

Probing the X-ray Variability of X-ray Binaries

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Abstract. Kilohertz quasi-periodic oscillations (kHz QPOs) has been regarded as representing the Keplerian frequency at the inner disk edge in the neutron star X-ray binaries. The so-called "parallel tracks" on the plot of the kHz QPO frequency vs. X-ray flux in neutron star X-ray binaries, on the other hand, show the correlation between the kHz QPO frequency and the X-ray flux on time scales from hours to days. This is suspected as caused by the variations of the mass accretion rate through the accretion disk surrounding the neutron star. We show here that by comparing the correlation between the kHz QPO frequency and the X-ray count rate on a certain QPO time scale observed approximately simultaneous in the Fourier power spectra of the X-ray light curve, we have found evidences that the X-ray flux of millihertz QPOs in neutron star X-ray binaries is generated inside the inner disk edge if adopting that the kilohertz QPO frequency is an orbital frequency at the inner disk edge.

1. Introduction

Kilohertz quasi-periodic oscillations (kHz QPOs) in the X-ray flux of about 20 neutron star low mass X-ray binaries (LMXBs) (see van der Klis 2000 for a recent review) are suggested to be the indicator of the orbital frequency at the inner disk edge (Strohmayer et al. 1996; Miller, Lamb & Psaltis 1998; Titarchuk, Lapidus & Muslimov 1998; Stella, Vietri & Morsink 1999;). One of the evidence for this, in addition to the millisecond time scales themselves, is that there are correlations between the kHz QPO frequency and the X-ray flux in these neutron star X-ray binaries on time scales from hours to days (e.g. Yu et al. 1997; Mendez et al. 1998; Zhang et al. 1998). Especially in the two neutron star soft X-ray transients (SXTs) 4U 1608-52 and Aquila X-1, the correlation holds in a large flux range up to an order of magnitude (Mendez 1999/astro-ph/9903469). The correlation forms the so-called "parallel tracks" in the plot of kHz QPO frequency vs. X-ray flux in "atoll" sources. For those "Z" sources the correlation in the plot of kHz QPO frequency vs. X-ray flux may appear as negative correlation, depending on the source branch it stays (Wijnands et al. 1997; Yu, van der Klis & Jonker 2001). These seem consistent with the general idea that an increase of the mass accretion rate (thus an increase/decrease of the X-ray flux) will cause the inner disk edge at radius R_{in} approach closer to

the neutron star, which would introduce an increase of the orbital frequency ν_O at the inner disk edge, and vice versa. The response of the inner disk radius to the mass accretion rate through the disk has been widely accepted in both theory and observations.

Under the assumption that the source movements on those correlation tracks are because of the variation of the mass accretion rate at the inner disk, and the kHz QPO frequency is an indicator of the orbital frequency at the inner disk edge (notice that the kHz QPO frequency is not necessary to be the orbital frequency itself), the correlation between the kHz QPO frequency and the X-ray flux on each correlation track then probably represents the correlation between the inner disk radius and the mass accretion rate through the inner disk. Thus the X-ray flux variabilities on each track which occurs on time scales of hours to days could be an accretion mode. Similar variability modes on shorter time scales of accretion origin will probably introduce the same correlation between the inner disk radius and the X-ray count rate on its time scale. This then leads to the same correlation between the kHz QPO frequency and the X-ray count rate as that on the long-term tracks, but on a shorter time scale. Usually the X-ray variability of the neutron star X-ray binaries contain a few simultaneous variability components, e.g. continuous noise components and QPOs, covering a large range of time scales from mHz to kHz. The correlation between the kHz QPO frequency and the X-ray count rate tracking a certain variability component then could be a diagnostic of the variability mode and answer whether it is the same as that forms the long-term correlation tracks.

2. Observations and Results

The “parallel tracks” are usually observed in those “atoll” sources such as 4U 1608-52 (Yu et al. 1997; Mendez et al. 1998), Aquila X-1 (Zhang et al. 1998; Mendez et al. 1999), and 4U 1728-34 (Mendez & van der Klis 1999). In those “Z” sources, the correlation between the kHz QPO frequency and the X-ray count rate is complicated. For example, on the Normal Branch (NB) of Sco X-1, the kHz QPO frequency appears anti-correlated with the X-ray count rate, but correlated to the inferred mass accretion rate (Yu, van der Klis & Jonker 2001).

2.1. mHz QPO in the “Atoll” source 4U 1608-52

4U 1608-52 is an X-ray burster and a soft X-ray transient (SXT). In the observations of its outburst decay by the *Rossi* X-ray timing explorer, kHz QPOs were observed showing its frequency correlated with the X-ray count rate on the time scales of hours to days but not longer (eg. Yu et al. 1997; Mendez et al. 1998). More recently, simultaneous with the kHz QPOs, millihertz QPOs at a frequency of $7\text{--}9 \times 10^{-3}$ Hz in the X-ray flux of 4U 1608-52 were observed. They are associated with the soft X-ray photons below 5 keV and probably have close relationship with the type I X-ray bursts. This leads to the speculation that the mHz QPO is caused by a mode of nuclear burning at the neutron star surface (Revnivtsev et al. 2001). The corresponding kHz QPO frequency evolution in 4U 1608-52 in response to the mHz pulses was studied with a peak-aligned method after removing the long-term trend by Yu & van der Klis (2002). They found that the kHz QPO frequency is anti-correlated with the mHz QPO flux

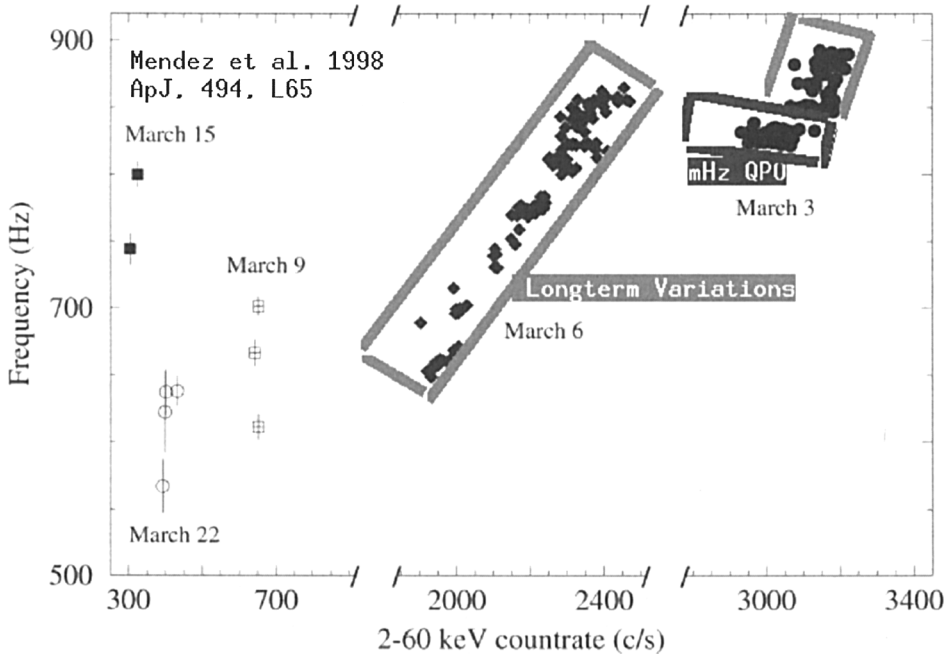


Figure 1. The positive correlations between the kHz QPO frequency and the X-ray count rate on long time scales and on short time scales corresponding to mHz QPOs in 4U 1608-52 (see also Yu & van der Klis 2002).

which can be tracked by the average mHz QPO count rate of 12 seconds. The kHz QPO frequency shift in response to the mHz QPOs is about 0.6 Hz.

2.2. Variability modes in the plot of kHz QPO frequency vs. X-ray count rate

To compare the X-ray count rate variation on a certain QPO time scales with that on longer time scales which forms “parallel” tracks in the plot of kHz QPO frequency vs. X-ray count rate, we show both the tracks and the branch corresponding to mHz QPOs showing the anti-correlation between the kHz QPO frequency and the X-ray count rate in Fig.1. On each correlation tracks, each data point represents the kHz QPO frequency and the X-ray count rate measured in 128 seconds. In the interval corresponding to the mHz QPOs, each data point represents that obtained in 32 seconds.

It is clearly visible that opposite to the overall positive correlation between kHz QPO frequency and X-ray count rate on longer time scales of hours, which forms two tracks from data on March 3, 1996 and March 6, 1996, respectively, the kHz QPO frequency is anti-correlated with the X-ray count rate on the interval corresponding to the mHz QPOs. On this mHz QPO interval, the mHz QPO dominates the X-ray count rate variation. Thus from the plot of kHz QPO

frequency vs. the X-ray count rate, we can discriminate the mHz QPO mode from that of the “parallel” tracks.

3. Discussion and Conclusion

Here I show that the mHz QPOs in 4U 1608-52 can be identified in the plot of the kHz QPO frequency vs. the X-ray flux or by studying their correlation on a certain timescale corresponding to the mHz QPOs. This can be applied to the X-ray variability components we know in both neutron star X-ray binaries and possibly black hole X-ray binaries. The application to the noise components and other QPOs in neutron star X-ray binaries is straight forward and we may be able to determine the origin of those variability modes.

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