Quasi-periodic oscillations and noise in neutron star and black-hole X-ray binaries

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ABSTRACT

Before the launch of the Rossi X-ray Timing Explorer (RXTE) satellite, the differences in the rapid X-ray variability between the two main types of neutron star binaries (i.e., the Z and atoll sources) could be explained by invoking different mass accretion rates and magnetic field strengths. However, the results obtained with RXTE now show that these systems are more similar than previously thought and although differences in mass accretion rate are still likely, the differences in the magnetic field strength have become questionable. The great similarities between the neutron star systems and the black-hole candidates at low mass accretion rates also point towards a similar origin of their timing phenomena indicating that the presence or absence of a solid surface, a magnetic field, or an event horizon do not play a significant role in the production mechanisms for the rapid X-ray variability.

NEUTRON STAR SYSTEMS: THE PRE-RXTE VIEW

Before the start of the RXTE mission, the neutron star (NS) low-mass X-ray binaries (LMXBs) had been intensively studied with previous X-ray instruments (i.e., EXOSAT and Ginga). The introduction of X-ray color-color diagrams (CDs; e.g., Hasinger & van der Klis 1989) proved to be extremely useful for the study of the correlations between the changes in X-ray spectrum and X-ray timing behavior of these systems. On the basis of this correlated behavior, they were classified into the Z sources and the atoll sources (Hasinger & van der Klis 1989). The Z sources trace out a Z shaped track in the CD (see Fig. 1) with the branches labeled, from top to bottom, the horizontal branch (HB), the normal branch (NB), and the flaring branch (FB). The power spectra show (Fig. 1) on the horizontal branch, strong band-limited noise (called low frequency noise or LFN) which cuts off below several Hertz, simultaneous with 15–60 Hz quasi-periodic oscillations (QPOs), which are called horizontal branch oscillations (HBOs). On the normal branch these QPOs can still be seen, often simultaneous with other 5–7 Hz QPOs, which are called normal branch oscillations (NBOs). The NBOs smoothly merge with the 7–20 Hz QPOs seen on the flaring branch, the flaring branch oscillations (FBOs). On all branches also two other noise components are found, one at very low frequencies (the very low frequency noise or VLFN), following a power law, and one at frequencies above 10 Hz (the high frequency noise or HFN), which cuts off between 50 and 100 Hz. Motion of the source along the Z track is thought (e.g., Hasinger & van der Klis 1989) to be due to variations in the mass accretion rate ($\dot{M}$), which is lowest on the horizontal branch, increasing on the normal branch onto the flaring branch, where it reaches the Eddington limit $\dot{M}$ ($\dot{M}_{\text{Edd}}$). The atoll sources trace out a curved branch in the CD (Fig. 1), which can be divided in the island state (IS) and the banana branch (sub-divided into the lower banana [LB] and upper banana [UB] branch). The power spectrum in the island state (Fig. 1) is dominated by very strong (sometimes more than 20% rms amplitude) band-limited noise, superimposed on which are broad bumps (sometimes called QPOs). The band-limited noise is also called HFN but it is at much lower frequencies then the HFN observed in the Z sources and most likely they are not related. In the power spectrum on the banana branch only a weak (several percent rms amplitude) power law noise

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component at low frequencies is observed (the VLFN), with sometimes another weak (again several percent rms) noise component at higher frequencies (the HFN) which cuts off around 10 Hz. For atoll sources $\dot{M}$ is thought (e.g., Hasinger & van der Klis 1989) to be lowest in the IS, and increasing on the banana branch from the lower banana onto the upper banana branch.

Prompted by the Z-atoll source phenomenology and the QPO models (e.g., Alpar & Shaham 1985; Lamb et al. 1985; Fortner et al. 1989; Alpar et al. 1992) it was proposed (e.g., Hasinger & van der Klis 1989) that the differences between the Z and the atoll sources could be explained by assuming that the Z sources can reach higher mass accretion rates than the atoll sources and that the neutron stars in the Z sources have a higher magnetic field strength $B$ than the neutron stars in the atoll sources. The $\dot{M}$ difference could explain the luminosity difference and the presence of the N/FBO in the Z sources; the $B$ difference could explain the presence of the HBO in the Z sources (see van der Klis 1995 and references therein). This hypothesis predicted that NBO-like QPOs could be present in the atoll source if they would reach $M_{\text{Edd}}$, but because of their lower $B$, HBO-like QPOs were not expected in the atoll sources, or at least with a much weaker amplitude than the HBOs observed in the Z sources (van der Klis 1995; however, it is possible, although not likely, that a connection exist between $\dot{M}$ and $B$ in such a way that HBO-like QPOs might be possible in the atoll sources at comparable strength as the HBOs in the Z sources). Below I will demonstrate that both predictions were proven to be incorrect.

**NEUTRON STAR SYSTEMS: THE RXTE-ERA**

The RXTE satellite fulfilled its promise and produced (and still is producing) a wealth of new data on neutron star X-ray binaries. Important discoveries such as those of the first accretion-driven millisecond
Fig. 2. The 63 Hz QPO found in the atoll source Serpens X-1 (a) and the 7 Hz QPO found in the atoll source 4U 1820–30 (b; Wijnands et al. 1999a).

X-ray pulsar SAX J1808.4–3658 (Wijnands & van der Klis 1998a), the nearly-coherent oscillations during type I X-ray bursts (e.g., Strohmayer et al. 1996), and the two simultaneous QPOs at frequencies between 300 and 1300 Hz (the twin kHz QPOs; e.g., Strohmayer et al. 1996; van der Klis et al. 1996) considerably improved our knowledge of those systems. I will not discuss those phenomena (see van der Klis 2000 for an excellent review) but instead I will concentrate on the timing phenomena below a few hundred Hertz.

HBO- and NBO-like QPOs in the atoll sources: Questioning QPO models

Soon after the launch of RXTE, it became clear that also the atoll sources can exhibit 20–70 Hz QPOs (e.g., Strohmayer et al. 1996; Ford & van der Klis 1998; Fig. 2a). The QPOs are usually seen together with the HFN (Fig. 2a) and are clearly related to the broad bump seen in the IS (e.g., Ford & van der Klis 1998). The frequencies of these low-frequency QPOs are correlated with the kHz QPOs frequencies, similar to what has been found for the HBOs and the kHz QPOs in the Z sources (e.g., Ford & van der Klis 1998; see van der Klis 2000). The similarities between these types of low-frequency QPOs indicates that it is likely that they are physically related to each other (however, the picture is not yet fully understood as discussed below). The presence of such QPOs in these sources (and at similar strength as the HBOs; Ford & van der Klis 1998) question the validity of the proposed higher $B$ in the Z sources compared to the atoll sources.

Besides the 20–70 Hz QPOs, in two atoll sources (4U 1820–30 and the possible atoll source XTE J1806–246), QPOs were also found with a frequency of $\sim$7 Hz when those two sources were accreting at their highest observed $\dot{M}$ (i.e., the upper banana branch in 4U 1820–30; Wijnands & van der Klis 1999c; Wijnands et al. 1999a). These QPO properties are similar to the NBOs observed in the Z sources. If these QPOs are indeed physically related then models explaining the NBOs (e.g., Fortner et al. 1989; Alpar et al. 1992), which require near-Eddington mass accretion rates, will not hold. The formation mechanism behind these QPOs is already activated in 4U 1820–30 well below $\dot{M}_{\text{Edd}}$ (Wijnands et al. 1999a).

The 1 Hz QPOs in the X-ray dippers and SAX J1808.4–3658

Low-frequency QPOs were also found in the neutron star X-ray dippers but with frequencies near 1 Hz (Jonker et al. 1999, 2000a; Homan et al. 1999; Fig. 3a). These QPOs are most likely related to the high-inclination of the X-ray dippers and could be due to matter at a certain disk radius coming periodically into the line of sight (Jonker et al. 1999). The properties of these 1 Hz QPOs suggest that they form a separate class of QPOs and that they are not related to the other low-frequency QPOs observed in the Z and atoll sources (Jonker et al. 1999, 2000a; Homan et al. 1999).
Recently, in several (but not all) RXTE observations taken of the millisecond X-ray pulsar during a long-period of low-level activity in early 2000, very strong flaring was observed which showed up as a very strong (up to 100% rms) 1 Hz QPO in the power spectrum (van der Klis et al. 2000; Fig. 3b). However, the differences between this QPO and the 1 Hz QPOs in the X-ray dippers (i.e., the coherence, the strength [100% rms versus ∼10% rms], and the likely low-inclination of SAX J1808.4–3658) suggest that these QPOs are caused by different physical mechanisms despite the similar frequencies. Similar strong flaring behavior has not been observed in the other atoll sources, but it might be present in these systems if they reach similar low mass accretion rates as were observed for SAX J1808.4–3658. However, it is also possible that this flaring is related to the fact that SAX J1808.4–3658 is a millisecond X-ray pulsar and it might then not be observable in the other non-pulsating atoll sources.

A NEW VIEW ON NEUTRON STAR LOW-MASS X-RAY BINARIES

The new obtained results with the RXTE satellite demonstrate that the timing behavior of the neutron star LMXBs is far more complex than previously thought. However, some general trends are already becoming visible. First of all, with RXTE all types of QPOs previously thought to be only present in the Z sources have now also been observed in the atoll sources. This has profound implications for the models for these QPOs and for our understanding of the differences and the similarities between Z and atoll sources. The Z and the atoll sources are likely to be much more similar than previously suspected and the individual sources only differ in detail from each other (the shape in the color-color diagram, the exact detailed shape of the power spectra and its evolution). The general behavior of both the Z sources and the atoll sources as suggested by these recent results can be summarized as follows:

At low $\dot{M}$ the power spectra are dominated by strong band-limited noise which follows approximately a power law at high frequencies but breaks at a certain frequency below which the power spectra are roughly flat. At frequencies above the break either a QPO or a broad bump is present. At frequencies around approximately 100 Hz a broad noise component is present (note that a detailed comparison of the Z sources HFN and the atoll source 100 Hz noise has not yet been performed which makes a conclusive statement about their connection impossible). KHz QPOs might already be detectable in some sources, but not in all. As $\dot{M}$ increases the frequency of the break and of the QPO (the bumps evolve into true QPOs) increases and the strength of both components decreases. The 100 Hz component does not change significantly (Wijnands & van der Klis 1998b; van Straaten et al. 2000; di Salvo et al. 2000), although it might become more
coherent (van Straaten et al. 2000). If not yet already present, kHz QPOs appear and their frequencies increase with $\dot{M}$. The band-limited noise, the low-frequency QPOs, and the kHz QPOs gradually disappear as $\dot{M}$ increases further and the power spectra become increasingly dominated by a very low frequency noise component following a power law. QPOs near 5–7 Hz appear when the sources are at very high $\dot{M}$, but these high $\dot{M}$ levels might not be reached in all systems. If $\dot{M}$ increases even further either these QPOs disappear or first increase in frequency to about 20 Hz before disappearing.

Possible exceptions to this general picture are the X-ray dippers and the millisecond X-ray pulsar. In the X-ray dippers, the general Z/atoll source behavior is likely to be distorted by the fact that we see these systems almost edge-on (e.g., Jonker et al. 1999). Different timing phenomena can occur at such high inclination (i.e., the 1 Hz QPOs), which are unrelated to the timing phenomena seen in the other low-inclination NS systems. The violent flaring in SAX J1808.4–3658 might be unique to this source and related to the fact that this source is the only known source of its kind, or perhaps similar phenomena might be detected in the other atoll sources when they are accreting at similarly low levels.

A fundamental question is why the atoll sources and the Z sources resemble each other in the way they do, despite their significant different luminosities. It is still likely that the mass accretion rate is significantly higher in the Z sources compared to the atoll sources, but it is unclear why the timing properties should be so similar. These similarities make it also increasingly unclear whether a difference in magnetic field strength is really present between the Z and the atoll sources. The source which might give more insight into the Z and atoll source connection is the enigmatic source Cir X-1. With EXOSAT it was observed during episodes of low-level X-ray activity and during that time it resembled the atoll sources (Oosterbroek et al. 1995). However, from the start of the RXTE mission, this source has continuously exhibited much higher flux levels during which it resembles the Z sources, both in the track traced out in the CD and in the timing phenomena (Shirey et al. 1999). It seems that this source can alternate between atoll-like states and Z-like states. Interestingly, the X-ray activity of Cir X-1 is steadily decreasing in the last few months which might indicate that the source is moving back to a much lower X-ray activity.

**BLACK-HOLE CANDIDATES**

Before RXTE, the ‘standard’ picture for black-hole candidates (BHCs) was a simple, one-dimensional view: the changes in the X-ray spectra and the rapid X-ray variability are caused by changes in $\dot{M}$ (Tanaka & Lewin 1995; van der Klis 1995). In the BHC low-state (LS), $\dot{M}$ is low, the spectra are hard, and the power spectra are dominated by a very strong (20%–50% rms amplitude) band-limited noise which follows approximately a power law with index 1 at high frequencies but below a certain frequency ($\nu_{\text{Break}}$) the power spectrum becomes roughly flat (Fig. 4 left). Above $\nu_{\text{Break}}$ a broad bump or QPO is present, although also QPOs with similar frequencies as the break frequency could be present (see Fig. 4 left). In some sources a second break is visible in the power spectrum above which the power law index increases to about ~2. In the high state (HS), $\dot{M}$ is higher, the spectra are much softer, and in the power spectra only a weak (a few percent) power law noise component is present. In the very high state (VHS), $\dot{M}$ is the highest, the spectra are harder but not as hard as in the LS, and in the power spectra noise is present similar to the weak HS noise or the LS band-limited noise, although weaker (1%–15% rms). Above $\nu_{\text{Break}}$, QPOs near 6 Hz are detected sometimes with a complex harmonic structure.

With the many observations performed with RXTE on BHCs, the behavior of BHCs turned out to be much more complex than previously thought. First of all, RXTE has expanded the range of frequencies at which the BHCs show variability up to 300 Hz (Remillard et al. 1999a,b; Cui et al. 2000; Homan et al. 2000). The nature of these BHC high-frequency QPOs is unclear, although recent evidence suggests that they might be related to the lower-frequency peak of the twin kHz QPOs in the neutron star systems (Psaltis et al. 1999). Also, with RXTE in many BHCs the VHS QPOs have now been found (e.g., Remillard et al. 1999b; Borozdin & Trudolyubov 2000; Cui et al. 2000; Homan et al. 2000; Revnivtsev et al. 2000), indicating that the VHS QPOs are a common feature of BHCs. The phenomenology of these QPOs is very complex and they are observed during different luminosity levels (at levels significantly below the highest observed luminosities, i.e., not only during the VHS but at states intermediate between the LS and the HS). An example of the complex structure of these QPOs is shown in Fig. 4 (right). In this figure different low-frequency QPOs are shown which were observed during different observations of the new BHC XTE
J1550–564 (Homan et al. 2000). The interrelationships of the QPOs in this source are not fully understood. The relationship between the QPOs observed in different BHCs is even less understood. However, from a detailed study of the state behavior in XTE J1550–564 it is clear that the one-dimensional picture described above for the BHC states (depending only on $\dot{M}$) does not hold in this particular source and another extra parameter is needed to explain its behavior (Homan et al. 2000). Similar behavior might also be observable for the other BHCs, however, not much information about this is available at the moment. A detailed discussion of this and the QPOs observed in the BHCs is beyond the scope of this manuscript.

**THE $\nu$-Break-$\nu$QPO RELATION**

In a study to characterize the aperiodic variability of the millisecond X-ray pulsar, Wijnands & van der Klis (1998b) showed that the power spectrum of this source is indistinguishable (besides the pulsations) from that of the atoll sources when they are in the IS. In Figures 5a and 5b the power spectra are shown for SAX J1808.4–3658 and a typical atoll source 4U 1728–34, respectively (Wijnands & van der Klis 1999a). For both sources the band-limited noise and the bump above the break frequency are present, but so is an extra noise component above 100 Hz. Wijnands & van der Klis (1998b) showed that this noise component is a common feature in the power spectra of atoll sources at low mass accretion rates. The resemblance between SAX J1808.4–3658 and 4U 1728–34 demonstrates that the millisecond X-ray pulsar can be classified as an atoll source at low $\dot{M}$ (i.e., it was in the IS; see Wijnands & van der Klis 1998b). It is unknown why for SAX J1808.4–3658 millisecond X-ray pulsations have been detected and not for any other atoll source.

The striking similarities between SAX J1808.4–3658 and the atoll sources, and the long-known similarities between the atoll sources in the island state and BHC in the low state (see van der Klis 1995 and references therein) initiated a detailed study to investigate these similarities (Wijnands & van der Klis 1999a). A typical power spectrum of a BHC (i.e., Cygnus X-1) at low mass accretion rate is shown in Figure 5c. From this figure it is clear that again the band-limited noise as well as the bump above the break frequency are present. However, above the bump a second break is present in the power spectrum above which the power spectrum follows a power law with index of $\sim 2$. Wijnands & van der Klis (1999a) found a very good correlation between the frequency of the QPO (or bump, but hereafter referred to as QPO; $\nu_{QPO}$) and the break-frequency ($\nu_{\text{Break}}$; see Figure 5e). The most intriguing point is that the BHCs and the atoll sources (including the millisecond X-ray pulsar) follow the same correlation. This strongly suggest that in all those
Fig. 5. Typical power spectra (see also Wijnands & van der Klis 1999a) of the millisecond X-ray pulsar (SAX J1808.4–3658; a), an atoll source (4U 1728–34; b), a BHC (Cyg X-1; c), and a Z source (GX 340+0; d). The obtained correlation between the frequency of the QPO versus the break frequency of the band-limited noise is shown in e. The solid circles are the points for the atoll sources (including the millisecond X-ray pulsar SAX J1808.4–3658) and the BHCs used by Wijnands & van der Klis (1999a); the filled squares are their Z source data. The open symbols are new data points obtained for several sources: GRO J0422+32 (open squares; van der Hooft et al. 1999), SLX 1735–269 (open diamond; Wijnands & van der Klis 1999b), 4U 1728–34 (open triangles; di Salvo et al. 2000), and 4U 0614+09 (open circles; van Straaten et al. 2000).

different source types, the band-limited noise and the QPO are produced by the same physical mechanism, which therefore cannot depend on the presence or absence of either a small magnetosphere (which definitely is present in SAX J1808.4–3658), a solid surface, or an event horizon. These components then most likely originate somewhere in the accretion disk, at a distance of at least several tens of kilometers from the central compact object, outside a possible magnetosphere. However, the large amplitudes of the band-limited noise (up to 50% rms) exclude the possibility that the emission carrying these fluctuations originates this far out in the accretion disk, because most of the gravitational energy of the accretion disk is released closer to the compact object. A modulation of the accretion rate due to instabilities in the flow in the region of the disk outside several 10 km from the compact object is the most likely mechanism for generating the band-limited noise and the QPO.

The question arises as to which fundamental properties of the source determine the exact place of the source in $\nu_{\text{Break}}-\nu_{\text{QPO}}$ plot. The effect of the magnetic field of the compact object is probably small in the region of the disk where the frequencies are determined. The other physical parameters which can affect the accretion disk are the mass and the spin of the central object, and $\dot{M}$. For a given source the mass and spin do not change and thus probably only $\dot{M}$ determines $\nu_{\text{Break}}$ and $\nu_{\text{QPO}}$. Usually the relation between the frequencies and $\dot{M}$ is a positive one-to-one correlation (see, e.g., van der Klis 1995), however, it has been shown that this is not the case for the millisecond X-ray pulsar (Wijnands & van der Klis 1998b) and the atoll source SLX 1735–269 (Wijnands & van der Klis 1999b). The reason for this is as yet unknown, but it might be related to the very low $\dot{M}$ observed in both sources. It however shows that at least at these very low mass accretion rates another parameter besides $\dot{M}$ is involved in determining the exact value of the frequencies. At higher accretion rates, when the frequencies are positively correlated with $\dot{M}$, the difference between sources with similar mass accretion rates would lie in the mass and/or the spin rate of
the compact object. This could explain why on average the BHCs have smaller frequencies than the neutron star systems. However, considerable overlap between these source types occurs, indicating that the mass accretion rate differences dominate the frequencies.

Where do the Z sources fit?

When the brightest neutron star LMXBs (the Z sources; Hasinger & van der Klis 1989) are at low $\dot{M}$ (i.e., at the left end of the HB) the power spectra are very similar to the one shown in Figure 5d. The LFN is present with the HBO above the break. The shape of these power spectra resemble the ones of the atoll sources and the BHCs at their lowest $\dot{M}$, although the QPO is much more coherent for the Z sources. Also, for the Z sources $\nu_{\text{QPO}}$ and $\nu_{\text{Break}}$ are correlated with each other, but they do not follow the same correlation as the atoll sources and the BHCs (see Figure 5e; Wijnands & van der Klis 1999a). Several arguments can explain why the Z sources follow a different correlation. The most simple one is that the noise and/or the QPOs in the Z sources are totally unrelated to any of the timing phenomena in the atoll sources and the BHCs. However, the correlation found between the frequencies of the kHz QPOs and the low-frequency QPOs in both the Z sources and the atoll sources indicate that the low-frequency QPOs in the atoll sources are likely to be related to the HBOs in the Z sources (e.g., Ford & van der Klis 1998; Psaltis et al. 1999). So disregarding any common physical mechanism behind the noise properties in the atoll and the Z sources seems premature. An alternative explanation could be that the LFN in the Z sources is not caused by the same physical mechanism as the HFN in the atoll sources (see, e.g., Wijnands & van der Klis 1999a). In the Z source Sco X-1 an extra noise component is present between $\nu_{\text{Break}}$ and $\nu_{\text{QPO}}$. Wijnands & van der Klis (1999a) tentatively suggested that this extra noise component could be related to the HFN in the atoll sources. When plotting $\nu_{\text{Break}}$ of this noise component versus $\nu_{\text{QPO}}$, Sco X-1 follows approximately the same relation as the atoll sources and the BHCs (Wijnands & van der Klis 1999a). However, Jonker et al. (2000b) reported a similar noise component in the Z source GX 340+0. The frequency of this noise component was approximately half the frequency of the HBO and could be its sub-harmonic. Identifying this sub-harmonic with the bump or QPO in the atoll sources, GX 340+0 follows the same correlation as the atoll sources and the BHCs (Jonker et al. 2000b). However, in this case GX 340+0 then does not follow the correlations found by Psaltis et al. (1999) between the low-frequency QPOs and the kHz QPOs. At the moment it is unclear how the Z sources fit in.

Cautionary statement

The similarities between the neutron star systems and the BHCs at low $\dot{M}$ (note that even some of the VHS QPOs of the BHCs fit into the correlation which might point towards a physical connection between these QPOs and neutron star 15–70 Hz QPOs; Wijnands & van der Klis 1999a) are striking and the correlation between $\nu_{\text{QPO}}$ and $\nu_{\text{Break}}$ is very suggestive of one underlying mechanism for the noise components in both types of systems. But as can been seen in Figure 5e, intrinsic scatter is present. The principal reason for the scatter could be the complex structure of the QPO. Considerable substructure, usually below the main QPO, is often present (see, e.g, Figure 5a and b). Moreover, in several sources two QPOs were detected, harmonically related to each other, or simultaneously QPOs and bumps were present (Wijnands & van der Klis 1999a). It is possible that in the other sources also extra harmonics or bumps are present, which are incorporated into the single Lorentzian used to fit the QPO. This would result in a measured QPO frequency that is slightly shifted from the correct value, producing the scatter. When in the power spectra multiple QPOs, bumps, or even multiple breaks are present, it is very difficult to identify which QPO or which break to use for the correlation. Correlations as the $\nu_{\text{Break}}$-$\nu_{\text{QPO}}$ correlation and the one found by Psaltis et al. (1999) might be severely biased towards the simplest systems because the more complex sources are not used in the correlations, resulting in an over simplification of the timing behavior of X-ray binaries.

Can we distinguish between neutron star systems and BHCs?

The above similarities between neutron star systems and BHCs make it hard to distinguish these systems from each other and when an X-ray binary does not exhibit X-ray pulsations or type I X-ray bursts, it is usually hard to determine the nature of the compact object solely from its rapid X-ray variability. However, a possible difference between neutron stars and black-holes might be present in the rapid X-ray variability above 100 Hz. First of all, so far no BHC has shown two simultaneous kHz QPOs, although single QPOs
up to approximately 300 Hz have been detected in BHCs (e.g., Remillard et al. 1999a, b; Cui et al. 2000; Homan et al. 2000). The presence of two simultaneous kHz QPOs strongly suggest the presence of a neutron star in the system. But at low mass accretion rates, neither the neutron star kHz QPOs (e.g., Méndez et al. 1997) nor the black-hole high-frequency QPOs (Remillard et al. 1999a,b; Homan et al. 2000) have been detected. A possible distinction between the NS systems and BHCs at these low accretion rates might still be possible on the basis of the broad-band noise properties above approximately 100 Hz. As discussed above, the neutron star systems display an extra noise component in this frequency range, but in the BHCs this noise component is absent (although van Straaten et al. [2000] tentatively suggested on the basis of the sometimes high coherence of this noise component that it might be related to the >100 Hz QPOs seen in BHCs). Instead of this 100 Hz noise component the power spectra of the BHCs show a second break above which the power spectra follow a steep (index ~ 2) power law. This difference in the high-frequency power spectra of BHCs and neutron star systems was recently emphasized by Sunyaev and Revnivtsev (2000) and it might turn out to be a useful tool to determine the nature of the compact object in X-ray transients which do not exhibit type I X-ray bursts nor pulsations.

CONCLUSIONS

With the launch of RXTE a new area has begun in the study of the X-ray variability of X-ray binaries. Although most of the attention has been focused on the QPOs observed above 100 Hz, a lot of new and exciting phenomena have been discovered at lower frequencies. These low-frequency phenomena seriously challenge the pre-RXTE view of X-ray binaries. It will be a challenge to construct a new consistent view of these systems which can both explain the striking similarities but also the significant differences among the different source types.

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