Near-Infrared Synchrotron Emission from the Compact Jet of GX 339-4

Corbel, S.; Fender, R.P.

Published in:
Astrophysical Journal

DOI:
10.1086/341870

The Astrophysical Journal, 573:L000–L000, 2002 July 1

NEAR-INFRARED SYNCHROTRON EMISSION FROM THE COMPACT JET OF GX 339−4

S. Corbel
Université Paris VII and Service d'Astrophysique, Centre d'Etudes de Saclay, Orme des Merisiers,
Batiment 709, F-91191 Gif-sur-Yvette, France; corbel@discovery.saclay.cea.fr
and
R. P. Fender
Astronomical Institute "Anton Pannekoek," University of Amsterdam, and Center for High Energy Astrophysics,
Kruislaan 403, 1098 SJ Amsterdam, Netherlands; rpf@astro.uva.nl
Received 2002 January 22; accepted 2002 May 15; published 2002 June 6

ABSTRACT

We have compiled contemporaneous broadband observations of the black hole candidate X-ray binary GX 339−4 when in the low/hard X-ray state in 1981 and 1997. The data clearly reveal the presence of two spectral components, with thermal and nonthermal spectra, overlapping in the optical–near-infrared bands. The nonthermal component lies on an extrapolation of the radio spectrum of the source, and we interpret it as optically thin synchrotron emission from the powerful, compact jet in the system. Detection of this break from self-absorbed to optically thin synchrotron emission from the jet allows us to place a firm lower limit on the ratio of jet (synchrotron) to X-ray luminosities of ≥5%. We further note that extrapolation of the optically thin synchrotron component from the near-infrared to higher frequencies coincides with the observed X-ray spectrum, supporting models in which the X-rays could originate via optically thin synchrotron emission from the jet (possibly instead of Comptonization).

Subject headings: black hole physics — ISM: jets and outflows — radiation mechanisms: nonthermal — radio continuum: stars — stars: individual (GX 339−4)

1. COMPACT JET FROM BLACK HOLE CANDIDATES IN THE LOW/HARD X-RAY STATE

Radio emission from black hole X-ray binaries has long been associated with bright radio flares (>100 mJy) starting around the onset of an X-ray outburst. This is usually interpreted as synchrotron emission from relativistic electrons ejected from the system with large bulk velocities; in a few cases, such jets have been directly imaged. In the rising phase of the flares, the radio spectrum is usually flat or inverted, a characteristic of optically thick synchrotron emission (spectral index $\alpha \geq 0$ for a flux density $S_\nu \propto \nu^\alpha$), and then quickly evolves to a decay phase characterized by optically thin emission with negative spectral index. For recent reviews, see Hjellming & Han (1995), Mirabel & Rodríguez (1999), and Fender & Kuulkers (2001).

By observing the persistent black hole candidates (BHCs) in our Galaxy (in particular, GX 339−4 and Cyg X-1), it has been possible to show that they were usually associated with weak (a few millijanskys) radio counterparts with different properties than the bright radio flaring transient BHCs. Indeed, GX 339−4 and Cyg X-1 are most of the time characterized by a persistent radio source with a flat or slightly inverted ($\alpha \geq 0$) radio spectrum (Martí et al. 1996; Corbel et al. 2000). Such radio properties have been interpreted as arising from a conical, self-absorbed compact jet (on milliarcsecond scales), similar to those considered for flat-spectrum active galactic nuclei (AGNs; Blandford & Königl 1979; Hjellming & Johnston 1988; Falcke & Biermann 1996). This interpretation has been successfully confirmed with the direct imaging of a compact jet in Cyg X-1 (Stirling et al. 2001). Radio emission has also been shown to be correlated with soft and hard X-ray emission (Hannikainen et al. 1998; Brocksopp et al. 1999; Corbel et al. 2000). Observations of GX 339−4 have shown that the compact jet was quenched in the high/soft state (Fender et al. 1999; Corbel et al. 2000). Recent observations of X-ray novae have shown that the compact jet was a ubiquitous property of BHCs in the low/hard state (Fender 2001a; Corbel et al. 2001a and references therein). The compact jet seems to be quenched in the intermediate/very high states, i.e., in any state where a strong soft X-ray component exists (Corbel et al. 2001a).

Compact jet models predict a cutoff or break to the flat or inverted spectral component above a frequency at which the jet is no longer self-absorbed, even at the base. This break is observed in the millimeter range for the compact cores of most flat-spectrum AGNs (e.g., Bloom et al. 1994). To date, there has been no clear detection of such a high-frequency break in the self-absorbed synchrotron spectrum from an X-ray binary system. Detection of such a high-frequency cutoff is important, as a firm lower limit to the radiative luminosity of the self-absorbed part of the compact jet can be established by measuring this high-frequency cutoff. The secondary star in GX 339−4 is very likely an evolved low-mass star (e.g., Shahbaz, Fender, & Charles 2001; Chaty et al. 2002) without significant thermal contribution in the near-infrared range. GX 339−4 is therefore maybe the best candidate to look for a high-frequency cutoff to the compact jet spectral component. We, therefore, looked at all published (to our knowledge) optical and near-infrared observations of GX 339−4 while in the low/hard state. We present evidence that the cutoff frequency of the compact jet is in the near-infrared range, based on observations performed in a bright low/hard state in 1981. This is confirmed by later observations in 1997. We then discuss the implication of this cutoff on the energetic content of the compact jet related to the bolometric X-ray luminosity of the system.

2. OBSERVATIONS

2.1. *A Bright Low/Hard State of GX 339−4 in 1981*

Observations in 1981 revealed that GX 339−4 had been very active with transitions to various X-ray states. Indeed, in

1981 March, optical observations showed that the optical counterpart was very faint ($B \approx 20.34 \pm 0.15$ mag, $V \geq 19.5$ mag) and therefore indicated that GX 339−4 was in the off state (Ilovaisky & Chevalier 1981, 1987). X-ray observations performed by the *Hakucho* satellite on April 7 failed to detect GX 339−4 with an upper limit of 15 mCrab (Maejima et al. 1984). On May 7, GX 339−4 was already in a brighter optical state, with $V \sim 16.3$ mag (Grindlay 1981). Subsequent optical and X-ray observations (see below) revealed that GX 339−4 was in the standard low/hard state up to June 27, where the X-ray monitoring observations performed by *Hakucho* showed that GX 339−4 made a transition to a high/soft state (Maejima et al. 1984). According to Motch et al. (1983), the peak of the low/hard state was around May 28.

2.1.1. *Optical, Near-Infrared, and X-Ray Observations*

When GX 339−4 was found to be in a bright low/hard state in 1981 May, several observations were performed in the optical and near-infrared bands. Here we decided to concentrate on the period from May 24 to June 4, as the flux from GX 339−4 was observed to be similar in *V* and *B* filters on May 28 and June 4. Near-infrared observations in *J*, *H*, *K*, and *L* bands were performed with the ESO 3.6 m telescope in La Silla, Chile, on May 24 by Motch, Ilovaisky, & Chevalier (1981). Using the 1.5 m Danish telescope at La Silla, Motch et al. (1981) also performed optical observations in the *B*, *V*, *R*, and *I* bands on May 28. Pedersen (1981) conducted *U*-, *B*-, and *V*-band optical observations on June 4. A conservative error of 0.1 mag is applied in this study to the various optical and near-infrared measurements. An optical extinction of $A_V = 3.7 \pm 0.3$ mag, coupled with the extinction law of Cardelli, Clayton, & Mathis (1989), has been used to deredden these data (Zdziarski et al. 1998). The uncertainty on the dereddened flux estimates is dominated by the uncertainties on the optical extinction. The optical and near-infrared data have been discussed in various papers but in a different framework than the one presented here (Motch et al. 1983, 1985; an optical extinction of $A_V = 2$ mag was used in Motch et al. 1985). The data used in this Letter are summarized in Table 1.

An X-ray spectrum in the 1–50 keV range was obtained by the *Ariel 6* satellite on 1981 May 30–31. The data were best fitted with a power law of photon index ∼1.5 (Ricketts 1983), typical for the low/hard X-ray state. As these X-ray data are simultaneous with the optical and near-infrared observations mentioned above, they have been used in this Letter to estimate the luminosity in soft and hard X-rays and are plotted in Figure 2.

2.1.2. *The Level of Radio Emission*

Hannikainen et al. (1998) first pointed out that the radio and X-ray emission in GX 339−4 were strongly correlated during the low/hard state, a correlation that has been studied in more detail by Corbel et al. (2000) using a longer, extensive set of data. Using simultaneous *Rossi X-Ray Timing Explorer* (*RXTE*; Proportional Counter Array and High-Energy X-Ray Timing Experiment) and radio observations, we have been able to improve significantly the quality of this study (previous works only used BATSE and *RXTE*/all-sky monitor [ASM] data). We observed a very strong power-law correlation between radio and soft and hard X-ray emissions in the low/hard state over 3 orders of magnitude in X-ray flux. The correlation corresponds to the relation $F_{\rm rad} = 1.72 F_{\rm X}^{0.71}$, where $F_{\rm rad}$ is the radio flux density (in millijanskys) at 8640 MHz and $F_{\rm X}$ the 3–9 keV flux (in units of 10^{-10} ergs s^{-1} cm^{-2}; S. Corbel et al. 2002, in preparation). As no radio observations were performed in 1981 (the radio counterpart was discovered in 1994 by Sood & Campbell-Wilson 1994), we can estimate the level of radio emission around the time of the optical–near-infrared observations, using the X-ray spectrum obtained simultaneously by *Ariel 6*. A flux of 22.3×10^{-10} ergs s^{-1} cm^{-2} in the 3–9 keV band is measured; the above mentioned fitting function therefore allows us to estimate the radio flux density of GX 339−4 to 16 mJy at 8640 MHz (with a conservative error of 1 mJy). As the correlation observed in GX 339−4 is maintained over several years (S. Corbel et al. 2002, in preparation), it is safe to assume that it represents the true level of radio emission of GX 339−4 that would have been detected on 1981 May 30. The typical spectral index of the inverted spectral component in the radio regime has been found to be around +0.15 during the most sensitive radio observations performed in the low/hard state (Corbel et al. 2000).

TABLE 1
Log of Optical and Near-Infrared Observations

Band	Date	Telescope	Flux (mag)	Flux[a] (mJy)	Reference
U ……	1981 Jun 4	Danish 1.5 m	16.2	132.1 ± 59.1	1
B ……	1981 Jun 4	Danish 1.5 m	16.3	122.8 ± 46.4	1
V ……	1981 Jun 4	Danish 1.5 m	15.5	69.9 ± 19.6	1
R ……	1981 May 28	Danish 1.5 m	14.8	44.1 ± 9.2	2
I …….	1981 May 28	Danish 1.5 m	13.9	31.7 ± 4.2	2
J …….	1981 May 24	ESO 3.6 m	12.6	39.3 ± 3.1	2
H ……	1981 May 24	ESO 3.6 m	12.1	29.6 ± 1.6	2
K ……	1981 May 24	ESO 3.6 m	10.9	43.3 ± 1.4	2
L ……	1981 May 24	ESO 3.6 m	9.4	56.6 ± 0.9	2
J …….	1997 Jul 19	ESO 2.2 m	14.2	8.9 ± 0.7	3
H ……	1997 Jul 19	ESO 2.2 m	13.1	11.4 ± 0.6	3
K ……	1997 Jul 19	ESO 2.2 m	12.4	10.8 ± 0.3	3

[a] Dereddened fluxes using an optical extinction of $A_V = 3.7 \pm 0.3$ mag; a conservative error of 0.1 mag is assumed.

References.—(1) Pedersen 1981; (2) Motch et al. 1981; (3) Chaty et al. 2002.

2.2. *Additional Observations Performed during a Low/Hard State*

In addition to the data from 1981, we found only one other case of near-infrared observation during a low/hard state, which appears not to be dominated by the thermal emission from the disk. It is data from the ESO 2.2 m telescope taken on 1997 July 19 (Chaty et al. 2002); they are presented in Table 1. Almost simultaneously, GX 339−4 was observed by the Molonglo Observatory Synthesis Telescope (MOST) at 843 MHz at a level of 4.2 ± 0.7 mJy on 1997 July 22. We also found that one X-ray observation (discussed in Wilms et al. 1999) was made by *RXTE* on 1997 July 7. We found that the *Compton Gamma Ray Observatory*/BATSE 20–100 keV and *RXTE*/ASM 2–12 keV fluxes were on average a factor of 1.75 fainter on July 7 compared to July 19. We therefore used this factor to scale the X-ray observation at the time of the near-infrared observations, as the shape of the X-ray energy spectrum stays almost constant in the low/hard state. Based on this *RXTE* spectrum and on the radio–X-ray correlation (S. Corbel et al. 2002, in preparation), the level of radio emission at 8640 MHz is estimated to be 5.0 ± 0.1 mJy, giving a spectral index of 0.08 ± 0.08 if we take into account the MOST detection.

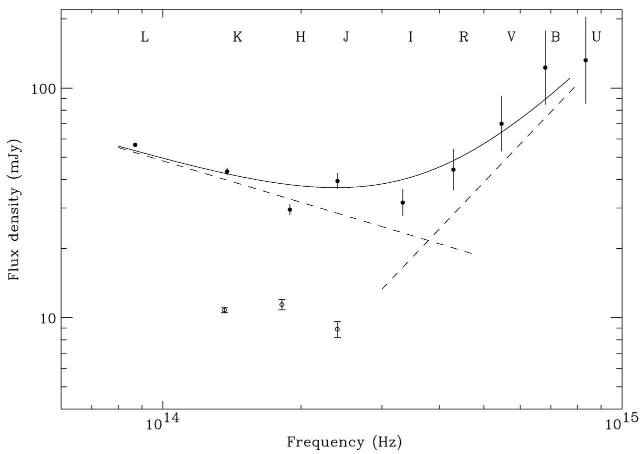

FIG. 1.—Optical and near-infrared magnitudes dereddened with an optical extinction of $A_V = 3.7 \pm 0.3$ mag. Filled circles are observations for the 1981 low/hard state, and open circles are for the 1997 low/hard state. For 1981, the data have been fitted with the sum (*solid line*) of two power-law components (*dotted lines*) with a spectral index of -0.6 for the near-infrared range and $+2.1$ for the optical range.

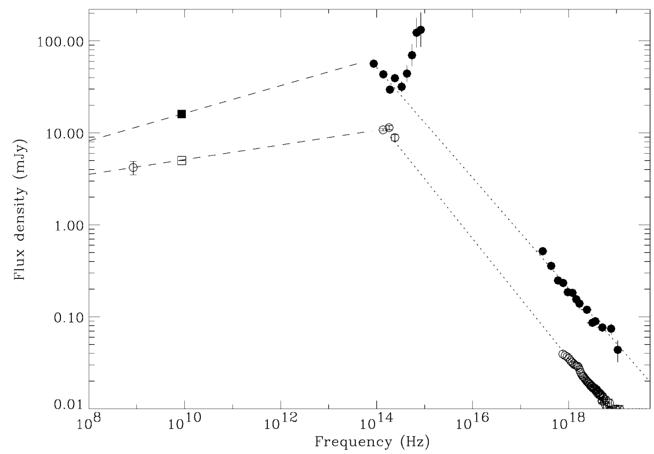

FIG. 2.—Broadband radio-infrared-optical and X-ray spectra of GX 339−4 during a low/hard state in 1981 (*filled symbols*) and 1997 (*open symbols*). Filled and open circles represent the various measurements obtained from quasi-simultaneous observations. The square symbol is the level of radio emission at 8640 MHz estimated from the measured X-ray fluxes based on the existing correlation between radio and X-ray emission (S. Corbel et al. 2002, in preparation). The long-dashed and short-dashed lines correspond to self-absorbed and optically thin regimes in the jet, respectively (spectral indexes of $+0.15$ and -0.6 for 1981; $+0.08$ and -0.65 for 1997). These two lines are for illustrative purposes only, as a smooth transition is expected between the two regimes (e.g., Markoff et al. 2001).

3. RESULTS AND DISCUSSION

3.1. *Spectral Energy Distribution in the Low/Hard State: Evidence of Near-Infrared Synchrotron Emission*

The optical and near-infrared flux, corrected for interstellar extinction, have been plotted in Figure 1 for the 1981 low/hard state data. At first inspection, it is obvious that the near-infrared data points clearly deviate from an extension of the optical slope. For illustration purposes, these observations have been fitted with a function consisting of a sum of two power laws, resulting in a spectral index of -0.6 for the near-infrared range and $+2.1$ for the optical data. The optical data are broadly consistent with thermal emission, presumably from an accretion disk. On the contrary, emission in the *J*, *H*, *K*, and *L* bands clearly points to an infrared excess of nonthermal origin.

In order to understand the nature of this infrared excess, we have plotted in Figure 2 the spectral energy distribution from radio to hard X-rays during the 1981 low/hard state of GX 339−4. Using an extrapolation of the radio spectrum (with typical spectral index) up to the infrared range, we find that the *L*-band data point is compatible with a simple extension of the power law originating from the radio domain. This seems to indicate that radio and near-infrared emission may have a common physical origin. Considering the fact that the radio emission of GX 339−4 or other BHCs in the low/hard state has been interpreted as the optically thick synchrotron emission from a compact jet (Corbel et al. 2000; Fender 2001a), it is likely that we are observing the near-infrared synchrotron emission from the compact jet of GX 339−4. The negative spectral index of the near-infrared data indicates that they lie above the optically thin break, which probably lies at a wavelength of a few microns.

In Figures 1 and 2, we also plot the broadband data from 1997 July. Again, the near-infrared level is compatible with an extension of the flat component originating in the radio domain. Connecting the *K*-band observation to the MOST detection with a power law results in a spectral index of 0.08, in agreement with the estimated spectral index in radio range. It is interesting to note that the radio, near-infrared, and X-ray emission all varied by about the same factor (~4 times fainter) between 1981 and 1997, which favors a direct link, if not a common physical origin, for all three spectral components. Inspection of Figure 1 may also indicate that the cutoff frequency was at slightly higher energy in 1997, but this would require verification by more observations.

In addition to GX 339−4, there has been some indication that near-infrared and/or optical synchrotron emission from a compact outflow also took place in a few other sources. Indeed, it has been shown that the inverted (or flat) radio spectra from GRO J0422+32, XTE J1118+480, GS 1354−64, XTE J1550−564, GRS 1915+105, and GS 2023+338 (see references in Fender 2001a and Corbel et al. 2001a) probably extend up to the near-infrared–optical range, but no high-frequency break to this component has yet been directly observed. Such a break has been inferred at a wavelength of a few microns for the low/hard state transient XTE J1118+480 (Markoff, Falcke, & Fender 2001); in this source, it seems clear that, whatever the model, there is excess flux in the near-infrared that cannot be explained by an accretion disk alone (Hynes et al. 2000; see also Hynes et al. 2002 for XTE J1859+226). In XTE J1550−564, there was fairly good evidence that the break frequency lies in the near-infrared (Corbel et al. 2001a, 2001b). Recently, Jain et al. (2001) confirmed our interpretation, based on their near-infrared and optical monitoring of XTE J1550−564 during the 2000 X-ray outburst. Indeed, a secondary flare (prominent in near-infrared but also visible in optical) was associated with the transition to the low/hard state and the reappearance of the compact jet.

With these observations of GX 339−4, taken during the bright low/hard state in 1981, we clearly detect two emission components in the near-infrared–optical domain. The optical data points typically represent the thermal emission from the outer part of the accretion disk, whereas the near-infrared points correspond to the optically thin regime of the synchrotron emission from the electron distribution. The high-frequency cutoff to the flat (or inverted) spectra from the compact jet therefore probably falls in the near-infrared range. This is the first time that such a high-frequency break is unambiguously detected in the flat (or inverted) synchrotron spectrum from a compact jet. The observations taken during the 1997 low/hard state also show similar cutoff (Fig. 1) and therefore favor this scenario.

3.2. *A Powerful Compact Jet*

The detection of a high-frequency cutoff to the optically thick spectral component is vitally important in order to estimate the total radiative luminosity of the compact jet. In the rest of this Letter, we consider only the optically thick spectral component of the jet—while optically thin synchrotron emission may extend through the optical, UV, and X-ray bands (e.g., Markoff et al. 2001), in that energy regime disentangling its contribution from that of thermal, Comptonized, or other high-energy components is not straightforward. With the observed level of near-infrared emission, a spectral index of +0.15, and the high-frequency synchrotron break at a few microns ($\sim 10^{14}$ Hz), the total radiative luminosity of the compact jet of GX 339−4 (during the 1981 low/hard state) is about $L_J = 10^{35}$ ergs s^{-1} (10^{28} W) for a distance of 4 kpc. The total jet power, P_J, can be estimated as $P_J = L_J \eta^{-1} F(\beta, i)$, where η represents the radiative efficiency for the jet and $F(\beta, i)$ is a correction factor for bulk relativistic motion (dependent on the bulk motion velocity β in units of c and the angle i to the line of sight; see discussion in Fender 2001a, 2001b). A value of $\eta = 0.05$ seems a conservative estimate of the radiative efficiency of the jet, based on the minimum power requirement of the repeated ejections from GRS 1915+105 (Fender & Pooley 2000; Fender 2001b), which also have a flat spectrum from radio to near-infrared. The effect of bulk relativistic motion cannot be precisely determined, but this results in overestimating the jet power only for low values of the inclination angle (see Fig. 6 in Fender 2001a). As the jet is both radiatively inefficient and likely to have a large, possibly dominant, kinetic energy component, this represents a firm lower limit on the jet power. With these limitations in mind, a likely lower limit to the total power of the compact jet in GX 339−4 (during the 1981 low/hard state) is estimated to be around $P_J = 2 \times 10^{36}$ ergs s^{-1} (2×10^{29} W).

Based on the simultaneous *Ariel 6* observations (Fig. 2), the integrated X-ray luminosity of GX 339−4 in the 1–50 keV band is 2×10^{37} ergs s^{-1} (2×10^{30} W). As the X-ray luminosity of BHCs in the low/hard state is known to peak around ~100 keV, extrapolating the *Ariel 6* X-ray spectrum up to 200 keV results in a 1–200 keV X-ray luminosity of $L_X = 4 \times 10^{37}$ ergs s^{-1} (4×10^{30} W). Therefore, it is fairly safe to say that the jet power of GX 339−4 is at least 5% of the bolometric X-ray luminosity (which is presumed to reflect the accretion rate). (For the observations in 1997, we obtained a total jet power of $P_J = 5 \times 10^{35}$ ergs s^{-1} and a 1–200 keV X-ray luminosity $L_X = 5 \times 10^{36}$ ergs s^{-1}, resulting in a fraction of 8%.) In XTE J1550−564, Corbel et al. (2001a) derived a similar value for the ratio of jet to accretion luminosities. Based on similar arguments, Fender (2001a) obtained a similar value for the compact jet of Cyg X-1 using an extrapolation of the radio-millimeter spectrum up to the near-infrared range. A higher ratio (~20%) has been found for the recently discovered X-ray transient XTE J1118+480 (Fender et al. 2001). The general trend that is starting to emerge from these repeated multiwavelength observations of compact jet sources is that the power in the jet may be a significant fraction (similar in all sources?) of the total accretion luminosity.

The base of the jet is probably located very close to, or coexistent with, the corona (Fender et al. 1999), which would explain why there is a very strong coupling between the hard X-ray emission from the corona and the radio emission from the compact jet (Hannikainen et al. 1998; Corbel et al. 2000). This may arise via Comptonization of electrons in the base of the jet or, more radically, it may be that the X-ray emission observed in the low/hard spectral state is also optically thin synchrotron emission directly from the jet (Markoff et al. 2001). In Figure 2, as well as the radio-infrared-optical data, we also plot the contemporaneous X-ray data. Extrapolation of the optically thin synchrotron component in the near-infrared agrees remarkably well with the measured X-ray spectra. Despite the limited data sets, we consider this to be a support to the model of Markoff et al. (2001), but this interpretation will need to be confirmed by further broadband observations and will be discussed in another paper (S. Markoff et al. 2002, in preparation).

4. CONCLUSIONS

The compilation of data presented here for the black hole candidate X-ray binary GX 339−4 clearly reveals the presence of an additional, apparently nonthermal, spectral component in the optical/near-infrared spectral bands, above the thermal emission expected from the accretion flow/disk. We interpret this nonthermal spectral component as optically thin synchrotron emission from just above the frequency at which the self-absorbed spectrum observed in the radio band breaks to optically thin (i.e., it is no longer self-absorbed in any part of the jet). This is the strongest evidence to date that this break lies in the spectral region of the near-infrared to optical bands. We further note that extrapolation of this nonthermal component is coincident with the X-ray spectrum, supporting models in which the X-rays could arise via optically thin synchrotron emission from the jet (instead of Comptonization).

However, the interpretation of the X-ray spectra is necessarily complex, and the relative contributions of disk, Comptonized, synchrotron, and other components is not straightforward to separate. Our approximate measurement of the high-frequency extent of the self-absorbed synchrotron component does, however, give us a very firm and conservative lower limit to the power associated with the jet. Comparing this with the measured X-ray emission, we find that the jet requires *at least* 5% of the total accretion power. This is further evidence for the ubiquity of powerful jets in the low/hard spectral state of accreting black holes.

The authors acknowledge useful discussions with Sera Markoff.

REFERENCES

Blandford, R. D., & Königl, A. 1979, ApJ, 232, 34
Bloom, S. D., Marscher, A. P., Gear, W. K., Terasranta, H., Valtaoja, E., Aller, H. D., & Aller, M. F. 1994, AJ, 108, 398
Brocksopp, C., Fender, R. P., Larionov, V., Lyuty, V. M., Tarasov, A. E., Pooley, G. G., Paciesas, W. S., & Roche P. 1999, MNRAS, 309, 1063
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chaty, S., Mirabel, I. F., Geldoni, P., Mereghetti, S., Duc, P.-A., Martí, J., & Mignani, R. P. 2002, MNRAS, 331, 1065
Corbel, S., Fender, R. P., Tzioumis, A. K., Nowak, M., McIntyre, V., Durouchoux, P., & Sood, R. 2000, A&A, 359, 251

Corbel, S., et al. 2001a, ApJ, 554, 43
———. 2001b, in AIP Conf. Proc. 587, Gamma 2001: Gamma-Ray Astrophysics 2001, ed. S. Ritz, N. Gehrels, & C. R. Shrader (New York: AIP), 126
Falcke, H., & Biermann, P. L. 1996, A&A, 308, 321
Fender, R. P. 2001a, MNRAS, 322, 31
Fender, R. P. 2001b, Ap&SS Suppl., 276, 69
Fender, R. P., Hjellming, R. M., Tilamus, R. P. J., Pooley, G. G., Deane, J. R., Ogley, R. N., & Spencer, R. E. 2001, MNRAS, 322, L23
Fender, R. P., & Kuulkers, E. 2001, MNRAS, 324, 923
Fender, R. P., & Pooley, G. G. 2000, MNRAS, 318, L1
Fender, R. P., et al. 1999, ApJ, 519, L165
Grindlay, J. 1981, IAU Circ. 3613
Hannikainen, D. C., Hunstead, R. W., Campbell-Wilson, D., & Sood, R. K. 1998, A&A, 337, 460
Hjellming, R. M., & Han, X. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 308
Hjellming, R. M., & Johnston, K. J. 1988, ApJ, 328, 600
Hynes, R. I., Haswell, C. A., Chaty, S., Shrader, C. R., & Cui, W. 2002, MNRAS, 331, 169
Hynes, R. I., Mauche, C. W., Haswell, C. A., Shrader, C. R., Cui, W., & Chaty, S. 2000, ApJ, 539, L37
Ilovaisky, S. A., & Chevalier, C. 1981, IAU Circ. 3586
Ilovaisky, S. A., & Chevalier, C. 1987, IAU Circ. 4394
Jain, R. K., Bailyn, C. D., Orosz, J. A., McClintock, J. E., & Remillard, R. A. 2001, ApJ, 554, L181
Maejima, Y., Makishima, K., Matsuoka, M., Ogawara, Y., Oda, M., Tawara, Y., & Doi, K. 1984, ApJ, 285, 712
Markoff, S., Falcke, H., & Fender, R. 2001, A&A, 372, L25
Martí, J., Rodríguez, L. F., Mirabel, I. F., & Paredes, J. M. 1996, A&A, 306, 449
Mirabel, I. F., & Rodríguez, L. F. 1999, ARA&A, 37, 409
Motch, C., Ilovaisky, S. A., & Chevalier, C. 1981, IAU Circ. 3609
Motch, C., Ilovaisky, S. A., Chevalier, C., & Angebault, P. 1985, Space Sci. Rev., 40, 219
Motch, C., Ricketts, M. J., Page, C. G., Ilovaisky, S. A., & Chevalier, C. 1983, A&A, 119, 171
Pedersen, H. 1981, IAU Circ. 3613
Ricketts, M. J. 1983, A&A, 118, L3
Shahbaz, T., Fender, R., & Charles, P. A. 2001, A&A, 376, L17
Sood, R. K., & Campbell-Wilson, D. 1994, IAU Circ. 6006
Stirling, A. M., Spencer, R. E., de la Force, C. J., Garrett, M. A., Fender, R. P., & Ogley, R. N. 2001, MNRAS, 327, 1273
Wilms, J., Nowak, M. A., Dove, J. B., Fender, R. P., & Di Matteo, T. 1999, ApJ, 522, 460
Zdziarski, A. A., Poutanen, J., Mikolajewska, J., Gierliński, M., Ebisawa, K., & Johnson, W. N. 1998, MNRAS, 301, 435