LINING JET EMISSION, X-RAY STATES, AND HARD X-RAY TAILS IN THE NEUTRON STAR X-RAY BINARY GX 17+2

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Received 2007 June 26; accepted 2007 August 13

ABSTRACT

We present the results of simultaneous radio (VLA) and X-ray (RXTE) observations of the Z-type neutron star X-ray binary GX 17+2. The aim is to assess the coupling between X-ray and radio properties throughout its three rapidly variable X-ray states and during the time-resolved transitions. These observations allow us, for the first time, to investigate quantitatively the possible relations between the radio emission and the presence of hard X-ray tails and the X-ray state of the source. The observations reveal (1) a coupling between the radio jet emission and the X-ray state of the source, that is, the position in the X-ray hardness-intensity diagram (HID); (2) a coupling between the presence of a hard X-ray tail and the position in the HID, qualitatively similar to that found for the radio emission; (3) an indication of a quantitative positive correlation between the radio flux density and the X-ray flux in the hard tail power-law component; (4) evidence for the formation of a radio jet associated with the flaring branch–to–normal branch X-ray state transition; and (5) that the radio flux density of the newly formed jet stabilizes when the normal-branch oscillation (NBO) in the X-ray power spectrum stabilizes its characteristic frequency, suggesting a possible relation between X-ray variability associated with the NBO and jet formation. We discuss our results in the context of jet models.

Subject headings: accretion, accretion disks — ISM: jets and outflows — radio continuum: general — stars: individual (GX 17+2) — X-rays: binaries

Online material: color figure

1. INTRODUCTION

The study of relativistic radio jets in X-ray binaries (XRBs) and their coupling with X-ray properties revealed a boost in the last decade thanks to coordinated multiwavelength observations. Black hole (BH) systems are surely the best studied among the relativistic jet XRB sources (see Fender 2006 for a review). However, relativistic jets are not exclusively associated with BHs. The jet phenomenology observed in BHs can be found in neutron star (NS) XRBs as well: (1) highly accreting NS XRBs can launch transient jets at ultrarelativistic velocities (e.g., with bulk Lorentz factors higher than 15 in Cir X-1; Fender et al. 2004a); (2) low-luminosity NS XRBs can form a compact jet of the same kind as observed in BH XRBs and active galactic nuclei (i.e., 4U 0614+091; Migliari et al. 2006). The necessary ingredients for the formation and launching of relativistic jets seem not to be related to the nature of the compact object. Therefore, studies of NS jets and their connections to the accretion properties have an important impact on our understanding of jet sources in general. In BH XRBs, studies of the accretion mode transitions and their coupling to the jet activity (e.g., Fender et al. 2004b) rely on observations of occasional outbursts, of which there are one or two per year, usually lasting a few months. In the case of NS XRBs, and especially in the highly accreting class of NSs called “Z-type” (see below), we observe periodic X-ray state transitions on timescales of a few days. These state transitions are thought to be triggered by changes in accretion rate. Z sources can be considered the NS “counterparts” of transient, strongly accreting BHs such as GRS 1915+105 (see, e.g., discussion in Migliari & Fender 2006). By studying Z-type NSs, therefore, we are able to assess the evolution of the accretion and jet activity in a very short observational time and more regularly than in transient BH sources.

Z-type NS XRBs are a class of seven among the brightest XRBs in our Galaxy: Sco X-1, Cyg X-2, GX 17+2, GX 5–1, GX 340+0, GX 349+2, and XTE J1701–462 (eight, if one adds the “peculiar” Z source Cir X-1; Shirey et al. 1999). The name derives from the characteristic Z shape they trace in the color–color diagram (CD; Hasinger & van der Klis 1989; see van der Klis 2006 for a review). The three branches that form the Z-shaped CD are called the horizontal branch (HB), normal branch (NB), and flaring branch (FB), and these define three distinct states of the systems, each with its own specific X-ray spectral and timing properties (see, e.g., Homan et al. 2002 for the particular case of GX 17+2). The relations between spectral and timing properties and position on the CD suggest that the accretion rate is the major physical parameter behind the position along the Z track (see, e.g., van der Klis 2006 for a review). Homan et al. (2007) showed that the complex variability behavior of XTE J1701–462 could be explained if the changes along the track are governed not simply by the mass accretion rate through the disk but by the ratio between this quantity and its time-averaged variations (see also van der Klis 2000). Z sources show luminosities persistently near or above the Eddington limit and are very bright and rapidly variable, both in X-rays and in the radio band. The Z-type NSs change X-ray state on timescales of hours to days, so they are always at the “edge” of a state transition. They are therefore very good laboratories for studying the connection between X-ray properties, state changes, and radio behavior in X-ray binary systems.
Z-type NSs exhibit optically thick radio emission (i.e., $\alpha \approx 0$, where $F_\nu \propto \nu^\alpha$ and $F_\nu$ is the flux density at frequency $\nu$) and frequent, optically thin radio flares ($\alpha < 0$). The optically thick emission is usually interpreted as radiation from a continuously replenished, compact jet (see Fender 2006 for a review), while the optically thin radio flares are possible signatures of fast ejected plasmons, already observed as extended lobes in Sco X-1 (Fomalont et al. 2001a, 2001b) and Cir X-1 (Fender et al. 1999, 2004a).

Looking in detail at the radio behavior of Z sources as a function of their X-ray properties, Penninx et al. (1988) first found in GX 17+2 that the radio emission varies as a function of position in the X-ray CD, decreasing with increasing inferred mass accretion rate from the HB (strongest radio emission) to the FB (weakest radio emission). Behavior consistent with that of GX 17+2 has also been found in Cyg X-2 (Hjellming et al. 1990a and D’Amico et al. 1990b); the exception seems to be GX 5-1 (Tan et al. 1992; but see discussion in Migliari & Fender 2006).

Based on the results of these previous simultaneous radio and X-ray observations and, mostly, on observations of Sco X-1 (Kumagai et al. 2001; Brashaw et al. 2003), a possible coherent phenomenological picture of Z sources, coupling X-rays (<20 keV) and radio properties, has been drawn (Migliari & Fender 2006). In this sketch, (1) the compact jet is mostly responsible for the radio emission in the HB and partially responsible for that in the NB, and (2) X-ray state transitions are coupled with transitions in the jet emission—in particular, transient, optically thin radio flares appear to occur at the HB-to-NB transition (see Fig. 6 of Migliari & Fender 2006).

Nonthermal hard tails in the X-ray energy spectra, dominating above ~30 keV, have been observed in almost all known Z sources: GX 5-1 (Asai et al. 1994; Paizis et al. 2006), GX 17+2 (Di Salvo et al. 2000), Sco X-1 (D’Amico et al. 2001a; see also Di Salvo et al. 2006 and D’Amico et al. 2007), RXTE 349+2 (Di Salvo et al. 2001; see also D’Amico et al. 2001b), Cir X-1 (Iaria et al. 2001), and Cyg X-2 (Di Salvo et al. 2002; see also D’Amico et al. 2001b). These hard X-ray tails can be fitted with a power law with photon index ranging between 1.6 and 3.3 and can contribute up to 10% of the bolometric X-ray luminosity. Although the details of the individual Z sources are more complicated, one might say that as a general trend, the hard X-ray tail in the spectrum seems to be related to the position in the CD: the hard X-ray component is strongest in the HB and becomes weaker toward the FB. In previous X-ray observations of GX 17+2, for example, the spectrum showed a hard power-law tail with a photon index of ~2.7 that was strongest in the HB and weakened as the source moved toward the NB, disappearing in the NB (Di Salvo et al. 2000). However, a possible counterexample seems to be Sco X-1, in which no obvious relation between the hard tail X-ray flux and the position on the CD has been observed (D’Amico et al. 2001a).

The physical origin of this nonthermal component is still an area of controversy. In particular, two main possibilities are under debate, both suggesting that the physical site of the emission is the central core region, close to the compact object: inverse Compton scattering from a nonthermal electron population in a “corona” (e.g., Poutanen & Coppi 1998), or in the base of a jet (see, e.g., Markoff et al. 2005 for a discussion). Another possible explanation, bulk motion Comptonization (BMC), which was first explored by Titarchuk et al. (1996) for BHs, has also been proposed for NS systems (e.g., Titarchuk & Zannias 1998). In the specific case of GX 17+2, for example, Farinelli et al. (2007) suggested that the spectrum derived from the BMC of soft photons by energetic electrons flowing onto the NS can produce a hard X-ray tail consistent with the observations.

In this work, we present a study of simultaneous radio and X-ray observations of the Z source GX 17+2 in order to assess the coupling between X-ray and radio properties throughout its three X-ray states (§ 3.1) and during the transitions between states (§ 3.2). Furthermore, these observations allow us, for the first time, to investigate more quantitatively the possible relations between the radio emission and the presence of the hard X-ray tails (§ 3.3), which are observed to be associated with the position of the source in the CD.

2. OBSERVATIONS

We observed the Z-type NS XRB GX 17+2 simultaneously in X-rays with RXTE and in the radio band with the Very Large Array (VLA), covering all three of its X-ray branches.

2.1. RXTE Observations and Data Analysis

The Rossi X-ray Timing Explorer (RXTE) observed GX 17+2 starting on 2002 November 4 for a total of ~35 hr over about 11 days. The 3–20 keV light curve of the observations is shown in Figure 1 (middle row). We used the Proportional Counter Array (PCA) “Standard2” data from PCU2 (working in all the observations) to produce the CD and the hardness-intensity diagram (HID) from all the RXTE observations of GX 17+2. The soft color and hard color are defined as the count-rate ratios (4.6-7.1 keV)/(2.9-4.6 keV) and (10.5-19.6 keV)/(7.1-10.5 keV), respectively. The HID in Figure 2 clearly shows the three distinct X-ray branches of the source.

For the spectral analysis, we extracted X-ray energy spectra using PCA Standard2 and High Energy X-Ray Timing Experiment (HEXTE) Standard mode data. For the PCA data, we subtracted the background estimated using pcabackest version 3.0, produced the detector response matrix with pcresp version 10.1, and analyzed the energy spectrum in the range 3–25 keV. A systematic error of 0.5% was added to account for uncertainties in the calibration. For the HEXTE data, we corrected for dead time, subtracted the background, extracted the response matrix using FTOOLS version 6.1.2, and analyzed the spectra between 20 and 100 keV (there is no significant detection above this energy in any of the observations). We show the log of the RXTE observations...
in Table 1. The 3–100 keV spectra are well fitted (see also Di Salvo et al. 2000) using a blackbody, a thermal Comptonization model (compTT), a Gaussian emission line in the range 6.4–6.7 keV, and an edge at 9 keV. An additional power law to account for an excess, of nonthermal origin, in the higher energy range above 30 keV was also necessary for the other three observations (see § 3.3 for a discussion). For a detailed X-ray spectral analysis of GX 17+2 with other models, see, e.g., Farinelli et al. (2005). For the temporal analysis, we have used event and binned data with a time resolution of 125 μs for the production of the power density spectra. We used time bins such that the Nyquist frequency was 4096 Hz. For each observation, we created power spectra from segments of 64 s length using fast Fourier transform techniques (van der Klis 1989 and references therein), but no background subtraction was performed. No dead-time corrections were applied before creating the power spectra. We averaged the Leahy-normalized power spectra (Leahy et al. 1983) and subtracted the predicted Poisson noise spectrum by applying the method of Zhang et al. (1995), shifted in power to match the spectrum between 3000 and 4000 Hz. We converted the normalization of the power spectra to squared fractional rms (e.g., Belloni & Hasinger 1990; see van der Klis 1995).

### TABLE 2

**Best-Fit Parameters for the Observations, Corresponding to Five Different Positions on the HID**

| Parameter       | HB$_{high}$ | HB | NB | NB$_{low}$ | FB |
|-----------------|-------------|----|----|------------|----|
| $N_H$ ($10^{22}$ cm$^{-2}$) | 2 (fixed) | 2 (fixed) | 2 (fixed) | 2 (fixed) | 2 (fixed) |
| $kT_{in}$ (keV) | $0.55 \pm 0.07$ | $0.46^{+0.03}_{-0.07}$ | $0.57^{+0.01}_{-0.02}$ | $0.53^{+0.09}_{-0.07}$ | $0.80^{+0.07}_{-0.05}$ |
| $N_{BB}$ ($\times 10^{26}$) | $2.37^{+0.18}_{-0.17}$ | $2.37^{+0.18}_{-0.17}$ | $3.93^{+0.39}_{-0.46}$ | $4.74^{+0.87}_{-0.76}$ | $9.08^{+0.13}_{-0.12}$ |
| $kT_W$ | $0.82^{+0.07}_{-0.01}$ | $0.78^{+0.01}_{-0.01}$ | $0.90^{+0.01}_{-0.01}$ | $0.96^{+0.01}_{-0.01}$ | $1.35^{+0.01}_{-0.01}$ |
| $kT_{e}$ | $3.0^{+0.3}_{-0.2}^{0.0}$ | $3.21^{+0.01}_{-0.01}$ | $2.97^{+0.01}_{-0.01}$ | $2.93^{+0.02}_{-0.02}$ | $2.86^{+0.01}_{-0.01}$ |
| $\tau$ | $6.29^{+0.03}_{-0.03}$ | $6.06^{+0.03}_{-0.03}$ | $5.24^{+0.04}_{-0.04}$ | $4.16^{+0.06}_{-0.06}$ | $5.57^{+0.04}_{-0.04}$ |
| $N_{Comp}$ | $1.06^{+0.09}_{-0.05}$ | $0.97^{+0.01}_{-0.01}$ | $1.24^{+0.01}_{-0.01}$ | $1.06^{+0.01}_{-0.01}$ | $1.34^{+0.02}_{-0.02}$ |
| $E_{Fe}$ | $6.53^{+0.06}_{-0.06}$ | $6.52^{+0.06}_{-0.06}$ | $6.52^{+0.06}_{-0.06}$ | $6.60^{+0.04}_{-0.04}$ | $6.51^{+0.05}_{-0.05}$ |
| $E_{W_{Fe}}$ | $0.08^{+0.01}_{-0.01}$ | $0.07^{+0.01}_{-0.01}$ | $0.07^{+0.01}_{-0.01}$ | $0.13^{+0.01}_{-0.01}$ | $0.09^{+0.01}_{-0.01}$ |
| $\sigma_{Fe}$ | $0.41^{+0.08}_{-0.13}$ | $0.28^{+0.13}_{-0.13}$ | $0.33^{+0.13}_{-0.13}$ | $0.46^{+0.08}_{-0.08}$ | $0.36^{+0.14}_{-0.14}$ |
| $\lambda_{edge}$ | $9.2^{+0.2}_{-0.2}$ | $9.06^{+0.01}_{-0.01}$ | $9.18^{+0.01}_{-0.01}$ | $9.47^{+0.15}_{-0.15}$ | $9.04^{+0.16}_{-0.16}$ |
| $\lambda_{max}$ | $3.0^{+0.2}_{-0.2}$ | $3.89^{+0.30}_{-0.31}$ | $3.27^{+0.19}_{-0.20}$ | $4.16^{+0.09}_{-0.09}$ | $4.06^{+0.07}_{-0.07}$ |
| $\Gamma_L$ | $2.8^{+0.02}_{-0.02}$ | $2.77^{+0.03}_{-0.03}$ | $2.79^{+0.03}_{-0.03}$ | $3^{+0.01}_{-0.01}$ | $...$ |
| $\Gamma_{PL}$ | $3.73^{+0.47}_{-0.74}$ | $1.99^{+0.31}_{-0.31}$ | $0.21^{+0.20}_{-0.20}$ | $...$ | $...$ |
| $\chi_{red}$ | $36 \pm 6$ | $23 \pm 3$ | $2.4^{+0.04}_{-0.04}$ | $<0.1$ | $<0.1$ |
| $\chi_{red}$ (dof) | $1.17 (95)$ | $1.22 (95)$ | $1.33 (95)$ | $0.97 (99)$ | $0.86 (99)$ |
| $F_{test}(PL)$ | $5.1 \times 10^{-7}$ | $3.0 \times 10^{-24}$ | $8.9 \times 10^{-6}$ | $...$ | $...$ |

**Notes.**—For the HB, we analyzed observation 70073-01-01-00, for HB$_{high}$ the first two orbits of 70073-01-03-00 and 70073-01-01-00, and for FB and NB$_{low}$ we analyzed the first and the fourth orbit of 70073-01-02-00, respectively. Errors are at the 68% confidence level for a single parameter. We fitted the 3–100 keV spectra using a model consisting of a blackbody ($kT_{in}$ is the blackbody temperature). $N_{BB}$ is the normalization in units of $L_{20}/D_{10}^2$, where $L_{20}$ is the luminosity of the source in units of $10^{39}$ ergs s$^{-1}$ and $D_{10}$ is the distance to the source in units of 10 kpc); a Gaussian emission line ($E_{W_{Fe}}$, $\sigma_{Fe}$ is the line width in keV, $E_{W_{Fe}}$ is the line equivalent width in keV, $\Gamma_L$ is the line width in keV, $\Gamma_{PL}$ is the total photons cm$^{-2}$ s$^{-1}$ in the line), compTT ($kT_w$ is the input soft-photon Wien temperature in keV, $\lambda_{max}$ is the plasma temperature in keV, $\tau$ is the plasma optical depth), an absorption edge ($E_{edge}$ is the threshold energy in keV, “Max. $\tau$” is the maximum absorption factor at threshold), and a power law (photon index $\Gamma_{PL}$, $\Gamma_{edge}$ is the normalization in photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV) when needed, all corrected for photoelectric absorption ($N_H$). “$F_{test}$” is the probability of chance improvement for the addition of a power-law component. $F_{test}$ is the 2–100 keV flux of the additional power-law component in units of $10^{-10}$ ergs cm$^{-2}$ s$^{-1}$.

3. RESULTS AND DISCUSSION

3.1. Radio Emission Correlated with Position in the HID

In Figure 1, we show the 5 and 8.5 GHz VLA (top), 3–20 keV RXTE PCA (middle), and hard X-ray color (bottom) light curves of GX 17+2. The simultaneous X-ray and radio light curves show no obvious correlations between the X-ray count rate and the radio flux densities. However, in the radio observations we note an overall correlation between the mean radio flux density and the mean hard color (top and bottom): the higher the mean radio flux density, the higher the hard color. More specifically, the radio emission is strongly related to the position in the HID. In Figure 2, we show the HID of GX 17+2: the gray dots are the...
PCA observations, with a time resolution of 16 s, and the superposed open circles indicate the radio emission’s strength: the larger the circle, the higher the radio flux density. One can clearly see that the radio flux density is strictly related to the position in the HID, in a way consistent with previous observations (Penninx et al. 1988) and with the disk-jet coupling scenario described in Migliari & Fender (2006): the radio flux density increases from the FB to the NB and is highest in the HB. We also note an enhancement of radio flux density in the HB (which we call HB$_{high}$), corresponding to an increase in intensity of the source, with no significant change in hard color.

The overall radio emission is consistent with being optically thick except possibly for the observations during HB$_{high}$, which correspond to what seems to be the decay of an optically thin radio flare (with $\alpha = -0.16 \pm 0.01$, measured by fitting the flux densities at 1.4, 5, 8.5, and 15 GHz of the averaged observations for the range of times less than $10^4$ s from the beginning of our observations; see Fig. 1, top left). The radio decay in the top left panel of Figure 1 might be associated with the (preceding) X-ray count rate decay shown in the middle left panel. In this case, a possible scenario would be that of a radio flare associated with the NB-to-HB transition (not observed), of which we only see the decaying part. However, the X-ray count rate decay could also represent the decay of a long, type I X-ray burst of the same kind observed from this source in previous RXTE observations (e.g., the long “burst 6” reported by Kuulkers et al. 2002). Indeed, the X-ray decay shown in the PCA light curve seems to be exponential, supporting the interpretation as a type I burst. We tried to investigate this possibility by fitting the 2–25 keV PCA energy spectrum of the X-ray decay (the first 1700 s of observation 70023-01-01-01) with the model described in § 2.1,
without the power-law component, plus an extra blackbody component to account for the possible thermal emission from the surface of the NS, but the additional blackbody does not provide a significant statistical improvement to the fit. The radio/X-ray flux decay simultaneity would be, in the case of a type I burst, only coincidental.

3.2. A Radio Jet Switches On at the FB-to-NB State Transition

The HID in Figure 2 shows that during the FB no radio emission is detected, whereas emission, although weak, is observed in the lower NB. Our observations cover the exact time during which the source made a transition from the FB to the lower NB (Fig. 1, middle column). In Figure 3, we show the radio and X-ray light curves of GX 17+2 during the transition from FB to NB. The top panel shows the radio light curve at 8.5 GHz (rebinned to a higher temporal resolution with respect to that in Fig. 1). The first part of the observation, that is, up to 4.47 × 10^5 s, the source is not significantly detected (with a nominal flux density of 0.024 ± 0.048 mJy). However, after 4.48 × 10^5 s the radio source is detected at 8.5 GHz at a significance level of 8.8 σ and at 5 GHz at a significance level of 6.8 σ. The radio power-law spectral index is α = −0.27 ± 0.33. Physically, we interpret this as a compact jet that switches on soon after the FB-to-NB transition. (Note that since the radio spectral index is not well constrained, an optically thin radio flare cannot be ruled out.) A sketch of the (phenomenological) jet/X-ray state coupling model for Z sources, adapted from Migliari & Fender (2006) to include this result, is shown in Figure 2 (inset). For clarity, the drawings of the jet in this illustration refer only to the cycle from HB to FB. Indeed, if a compact jet is re-formed during the FB-to-NB transition, optically thin shocks and transient jets may not be present in the NB.

In Figure 3, the panels that are third from the top show the dynamical power density spectra of the two orbits (in black are evident the changes in the characteristic frequency of the QPOs), and the bottom panels show the positions of the observations on the HID as black dots. The lower FB is usually characterized by the presence of the so-called flaring-branch oscillation (FBO), which has a typical characteristic frequency above 14 Hz, while the NB power density spectra usually show the so-called normal-branch oscillation (NBO), which has a typical characteristic frequency below 10 Hz (see Homan et al. 2002). The first PCA orbit shows the actual X-ray state transition from the FB to the lower NB: the black points in the HID are spread between the FB and the NB, and the dynamical power density spectrum shows a transition between the FBO and the NBO, with the QPO frequency oscillating between the typical frequencies of the two QPOs; a fit to the averaged power density spectrum gives a characteristic frequency of νQPO = 10.7 ± 0.1 Hz (the same kind of “intermediate” QPO has already been observed in previous observations of GX 17+2; Homan et al. 2002). The QPO stabilizes into an NBO only in the second orbit, with a characteristic frequency of νNBO = 7.8 ± 0.1 Hz. This stable NBO is simultaneous with clearly renewed radio activity of the source. As the QPO frequency stabilizes into an NBO, the compact jet appears to reestablish itself. The parallel between the stability of the NBO and the radio emission—and given that in Z sources the NBO, as well as the radio emission, has been observed in all the X-ray states with the exception of the FB—suggests a relation between the formation of the jet and the X-ray variability associated with the NBO. In an attempt to draw analogies between the fast X-ray variability observed in Z sources and in BH XRBs, Casella et al. (2005) studied the properties of the low-frequency QPOs in the two types of systems and related the FBO to the so-called type A QPOs, the NBO to type B QPOs, and the horizontal-branch oscillation to type C QPOs. In this framework, jet formation in BHs might be related to the type B QPOs, to the transition between type A and type B QPOs, or to both. An association between the presence of QPOs and radio jet activity, similar to what we see in GX 17+2, can be found in some BH XRBs, albeit with a much slower timescale. A clear example comes from multiwavelength studies of the decay of the outburst in H1743−322 (Kalemci et al. 2006). The power density spectrum of this source shows a low-frequency QPO that appears during the transition from the thermal/soft state, in which the radio jet is undetected, to the hard X-ray state (see also, e.g., Homan & Belloni 2005). While the source is in an
intermediate state and entering the hard state, the characteristic frequency of the QPO decreases in time (possibly also changing “type”; in their work, Kalemci et al. did not classify the QPOs by type), and when the source is in its hard state, the radio jet renews its activity.

In the bright atoll source GX 13+1, Homan et al. (2004) observed a delay of approximately 40 minutes between the changes in the X-ray spectral hardness and the subsequent radio flares. In GX 17+2, we observe renewed radio activity at around $4.5 \times 10^5$ s (Fig. 3, top). If we associate this radio flux increase with the preceding FB-to-NB transition, the delay is $\sim 2$ hr. This time delay is about 3 times that found in GX 13+1 and about twice the delays observed in the strongly accreting BH XRB GRS 1915+105 between the beginning of the X-ray hard dips and the following radio flares (see Klein-Wolt et al. 2002), that is, taking the hard X-ray dips’ duration as the time that it takes the compact jet to re-form. If, on the other hand, the radio activity is associated with the stability of the characteristic frequency of the NBO, we obtain an upper limit of $< 4000$ s on the X-ray/radio activity delay, consistent with what has been observed in the NS GX 13+1 and the BH GRS 1915+105. For comparison, more “traditional” BHs such as H1743$-$322 and 4U 1543$-$47 (Kalemci et al. 2005, 2006) during the decay of the outburst show a time delay of at least a few days between the end of the thermal/soft state and the detection of the radio jet.

### 3.3. Radio Emission and Hard X-Ray Tails

We have analyzed the 3–100 keV energy spectra of five observations along the HID. In Table 2, we show the best-fit parameters of the X-ray energy spectra using the model described in § 2.1. A hard X-ray tail is present in the HB$_{\text{high}}$ and HB portions (an $F$-test for the addition of a power-law component gives a chance-improvement probability of $\sim 5 \times 10^{-4}$). During HB$_{\text{high}}$ and $\sim 3 \times 10^{-24}$ in the HB (Fig. 4, top), and the 2–100 keV flux in the power-law component is approximately 15% and 10%, respectively, of the total 2–100 keV flux of the source. In the NB, an extra power-law component is also needed in the fit of the energy spectrum (an $F$-test gives $\sim 9 \times 10^{-6}$ chance probability), but the power-law flux decreases to approximately 1% of the total 2–100 keV flux. No additional component is needed in the spectral fits when the source is in NB$_{\text{low}}$ or the FB (Fig. 4, bottom). Therefore, we confirm that in GX 17+2 there is a clear correspondence between the presence of a hard tail in the X-ray spectra and the position on the HID.

The behavior of the hard X-ray tail in GX 17+2 as a function of position in the HID is qualitatively the same as that observed for the radio emission, suggesting a common physical driver for the production of the radio and hard X-ray tail emission. In order to quantify this qualitative correspondence between the radio emission and hard tail, in Figure 5 we plot the mean radio flux density at 8.5 GHz against the 2–100 keV flux of the hard tail power-law component for the observations in FB, NB$_{\text{low}}$, NB, HB, and HB$_{\text{high}}$. The three observations for which the presence of the X-ray hard tail power law and the radio emission is significantly detected show a positive correlation between the two quantities (with a correlation coefficient of 99%): the radio flux density increases as the power-law X-ray flux increases. The upper limits on the other two observations are consistent with this trend. However, given the present statistics, the correlation cannot be firmly constrained, and additional observations are needed in order to confirm and properly quantify the radio/hard X-ray dependence.

For BH systems, it has been suggested that the Comptonizing corona is ejected during a radio flare (e.g., Vadawale et al. 2003; Fender et al. 2004b), hence the transition of the source into the soft state. In the NS system GX 17+2, we appear to see a correlation between the hard X-ray tail and the radio emission, with a strong hard X-ray tail also present during a radio flare. However, although during the HB$_{\text{high}}$ observation what we see is likely the decay portion of a radio flare, thus being associated with a preceding “transient” ejection, the radio spectra of GX 17+2 during the other X-ray states are consistent with the emission from a “compact” jet. The compact jet, which can also be present during HB$_{\text{high}}$,
is what appears to be associated with the hard X-ray tail. Similarly, in BH systems the radio compact jet is observed in the quiescent/hard state, when a hard Comptonizing “corona” is also present.

4. CONCLUSIONS

We have analyzed simultaneous radio (VLA) and X-ray (RXTE) observations covering all three X-ray branches of the Z-type NS XRB GX 17+2 and found the following:

1. There is a relation between the radio emission and the position in the HID: the radio flux density is strongest in the HB, decreases in the NB, and is weakest in the FB (Fig. 2).

2. There is also a relation between the presence of a hard X-ray tail and the position on the HID: the hard power-law tail is observed in the HB and the NB and is not detected in the lower NB or in the FB (Fig. 4 and Table 2).

3. There is a link between X-ray state transitions and the jet activity: a jet, likely a compact jet, forms soon after the FB-to-NB transition, with a time delay of less than 2 hr (Fig. 3).

4. The radio emission of the jet that (re-) forms after the FB-to-NB state transition stabilizes when the NBO characteristic frequency in the X-ray power spectrum also stabilizes (Fig. 3). This finding, together with the fact that in Z sources the NBO, as well as the radio emission, has been observed in all the X-ray states with the exception of the FB, suggests a relation between the formation of the jet and the X-ray variability associated with the NBO. A similar behavior, albeit with a longer timescale, may be found in BH systems, where the decrease of the characteristic frequency and change of “type” of the low-frequency QPO is followed by renewed activity of the jet (see § 3.2).

5. There is an indication of a quantitative relation between radio emission and the hard tail in the X-ray spectrum: a positive correlation exists between the hard tail power-law X-ray flux and the radio flux density (Fig. 5). If further confirmed with a larger sample and improved statistics, especially in the measurement of the hard X-ray tail’s flux, this relation would point to a common mechanism for the production of the jet and the hard X-ray tails in the system.

S. M. would like to thank Tommy Thompson for useful discussions. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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