A LACK OF RADIO EMISSION FROM NEUTRON STAR LOW-MASS X-RAY BINARIES

MICHAEL P. MUNO, 1,2 TOMASO BELLONI, 3 VIVEK DHAWAN, 4 EDWARD H. MORGAN, 5
RONALD A. REMILLARD, 5 AND MICHAEL P. RUPEN 4

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ABSTRACT

We report strict upper limits to the radio luminosities of three neutron star low-mass X-ray binaries obtained with the Very Large Array while they were in hard X-ray states as observed with the Rossi X-Ray Timing Explorer: 1E 1724−307, 4U 1812−12, and SLX 1735−269. We compare these upper limits to the radio luminosities of several black hole binaries in very similar hard states and find that the neutron star systems are as faint as or fainter than all of the black hole candidates. The differences in luminosities can partly be attributed to the lower masses of the neutron star systems, which, on theoretical and observational grounds are expected to decrease the radio luminosities as $M^{0.8}$. However, there still remains a factor of 30 scatter in the radio luminosities of black hole and neutron star X-ray binaries, particularly at X-ray luminosities of a few percent Eddington. We find no obvious differences in the X-ray timing and spectral properties that can be correlated with the radio luminosity. We discuss the implications of these results on current models for the relationship between accretion and jets.

Subject headings: accretion, accretion disks — stars: neutron — X-rays: binaries — X-rays: individual (1E 1724−307, 4U 1812−12, SLX 1735−269)

1. INTRODUCTION

Astrophysical jets are introduced from a wide range of systems, including active galactic nuclei (Lynden-Bell 1996), young stellar objects (Bachiller 1996), accreting white dwarfs in symbiotic binaries (Crocker et al. 2002; Sokoloski & Kenyon 2003) and supersoft X-ray sources (Cowley et al. 1998), and neutron stars and black holes in X-ray binaries (Fender 2005). Although it is generally accepted that the power supplied from these jets has its origin in accretion, the details of the mechanisms producing the jets are not fully established (e.g., Heinz & Sunyaev 2003; Falcke et al. 2004; Meier et al. 2001). Observationally, one impediment to understanding these mechanisms is that the jets form on timescales at which changes occur in the accretion flows (e.g., the viscous timescale; see Hartmann & Kenyon 1996; Mirabel et al. 1998; Sokoloski & Kenyon 2003). For young stellar objects and active galactic nuclei, that timescale is months to years, which makes it difficult to obtain well-sampled observations of jets as they form. Therefore, in trying to establish what conditions are needed to produce jets, it is often difficult to disentangle the relative importance of the state of the accretion flow from the physical properties of the systems as a whole, such as their binary orbital periods or the rotation rates of the accreting objects. The exceptions are accreting, stellar-mass compact objects, in which, because of their small size, the structure of the accretion flows are observed to change on timescales of hours to days. Recent observations of X-ray binaries have provided the first information about the time-dependent relationship between the accretion flows and the formation of jets (e.g., Mirabel et al. 1998; Fomalont et al. 2001; Fender et al. 2004a, 2004b).

A particularly striking picture of the relationship between accretion and jets has emerged for black hole X-ray binaries (see Fender 2005, for a review). The accretion flows can be characterized by three states based on the spectral and timing properties of their X-ray and gamma-ray emission (0.5−500 keV): (1) a hard state that usually occurs at relatively low accretion rates in which the X-ray emission forms a power law with photon index $\Gamma \approx 1.5−2.0$ that is exponentially cut off at an energy of $\sim 100$ keV, and the power spectrum resembles band-limited white noise with a power of 10%−30% rms; (2) a thermal state at higher accretion rates, in which the X-ray emission resembles that expected from a canonical optically thick, geometrically thin accretion disk with a temperature of $\sim 1$ keV (Shakura & Sunyaev 1973), and in which the power spectrum exhibits only weak noise (1%−6% rms) with a power-law shape; and (3) a steep power-law state in which the spectrum is the sum of thermal emission plus a power law of photon index $\Gamma = 2−3$ that extends without a break to $\sim 500$ keV, and the power spectrum usually contains quasi-periodic oscillations (QPOs) at low frequency (0.1−20 Hz), and less often at high frequency (150−450 Hz) or in the mHz range (see McClintock & Remillard 2004 for further discussion).

The radio emission associated with these states comes in two forms. First, optically thick radio emission from compact jets that extend only tens of AU (Dhawan et al. 2000; Stirling et al. 2001) is observed to coincide with the X-ray hard power-law state ($\Gamma = 1.5−2.0$; Brockopp et al. 1999; Corbel et al. 2000; Gallo et al. 2003). The hard states and their jets can persist for days to months with relatively steady flux, and yet the jets become quenched when sources enter thermal-dominated states.6 Second, transitions between these states are often observed to coincide with the formation of discrete synchrotron-emitting structures that travel relativistically across the sky (e.g., Mirabel & Rodríguez 1994; Fender et al. 1999; Fender & Kuulkers 2001). These ballistic jets form on timescales of a day and eventually travel thousands of AU from the central black hole.

6 Note that it is unclear whether optically thick radio emission accompanies the rarer steep power-law states (e.g., Tavani et al. 1996; Fender et al. 2004b).
X-ray binaries containing neutron stars with relatively weak magnetic fields ($B \lesssim 10^9$ G; these are almost always found in low-mass X-ray binaries, or LMXBs) resemble black hole systems in some respects, because the inner edge of the accretion disks can extend to near the innermost stable general relativistic orbits in both types of systems. However, the relationships between X-ray and radio emission from neutron star LMXBs have not been as firmly established. Similar to the black hole X-ray binaries, neutron star LMXBs exhibit a hard X-ray state with orbits in both types of systems. However, the relationships between X-ray and radio emission from neutron star LMXBs have not been as firmly established. Similar to the black hole X-ray binaries, neutron star LMXBs exhibit a hard X-ray state with a $\Gamma \approx 2.0$ power law. However, the analogs of the thermal-dominated and steep power-law states appear to be replaced by a soft state in which most of the X-ray emission is produced by the boundary between the accretion disk and the neutron star (e.g., Done & Gierlinski 2003). Transient radio emission has been observed from neutron star X-ray binaries during periods in which their X-ray spectra were variable (e.g., Penninx et al. 1988; Berendsen et al. 2000; Homan et al. 2004; Migliari et al. 2003), and in two cases this emission was resolved into ballistic jets (Fomalont et al. 2001; Fender et al. 2004a). However, the peak luminosities of their radio emission are factors of $\approx 30$ lower than the black hole systems (Fender & Kuulkers 2001). Radio emission was also detected from two neutron star systems in persistently soft X-ray states (4U 1820–30 and Ser X-1; Migliari et al. 2004); this emission does not easily fit into the paradigm derived from black holes. However, no study has systematically targeted neutron star X-ray binaries in their hard, $\Gamma = 2.0$ power-law states to determine whether or not they exhibit steady, compact radio jets.

In this paper, we report on Very Large Array (VLA)\(^7\) observations that we used to search for radio emission from three neutron star LMXBs in hard X-ray states, in order to determine whether the formation of compact jets is affected by changing the central compact object from a black hole to a neutron star.

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We have observed three systems that remained in hard, $\Gamma = 1.5$–$2.0$ power-law states for the first 5 yr of observations with the Rossi X-Ray Timing Explorer (RXTE): 1E 1724$-$307 in Terzan 2, SLX 1735$-$269, and 4U 1812$-$12. Each of these systems exhibits thermonuclear X-ray bursts, which demonstrates unambiguously that they contain neutron stars (Grindlay et al. 1980; Murakami et al. 1983; Bazzano et al. 1997). However, their X-ray properties are otherwise almost indistinguishable from those of black holes in their hard states (Olive et al. 1998; Wijnands & van der Klis 1999; Barret et al. 1999, 2000, 2003; Belloni et al. 2002).

The organization of this paper is as follows. In \S\ 2.1, we explain how we selected our sample of sources and report on the X-ray emission derived with RXTE. We include considerable detail in order to establish the degree to which these systems resemble black hole X-ray binaries in the hard state. In \S\ 2.2, we report on strict upper limits to the radio emission from three LMXBs in our sample that were obtained with the VLA, nearly simultaneously with the RXTE observations. In \S\ 3, we briefly discuss the implications of a lack of radio emission from neutron LMXBs in the hard state.

\section{2. Observations}

The basic observational properties of the three neutron star LMXBs that we have studied are listed in Tables 1 and 2.

\subsection{2.1. RXTE}

RXTE carries three instruments: the All-Sky Monitor (ASM), consisting of three 30 cm\(^2\) proportional counters sensitive between 1.5–12 keV, which scan 80\% of the sky every 90 minutes (Levine et al. 1996); the Proportional Counter Array (PCA), consisting of five 1300 cm\(^2\) detectors, which record events with the capability for microsecond time resolution and 256 channels of spectral resolution between 2–60 keV (Jahoda et al. 1996); and the High-Energy X-Ray Timing Experiment, consisting of two clusters of scintillation detectors, each with an effective area of 800 cm\(^2\) and sensitivity between 15–250 keV (HEXTE;
Fig. 1.—ASM light curves and PCA color-color diagrams illustrating the stability of the X-ray emission from the three sources we studied. The left panels plot weekly averages of the individual 90 s dwells. The horizontal bars at a count rate of $\sim 1$ indicate periods when the Sun was within 35° of the source. The vertical bars indicate the times of PCA observations, a subset of which were analyzed in detail for this paper. The right panels contain the hard and soft colors from the PCA data, which are defined as the ratio of the background-subtracted detector counts in the (3.6–5.0)/(2.2–3.6) keV and the (8.6–18.0)/(5.0–8.6) keV energy bands, respectively. All of the sources remained in the hard portion of the color-color diagram prior to 2001, although SLX 1735–269 became softer during observations in 2002 January.

Fig. 2.—PCA and HEXTE spectra of the sources in this study, in units of detector counts. The residuals from the best-fit absorbed Comptonization spectra are displayed in the bottom panels, in units of the uncertainty in the data. Residuals between 6–20 keV in 4U 1812–12 and SLX 1735–269 are probably produced by hard photons that reflect off the optically thick accretion disk. We have plotted the spectrum of Cyg X-1 in the hard state with a dashed line, for comparison to this sample of neutron star LMXBs.
Rothschild et al. 1998). Data from all three instruments were used to characterize the X-ray emission from the LMXBs in our sample.

We first used data from the PCA and ASM to identify several neutron star LMXBs that persistently remained in a hard state (sometimes also referred to as the “island” of the atoll shape in the color-color diagram) from the sample of systems that exhibit thermonuclear X-ray bursts (D. Galloway et al. 2005, in preparation). We first confirmed that the X-ray emission was steady, using data from the RXTE ASM. We then measured the hardness of the X-ray spectra, using a hard color, which was defined as the ratio of the background-subtracted PCA counts in the (8.6–18.0)/(5.0–8.6) keV energy bands. The counts were normalized to account for changes in the gain of the proportional counter units (see Muno et al. 2002). Eight sources qualified as persistently hard neutron star LMXBs that persistently remained in a hard state.

To produce spectra, we extracted data in 128 energy channels from the top layer of each active detector of the PCA and in 64 channels from cluster 0 of HEXT. For the PCA, the detector response and background were estimated using standard tools in FTOOLS version 5.3.1. For HEXT, the background was from the intervals during which the cluster was pointed off source, and the response and effective area estimates were obtained from CALDB version 2.23. We modeled the spectra jointly in XSPEC version 11.3.1, using the 3–20 keV energy range from the PCA and the 15–200 keV energy range from HEXT. We applied a constant normalization to account for differences in the calibrated effective area of the PCA and HEXT and a 1% systematic uncertainty added in quadrature to the count spectra from the PCA to account for uncertainties in the detector calibration near the Xe edge at 4.5 keV. After confirming that the spectrum did not vary significantly over the course of the observations that we considered, we averaged the spectra to obtain a better signal-to-noise ratio at high energies. The resulting spectra are displayed in Figure 2.

We modeled the spectra using a phenomenological model that included a power-law continuum that produced most of the 3–200 keV flux; a blackbody component at low energies to remove residuals below 4 keV, which could result from emission from the neutron star’s surface or the inner accretion disk; a reflection component to account for residuals between 6–7 and 10–20 keV, which may be produced by hard X-rays impinging on an optically thick accretion disk (refsch in XSPEC; Fabian et al. 1989; Magdziarz & Zdziarski 1995); and low-energy absorption caused by interstellar gas. The column densities of interstellar matter ($N_H$) were fixed to the values determined from previous observations of each source by either ASCA or BeppoSAX (David et al. 1997; Guainazzi et al. 1998; Barret et al. 1999, 2003). The parameters of the reflection components could not all be constrained independently, so we fixed the inner and outer radii of the disk to 10 and 100 gravitational radii ($GM/c^2$), the power-law indices for reflection emissivity to −2,

### Table 3

| Parameter | 4U 1812–12 | SLX 1735–269 | 1E 1724–307 |
|-----------|------------|--------------|------------|
| $N_H$ (cm$^{-2}$; fixed) | 1.5 | 1.5 | 1.0 |
| $kT_{bb}$ (keV) | 0.46±0.01 | 0.32±0.05 | ... |
| $N_{bb}$ (km [10 kpc]$^{-1}$) | 15±1 | 50±20 | <1 |
| $\Gamma$ | 1.80±0.02 | 2.08±0.03 | 2.05±0.01 |
| $E_{tot}$ (fixed) | 300 | 300 | 300 |
| $R$ (kev) | 0.31±0.02 | 0.47±0.09 | 0.20±0.02 |
| $\xi$ (ergs cm$^{-3}$) | 0.3 | 700 | 300 |
| $N_e$ (photons cm$^{-2}$ s$^{-1}$) | 0.097±0.003 | 0.12±0.01 | 0.188±0.001 |
| $\chi^2/\nu$ | 109/79 | 96/79 | 73/79 |
| $F_{2-10}$ keV (10$^{-10}$ ergs cm$^{-2}$ s$^{-1}$) | 3.8 | 3.2 | 4.6 |
| $F_{20-200}$ keV (10$^{-10}$ ergs cm$^{-2}$ s$^{-1}$) | 2.0 | 1.2 | 1.9 |
| $F_{20-200}$ keV (10$^{-10}$ ergs cm$^{-2}$ s$^{-1}$) | 6.1 | 1.8 | 4.4 |

Note.—All fluxes are deabsorbed.

The sample of persistently hard neutron star LMXBs also includes 4U 1323–619, SAX J1712.6–3739, GS 1826–25, 4U 1832–330, and 4U 1850–087.

### 2.1.2. X-Ray Timing

We produced power spectra using PCA data with 122 µs (2–13 s) time resolution in a single energy channel (2–30 keV). We computed power spectra in 256 s intervals and averaged them weighted by the total counts to produce an accurate estimate of the continuum power. We then subtracted the deadtime-corrected Poisson noise levels from the power spectra (Zhang et al. 1996), rebinned them logarithmically, and estimated uncertainties from the standard deviations in the individual points that were averaged to compute the final power spectra. To quantify the shape of the power spectra, we modeled the continuum with several zero-centered Lorentzian functions and any QPOs with Lorentzians with variable centroid frequencies. We added Lorentzians until doing so no longer led to a significant decrease in $\chi^2$. The results are listed in Table 4 and displayed in Figure 3.

As before, the power spectra of these LMXBs strongly resemble those from black hole candidates such as Cyg X-1 (e.g., Di Salvo et al. 2001) and GX 339–4 (e.g., Wilms et al. 1999). To highlight this similarity, we plot the spectrum of Cyg X-1 from a 21 ks RXTE exposure taken on 1996 October 23 in each of the panels in Figure 2. The only substantial difference is that the slopes of the power-law components from the black hole LMXBs are often a bit flatter ($\Gamma \approx 1.5$) than those from the neutron star LMXBs ($\Gamma \approx 2$).

### 2.2. VLA

The VLA is a multifrequency, multiconfiguration aperture synthesis imaging instrument, consisting of 27 antennas of 25 m diameter. We obtained VLA observations of 4U 1812–12 under program AR 458 and of 1E 1724–307 and SLX 1735–269 under program AM 703 (Table 1). The observation under...
AR 458 was a 15 minute integration at 8.45 GHz. The observations under program AM 703 were 1 hr integrations at 1.42 GHz and 2 hr integrations at 5.0 and 8.45 GHz. In all cases, we obtained two adjacent bands of 50 MHz nominal bandwidth processed in continuum mode. Calibration and imaging were carried out with standard tasks in the NRAO Astronomical Image Processing System (AIPS) package.

None of the three sources was detected in the radio. We estimated 1σ upper limits to the radio fluxes by measuring the rms dispersions in the noise within 5″ of each source. These upper limits are listed in Table 1.

### 3. DISCUSSION

We have placed strict upper limits on the radio emission from three neutron star LMXBs that are known to have been in hard X-ray states. In Figure 4, we compare the luminosities of these neutron star LMXBs in the radio and X-ray bands with those of several black hole X-ray binaries. For the black holes, the luminosities were obtained from the references tabulated by Gallo et al. (2003; see the figure caption for details), using the most current distances listed in McClintock & Remillard (2004). We have also included measurements of the neutron star LMXB 4U 1728–34 from Migliari et al. (2003), although we note that most of the measurements are from soft or variable states. The neutron star LMXBs have the lowest radio luminosities of the X-ray binaries in Figure 4.

Several authors have found that the relationship between the X-ray and radio luminosities of both individual black hole systems and the ensemble of systems follows the relationship $L_R \propto L_X^{0.7}$ (Corbel et al. 2003; Gallo et al. 2003). Remarkably, this scaling follows the spectral energy distribution expected from models of a standard conical radio jet that extracts a fixed fraction of the total energy from accretion (Blandford & Königl 1979; Markoff et al. 2003; Heinz & Sunyaev 2003; Merloni et al. 2003). Therefore, we also plot in Figure 4 lines of $L_R \propto L_X^{0.7}$ that intercept data from V404 Cyg, Cyg X-1, and GRS 1758–258; these lines bound the observed scatter in radio luminosities. The upper limits on the radio luminosities of the neutron star X-ray binaries are equal to or below the line of $L_R \propto L_X^{0.7}$ that passes through the faintest black hole X-ray binary observed in the hard X-ray state, GRS 1758–258 (Lin et al. 2000; Marti et al. 2002). The strictest 1σ upper limit on the radio luminosity, from 1E 1724–307, is a factor of ≈4 below the relationship for GRS 1758–258. For comparison, there is a factor of ≈30 difference in the radio luminosities of GRS 1758–258 and those of V404 Cyg and GX 339–4.

### TABLE 4

**X-RAY TIMING**

| Parameter | 4U 1812–12 | SLX 1735–269 | 1E 1724–307 |
|-----------|------------|--------------|-------------|
| Constant ($\times 10^{-6}$) | 11(4) | 4(1) | 16(5) |
| $\nu_1$, $w_1$, $N_1$ | 0, 0.25(3), 0.039(3) | 0, 0.28(1), 0.056(5) | 0, 0.9(2), 4.7(6) $\times 10^{-3}$ |
| $\nu_2$, $w_2$, $N_2$ | $<0.5$, 2(1), 2(1) $\times 10^{-3}$ | 0, 3.0, 2.0(9) $\times 10^{-3}$ | 0, 7(1), 1.5(4) $\times 10^{-3}$ |
| $\nu_3$, $w_3$, $N_3$ | 0, 25(6), 5(2) $\times 10^{-4}$ | 0, 19.3(9), 1.0(1) $\times 10^{-3}$ | ... |
| $\nu_4$, $w_4$, $N_4$ | ... | 0, 371(90), 4.2(7) $\times 10^{-5}$ | ... |
| $\nu_5$, $w_5$, $N_5$ | ... | 0.64(1), 0.17(7), 4.4(5) $\times 10^{-3}$ | ... |
| $\nu_6$, $w_6$, $N_6$ | ... | 0.62(8), 1.4(2), 6(1) $\times 10^{-3}$ | ... |
| $\chi^2$/dof | 135/98 | 119/89 | 76/54 |

**Note.**—Power spectra were fit with Lorentzians, the parameters of which were the centroid ($\nu$), width ($w$), and normalization ($N$).
By comparing a sample of accreting black holes in X-ray binaries and active galactic nuclei, Merloni et al. (2003) and Falcke et al. (2004) have found an additional dependence on black hole mass: \[ \log L_R = 0.6 \log L_X + 0.8 \log M. \] This dependence is also expected from conical jet models (Falcke et al. 2004; Robertson & Leiter 2004). Therefore, in Figure 5 we replot the data in Figure 4 with the x-axis scaled by a factor \( (M/M_\odot)^{0.8} \). All of the black holes in the sample have masses that are between 5 and 15 \( M_\odot \) (McClintock & Remillard 2004), so the proposed dependence on mass does not account for the scatter in the radio Luminosity of black holes. However, if we account for the fact that the neutron stars are likely to have masses near 1.4 \( M_\odot \) (Thorsett & Chakrabarty 1999), then the upper limits on their radio luminosities are consistent with the relationship defined by GRS 1758–258. Nevertheless, the mean luminosity of the neutron star LMXBs is still lower than that of the black holes.

This dispersion in the radio and X-ray luminosities could have any of several explanations. If we assume that the mechanism for producing jets is the same in black hole and neutron-star LMXBs, then there are at least three possibilities. First, the radio emission from several black hole systems, particularly GRS 1758–258, appears to be “quenched” when they accrete at relatively high rates \( (\dot{M} \approx 0.01–0.04 \dot{M}_{\text{Edd}}) \) (Gallo et al. 2003), and a similar phenomenon could be occurring in the neutron star

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**Fig. 4.** Comparison of the radio and X-ray luminosity of the neutron star LMXBs in our sample (red symbols), with those from several black hole candidates in the hard X-ray state (blue symbols). The dashed line illustrates a linear \( L_R \propto L_X^5 \) correlation observed for several individual sources (Corbel et al. 2003; Gallo et al. 2003). The dotted line illustrates a linear \( L_R \propto L_X \) proportionality that is normalized to the radio flux from GRS 1758–258. The radio flux is defined as that in a 5 GHz band around a central frequency of 5 GHz, assuming a flat radio spectrum. If 5 GHz measurements were not available, then either measurements at other frequencies were interpolated onto 5 GHz, or measurements at a single frequency were used under the assumption that the spectrum was flat (this introduced at most a 10% error). The X-ray luminosity is defined as that between 2–10 keV, deabsorbed. Values taken in different energy bands were extrapolated into the 2–10 keV band using the observed spectrum, or in one case (V404 Cyg) assuming a \( \Gamma = 1.5 \) power-law spectrum. Distances to the neutron star systems were obtained as follows: for 1E 1724–307, we used the distance to Terzan 2 (4.1 kpc; Barbuy et al. 1998); for 4U 1812–12, we used the peak flux of an Eddington-limited burst (6.6 kpc, taking \( L_{\text{Edd}} = 3.5 \times 10^{38} \) erg s\(^{-1}\) for pure He; Murakami et al. 1983); and for SLX 1735–269, we assumed that a burst that had no spectral information was Eddington-limited and derived an upper limit to the distance (<12 kpc; Bazzano et al. 1997). For the black hole candidates, the distances were taken from McClintock & Remillard (2004), except for GRS 1758–258, which was taken from Gallo et al. (2003). References for radio and X-ray fluxes of the systems not observed for this paper are as follows: 4U 1728–34 (Migliari et al. 2003), GRS 1915+105 (Muno et al. 2001), Cyg X-1 (Stirling et al. 2001; Di Salvo et al. 2001), GX 339–4 (Corbel et al. 2003), XTE J1118+480 (McClintock et al. 2001; Fender et al. 2001), V404 Cyg (Han & Hjellming 1992), XTE J1550–564 (Corbel et al. 2001; Tomsick et al. 2001), and GRS 1758–258 (Lin et al. 2000).

**Fig. 5.** Same as Fig. 4, except that the X-ray luminosity includes an extra mass-dependent term \( (M/M_\odot)^{0.8} \) (Merloni et al. 2003; Falcke et al. 2004). Including this mass dependence demonstrates that the radio upper limits from the three neutron star systems are all consistent with the fundamental plane defined by the faintest black hole system, GRS 1758–258.
systems. However, this hypothesis does not provide a natural explanation for why the X-ray spectral and timing properties from systems with a range of radio luminosities looks so similar (see Lin et al. [2000] for GRS 1758—258, and Figs. 2 and 3 for the neutron star LMXBs). Second, different Doppler boosting factors could produce some of the observed dispersion (Gallo et al. 2003; Heinz & Merloni 2004). However, if the jets have the same velocities, then the uniformity low radio luminosities of the neutron stars would require that their jets all lie in the plane of the sky. Finally, if both the X-ray and radio emission in the low-hard state are produced in jets by the same electron population, then the dispersion may be explained by some property of the particle-accelerating shocks in the jets, such as their radial distances from the central sources (e.g., Markoff et al. 2001, 2003). Evaluating this hypothesis would require further modeling of the radiative properties of jets, particularly the effect of inverse-Compton and synchrotron self-Compton emission (Heinz 2004; S. Markoff et al. 2005, in preparation).

Alternatively, the jets may tend to be weaker from neutron star systems because of their physical differences with black holes. First, neutron stars have a hard surface that must arrest the accretion flow (e.g., Popham & Sunyaev 2001), which could alter the structure of a jet or produce photons that cool the electrons in the jet. Again, this hypothesis could be problematic, because the X-ray properties of the black hole and neutron star systems are so similar. Second, black holes can in principle spin much faster than neutron stars, which could affect the amount of energy available to the jet (e.g., Blandford & Payne 1982; Wilson & Colbert 1995; Meier 2001). This hypothesis may be testable, if it can be established that the millisecond quasi-periodic oscillations in the X-ray fluxes from LMXBs occur with general relativistic orbital frequencies (e.g., Stella & Vietri 1999; van der Klis 2005).

4. CONCLUSIONS

We have obtained upper limits on the radio emission from three neutron star LMXBs, concurrent with X-ray observations that demonstrated that they were in hard X-ray states. We have compared these upper limits to the radio luminosities of several black holes in very similar hard states and found that the neutron star systems are as faint as or fainter than the black hole candidates with the lowest observed radio luminosity, GRS 1758—258. The difference in radio luminosity can partly be attributed to the lower masses of the neutron star systems, which on theoretical and observational grounds is expected to decrease as $M^{-0.8}$. However, there still remains a factor of 30 scatter in the radio luminosities of black hole and neutron star X-ray binaries, particularly at X-ray luminosities of a few percent Eddington. We find no obvious differences among the X-ray timing and spectral properties to explain this dispersion.

Two future observations could help resolve why there is such a large dispersion in the radio luminosities of black hole X-ray binaries and why neutron stars tend to fall on or below the faint end of this dispersion. First, it is important to either detect, or place much stricter upper limits on, the radio luminosities of neutron star LMXBs in the X-ray hard state. This would help resolve whether there is indeed a physical difference that causes the relative faintness of neutron star LMXBs or whether the three sources we observe just happen to fall on the low end of a dispersion in radio luminosity. Second, radio observations of the fainter radio sources, i.e., GRS 1758—298 and the neutron star LMXBs, at lower X-ray luminosities could reveal whether they are indeed quenched near $L_{\text{edd}} \sim 0.01$ or whether another parameter is needed to explain the radio luminosity of X-ray binaries in hard states.

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REFERENCES

Dhawan, V., Mirabel, I. F., & Rodriguez, L. F. 2000, ApJ, 543, 373
Di Salvo, T., Done, C., Zycki, P. T., Burderi, L., & Robba, N. R. 2001, ApJ, 547, 1024
Done, C., & Gierliński, M. 2003, MNRAS, 342, 1041
Fabian, A. C., Rees, M. J., Stella, L., & White, N. E. 1989, MNRAS, 238, 729
Falcke, H., König, E., & Markoff, S. 2004, A&A, 414, 895
Fender, R. P. 2005, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), preprint (astro-ph/0303339)
Fender, R. P., Belloni, T. M., & Gallo, E. 2004b, MNRAS, 355, 1105
Fender, R. P., Garrington, S. T., McKay, D. J., Muxlow, T. W. B., Pooley, G. G., Spencer, R. E., Stirling, A. M., & Wiltman, E. B. 1999, MNRAS, 304, 865
Fender, R. P., Hjellming, R. M., Tiuans, R. J. P., Pooley, G. G., Deane, J. R., Ogley, R. N., & Spencer, R. E. 2001, MNRAS, 322, L23
Fender, R. P., & Kuulkers, E. 2001, MNRAS, 324, 923
Fender, R., Wu, K., Johnston, H., Tzioumis, T., Jonker, P., Spencer, R., & van der Klis, M. 2004a, Nature, 427, 222
Fomalont, E. B., Geldzahler, B. J., & Bradshaw, C. F. 2001, ApJ, 553, L27
Gallo, E., Fender, R. P., & Pooley, G. G. 2003, MNRAS, 344, 60
Grindlay, J. E., et al. 1980, ApJ, 240, L121
Guainazzi, M., Parmar, A. N., Segreto, A., Stella, L., Dal Fiume, D., & Oosterbroek, T. 1998, A&A, 339, 502
Han, X., & Hjellming, R. M. 1992, ApJ, 400, 304
Hartmann, L., & Kenyon, S. J. 1996, ARA&A, 34, 207
Heinz, S. 2004, MNRAS, 355, 835
Heinz, S., & Merloni, A. 2004, MNRAS, 355, L1
