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## CORRELATIONS IN QUASI-PERIODIC OSCILLATION AND NOISE FREQUENCIES AMONG NEUTRON STAR AND BLACK HOLE X-RAY BINARIES

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### ABSTRACT

We study systematically the  $\simeq 0.1$ –1200 Hz quasi-periodic oscillations (QPOs) and broad noise components observed in the power spectra of nonpulsing neutron star and black hole low-mass X-ray binaries. We show that among these components we can identify two, occurring over a wide range of source types and luminosities, whose frequencies follow a tight correlation. The variability components involved in this correlation include neutron star kilohertz QPOs and horizontal-branch oscillations, as well as black hole QPOs and noise components. Our results suggest that the same types of variability may occur in both neutron star and black hole systems over 3 orders of magnitude in frequency and with coherences that vary widely but systematically. Confirmation of this hypothesis will strongly constrain theoretical models of these phenomena and provide additional clues to understanding their nature.

*Subject headings:* accretion, accretion disks — black hole physics — stars: neutron — stars: oscillations — X-rays: stars

### 1. INTRODUCTION

Fast quasi-periodic oscillations (QPOs) in the X-ray brightness of neutron star and black hole X-ray binaries provide a useful probe into the inner accretion flows around such compact objects. Since the original discovery of  $\simeq 20$ –50 Hz QPOs in the luminous neutron star binary GX 5–1 (van der Klis et al. 1985), a variety of additional QPOs as well as broad noise components have been observed with properties that depend on the spectral state of the sources (see van der Klis 1995, 1998 for reviews).

The Z sources, which are luminous neutron star low-mass X-ray binaries (Hasinger & van der Klis 1989), typically show four distinct types of QPOs. In current nomenclature, these are the  $\simeq 5$ –20 Hz normal branch oscillation (NBO), the  $\simeq 15$ –60 Hz horizontal-branch oscillation (HBO; see van der Klis 1989 for a review of these low-frequency QPOs), and the  $\simeq 200$ –1200 Hz kilohertz QPOs, which typically occur in pairs (van der Klis et al. 1996). The atoll sources, which are less luminous neutron star low-mass X-ray binaries, typically show  $\sim 500$ –1250 Hz kilohertz QPOs that occur in pairs (Strohmayer et al. 1996), as well as  $\sim 20$ –60 Hz QPOs and broad noise components that have been identified as possibly similar to horizontal-branch oscillations (see, e.g., Hasinger & van der Klis 1989; Homan et al. 1998). All of these QPOs have centroid frequencies that increase with inferred mass accretion rate. In several atoll sources, nearly coherent  $\simeq 300$ –600 Hz oscillations have also been detected during thermonuclear type I X-ray bursts (see, e.g., Strohmayer et al. 1996).

The phenomenology of QPOs in black hole X-ray binaries has not so far been developed to the same extent. Several low-frequency ( $\sim 10^{-1}$  to 10 Hz) QPOs have been detected with frequencies that depend on inferred mass accretion rate (see, e.g., Chen, Swank, & Taam 1997; Morgan, Remillard, & Greiner 1997), as well as three cases of QPOs with higher frequencies, two of which may or may not be

constant ( $\simeq 67$  Hz in GRS 1915+105: Morgan, et al. 1997;  $\simeq 300$  Hz in GRO 1655–40: Remillard et al. 1999b;  $\sim 160$ –220 Hz in XTE J1550–564: Remillard et al. 1999a). Broad noise components are also prominent in the power-density spectra of black hole X-ray binaries and show many similarities with those of neutron star sources (van der Klis 1994a, 1994b; Wijnands & van der Klis 1999).

A large variety of theoretical models have been proposed for the different QPOs in neutron star and black hole systems. The rms amplitudes of almost all QPOs increase with increasing photon energy up to  $\simeq 10$ –30 keV, and their frequencies usually depend strongly on the mass accretion rate (see, however, Jonker, van der Klis, & Wijnands 1999). For these and other reasons, such QPOs are thought to originate close to the compact objects, and their frequencies have been identified with various characteristic frequencies in the inner accretion flows. For example, theoretical models attribute some of the observed QPOs to Keplerian orbital frequencies in the disk (e.g., Alpar et al. 1992; Miller, Lamb, & Psaltis 1998), to the beat of such frequencies with the stellar spin (e.g., Alpar & Shaham 1985; Lamb et al. 1985; Miller et al. 1998), to radiation-hydrodynamic (Fortner, Lamb, & Miller 1989; Klein et al. 1996) or oscillatory disk and stellar modes (e.g., Nowak & Wagoner 1991; Bildsten & Cutler 1995; Kanetake, Takauti, & Fukue 1995; Alpar & Yilmaz 1998; Titarchuk, Lapidus, & Muslimov 1998), to general relativistic effects (Ipser 1996; Stella & Vietri 1998b, 1999), and so on. Some of these models depend explicitly on the existence of a hard surface or a large-scale magnetic field and therefore are valid only for QPOs in neutron star systems, whereas others are applicable only to black hole systems or to both.

The detection of several QPOs at the same time in a single source provides multiple probes to the inner accretion flow around the compact object. Such a simultaneous detection is often attributed to actions of distinct mechanisms affecting the X-ray brightness of the source simulta-

neously in different ways, whereas in other models all QPOs correspond to different modes of the same fundamental mechanism (e.g., Titarchuk & Muslimov 1997). When several types of QPO are observed in the X-ray brightness of a system simultaneously, their frequencies, which commonly increase with mass accretion rate, are often tightly correlated (see, e.g., van der Klis et al. 1996; Ford & van der Klis 1998; Psaltis et al. 1998, 1999). In some cases, these correlations appear to depend only weakly on the other properties of the sources. For example, the frequencies of the upper and lower kilohertz QPOs (hereafter kHz QPOs), as well as the frequencies of the upper kHz QPO and the HBO, are consistent with following very similar relations in all Z sources (Psaltis et al. 1998, 1999).

Here we study the systematics of QPOs and peaked broad noise components observed in nonpulsing neutron star and black hole low-mass X-ray binaries. We find tight correlations among them. In particular, we find an indication that two types of variability, showing up in some systems as an HBO and a kHz QPO, may occur, at widely different coherences and over a wide range of frequencies, in both neutron star and black hole systems. We caution, however, that the striking correlations we report here might be an artifact produced by the accidental line-up of multiple, independent correlations. If future observation confirm our results, this will strongly constrain theoretical models of QPOs in neutron star and black hole systems.

## 2. IDENTIFICATION OF QPOS IN NEUTRON STAR AND BLACK HOLE SYSTEMS

Quasi-periodic oscillations and peaked broad noise components have been detected in both neutron star and black hole systems. In this section we discuss observations of such systems in which at least one QPO has been detected together with one more peaked variability component and attempt to identify the various power-spectral components with QPOs and noise components in other sources, primarily on the basis of their frequencies. We restrict our study to phenomena with frequencies  $\geq 0.1$  Hz to avoid the very complicated timing behavior of the microquasars at these low frequencies (see, e.g., Remillard et al. 1999b). We do not consider in our study the peculiar  $\approx 1$  Hz QPO in the dipper 4U 1323–62 (Jonker et al. 1999), which has properties very different from all other QPOs in nonpulsing neutron star sources. We will also exclude from our study QPOs observed in accretion-powered pulsars, most of which are thought to be strongly magnetic ( $\sim 10^{12}$  G) and hence to have different inner accretion flow properties than the nonpulsing neutron star sources. The QPO and noise properties in the only known millisecond accretion powered pulsar, SAX J1808.4–3658, have been compared to those of the nonpulsing sources by Wijnands & van der Klis (1999) and are also excluded in the present study.

### 2.1. Neutron Star Sources

*Z sources.*—In the power spectra of Z sources, the identification of QPOs and noise components is unambiguous. For example, four distinct QPO peaks that are not harmonically related are often observed simultaneously in Sco X-1 (van der Klis et al. 1996). In this as well as the other Z sources, these QPO peaks are identified as NBOs, HBOs, or kHz QPOs, based on their frequencies and occurrence in different spectral branches. Figure 1 shows a power-density

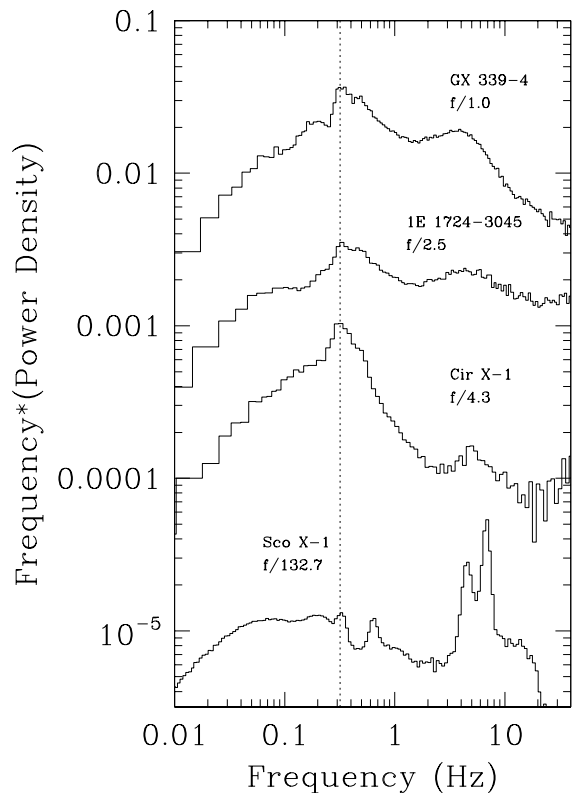


FIG. 1.—Examples of power spectra of low-mass X-ray binaries, in which more than one QPO or broadband noise components are detected. The individual power spectra were shifted along the vertical axis for clarity and along the horizontal axis, by the amounts displayed, for the low-frequency QPOs to be aligned (dotted line). The sample of sources includes a black hole candidate (GX 339–4; Méndez et al. 1998), an X-ray burster (1E 1724–3045; Olive et al. 1998), a luminous neutron star (Cir X-1; Shirey 1998), and a Z source (Sco X-1). The continuum in the power spectrum of Sco X-1 at high frequencies is affected by instrumental effects.

spectrum of Sco X-1 (based on the data described in van der Klis et al. 1997) in which an HBO and its harmonic as well as a lower and an upper kHz QPO are evident (notice that frequency shifts were applied to the power spectra shown in Fig. 1). In the five Z sources in which HBOs have been observed simultaneously with two kHz QPOs, the frequency of the HBO is tightly correlated to the frequency of the upper kHz QPO (Wijnands et al. 1998a, 1998b; Homan et al. 1998; see also Stella & Vietri 1998a; Psaltis et al. 1999). At the same time, the frequencies of the lower and upper kHz QPOs are also tightly correlated in a way that is well described by a simple empirical power-law relation (Psaltis et al. 1998). Both correlations are consistent with their being very similar in all Z sources. In Sco X-1, which is the only Z source that simultaneously shows NBOs and kHz QPOs, the frequencies of these QPOs are also tightly correlated (van der Klis et al. 1997). Here in discussing the QPOs detected in Z sources, we shall use *RXTE* data that have been previously published (see Table 1).

The upper kHz QPO, HBO, and NBO frequencies detected in the above Z sources are plotted in Figure 2 against the lower kHz QPO frequency (*red symbols*). The HBO frequency  $\nu_{\text{HBO}}$  appears to be well correlated to the frequency  $\nu_1$  of the lower kHz QPO, as expected given their previously known common dependence on the frequency of the upper kHz QPO. When  $\nu_1 \lesssim 550$  Hz, the data points for

TABLE 1  
QPO OBSERVATIONS<sup>a</sup>

Source	$\nu_1$ (Hz) <sup>b</sup>	$\nu_2$ (Hz) <sup>c</sup>	$\nu$ (Hz) <sup>d</sup>	References
Cyg X-2 .....	530	730–1010	36–57	1
GX 17+2 .....	480–780	640–1090	25–61	2
Sco X-1 .....	550–860	870–1080	41–48	3
GX 5–1 .....	210–660	500–890	17–51	4
GX 340+0 .....	250–500	560–820	22–45	5
4U 1728–34 .....	600–790	440–1120	10–42	6, 7
KS 1731–26 .....	900	1170	26	8, 9
4U 1636–536 .....	900–920	1150–1190	...	10, 11, 12
4U 0614+091 .....	480–800	820–1150	...	13, 14, 15
4U 1820–30 .....	800	1066	70	16
4U 1735–44 .....	900	1150	20–67	1
4U 1608–52 .....	470–870	800–1090	10–50	17, 18, 19
Cir X-1 .....	20–100	...	1–10	20, 21
1E 1724–3045 .....	10	...	1	22
GS 1826–36 .....	6	...	1	23
GX 339–4 .....	3	...	0.3	24, 25
GRO J0422+32 .....	3	...	0.23	26
XTE 1550–564 .....	2–220	...	0.08–13	27, 28
GRS 1915+105 .....	7	...	0.7	29, 30, 31
GRO 1655–40 .....	300	...	10	32

<sup>a</sup> Observations in which one QPO was detected simultaneously with at least one more variability component, either QPO or broadband noise.

<sup>b</sup> Frequency of the lower kHz QPO or the broad band noise component we have tentatively identified as such.

<sup>c</sup> Frequency of the upper kHz QPO.

<sup>d</sup> Frequency of the HBO in Z sources or the QPO in other sources we have tentatively identified as such.

REFERENCES.—(1) Wijnands et al. 1998a; (2) Wijnands et al. 1997a; (3) van der Klis et al. 1997; (4) Wijnands et al. 1998b; (5) Jonker et al. 1998; (6) Strohmayer et al. 1996; (7) Ford & van der Klis 1998; (8) Smith et al. 1997; (9) Wijnands & van der Klis 1997; (10) Zhang et al. 1996; (11) Wijnands et al. 1997b (12) Yu et al. 1997; (13) Ford et al. 1997a; (14) Ford et al. 1997b; (15) Méndez et al. 1997; (16) Smale et al. 1997; (17) Berger et al. 1996; (18) Méndez et al. 1998; (19) Méndez et al. 1999; (20) Shirey et al. 1996; (21) Shirey et al. 1998; (22) Olive et al. 1998; (23) Kuulkers et al. 1999; (24) Nowak et al. 1999; (25) Belloni et al. 1999a; (26) Grove et al. 1998; (27) Cui et al. 1999; (28) Remillard et al. 1999b; (29) Morgan et al. 1997; (30) Markwardt et al. 1999b; (31) Belloni et al. 1999b; (32) Remillard et al. 1999a.

the Z sources are consistent with the empirical relation  $\nu_{\text{HBO}} \simeq (42 \pm 3 \text{ Hz})(\nu_1/500 \text{ Hz})^{0.95 \pm 0.16}$ , in which the normalization constant depends on the peak separation of the kHz QPOs, which is very similar between sources (compare Psaltis et al. 1998, 1999; when  $\nu_1 \gtrsim 550$  Hz,  $\nu_{\text{HBO}}$  increases slower with  $\nu_1$ ). Figure 2 shows this relation (*dashed line*), extrapolated by more than 2 orders of magnitude toward lower frequencies.

*Atoll sources.*—In most atoll sources in which QPOs have been detected, kHz QPOs can be easily identified when at high frequencies because of these high frequencies and their common occurrence in pairs. However, when their frequencies become low, the coherence of the QPO decreases and confusion becomes more likely, especially with other  $\sim 100$  Hz components of the power spectra (Ford & van der Klis 1998). As in the case of the Z sources, the frequencies of simultaneously detected lower and upper kHz QPOs are tightly correlated. They are consistent with following empirical power-law relations similar to the one followed by the Z sources (Psaltis et al. 1998). Here we shall use kHz QPO data for atoll sources that have been obtained by *RXTE* and have been previously published (see Table 1). Figure 2 shows the upper kHz QPO frequencies detected in atoll sources plotted against the lower kHz QPO frequencies (*blue symbols* near the top of the graph).

Single QPOs at frequencies  $\simeq 20$ –70 Hz have occasionally been detected in some atoll sources simultaneously with the kHz QPOs; here we use the *RXTE* data on 4U 1820–30 (Smale, Zhang, & White 1997), KS 1731–26 (Wijnands, & van der Klis 1997), 4U 1608–52 (Méndez et al. 1999), 4U 1728–34 (Ford & van der Klis 1998), and 4U 1702–429 (Markwardt, Strohmayer, & Swank 1999a); see also Table 1. Given their low frequencies, it has been suggested that these QPOs can be identified with the HBO. In 4U 1728–34, these QPOs have frequencies that increase with those of the kHz QPOs; during some of the observations, the correlation between the  $\simeq 20$ –70 Hz QPO and upper kHz QPO frequencies was similar to the one followed by the Z sources, whereas during one other observation the HBO frequencies were systematically lower by a factor of  $\simeq 2$  (Ford & van der Klis 1998). In 4U 1735–44, two low-frequency QPOs have been simultaneously detected with the kHz QPOs (Wijnands et al. 1998a), reminiscent of the simultaneous detection of HBOs and NBOs in the Z sources. In 4U 1702–429, multiple  $\sim 10$ –100 Hz QPOs are occasionally detected, but not simultaneously with kHz QPOs (Markwardt et al. 1999a). Finally, in 4U 1820–30, a  $\simeq 7$  Hz QPO is occasionally detected, but not simultaneously with kHz QPOs (Wijnands, van der Klis, & Rijkhorst 1999).

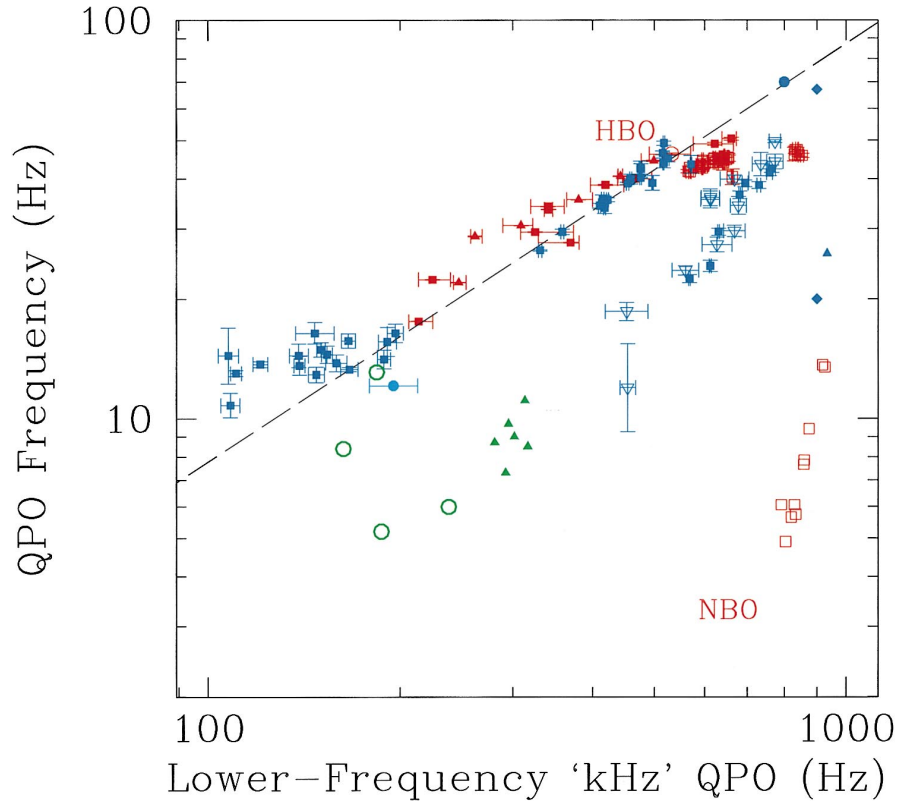
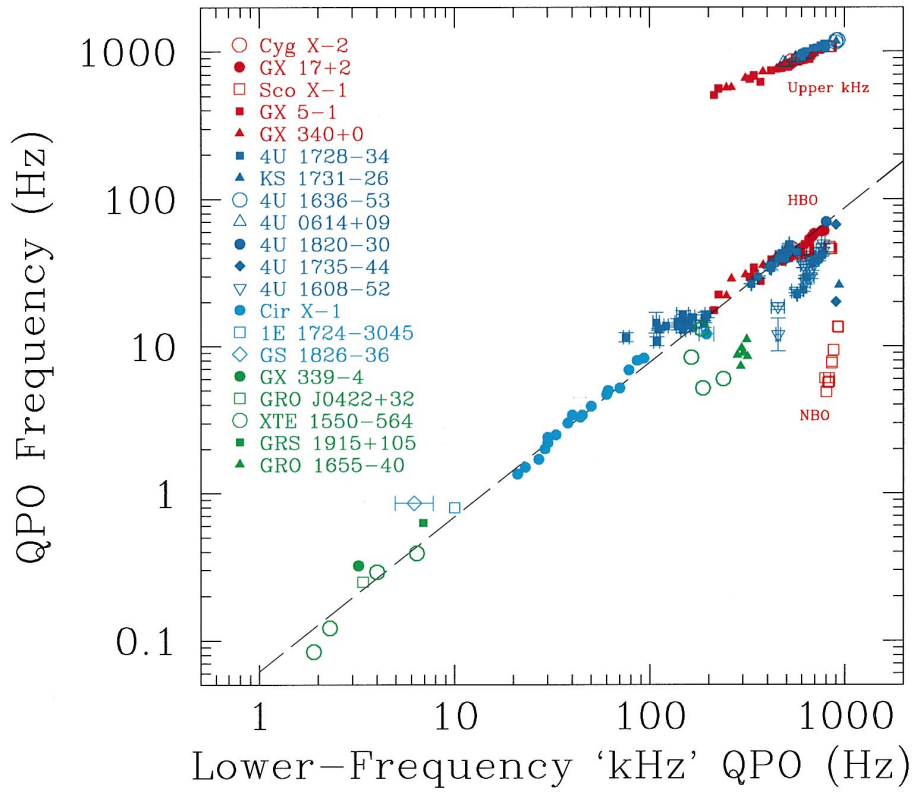


FIG. 2.—*Top Panel*: Correlations between frequencies of QPO and noise components in low-mass X-ray binaries, including several Z sources (*red symbols*), atoll sources (*blue symbols*), and other neutron star sources (*cyan symbols*) and black hole candidates (*green symbols*). The dashed line represents the correlation between the HBO and lower kHz QPO frequencies in Z sources, when the latter are between 200–550 Hz, extrapolated by  $\geq 2$  orders of magnitude toward lower frequencies. When not shown, the error bars are typically similar to the size of the symbols. The Cir X-1 point with the error bar is the *EXOSAT* detection reported in Tennant (1987). For some data points of 4U 1728–34, the frequency of the lower kHz QPO, which was not always detected, has been estimated by subtracting the assumed constant peak separation of 363 Hz from the frequency of the upper kHz QPO that has been detected (see Ford & van der Klis 1998). *Bottom Panel*: Detail of the top panel showing the correlation of the HBO and NBO frequencies with the lower kHz QPO frequency at high frequencies.

Figure 2 shows the frequencies of the  $\approx 20$ –70 Hz QPOs observed in atoll sources plotted against the frequencies of the simultaneously detected lower kHz QPOs (*blue symbols* in the middle of the graph<sup>1</sup>). The QPO in 4U 1820–30, the higher of the two low-frequency QPOs in 4U 1735–44, and most of the data points of 4U 1728–34 follow a trend very similar to the correlation between the HBO and lower kHz QPO frequencies observed in Z sources. On the other hand, some of the data points of 4U 1728–34 as well as the data points of 4U 1608–52 follow a similar trend, but at systematically lower frequencies (see also Ford & van der Klis 1998). Finally, the QPO in KS 1731–26 and the lower of the two low-frequency QPOs in 4U 1735–44 do not follow either of the above two correlations, showing a hint of similarity with the NBO observed in Sco X-1.

*Other neutron star sources.*—Cir X-1 is a probable neutron star low-mass X-ray binary (Tennant, Fabian, & Shafer 1986) that was initially labeled as a black hole candidate (Toor 1977; Samimi et al. 1979) and shows similarities to black holes as well as to both Z and atoll sources (Oosterbroek et al. 1995; Shirey 1998). At intermediate luminosities, one QPO is detected in this source at frequencies varying between  $\approx 1$  and 10 Hz, together with a broader power-spectral component with a centroid frequency varying between  $\approx 10$  and 100 Hz (Shirey et al. 1996, 1998; Shirey 1998; see Fig. 1; see also Tennant 1987 for a possible detection of a  $\approx 200$  Hz broad component simultaneously with a  $\approx 12$  Hz QPO using *EXOSAT*).

The dependence on count rate of the frequencies of the narrow  $\approx 1$ –10 Hz QPO and of the broad  $\approx 10$ –100 Hz component as well as their frequency ratio are similar to those of the HBO and lower kHz QPO seen in Z sources (Shirey et al. 1996, 1998, 1999; Shirey 1998). Therefore, in spite of the broad component being much less coherent than the lower kHz QPOs seen in other sources, we tentatively identify these two components seen in Cir X-1 with the HBO and the lower kHz QPO seen in Z sources (see also Shirey et al. 1999). Figure 2 shows the frequency of the narrow QPO in Cir X-1, which we have identified with the HBO, plotted against the frequency of the broad noise components, which we have identified with the lower kHz QPO (*cyan symbols*). The data points of Cir X-1 are consistent ( $\chi^2/\text{degrees of freedom} \approx 1$ ) with the relation between the HBO and lower kHz QPO frequencies observed in Z sources and extrapolated toward lower frequencies, strengthening our identification.

A similar combination of a  $\approx 1$  Hz QPO and a  $\approx 5$ –10 Hz broad power-spectral component has also been observed in the X-ray bursters GS 1826–36 (Kuulkers et al. 1999) and 1E 1724–3045 (Olive et al. 1998). Note here that Olive et al. (1998) demonstrated that the power spectrum of 1E 1724–3045 at high ( $\gtrsim 1$  Hz) frequencies is well described by the sum of two zero-centered Lorentzians; here we describe the same power spectra at high frequencies, using instead a power-law continuum and a  $\approx 10$  Hz, broad noise component (see Fig. 1), and plot their frequencies in Figure 2 (*cyan symbols* in the lower left-hand

part of the figure). We again tentatively identify the narrow QPO and broad noise component observed in these two bursters with the HBO and lower kHz QPO of the Z sources as suggested by Figure 2.

## 2.2. Black Hole Sources

Low-mass X-ray binaries with black holes show at some spectral states a narrow  $\approx 0.1$ –10 Hz QPO that is often accompanied with peaks at its harmonics or even at its first subharmonic. The frequency of this QPO shows a strong correlation with count rate (see, e.g., van der Klis 1995 for a review) as well as with the frequency of the break of the power-density spectrum that occurs at lower frequencies (Wijnands & van der Klis 1999). This correlation is very similar between black hole sources and is also similar to the one between the frequencies of the HBO and the spectral break in atoll and Z neutron star sources (Wijnands & van der Klis 1999). Based on these properties, it is therefore tempting to identify the  $\sim 0.1$ –10 Hz QPO observed in black hole sources with the HBO observed in neutron star sources.

No pairs of QPOs with properties similar to those of the neutron star kHz QPOs have ever been observed in any black hole source. Narrow  $\sim 50$ –300 Hz QPOs with frequencies that appear to depend only weakly on count rate have been observed from some of these sources, two of which are the microquasars GRS 1915+105 (Morgan et al. 1997) and GRO 1655–40 (Remillard et al. 1999b). In other sources, the low-frequency QPOs are occasionally accompanied by a  $\approx 1$ –200 Hz broad power-spectral component, similar to those observed in Cir X-1 (see below). Here we discuss some timing properties of black hole candidates for which QPOs have been reported so far and attempt to identify their power-spectral components with similar features seen in neutron star sources. Because we are interested in variability components similar to the neutron star kHz QPOs, we will study only the peaked power-spectral components that occur at frequencies higher than the  $\sim 0.1$ –10 Hz QPOs. Our study, therefore, complements the one of Wijnands & van der Klis (1999), who studied power-spectral components that occur at frequencies lower than these QPOs.

*GX 339–4.*—Optical QPOs have been often observed from this black hole candidate with frequencies  $\approx 0.05$ –0.15 Hz (Motch et al. 1983, 1985; Imamura et al. 1990; Steiman-Cameron et al. 1997). At one incidence, when the source was in its low state, the QPO had a frequency of  $\approx 0.05$  Hz and was detected simultaneously in X-rays with *Ariel 6* (Motch et al. 1983). None of these QPOs was detected simultaneously with another peaked variability component, and hence they cannot be used in the present study.

SIGMA observations of GX 339–4 revealed a 0.8 Hz QPO with a complex, possibly peaked noise component at frequencies  $\approx 5$ –10 Hz, when the source was in the low state (Grebenev et al. 1991, 1993). *Ginga* observations of the same source at the low state gave hints of a  $\approx 0.1$  Hz QPO detected simultaneously with a  $\approx 1$ –2 Hz peaked noise component (Miyamoto et al. 1992). Recent *RXTE* observations of this source at the low state showed a clear  $\approx 0.3$  Hz QPO together with a  $\approx 3$  Hz peaked noise component (Nowak, Wilms, & Dove 1999; Wijnands & van der Klis 1999; Belloni et al. 1999a; see also Fig. 1). Given the striking similarity, after a shift of about 1 decade in

<sup>1</sup> Note that in plotting most of the data points of 4U 1728–34 we have inferred the frequency of the lower kHz QPO, which was not always detected, by subtracting the 363 Hz frequency of the oscillations observed during type I X-ray bursts from this source from the frequency of the detected upper kHz QPO.

frequency, between the power spectra of GX 339–4 observed by *RXTE* and the power spectra of the bursters 1E 1724–3045, GS 1826–36, and of Cir X-1 (see Fig. 1), as well as the position of the data points that correspond to GX 339–4 in Figure 2, we tentatively identify these neutron star and black hole power spectral components as being similar in nature. In Figure 2 we do not include the data points from the *SIGMA* and *Ginga* observations because the exact frequencies of the noise components were not reported for them. However, the power spectra of those two observations appear also consistent with the general trend shown in Figure 2.

*Ginga* observations of GX 339–4 in the very high state showed a  $\approx 5.8$ – $7.4$  Hz QPO simultaneously with an often peaked noise component with a photon-energy-dependent frequency of  $\approx 1$ – $2$  Hz (Miyamoto et al. 1991; Belloni et al. 1997; Rutledge et al. 1999). This noise component is at frequencies lower than those of the QPO, and the frequencies of the two components follow the correlation between the frequencies of the break in the power spectrum and the QPO found by Wijnands & van der Klis (1999); we therefore also identify them as such. No other QPO or peaked noise component was detected at this spectral state.

*Cyg X-1*.—Various detections of rather broad QPOs from Cyg X-1 have been reported in the literature. *SIGMA* observations revealed such a QPO at frequencies  $\approx 0.05$ – $0.1$  Hz (Vikhlinin et al. 1994), *Ginga* observations revealed a  $\approx 1$ – $10$  Hz broad QPO with spectral properties similar to the narrow QPO seen in GX 339–4 (see Rutledge et al. 1999 and references therein), and *RXTE* observations resulted in the detection of a  $\sim 3$ – $10$  Hz QPO during spectral state transitions (Cui et al. 1997). The correlation between the frequencies of the QPO and the power-spectral break in the *RXTE* observations follow the correlation between the frequencies of the narrow QPOs and power-spectral breaks seen in other black hole and neutron star systems (Wijnands & van der Klis 1999), thereby suggesting that these QPOs are similar in nature. The  $\approx 1$  Hz QPO in the *Ginga* observations reported by Rutledge et al. (1999) is often accompanied by a  $\approx 10$  Hz broad, peaked power-spectral component at higher frequencies that appears to be consistent with the correlations suggested by Figure 2; the frequencies of the latter component have not been reported and, therefore, cannot be used in the present study.

*GRO J0422+32*.—A prominent QPO at a frequency  $\approx 0.2$ – $0.3$  Hz was discovered during the 1992 outburst of this source by *SIGMA* (Vikhlinin et al. 1995), *BATSE* (Kouveliotou, Finger, & Fishman 1992), and *OSSE* (Grove et al. 1998). In the *OSSE* power spectrum a broad noise component at  $\approx 3$  Hz is also evident. Given the striking similarity between this power spectrum and the power spectra of neutron star sources, such as Cir X-1 and 1E 1724–3045 (see, e.g., Olive et al. 1998), and black hole sources, such as GX 339–4, we identify the QPO and broad noise component in all these sources as similar in nature. Figure 2 shows that the frequencies of the QPO and broad noise component in GRO J0422+32 agree well with the correlation between the HBO and lower kHz QPO observed in Z and atoll sources, hence strengthening our identification.

*XTE J1550–564*.—A QPO with a frequency that depends strongly on count rate has been observed from this newly discovered X-ray nova. During the initial phase of the outburst, the QPO frequency increased from  $\approx 0.082$  Hz to

$\approx 13$  Hz (Cui et al. 1999; Remillard et al. 1999a). During the phase after the peak of the outburst, the QPO reappeared at a frequency that drifted from  $\approx 10$  to  $\approx 2.5$  Hz (Remillard et al. 1999a). The QPO frequency was found to vary erratically with the spectral properties and count rate of the source, in a way that was different between the initial phase and the one after the peak of the outburst (Remillard et al. 1999a).

During the initial phase of the outburst, when the source was turning into the low state, the QPO was at a frequency  $\sim 0.08$ – $0.4$  Hz and was accompanied by a broader peaked noise component at frequencies  $\sim 2$ – $7$  Hz (Cui et al. 1999). Figure 2 shows the correlation between the QPO and noise components at this phase of the outburst (*green open circles* at the lower left-hand corner), which agrees with the correlation between the HBO and lower kHz QPO frequencies seen in Z and atoll sources, extrapolated by more than 2 orders of magnitude in frequency.

In both phases of the outburst, when the QPO frequency was  $\geq 5$  Hz, it was sometimes detected simultaneously with another variable-frequency  $\approx 160$ – $220$  Hz QPO (Remillard et al. 1999a). Given the magnitudes and variability of their frequencies as well as the identification of the  $\sim 0.08$ – $13$  Hz QPO with the HBO, we tentatively identify the  $\sim 160$ – $220$  Hz QPO with the lower kHz QPO seen in neutron star sources. Figure 2 shows the correlation between the frequencies of these two QPOs and compares it with those of the other neutron star and black hole sources. The data points that correspond to the initial and decay phase of the outburst lie on different branches in Figure 2, in agreement with the fact that the QPO properties are different between the two phases of the outburst.

*GRS 1915+105*.—A rich phenomenology of QPO properties for this source has emerged from recent *RXTE* observations (see, e.g., Morgan et al. 1997; Trudolyubov, Churazov, & Gilfanov 1999). When the source was in the very bright state (Morgan et al. 1997), a variety of QPOs with frequencies  $\approx 0.001$ – $10$  Hz as well as a  $\approx 67$  Hz QPO were observed. These QPOs did not seem to be related to any of the QPOs observed in other neutron star and black hole sources and may be related to the activity of GRS 1915+105 as a microquasar. We therefore do not consider these QPOs in the present study. On the other hand, in its hard state the source showed a  $\approx 0.5$ – $10$  Hz QPO with a frequency that depended strongly on count rate (Morgan et al. 1997; Chen, Swank, & Taam 1997; Markwardt, Swank, & Taam 1999b; Belloni et al. 1999a). When the frequency of this QPO was  $\approx 0.7$  Hz, an excess of the power-spectral density at  $\approx 7$  Hz was also evident (Belloni et al. 1999a). As before, we identify the narrow QPO with the HBO and the broad power-spectral excess with the lower kHz QPO seen in atoll and Z sources. Figure 2 shows that the frequencies of these two components are consistent with the correlation between the HBO and lower kHz QPO frequencies seen in neutron star sources.

*GRO 1655–40*.—A  $\approx 300$  Hz QPO has been detected from this source, always accompanied by a QPO at  $\approx 10$  Hz (Remillard et al. 1999b). Identifying the  $\approx 300$  Hz QPO with the lower kHz QPO seen in atoll and Z sources, suggests that the  $\approx 10$  Hz QPO is similar to the  $\approx 10$ – $50$  Hz QPO seen in 4U 1728–34 and in 4U 1608–52 (see Fig. 2). Moreover, this identification suggests that the two QPOs in GRO 1655–40 discussed above are similar to the  $\sim 0.08$ – $13$  Hz and  $\sim 160$ – $220$  Hz QPOs seen in XTE 1550–564

during the decay phase of its outburst. However, we stress here that this identification is very tentative. A number of additional QPOs and broad peaks are seen in GRO 1655–40, which are not harmonically related to the ones discussed above (Remillard et al. 1999a). A careful analysis of the timing properties of this source is needed, in view of the hypothesis put forward here, for a more detailed comparison of this with other sources.

*Other black hole sources.*—A number of additional black hole sources and black hole candidate sources show similar  $\approx 0.1$ –10 Hz QPOs; for example, GS 1124–683 (Miyamoto et al. 1994; Tanaka & Lewin 1995; Takizawa et al. 1997; Belloni et al. 1997; Rutledge et al. 1999), LMC X-1 (Ebisawa, Mitsuda, & Inoue 1989), GRO J1719–24 (van der Hooft et al. 1996), 1E 1740.7–2942 (Smith et al. 1997), GRS 1758–258 (Smith et al. 1997), and GS 2023+338 (Oosterbroek et al. 1997). These QPOs are often accompanied by a power-spectral break at lower frequencies. In some cases (e.g., GS 1124–683 and GS 2023+338), broad components at frequencies higher than the frequency of the QPO are also seen; however, the properties and frequencies of these features have not been reported and therefore cannot be used in the present study.

### 2.3. Correlations between QPOs and Noise Frequencies

Figure 2 shows the frequencies of the various types of variability components detected in Z and atoll sources, as well as in several other neutron star systems and in a number of black hole binaries, as a function of either the frequency of the lower kHz QPO or the broad noise component that we tentatively identify as such. The previously discussed correlations (Psaltis et al. 1998, 1999) between the frequencies of the upper and lower kHz QPOs in Z and atoll sources as well as between the frequencies of the HBO and the kHz QPOs in Z sources are evident. Moreover, Figure 2 shows that remarkably tight correlations exist between these frequencies in the other low-mass X-ray binaries as well.

In particular, there is one correlation extending over nearly 3 orders of magnitude in frequency that appears to depend very little on the properties of the compact objects and apparently encompasses the HBO and lower kHz QPO observed in Z and atoll sources, the  $\sim 1$ –10 Hz QPO and  $\sim 10$ –100 Hz noise component in Cir X-1 as well as the  $\approx 0.1$ –1 Hz QPO and  $\approx 1$ –10 Hz noise component in other neutron star and black hole systems. This relation is consistent with the data points of 4U 1820–30, 4U 1735–44, Cir X-1, 1E 1724–3045, GRO 0422+32, and XTE J1550–564 but statistically only marginally consistent with the data points of 4U 1728–34, GS 1826–36, GRS 1915+105, and GX 339–4. The latter does not necessarily imply that the relation is not consistent with the true frequencies of these components in the last four sources, as the low coherence of the broad noise components ( $\Delta\nu/\nu$  is of order unity in these sources) implies that systematic effects such as continuum subtraction, which we have not taken into account in our error estimates, dominate the uncertainties in the measurement of the centroid frequencies.

In addition to the HBO and the upper kHz QPO, the NBO frequencies of Sco X-1 are also correlated to the frequency of the lower kHz QPO (van der Klis et al. 1997). Further structure is visible in Figure 2 between the HBO and NBO correlations, consisting mostly of QPOs observed in 4U 1728–34, 4U 1608–52, XTE J1550–564, and

GRO 1655–40. These QPOs may represent the sub-harmonics of the HBO or demonstrate the existence of a different type of QPO (see Ford & van der Klis 1998 for a discussion). Of course, we could always hypothesize that there are two types of lower kHz QPOs. Note here that the very flat correlation between the HBO and kHz QPO frequencies seen in Sco X-1 (see Psaltis et al. 1999) may be due to a transition from one branch to the other, as Figure 2 suggests. Figure 2 also suggests some other QPO identifications that have not been previously made.

### 3. DISCUSSION

We studied the various types of QPOs and broad noise components observed in neutron star and black hole X-ray binaries. We found that among the frequencies of these various types of variability components it is possible to find two that are tightly correlated in a way that seems to depend only weakly on the other properties of the sources, such as the mass, magnetic field, or possibly the presence of a hard surface in the compact object. Such correlations suggest that similar physical mechanisms may be responsible for some QPOs and noise components, which can be found over wide ranges of frequencies and coherences, in Z, atoll, and possibly even black hole sources.

Figure 2 shows these correlations and includes observations of neutron star and black hole sources in which a QPO (with frequency  $\geq 0.1$  Hz) has been detected simultaneously with at least one more variability component, either broadband noise or QPO, for which we could obtain reliable frequency estimates. There exist other observations of the same and related sources, where no variability component, or only one, of the types discussed here is detected. It is not clear what determines the number and type of detectable variability components in a given source and at a given spectral state. However, it appears that when the variability components we have identified above are detected in a source, their frequencies follow one of a small number of correlations shown in Figure 2.

In particular, we find indications that the low-frequency ( $\approx 0.1$ –100 Hz) QPOs observed in some atoll sources, in Cir X-1 and other neutron star sources, and possibly in some black hole sources may be the same phenomenon as the HBO observed in Z sources. Moreover, we suggest that the broad noise components at frequencies  $\approx 1$ –100 Hz observed in Cir X-1, some neutron star sources, and possibly in some black hole sources may be the same phenomenon as the lower kHz QPOs observed in Z and atoll sources.

We caution here that the identification of broad noise components in some sources with narrow QPOs in others relies so far entirely on the tight correlations between their frequencies shown in Figure 2. No transition from a narrow QPO peak to a broad noise component has been observed so far in a single source. Note, however, that the relative widths of the variability components identified here as the lower kHz QPO increase systematically with decreasing centroid frequency when different sources are compared:  $\Delta\nu/\nu \approx 0.01$ –0.5 in the  $\approx 200$ –800 Hz lower kHz QPOs in Z and atoll sources,  $\Delta\nu/\nu \approx 0.2$ –1 in the  $\approx 20$ –100 Hz broad noise component in Cir X-1, and  $\Delta\nu/\nu \approx 1$ –3 in the  $\approx 1$ –10 Hz broad noise components in the black hole sources. In Sco X-1, the relative width of the lower kHz QPO also increases systematically with decreasing QPO frequency in a way that is consistent with the decrease of coherence



between sources discussed above. Detection of a transition from a narrow kHz QPO to a broad, lower frequency noise component would give more weight to the conjecture put forward here. On the other hand, detection of one or two narrow kHz QPOs together with the broadband noise components at lower frequencies that follows the tight correlation shown in Figure 2 will reject our hypothesis.

If confirmed, the detection of HBOs and lower kHz QPOs over a wide range of frequencies in neutron star systems will pose strong constraints on theoretical models of their nature. A successful model must be able to explain the presence of the same type of variability in sources with significantly different mass accretion rates, with values for the frequencies and coherences that span over 2 orders of magnitude. Figure 2 gives a hint that HBOs and lower kHz QPOs may have been detected in some black hole candidates. Detailed analysis of the properties of these QPOs and further comparison between the power spectra of neutron star and black hole sources are required to test such a conjecture. Confirmation of the identification of the same type of QPO in both neutron star and black hole sources will

challenge models of such QPOs that depend on the existence of a hard surface or of an ordered magnetic field around the compact object.

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