Origin of the X-ray emission in the nuclei of FR Is

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Abstract. We investigate the X-ray origin in FR Is using the multi-waveband high resolution data of eight FR I sources, which have very low Eddington ratios. We fit their multi-waveband spectrum using a coupled accretion-jet model. We find that X-ray emission in the source with the highest $L_X (\sim 1.8 \times 10^{-4} L_{\text{Edd}})$ is from the advection-dominated accretion flow (ADAF). Four sources with moderate $L_X (\sim \text{several} \times 10^{-6} L_{\text{Edd}})$ are complicated. The X-ray emission of one FR I is from the jet, and the other three is from the sum of the jet and ADAF. The X-ray emission in the three least luminous sources ($L_X \leq 1.0 \times 10^{-6} L_{\text{Edd}}$) is dominated by the jet. These results roughly support the predictions of Yuan and Cui (2005) where they predict that when the X-ray luminosity of the system is below a critical value, the X-radiation will not be dominated by the emission from the ADAF any longer, but by the jet. We also find that the accretion rates in four sources must be higher than the Bondi rates, which implies that other fuel supply (e.g., stellar winds) inside the Bondi radius should be important.

1. Introduction

Radio galaxies are usually classified as FRI or FRII sources depending on their radio morphology. FRI radio galaxies (defined by edge-darkened radio structure) have lower radio power than FRII galaxies (defined by edge-brightened radio structure due to compact jet terminating hot spots) (Fanaroff & Riley 1974). Different explanations of division of FRI and FRII radio galaxies invoke either the interaction of the jet with the ambient medium or the intrinsic nuclei properties of accretion and jet formation processes (e.g., Bicknell 1995; Reynolds et al 1996a; Hardcastle et al 2007). Accretion mode in low power FR Is may be different from that in powerful FR IIs. There is growing evidence to suggest that FR Is type radio galaxy nuclei possess advection-dominated accretion flow (ADAF; or “radiative inefficient accretion flows”; see Narayan & McMillion 2008 for a review). In fact, we now have strong observational evidence that ADAFs may be powering various types of low-luminosity active galactic nuclei (LLAGNs; e.g., Yuan 2007; Ho 2008 for reviews), not only FR Is. It was found that the hard X-ray photon indices of both X-ray binaries (XRBs) and AGNs are anti-correlated with the Eddington ratios when the Eddington ratio is less than a critical value, while they become positively correlated when the Eddington ratios higher than the critical value (e.g., Wu and Gu 2008). This results provide evidence for the accretion mode transition near the critical Eddington ratio.

One of the uncertainties in FR Is is the respective contribution of ADAFs and jets at various wavebands. The least controversial nuclear emission are the radio and also optical emission, which is believed to be dominated by the jet (e.g., Wu and Cao 2005; Chiaberge et al 2006). It is still an open question for the origin of the core X-ray emission in FR Is (and also LLAGNs).
One possibility for the X-ray emission is dominated by the ADAF (e.g., Reynolds et al. 1996b; Quataert et al. 1999; Merloni 2003). The other possibility is from the jet (e.g., Falcke et al. 2004; Markoff et al. 2008), and recent observation on some individual extremely low luminosity sources supported this possibility (e.g., Garcia et al. 2005 for M31; Pellegrini et al. 2007 for NGC 821, etc.). Then an important question is systematically in what kind of condition the radiation from the jet or ADAF will be important in X-ray band.

2. Sample
The FR I sample used for the present investigation is selected from Donato et al. (2004), which have the estimated black hole mass, Bondi accretion rate, optical, radio, and X-ray nuclear emission (Table 1). There are 9 FR Is in their sample which 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 ($N_H \sim 10^{22} \text{cm}^{-2}$). Therefore, our final sample include 8 FR Is.

3. Coupled accretion-jet model
The accretion flow is described by a hot, optically thin, geometrically thick advection-dominated accretion flow. Following the proposal of Blandford and Begelman (1999), we parameterize the radial variation of the accretion rate with the parameter $p_w$ caused by the possible wind (e.g., Stone et al. 1999), $\dot{M} = \dot{M}_{\text{out}} (R/R_{\text{out}})^{p_w}$, where $\dot{M}_{\text{out}}$ is the accretion rate at the outer boundary of the ADAF $R_{\text{out}}$. We calculate the global solution of the ADAF. The viscosity parameter $\alpha$ and magnetic parameter $\beta$ (defined as ratio of gas to total pressure in the accretion flow, $\beta = P_g/P_{\text{tot}}$) are fixed to be $\alpha = 0.3$ and $\beta = 0.9$. Another parameter is $\delta$, describing the fraction of the turbulent dissipation which directly heats electrons. Following Yuan et al. (2006), we use $\delta = 0.3$ and $p_w = 0.25$ in all our calculations. The radiative processes we consider include synchrotron, bremsstrahlung and their Comptonization. We set the outer boundary of the ADAF at the Bondi radius $R_B = 2GM_{\text{BH}}/c_s^2$, where $c_s = \sqrt{\gamma k T/\mu m_p}$ 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 adiabatic index of the X-ray emitting gas. After the ADAF structure is obtained, the spectrum of the flow can be calculated (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 (e.g., Piran 1999). A fraction of the material in the accretion flow is assumed to be transferred into the vertical direction to form a jet due to the possible standing shock near the black hole (BH). From the shock jump conditions, we calculate the properties of the post-shock flow, such as electron temperature $T_e$. The jet is assumed to have a conical geometry with half-open angle $\phi$ and bulk Lorentz factor $\Gamma_j$ which are independent of the distance from the BH. The internal shock in the jets should occur as a result of the collision of shells with different $\Gamma_j$, and 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 $\xi_e = 10\%$ and a typical value of $\phi = 0.1$ (e.g., Laing & Bridle 2002) in our calculations. Following the widely adopted approach in the study of GRBs, the energy density of accelerated electrons and amplified magnetic field are described by two free parameters, $\xi_e$ and $\epsilon_B$. Obviously, $\xi_e$ and $\epsilon_B$ are not independent. The Lorentz factor of most FR Is are determined from the observations and a typical value $\Gamma_j = 2.3$ (corresponding to $v/c = 0.9$, e.g., Verdoes Kleijn et al. 2002; Laing & Bridle 2002) is adopted for those not having estimations, which will not affect our main conclusion since that our results are not very sensitive to the Lorentz factor.
4. Results
We use the ADAF-jet model to fit the spectrum of FRIs. As we state in Sect. 1, the radio emission, and perhaps optical as well, is from the jet. Based on the assumption to the jet model described in Sect. 3, the contribution of the jet to the X-ray band is well constrained once we require the jet model to fit the radio and optical data. We then adjust the parameter of the ADAF and combine it with the jet contribution to fit the X-ray spectrum.

4.1. ADAF dominated the nuclear X-ray emission for higher Eddington ratio sources
The radio morphology and power of 3C 346 would rank as either a low-power FR II source or a high-power FR I. Chandra observations have detected an unresolved core with \( L_X (2-10 \text{ keV}) = 1.9 \times 10^{43} \text{ erg s}^{-1} \) and a photon index of \( \Gamma = 1.69 \pm 0.09 \) (Donato et al 2004). Figure 1 shows the fitting result. 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 well the radio and optical data. But the X-ray emission of the jet model is several times lower than the Chandra observations, and the X-ray data can be well fitted by the ADAF. The required accretion rate is \( \dot{m}_{\text{out}} = 2.8 \times 10^{-2} \). The ratio of mass loss rate in the jet to accretion rate of ADAF at \( 10 R_S \) is about \( \dot{m}_{\text{jet}}/\dot{m}(10 R_S) = 0.9\% \), where \( R_S \) is the Schwarzschild radius. This source is relatively luminous, with \( L_X/L_{\text{Edd}} = 1.8 \times 10^{-4} \), and the X-ray emission is dominated by the ADAF, not by the jet.

Figure 1. Spectral energy distribution of 3C 346. The dot-dashed, dashed, and the solid lines show the emissions from the ADAF, jet, and their sum, respectively. The thin long-dashed line is synchrotron-self-Compton spectrum of the jet.

Figure 2. The same as Fig. 1, but for 3C 31.

4.2. ADAF+jet for moderate Eddington ratio sources
3C 31 is a twin-jet FR I radio galaxy. The X-ray spectrum of the core is quite flat, with a photon index \( \Gamma = 1.48_{-0.32}^{+0.28} \) and \( L_X (2-10 \text{ keV}) = 4.7 \times 10^{40} \text{ erg s}^{-1} \) \((\sim 4.4 \times 10^{-6} L_{\text{Edd}})\) (Evans et al 2006). Figure 2 shows the fitting result of 3C 31. The parameters of the jet are \( \dot{m}_{\text{jet}} = 2.7 \times 10^{-5} \), \( \epsilon_e = 0.2 \), \( \epsilon_B = 0.02 \), and \( p = 2.5 \). We find that the radio, optical and even the soft X-rays nuclear emission (e.g., 1 keV) can be well-fitted by a pure jet model. However, the hard X-rays cannot be
fitted by a jet, but can be well-fitted by the ADAF with an accretion rate of \( \dot{m}_{\text{out}} = 3.7 \times 10^{-3} \). The ratio, \( \dot{m}_{\text{jet}}/\dot{m}(10 R_s) \), is about 9%. We can see that jet contribution is important at soft X-ray band, while the ADAF contribution is important at the hard X-ray band.

This is also the case for other FR Is with moderate Eddington ratios (\( L_X/L_{\text{Edd}} \sim \text{several} \times 10^{-6} \), e.g., 3C 317, B2 0055+30, and possibly also 3C 449), except B2 0755+37, where all the emission can be fitted by a pure jet model (see Wu et al 2007 for more details).

4.3. Jet dominated the nuclear X-ray emission for lower Eddington ratio sources

The point-like nucleus is detected in 3C 66B by Chandra yielding \( L_X(2-10 \text{ keV}) = 1.1 \times 10^{41} \text{ ergs}^{-1} \) \((\sim 1 \times 10^{-6} L_{\text{Edd}})\) and a photon index of \( \Gamma = 2.17^{+0.14}_{-0.15} \) (e.g., Donato et al 2004). Figure 3 shows the fitting result of nucleus of 3C 66B. We find that all the radio, sub-millimetre, optical and X-ray can be fitted by a pure jet model very well (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 \( p = 2.35 \). 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). The predicted spectrum by an ADAF is too hard to be consistent with the observations (so the accretion rate in the ADAF should be smaller than \( 2.6 \times 10^{-3} \)). The X-ray emission in this source should be produced by the jet.

3C 272.1 is the lowest Eddington source \((\sim 6.8 \times 10^{-8} L_{\text{Edd}})\), for which many waveband high resolution observations from radio to X-ray have been carried out. Figure 4 shows the fitting result of nucleus of 3C 272.1. The parameters of the jet are \( \dot{m}_{\text{jet}} = 4.9 \times 10^{-6} \), \( \epsilon_e = 0.28 \), \( \epsilon_B = 0.005 \), and \( p = 2.5 \). We can see that the radio, sub-millimetre, optical, and especially, the X-ray emission can be fitted by the jet model very well. On the other hand, the predicted spectrum by 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 also dominated by the jet.

4.4. Fuel supply in these FR Is

Typically, the Bondi accretion rate is a good estimation to the mass accretion rate. However, Pellegrini (2005) show that there is no relation between the nuclear X-ray luminosity and the Bondi accretion rate in LLAGNs, and the X-ray emission of some sources is higher than the
values predicted by ADAFs with the Bondi accretion rate. The Bondi accretion rate in our sample has been estimated (see, Donato et al 2004). We find that the accretion rates \( \dot{m}_{\text{out}} \) required in our model of four FRIs (3C 346, 3C 31, 3C 449, and 3C 317), among the five in which we can have good constraints to their accretion rates, are higher than their Bondi rates by factors of 9, 18, 112, and 1.05, respectively (see also table 1). Given that the radial velocity of the accretion flow is \( c \alpha \), a more accurate estimation of the accretion rate is \( \dot{m}_{\text{out}} \sim \alpha \dot{m}_{\text{Bondi}} \) where \( \alpha \) is the viscous parameter (Narayan 2002). Therefore, the Bondi accretion rate is only a lower limit of the real rate and other fuel supply must be important, such as the gas released by the stellar population inside the Bondi radius (Soria et al 2006; Pellegrini 2007).

### Table 1. Accretion and jet properties.

| Source    | \( \log_{10}(M_{\text{BH}}) \) | \( \frac{L_X(2\text{--}10\text{keV})}{L_{\text{Edd}}} \) | \( \frac{\dot{m}_{\text{jet}}}{\bar{m}(10R_s)} \) | \( \dot{m}(R_B)^a \) | \( \bar{m}_B \) | \( \frac{L_{\text{Kin}}}{M(10R_s)c^2} \) |
|-----------|-------------------------------|---------------------------------|------------------|-------------------|-----------------|---------------------------------|
| 3C 346    | 8.89                          | \( 1.8 \times 10^{-4} \)        | 0.91\%           | \( 2.8 \times 10^{-2} \) | \( 3.1 \times 10^{-3} \) | 0.03                            |
| B2 0755+37| 8.93                          | \( 5.2 \times 10^{-6} \)        | \( > 3.9\% \)    | \( < 8.9 \times 10^{-3} \) | \( 3.2 \times 10^{-2} \) | \( > 0.10 \)                     |
| 3C 31     | 7.89                          | \( 4.4 \times 10^{-6} \)        | 9.0\%            | \( 3.7 \times 10^{-3} \) | \( 2.1 \times 10^{-4} \) | 0.19                            |
| 3C 317    | 8.80                          | \( 3.4 \times 10^{-6} \)        | 8.9\%            | \( 4.7 \times 10^{-3} \) | \( 4.5 \times 10^{-3} \) | 0.28                            |
| B2 0055+30| 9.18                          | \( 2.4 \times 10^{-6} \)        | 3.5\%            | \( 2.7 \times 10^{-3} \) | \( 1.4 \times 10^{-2} \) | 0.08                            |
| 3C 66B    | 8.84                          | \( 1.0 \times 10^{-6} \)        | \( > 5.9\% \)    | \( < 2.6 \times 10^{-3} \) | \( 2.5 \times 10^{-2} \) | \( > 0.18 \)                     |
| 3C 449    | 8.42                          | \( 8.0 \times 10^{-7} \)        | 14.3\%           | \( 1.9 \times 10^{-3} \) | \( 1.7 \times 10^{-5} \) | 0.44                            |
| 3C 272.1  | 8.35                          | \( 8.3 \times 10^{-8} \)        | \( > 7.3\% \)    | \( < 1.9 \times 10^{-3} \) | \( 6.0 \times 10^{-2} \) | \( > 0.22 \)                     |

(a) \( \dot{m}(R_B) \) is the dimensionless accretion rate at the Bondi radius through our spectra fitting;
(b) \( \bar{m}_B \) is the dimensionless Bondi accretion rate estimated from the X-ray observation.

### 5. Discussion and Conclusion

Two possibilities exist for the X-ray origin in FRIs: ADAF or jet. We use a coupled ADAF-jet model to fit the multi-waveband spectrum to try to investigate this problem. We find that the jet can well describe the radio and optical spectra for most FRIs in our sample. The soft X-ray flux at \( \sim 1 \text{keV} \) of all FRIs is roughly consistent with the predictions of the jet. This result indicates why a tight correlation is found among radio, optical and soft X-ray (Evans et al 2006; Balmaverde et al 2006). For 3C 346, the highest X-ray luminosity source in our sample which has \( L_X = 1.8 \times 10^{-4} L_{\text{Edd}} \), its X-ray spectrum is dominated by the ADAF and the jet contribution is negligible. However, for the four sources with “intermediate X-ray luminosities” (B2 0755+37, 3C 31, 3C 317, and B2 0055+30; \( L_X = (2.4 - 5.2) \times 10^{-6} L_{\text{Edd}} \)), their X-ray origin is complicated. The X-ray spectrum of B2 0755+37 is dominated by the jet, while for 3C 31 and B2 0055+30 spectra are dominated by the ADAF. For the other 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 \( L_X = (6.8 \times 10^{-8} - 1 \times 10^{-6}) L_{\text{Edd}} \), their X-ray spectra are dominated by the jet. The X-ray emission of 3C 449 is also interpreted by the sum of a jet and an ADAF, which requires higher quality data to further constrain it. Our results are roughly consistent with the predictions of Yuan and Cui (2005). The “intermediate luminosity” here in our sample corresponds to the critical luminosity in Yuan and 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 is adopted in Yuan and Cui (2005) from fitting the data of a black hole X-ray binary—XTE J1118+480. The current
result indicates that the ratio in FR Is is about 10 times higher than in XTEJ1118+480. One possible reason could be that systematically the black holes in FR Is are spinning more rapidly. We note that the critical luminosity (or Eddington ratio) in this work is for the transition of X-ray emission dominated by the ADAF or by the jet, which is different from the critical value for the transition of the jet power dominated systems and accretion power dominated systems (Wu and Cao 2008 for more details and references therein).

The kinetic luminosity, \( L_{\text{kin}} = \Gamma_j (\Gamma_j - 1) \dot{M}_{\text{jet}} c^2 \), can be derived from our modeling results. We use \( \eta_{\text{jet}} = L_{\text{kin}} / \dot{M} (10 R_S) c^2 \) to describe the efficiency of the jet power converted from the accretion power, where \( \dot{M} (10 R_S) \) is mass accretion rate at \( 10 R_S \). We find that \( \eta_{\text{jet}} = 0.03 - 0.44 \) for the sources in this sample (see Table 1), and most of them (six of eight) have \( \eta_{\text{jet}} \) significantly higher than 0.057, which is the largest available accretion energy at the innermost stable circular orbit (ISCO) for a non-rotating black hole. It implies that the black holes in these sources are spinning rapidly (so ISCO is smaller thus more accretion energy is available).

Acknowledgments

Wu Q W thanks the local organizing committee of the conference for partial financial support. This work is supported by the One-Hundred-Talent Program of China, the National Science Fund for Distinguished Young Scholars (grant 10325314), the NSFC (grants number 10773024, 10773020, 10703009 and 10633010), and a postdoctoral fellowship of the KASI.

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