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Time lags in the kilohertz quasi-periodic oscillations of the low-mass X-ray binary 4U 1608-52

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Since (part of) the high-energy radiation emitted in X-rays from the surface of the neutron star (NS) is reprocessed an re-emitted at lower energies in the accretion disk, one can constrain the size of the (re-)emitting region measuring the time lags between low- and high-energy photons of the kilohertz quasi-periodic oscillations (kHz QPOs). We studied the system 4U 1608-52, in which the frequency of the kHz QPOs ranges from 540 to 1060 Hz. If these QPOs come from the inner edge of the accretion disk, the time lags should change with frequency, as the inner disc radius changes. We find a significant dependence of the time lags with energy, but a weak (if any) dependence with frequency and use these results to constrain the location at which these QPOs are produced.

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1. Introduction

In binary systems with a weakly magnetized neutron star (NS) as primary and a low-mass secondary star there is an accretion disc that extends very close to the surface of the NS. The kilohertz quasi-periodic oscillations (kHz QPOs) in this kind of systems are thought to be produced at (or close to) the inner edge of the accretion disk. In this paper we study the neutron star X-ray binary source 4U 1608-52 using data from the Rossi X-ray Timing Explorer (RXTE) of the 1998 outburst of the source.

In 4U 1608-52, the kHz QPOs appear in pairs and we now know that the kHz QPOs drift in frequency and so their properties vary, for instance the peak separation is not constant but has a complex relation [1], [2].

Energy-dependent time/phase lags are one of the most powerful and promising tools to constrain the X-ray emission mechanisms and geometry in these systems [7], [8]. In this paper we develop a method for selecting our data in energy channels and in frequency (of the centroid frequency for the lower and upper kHz QPOs) to keep track of the QPO parameters as a function of frequency, keeping the balance among the selections and optimizing the statistics.

We confirm that on time scales of the kHz QPOs the soft photons lag the hard ones by $\sim 10\mu sec$ to $\sim 70\mu sec$ [3]. The soft lags increase with energy but depend weakly (if at all) on the QPO frequency. Using a model proposed to explain these delays [4], we calculate the size of the emitting region and compare with other results [5].

Finally we find that the Fourier coherence on the time scale of the kHz QPO is consistent with unity. We also confirm that in 4U 1608-52 the quality factor of the lower kHz QPO drops above $\sim 745Hz$, which has been proposed as an indication of the accretions disc reaching the ISCO [6] or due to a change in the properties of the accretion flow [9] around the neutron star and in the modulation mechanisms [10].

2. Observations and Methodology

We have studied the low mass X-ray binary 4U 1608-52 using data from the RXTE (Rossi X-Ray Time Explorer) satellite of the 1998 outburst, from 24 to 29/03/1998, a subset of the observations used by the authors in [1]. The data come in two modes, each with different definitions of the energy channels (32M and 64M) of the PCA detector onboard RXTE. At that time 4U 1608-52 was in the final stage of the transition between the lower banana and the island state state.

We produced Fourier Power Density Spectra (PDS) every 16 seconds with a Nyquist frequency of 2048 Hz selecting our data in energy and frequency bands as shown in the tables 1, 2 and 3.

The criterium for the frequency selection was defined to comprise a suficiently small range in order to minimize the effects of the changes of the properties of the QPO with frequency, and to have a suficiently large number (balanced among the bands) of PDS in order to reduce their statistical uncertainties.

We used the shift-and-add technique [2] for each frequency interval and for each energy band in order to improve the statistics and then we fitted a constant plus a lorentzian function to the signal of the QPO. Using these selections we calculated the time delays via the cross-spectrum of the

32M		64M	
Channels (abs)	<E> [keV]	Channels (abs)	<E> [keV]
8-12	3.75	8-12	3.75
13-18	5.56	13-17	5.42
19-26	7.96	18-23	7.34
27-35	10.94	24-29	9.47
36-45	14.33	30-41	12.29
46-51	17.49	42-46	15.86
		47-55	18.10

Table 1: Energy modes - averaged by flux

$\Delta\nu$ (Hz)	Width (Hz)	#PDS 32M	#PDS 64M
540-610	70	635	0
610-690	80	553	238
690-770	80	582	399
770-823	53	616	309

Table 2: Lower kHz QPO - counting all observations in that mode together

$\Delta\nu$ (Hz)	Width (Hz)	#PDS 32M	#PDS 64M
859-910	53	612	0
910-993	81	549	176
993-1040	47	604	353
1040-1064	24	622	417

Table 3: Upper kHz QPO - counting all observations in that mode together

higher energy bands relatively to the reference energy band, defined to be the absolute channels 8-12 of both modes, with mean energy 3.75 keV. This was done for each frequency selection. Notice that it was possible to combine the data of both modes, 32M and 64M, because we defined the same reference energy band for both, and simultaneously intercalated the other channels without superposition in energy, much like a ladder.

3. Results

In figure 1 we plotted the lags for three of the frequency selections for the lower kHz QPO. It shows clearly that soft photons lag the hard ones. The solid curves are the best fitting for the model we used (see below).

The fits give the equivalent density of the reflector (the disc); we calculated the typical size of the scattering region in the disc for different optical depths for each frequency band except the first frequency band (540-610 Hz) that shows no significant trend of the lags with energy [see table 4].

We assumed, at first, that these lags are due to the inner edge of the disc that downscatters the photons and thus adopted the geometry in ref. [4]. We found soft lags and for this reason we used the approximation below (valid in this case) in order to fit our data [see ref. [4]].

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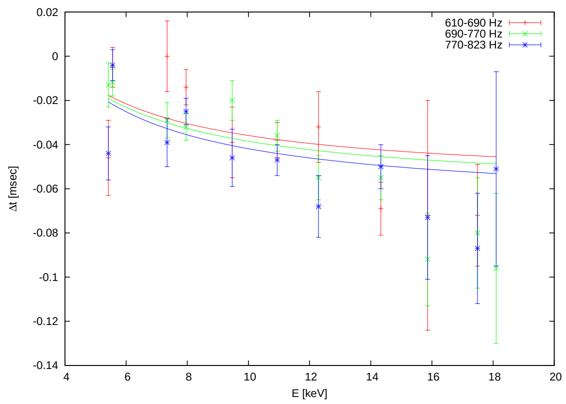

Figure 1: Lag [msec] vs energy [keV], lower kHz QPO in frequency bands 610-690 Hz (red), 690-770 Hz (green) and 770-823 Hz (blue). The lines are the best fit for the density number of the emitting region (the color indicates the frequency band the fitted curve belongs to.)

$$\Delta t \approx -\frac{1}{\sigma_{\rm T} n_{\rm e}^{\rm ref} c}\left(\frac{1}{z_*}-\frac{1}{z}\right). \tag{3.1}$$

$$u \equiv \frac{c\tau_{opt}\delta t}{a} = n_e \sigma_T c \delta t \Rightarrow a = \frac{\tau_{opt}}{n_e \sigma_T}. \tag{3.2}$$

$\Delta\nu$ (Hz)	n_e $[10^{20} cm^{-3}]$	$a_1[km]$	$a_5[km]$
610-690	1.19 +/- 0.23	0.13 +/- 0.02	0.63 +/- 0.12
690-770	1.11 +/- 0.11	0.14 +/- 0.01	0.68 +/- 0.07
770-823	1.02 +/- 0.11	0.15 +/- 0.02	0.74 +/- 0.08

Table 4: Sizes of the scattering region given by the best-fitting the density, for $\tau = 1$ (a_1; threshold of optically thin disc) and $\tau = 5$ (a_5; optically thick).

There is no significant dependence of the lags with energy for the upper kHz QPO since the signal is weaker and the kHz QPO is broad therefore the QPO is less significant in each selection [see figure 2]. However, given the large error bars, we cannot discard that the energy dependence of the lags of the upper kHz QPO is similar to that of the lower kHz QPO.

We calculated the relative intrinsic Fourier coherence between the energy bands to the 3.75 keV band [see figure 3]. Because of the poor statistics, the coherence of the upper kHz QPO is unconstrained.

We also calculated the FHWM of the QPO signal [see figures 4 and 5]. The results are similar to those obtained by the authors of ref. [6].

4. Main conclusions and Next Steps

- The size of the downscattering region is very small, which means that the delays are produced very near the neutron star; the size of the downscattering region is consistent with being the same for the three frequency bands.

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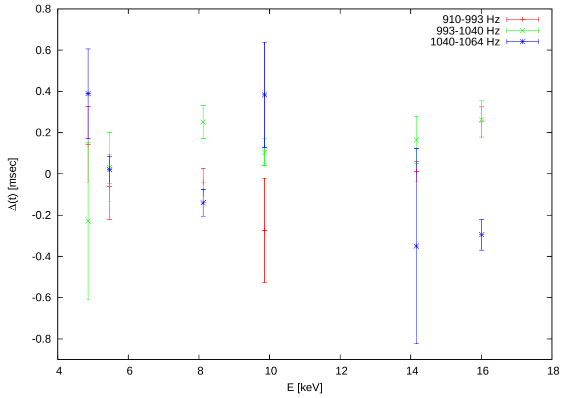

Figure 2: Lag [msec] vs energy [keV], upper kHz QPO in all frequency selections.

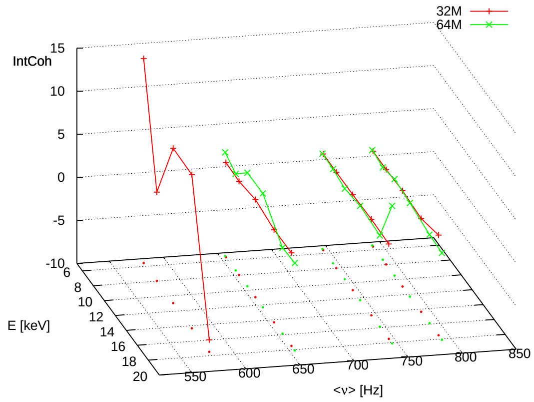

Figure 3: Intrinsic Fourier-coherence vs Energy [keV] vs Mean Frequency; data modes 32M and 64M.

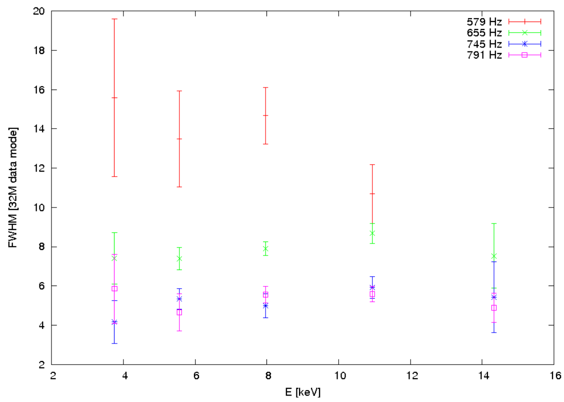

Figure 4: FWHM vs Energy [keV]; data mode 32M.

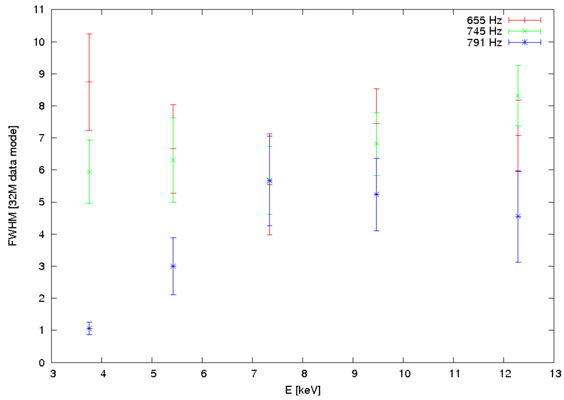

Figure 5: FWHM vs Energy [keV]; data mode 64M.

- The results are based on the model of downscattering of hard photons from the neutron star surface off the inner edge of the disc [4], and we are now working to develop a model that considers reprocessing in the disc.

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