TRACING THE JET CONTRIBUTION TO THE MID-IR OVER THE 2005 OUTBURST OF GRO J1655—40 VIA BROADBAND SPECTRAL MODELING

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ABSTRACT

We present new results from a multiwavelength (radio/infrared/optical/X-ray) study of the black hole X-ray binary GRO J1655—40 during its 2005 outburst. We detected, for the first time, mid-infrared emission at 24 μm from the compact jet of the black hole X-ray binary during its hard state, when the source shows emission from a radio compact jet, as well as a strong nonthermal hard X-ray component. These detections strongly constrain the optically thick part of the synchrotron spectrum of the compact jet, which is consistent with it being flat over 4 orders of magnitude in frequency. Moreover, using this unprecedented coverage, and especially thanks to the new Spitzer observations, we can test broadband disk and jet models during the hard state. Two of the hard-state broadband spectra are reasonably well fitted using a jet model with parameters that overall are similar to those previously found for Cyg X-1 and GX 339—4. Differences are also present; most notably, the jet power in GRO J1655—40 appears to be a factor of at least ~3–5 higher (depending on the distance) than those of Cyg X-1 and GX 339—4 at comparable disk luminosities. Furthermore, a few discrepancies between the model and the data, previously not found for the other two black hole systems for which there was no mid-IR/IR and optical coverage, are evident, and will help to constrain and refine theoretical models.

Subject headings: accretion, accretion disks — ISM: jets and outflows — stars: individual (GRO J1655—40) — X-rays: binaries

Online material: color figures

1. INTRODUCTION

Galactic black hole (BH) X-ray binaries (XRBs) spend most of their time in quiescence (a notable exception is Cyg X-1; see, e.g., Wilms et al. 2006), but occasionally show transient outbursts resulting in an increase in luminosity of many orders of magnitude at all wavelengths. These outbursts are explained as the result of disk instabilities, possibly due to a dramatic increase in the mass accretion rate. The outbursts of BHs have been extensively monitored at all wavelengths: in the radio band, infrared (IR), optical, X-rays, and up to γ-rays. Each observing band provides distinct windows on the radiative processes related to the different components in the binary systems. In X-rays, we observe the regions of the systems close to the compact object: inner disk, Comptonizing corona (e.g., Zdziarski et al. 1998; Nowak et al. 1999) and/or external Compton, and synchrotron self-Compton (SSC) from the base of a jet (see, e.g., Markoff et al. 2005). In the radio band, we observe synchrotron radiation from a relativistic jet (see, e.g., Fender 2006 for a review). In the optical/IR band, three components may overlap: the outer and irradiated disk, the companion star, and the jet (e.g., Russell et al. 2006).

In X-rays, the different stages of an outburst can be described in terms of transitions between X-ray states. The definitions of the X-ray states are based on X-ray spectral and temporal behavior, but their details are still under debate (e.g., Homan & Belloni 2005; Homan et al. 2005a; McClintock & Remillard 2006). In this work we follow the nomenclature in Remillard & McClintock (2006), in particular the following: (1) the thermal (or soft) state is when the disk flux fraction in the 2–20 keV energy spectrum is above 75%, the quasi-periodic oscillation (QPO) in the power density spectrum is absent or weak, and the 2–10 keV power continuum has an integrated rms noise level <7.5%; and (2) the hard state is when the fraction of flux of the power-law component is >80%, the power-law spectral index is 1.4 < Γ < 2.1, and the power density spectrum rms is >10%.

These X-ray spectral states are also associated with a specific radio (jet) behavior (see Fender 2006 for a review). During the hard X-ray state (i.e., quiescence to rise of the outburst), the accretion rate is usually below 10% of the Eddington limit and the X-ray spectrum is dominated by nonthermal power-law emission. The model to explain this nonthermal radiation is an area of controversy; the two alternate scenarios currently in consideration are a Comptonizing corona of hot electrons above an accretion disk, and Comptonizing electrons in the base of a jet, with a contribution also from synchrotron emission. A steady “compact jet” is observed during this spectral state (see Fender 2006 for a recent review). The compact jet is characterized by an optically thick (∝ ≥ 0, where Sν ∝ να and Sν is the radio flux density at a frequency ν) synchrotron radio spectrum, and it has been identified spectrally in many sources and spatially resolved in two BH XRBs: Cyg X-1 (Stirling et al. 2001) and GRS 1915+105 (Dhawan et al. 2000). The structure of the disk that can lead to such a jet is still being debated, although magnetohydrodynamic simulations seem...
to suggest a geometrically thick disk (Meier 2001). During the thermal X-ray state, the thermal component can be modeled with an optically thick, geometrically thin accretion disk (Shakura & Sunyaev 1973), and the radio emission is quenched, likely due to a physical suppression of the compact jet (Fender et al. 1999, 2004; Corbel et al. 2004). The hard-to-soft state transition is likely associated with optically thin radio flares, a signature of the ejection of transient jets (e.g., Gallo et al. 2004).

1.1. GRO J1655−40

The BH XRB GRO J1655−40 was the second superluminal jet source discovered in our Galaxy (Tingay et al. 1995; Hjellming & Rupen 1995). The mass of the compact object has been dynamically estimated to be $M = 6.3 \pm 0.5 M_\odot$, and from the optical photometry an inclination of the binary of $70.2^\circ \pm 1.9^\circ$ has also been derived (Greene et al. 2001). From very long baseline interferometry (VLBI) observations of the transient radio jets of GRO J1655−40, Hjellming & Rupen (1995) derived, using a distance of 3.2 kpc (in agreement with previous estimates; McKay & Kesteven 1994; Tingay et al. 1995), a jet axis inclination of $\sim 85^\circ$ to the line of sight, with a possible precession of the jet around the axis of $\sim 2^\circ$. Foellmi et al. (2006), based on the estimated optical absorption toward GRO J1655−40, have recently placed an upper limit on the distance to the source of $\sim 1.7$ kpc. With this new distance, the transient jets that were previously observed would no longer be superluminal. Also, using the lower distance of 1.7 kpc, the inclination of the jet axis as derived by the VLBI observations would be a few degrees lower. In this paper we use a distance of 1.7 kpc for our calculations and fits. As a caveat, note that the distance is still under debate. Another work, still in preparation, argues that a distance greater than 3 kpc is required to explain the ellipsoidal variations observed in the optical and near-infrared (C. D. Bailyn et al. 2008, in preparation).

After 7 yr of quiescence, GRO J1655−40 entered a new outburst in 2005 February, when the source showed an increase in the X-ray flux (Markward & Swank 2005) and optical and near-IR magnitude (Torres et al. 2005; Buxton et al. 2005) and renewed radio activity (Rupen et al. 2005a). The outburst lasted about 8 months and has been extensively followed, when possible on a daily basis, at all wavelengths. In March, a state transition occurred as GRO J1655−40 entered a thermal state and the radio counterpart faded (Homan 2005; Rupen et al. 2005c). In May, the source entered a highly variable, high X-ray luminosity state (Homan et al. 2005b) coupled with renewed radio emission (Rupen et al. 2005b). GRO J1655−40 then entered a soft state, with no radio detection, and returned to a hard state on September 23 (Homan et al. 2005c). The source returned to radio activity on September 21 (Brocksopp et al. 2005).

In this work we present new results from a multicolor campaign of GRO J1655−40 during its 2005 outburst. We study the broadband spectral energy distribution (SED) during the different stages of the outburst, with particular emphasis on the important new simultaneous observations in mid-infrared by Spitzer, which also allows for new constraints on the jet scenario. We provide an overview of the radio, mid/near-IR, optical, soft/hard X-ray observations and data analysis in § 2; we discuss the evolution of the spectra during the outburst in § 3.1 and the detection of the mid-IR emission from the compact jet in § 3.2, and the results of the fit of the broadband spectra in the context of a jet model and the discussion are in § 3.3.

2. OBSERVATIONS

We have observed GRO J1655−40 with the Multiband Imaging Photometer for Spitzer (MIPS) during the outburst that started in 2005, following the different stages from the rise of the outburst until quiescence in 2006: (1) in a hard state during the rise on 2005 March 10, (2) in a thermal state after the first X-ray flux peak on 2005 April 6, (3) in a thermal state after the second and brightest X-ray flux peak on 2005 August 28, (4) during the decay of the outburst, immediately after the BH returns in the hard state on 2005 September 23 and, finally, (5) after the outburst ended, during quiescence on 2006 April 1. The arrows at the top of Figure 1 (bottom) show when these observations have been performed with respect to the 2–12 keV light curve of the All Sky Monitor (ASM) on board the Rossi X-ray Timing Explorer (RXTE). Since the 2005 outburst started, GRO J1655−40 has been monitored daily in X-rays with pointed RXTE observations (J. Homan and coworkers) and by the International Gamma-Ray Astrophysics Laboratory (INTEGRAL; INTEGRAL Galactic bulge group) in optical/near-IR with the Small and Medium Aperture Research Telescope System (SMARTS; M. Buxton and C. Bailyn)12, and with good coverage also in the radio band with the Very Large Array (VLA; M. Rupen and coworkers);13 see also Shaposhnikov et al. (2007). The four Spitzer MIPS observations during the outburst (see Fig. 1, top) were all simultaneous with pointed RXTE, SMARTS, and radio (either with the VLA or the Australia Telescope Compact Array) observations, allowing us to study the evolution of the complete broadband spectrum of the BH during the different stages. GRO J1655−40 has also been observed with the Spitzer Infrared Array Camera (IRAC) in the hard state on September 29, simultaneously with RXTE and SMARTS and quasi-simultaneously (on 2005 October 2) with VLA observations. The Spitzer MIPS observation in quiescence, on 2006 April 1, had no coverage at other wavelengths, except for the 2–12 keV observations of the RXTE ASM. The logs of the RXTE and Spitzer observations are shown in Table 1.

2.1. Infrared and Mid-Infrared: Spitzer IRAC and MIPS

We have processed the Basic Calibrated Data of the MIPS observations at 24 µm and IRAC observations at 3.6, 4.5, 5.8, and 8 µm using the software MOPEX (Makovoz & Marleau 2005). We created mosaics from the 70 and 59 frames band pass obtained in the MIPS and IRAC observations, respectively. GRO J1655−40 is a few arcseconds south of an extended mid-IR-emitting source, and very bright at 24 µm (see Fig. 1, top), which enhances the background in the region of the BH and increases the uncertainties in its flux estimates. GRO J1655−40 is observed to vary significantly over our five MIPS observations, and the mid-IR emission appears to be off when the source is in its quiescent state, on 2006 April 1. We extracted the flux density in a circular region centered at the optical coordinates of GRO J1655−40 with a radius of 10″ in the quiescent state observation, and used this flux (540 µJy) as background for the estimate of the flux density of the source in the other MIPS observations. We extracted the flux density of GRO J1655−40 in the other five MIPS observations and in the IRAC observation using aperture photometry, with a 10″ radius circle. For each observation, we created the point-response functions (PRFs) with prf_estimate and calculated the aperture corrections using the extracted PRF. We have corrected for interstellar extinction using $A_v = 3.72$, derived from Greene et al. (2001) and following the standard optical-to-IR interstellar extinction law

10 See http://tahti.mit.edu/opensource/1655/.
11 See http://www.integral.soton.ac.uk/projects/bulge/SOURCES/GRO_ J1655-40/GRO_J1655-40.html.
12 See http://www.astro.yale.edu/~buxton/smarts/light_curves/ori_gro. jgro.
13 See http://www.aoc.nrao.edu/~hreuropen/XRT/GRJ1655-40/grj1655-40 .shtml.
(e.g., Rieke & Lebofsky 1985; Cardelli et al. 1989). Note that if we followed Foellmi et al. (2006) instead, we would have obtained a slightly lower value of $A_v = 3.53$. We added 5% and 10% systematic errors on the estimate of the flux densities in the IRAC and 24 $\mu$m MIPS observations, respectively, to take into account the uncertainties in the photometric calibration (see Reach et al. 2005). The flux densities of the Spitzer observations are shown in Table 2.

2.2. Optical/Near-Infrared: SMARTS

Optical and IR monitoring of GRO J1655–40 was carried out throughout the 2005 outburst using the SMARTS consortium...
telescopes. Starting 2005 February 21, observations were carried out each clear night with the 1.3m telescope at CTIO and the ANDICAM instrument. The ANDICAM (Depoy et al. 2003) is a dual-channel imager containing an optical CCD and an IR array, so simultaneous observations can be obtained from one optical (BVRI) and one IR (JHK) bandpasses. In the case of the outburst of GRO J1655−40, nightly observations were obtained in B, V, I, J, and K (Buxton et al. 2005; Buxton & Bailyn 2005). The full SMARTS light curve will be presented elsewhere.

Standard flat-fielding and sky subtraction procedures were applied to each night’s data, and the internal dithers in the IR were combined as described in Buxton & Bailyn (2004). Differential photometry was carried out each night with a set of reference stars present in the field of view of GRO J1655−40. The IR photometry was carried out each night with a set of reference stars of similar brightness to the source suggesting a precision of <0.02 mag in all bands. We show the apparent magnitudes, not dereddened, in Table 3. We estimate the accuracy of our standard field calibration to be better than 0.05 mag in all bands. We show the apparent magnitudes, not yet dereddened, in Table 3.

2.3. X-Rays: RXTE

2.3.1. X-Ray Spectral Analysis

We have analyzed the RXTE pointed observations performed simultaneously with our Spitzer observations. We have used the PCA Standard2 data of the proportional counter unit 2 (PCU 2), which was on in all the observations, to produce the hardness-intensity diagram (HID) shown in Figure 2. The hard color is defined as the count rate ratio 9.4–18.5 keV/2.5–6.1 keV. For the energy spectral analysis, we have used PCA Standard2 data of all the PCUs available, and HXTE Standard Mode cluster A

| Date         | Wavelength (µm) | X-Ray State | Flux Density (mJy) |
|--------------|----------------|-------------|--------------------|
| 2005 Mar 10  | 24             | Hard/HIMS   | 1.40 ± 0.23        |
| 2005 Apr 6   | 24             | Thermal     | 1.37 ± 0.22        |
| 2005 Aug 28  | 24             | Thermal     | 0.26 ± 0.13        |
| 2005 Sep 23  | 3.6            | Hard        | 5.67 ± 0.39        |
| 4.5          | 3.90 ± 0.29    |
| 5.8          | 3.02 ± 0.52    |
| 8            | 2.40 ± 0.57    |
| 2005 Sep 29  | 24             | Hard        | 2.07 ± 0.27        |
| 2006 Apr 1   | 24             | Quiescence  | <0.54              |

Note.—Errors are 1 σ rms.
Figure 2.—HID of the five RXTE pointed observations, simultaneous with Spitzer.

and B data. For the PCA data, we have subtracted the background estimated using pcarboul v version 3.0, produced the detector response matrix with pcaarmp version 10.1, and analyzed the energy spectra in the range 3–25 keV. A systematic error of 0.5% was added to account for uncertainties in the calibration. For the HXTE data, we corrected for dead time, subtracted the background, and extracted the response matrix using FTOOLS version 6.1.2. We have analyzed the HXTE spectra between 20 and 200 keV. The 3–200 keV spectra are well fitted using a multicolor disk blackbody, a power law with a cutoff for the March 10 and April 6 spectra, and a smeared edge around 7–9 keV (we constrained the width of the edge to be <15 keV); for the April 6 observation, a Gaussian emission line around 6.2 keV is required, possibly a redshifted iron line, although the energy is still marginally consistent with neutral iron line centered at 6.4 keV. We also accounted for photoelectric absorption from interstellar material. The inner temperature of the disk is particularly low for the first three hard-state observations, and we fixed it to 0.5 keV because it cannot be well constrained. Also, we fixed the equivalent hydrogen column density to \( N_H = 8 \times 10^{21} \text{ cm}^{-2} \), a value comparable to those measured in previous observations of GRO J1655–40 (e.g., Tomsick et al. 1999). We show the best-fit parameters of each of the 3–200 keV spectra in Table 4.

2.3.2. X-Ray Temporal Analysis

For each observation, we compute the power density spectra from the PCA data using IDL programs developed at the University of Tübingen (Pottschmidt 2002). The power density spectrum is normalized as described in Miyamoto & Kitamoto (1989) and corrected for the dead-time effects according to Zhang et al. (1995). Using 256 s time segments, we investigate the low-frequency QPOs and the timing properties of the continuum up to 100 Hz. We fit all the power density spectra with a broad and narrow Lorentzians (Fig. 3) with our standard timing analysis techniques (e.g., Kalenck et al. 2005; see Belloni et al. 2002; Nowak 2000; Pottschmidt et al. 2003). The rms amplitudes are calculated over the whole frequency range of the power density spectrum, calculated from zero to infinity from the fitted Lorentzians, integrated over 2–15 keV. Although the aperiodic X-ray variability features are still poorly understood in detail, they are thought to be related to physical timescales in the accretion disk (see, e.g., van der Klis 2006 for a review). The multi-Lorentzian model description of the power spectra, although not necessarily physically motivated, makes it possible to identify the different components in the power density spectrum.

### Table 4

| Parameter | Mar 10 | Apr 6 | Aug 28 | Sep 24 | Sep 29 |
|-----------|--------|-------|--------|--------|--------|
| \( BT \) (keV) | 0.5 fixed | 1.25±0.01 | 0.87±0.01 | 0.5 fixed | 0.5 fixed |
| \( N_{BH} \) | 1969±139 | 718±26 | 1904±115 | 115±29 | 106±18 |
| Gaussian | | | | | |
| \( E_{1/2} \) (keV) | ... | 6.24±0.07 | ... | ... | ... |
| \( \sigma_{E} \) (keV) | ... | 0.1 fixed | ... | ... | ... |
| \( N_{E} (\times 10^{-3} \text{ phot. cm}^{-2} \text{ s}^{-1}) \) | ... | 9.02±0.01 | ... | ... | ... |
| Power Law | | | | | |
| \( \Gamma_{PL} \) | 1.72±0.01 | 2.93±0.07 | 2.28±0.07 | 1.57±0.01 | 1.57±0.01 |
| \( N_{PL} (10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}) \) | 4296±13 | 5025±10 | 4985±17 | 462±2 | 205±1 |
| High-Energy Cutoff | | | | | |
| \( E_{c} \) (keV) | 33±3 | 11.9±2 | 8.6±1 | 6.8±0.1 | 6.7±0.1 |
| \( E_{d} \) (keV) | 160±12 | 4.6±0.9 | ... | ... | ... |
| Smedge | | | | | |
| \( E_{\text{edge}} \) (keV) | 7.44±0.06 | 6.46±0.08 | 8.64±0.09 | 6.8±0.1 | 6.7±0.1 |
| \( MaxT \) | 1.81±0.05 | 1.00±0.3 | 5.0±0.4 | 1.46±0.08 | 0.6±0.3 |
| \( \text{Width}_{\text{edge}} \) (keV) | >10.6 | 1.4±0.6 | >8.7 | >7.5 | 5.6±2.8 |
| Fit Statistics | | | | | |
| \( \chi^2 \) (dof) | 1.09 (85) | 1.53 (38) | 1.26 (85) | 0.64 (86) | 0.73 (86) |

Note.—Errors are 68% confidence for one interesting parameter.
and follow their variations in relation with other observational parameters (see Belloni et al. 2002). These characteristics make the power density spectra a powerful (complementary) tool to classify the different observational states of the XRBs. In this work we study the power density spectra only for classification purposes, following Remillard & McClintock (2006) and Homan & Belloni (2005) (see also van der Klis 2006). The power density spectra on April 6 and August 28 are well fitted with two broad Lorentzians, no QPOs are present, and the total rms is $P_{5\%}$, which is typical of observations in a thermal state. More than two Lorentzians are needed to fit the more complex power density spectra of the March 10, September 24, and September 29 observations. At least three broad Lorentzians and one QPO component (plus the first harmonic of the QPO in the case of the March 10 observation) are necessary. The presence of a $0.1–10$ Hz QPO and the total rms $\gtrsim 25\%$ indicate that the observations are in or very close to a hard state. We show the power density spectra of the five observations with the multi-Lorentzian fitting components in Figure 3.

2.4. Radio: VLA

In this work, we used the VLA radio flux densities at 5 and 8.5 GHz from Shaposhnikov et al. (2007) for the 2005 March 10 observation, those at 5 GHz from Brocksopp et al. (2005) for

![Figure 3: X-ray power density spectra of the five RXTE PCA observations simultaneous with Spitzer. The dashed lines indicate individual Lorentzian components, whereas the solid lines show the total fit.](image-url)
the 2005 September 22 observation, and those at 5 GHz from M. Rupen and collaborators' Web page\(^\text{14}\) for the observations on 2005 April 6, August 28, and October 2. The radio—X-ray SEDs of the five observations of GRO J1655—40 are shown in Figure 4.

\(^{14}\) See http://www.aoc.nrao.edu/~mrupen/XRT/GRJ1655-40/grj1655-40.shtml.

3. RESULTS AND DISCUSSION

3.1. The Outburst Evolution

We follow the evolution of our six observations during the outburst using the X-ray light curve (Fig. 1), the HID (Fig. 2), the power density spectra (Fig. 3), and the SEDs (Fig. 4). We inspected the PCA light curves with 16 s time resolution for the observations taken on March 10, April 6, August 28, September 24.
and September 29. We do not see any long-term trends in the count rate over the duration of the observations (on a timescale of hours), or any X-ray dips or flares with amplitudes greater than ~15%.

**Observation 1.**—Based on the X-ray definition in Remillard & McClintock (2006), on 2005 March 10 the source is in the hard state. The power density spectrum shows a high rms of ~34% and broad features, as well as a narrow QPO around 2 Hz. The X-ray energy spectra show a disk flux of ~5% of the total 2–20 keV flux, which is also consistent with their definition of hard state. However, the X-ray flux has already started its abrupt rise toward the first peak of the outburst. The position on the HID, if compared to those of September 24 and 29, which are also in the hard state (see below; see also J. Homan’s “open source” Web page for a comparison with other GRO J1655—40 observations), suggests that the source was leaving the hard state. Indeed, if we follow the nomenclature of Homan & Belloni (2005) instead, which is based on the spectral index of the X-ray power law and the QPO and integrated rms strength in the power density spectra, we would identify March 10 as a hard intermediate state (HIMS) observation (see also Shaposhnikov et al. 2007). The radio emission is significantly detected in two bands (5 and 8.6 GHz), with a spectral index of \( \alpha = -0.36 \pm 0.34 \); this spectral index is consistent with either a compact jet, as typically observed in hard state observations, or an optically thick synchrotron emitting jet, possibly indicating that the outer part of the jet was decoupled from the system and the source had already left the hard state. Given the lack of conclusive proof, we discuss both the hard state and HIMS classifications, where with “hard state” we also imply that a radio optically thick jet is present. An excess in the spectrum at 24 μm suggests that the jet component is dominant in the IR band also (see § 3.2 for a discussion). In case the source is in a hard state and the radio emission is from a compact jet, a power-law fit of the radio-to-IR spectrum gives an almost flat spectral index of \( \alpha = 0.08 \pm 0.03 \).

**Observation 2.**—On 2005 April 6, the source is in a thermal state. The X-ray light curve shows that during this observation GRO J1655—40 is in a steady high-flux state, between the two outburst peaks. The power density spectrum shows a rms ~5% of the total 2–20 keV flux, and the source is, accordingly, in the upper left, soft region of the HID pattern. The radio emission is already quenched with a 5 GHz 3σ upper limit of 1 mJy, and the thermal emission dominates the energy spectrum in the X-ray, optical, and mid-IR bands: Spitzer MIPS detected the IR tail of the bright disk at 24 μm. Note also that the hard X-ray component above ~30 keV does not appear in this observation, going below the detection threshold of HEXT.

**Observation 3.**—On 2005 August 28, GRO J1655—40 is in a thermal state. The X-ray light curve shows that the source is still at a high flux level, but already starting its decay toward the hard state. The rms noise in the power density spectrum is ~2%, typical of a thermal state, as is its position on the far left of the HID. The energy spectrum still shows a bright disk in the soft X-rays, where the disk flux is 94% of the total 2–20 keV flux. We also see the reappearance of the hard X-ray component above 30 keV. The radio emission is not detected down to a 3σ upper limit of ~1 mJy, and the source is only marginally detected at 24 μm.

**Observations 4 and 5.**—On 2005 September 24 and 29, GRO J1655—40 is observed during the decay of the outburst, when it returns to the hard state. The rms values in the power density spectra increase significantly to ~25%, and some features, like a QPO around 0.3 Hz, appear on September 24. The source reaches the lower right part of the HID, and the X-ray spectra are dominated by a nonthermal power-law component whose 2–20 keV flux is more than 90% of the total flux. The IR emission (IRAC on September 24 and MIPS on September 29) shows an excess due to the rebrightening of the jet. This jet rebrightening is clearly visible in the radio band, where its flux density at 5 GHz increases between September 24 and 29, contrary to the X-ray flux that is still decaying in time: no radio/X-ray flux positive correlation is present.

**Observation 6.**—On 2006 April 1, the source has already returned to quiescence; no pointed RXTE, radio, and optical observations are available. The Spitzer MIPS observations do not detect the source at 24 μm.

### 3.2. Mid-Infrared Emission from the Compact Jet

We detect mid-IR emission at 24 μm from the hard-state observations of GRO J1655—40 on September 29 and the hard (or HIMS) observation on March 10. The source is also detected on April 6, when GRO J1655—40 was in a thermal state. Thanks to the optical and near-IR simultaneous observations, we can clearly distinguish the contribution of the companion star in the binary system; its spectrum can be represented by a blackbody peaking at a few 1014 Hz, which should show a Rayleigh-Jeans decay at lower frequencies. The comparison of the near-IR flux distribution with a power law with a spectral index of 2 and normalized to the flux in the K band (1.39 × 1014 Hz) clearly shows in both the March 10 and the September 29 observation a deviation from a Rayleigh-Jeans spectrum in the mid-IR, with an excess at 24 μm. Other possible contributors to the mid-IR emission are the jet and the irradiated disk components (Cunningham 1976; Vrtilek et al. 1990; Hynes et al. 2002; see also Russell et al. 2006 for a discussion). The variability observed in the mid-IR rules out a circumbinary disk origin.

In the March 10 observation, the disk emission is significantly higher than in the other hard-state observations, and the contribution of the disk irradiation might be significant. Mid-IR emission is also detected during the April 6 observation, when GRO J1655—40 was in a thermal state. The disk component dominates the X-ray spectrum, and a blackbody dominates the optical-IR band (see Fig. 4). The jet is not detected in the radio band with a 3σ upper limit of 1 mJy, supporting the evidence that in BHs the compact jet is suppressed during the thermal state. In this case, the mid-IR emission is most likely due to the contribution of an irradiated disk component. The 24 μm flux of the April 6 and March 10 observations are comparable (see Table 2). However, during the March 10 observation both the disk and the blackbody component are much fainter, indicating, therefore, a significant contribution in the mid-IR by another component, i.e., the jet, which is also detected in the radio band.

In the September 29 observation the mid-IR emission is about 50% higher than on March 10 (Table 2), but the disk emission is much weaker (Table 4), strongly indicating that the compact jet, also clearly detected in the radio band, is the dominant contributor to the mid-IR. Indeed, a fit with a power-law model from the radio band to the mid-IR gives a spectral index of \( \alpha = 0.07 \pm 0.04 \), consistent with a flat optically thick synchrotron emission from a compact jet. A deviation from a Rayleigh-Jeans spectrum is observed also on September 24, where an excess flux is already present at 8 μm. This excess, as well as in the September 29 observation, is likely dominated by the jet.

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15 See http://tahti.mit.edu/opensource/1655/.
3.3. Modeling the SEDs: New Constraints on Jet Models

Different theoretical models exist to explain the emission mechanism for BH XRBs in the hard state (for a discussion, see, e.g., Tomsick et al. 2004 and references therein). One of the possibilities that we further explore in this paper is that the compact jet, observed to produce synchrotron emission from the radio to at least the IR band, is also responsible for the hard X-ray emission, which comes from the base of the jet (e.g., Markoff et al. 2001, 2005; Markoff & Nowak 2004). Difficulties in reproducing some of the observed features seem to disfavor the direct synchrotron emission from the base of the jet as the “dominating” X-ray-emitting mechanism in at least a few hard-state observations, as in the case of the BH 4U 1543–47 (Kal senti et al. 2005). On the other hand, K"ording et al. (2006), based on statistical analysis of the sample of BH systems in the “fundamental plane” (Merloni et al. 2003; Falcke et al. 2004; see also the discussion in Heinz 2004), pointed out that a synchrotron/jet scenario, discussed in the more updated prescription including external Compton and SSC, is still in agreement with the fundamental plane for hard-state BHs. Other possible arguments against the synchrotron-only jet model as the dominant X-ray emission mechanisms in XRBs have been discussed in, e.g., Maccarone (2005 and references therein). In the following, we test the most updated version of the “jet model” which also includes SSC and external inverse Compton. Other models exist to interpret the observed broadband spectra, and to date there are no conclusive arguments which favor the jet model. Yuan et al. (2005) proposed, for example, an accretion-jet model to interpret the broadband energy spectra of the BH XTE J1118+480 in hard state (the same source also successfully fitted with the earlier version of the jet model in Markoff et al. 2001), where a simple synchrotron-emitting compact jet is superimposed ad hoc to a “hot accretion flow” model fitting the X-ray spectrum (i.e., an outer thin disk coexisting with an inner advection dominated or luminous-hot accretion flow). In their model, the hard X-ray emission comes from the hot accretion flow through thermal Comptonization. However, this model is not yet testable statistically and self-consistently in the whole broadband spectrum. Indeed, among the different models available to test against our new broadband SEDs, the jet model described in Markoff et al. (2005) is the only refined broadband model that can be tested with $\chi^2$ statistics from the radio band to the hard X-rays.

This jet model, in its latest prescription, has already started to be explored by fitting the broadband energy spectra of two BH XRBs in hard state. Most notably, Markoff & Nowak (2004) show that either a Comptonizing corona or synchrotron self-Compton from the base of a compact jet can fit the X-ray part of the energy spectra of Cyg X-1 and GX 339–4 in hard state with the same statistical quality. Also, the nonthermal hard tail in the X-ray spectra of GRO J1655–40 can be well fit with “corona” models. The best-fit values from a simple fit using a power law to account for the hard X-ray tails are shown in Table 4. One of the advantages of the jet model is that it can interpret the whole observable broadband spectrum, from the radio band to the highest energies, in a self-consistent manner. For Cyg X-1 and GX 339–4, however, the broadband spectra analyzed in Markoff et al. (2005) relied on simultaneous radio and X-ray observations, leaving the optical and IR portion of the spectrum uncovered. The mid-IR, IR, and optical bands are indeed critical for testing the assumptions of the model and constraining fundamental jet model parameters.

3.3.1. The Jet Model

For a detailed discussion of the jet radiative model, we refer the reader to, e.g., Markoff & Nowak (2004) and Markoff et al. (2005). We recall here some fundamental assumptions and a brief description of the model, as outlined in Markoff et al. (2005): (1) the total power in the jet scales proportionally with the accretion power at the inner edge of the disk; (2) the jet is expanding freely and, at the very base, is only slightly accelerated as a result of the pressure gradient; (3) the jet contains cold protons that carry most of the kinetic energy, while the leptons are the dominant source of radiating energy; (4) some particles are eventually accelerated into a power-law distribution; and (5) the power law is maintained along the jet beyond the shock region. Geometrically, the base of the jet comprises a region with (nozzle) radius $r_0$, whose lower limit is the innermost stable orbit of the disk around the black hole. The uncertainties about the physics of jet formation are absorbed by initializing parameters in this region for the rest of the jet. The jet starts as a cylindrical flow with constant radius $r_0$. After this small nozzle region, above $\sim 10$ gravitational radii ($r_g$), the jet expands sideways at the sound speed for a proton/electron plasma (i.e., $\sim 0.4c$) and is only slightly accelerated by the resulting pressure gradient. At a distance of $10r_g-100r_g$ the particles in the jet, which started with a quasi-thermal distribution, are accelerated into a power-law distribution.

To zeroth order (for a more detailed discussion of other cooling effects already present or not yet present in the model, see Markoff et al. 2005), the resulting jet emission spectrum is the superposition of (1) an optically thick synchrotron spectrum coming from the outer regions of the jet, beyond the shock region, emitting in the radio up to likely the IR band with a flat or slightly inverted power-law spectrum; (2) an optically thin synchrotron spectrum, still coming from the postshock region but emitting at frequencies above which the jet is transparent, which emits a power-law spectrum with a negative spectral index dependent on the electron power-law distribution; (3) an optically thin and optically thick synchrotron emission from the quasi-thermal distribution of particles coming from the preshock jet region; and (4) external Compton from the accretion disk plus an SSC spectrum coming from the very base of the jet, from the nozzle region. Effects of high-energy cooling are added to this spectrum, so that the optically thin part synchrotron spectrum decays exponentially above a certain frequency; the maximum electron energy is calculated self-consistently for the local cooling rate. A multicolor disk blackbody is added as an independent, fitted spectral component, whose photons are included for upscattering in the jet. Note that an irradiated disk component is not yet included in this version of the code.

3.3.2. The Fits

We focus only on the hard-state observations. We fitted the energy spectra of 2005 March 10, September 24, and September 29, using the Interactive Spectral Interpretation System (ISIS; Houck & Denicola 2000). This software has two main advantages: (1) we can deal easily with broadband spectra, combining spectra with response matrices and ASCII tables listing energy channels and flux densities, without response matrices; and (2) it can create model-independent unfolded spectra. We refer to the work of Nowak et al. (2005) for a detailed discussion. As in Markoff et al. (2005), we started the fit manually, trying to reach a $\chi^2$ such that $\chi^2 < 10$. Then we use these parameters as a starting set of parameters for the fit with ISIS. This procedure helps to avoid the automatic minimization in ISIS falling in local minima. The fitting analysis, starting from the manual fitting, is a fairly long procedure that can take up to a week per spectrum.

The fitting model we used consists of three components, corrected for photoelectric absorption: (1) the disk and jet models discussed above; (2) a blackbody to model the companion star,
likely a F6 III–F7 IV (Shahbaz et al. 1999; Israeli et al. 1999; Foellmi et al. 2006); and (3) a disk reflection component (pexriv in ISIS) with a single Gaussian emission line in the range 6–7 keV. The values with the best-fit parameters of the September 24 and 29 spectra are shown in Table 5. We first fixed the physical parameters which can be constrained by observations. We fixed the mass of the BH to 7 $M_\odot$ (Orosz & Bailyn 1997; see also Greene et al. 2001), and the distance to its most recent inferred upper limit of 1.7 kpc (Foellmi et al. 2006). In § 1.1 we noted that the upper limit of 1.7 kpc on the distance is still under debate and that there are arguments that still indicate a lower limit of 3 kpc (C. D. Bailyn et al. 2008, in preparation). A debate on the distance goes beyond the scope of this paper, and we decided primarily to use the latest published value. However, since the distance enters nonlinearly in many parameters of the fitting jet model, and a simple rescaling of the best-fit values in Table 5 is not possible for all of them, for comparison we also report in Table 5 the results of a fit to the September 29 observations with a fixed distance of 3.2 kpc. We fixed the inclination of the jet, at first, to 75°, and then we calculated a second fit for the September 29 observation with the inclination free, as this observation requires a somewhat flatter optically thick synchrotron spectrum (see below for a more detailed discussion). An inclination of 75° is consistent with the jet axis inclination inferred from the radio lobe observations by Hjellming & Rupen (1995), revised with the new upper limit on the distance to the source of 1.7 kpc. This value is also consistent with the disk inclination of ~70° inferred by Greene et al. (2001) and allowing a disk-jet misalignment of less than 15° (e.g., Maccarone 2002). We also fixed the parameters known from previous works to fall in the same range for the other BHs (Cyg X-1, GX 339–4; this choice is made as a starting point to explore the parameter space; see also Markoff et al. 2005 for discussion). The relevant fitting parameters are shown in Table 5.

3.3.3. A Comparison with other BHs

In Table 5 we show the best-fit parameters of the September 24 and 29 observations (during the decay of the outburst) using the jet model, as described above. We show the SEDs of the observations with the fitting model components in Figures 5, 6, and 7. The observation on March 10 during the rise of the outburst did not give a good fit [$\chi^2_\nu = 8.35$ (80 dof)], and we discuss it in more detail in § 3.3.4. The jet model fit fairly well the data of September 24,
with a $\chi^2 = 1.72$ (81 dof), and September 29, with a $\chi^2 = 0.90$ (56 dof), fixing the jet inclination to 75°. Note that the high $\chi^2$ might, at least in part, be due to the fact that the optical and IR part of the spectrum has been fitted with a simple blackbody spectrum, which was added as an independent component to the jet model. In the September 29 fit (Fig. 5), although the fit is good in a statistical sense, the model somewhat underestimates the radio emission. The slope of the optically thick part of the synchrotron spectrum in the modeled jet is steeper than the slope required by the observations. In order to obtain a flatter radio–IR synchrotron spectrum, we let the jet inclination be a free parameter, and the best-fit inclination obtained is $\sim 40°$ [$\chi^2 = 0.94$ (55 dof); see Fig. 7]. We would like to stress that, at this stage, the free inclination is meant to be an artificial modification to try to obtain a better by-eye fit in the radio band. A jet inclination of $\sim 40°$ seems unlikely given a disk inclination of 70° (Greene et al. 2001) and the previous estimates of the jet inclination (e.g., Hjellming & Rupen 1995), even using the smaller distance in Foellmi et al. (2006). Furthermore, the uncertainties in modeling the jet emission are still too large to attempt an estimate of the jet inclination using these fits. The $\chi^2$ values for this fit are comparable because the statistics are dominated by the X-ray and optical part of the spectrum, but there is an improvement in the fit in the radio band.

A remarkable result of these fits is that the same model that can fit GX 339–4 and Cyg X-1 broadband spectra well seems not to reproduce equally well the optically thick part of the synchrotron emission in GRO J1655–40, which is flatter than the model predicts. Possible ways to make the radio–IR emission flatter would be (1) to have a less beamed jet (which is the case emulated in the fit by the smaller jet inclination angle), which can be due to, e.g., a smaller gradient in the regions contributing to the

Fig. 5.—Jet model fits with residuals of the radio—to—X-ray (top) and X-ray spectra (bottom) of the September 24 observation of GRO J1655–40, with the jet inclination angle fixed to 75°. The light green dashed line is the preshock synchrotron component, the darker green dash-dotted line is the postshock synchrotron component, the orange dash-dotted line represents the SSC plus the disk external Compton component, and the purple dotted line is the multitemperature disk black body plus a blackbody representing the companion star in the binary system. The solid red line is the total model. Note that the model components in this representation are not absorbed and are not convolved with the response matrices. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 6.—Jet model fits with residuals of the radio—to—X-ray (top) and X-ray (bottom) spectra of the September 29 observation of GRO J1655–40, with the jet inclination angle fixed to 75°. Model components are as in Fig. 5. [See the electronic edition of the Journal for a color version of this figure.]
that (1) the total initial power that goes into the jet is similar for these three different BHs. Some differences are present, however; we find that the power that GRO J1655–40 put into the jet is higher than that in the other two BHs by a factor of $\approx 3$ (the jet power is of the same order of $N_j$ in Table 5; see also Appendix A2 in Markoff et al. 2005). Also, the nozzle radius is smaller than that of GX 339–4 and very similar to that of Cyg X-1, reflecting the higher X-ray/radio flux ratio. The electron temperature is approximately the same as that found for the other two BHs, as is the spectral index of the electron distribution. The model finds solutions for a jet close to equipartition ($k \approx 1$ in Table 5) only in the case of September 29, but only if we let the jet inclination free to adjust for the otherwise steeper optically thick radio-to-IR spectrum observed. The September 24 and 29 observations with a fixed inclination of 75° find a solution for a weakly magnetically dominated jet ($k \approx 4$ and $k \approx 5$, respectively) which is different from what is found for other two BH XRBs, but close to the values found for, e.g., low-luminosity active galactic nuclei such as Sgr A* and M81 (e.g., Markoff et al. 2004). Note, however, that this equipartition parameter is still not very well constrained and, also, that there is no physical reason to prefer a solution with a jet in equipartition over that of a (weakly) magnetized jet. Using a distance of 3.2 kpc, the jet power of GRO J1655–40 would be about 5 times higher than that derived in the fits of Cyg X-1 and GX 339–4 for comparable disk luminosities. The jet and the disk luminosities seem to be the only two parameters that change significantly (increase) using a distance of 3.2 kpc (see Table 5).

3.3.4. March 10: X-Rays from a Corona or from the Base of the Jet?

We are not able to obtain a statistically good fit for the observation on 2005 March 10. We fitted this broadband spectrum with the same model components we used for the September observations, in order to emphasize the differences between this and the other hard state spectra. The reflection fraction parameter was left free during the fit and reached a value of $\approx 70\%$. Such a high reflection fraction is 2 times the one found in the September observations (Table 5, using a distance of 1.7 kpc) and is physically incompatible with a mildly relativistic beamed corona or a jet model (Beloborodov 1999; Markoff & Nowak 2004). An edge around 6–7 keV and/or a stronger iron line at a different peak energy might be needed to slightly improve the spectral fitting. However, the “hard-state” jet model in the present form seems to not be sufficient to describe statistically well the observed broadband data. On March 10, the source is either in a hard state or in a HIMS (according to the definitions in Remillard & McClintock [2006] or Homan & Belloni [2005], respectively). The radio emission is present, and the radio spectral index is consistent with both a compact and an optically thin synchrotron jet ($\alpha = \pm 0.34$). If the source is in a HIMS and the radio spectrum is optically thin, e.g., the outer part of the jet is already decoupled from the system and the assumption of a radio compact jet is not valid anymore, the jet model in the present form cannot be used to fit the spectrum. On the other hand, if the source is in a hard state and the radio jet is still optically thick, the almost flat radio-to-IR spectral index ($\alpha = \pm 0.08$) is consistent with a compact jet, and the jet model should in principle be able to fit this observation reasonably well, as it does for the other hard-state observations of GRO J1655–40 and other BHs. The SED of March 10 seems, however, to have a very high X-ray-to-radio flux ratio—too

optically thick part of the jet; and (2) to have a more collimated jet, such as what may be expected in the case of magnetic collimation, which is still poorly understood and not included here.

As mentioned above, Markoff et al. (2005) fitted, using the jet model, some typical hard-state observations of the BH XRBs Cyg X-1 and GX 339–4, and discussed the differences and similarities found in the best-fit parameters. In particular, they found that (1) the total initial power that goes into the jet $N_j$ is similar for both sources; (2) Cyg X-1 seems to favor a more compact jet base, with the same radius-to-height ratio ($h_0$), but with $4.4r_g < r_0 < 9.1r_g$ for Cyg X-1 against the $9.6r_g < r_0 < 20.2r_g$ of GX 339–4. The smaller $r_0$, with a similar $N_j$, reflects the higher X-ray–radio flux ratio of Cyg X-1 with respect to GX 339–4; (3) the temperature of the electrons in GX 339–4 is $T_e \approx 4000$ keV, a factor of 2 larger than in Cyg X-1; (4) the spectral index of the electron distribution $\gamma$, the fraction of accelerated electrons $p_f$ (which was large and then fixed to 75% in this work, as suggested in their paper), and the location of the acceleration region $z_{acc}$ (approximately $20r_g$) are roughly the same for the two BHs; and (5) both BHs appear to have the jets close to equipartition.

Comparing the parameters of GRO J1655–40 with those of the other two BHs (Table 5), it is remarkable that most of the parameters are very similar for these three different BHs. Some differences are present, however; we find that the power that GRO J1655–40 put into the jet is higher than that in the other two BHs by a factor of $\approx 3$ (the jet power is of the same order of $N_j$ in Table 5; see also Appendix A2 in Markoff et al. 2005). Also, the nozzle radius is smaller than that of GX 339–4 and very similar to that of Cyg X-1, reflecting the higher X-ray/radio flux ratio. The electron temperature is approximately the same as that found for the other two BHs, as is the spectral index of the electron distribution. The model finds solutions for a jet close to equipartition ($k \approx 1$ in Table 5) only in the case of September 29, but only if we let the jet inclination free to adjust for the otherwise steeper optically thick radio-to-IR spectrum observed. The September 24 and 29 observations with a fixed inclination of 75° find a solution for a weakly magnetically dominated jet ($k \approx 4$ and $k \approx 5$, respectively) which is different from what is found for other two BH XRBs, but close to the values found for, e.g., low-luminosity active galactic nuclei such as Sgr A* and M81 (e.g., Markoff et al. 2004). Note, however, that this equipartition parameter is still not very well constrained and, also, that there is no physical reason to prefer a solution with a jet in equipartition over that of a (weakly) magnetized jet. Using a distance of 3.2 kpc, the jet power of GRO J1655–40 would be about 5 times higher than that derived in the fits of Cyg X-1 and GX 339–4 for comparable disk luminosities. The jet and the disk luminosities seem to be the only two parameters that change significantly (increase) using a distance of 3.2 kpc (see Table 5).
high for the model to find a good set of parameters to reproduce it. In this case, therefore, it is tempting to claim that at least part of the hard X-ray emission, assumed in the jet model to be produced at the base of the jet, does actually come from a physically different emitting source.

We must note that on March 10 GRO J1655–40 is already starting the X-ray rise of the outburst, the disk emission is higher than that of the other hard-state spectra, and only a few days later the source is in a thermal state. Therefore, a possible explanation for the bad fit is that, e.g., the compact jet is already fading, while the accretion rate, and thus the soft X-ray emission, is increasing. However, we still encounter the problem of explaining the high nonthermal hard X-ray flux in the spectrum coming from a fading jet. Given the power in the compact jet, the model cannot find a good set of parameters that reproduces the hard X-ray emission observed. Therefore, if the source is in a hard state with a compact radio jet, and if the other assumptions in the model are not significantly incorrect, we appear to observe an alternative source of the hard X-ray emission, other than the jet. However, since the March 10 observation is possibly in a transitional state, a time-dependent jet model may be required in this case. Such a model is currently under development, and we plan to revisit the March 10 SED when it is available.

4. CONCLUSIONS

We have analyzed five multiwavelength observations of GRO J1655–40 during its outburst in 2005. The unprecedented coverage from the radio band to X-rays, and especially the new inclusion of simultaneous optical/IR and mid-IR observations, allowed us to give new constraints on the jet in a BH XRB.

1. We detect, for the first time, emission from a compact jet in the mid-IR, at 24 μm, with Spitzer MIPS.

2. We obtain a strong constraint on the spectral index of the compact jet, which is consistent with being flat from the radio band to the mid-IR: \( \alpha = 0.07 \pm 0.04 \) for the September 29 observation and, possibly (see caveats in § 3.1), \( \alpha = 0.08 \pm 0.03 \) for the March 10 observation.

3. Using the broadband SEDs in the hard state, we tested the jet scenario. We find good fits for two out of the three hard-state observations. The physical parameters of the jet are overall similar to those previously found in other two BH XRBs, Cyg X-1 and GX339–4. The most notable exception is the jet power, which seems to be a factor of at least 3–5 times higher, depending on the distance, in GRO J1655–40, for comparable disk luminosities. We also note that the radio-to-IR power-law spectrum observed seems to be somewhat flatter than the model predicts.

4. The jet model does not give a good fit for the observation on March 10, which can be either in a hard state or in a hard intermediate state, depending on X-ray state definitions we adopt, and has an unconstrained radio spectral index consistent with either a compact or a detached optically thin radio jet. In the case of a hard-state observation, with a compact jet emitting an almost flat spectrum from the radio band to the mid-IR, this model-data discrepancy might be explained by the presence of an alternative source of hard X-rays, other than the jet.

The results presented in this work show how the wide energy range covered by our multiwavelength campaign, with a particular key role played by the mid-IR observations, can give strong constraints on the radiative components of XRB systems. The SEDs will be further used to test improved jet models (with, e.g., the inclusion of an irradiated disk, with time-dependent parameters), as well as other disk and jet models based on different scenarios (e.g., Yuan et al. 2005), as soon as they can be statistically tested over the whole broadband energy spectrum.

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REFERENCES

Belloni, T., Psaltis, D., & van der Klis, M. 2002, ApJ, 572, 392
Beloborodov, A. M. 1999, ApJ, 510, L123
Brockopp, K., et al. 2005, ATel 612
Buxton, M., & Bailyn, C. D. 2004, ApJ, 615, 880
———. 2005, ATel 608
Buxton, M., Bailyn, C. D., & Maitra, D. 2005b, ATel 418
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Corbel, S., Fender, R. P., Tomsett, J. A., Tzioumis, A. K., & Tingay, S. 2004, ApJ, 617, 1272
Cunningham, C. 1976, ApJ, 208, 534
Depoy et al. 2003, Proc. SPIE, 4841, 827
Dhawan, V., Mirabel, I. F., Rodriguez, L. F. 2000, ApJ, 543, 373
Falcke, H., Körding, E., & Markoff, S. 2004, A&A, 414, 895
Fender, R. P. 2006, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 381
Fender, R. P., Belloni, T. M., & Gallo, E. 2004, MNRAS, 355, 1105
Fender, R. P., et al. 1999, ApJ, 519, L165
Foellmi, C., Depagne, E., Dall, T. H., & Mirabel, I. F. 2006, A&A, 457, 249
Gallo, E., Corbel, S., Fender, R. P., Markoff, S., Tzioumis, A. K. 2004, MNRAS, 347, L53
Greene, J., Bailyn, C. D., & Orosz, J. A. 2001, ApJ, 554, 1290
Heinz, S. 2004, MNRAS, 355, 835
Homan, J. 2005, ATel 440
Homan, J., & Belloni, T. 2005, Ap&SS, 300, 107
Homan, J., Buxton, M., Markoff, S., Bailyn, C. D., Nespoli, E., & Belloni, T. 2005a, ApJ, 624, 295
Homan, J., Miller, J. M., Wijnands, R., & Lewin, W. H. G. 2005b, ATel 487
———. 2005c, ATel 607
Houck, J. C., & Denicolia, L. A. 2000, in ASP Conf. Proc. 216, Astronomical Data Analysis Software and Systems IX, ed. N. Manset, C. Veillet, & D. Crabtree (San Francisco: ASP), 591
Hjellming, R. M., & Rupen, M. P. 1995, Nature, 375, 464
Hynes, R. I., Haswell, C. A., Chaty, S., Shrader, C. R., & Cui, W. 2002, MNRAS, 331, 169
Israelian, G., Rebolo, R., Basri, G., Casares, J., & Martin, E. L. 1999, Nature, 401, 142
Kalenci, E., et al. 2005, ApJ, 622, 508
Körding, E., Falcke, H., & Corbel, S. 2006, A&A, 456, 439
Landolt 1992, AJ, 104, 340
Markwardt, C. B., & Swank, J. H. 2005, ATel 414
Makovoz, D., & Marleau, F. 2005, PASP, 117, 1113
Markoff, S., Falcke H., & Fender R. 2001, A&A, 372, 125
Markoff, S., & Nowak, M. A. 2004, ApJ, 609, 972
Markoff, S., Nowak, M., Falcke, H., Maccarone, T., & Fender, R. 2004, Nucl. Phys. B Proc. Supp., 132, 129
Markoff, S., Nowak, M. A., & Wilms, J. 2005, ApJ, 635, 1203
Markwardt, C. B., & Swank, J. H. 2005, ATel 414
McCintock, J. E., & Remillard, R. A. 2006, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 157
McKay, D. J., & Kesteven, M. 1994, IAU Circ. 606
Meier, D. L. 2001, ApJ, 548, 19
Merloni A., Heinz S., & Di Matteo T. 2003, MNRAS, 345, 1057
Miyamoto, S., & Kitamoto, S. 1989, Nature, 342, 773
Nowak, M. A. 2000, MNRAS, 318, 361
Nowak, M. A., Wilms, J., Heinz, S., Pooley, G., Pottschmidt, K., & Corbel, S. 2005, ApJ, 626, 1006
Nowak, M. A., Wilms, J., Vaughan, B. A., Dove, J. B., & Begelman, M. C. 1999, ApJ, 522, 476
Orosz, J. A., & Bailyn, C. D. 1997, ApJ, 477, 876
Pottschmidt, K. 2002, Ph.D. thesis, Univ. Tübingen
Pottschmidt, K., et al. 2003, A&A, 407, 1039
Reach, W. T., et al. 2005, PASP, 117, 978
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Ricke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Rupen, M. P., Dhawan, V., & Mioduszewski, A. J. 2005a, ATel 419
———. 2005b, ATel 489
Rupen, M. P., Mioduszewski, A. J., & Dhawan, V. 2005c, ATel 441
Russell, D. M., Fender, R. P., Hynes, R. I., Brocksopp, C., Homan, J., Jonker, P. G., & Buxton, M. M. 2006, MNRAS, 371, 1334
Shahbaz, T., van der Hooft, F., Casares, J., Charles, P. A., & van Paradijs, J. 1999, MNRAS, 306, 89
Shakura, N. I., & Syunyaev, R. A. 1973, A&A, 24, 337
Shaposhnikov, N., Swank, J., Shrader, C. R., Rupen, M., Beckmann, V., Markwardt, C. B., & Smith, D. A. 2007, ApJ, 655, 434
Stirling, A. M., Spencer, R. E., de la Force, C. J., Garrett, M. A., Fender, R. P., & Ogley, R. N. 2001, MNRAS, 327, 1273
Tingay, S. J., et al. 1995, Nature, 374, 141
Tomsick, J. A., Kaaret, P., Kroeger, R. A., & Remillard, R. A. 1999, ApJ, 512, 892
Tomsick, J. A., Kalenici, E., & Kaaret, P. 2004, ApJ, 601, 439
Torres, M. A. P., Steeghs, D., Jonker, P., & Martini, P. 2005, ATel 417
van der Klis M. 2006, in Compact Stellar X-Ray Sources, ed. W. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 39
Vrtilek, S. D., Raymond, J. C., Garcia, M. R., Verbunt, F., Hasinger, G., & Kurster, M. 1990, A&A, 235, 162
Wilms J., Nowak, M. A., Pottschmidt, K., Pooley, G. G., & Fritz, S. 2006, A&A, 447, 245
Yuan, F., Cui, W., & Narayan, R. 2005, ApJ, 620, 905
Zdziarski, A. A., Poutanen, J., Mikolajewska, J., Gierlinski, M., Ebisawa, K., & Johnson, W. N. 1998, MNRAS, 301, 435
Zhang, W., Jahoda, K., Swank, J. H., Morgan, E. H., & Giles, A. B. 1995, ApJ, 449, 930