CORRELATED RADIO–X-RAY VARIABILITY OF GALACTIC BLACK HOLES:
A RADIO–X-RAY FLARE IN CYGNUS X-1

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ABSTRACT

We report on the first detection of a quasi-simultaneous radio–X-ray flare of Cygnus X-1. The detection was made on 2005 April 16 with pointed observations by the RXTE and the Ryle telescope, during a phase where the black hole candidate was close to a transition from its soft state to its hard state. The radio flare lagged the X-rays by ~7 minutes, peaking at 3:20 hr barycentric time (TDB 2,453,476.63864). We discuss this lag in the context of models explaining such flaring events as the ejection of electron bubbles emitting synchrotron radiation.

Subject headings: accretion, accretion disks — black hole physics — X-rays: binaries — X-rays: stars

Online material: color figure

1.INTRODUCTION

With the increased availability of simultaneous radio and observations in the last decade, there is now a large amount of evidence available pointing toward a very close interaction between the accretion disk and the jet in black hole X-ray binaries and active galactic nuclei. Most convincingly, this disk-jet interaction has been shown for microquasars, i.e., black hole binaries with strongly relativistic jets such as GRS 1915+105 or GRO J1655−40. In these systems, the correlated flaring in the X-rays, optical/infrared, and radio seen at certain times is generally interpreted as the evidence for (ballistic) ejection events of synchrotron radiation–emitting electron bubbles (Rothstein et al. 2005; Fender & Belloni 2004; Klein-Wolt et al. 2002; Eikenberry et al. 1998 and therein). In this model, the X-ray flare represents the ejection of the synchrotron radiation–emitting bubble, which then adiabatically expands within the jet flow and cools down, resulting in the peak of the emission shifting downward in frequency with time (van der Laan 1966; Hjellming & Johnston 1988). Simultaneous broadband observations of such events, which show minute-long delays between the different wave bands, are consistent with this picture (Mirabel & Rodríguez 1994; Mirabel et al. 1998; Pooley & Fender 1997; Eikenberry et al. 1998). The model has also been confirmed by proper-motion measurements in the radio, which reveal intrinsic jet speeds of ≳0.57c for GRS 1915+105 (Miller-Jones et al. 2005). Comparable behavior was also detected in 3C 120, suggesting that similar ejections also occur in active galactic nuclei, on correspondingly longer timescales (Marscher et al. 2002).

For black hole binaries with weakly relativistic jets, the evidence for jet-disk interaction is less direct. This evidence includes the correlation between X-ray states and radio emission in black hole transients (e.g., in GX 339−4; Corbel et al. 2003; Belloni et al. 2005) and the success of modeling the radio–X-ray broadband spectrum of black hole candidates with outflow-dominated models (Markoff et al. 2005; Markoff & Nowak 2004 and therein). Furthermore, at least for Cygnus X-1, there is also evidence for the presence of an energetically significant, strong outflow (Stirling et al. 1998, 2001; Gallo et al. 2005; Miller-Jones et al. 2006). A relativistic jet with v ≳ 0.3c has been associated with radio flares in this system (Fender et al. 2006).

Apart from GRS 1915+105, however, none of these observations show direct evidence for a causal connection between the X-rays and the jet on timescales of minutes. Prompted by this lack of quasi-simultaneous short-term radio–X-ray correlations, in 1998 we initiated a long-term monitoring campaign of Cyg X-1 with the Rossi X-Ray Timing Explorer (RXTE) and the Ryle telescope. Biweekly 3–10 ks–long simultaneous observations started in 1999. Previous searches for flares in campaign data taken between 1999 and mid-2003 did not reveal evidence for coherent short-term activity in both bands, although a significant correlation on timescales of weeks was found, especially above ∼10 keV (Gleissner et al. 2004; Wilms et al. 2006). In this Letter, we report on the observation made on 2005 April 16, in which the first clear quasi-simultaneous radio–X-ray flare was detected in Cyg X-1. The remainder of this Letter is structured as follows. In § 2 we describe the observations, followed by the analysis of the flare in § 3. We discuss the physics of the flare in the context of emission models for the radio and X-ray emission in § 4.

2. OBSERVATIONS AND DATA REDUCTION

We use data from both instruments on board the RXTE, the low-energy Proportional Counter Array (PCA; Jahoda et al. 2006) and the High Energy X-Ray Timing Experiment (HEXTE; Rothschild et al. 1998). The data analysis was performed using the standard RXTE data analysis software, HEASOFT 6.1.2. Spectral fitting was performed with XSPEC 11.3.2aa (Arnaud 1996).

A crucial part of the observation happened during the early phase of the RXTE observation, shortly after the source rose above the Earth’s horizon. Due to auroral emission in the far-ultraviolet and soft X-rays and due to cosmic-ray reprocessing in the hard X-rays, the Earth’s atmosphere is not completely X-ray dark. The
typical 2.5–20 keV X-ray flux at the typical magnetic latitude of the RXTE orbit is too low, however, to influence our measurements (Petricec et al. 2000; Sazonov et al. 2007). We therefore use all data taken while the source was ≥1° above the Earth’s horizon and had a source offset of ≤0.01°. We use PCA data from the standard1 mode, which gives the full 2.5–128 keV PCA count rate with a time resolution of 0.125 s and no energy information, and from the standard2f mode, a binned data mode with a 128 channel energy resolution and a time resolution of 16 s. X-ray light curves were extracted with the intrinsic time resolution of each mode and then barycentered and rebinned.

The Ryle telescope data were taken at 15 GHz with a time resolution of ~8 s. The typical 1σ uncertainty of the radio measurements is 9 mJy. The observations are interrupted every ~1600 s for phase-calibration observations of J2007+4029. The amplitude calibration of the Ryle data corresponds to the flux scale of Baars et al. (1977) and is performed using nearby observations of 3C 48 and 3C 286. See Pooley & Fender (1997) for further information on the Ryle telescope.

3. A QUASI-SIMULTANEOUS RADIO–X-RAY FLARE

As shown in Figure 1, 2005 April marks the possible end of a longer X-ray flaring episode of Cyg X-1 that started in early 2004 (Wilms et al. 2006). While clearly defined radio flares are not uncommon in Cyg X-1 (e.g., Hjellming 1973), increased radio emission and radio flaring are generally seen when the source is in the intermediate state between the hard and soft states, while the radio is weak once the X-ray source approaches the soft state (Wilms et al. 2006 and therein). At the time of our pointed observations, the soft X-ray flux had just come down from a large flare. Shortly after the observation, the 1 day averaged 15 GHz flux peaked, reaching a maximum of ~30 mJy, close to the brightest radio flux of Cyg X-1 during 2004/2005.

Figure 2 shows the 15 GHz radio flux and the RXTE PCA count rate light curve measured on 2005 April 16. Close to the start of the observation, a radio flare is readily apparent.

The total duration of the flare is ~15 minutes. During this interval, the 15 GHz flux increased by a factor of ~3 to a peak radio flux of 70 mJy. This radio flux is among the highest seen during the Ryle monitoring. Previous radio flares, however, did not occur during pointed RXTE observations (Gleissner et al. 2004; Fender et al. 2006), and the source monitoring provided by the RXTE All-Sky Monitor (ASM) is too coarse to pick up such short-lived X-ray events.

RXTE started observing Cyg X-1 about 10 minutes before the peak radio flux. The X-ray light curve shown in Figure 2 shows a similar shape to the radio one, although with more substructure. The earlier maximum of the X-ray flare did not allow RXTE to catch the start of the X-ray flare, or to determine whether or not the maximum X-ray flux seen is indeed the peak of the X-ray flare. A cross correlation function (CCF) analysis using the algorithm of Scargle (1989) reveals a 413 ± 165 s time lag of the radio with respect to the X-rays, where the 1σ uncertainty was determined using a standard bootstrapping method with 1000 realizations. Other approaches to calculate the CCF for nonuniformly sampled data (Alexander 1997; Edelson & Krolik 1988) give essentially the same result. With a maximum Scargle (1989) CCF of 0.38, this analysis formally confirms the general similarity of the X-ray and radio light curves (Fig. 3). Since the substructure of the X-ray light curve, i.e., the two smaller flares after the main flare, is clearly different from that in the radio flare, and since the start of the X-ray flare is not covered by our observations, the peak CCF value is not higher. For the same reasons, the formal uncertainty of the lag measurement is rather large.

To characterize the shape of the radio flare, we fit the radio data (rebinned to a resolution of 8 s) with the sum of a linear flux trend and a Gaussian representing the flare,

\[ f(t) = a(t - t') + b + A \exp \left[ -\frac{(t - T)^2}{\sigma^2} \right], \]

where \( t' \) is a reference time, taken as the center of the time
one interesting parameter). The peak flux of the flare component
of Cyg X-1 (Wilms et al. 2006). The spectral parameters are a lower
exponentially cutoff broken power-law model. This empirical model
fits to the standard $f$ spectra), a value typical for the inter-
mediate state of this source (Wilms et al. 2006).

Modeling the RXTE-PCA light curve is complicated by the flare
already being in progress when the measurements started. Fur-
thermore, contrary to the radio data, where the scatter in the
light curve is mainly due to the measurement uncertainty, the X-ray
data are dominated by strong low-frequency noise onto which the X-ray flare is superimposed. Consequently, the empirical model of equation (1) does not result in a good
description of the X-ray data.

To study the spectral evolution of Cyg X-1 during the flare, we perform a spectral analysis of the 2.5–20 keV PCA standard $2f$ data at 16 s time resolution using a simple photoab-
sorbed power law, which proves sufficient to describe the spec-
trum at this lower signal-to-noise ratio level. For spectra taken
during the flare, at PCA count rates above 1000 counts $s^{-1}$
PCU$^{-1}$, the mean power-law index $\Gamma = 2.10 \pm 0.03$. The spec-
trum hardens outside of the flare to $\Gamma = 1.98 \pm 0.03$ (errors
given are the standard deviation of the individual power-law
fits to the standard $2f$ spectra), a value typical for the inter-
mediate state of this source (Wilms et al. 2006).

That Cyg X-1 was in the intermediate state on the day of the
flare can also be confirmed by modeling the 2.5–150 keV PCA and
HEXTE spectrum of an
flare (to avoid possible “contamination” by the flaring activity) with
the sum of a photoabsorbed ($N_{HI} = 6 \times 10^{21}$ cm$^{-2}$, held fixed),
exponentially cutoff broken power-law model. This empirical model
has been shown to give a good characterization of the spectral shape
of Cyg X-1 (Wilms et al. 2006). The spectral parameters are a lower
photon index $\Gamma_1 = 2.01 \pm 0.01$, breaking at $E_{break} = 10.0^{+0.3}_{-0.2}$
keV into a power law with $\Gamma_2 = 1.62^{+0.05}_{-0.03}$. At $E_{cut} = 26 \pm 3$
keV, the exponential cutoff starts with a folding energy of
$E_{fold} = 137 \pm 11$ keV (all uncertainties are at the 90% level). In
addition, a Fe K$\alpha$ line from neutral iron is present with an equivalent
width of 135 eV. The 3–10 keV source flux is $6.17 \times 10^{-6}$ ergs
cm$^{-2}$ s$^{-1}$. The parameters of the continuum are again consistent
with an intermediate state and fit well with the empirical picture
that radio flaring in black hole candidates occurs most frequently
in this state (Fender et al. 2004; Wilms et al. 2006).

To allow the interpretation of the observed softening during
the flare with the general behavior of Cyg X-1, Figure 4 shows
the X-ray hardness intensity diagram for the PCA top-layer stan-
dard $2f$ 16 s spectra in the context of the pointed RXTE observ-
ations of the monitoring campaign. For black hole transients,
this diagram is seen to have an approximate $q$ shape (Belloni et
al. 2006 and therein). As a persistent hard-state source, Cyg X-
1 is typically found in the top right-hand corner of the diagram.
Outside of the flare, the source is situated at a hardness of $0.55$
with a typical 1–128 keV PCA count rate of $\sim 900$ counts $s^{-1}$
PCU$^{-1}$. During the flare, the source softens and brightens. It
leaves the region of the diagram where Cyg X-1 is usually found
during our monitoring campaign, by moving to higher count
rates, for this hardness, than usually observed.

Flaring behavior in Cyg X-1 is usually observed whenever the
source is close to the “jet line” in its hardness intensity diagram,
while the radio flux gets quenched once the source moves away
from the jet line to the left of the diagram (Gallo et al. 2003; Fender
et al. 2004). In spectral fits based on the eqpair model of Coppi
(1999), the radio fluxes of Cyg X-1 are at their maximum when
the compactness ratio $l_\nu/l_\nu \sim 3$ (Fig. 16 of Wilms et al. 2006; the
compactness ratio is a measure for the relative importance of the
energy dumped into the Comptonizing plasma and that dissipated
in the accretion disk), corresponding to a soft power-law index of
$\Gamma \sim 2.1$. From our database of spectra of Cyg X-1, we find that
these observations have a $(7.1–11.7$ keV)/(4.6–7.1 keV) hardness
ratio of 0.52, indicated by the dotted line in Figure 4. During the
2005 April 16 observation, the source was therefore close to this
line of maximum radio flux and approached it asymptotically during
the flare.

4. DISCUSSION

In this Letter we have presented the first evidence for a direct
relationship of the X-ray and radio emission in Cyg X-1 on
timescales of minutes. The data show the radio to lag the X-
rays by 413 ± 165 s and the X-ray spectral shape to approach

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**Fig. 3.**—CCF (Scargle 1989) for the radio data with respect to the RXTE-PCA data. A negative time lag indicates the radio lagging the X-rays.
the X-ray hardness ratio where the source is typically found at its largest radio flux in our long-term monitoring, hinting toward a general similarity in the physics of individual flare events and the overall radio–X-ray connection. Although the X-ray data do not cover the start of the X-ray flare, explaining the rather large uncertainty of the lag determination, the morphological similarities between the X-ray and radio light curves also suggest that the same event is observed in both wavebands.

Similar events in microquasars show that lags with timescales of several hundred seconds are typical for the coherent behavior of these systems, such as a lag of $310 \pm 20$ s between the soft X-rays and the IR (Eikenberry et al. 1998), and $800$ s between the X-rays and the radio (Pooley & Fender 1997), in GRS 1915+105. The timescale observed in Cyg X-1 allows us to place an upper limit on the physical separation of the X-ray–emitting and radio-emitting regions of the accretion/ejection flow. We assume that the emission coincides with the imaged jet and that the jet is perpendicular to the orbital plane of the HDE 226868/Cyg X-1 system (although this is not a priori certain; Maccarone 2002), and that the emission coincides with the imaged jet and that the jet is relativistic. Taking light-travel time effects into account, for jet speeds of 0.3c, the lower limit implied by observations of the transient jet ejection discussed by Fender et al. (2006), the measured delay implies a separation of $1.1 \pm 0.5$ AU between the location of X-ray emission and the location of radio emission. If the jet is relativistic instead, with a speed of 0.99c, the distance increases to $5.8 \pm 2.3$ AU. Note that similar values for the length of the jet are obtained by considering that the $10$ minute duration of the radio flare is roughly equal to the dynamical timescale of the jet. Assuming a distance of 2.5 kpc, these values imply a maximum projected angular separation between the X-ray–emitting and radio-emitting region of $10^{-3}$ mas.

What is the physics of the observed event? In the model of Fender et al. (2004) for transient radio events, the inner edge of a thin accretion disk is posited to move rapidly toward the black hole. The temperature at the inner edge therefore increases, leading to a softening of the source in the RXTE PCA as more disk photons enter the instrument’s bandpass. This X-ray flare is then followed by the ejection of an electron bubble, which rapidly expands, producing the observed radio emission. At least qualitatively, this behavior and also the timescales deduced above seem to agree with our observations, although the model was originally invented for the large-scale variability of black hole candidates and not for such short events as the one discussed here. Note that while the main flare dominates the measured time lag and therefore the sizes estimated above, it is followed by two short spikes, which are both present in the radio and the X-ray light curves, but at different time delays. These spikes could indicate that more than one blob of material was ejected at different speeds but that they cannot be separated once the blobs have expanded and their radiation peaks in the radio. Such a behavior could be typical for flares in Cyg X-1, since the large radio flare of Cyg X-1 from 2005 February 20 also shows very little substructure (Fender et al. 2006).

The lack of further detections of radio–X-ray flares in over 1.5 Ms of simultaneous radio–X-ray data precludes a more detailed discussion of the properties of the ejected material (from a comparison of the source behavior during different flares). The observation of the flare itself, however, stresses the importance of long-term multiwavelength campaigns to detect such rare events; these campaigns are necessary to further our insight into the physics of the emission from black holes.

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Facilities: RXTE(PCA, HEXTE), Ryle

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