EVIDENCE OF AN UNTRUNCATED ACCRETION DISK IN THE BROAD-LINE RADIO GALAXY 4C 74.26

D. R. BALLANTYNE\textsuperscript{1} and A. C. FABIAN\textsuperscript{2}

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ABSTRACT

We present evidence of a broad ionized Fe Kα line in the \textit{XMM-Newton} spectrum of the broad-line radio galaxy (BLRG) 4C 74.26. This is the first indication that the innermost regions of the accretion flow in BLRGs contain thin, radiatively efficient disks. Analysis of the 35 ks \textit{XMM-Newton} observation finds a broad line with an inner radius close to the innermost stable circular orbit for a maximally spinning black hole. The outer radius of the relativistic line is also found to be within 10 gravitational radii. The Fe Kα line profile gives an inclination angle of ∼40°, consistent with the radio limit. There are two narrow components to the Fe Kα complex: one at 6.4 keV from neutral Fe and one at 6.2 keV. These may form the blue and red horns of a diskline from farther out on the disk, but a longer observation is required to confirm this hypothesis. We discuss the implications of this observation for models of jet production and suggest that BLRGs and radio-loud quasars will have larger-than-average black hole masses, thus resulting in thicker accretion flows close to the black hole.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: individual (4C 74.26) — galaxies: jets — X-rays: galaxies

1. INTRODUCTION

A long-standing problem in modern astrophysics is to understand the production of large-scale relativistic jets. In terms of the active galactic nucleus (AGN) phenomenon, this problem has traditionally manifested itself as understanding the underlying physical difference between the majority radio-quiet population and the minority radio-loud sources (e.g., Kellerman et al. 1989; Wilson & Colbert 1995). A potentially promising way to elucidate this difference is to compare X-ray observations of the two populations, since the X-rays originate from the inner regions of the accretion flow, as do relativistic jets (Blandford & Znajek 1977; Blandford & Payne 1982; Koide 2004). Studies of broad-line radio galaxies (BLRGs) with ASCA, RXTE, and \textit{BeppoSAX} seemed to indicate that they had weaker reflection features and Fe Kα lines than their radio-quiet Seyfert 1 counterparts (Eracleous & Halpern 1998; Wozniak et al. 1998; Eracleous et al. 2000). This could be explained if BLRGs contain a truncated accretion flow, where the geometrically thin, radiatively efficient accretion disk transforms close to the black hole into a thicker, tenuous, and radiatively inefficient configuration such as an advection-dominated accretion flow (ADAF; e.g., Narayan & Yi 1995). This idea has some theoretical justification, as models of jet production have emphasized the importance and connection of the poloidal magnetic field to the inner accretion flow (Meier 1999, 2001; Livio et al. 1999, 2003). Furthermore, Galactic black holes show radio emission (and, when resolved, jet structure) only in the low-luminosity “hard” or “power-law–dominated” state (e.g., Fender et al. 2004) where the accretion rate is expected to be very low compared to the Eddington rate.

An alternative explanation for the weak reflection features observed in BLRGs was put forward by Ballantyne et al. (2002), who suggested an origin in an ionized nontruncated accretion disk. This might be expected if the accretion rate was a much larger fraction of Eddington. More sensitive observations of BLRGs by \textit{XMM-Newton} were expected to discriminate between the two explanations, but until now, the results have been inconclusive (NGC 6251, Gliozzi et al. 2004; 3C 120, Ballantyne et al. 2004; 3C 111, Lewis et al. 2005). In this Letter, we present the first evidence, in the form of a broad Fe Kα line, of an untruncated accretion disk in a luminous BLRG. The line is broad enough to require emission within the innermost stable circular orbit (ISCO) of a Schwarzschild black hole and, along with the reflection continuum, is well fit by a moderately ionized reflector. Thus, this observation may provide important constraints on the geometry of the inner accretion flow in jet-producing systems.

In the next section, we provide a brief introduction to the BLRG 4C 74.26 and then describe the \textit{XMM-Newton} observation and data reduction in § 3. The spectral analysis is presented in § 4, and then we discuss the implications of the results in the final section. Throughout this Letter, a \textit{Wilkinson Microwave Anisotropy Probe} cosmology ($H_0 = 70$ km s\(^{-1}\) Mpc\(^{-1}\), $\Omega_m = 0.73$, $\Omega_\Lambda = 1$; Spergel et al. 2003) is assumed.

2. THE BROAD-LINE RADIO GALAXY 4C 74.26

4C 74.26 ($z = 0.104$; Riley et al. 1989) is a low-luminosity radio-loud quasar notable for its 10′ radio lobes (Riley et al. 1989). A one-sided jet has been detected by the Very Large Array (Riley & Warner 1990) and at parsec scales by very long baseline interferometry (Pearson et al. 1992). The lack of a counterjet gives a limit to the inclination angle of $i \lesssim 49°$ (Pearson et al. 1992). The total radio luminosity of the source places it on the border between the FR I/II classes, although the observed structure is similar to an FR II source (Riley et al. 1989). Wu & Urry (2002a) quote a bolometric luminosity of $L_b \approx 2 \times 10^{44}$ erg s\(^{-1}\). Optical spectra of 4C 74.26 show very broad permitted lines, with Corbin (1997) measuring an Hβ FWHM of 11,000 km s\(^{-1}\), although other authors give values closer to 8000 km s\(^{-1}\) (Riley et al. 1989; Brinkmann et al. 1998; Robinson et al. 1999). Using the Corbin (1997) value of the FWHM and the Kaspi et al. (2000) radius-luminosity relation, Wu & Urry (2002a) estimate the black hole mass in 4C 74.26 to be $\sim 4 \times 10^9 M_\odot$.

A 23 ks ASCA observation of 4C 74.26 yielded inconclusive results despite three separate analyses. Brinkmann et al. (1998) and Reeves & Turner (2000) uncovered an Fe Kα line at the
97% level, but Sambruna et al. (1999) claimed that the line was significant at greater than 99%. The data could not determine if the line was broadened. The spectrum showed evidence of hardening at high energies, which Sambruna et al. (1999) fit by a separate power-law component, attributed to jet emission. When the data were fit by reflection models, reflection fractions much greater than unity were found (R ≈ 6 [Brinkmann et al. 1998] or R ≈ 3 [Reeves & Turner 2000]). An unresolved line was clearly detected in the 100 ks BeppoSAX observation reported by Hasenkopf et al. (2002). The broadband fits indicated a Compton reflection component at the 98.7% level with R ≈ 1. This fact, along with the flat light curve at high energies, shows that the X-rays are not significantly contaminated by jet emission.

3. OBSERVATIONS AND DATA REDUCTION

*XMM-Newton* (Jansen et al. 2001) observed 4C 74.26 during revolution 762 between 2004 February 6 13:57:42 UT and 23:22:54 UT. The European Photon Imaging Camera, comprising two MOS detectors (Turner et al. 2001) and one pn detector (Strüder et al. 2001), was operated in large window mode with the medium optical filter in place. Calibrated event lists were extracted from the observation data files using the standard processing chains (EPCHAIN and EMCHAIN) provided by the *XMM-Newton* Science Analysis System (SAS) version 6.1. A circular region with radius 115″ (as suggested by the SAS “extraction optimizer”) was employed to extract a pn spectrum of 4C 74.26 that included both single and double events. The background spectrum was extracted from a source-free area on the same CCD using a circular region with a radius of 60″. Contamination from a background flare ∼22 ks into the observation was removed with the use of a good-time interval file. The SAS task EPATPLOT confirmed that the pn spectrum was free from pileup but found evidence for it in the MOS spectra. These data were thus excluded from spectral analysis. The final background-subtracted pn spectrum contains 252,050 counts obtained in 28.8 ks of good exposure time, for a mean count rate of 8.6 s⁻¹. The response matrix and ancillary response file for the pn spectrum were generated using the RMFGEN and ARFGEN tools within the SAS.

4. SPECTRAL ANALYSIS

As this Letter is concentrating on the Fe Kα region of the spectrum, we restrict our analysis to the 2–12 keV region of the pn data (full broadband fits will be presented in a forthcoming paper). Prior to spectral analysis, the data were grouped to have a minimum of 20 counts per bin. Model fitting was performed with XSPEC version 11.3.1p (Arnaud 1996). The uncertainties quoted on the best-fit parameters are the 2 σ error bars for one parameter of interest (i.e., Δχ² = 2.71). The Galactic absorption column of 1.19 × 10²² cm⁻² (Dickey & Lockman 1990) is included in all the spectral fits presented below and is modeled with the TBABS code (Wilms et al. 2000) within XSPEC. All energies are quoted in the rest frame, while the figures are plotted in the observed frame.

To get an overall sense of the Fe Kα region in 4C 74.26, we begin by fitting the 2–12 keV spectrum with a simple power-law model but excluding the region between 5 and 7 keV. A good fit (χ²/dof = 857/939; dof = degrees of freedom) was obtained with Γ = 1.69 ± 0.02. Figure 1 plots the residuals to this fit including the previously ignored energy range. The figure reveals a well-resolved Fe Kα line profile consisting of

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**TABLE 1**

| Model Parameters from Fitting the 2–12 keV (Observed Frame) Spectrum of 4C 74.26 |
|---------------------------------------------------------------|
| Model | Γ | E_G | EW | R | r_out | i | EW_L | log ξ | χ²/dof |
|-------|---|-----|----|---|-------|---|------|------|--------|
| PL+G' | 1.71 ± 0.02 | 6.46 ± 0.04 | 45° | ... | ... | ... | ... | ... | 1163/1301 |
| PL+G'+L | 1.74 ± 0.02 | 6.46 ± 0.04 | 28° | ... | 7.1±0.4 | 45° | 238.77 | ... | 1138/1298 |
| PEXRAV+G'+L | 1.81 ± 0.06 | 6.46 ± 0.04 | 25° | ... | 1.2±0.7 | 5.4±0.7 | 45° | 167.94 | ... | 1128/1298 |
| IONDISK*blr'+'IONDISK' | 1.82 ± 0.02 | ... | 35° | 1° | 6.3±1.2 | 37° | 54° | 154 | 2.64±0.06 | 1130/1299 |
| IONDISK*blr'+'IONDISK' | 1.82 ± 0.02 | 6.23 ± 0.05 | 38 and 20 | 1° | 6.3±1.5 | 34° | 10° | 134 | 2.60±0.04 | 1121/1297 |

Notes.—In the model descriptions, PL = power-law, G = Gaussian emission line, Γ = Laor (1991) relativistic line, PEXRAV = neutral reflection continuum of Magdziarz & Zdziarski (1995), IONDISK = ionized reflection spectrum of Ross et al. (1992), and blr = blurred with the Laor relativistic kernel. E_G is the energy of the added Gaussian line in units of keV; Γ is the equivalent width(s) of any narrow component in units of eV; R is the reflection fraction, r_out is the outer radius of the relativistic emission line in r_g, i is the inclination angle in degrees, EW, is the equivalent width of the relativistic line in units of eV, and ξ is the ionization parameter in the IONDISK model.

1. Γ = 0 (parameter fixed at value).
2. Γ = 1.235, emissivity = −3, E = 6.4 keV (parameters fixed at values).
3. E_G = 200 keV, abundances = solar (parameters fixed at values).
4. r_out = 1.235, emissivity = −3 (parameters fixed at values).
5. Reflection-dominated, log ξ = 1 (parameter fixed at value).
6. Parameter fixed at value.
a broad red wing and potentially two narrow components contributing to the line core. At higher energies, the residuals show the spectral hardening indicative of a reflection continuum.

Results of the spectral fitting are shown in Table 1. All the fits provide a very acceptable statistical fit to the data, but significant improvements were found with the addition of a broad Fe Kα component, reflection, and a narrow line at ∼6.2 keV. After many trials with the Laor (1991) and “diskline” (Fabian et al. 1989) relativistic line models, the best fit was found with an inner radius close to the ISCO for a spinning Kerr black hole and an outer radius at ∼6rc, where rc = GM/c2 is the gravitational radius for a black hole with mass M. Broad lines with larger inner radii not only had larger χ2 (Δχ2 ≈ +10) but gave inclination angles i ∼ 20°, implying that the physical size of the 4C 74.26 radio source is ∼3 Mpc, larger than almost any other known giant radio galaxy (GRG; Lara et al. 2001, 2004). The broad Laor line results in a larger inclination angle and therefore a smaller physical size of ∼2 Mpc, more in line with other GRGs. Allowing the line emissivity β to vary did not improve the fit (β = −3.1±1.0).

The rest energy of the Laor line was fixed at the emission energy for neutral iron at 6.4 keV, but when that line and the PEXRAV continuum were replaced with the ionized reflection model of Ross et al. (1999), the ionization parameter was found to be tightly constrained at ξ ≈ 400 and predicted emission from helium like Fe at 6.7 keV. For this model, denoted IONDISK*blr+IONDISK in Table 1, a reflection-dominated neutral continuum accounted for the sharp core of the line. Figure 2 plots this model and the residuals to this fit. The residuals show a possible additional emission feature associated with the Fe Kα complex. A narrow Gaussian added to the model was found to be significant at the 99% level and had a best-fit energy of 6.2 keV and an equivalent width (EW) of 20 eV. The origin of this line is unknown. It is possible that it and the 6.4 keV component, reflection, and a narrow line at ∼6rc, where rc = GM/c2 is the gravitational radius for a black hole with mass M. Broad lines with larger inner radii not only had larger χ2 (Δχ2 ≈ +10) but gave inclination angles i ∼ 20°, implying that the physical size of the 4C 74.26 radio source is ∼3 Mpc, larger than almost any other known giant radio galaxy (GRG; Lara et al. 2001, 2004). The broad Laor line results in a larger inclination angle and therefore a smaller physical size of ∼2 Mpc, more in line with other GRGs. Allowing the line emissivity β to vary did not improve the fit (β = −3.1±1.0).

The last model in Table 1 yields a 2–10 keV flux of $F_{2-10\text{keV}} = 2.43 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$. The earlier ASCA and BeppoSAX observations found $F_{2-10\text{keV}} = 1.7 \times 10^{-11}$ and $1.4 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$, respectively, indicating that this XMM-Newton observation caught 4C 74.26 in a higher flux state. The unabsorbed rest-frame 2–10 keV XMM-Newton luminosity is $L_{2-10\text{keV}} = 6.6 \times 10^{44}$ ergs s$^{-1}$. The total unabsorbed 0.3–12 keV luminosity of 4C 74.26 is $L_{0.3-12\text{keV}} = 1.6 \times 10^{45}$ ergs s$^{-1}$. Assuming that this comprises about 10% of the bolometric luminosity, $L_{\text{bol}} \approx 1.6 \times 10^{46}$ ergs s$^{-1}$, in good agreement with the $L_{\text{bol}}$ found by Wu & Urry (2002a). A black hole mass of $4 \times 10^9 M_\odot$ (Wu & Urry 2002a) then gives an observed Eddington ratio of 0.04, consistent with the presence of an untruncated thin accretion disk over an inner ADAF-like flow (which requires $M_{\text{edd}} \lesssim \alpha^2 c^2$, where $\alpha \sim 0.1$ is the Shakura & Sunyaev 1973 viscosity parameter; Rees et al. 1982).

5. DISCUSSION

In the previous section we presented evidence that the X-ray spectrum of 4C 74.26 exhibits a broad ionized Fe Kα line extending very close to a spinning black hole. This evidence is by no means conclusive (e.g., it is difficult to rule out the possibility that the line shape is actually due to a complex series of absorbers), but it is suggestive. A longer XMM-Newton observation is required to confirm its presence and extent. Below, we assume that the line is as measured above and discuss how it may shed light on the problem of jet formation.

It may be constructive to compare the properties of 4C 74.26 to those of the well-known radio-quiet Seyfert 1 MCG −6–30–15, which also has a broad line that implies a spinning black hole (Fabian et al. 2002). What quality (or qualities) allows 4C 74.26 to produce a strong radio jet and inhibits one in MCG −6–30–15? Evidently, the spin of the black hole seems not to be important, as there is increasing evidence (albeit circumstantial) that most black holes are spinning. This is based on comparisons of the accreted black hole mass density (as judged from the X-ray background) to the local density of black holes (Elvis et al. 2002; Barger et al. 2005) and from simulations of black hole growth including both mergers and accretion (Shapiro 2005). Moreover, the observation that radio emission is quenched as Galactic black holes move from the low state to the high state precludes a strict spin dependence. The accretion rates may also be ruled out as the governing parameter since radio-loud quasars produce jets at high accretion rates, as does the BLRG 3C 120 (Ballantyne et al. 2004).

Interestingly, the mass of the black hole in 4C 74.26 is estimated to be $\sim 10^7$ times larger than the one in MCG −6–30–15 (Bian & Zhao 2003). In the last few years, other authors have presented evidence that radio-loud AGNs preferentially have large black hole masses (Laor 2000; McLure & Dunlop 2002; McLure & Jarvis 2004), although there have been dissenting views (Ho 2002; Wu & Urry 2002b). Assuming the same accretion rate and a radiation pressure–dominated inner disk, a larger black hole mass will increase the scale height $H$ and decrease the density of the accretion flow (Shakura & Sunyaev 1973). The larger value of $H/r$ (where $r$ is the radius along the disk) may enhance the poloidal magnetic field over the lower mass AGNs and increase the chances of jet formation.
There now seems to be two types of sources that produce strong radio emission (Marchesini et al. 2004). The first are low accretion rate objects, such as LINERs and other low-luminosity AGNs, and Galactically black holes in the low power–law–dominated state (e.g., Ho 2002). These are the sources that populate the fundamental plane of black hole activity recently discovered by Merloni et al. (2003). The second class of sources has much higher luminosities and accretion rates, and we would argue that it includes BLRGs and radio-loud quasars. These objects would have untruncated, radiatively efficient accretion disks but relatively high black hole masses and thus a larger accretion rate. This would also explain the possible very thick and would have enhanced poloidal magnetic fields. The connection among all jet-emitting sources would then be the structure and magnetic strength of the inner accretion flow. Hopefully, this hypothesis can be confirmed by numerical simulations of jet formation.

In summary, the broad Fe Kα line detected in the XMM-Newton observation of 4C 74.26 rules out the possibility of a truncated accretion disk in BLRGs. Rather, the observation strengthens the scenario that the disk thickness (in the sense of $H_{\text{ir}}$) close to the black hole is the important parameter for jet production. For high accretion rate sources, such as BLRGs, the thickness is a result of a relatively high black hole mass. In low accretion rate sources, such as low-state X-ray binaries, it is caused by a radiatively inefficient accretion flow.

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REFERENCES

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco: ASP), 17
Ballantyne, D. R., Fabian, A. C., & Iwasawa, K. 2004, MNRAS, 354, 839
Ballantyne, D. R., & Ross, R. 2002, MNRAS, 332, 777
Ballantyne, D. R., Ross, R. R., & Fabian, A. C. 2002, MNRAS, 332, L45
Barger, A. J., Cowie, L. L., Mushotzky, R. F., Yang, Y., Wang, W.-H., Steffen, A. T., & Capak, P. 2005, AJ, 129, 578
Bian, W., & Zhao, Y. 2003, MNRAS, 343, 164
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Blandford, R. D., & Znajek, R. 1977, MNRAS, 179, 433
Brinkmann, W., Otani, C., Wagner, S. J., & Siebert, J. 1998, A&A, 330, 67
Corbin, M. R. 1997, ApJS, 113, 245
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Elvis, M., Risaliti, G., & Zamorani, G. 2002, ApJ, 565, L75
Eracleous, M., & Halpern, J. P. 1998, ApJ, 505, 1279
Fender, R. P., Belloni, T. M., & Gallo, E. 2004, MNRAS, 355, L1
Fabian, A. C., et al. 2002, MNRAS, 335, L1
Lea, S. A. 1989, MNRAS, 238, 729
Kellerman, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, AJ, 98, 1195
Koide, S. 2004, ApJ, 606, L45
Laor, A. 1991, ApJ, 376, 90
———. 2000, ApJ, 543, L11
Lewis, K. T., Eracleous, M., Gliozzi, M., Sambruna, R. M., & Mushotzky, R. F. 2005, ApJ, in press (astro-ph/0412537)