Three main types of low-frequency quasi-periodic oscillations (LFQPOs) have been observed in black hole candidates. We reanalyzed RXTE data of the bright systems XTE J1859+226, XTE J1550–564, and GX 339–4, which show all three types. We review the main properties of these LFQPOs and show that they follow a well-defined correlation in a fractional rms versus softness diagram. We show that the frequency behavior through this correlation presents clear analogies with that of horizontal-, normal-, and flaring-branch oscillations in Z sources, with the inverse of the fractional rms being the equivalent of the curvilinear coordinate \( S_z \) through the Z track.

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

1. INTRODUCTION

Low-frequency quasi-periodic oscillations (LFQPOs) with centroid frequencies from millihertz to tens of hertz have been observed in the X-ray flux of many neutron star and black hole X-ray binaries (see van der Klis 2005 and references therein). In neutron star low-mass X-ray binaries (LMXBs) the timing behavior has long been known to correlate with spectral variations. In particular, the properties of the LFQPOs vary in systematic fashion along the pattern that these sources describe in the X-ray color-color diagram (CD). In high-luminosity neutron star systems (the so-called Z sources) (Hasinger & van der Klis 1989; van der Klis 2005), three types of LFQPOs have been associated with the position along the Z pattern that these sources describe in a CD: the horizontal branch oscillations (HBOs), normal branch oscillations (NBOs), and flaring branch oscillations (FBOs) (for details on these LFQPOs and how they are tracked through the Z pattern by using the curvilinear coordinate \( S_z \), see van der Klis 1995).

In the case of black hole candidates (BHCs) the general picture is at present less clear. Three main types of LFQPOs, dubbed types A, B, and C, respectively, originally identified in the light curve of XTE J1550–564 (see Wijnsands et al. 1999a; Remillard et al. 2002), have been seen in several sources (see § 2). On the other hand, three main bright states (in addition to the quiescent state) have been identified in these sources, based on their spectral and timing properties (for a review see Tanaka & Lewin 1995; van der Klis 1995, 2005; McClintock & Remillard 2005; Homan & Belloni 2005). It was only very recently that systematic variations in the energy spectra and intensity of transient BHCs could be identified in terms of the pattern described in an X-ray hardness-intensity diagram (HID) (see Homan et al. 2001; Belloni 2004; Homan & Belloni 2005; Belloni et al. 2005). Original states are found to correspond to different branches/areas of a square-like HID pattern. In this scheme the BHC LFQPO phenomenon appears to be confined to within a comparatively small range of spectral properties of these sources, requiring a deeper investigation over a restricted range in parameter space. Within this small range, attempts to correlate the QPO properties with other properties, such as the source position in the CD or the HID across different BHCs, have so far given inconclusive results. This is clearly at variance with neutron star LMXRBs.

Similarities between power spectra in BHCs and in Z sources have been stressed by several authors (see, e.g., Miyamoto et al. 1993). Van der Klis (1994) discussed the parallelism between NS and BH systems and underlined the importance of quantitatively studying the similarities between them. Wijnands & van der Klis (1999a) and Psaltis et al. (1999) found global correlations between characteristic frequencies in both NS and BH systems, involving type C LFQPOs and HBOs in BHCs and Z sources respectively, plus the low-frequency LFQPOs in atoll sources. These correlations suggested that the basic frequencies of these systems likely have the same origin as envisaged in some QPO models and yielded a possible association between type C LFQPOs and HBOs.

In this paper, we show that the QPO type and centroid frequency in BHCs vary systematically as a function of the inverse of the source rms fractional variation. This behavior is reproduced fairly accurately over different BHCs and presents clear similarities with the LFQPOs of neutron star low-mass X-ray binaries. Based on this analogy we suggest that C-, B-, and A-type LFQPOs in BHCs correspond to HBOs, NBOs, and FBOs of high-luminosity neutron star systems of the Z class, respectively.

2. QPO CLASSIFICATION

Several distinct types of LFQPOs showing different properties have been discovered in BHCs. An exhaustive classification has not yet been obtained, given the complexity and variety of the observed behaviors. However, three main LFQPO types (named types A, B, and C) stand out in the present scenario. In Table 1 we summarize their main properties.

2.1. Type C LFQPOs

Type C LFQPOs are characterized in the power spectrum by a strong (up to \( \sim 16\% \) ms), narrow \((v/\Delta v \sim 7-12)\), and variable peak (its centroid frequency and intensity varying by several percent in a few days; see, e.g., Casella et al. 2004, C04 hereafter) at frequencies \( \sim 0.1-15 \text{ Hz} \), superposed on a flat-top noise (FTN) that steepens above a frequency comparable to the QPO frequency (see Wijnands & van der Klis 1999a; Belloni et al. 2002). The total (QPO and FTN) fractional rms variability can
be as high as \( \sim 30\% \). A subharmonic and a second harmonic peak are often seen. Phase lags (i.e., the phase delay between two light curves at different energies) depend strongly on the frequency of the QPO, with a trend toward soft lags (i.e., soft X-ray variations lag those at hard X-ray energies) for increasing QPO frequency (see Reig et al. 2000), but they are usually consistently soft at the subharmonic and hard at the second harmonic (see, e.g., Remillard et al. 2002; C04). The QPO rms increases with energy, flattening above \(-10\) keV (see, e.g., C04). In some cases a decrease above \(20\) keV is observed (Tomsk & Kaaret 2001), which might be associated with a higher radio flux (Rodriguez et al. 2005).

Low-frequency QPOs that can be identified as type C were observed in a number of sources, e.g., GS 1124–684 (Miyamoto et al. 1993; Takizawa et al. 1997), XTE J1550–564 (Remillard et al. 2002), XTE J1859+226 (C04), GX 339–4 (Miyamoto et al. 1991), and GRO J1655–40 (Méndez et al. 1998).

The presence of a strong FTN component and the correlation of the QPO frequency with the source intensity and the FTN break frequency (Wijnands & van der Klis 1999a) strongly suggest the association of this low-frequency QPO type with the HBO observed in Z sources (Miyamoto et al. 1993).

### 2.2. Type B LFQPOs

Type B LFQPOs are characterized by a relatively strong (\( \sim 4\% \)) rms and broad (\( \nu/\Delta \nu \geq 6 \)) peak, which is found in a narrow range of centroid frequencies around \(6\) Hz. Unlike type C, there is no evidence for FTN, although a weak red noise (few percent rms) is detected at very low frequencies (\( \leq 0.1\) Hz). A weak second harmonic is often present, sometimes together with a subharmonic peak. In a few cases, the subharmonic peak is higher and narrower (resulting in a “cathedral-like” shape; see C04). Phase lags are hard at the fundamental and soft at the second harmonic, i.e., the opposite of the behavior observed for type C LFQPOs. However, phase lags are soft at the subharmonic, as in type C LFQPOs. The energy dependence of the QPO rms is similar to that of type C LFQPOs, but the rms values are systematically lower (by a factor of \( \sim 2 \)).

The presence of type B LFQPOs has been reported in different sources: see, e.g., GS 1124–684 (Miyamoto et al. 1993; Takizawa et al. 1997), XTE J1550–564 (Wijnands et al. 1999a), GX 339–4 (Nespoli et al. 2003; Belloni et al. 2005), XTE J1859+226 (C04), and GRS 1739–278 (Wijnands et al. 2001).

Rapid transitions in which type B LFQPOs appear/disappear are often observed in some of these sources. The transitions are unresolved at present, as they take place on a timescale shorter than a few tens of seconds. In GX 339–4, the QPO appearance is related to spectral hardening of the source flux (see Nespoli et al. 2004; Belloni et al. 2005), while in XTE J1859+226 transitions toward type C and type A LFQPOs appear to be related to a spectral softening and a spectral hardening, respectively (C04). A rapidly transient \( \sim 6\) Hz QPO was observed also in the atoll source 4U 1820–30 and was compared with both NBOs observed in Z sources (Wijnands et al. 1999b) and type B LFQPOs observed in BHCs (Belloni et al. 2004) (other NBO-like LFQPOs have been observed also in the atoll sources XTE J1806–2646 [Wijnands & van der Klis 1999b; Revnivtsev et al. 1999] and Aql X-1 [Reig et al. 2004]).

The centroid frequency of type B LFQPOs (which shows often marked variability on a timescale of \( \sim 10\) s; see Nespoli et al. 2003) is close to the frequency range (\( \sim 5–8\) Hz) over which NBOs are observed in neutron star systems of the Z class (and perhaps also a few lower luminosity systems; see van der Klis 1995). This frequency coincidence, together with the fact that both type B LFQPOs and NBOs show a low-amplitude noise, seems to suggest an association of these two LFQPO types. However, it must be noticed that some important differences still remain between the two LFQPOs, such as the higher coherence of type B LFQPOs and the lack of harmonic content in NBOs. Moreover, NBOs are seen simultaneously with HBOs in Z sources (see van der Klis 1995 and references therein), demonstrating that they are different phenomena. This does not happen in BHCs, where type B LFQPOs are seen to switch from/to type C LFQPOs (see previous paragraph) without any contemporaneity between the two. Furthermore, the centroid frequency of type B LFQPOs in XTE J1859+226 shows a weak positive correlation with the count rate (Casella et al. 2005). It is thus in principle possible that the \( \sim 1\) Hz QPO observed in GX 339–4 at low count rates (Belloni et al. 2005) could be identified as a type B. This would extend the frequency range over which type B LFQPOs are observed in BHCs.

2.3. Type A LFQPOs

Type A LFQPOs are characterized by a weak (few percent rms) and broad (\( \nu/\Delta \nu \leq 3\)) peak around \(8\) Hz. A very low amplitude red noise is observed, whereas neither a subharmonic nor a second harmonic were present (possibly because of the width of the fundamental peak). This LFQPO was observed in different sources: GS 1124–684 (Miyamoto et al. 1993; Takizawa et al. 1997), GX 339–4 (Nespoli et al. 2003; Belloni et al. 2005), and XTE J1859+226 (C04). C04 showed that phase lags at the frequency of the QPO are soft, while they were not measurable in the rest of the frequency range because of poor statistics. In some sources a deeper analysis is necessary in order to confirm these identifications.

At first, these LFQPOs were dubbed “type A-II” by Homan et al. (2001). LFQPOs dubbed “type A-I” (Wijnands et al. 1999a) were strong, broad, and accompanied by a very low-amplitude red noise. Moreover, a shoulder on the right-hand side of this QPO was clearly visible and interpreted as a very broadened second harmonic peak. In §3 we discuss that “type A-I” LFQPOs should be classified as type B.

The higher frequency and lower coherence of type A LFQPOs relative to type B LFQPOs is suggestive of an analogy with the FBOs observed in Z sources. Moreover, similarly to Z sources, in which the flaring branch is effectively “flaring” only in some sources (van der Klis 2005), also in BHCs the soft observations where type A LFQPOs appear correspond only in some sources to the highest flux values (see, e.g., C04 and Nespoli et al. 2003). However, there are also some differences. First, the rms amplitude of FBOs is usually stronger than that of type A LFQPOs. Second, rapid (tens of seconds) and unresolved transitions appear to take place between type A and B LFQPOs (see C04 and

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**TABLE 1**

**Summary of Type A, B, and C LFQPOs Properties**

| Property                      | Type C | Type B | Type A |
|-------------------------------|--------|--------|--------|
| Frequency (Hz)…………………. | \(\sim0.1–15\) | \(\sim5–6\) | \(\sim8\) |
| \(\nu/\Delta \nu\)……………… | \(\sim7–12\) | \(\geq6\) | \(\leq3\) |
| Amplitude (% rms)……………. | 3–16   | \(\sim2–4\) | \(\leq3\) |
| Noise ……………………. | Strong flat-top | Weak red | Weak red |
| Phase lag at \(\nu_{QPO}\)…………… | Soft/hard | Hard | Soft |
| Phase lag at \(\nu/2_{QPO}\)………. | Hard | Soft | … |
| Phase lag at \(\nu_{QPO}/2\)…………… | Soft | Soft | … |
3. CORRELATIONS

The three LFQPO types described in § 2 are in most cases observed in the top branch of the HID (see Belloni et al. 2005). In the three sources that have unambiguously shown all three types of LFQPOs (XTE J1550−564, XTE J1859+226, and GX 339−4), type Bs appear at lower hardness than type Cs and higher hardness than type As, thus identifying a well-defined sequence C → B → A.

However, given the lack of easily identifiable geometrical points of reference, it has not yet been possible to track unambiguously the evolution of LFQPOs properties along the HID, as has been done with the CDs in neutron stars. Perhaps this is because given the softness of the BH spectrum, the most dramatic spectral changes take place shortward of ~1−2 keV, where present instrumentation does not permit a detailed characterization of the small region of the HID where the different types of LFQPOs are observed.

In order to find a parameter unambiguously tracking the type C → B → A sequence, we plot the total integrated rms (0.06−64 Hz, in the 2−15 keV energy range) versus the softness (defined as the ratio between the PCA counts in the energy bands ~2−3.4 and ~9−20 keV) of the observations in which one of the three LFQPO types was observed in each of the three above-mentioned sources (see Fig. 1). For XTE J1859+226 and GX 339−4 we used the complete samples, using classifications reported, respectively, by C04 and Belloni et al. (2005). For XTE J1550−564 we chose all type A and B LFQPOs for which the identification was incontrovertible, and several type C LFQPOs covering the observed frequency range (identifications from Wijnands et al. 1999a, Homan et al. 2001, and Remillard et al. 2002). In order to obtain values of rms and

![Fig. 1.—Total 0.06−64 Hz rms (in the 2−15 keV band) vs. softness (defined as the ratio between ~2−3.4 keV and ~9−20 keV fluxes) for those observations in which a low-frequency QPO was observed. Symbols are explained in the inset table (see text for the irregular types).]

![Fig. 2.—Histogram of the $S_{\text{rms}}$ values. Different shadings indicate different LFQPO types.](image)

hardness consistent among the three sources, we reanalyzed all the data (for technical details on the analysis we refer to C04).

The behavior of the three sources in Figure 1 is similar: the softness and the rms show a monotonic, roughly linear anticorrelation, through which the C-B-A sequence is well defined. Only three points deviate from this scheme, all of them from XTE J1550−564 (framed square and triangles; see the inset table). In these three cases, the identification of the LFQPO is uncertain: one is a “B-cathedral” type with an unusual band-limited noise, the other two were classified as type A-I (see § 2.3 and the following). It is worth mentioning that in the case of XTE J1859+226, the points where no LFQPOs could be clearly identified (see C04) follow a different correlation in the rms versus softness diagram, lying on a flatter linear-like track (not shown in Fig. 1) at higher values of softness, and that the same happens in the case of GX 339−4 (Belloni et al. 2005).

However, studying in detail the complete evolution of the outburst in the rms-softness diagram is beyond the scope of this work, in which we concentrate on the study of the unambiguously classified LFQPOs.

While the range in softness differs from one source to another (see in particular the points for GX 339−4), it is apparent from Figure 1 that all three sources span a similar range in rms fractional variability. This suggest that the rms fractional variability can be used as a parameter tracking the three LFQPO types. In the histogram of Figure 2 we use a related parameter, the inverse of the rms (hereafter $S_{\text{rms}}$), in order to maintain the C-B-A sequence observed in the HID. It is evident that the points of the three sources cluster around three values of $S_{\text{rms}}$, with the three groups corresponding to the three LFQPO types reviewed in § 2.

In Figure 3 we plot the frequency of the LFQPOs versus $S_{\text{rms}}$. The separation among three LFQPO types is well defined, and data from the three sources overlap fairly accurately, creating a unique characteristic shape. The frequency of type C LFQPOs increases steeply up to ~8 Hz at $S_{\text{rms}} \sim 0.15$. After this point, type B LFQPOs appear with frequencies (mainly) close to ~6 Hz until $S_{\text{rms}} \sim 0.3$. Finally, for higher values of $S_{\text{rms}}$, only type A
LFQPOs are present, with frequencies around 8 Hz. It is worth noting that the three LFQPOs that deviated from the correlation in Figure 1 lie now in the region of the plot where type B LFQPOs are concentrated. If in the case of the “cathedral” LFQPO this is not surprising, in the other two cases this seems to be either an exception to the separation among the three LFQPO types or a problem with the “type A” definition of the QPOs themselves. On the other hand, the clustering of type A-I LFQPOs around $C/24^6$ Hz (Homan et al. 2001) clearly makes them standing out among type A LFQPOs. The strong difference in amplitude between type A-I and A-II leaves room for a separation of the two classes and for an association of type A-I with type B. In Figure 3 we also plot data from a few other sources (see inset table) that show only one of the three LFQPO types but clearly confirm the general scheme.

The behavior in Figure 3 is strongly reminiscent of the scheme observed in the Z sources, with the sequence HBO $\rightarrow$ NBO $\rightarrow$ FBO along the Z track. In Figure 4 we plot the QPO frequency versus the rank number $S_z$ of four Z sources. The similarity with Figure 3 is evident and further supports the association between Z sources’ and BHCs’ LFQPOs (see § 2).

4. CONCLUSIONS

We reviewed the evidence that BHCs present three main different types of low-frequency QPOs. Each of these three types has well-defined properties and shows strong similarities with one of the three types of LFQPOs observed in Z sources. The three types appear in a well-defined sequence along the HID, like the three types of LFQPO observed in Z sources do along the CD.

Furthermore, we found that their frequency follows a characteristic trend as a function of the total integrated fractional variability. This trend is clearly reminiscent of that observed along the Z track of Z sources. On the basis of these similarities we propose associating the C, B, and A types, respectively, with the HBO, NBO, and FBO observed in the Z sources, thus strengthening and extending the previously proposed associations. In Table 2 we summarize the main similarities in the properties of these LFQPOs.

If these associations are correct, then the type Cs in BHCs and the HBOs in Z sources might well be caused by a similar physical mechanism. The fact that the frequencies of the type Cs are roughly a factor of $\sim$6–7 lower than the frequencies of the HBOs suggests that these frequencies scale approximately as the inverse of the mass of the compact object, as expected for dynamical frequencies. On the other hand, both NBOs and type B LFQPOs have frequencies close to 6 Hz; thus, it is natural to suppose that the physical mechanism that determines their frequency is independent of (or only weakly dependent on) the mass of the compact object.

The presence of these two mechanisms in both types of compact objects would rule out all models that involve any interaction with the surface or the magnetosphere of the neutron star.

This work was partially supported by MIUR under CO-FIN grants 2002027145 and 2003027534.

| Property       | HBO/Type C   | NBO/Type B |
|----------------|--------------|------------|
| Frequency (Hz) | Intensity-dependent | 5–6        |
| Amplitude (% rms) | Anticorrelated with frequency | 2–4        |
| Noise          | Strong flat-top | Weak red   |
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