy density is very low (shown by thin long-dashed lines in the figures below). Secondly, Compton scattering of the external photons from the disk and emission lines should also not be important, because the disk emission is rather low and there may be a lack of broad emission lines in FR I’s (e.g., Chiaberge et al. 1999). Third, the inverse Compton scattering of cosmic microwave radiation should be unimportant for these FR I’s, since this mechanism requires high-velocity bulk motion of the jet, which may be present only in powerful FR II radio galaxies (e.g., Celotti et al. 2001).

We treat the mass-loss rate into the jet, $\dot{M}_{\text{jet}}$, and accretion rate in the accretion flow, $\dot{M}_{\text{ac}}$, as free parameters when fitting the spectrum, since the jet formation mechanism is still unclear. The other free parameters in the spectral fitting are the electron energy

| Filter     | log $\nu$ | log $\nu_{L_{\text{W}2}}$ | Resolution$^a$ | Reference |
|------------|-----------|----------------|-----------------|-----------|
| 3C 346     |           |                 |                 |           |
| 1.7 GHz    | 9.23      | 41.26           | $\sim 1\text{ mas}$ | 1         |
| 5 GHz      | 9.70      | 41.90           | $\sim 1''$     | 2         |
| 8 GHz      | 9.92      | 42.13           | $\sim 1\text{ mas}$ | 1         |
| F702W      | 14.63     | 43.14           | $\sim 0.1''$   | 3         |
|           |           |                 |                 |           |
| B2 0755+37 |           |                 |                 |           |
| 1.7 GHz    | 9.23      | 40.03           | $\sim 1''$     | 4         |
| 5 GHz      | 9.70      | 40.72           | $\sim 1''$     | 5         |
| F702W      | 14.63     | 42.04           | $\sim 0.1''$   | 5         |
| 3C 31      |           |                 |                 |           |
| 1.7 GHz    | 9.23      | 38.75           | $\sim 5\text{ mas}$ | 6         |
| 5 GHz      | 9.70      | 39.46           | $\sim 1\text{ mas}$ | 7         |
| 8.6 GHz    | 9.93      | 39.70           | $\sim 1''$     | 8         |
| 345 GHz    | 11.53     | 41.22           | $\sim 50''$    | 9         |
| F555W      | 14.57     | 40.86           | $\sim 0.1''$   | 10        |
| F814W      | 14.73     | 40.85           | $\sim 0.1''$   | 10        |
| 3C 317     |           |                 |                 |           |
| 1.7 GHz    | 9.23      | 40.19           | $\sim 1\text{ mas}$ | 11        |
| 5 GHz      | 9.70      | 40.73           | $\sim 1\text{ mas}$ | 11        |
| F210M      | 15.13     | 40.46           | $\sim 0.1''$   | 5         |
| F702W      | 14.63     | 41.37           | $\sim 0.1''$   | 5         |
| F160W      | 14.27     | 41.79           | $\sim 0.1''$   | 12        |
| B2 0055+30 |           |                 |                 |           |
| 5 GHz      | 9.70      | 40.26           | $\sim 1''$     | 13        |
| F814W      | 14.57     | 41.18           | $\sim 0.1''$   | 5         |
| 3C 66B     |           |                 |                 |           |
| 1.7 GHz    | 9.23      | 39.43           | $\sim 5\text{ mas}$ | 6         |
| 5 GHz      | 9.70      | 39.97           | $\sim 1\text{ mas}$ | 7         |
| 345 GHz    | 11.54     | 41.50           | $\sim 50''$    | 9         |
| LW1        | 13.82     | 42.54           | $\sim 1''$     | 9         |
| LW2        | 13.32     | 42.33           | $\sim 1''$     | 9         |
| LW3        | 13.40     | 42.54           | $\sim 1''$     | 9         |
| F814W      | 14.57     | 41.60           | $\sim 0.1''$   | 5         |
| 3C 449     |           |                 |                 |           |
| 1.5 GHz    | 9.17      | 38.26           | $\sim 1''$     | 14        |
| 5 GHz      | 9.70      | 39.08           | $\sim 1''$     | 14        |
| 8.3 GHz    | 9.92      | 39.37           | $\sim 1''$     | 14        |
| F702W      | 14.63     | 40.82           | $\sim 0.1''$   | 5         |
| 3C 272.1   |           |                 |                 |           |
| 1.7 GHz    | 9.23      | 37.72           | $\sim 1\text{ mas}$ | 15        |
| 5 GHz      | 9.70      | 38.30           | $\sim 1''$     | 2         |
| 8.1 GHz    | 9.90      | 38.48           | $\sim 1\text{ mas}$ | 15        |
| 146 GHz    | 11.17     | 39.64           | $\sim 10''$    | 16        |
| 221 GHz    | 11.34     | 39.82           | $\sim 10''$    | 16        |
| 345 GHz    | 11.53     | 39.96           | $\sim 10''$    | 9         |
| 350 GHz    | 11.54     | 40.10           | $\sim 10''$    | 16        |
| 677 GHz    | 11.82     | 40.16           | $\sim 10''$    | 16        |
| LW3        | 13.32     | 40.31           | $\sim 1''$     | 9         |
| LW7        | 13.49     | 40.57           | $\sim 1''$     | 9         |
| LW2        | 13.65     | 40.94           | $\sim 1''$     | 9         |
| L           | 13.93     | 40.53           | $\sim 1''$     | 9         |
spectral index \( p \), and the electron and magnetic energy parameters \( \epsilon_e \) and \( \epsilon_B \). We use the dimensionless accretion rate \( \dot{m} = \dot{M}/\dot{M}_{\text{Edd}} \) throughout the paper. Consistency between the ADAF and jet models is ensured by checking whether the value of \( \dot{M}_{\text{jet}}/\dot{M}_{\text{out}} \) or, more precisely, \( \dot{M}_{\text{jet}}/(10R_S) \) (see next section) is reasonable.

4. RESULTS OF SPECTRAL FITTING

We use the ADAF-jet model to fit the spectrum of the sources in our sample. As stated in \( \S \) 1, the radio emission, and perhaps the optical as well, is from the jet. Although the jet model is more uncertain than the ADAF, based on the assumptions for the jet model described in \( \S \) 3, the contribution of the jet to the X-ray band is well constrained once we require that the jet explain the radio and optical spectra. We then adjust the parameter of the ADAF and combine it with the jet contribution to fit the X-ray spectrum.

4.1. 3C 346

The radio morphology and power of 3C 346 would rank it as either a low-power FR II source or a high-power FR I (e.g., Spencer et al. 1991). Cotton et al. (1995) used the radio core dominance seen with very long baseline interferometry (VLBI) and the jet-to-counterjet ratio to argue for a jet viewing angle of \( \lesssim 32^\circ \) and a speed in excess of \( 0.8c \). Chandra observations have detected an unresolved core with \( 2-10 \text{ keV} \) luminosity of \( 1.9 \times 10^{44} \text{ ergs s}^{-1} \) and photon index of \( \Gamma = 1.69^{+0.09}_{-0.07} \) (Donato et al. 2004). An X-ray knot is also detected by Chandra with photon index \( \Gamma = 2.0 \pm 0.3 \) and no intrinsic absorption, which roughly corresponds to the brightest radio and optical knot (Worrall & Birkinshaw 2005).

Figure 1 shows the fit result. The dashed, dot-dashed, and solid lines show the emission from the jet and the ADAF and their sum, respectively. The parameters of the jet are \( \dot{m}_{\text{jet}} = 3.5 \times 10^{-5}, \epsilon_e = 0.14, \epsilon_B = 0.02, \) and \( p = 2.4 \). We find that the jet model can describe the nuclear radio and optical emission well. But the X-ray emission of the jet model is lower than the Chandra observations by a factor of several. The X-ray emission can be well fitted by the underlying ADAF. The required accretion rate is \( \dot{m}_{\text{out}} = 2.8 \times 10^{-2} \). The ratio of the mass-loss rate in the jet to the accretion rate of the ADAF at \( 10R_S \) is about \( \dot{m}_{\text{jet}}/\dot{m}_{\text{out}}(10R_S) = 0.9\% \), where \( R_S \) is the Schwarzschild radius.

This source is relatively luminous, with \( L_{\text{X}}/L_{\text{Edd}} = 1.8 \times 10^{-4} \). The X-ray luminosity is well above the critical luminosity defined in equation (1). Thus, according to Yuan & Cui (2005), the X-ray emission should be dominated by the ADAF rather than the jet. Our modeling confirms this prediction.

4.2. B2 0755+37

B2 0755+37 is a well-studied nearby FR I galaxy (\( z = 0.0428 \)) with two large symmetric lobes and very asymmetric jets. The inferred velocity of the jet is \( \sim 0.9c \) (\( 1^\circ \) from the core, \( \sim 0.5 \) kpc), and the viewing angle is about \( 30^\circ \) (Bondi et al. 2000). In the optical band, the galaxy has a rather smooth appearance without any sign of dust obscuration, and a bright optical nucleus is seen at its center (Capetti et al. 2002). An optical jet is also detected, and the optical brightness profile is similar to that in the radio band (Parma et al. 2003). A power-law fit to the nuclear emission observed by Chandra results in a power-law index \( \Gamma = 2.18^{+0.28}_{-0.19} \) and \( 2-10 \text{ keV} \) luminosity of \( 6.1 \times 10^{41} \text{ ergs s}^{-1} \sim 5.2 \times 10^{-6}L_{\text{Edd}} \) (Donato et al. 2004).

Figure 2 shows the fit result for B2 0755+37. The dashed line shows the jet emission. The parameters are \( \dot{m}_{\text{jet}} = 1.75 \times 10^{-5}, \epsilon_e = 0.12, \epsilon_B = 0.01, \) and \( p = 2.23 \). We find that the jet model can well describe not only the radio and optical spectra, but also the X-ray spectrum.

The dot-dashed line shows the emission from the ADAF model, with \( \dot{m}_{\text{out}} = 8.9 \times 10^{-3} \). This of course is not a “fit.” We show this result to illustrate that an ADAF would predict a much harder X-ray spectrum than observed. This is additional evidence for
the contributions from the ADAF and the jet are comparable. They inferred that the radio, optical, and even the soft X-ray nuclear emission can be well fitted by a jet model. However, the X-ray spectrum cannot be well fitted by the pure jet or underlying ADAF alone. Rather, it can be well fitted by their sum. The required accretion rate of the ADAF is $\dot{m}_{\text{out}} = 4.7 \times 10^{-3}$. The central compact core is also detected by Chandra with $2-10$ keV power-law luminosity $2.97 \times 10^{41}$ ergs s$^{-1}$ ($\sim 3.4 \times 10^{-6}L_{\text{Edd}}$) and photon index $\Gamma = 1.81^{+0.13}_{-0.11}$ (Donato et al. 2004).

Figure 4 shows the fit result for 3C 317. The parameters of the jet are $\dot{m}_{\text{jet}} = 1.7 \times 10^{-5}$, $\epsilon_e = 0.2$, $\epsilon_B = 0.15$, and $p = 2.25$. It is difficult to fit the radio and optical emission simultaneously, because of the steep optical-UV spectrum. Since the UV flux is very sensitive to the extinction, such a steep spectrum might not be intrinsic. We therefore used the $R$ band (F702W) in our fits, which is less susceptible to extinction than the UV band and less contaminated by possible dust emission than the near-infrared ($H$ band, F160W). The radio, optical, and even soft X-ray (e.g., 1 keV) emission can be fitted with a jet model. The hard X-ray spectrum cannot be well fitted by the pure jet or underlying ADAF alone. Rather, it can be well fitted by their sum. The required accretion rate of the ADAF is $\dot{m}_{\text{out}} = 4.7 \times 10^{-3}$.

4.5. B2 0055+30

The source B2 0055+30 (=NGC 315) is associated with a giant elliptical galaxy at a redshift of 0.0168, which has a two-sided structure extending roughly $1^\circ$ on the sky (Bridge et al. 1979). Canvin et al. (2005) applied a symmetric, decelerating, relativistic jet model to fit the radio jet and derived an inclination to the line of sight of $38^\circ \pm 2^\circ$ and an on-axis velocity $\beta = v/c \sim 0.9$. The jet is also detected by Chandra, with a power-law index $\Gamma = 1.5 \pm 0.7$ (Worrall et al. 2003). The $2-10$ keV nuclear luminosity detected by Chandra is $5.1 \times 10^{41}$ ergs s$^{-1}$ ($\sim 2.4 \times 10^{-6}L_{\text{Edd}}$) with photon index $\Gamma = 1.56^{+0.15}_{-0.05}$ (Donato et al. 2004).

Figure 5 shows the fit result for B2 0055+30. The parameters of the jet are $\dot{m}_{\text{jet}} = 7.0 \times 10^{-6}$, $\epsilon_e = 0.05$, $\epsilon_B = 0.02$, and $p = 2.2$. One can see from the figure that the radio and optical emission can be well fitted by the jet model. However, the X-ray spectrum is too hard to be fitted by the jet, but it can be well fitted by an ADAF with accretion rate $\dot{m}_{\text{out}} = 2.7 \times 10^{-3}$. The ratio $\dot{m}_{\text{jet}}/\dot{m}(10R_\odot)$ is about 3.5%.
The source 3C 66B has a redshift of 0.0212 and is associated with a 13th magnitude elliptical galaxy in a small group in the vicinity of the cluster Abell 347. A two-sided inner radio jet is seen, with both jets curving toward the east to a distance more than 20″–30″ from the core (Leahy et al. 1986). HST observed the optical jet on scales of ~0.1″ (Macchetto et al. 1991). The jet also has been imaged with the Infrared Space Observatory (ISO) and Chandra (Tansley et al. 2000; Hardcastle et al. 2001). The multiwavelength extended jet emission can be well fitted as synchrotron emission (e.g., Tansley et al. 2000). The pointlike nucleus is detected by Chandra with 2–10 keV luminosity 1.1 × 10^{41} erg s^{-1} (−1 × 10^{41} L_{\text{Edd}}) and photon index 2.17^{+0.14}_{-0.15} (e.g., Donato et al. 2004).

Figure 6 shows the fit result for the nucleus of 3C 66B. We find that the radio, submillimeter, optical, and X-ray emission can all be fitted very well by a pure jet model (dashed line). The parameters of the jet are \( \dot{m}_{\text{jet}} = 1 \times 10^{-5} \), \( \epsilon_{e} = 0.18 \), \( \epsilon_{B} = 0.02 \), and \( \rho = 2.35 \). For illustration purposes, we also show the X-ray emission using an ADAF model with \( \dot{m}_{\text{out}} = 2.6 \times 10^{-3} \) (dot-dashed line). One can see that the predicted spectrum from an ADAF is too hard to be consistent with the observations (so the accretion rate in the ADAF should be smaller than 2.6 × 10^{-3}). The X-ray emission in this source should be from the jet.

The source 3C 66B is a low-redshift (z = 0.0171), twin-jet FR I–type radio galaxy that is hosted by the elliptical galaxy UGC 12064. Its symmetric inner jets have been well studied in radio observations (e.g., Feretti et al. 1999). On large scales, the southern jet flares into a lobe, while the northern jet continues to be well collimated until it fades into the noise (e.g., Andernach et al. 1992; Feretti et al. 1999). From application of the adiabatic model to the jet, evidence of strong jet deceleration within 10″ (5 kpc) from the nucleus is found. A satisfactory fit to the data is found assuming an initial jet velocity 0.9c and a jet inclination to the line of sight of 82.5° (e.g., Feretti et al. 1999). The nucleus is an unresolved point source from HST observations (e.g., Martel et al. 1999). Chandra observations reveal an X-ray central compact core with a power-law photon index \( \Gamma = 1.67^{+0.45}_{-0.46} \), and the 2–10 keV power-law luminosity is less than 2.9 × 10^{40} erg s^{-1} (~8 × 10^{40} L_{\text{Edd}}) (Evans et al. 2006). Evans et al. showed that the X-ray luminosity observed by Chandra is several times lower than that measured by XMM-Newton, and its photon index is also flatter than the \( \Gamma = 2.13^{+0.65}_{-0.55} \) from XMM-Newton (Donato et al. 2004). Although variability is a possible explanation for the differences observed by Chandra and XMM-Newton, it also may be due to the different resolution of the telescopes. The spectrum is extracted in a smaller circle (radius typically 2.5 pixels, or 1.23″) in the case of Chandra than the 35″ for XMM-Newton (Evans et al. 2006). Chandra observations should reflect the intrinsic nuclear X-ray emission, while the XMM-Newton observation may be contaminated by the X-ray jet emission or X-ray binaries.

Since the observational error in the X-ray photon index is very large, we also tried to fit the X-ray emission with the sum of a jet and an ADAF. The thin short-dashed and dot-dashed lines show the emission from the jet and the ADAF, respectively, and the solid line shows their sum. The parameters of the jet are \( \dot{m}_{\text{jet}} = 2.0 \times 10^{-3} \), \( \epsilon_{e} = 0.35 \), \( \epsilon_{B} = 0.01 \), and \( \rho = 2.4 \). The accretion rate of the ADAF is \( \dot{m}_{\text{out}} = 1.9 \times 10^{-3} \). One can see that the X-ray emission can also be fitted (slightly better, thanks to more free parameters) by the sum of the ADAF and jet. The value of \( \dot{m}_{\text{jet}}/ \dot{m}_{\text{Edd}}(10R_{S}) \) is about 14.3%. Higher quality X-ray data are desirable to further constrain the origin of the X-ray emission in 3C 449.

The source 3C 272.1 (=M84 = NGC 4374) is an E1 galaxy in the core of the Virgo Cluster (z = 0.0029). Radio observations at...
1.4 and 4.9 GHz show two lobes and a jet (Laing & Bridle 1987). In the SCUBA 850 μm submillimeter image, the galaxy is found to be a point source (diameter less than 15″, or 1.5 kpc). The submillimeter emission was suggested to be from the inner jet, or the thermal emission of cold diffuse dust (Leeuw et al. 2000). The HST showed that the optical-to-UV continuum is very red, similar to the spectral energy distribution of BL Lac (Bower et al. 2000). The Chandra image shows that the soft X-ray emission has a very disturbed morphology. Donato et al. (2004) defined this source as a candidate compact core X-ray source, since its radial profile cannot be fitted with a β-model. The 2–10 keV luminosity is $2.2 \times 10^{39}$ ergs$^{-1}$ ($\sim 6.8 \times 10^{-8} L_{\text{Edd}}$) with photon index $\Gamma = 2.14 \pm 0.34$ (Evans et al. 2006).

Figure 8 shows the fit result for the nucleus of 3C 272.1. The parameters of the jet are $\dot{m}_{\text{jet}} = 4.9 \times 10^{-6}$, $e_p = 0.28$, $e_B = 0.005$, and $p = 2.5$. One can see that the radio, submillimeter, optical, and, especially, X-ray emission can be fitted by the jet model very well. On the other hand, the spectrum of the jet from an ADAF (with $\dot{m}_{\text{out}} = 1.9 \times 10^{-3}$) is too hard to be consistent with the observations. So in this source, the X-ray emission is dominated by a jet.

5. DISCUSSION

In this paper we have investigated the origin of the X-ray emission in a small sample of FR I galaxies from Donato et al. (2004). The accretion flow in these objects is generally believed to be described by an ADAF rather than a standard thin disk, since the Bondi accretion rates (which should be a lower limit; see discussion below) would produce a luminosity several orders of magnitude higher than that observed if we assume a standard thin disk with an efficiency of $\sim 0.1$ as in a standard thin disk. Two possibilities exist for the X-ray origin in FR I galaxies—ADAF and jet. We used a coupled ADAF-jet model to fit the multiwave-band spectra to try to investigate this problem. More specifically, we wanted to examine the prediction of Yuan & Cui (2005) that, statistically, the X-ray emission in LLAGNs should be dominated by ADAFs when their X-ray luminosity is higher than a few times $10^{-7} L_{\text{Edd}}$ but will be dominated by a jet when the luminosity is lower than this value.

We find that a jet can well describe the radio and optical spectra for all the galaxies in our sample except the optical-UV spectrum of 3C 317 (see § 4.4). The soft X-ray flux at $\sim 1$ keV for all these FR I’s is roughly consistent with the predictions for a jet. This result indicates why a tight correlation is found among radio, optical, and soft X-ray emission (e.g., Chiaberge et al. 1999; Evans et al. 2006; Balmaverde et al. 2006).

For the source with the highest luminosity in our sample, 3C 346, which has $L_X = 1.8 \times 10^{-4} L_{\text{Edd}}$, the X-ray spectrum is dominated by the ADAF and the jet contribution is negligible. However, for the four sources with “intermediate” luminosities [B2 0755+37, 3C 31, 3C 317, and B2 0055+30; $L_X = (2.4−5.2) \times 10^{-6} L_{\text{Edd}}$], the origin of the X-rays is complicated. The X-ray spectrum of B2 0755+37 is dominated by the jet, while those of 3C 31 and B2 0055+30 are dominated by the ADAF. For the remaining one (3C 317), the contributions of the ADAF and jet are comparable. For the three least luminous sources (3C 66B, 3C 449, and 3C 272.1), which have $L_X = 6.8 \times 10^{-8} L_{\text{Edd}}$ to $1 \times 10^{-6} L_{\text{Edd}}$, the X-ray spectra are dominated by the jet. The X-ray emission of 3C 449 is also interpreted as the sum of a jet and an ADAF, but higher quality data are required in order to further constrain it.

Our results are roughly consistent with the predictions of Yuan & Cui (2005). The “intermediate luminosity” here in our sample corresponds to the critical luminosity in Yuan & Cui (2005). However, the former is about 10 times higher than the latter. The value of the critical luminosity depends on the ratio of the mass-loss rate in the jet to the mass accretion rate in the ADAF. This ratio was determined in Yuan & Cui (2005) by fitting the data for a black hole X-ray binary—XTE J1118+480. The current results indicate that the ratio in FR I galaxies is about 10 times higher than in XTE J1118+480. This seems reasonable given that the
jets in FR I’s are systematically more powerful than those in normal LLAGNs. One possible reason could be that, systematically, the black holes in FR I’s spin more rapidly.

The sample we used in the present paper is rather small. Obviously, to systematically study the X-ray origin of FR I’s and more generally LLAGNs, a much larger sample is required, and this is our future work (F. Yuan et al. 2007, in preparation). We note that current results from the literature seem to support the prediction of Yuan & Cui (2005). In addition to the observational evidence listed in Yuan & Cui (2005), the X-ray emission of some LLAGNs claimed to be dominated by jets always have evidence listed in Yuan & Cui (2005), the X-ray emission of one should combine the radio and X-ray data at different luminosities only for A0620−00. Although we do have X-ray and radio observations during its 1975 outburst (Kuulkers 1998), we are unfortunately not able to convert the X-ray “counts” to physical flux, for instrumental reasons.

Typically, the Bondi accretion rate is a good estimate of the mass accretion rate. However, Pellegrini (2005) showed that there is no relation between the nuclear X-ray luminosity and Bondi accretion rate in LLAGNs, and the X-ray emission of some sources is higher than the values predicted by ADAFs with Bondi accretion rate. In this paper, the Bondi accretion rates in our sample have been estimated (Donato et al. 2004). We find that the accretion rates $\dot{m}_{\text{out}}$ required in our model for four FR I’s (3C 346, 3C 31, 3C 449, 3C 317) among the five for which we have good constraints on their accretion rates are higher than the Bondi rates by factors of 9, 11, 12, and 1.05, respectively. Given that the radial velocity of the accretion flow is $\alpha_{\text{cs}}$, a more accurate estimate of the accretion rate is $\dot{m}_{\text{out}} \sim \alpha \dot{m}_{\text{Bondi}}$, where $\alpha$ is the viscosity parameter (Narayan 2002). Therefore, the Bondi accretion rate is only a lower limit to the real rate and another fuel supply must be important, such as the gas released by the stellar population within the Bondi radius (Soria et al. 2006; Pellegrini 2007). In our calculation, given the theoretical uncertainties regarding the values of $p_{\text{out}}$ and $\delta$, we chose the values of these two parameters from the best-studied source, Sgr A* (Yuan et al. 2003, 2006), because we think the physics of accretion should be the same, independent of different sources. A higher $\delta$ and lower $p_{\text{out}}$ tend to require a smaller accretion rate. But we find that even though we use $\delta = 0.5$, which means that half of the viscous dissipation directly heats electrons, and $p_{\text{out}} = 0$, which means no outflow, the required accretion rates for 3C 346, 3C 31, and 3C 449 are still larger than their Bondi accretion rates. Therefore, another fuel supply must be important in these sources.

| Source       | Redshift | $\text{Angle}^c$ (deg) | $\log M_{\text{Bol}}^b$ | $L_{X}/L_{\text{Edd}}^e$ | $\dot{m}_{\text{jet}}$ | $\dot{m}(10R_{S})$ | Ratio$^d$ (%) | $\dot{m}(R_{S})^f$ | $\dot{m}_{\text{f}}^f$ | $L_{\text{kin}}/M(10R_{S})c^2$ |
|--------------|----------|------------------------|-------------------------|-------------------------|----------------------|------------------|----------------|------------------|------------------|----------------------|
| 3C 346       | 0.1620   | 30                     | 8.89                    | $1.8 \times 10^{-4}$   | $3.5 \times 10^{-5}$ | $4.4 \times 10^{-3}$ | 0.91          | $2.8 \times 10^{-2}$ | 3.1 $\times 10^{-3}$ | 0.03                 |
| B2 0755+37   | 0.0428   | 34                     | 8.93                    | $5.2 \times 10^{-6}$   | $1.75 \times 10^{-5}$ | $<4.5 \times 10^{-4}$ | $<3.9$        | $<8.9 \times 10^{-3}$ | 3.2 $\times 10^{-2}$ | $>0.10$              |
| 3C 31        | 0.0170   | 52                     | 7.89                    | $4.4 \times 10^{-6}$   | $2.7 \times 10^{-5}$ | $3.0 \times 10^{-4}$ | 0.90          | $3.7 \times 10^{-3}$ | 2.1 $\times 10^{-4}$ | 0.19                 |
| 3C 317       | 0.0345   | 50                     | 8.80                    | $3.4 \times 10^{-6}$   | $1.7 \times 10^{-5}$ | $1.9 \times 10^{-4}$ | 0.89          | $4.7 \times 10^{-3}$ | 4.5 $\times 10^{-3}$ | 0.28                 |
| B2 0055+03   | 0.0165   | 35                     | 9.18                    | $2.4 \times 10^{-6}$   | $7.0 \times 10^{-5}$ | $2.0 \times 10^{-4}$ | 3.5           | $2.7 \times 10^{-3}$ | 1.4 $\times 10^{-2}$ | 0.08                 |
| 3C 66B       | 0.0213   | 45                     | 8.84                    | $1.0 \times 10^{-6}$   | $1.0 \times 10^{-5}$ | $<1.7 \times 10^{-4}$ | $<5.9$        | $<2.6 \times 10^{-3}$ | 2.5 $\times 10^{-2}$ | $>0.18$              |
| 3C 449       | 0.0171   | 80                     | 8.42                    | $8.0 \times 10^{-7}$   | $2.0 \times 10^{-5}$ | $1.4 \times 10^{-4}$ | 14.3          | $1.9 \times 10^{-3}$ | 1.7 $\times 10^{-5}$ | 0.44                 |
| 3C 272.1     | 0.0035   | 63                     | 8.35                    | $8.3 \times 10^{-8}$   | $4.9 \times 10^{-6}$ | $<6.7 \times 10^{-5}$ | $>7.3$        | $<1.9 \times 10^{-3}$ | 6.0 $\times 10^{-2}$ | $>0.22$              |

$^a$ Inclination angle of the jet, with an uncertainty of several degrees.
$^b$ In units of $M_{\odot}$, derived from the correlation between the stellar velocity dispersion of the host’s bulge and its $\beta$-band magnitude (Marchesini et al. 2004).
$^c$ $L_{X}$ is the X-ray luminosity in the 2–10 keV band.
$^d$ The ratio is $\dot{m}_{\text{jet}}/\dot{m}(10 R_{S})$.
$^e$ Dimensionless Bondi accretion rate estimated from the X-ray observations.
black hole. This implies either that the black holes in these sources are spinning rapidly (so the ISCO is smaller and more accretion energy is thus available, or the jet power is extracted from the spinning black holes by means of the B-Z process; Blandford & Znajek 1977; Reynolds et al. 2006), or that the accretion energy within the ISCO can be extracted through the magnetic field. We have assumed that the jet includes equal numbers of protons and electrons. If the jet is enhanced by pair production, it could generate the same emission but with much less kinetic luminosity and lower black hole spin.

6. SUMMARY

We have fitted the multi-wave-band spectra of eight FR I galaxies ranging from radio to X-rays with our coupled ADAF-jet model. We find that the origin of the X-ray emission can be from an ADAF, a jet, or a combination, depending on the ratio $L_X/L_{\text{Edd}}$, where $L_X$ is the X-ray luminosity. When $L_X$ is significantly larger than a critical value $L_{X,\text{crit}}$, the X-ray emission will be dominated by the ADAF. When $L_X$ is significantly smaller than $L_{X,\text{crit}}$, it will be dominated by the jet. The contributions of the ADAF and jet are comparable when $L_X \sim L_{X,\text{crit}}$. These results roughly support the prediction of Yuan & Cui (2005), except that the value of $L_{X,\text{crit}}$ here, several times $10^{-6}L_{\text{Edd,i s}}$, is ∼10 times higher than the predicted value from Yuan & Cui (2005). This discrepancy may indicate that the jets in FR I galaxies are systematically stronger than LLAGNs in general.

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