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Low Frequency Quasi-periodic Oscillations in the High-eccentric LMXB Cir X-1: Extending the WK Correlation for Z Sources

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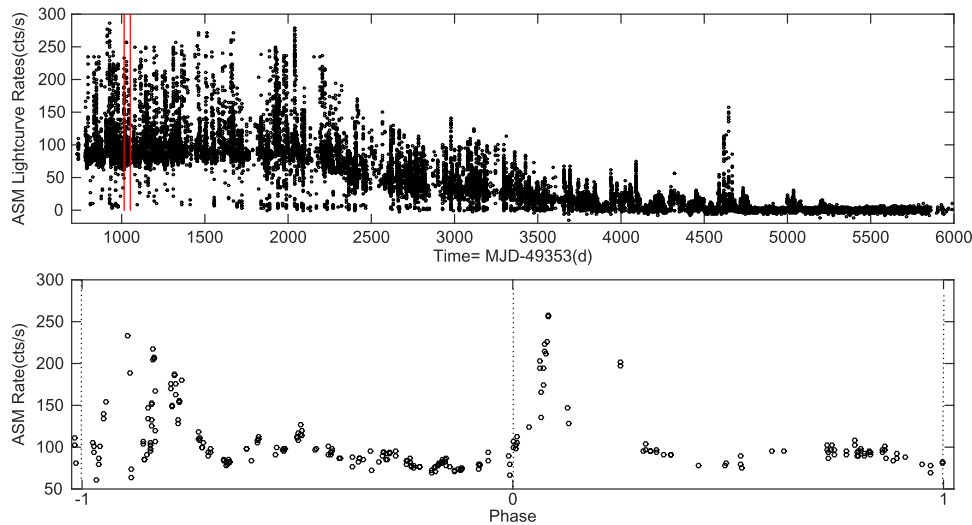


Figure 1. Upper panel: *RXTE* ASM light curve of Cir X-1 in the energy band 2–12 keV, covering the entire life of the *RXTE* mission. Lower panel: two complete orbital cycles observed with the ASM, extracted from the time period marked by red lines in the upper panel. The vertical dotted lines indicate phase zero. Data points are 90 s averages.

2. Data Reduction and Analysis

2.1. Data Selection

We analyzed all the public data of Cir X-1, 811 observations, collected with the *RXTE*/PCA. The X-ray light curve of Cir X-1 from the All-sky Monitor (ASM) on board *RXTE* is shown in Figure 1 (upper panel). It was one of the brightest NS-LMXB sources at ~ 3 Crab level (1 Crab ~ 75

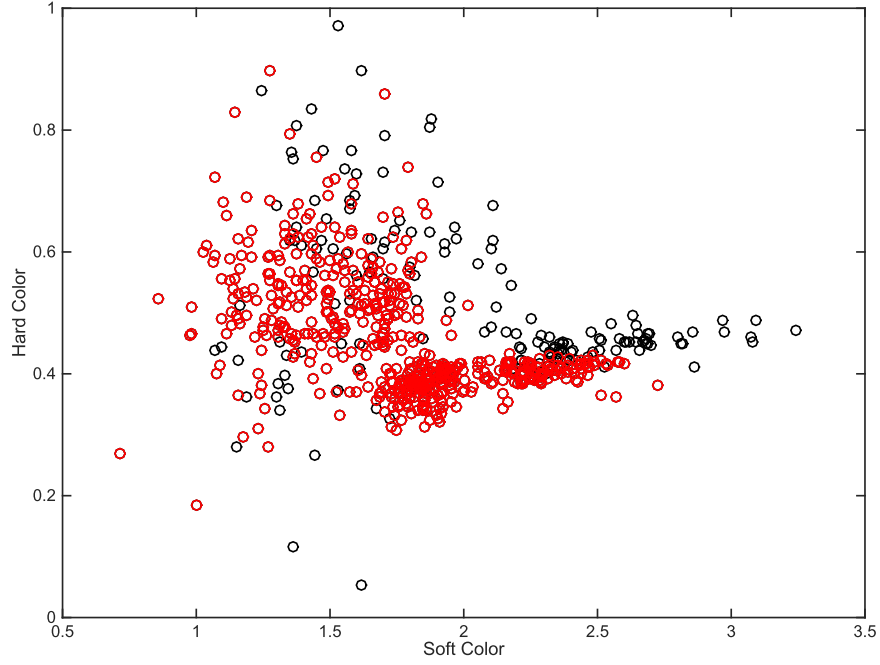


Figure 2. Color-color diagram for the observations from MJD 55327–55764. In the CD, soft color is defined as the ratio of count rate in the 5.3–6.9 keV/4.1–5.3 keV bands, and hard color is defined as the ratio in the 10.6–22.3 keV/6.1–10.6 keV bands. Observations from Fridriksson et al. (2015) are plotted as red points, which are confirmed as atoll state, corresponding to MJD 55343.4–55350.7.

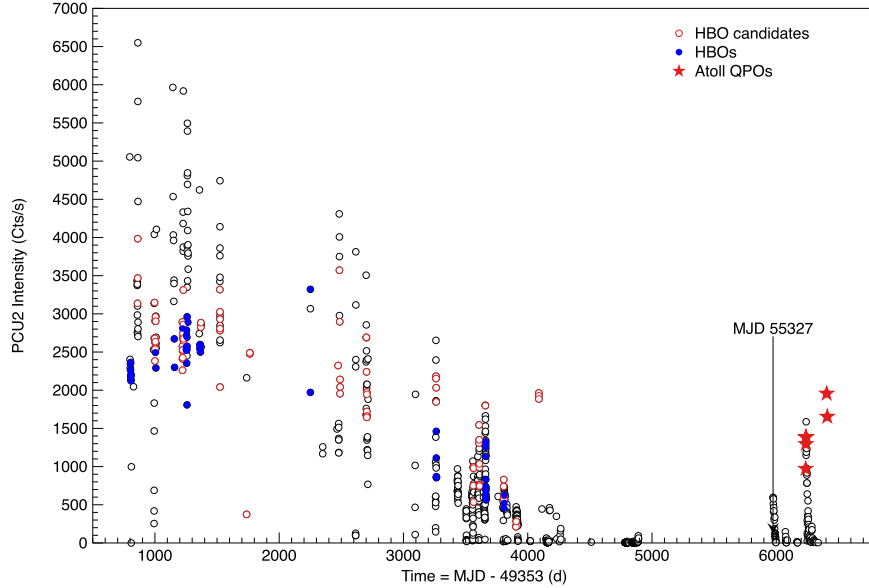


Figure 3. A long-term light curve of the source extracted from energy band 2–12 keV, with each data point being the average of one observation. Only PCU2 data is used. Observations with significant LFQPOs are indicated with red dots, and the QPOs confirmed as HBOs

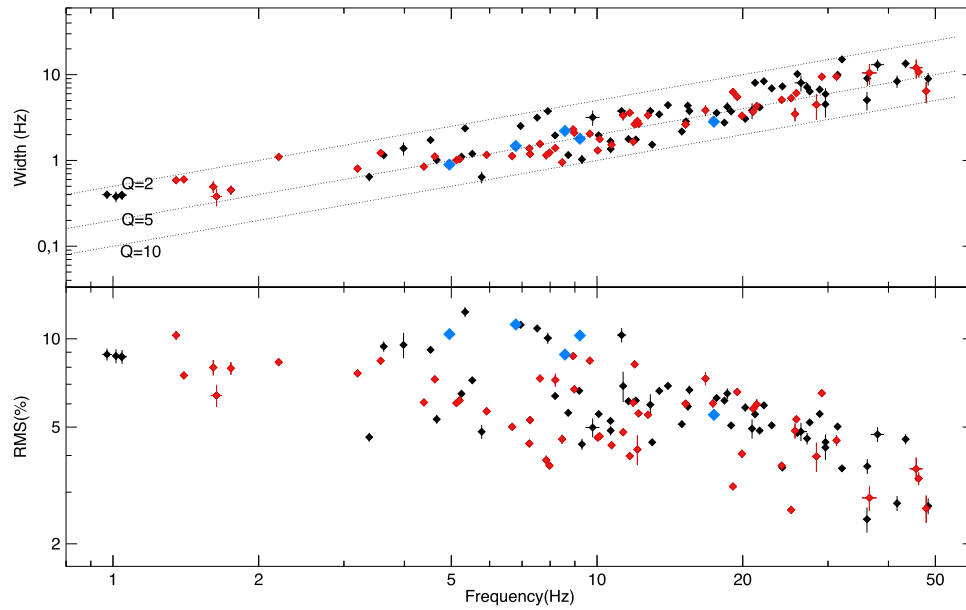


Figure 4. Upper panel: LFQPO width as a function of its centroid frequency. Each point represents a single observation. LFQPOs from the atoll state are marked with blue diamonds, confirmed HBOs are marked as red diamonds, and HBO candidates are plotted as black diamonds. The dotted lines indicate different Q values, from 2 to 10. Lower panel: LFQPO fractional rms as a function of its centroid frequency.

LFQPOs are easy to detect and identify because of their high quality factor, while L_b has to be identified among the remaining components in the PDS. Generally, we define L_b as the first noise component below the LFQPO, or below the sub-harmonic if this is detected. Whether to include a sub-harmonic or not in the fitted model was judged by the goodness of fit (reduced chi-square). In Figure 6, we show two pairs of PDSs with similar LFQPOs at ~ 5 and ~ 10 Hz, with and without significant sub-harmonics. Among the 122 observations, we found 50 of them with a significant sub-harmonic. In order to check whether the L_{har} is really a sub-harmonic, in Figure 7, we plot its centroid frequency as a function of that of the LFQPO. The points follow a $y = 2x$ relation, confirming the harmonic relation. For those observations without significant sub-harmonics, in order to have a homogeneous model for all PDSs, we also included a sub-harmonic component with a central frequency at half of the LFQPO centroid frequency.

Figure 8 shows the characteristic frequency of the LFQPO as

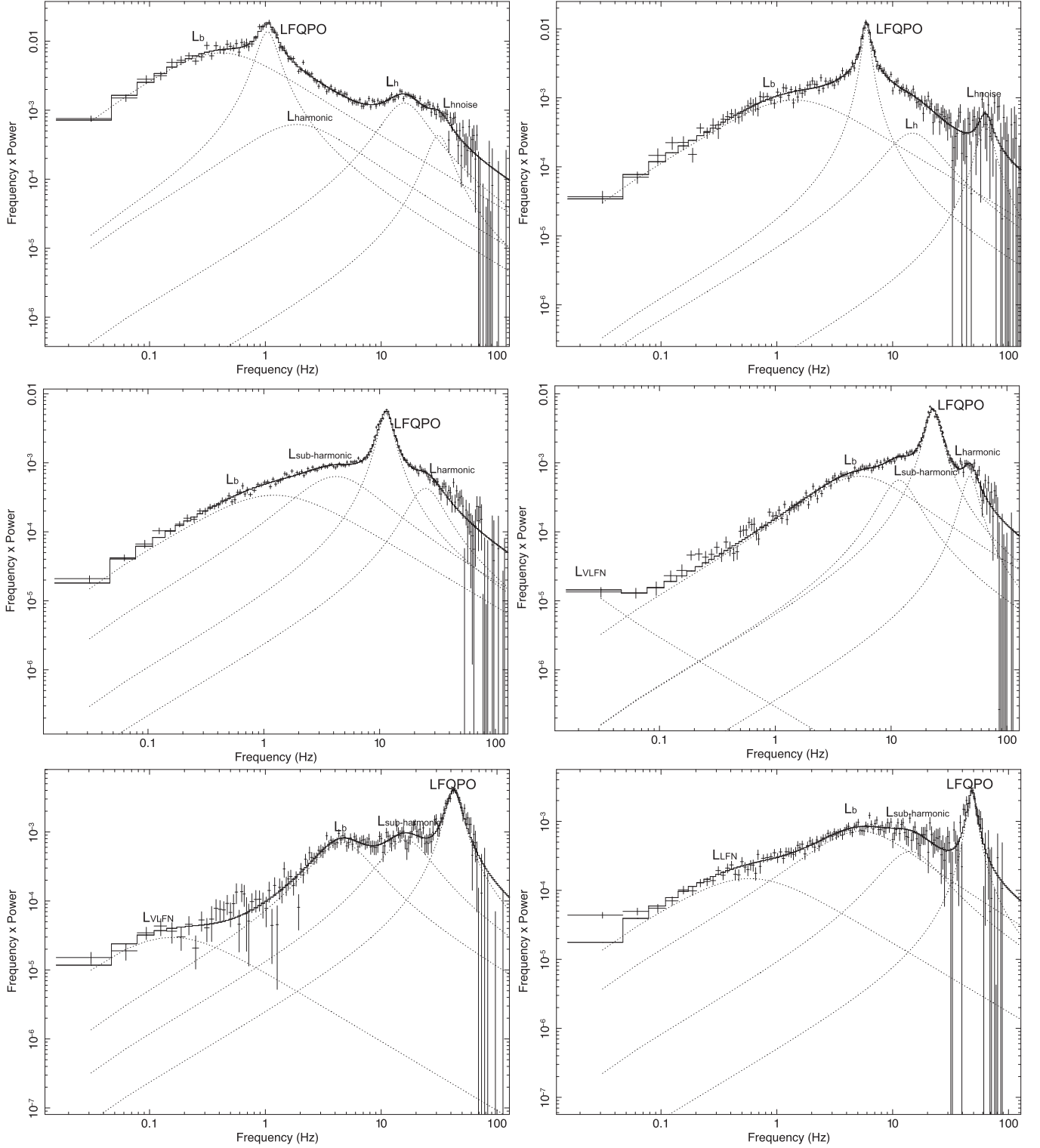


Figure 5. Six representative PDSs of Cir X-1 together with their best-fit components. L_{VLFN} , L_{LFN} , L_b , L_{subh} , LFQPO , L_{harmonic} , L_h , and L_{noise} are labeled in the figure. The following *RXTE* ObsIDs were used: from left to right, top to bottom, 30081-06-03-03, 20097-01-24-00, 20095-01-11-00, 20095-01-23-01, 70020-01-02-02, and 80027-01-05-01.

To better understand how the LFQPO properties evolve as a function of phase, we plot the LFQPO centroid frequency as a function of orbital phase in Figure 1

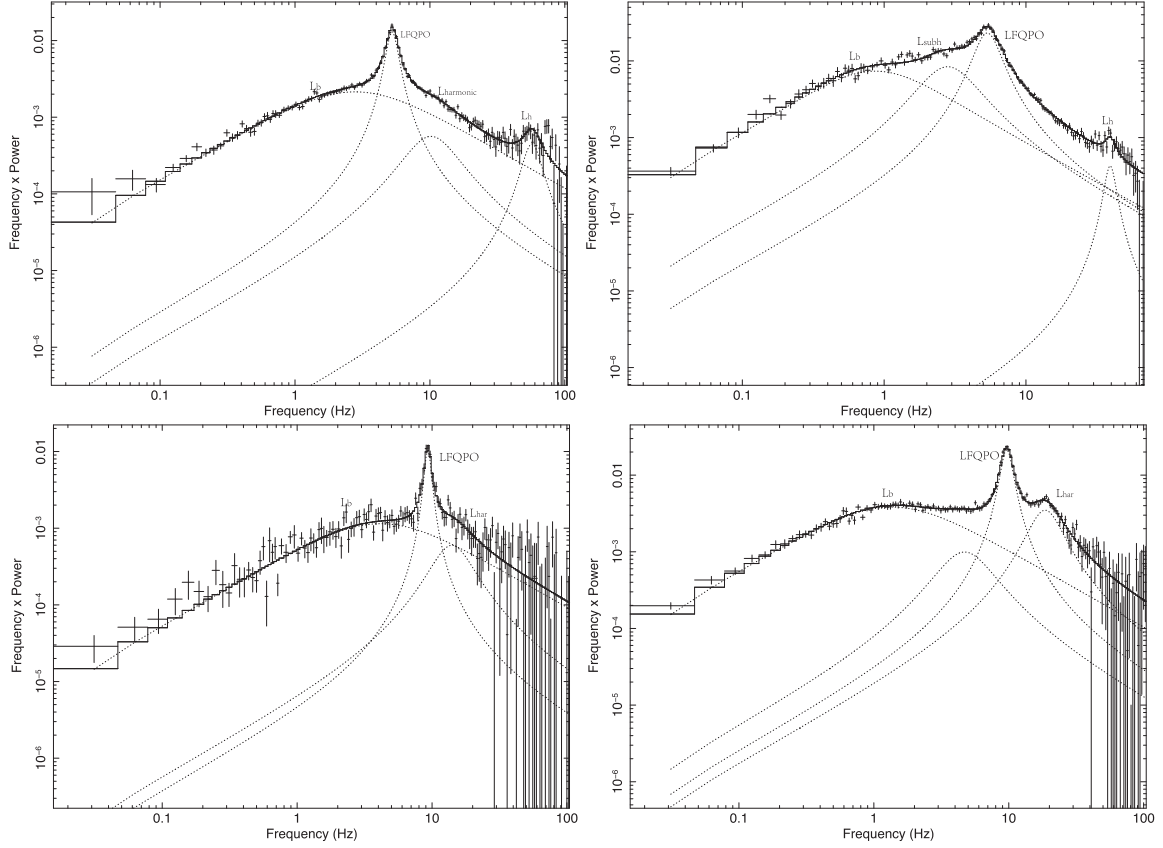
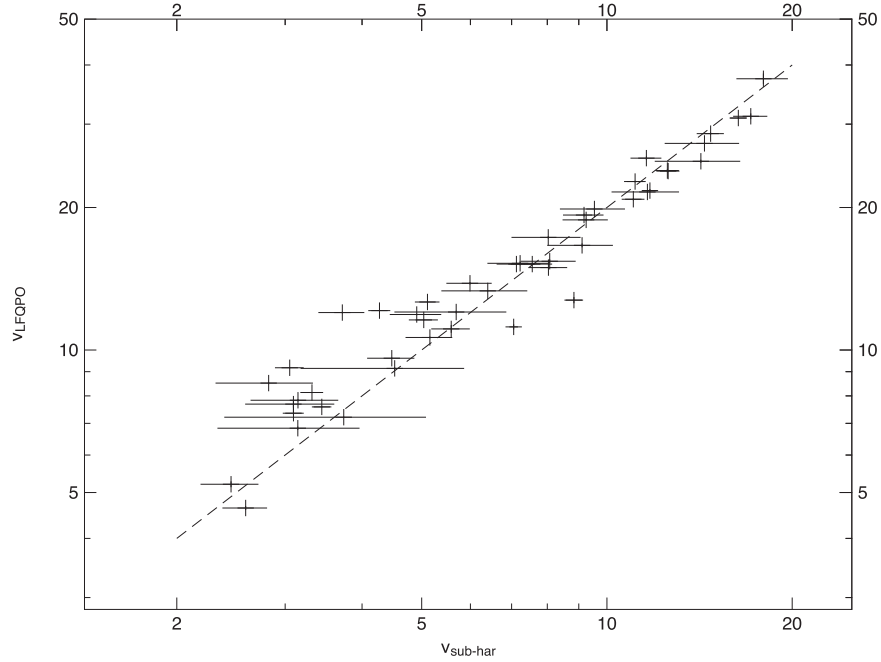


Figure 6. Comparison of power spectra of Cir X-1 QPO without (left panels) or with (right panels) sub-harmonics for the same QPO frequency (~ 5 Hz for the top panels, ~ 10 Hz for the bottom panels). Observations are 10122-01-11-01, 20071-01-07-00, 30080-01-01-12, and 70020-01-04-01 from left to right, top to bottom.



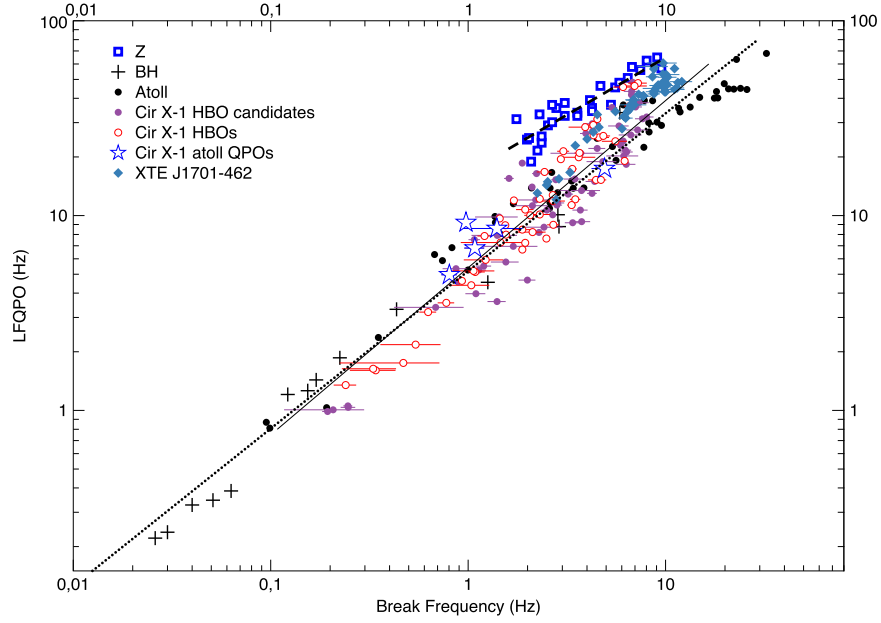
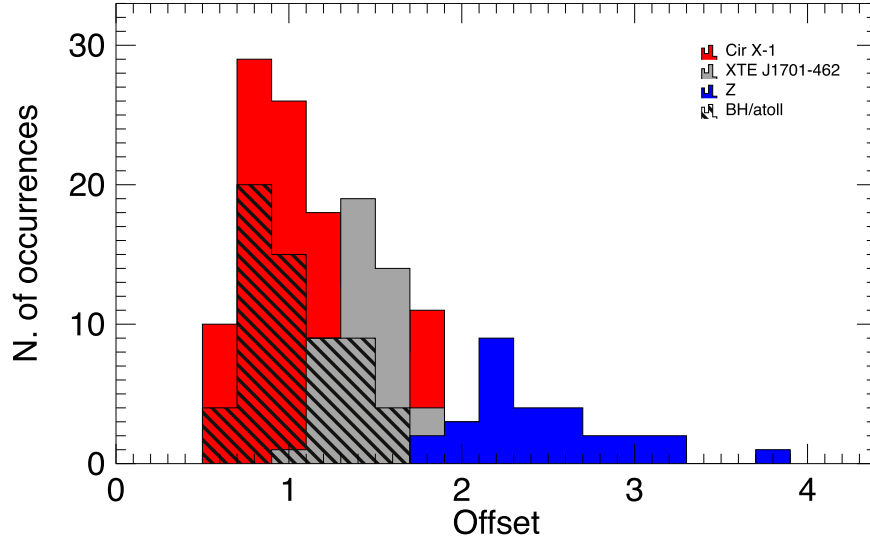


Figure 8. LFQPO frequency as a function of break frequency (the WK correlation), including HBOs from Cir X-1 (red circles), HBO candidates (purple filled circles), and LFQPOs (blue stars) from the atoll state of Cir X-1. Black hole (black crosses) and atoll (filled black circles) sources from Wijnands & van der Klis (1999), Z sources (open blue squares) from Wijnands & van der Klis (1999), and XTE J1701-462 (filled cyan squares) from Bu et al. (2015). The lines are power-law fits to BH/atoll (dotted line), Z sources (dashed line), and Cir X-1 (filled line).



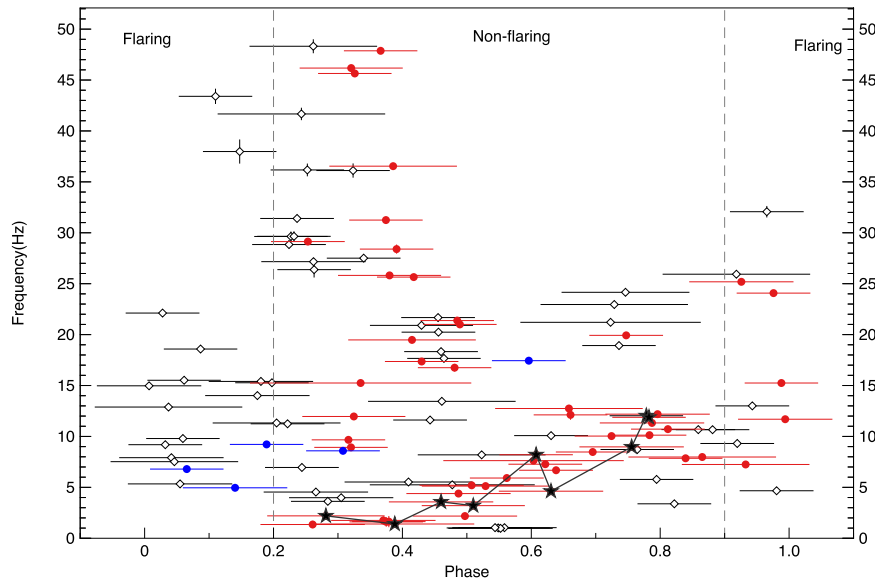
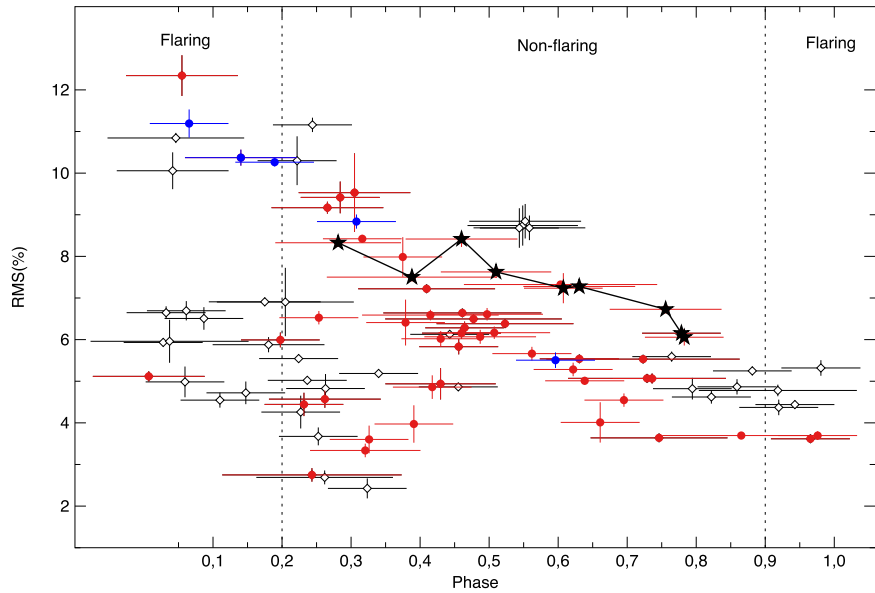


Figure 10. LFQPO frequency as a function of orbital phase. The dashed lines separate the flaring stage ($0.9 < \phi < 0.2$) from the non-flaring phase ($0.2 < \phi < 0.9$). Points from Shirey et al. (1996) are marked as black stars. Open diamonds, red dots, and blue dots represent HBO candidates, HBOs, and LFQPOs from the atoll state of Cir X-1, respectively.



Besides LFQPO frequencies, the WK correlation can also be offset by changes in the break frequency. As mentioned above, the value of ν_b is affected by its nearby LFQPO or sub-harmonic component. However, the sub-harmonic is not always detected significantly. Boutloukos et al. (2006) also studied the timing features of Cir X-1 and found scattering of L_b for certain values of LFQPOs. They suggested that the scattering is caused by two sets of break frequency components. However, after we added a sub-harmonic component in our fit models, the scattering of L_b had obviously reduced. In this case, the second break component mentioned in Boutloukos et al. (2006) could be a non-significant sub-harmonic component.

Our results show that the two transitional Z sources XTE J1701-462 and Cir X-1 lie close to the atoll/BH branch of the WK correlation, offset from the branch of persistent Z sources. We have shown that the presence of a second branch is compatible with being due to a misidentification of the fundamental frequency of the HBO. This dichotomy appears to be visible also in the high-frequency part of the PBK correlation (Psaltis et al. 1999; Belloni et al. 2002).

A model for HBOs based on relativistic LT precession has been proposed by Stella & Vietri (1998). Within this model, the kHz QPOs found in NS binaries are also associated to relativistic frequencies, and it explains naturally the PBK correlation (Stella et al. 1999). This model, which only considers fundamental frequencies set by General Relativity at a single radius, does not address the flat-top noise component and therefore the WK correlation. This model applies both to BH and NS sources. Ingram et al. (2009) and Ingram & Done (2010) proposed a more complex model based on the same frequencies involving the LT precession of a hot inner flow within a truncated accretion disk. Within this model, the flat-top noise arises from variations in mass accretion rate from the outer regions of the accretion flow that propagate inward.