Low and High Frequency Quasi-Periodic Oscillations in 4U1915-05

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Abstract. The X-ray burster and dipper 4U1915-05 (also known as XB1916-053) was observed 19 times for a total exposure of roughly 140 ks between 1996 February and October with the proportional counter array (PCA) aboard Rossi X-ray Timing Explorer (RXTE). We present here the detailed timing study of its X-ray emission. The source was observed in both a high intensity/soft spectral and a low intensity/hard spectral state. The 2-20 keV luminosities are about $1.4 \times 10^{37}$ and $3.2 \times 10^{36}$ ergs s$^{-1}$ in the two regimes respectively (assuming a source distance of 9.3 kpc). We confirm that 4U1915-05 is an atoll source based on its spectral behavior and its aperiodic variability in the frequency range $\sim 4 \times 10^{-3} - 128$ Hz. 4U1915-05 displays red noise below $\sim 1$ Hz, but is especially remarkable for its quasi-periodic variability detected for the first time at several timescales. We detect low frequency quasi-periodic oscillations (LFQPOs) between $\sim 5$ and 80 Hz, as well as high frequency quasi-periodic oscillations (HFQPOs) between $\sim 200$ and 1300 Hz. Both LFQPOs and HFQPOs frequencies positively correlate with the mass accretion rate inferred from the position of the source on the color-color diagram. In a narrow range of luminosity, we also detect twin simultaneous HFQPOs separated by $348 \pm 12$ Hz.

1. Introduction

1.1. High frequency quasi-periodic oscillations in low-mass X-ray binaries

One of the greatest successes of RXTE is the discovery of HFQPOs in the X-ray emission of low-mass X-ray binaries (LMXBs). RXTE made it possible by the combination of the large effective area of the PCA, an excellent time resolution, an extended telemetry bandwidth and optimized observing efficiency. HFQPOs ranging from $\sim 300$ to $\sim 1200$ Hz have been reported so far from 21 neutron star LMXBs [Van der Klis, 1999]. The 6 Z sources, 12 known atoll sources, the unknown bursting source in the galactic center region, the recently discovered X-ray bursters XTE J2123-058 and XTE J1723-376 [Marshall and Markwardt, 1999]. Following their discoveries, it has been realized that they could possibly be used to constrain the fundamental parameters of neutron stars, such as their spin periods, their masses, and their radii. Implications of general relativity in the interpretation of these HFQPOs have also been discussed by several authors like, e.g., Kaaret et al. [1997], Kluźniak [1998], Miller et al. [1998].

In most systems, twin HFQPOs are observed with a separation in the range 220-360 Hz. Changes in the source luminosity cause the twin peaks to shift simultaneously in a way that their separation remains approximately constant. For the Z source Sco X-1 and the atoll sources 4U1608-52, 4U1728-34 and 4U1735-44, however, the frequency separation significantly decreases as the HFQPOs frequencies increase [Van der Klis et al., 1997; Méndez et al., 1998b; Méndez and Van der Klis, 1999; Ford et al., 1998; Psaltis et al., 1998]. In a few X-ray bursters (e.g. 4U1702-43, KS1731-260), which are atoll sources, coherent pulsations have been seen during type I X-ray bursts at frequencies equal or twice the frequency difference between the twin HFQPOs [Markwardt et al., 1999; Smith et al., 1999]. In 4U1636-53 and 4U1728-34, burst oscillations have been detected at a frequency significantly greater than the twin HFQPOs separation [Méndez et al., 1998a; Méndez and Van der Klis, 1999].

Specific also to the atoll sources, HFQPOs are detected when the source is in the so-called island state and on the lower branch of the banana state. These two states are easily identified in color-color diagrams and there is conclusive evidence that the accretion rate increases from the island to the banana state [Hasinger and Van der Klis, 1989]. They are associated with different types of power density spectra (PDS) at low frequencies (in the remainder of this paper we define low frequencies as frequencies below 100 Hz). In the island state, the source displays high frequency noise (HFN also called “flat topped noise”) and the PDS can be approximated by a zero-centered Lorentzian (Olive et al., 1998, for 1E1724-3045), or alternatively by broken power laws (Wijnands and Van der Klis, 1999a, for example). Super-
posed to the noise, a QPO-like feature is generally seen around $\sim 0.5 - 70$ Hz (see Table 1 for a review). In this state, the root mean square (RMS) values of the fluctuations (to the mean flux) reach 50% \cite{van der Klis, 1994}. On the other hand, on the banana branch, the shape of the PDS is roughly a power law with an index of -1.0; the so-called very low frequency noise (VLFN) or red noise \cite{Hasinger, 1989}. In this state, the RMS is around 10% or less. In the lower part of the banana branch, a broad structure, often referred to as "peaked HFN", or a QPO is seen at frequencies in the range 1-70 Hz (see Table 1). A correlation between the centroid frequency of the bump, and the frequency of the upper kHz QPO has been found in several LMXBs \cite[e.g. KS1731-260]{Stella, 1998, Stella, 1999}, and interpreted in the framework of a Lense-Thirring effect \cite{Stella, 1998, Stella, 1999} or a two-oscillator model \cite{Titarchuk, 1999, Osherovich, 1999}.

### Table 1. Sources for which a QPO (or a QPO-like feature or peaked HFN) has been reported in addition to either flat topped noise or red noise in their low frequency ($\sim 10^{-3} - 100$ Hz) PDS.

| Source | Type | Flat topped noise and QPO References | Red noise and QPO References |
|--------|------|-------------------------------------|------------------------------|
| 4U 0614+09 | A | Y 1, 2 | Y 44, 45 |
| 4U 1608-52 | A | Y 3, 4, 5, 2 | - |
| 4U 1702-42 | A | - | Y 14 |
| 4U 1705-44 | A | Y 6, 5, 7 | Y 5 |
| 4E 1724-30 | A | Y 8, 9 | - |
| 4U 1728-34 | A | Y 10, 11 | - |
| KS 1731-260 | A | - | Y 15, 9 |
| 4U 1735-44 | A | Y 2 | Y 16 |
| SLX 1735-269 | A | Y 12, 9 | - |
| 4U 1744-26 | A | - | Y 17, 18 |
| XTE J1806-246 | - | - | - |
| SAX J1808.4-3658 | P | Y 13 | - |
| GX 13+1 | A | - | Y 21 |
| 4U 1812-12 | A | Y 2 | - |
| 4U 1820-39 | A | - | Y 22 |
| GS 1826-238 | A | Y 9 | - |
| 4U 1915-05 | A | - | Y 46 |
| XTE J2123-058 | A | - | Y 23, 24 |
| Sco X-1 | Z | Y 25, 2 | Y 25, 26, 27 |
| GX 340+0 | Z | Y 2 | Y 28 |
| GX 349+2 | Z | - | Y 29 |
| GX 5-1 | Z | Y 2 | Y 30, 31, 32 |
| GX 17+2 | Z | Y 3, 33 | Y 33, 34, 35 |
| Cyg X-2 | Z | Y 3, 36, 37, 38 | Y 36, 37, 38, 39 |
| Cir X-1 | Z | Y 40, 41, 42, 43 | Y 40, 42, 43 |

a A, atoll source; Z, Z source; P, millisecond X-ray pulsar.
b See Van Paradijs \cite{1995} for complementary references up to 1995.
c After the power spectra published in the literature.
d Both atoll and Z classifications have been proposed \cite{Wijnands, 1999, Revnivtsev, 1999}.

References: (1) Mendez et al. \cite{1997}; (2) Wijnands and Van der Klis \cite{1999}; (3) Yoshida et al. \cite{1993}; (4) Yu et al. \cite{1997}; (5) Berger and Van der Klis \cite{1998}; (6) Hasinger and Van der Klis \cite{1998}; (7) Ford et al. \cite{1998}; (8) Olive et al. \cite{1998}; (9) Barret et al. \cite{2000}; (10) Strohmayer et al. \cite{1996}; (11) Ford and Van der Klis \cite{1998}; (12) Wijnands and Van der Klis \cite{1999}; (13) Wijnands and Van der Klis \cite{1999}; (14) Markwardt et al. \cite{1999}; (15) Wijnands and Van der Klis \cite{1997}; (16) Wijnands et al. \cite{1998}; (17) Lewin et al. \cite{1987}; (18) Strohmayer \cite{1998}; (19) Wijnands and Van der Klis \cite{1999}; (20) Revnivtsev et al. \cite{1999}; (21) Homan et al. \cite{1999}; (22) Wijnands et al. \cite{1999}; (23) Homan et al. \cite{1999}; (24) Tomicki et al. \cite{1999}; (25) Van der Klis et al. \cite{1999}; (26) Van der Klis et al. \cite{1999}; (27) Dieters and Van der Klis \cite{2000}; (28) Jonker et al. \cite{1998}; (29) Kuulkers and Van der Klis \cite{1998}; (30) Kamado et al. \cite{1997}; (31) Wijnands et al. \cite{1998a}; (32) Vaughan et al. \cite{1999}; (33) Kuulkers et al. \cite{1997}; (34) Wijnands et al. \cite{1999}; (35) Wijnands et al. \cite{1999a}; (36) Wijnands et al. \cite{1997a}; (37) Kuulkers et al. \cite{1999}; (38) Focke \cite{1999}; (39) Wijnands et al. \cite{1998}; (40) Oosterbroek et al. \cite{1999}; (41) Shirey et al. \cite{1999}; (42) Shirey et al. \cite{1999}; (43) Shirey et al. \cite{1999}; (44) Ford et al. \cite{1997}; (45) Ford \cite{1997}; (46) This paper.

### 1.2. 4U1915-05

In the context of these results, we have analyzed our RXTE observations of the type I X-ray burster 4U1915-05. This source is known as the first dipping X-ray source discovered, providing the first reliable evidence for the binary nature of such sources \cite{1982, White, 1982, Swank, 1982, Smale, 1988}.

The period of the dips in X-rays is 50 minutes, the shortest among dipping sources \cite{1982, White, 1982, Swank, 1982, Smale, 1988}. A modulation is seen in the optical but at a period $\sim$ 1% larger than the X-ray dip period \cite{Callanan, 1995}. The discrepancy between the two periods is confirmed by Chou et al. \cite{1999} who combined historical and recent data (including the RXTE data used in this paper). This discrepancy
has led to several interpretations among which the SU UMa model is preferred, although the hierarchical triple system model proposed by Grindlay et al. (1988) is still possible (Chou et al., 1999).

To date, the only timing study of the non-dipping and non-bursting emission of 4U1915-05 was carried out with the Ginga data, which represented the most extensive X-ray observations of the source before the launch of BeppoSAX and RXTE. The 1.37 keV luminosity varied between $5 \times 10^{36}$ and $1.2 \times 10^{37}$ erg s$^{-1}$, in the range of luminosities previously observed for the source. A V-shape was observed in the hardness (7-18/1-7 keV) intensity (1-18 keV) diagram (Yoshida, 1992). The $3 \times 10^{-3} - 1$ Hz PDS were fitted with a power law of index $-0.6$ for the left branch of the V data and of index roughly $-1.1$ for the right branch data. Yoshida (1992) suggested that 4U1915-05 was an atoll source. Yoshida (1992) interpreted the left branch of the hardness intensity diagram as the island state and the right branch as the banana state, although the two branches overlapped in the color-color diagram.

From an X-ray burst showing photospheric radius expansion in the Ginga data, the distance to the source was estimated as 9.3 kpc (Yoshida, 1992). 4U1915-05 was observed at energies up to 100 keV by BeppoSAX (Church et al., 1998). This was the first observation of a hard X-ray tail in the spectrum of 4U1915-05. Indeed, previous pointed and monitoring observations at high energies with OSSE and BATSE aboard the Compton Gamma-Ray Observatory had failed to detect the burster (Barret et al., 1996; Bloser et al., 1996). 4U1915-05 is the first dipping source to belong to the growing group of LMXBs detected up to $\sim 100$ keV (Barret et al., 2000).

In this paper we report on the timing analysis of the X-ray emission which led to the discovery of HFQPOs and LFQPOs in 4U1915-05. In the next section, we describe the observations and the data analysis. Then, we present the results. Finally, we compare 4U1915-05 to similar sources and discuss the results in the framework of currently proposed models of HF and LFQPOs.

### 2. Observations and data analysis

#### 2.1. The RXTE/PCA observations

4U1915-05 was observed by RXTE on 19 occasions in 1996: on February 10th, March 13th, May 5-6th, May 14th to 23rd, June 1st, July 15th, August 16th, September 6th and October 29th. The log of the observations is presented in Table 2. An observation has an exposure time of roughly 8000 seconds and is provided as typically three data files with gaps between files. These files are referred as segments of observation in our analysis. We report on the data collected in the 2-60 keV range with the PCA. It consists of 5 nearly identical large area Proportional Counter Units (PCU 0 to 4) corresponding to a total collecting area of $\sim 6500 \text{cm}^2$ (Jahoda et al., 1996). For safety reasons, PCUs are switched on and off in the course of an observation. During our observations, the data were mainly obtained in three different PCU configurations: all PCUs on, first four on and first three on. Furthermore, our observations cover two PCA gain

| Name     | Start       | End         | P | M | T$_{\text{total}}$ | B | D | T | R |
|----------|-------------|-------------|---|---|-----------------|---|---|---|---|
| 02/10$^1$ | Feb. 10     | Feb. 10     | 5 | G | 6750            | 0 | 3 | 4112 | 73.0 |
| 03/13$^1$ | March 13    | March 14    | 5 | G | 3316            | 0 | 0 | 2880 | 97.1 |
| 05/05     | May 5       | May 5       | 3, 4 | G | 4039            | 0 | 0 | 3904 | 68.7 |
| 05/06     | May 5       | May 6       | 3, 37 | 4, CB | 6912 | 1 | 0 | 6592 | 62.1 |
| 05/14     | May 14      | May 14      | 4 | E | 6759            | 0 | 3 | 4432 | 29.5 |
| 05/15     | May 15      | May 15      | 3 | E | 6622            | 0 | 0 | 6592 | 41.5 |
| 05/16     | May 16      | May 16      | 3, 11 | E | 7955            | 4 | 0 | 5936 | 42.6 |
| 05/17     | May 17      | May 17      | 3 | G | 7640            | 0 | 4 | 2864 | 35.4 |
| 05/18     | May 18      | May 18      | 3, 12 | 3, E | 7495 | 2 | 4 | 3168 | 21.7 |
| 05/19     | May 19      | May 19      | 2 | E | 7389            | 0 | 2 | 2560 | 22.6 |
| 05/20     | May 20      | May 20      | 3 | E | 7496            | 0 | 2 | 3904 | 25.2 |
| 05/21     | May 21      | May 21      | 3 | E | 7494            | 0 | 4 | 2400 | 23.3 |
| 05/22     | May 22      | May 22      | 3 | E | 8624            | 0 | 6 | 3584 | 27.6 |
| 05/23$^a$ | May 23      | May 23      | 4 | E | 7723            | 0 | 8 | 4128 | 39.8 |
| 06/01     | June 1      | June 1      | 5 | E, CB | 9336 | 1 | 4 | 4544 | 46.3 |
| 07/15     | July 15     | July 15     | 4 | E | 9786            | 0 | 6 | 5168 | 33.9 |
| 08/16     | Aug. 16     | Aug. 16     | 4 | E | 9983            | 1 | 5 | 6384 | 28.1 |
| 09/06     | Sept. 6     | Sept. 6     | 5 | E | 9344            | 0 | 1 | 6032 | 39.5 |
| 10/29     | Oct. 29     | Oct. 29     | 5 | E | 9464            | 1 | 2 | 5120 | 35.9 |

Table 2. Observation log. We list the name assigned to the observation, its start and stop times (day and UT hour), the number of PCUs working (P), the high time resolution data modes M available (G, E and CB designate the \(E_{25} \text{ms} \cdot f_{0.01} \text{Ms} \cdot \text{L}s\), GoodXenon\(16s\) and \(CB \text{ms} \cdot f_{0.01} \text{Ms} \cdot \text{L}s\) and \(2 \text{ms} \cdot f_{0.01} \text{Ms} \cdot \text{L}s\) (Binned Burst Catcher) configurations respectively), the total exposure time (T$_{\text{total}}$) in seconds after screening (on elevation and offset), the number of bursts (B) and dips (D) present, the exposure time in seconds of the persistent light curve after filtering out the bursting and dipping parts (T) and the 2-20 keV background subtracted count rate in units of cts s$^{-1}$ PCU$^{-1}$ (R) of the persistent emission. 

$^1$ Gain epoch 1 data (the other observations are gain epoch 3). 

$^a$ Two small observations were carried out on May 23rd, we merged them together for clarity.
epochs: the February 10th and March 13th observations belong to the first one whereas the following observations belong to the third one. Different response matrices were used for each set. More than 138 ks of good data are available after recommended screening (elevation angle above the Earth’s limb greater than 10 degrees and pointing offset angle less than 0.02 degree).

The all-sky monitor (ASM) aboard RXTE consists of three coded-aperture cameras mounted on a motorized rotation drive, allowing to view different regions of the sky during a satellite orbit [Levine et al., 1996]. The instrument is sensitive in the energy range $\sim 2-12$ keV. Fig. 1 is the ASM light curve of 4U1915-05 during 1996. The binning time is one day. The times of the PCA observations are flagged with arrows. Four X-ray bursts were recorded during the PCA observations: on May 5th, June 1st, August 16th and October 29th. With the exception of the first one, they began during a dip.

2.2. Data modes

The Standard 2 mode is available for each observation. This mode provides counts integrated during 16 seconds in 128 energy channels covering the 2-60 keV energy range. The high time resolution data were provided in two different modes, depending on the observations (see Table 3): the E\textsubscript{125s,\textsubscript{64M,\textsubscript{0,1s}} mode with 122 $\mu$s resolution or the GoodXenon\textsubscript{16s mode with $\sim 1$ $\mu$s resolution. The bursts that occurred on October 29th and August 16th were recorded in the 122 $\mu$s resolution mode. The bursts that occurred on May 5th and June 1st were recorded during 3.75 seconds in a burst catcher mode with 2 ms resolution.

2.3. Data analysis

2.3.1. Light curves, color-color and hardness-intensity diagrams

For the light curves, color-color and hardness-intensity diagrams, we have used the Standard 2 mode data. We made light curves in adjacent energy bands. The bursts and dips were then filtered out after visual screening of the light curves to generate the color-color and hardness-intensity diagrams for the persistent emission. The soft color was calculated as the 3-5 keV/1.7-3 keV count rate ratio, and the hard color as 10-30 keV/5-10 keV.

As all the PCUs have different energy responses, the absence of a PCU can mimic spectral variations. Thus, we used the data collected with the first three PCUs since they were continuously operating during all our observations.

Differences between response matrix of gain epoch 1 and 3 introduce differences in the boundaries of the energy channels used. This instrumental effect introduces shifts between the colors or count rates obtained from different epochs. We quantified these shifts using the Crab nebula which is a steady source. We find that the correction factors to apply to gain epoch 1 data in order to make them match the epoch 3 region are $+10.1\%$, $-1.5\%$, $-1.1\%$ and $+2.8\%$ for the count rates in the energy bands 1.7-3, 3-5, 5-10 and 10-30 keV respectively. The correction factors are $-10.5\%$ and $+4.0\%$ for the soft and hard colors respectively. We applied these correction factors to 4U1915-05 data.

2.3.2. Power density spectra

To investigate the variability of 4U1915-05, we computed PDS using the FTOOLS powspec. We treated separately the data obtained from the different high time resolution modes. To reach timescales ranging from roughly 10 ms to 4 minutes, the data were rebinned to a $\sim 4$ ms resolution. Then, each continuous set was divided into segments of 65536 bins. A fast Fourier transform (FFT) of each segment was computed yielding a low frequency PDS in the range $\sim 4 \times 10^{-3} - 128$ Hz.

To reach timescales ranging from roughly 0.25 ms to 1 second, the data were rebinned to a $\sim 122$ $\mu$s resolution. Each continuous set was divided into segments of 8192
bins. A FFT of each segment was computed leading to high frequency PDS in the range 1-4096 Hz. Then, the low or high frequency PDS obtained from a given set of observations, a given observation or a given segment of observation were averaged together to obtain a final PDS representative of the set, observation or segment.

The PDS were normalized according to Leahy et al. (1983) so that the average power expected from a Poisson distribution is 2. We have checked in the high frequency PDS that the average white noise level above 1500 Hz was indeed 2, indicating that deadtime corrections were not needed.

The error on each PDS bin has been set to

\[ E = \frac{P_{\text{ref}}}{\sqrt{MW}} \]

where \( M \) is the number of raw PDS averaged together, \( W \) the number of raw frequency bins averaged together (Van der Klis, 1989). \( P_{\text{ref}} \) is set to the Fourier power at the point considered for low frequency PDS (where the power can differ significantly from the white noise level 2 because of the source aperiodic variability) and to 2 for the high frequency PDS. Both logarithmic and linear rebinnings were applied.

Different components were summed to fit the resulting PDS: a constant for the white noise level (C), a power law for the VLFN (PL), a cutoff power law for the HFN (CPL). The functional shapes used for the latter components are \( A\nu^\alpha \) for the VLFN and \( A\nu^\alpha \exp(-\nu/\nu_{\text{cutoff}}) \) respectively, where \( A \) is the normalization, \( \alpha \) the power law index, \( \nu \) the frequency and \( \nu_{\text{cutoff}} \) the cutoff frequency. C is a free parameter for the high frequency PDS and is set to 2 for the low frequency PDS. We used Gaussians (G) to describe the QPO features. Note that Lorentzians are also considered (Van der Klis, 1995).

The fits were performed using a \( \chi^2 \) minimization technique. The errors on the analytic model parameters correspond to a \( \chi^2 \) variation of 2.7, equivalent to the 90 % confidence region for a single interesting parameter.

To compute the RMS, the PDS were normalized according to Belloni and Hasinger (1994) taking into account the total and background count rates. The RMS was then obtained by integrating the normalized PDS in the appropriate frequency range.

We have also computed PDS of data from the bursts. For the bursts recorded in the 122 \( \mu \)s resolution mode, we have calculated an FFT power spectrum using 4096 bins lasting 244 \( \mu \)s, so that one PDS corresponds to a segment of the burst of 1 sec duration and the Nyquist frequency is 2048 Hz. For the other bursts, the time resolution is only \( \sim 2 \) ms, yielding a Nyquist frequency of 256 Hz.

2.3.3. Search technique for quasi-periodic oscillations

To look for weak QPOs in the PDS (as in the case of 4U1915-05), we developed an algorithm which computes for each PDS the width of the window which maximises the signal to noise ratio (SNR) within the window. Assuming that a given window of width \( w \) contains N frequency bins, the error on the binned points becomes

\[ E_P = \frac{P_{\text{ref}}}{\sqrt{MN}} \]

and the SNR can be computed as:

\[ \text{SNR}(in \sigma) = \frac{1}{E_P} \sum P_j - P_{\text{ref}} \]

where \( P_j \) are the N PDS points contained in the window of width \( w \) and \( P_{\text{ref}} \) is the reference power. For the low frequency PDS, given the weakness of the VLFN component above \( \sim 1 \) Hz, we looked for excesses above \( P_{\text{ref}} = 2 \), the theoretical level expected from Poissonian noise. PDS have been processed through the algorithm and searched for excesses of widths from 1 to 50 Hz in the frequency range 1-100 Hz. For the high frequency PDS, we looked for excesses of widths 5-200 Hz in the frequency range 100-1500 Hz. We used the noise level averaged above 1500 Hz (\( \sim 2.0 \)) as the reference \( P_{\text{ref}} \) for the search of excesses in the PDS. In both cases, we first selected the positive detections above 3.5 \( \sigma \). A new significance level inferred from the fit was then attributed to each excess in order to take into account the excess shape. We report here on the LFQPOs and HFQPOs which have a significance level greater than 3 \( \sigma \). This significance level is reported in Table 4 with the properties of the QPOs detected in 4U1915-05. We do mention either the observation or the segments, so that no overlapping is possible.

This algorithm does not take into account the number of trials in determining the significance level. To determine the real significance of the detections, we follow Van der Klis (1989) and define the \((1 - \epsilon)\) confidence level \( P_{\text{detect}} \) as the power level that has only the small probability \( \epsilon / N_{\text{trial}} \) to be exceeded by a noise power. \( N_{\text{trial}} \) is the number of different power values that one wishes to compare with \( P_{\text{detect}} \). It may be the total number of bins in the PDS, or less if only a given frequency range is looked for excesses. The number of different PDS looked at may also be included in the number of trials but we did not take it into consideration. In our case, the high frequency PDS are scanned over a frequency range of 1400 Hz. The exposure time of a raw PDS is 1 second (corresponding to a frequency resolution of 1 Hz). The typical exposure time for a segment of observation is 3000 seconds so that M=3000 raw PDS are averaged together to create the PDS representative of the segment. Assuming that the algorithm finds a maximum excess of width 20 Hz (corresponding to a final rebinning factor NW of 20) at 5 \( \sigma \), then \( N_{\text{trial}} = 70 \) and the actual significance level of the signal is 99.998 %. In the worst case of an excess of width 5 Hz (i.e the minimum width considered) found at 3.5 \( \sigma \) (i.e the minimum level obtained from the algorithm considered), \( N_{\text{trial}} = 280 \) and the actual significance level is 92.7 %. The low frequency PDS are scanned over a frequency range of 100 Hz. The exposure time of a raw PDS is \( \sim 256 \) seconds (corresponding to a frequency resolution of \( 4 \times 10^{-3} \) Hz). A PDS representative of a 3000 seconds segment is obtained from M=12 raw PDS. In the worst case of an excess of width 1 Hz (e.g NW=256) at 3.5 \( \sigma \), then \( N_{\text{trial}} = 100 \) and the true significance level is 97.0 %.
3. Results

3.1. Light curves, color-color and hardness-intensity diagrams

Fig. 2 shows the global evolution of the persistent emission during our observations. Each point gives the 2-20 keV background subtracted count rates averaged over each observation. The corresponding exposure time is given in Table 2. The symbols labeled with the date of the observation will be used throughout the remainder of this paper.

![Fig. 2. Evolution of the persistent emission during the observations. The 2-20 keV background subtracted count rates are averaged over each observation. The corresponding exposure time is given in Table 2. The symbols labeled with the date of the observation will be used throughout the remainder of this paper.](image)

Fig. 3 shows the color-color diagram. The points seem to form a “Banana” shape than can be approximated by a spline.

![Fig. 3. Color-Color diagram. The binning time is 512 seconds and a typical error bar is shown. The thick line is the spline used to approximate the position on the color-color diagram. This position is quantified by the curvilinear coordinate $S_a$ chosen arbitrary. The positions $S_a=1$ and $S_a=2$ are indicated by arrows.](image)

![Fig. 4. Hardness-intensity diagrams for the soft color (top panel) and the hard color (bottom panel). In the main panels, the binning time is 512 seconds and a typical error bar is shown. In the inset panels, each point is the average over an observation. The asterisks and the large crosses indicate observations of the LS and HS respectively.](image)

20 keV background subtracted count rate integrated over a single observation. Each plotting symbol is associated with an observation (see the right corner of Fig. 3). As could have been anticipated from Fig. 2, our observations sampled various intensity states of the source: the PCA count rate changes by a factor of $\sim 5$ from roughly 20 to 100 cts s$^{-1}$ PCU$^{-1}$. We also generated light curves in different energy bands between 2 and 30 keV for each observation. No substantial variation is noticeable in the persistent emission over timescales of a few hours.

Fig. 3 shows the color-color diagram. The points seem to form a “Banana” shape than can be approximated by a spline.
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Fig. 5. Average PDS in the LS (left panel) and HS (right panel). The first one is obtained by averaging the PDS of the LS observations available in the 122 μs resolution mode: all the LS observations except a segment of the June 1st observation and the May 17th observation. The second PDS is obtained by averaging the PDS of the HS observations: February 10th, March 13th, May 5th and 6th (all obtained in 1 μs resolution mode). The total exposure time of the first PDS is more than 15 hours whereas it is only \(\sim 3\) hours for the second one. The inset panel is a zoom of the PDS above 1 Hz. The solid lines are the best fits to the data.

| State | Energy (keV) | VLFN \(\chi^2/d.o.f\) | HFN \(\chi^2/d.o.f\) | QPO \(\chi^2/d.o.f\) |
|-------|-------------|--------------------------|--------------------------|--------------------------|
| LS 5-30 | -1.03\(^{+0.16}_{-0.14}\) | 3.7\(^{+0.2}_{-0.2}\) | 0.5\(^{+0.2}_{-0.2}\) | 18.9\(^{+0.4}_{-0.4}\) | 17.5\(^{+0.5}_{-0.5}\) | 0.19\(^{+0.01}_{-0.01}\) | 0.02\(^{+0.01}_{-0.01}\) | 1.9\(^{+0.2}_{-0.2}\) | 159/143 |
| 2-30 | -0.92\(^{+0.08}_{-0.08}\) | 3.8\(^{+0.1}_{-0.1}\) | 0.6\(^{+0.2}_{-0.3}\) | 14\(^{+1}_{-1}\) | 15.4\(^{+0.3}_{-0.3}\) | 0.19\(^{+0.01}_{-0.01}\) | 0.014\(^{+0.002}_{-0.004}\) | 1.9\(^{+0.2}_{-0.2}\) | 175/143 |
| HS 5-30 | -1.24\(^{+0.14}_{-0.14}\) | 3.9\(^{+0.2}_{-0.2}\) | - | 3.8\(^{+0.6}_{-0.6}\) | - | - | - | 0.8\(^{+0.3}_{-0.3}\) | 146/149 |

Table 3. Best fit parameters obtained for the state averaged PDS shown in Fig. 5. The RMS is given in the frequency range \(4 \times 10^{-3} - 1\) Hz for the VLFN, 1-128 Hz for the HFN and 0.1-0.3 Hz for the QPO.

Fig. 4 shows the soft (top panel) and hard (bottom panel) colors as a function of the count rate. In the main panels, the binning time is 512 seconds while in the inset panels, each point is the average over an observation.

Looking at the behaviour of the source within an observation, we see, from the vertical tracks drawn by the points with a same symbol (main panels), that the colors can vary a lot while the intensity remains nearly constant, especially the hard color at low count rates.

Looking at the global behaviour of the source along the observations (inset panels), two groups corresponding to two different spectral states may be distinguished: we refer to the observations with the 5-30 keV intensity below and above \(\sim 30\) cts s\(^{-1}\) PCU\(^{-1}\) as being in the low and high states (LS, HS) respectively. In the LS, we see a trend for the mean hard color to decrease as the intensity increases (Fig. 4 bottom), while the soft color remains nearly constant (Fig. 4 top), so that, on average, the emission softens with the intensity. On the contrary, in the HS, the hard color is nearly constant (Fig. 4 bottom), while the soft color increases with the intensity (Fig. 4 top), so that, on average, the emission hardens. 4U1915-05 is in a low intensity/hard spectrum regime in the LS and in a high intensity/soft spectrum regime in the HS. The spectral modeling of the persistent emission confirms this picture (Bloser et al., 2000). Assuming a source distance of 9.3 kpc, we derived a 2-20 keV luminosity of \(1 \times 10^{37}\) ergs s\(^{-1}\) on March 13th (when 4U1915-05 is the brightest and in the HS) and of \(3 \times 10^{36}\) ergs s\(^{-1}\) on May 18th (when 4U1915-05 is the faintest and in the LS).

3.2. Variability in the \(4 \times 10^{-3} - 128\) Hz frequency range

3.2.1. Average power density spectra

In order to better characterize the source, we looked for possible correlations between the aperiodic variability and the spectral behaviour. We thus averaged together low frequency PDS of the LS on one hand (Fig. 5 left), and PDS of the HS on the other hand (Fig. 5 right), provided that they were obtained from the same timing mode data.

The average PDS of Fig. 5 (left) has an integrated RMS over the entire \(4 \times 10^{-3} - 128\) Hz frequency range...
of 18.8±0.6 %. The PDS shows VLFN up to roughly 1 Hz and HFN around 20 Hz. The model C+PL+CPL provides a better fit than a simple PL ($\chi^2$/d.o.f $\sim 166/146$ and 324/149 respectively). Looking at Fig. 5 (right), we note an excess power around 0.2 Hz. We have fitted that excess with a Gaussian and assessed its significance through the standard F-test. We define P as the probability of rejecting the hypothesis that the fit is better with the additional Gaussian component. In the present case, we have P = 0.09, which means that the QPO is significant at a level of $\sim 91 \%$. With the 0.2 Hz Gaussian added, the results of the best fit are given in Table 3.

We have searched for the same signal in different energy ranges. As an example, in the 2-30 keV band, the significance of the 0.2 Hz signal reaches 93 %. The best fit parameters are given in Table 3. In addition to the state averaged PDS, we computed PDS for each observing day. In some of these PDS, power excesses are visible around 0.2 Hz. However, they are statistically marginal with significance levels less than 90 %.

In the HS, the source displays very low variability. The total RMS in the 5-30 keV energy range is 5.3 ± 0.2 %. At low frequencies, the PDS is still dominated by VLFN up to roughly 0.1 Hz. But above this frequency, the PDS is consistent with having no power. No QPO nor HFN component are present in the PDS. The best fit parameters are given in Table 3.

Looking at each individual PDS, we found that what we called previously the HFN component in the state averaged PDS could be in fact resolved into broad QPO-like features of varying centroid frequencies. In the following, we call these features LFQPOs. Fig. 6 shows two examples of daily-averaged PDS where such a LFQPO is clearly detected. Detailed properties of the LFQPOs are given in the next section. To conclude, 4U1915-05 displays aperiodic variability below $\sim 1$ Hz (the VLFN) and quasi-periodic variability or no variability above 1 Hz.

Fig. 7 displays the RMS as a function of the count rate for each observation. The RMS is given in the $3 \times 10^{-3} - 1$ Hz frequency range where the VLFN dominates, and between 1-100 Hz where the LFQPO is detected. The RMS of the VLFN component ranges between $\sim 3$ and 6 %, whereas the RMS above 1 Hz ranges between $\sim 5$ and 25 %. In the LS, the RMS is high and decreases as the average count rate per observation increases. On the other hand, in the HS, the RMS, after reaching a low threshold,
does not significantly vary as the count rate increases. Thus, the timing behaviour of 4U1915-05 is different in its two states.

3.2.2. Low frequency quasi-periodic oscillations

To further investigate the properties of the LFQPOs detected between a few Hz and 100 Hz in 4U1915-05 (see Fig. 3), and given their relative weakness in the persistent emission, we searched for them in the persistent and dipping emission combined rather than in the persistent emission alone. Although we note that we may be looking at different signals when combining the persistent and dipping emissions, we aimed to get the best signal to noise ratio. The study of the LFQPOs is carried out in the 5-30 keV energy range in order to make easier the comparison with the HFQPOs detected in that energy range with the best signal to noise ratio (see next section). The dipping is large but not complete in that energy range. So, adding the dipping parts, which represent roughly 40 % of the data set, actually increases the signal to noise ratio. This is not negligible because 4U1915-05 is relatively faint in the PCA (2-20 keV background subtracted count rate around 35 cts s$^{-1}$ PCU$^{-1}$, to be compared with $\sim 30000$ cts s$^{-1}$ PCU$^{-1}$ for Sco X-1) and observed with only 3 PCUs for more than the half of our observation (see Table 2). Furthermore, the ingress or egress of a dip lasts more than 1 second (typically 40 s). So, above 1 Hz where the LFQPOs are detected, the PDS of the persistent and dipping emission is not contaminated by the dip phenomenon itself. PDS were computed in the range $\sim 4 \times 10^{-3}$ - 128 Hz the same way as for the persistent emission alone. We averaged together PDS of the same observation or the same segment.

The LFQPO frequencies, FWHM, RMS and significance level are listed in Table 3. Their frequency ranges between 5 and 80 Hz. Their FWHM is around 16 Hz but can vary from 0.5 to 45 Hz, so that their coherence (Q=$\nu$/FWHM) changes roughly from 0.5 to 26 with a mean value of 4. The designation of QPO is then sometimes improper since this is usually used for signals with Q values greater than 2 (Van der Klis, 1995). One of the LFQPOs is shown in Fig. 8. In the second segment of September 6th, we found an excess in the PDS between 1 and $\sim 50$ Hz ($\sim 6.3 \sigma$). A visual inspection of the PDS indicates that this excess is flat, yet above the noise level. For this reason, we were unable to fit it with a Gaussian, and therefore we do not consider this excess as a LFQPO, as defined above. Interestingly enough, however we note that the centroid of the excess ($\sim 30$ Hz) would fall on the correlation between LFQPO frequency and the upper HFQPO frequency, as shown in Fig. 3 (see section 4.3).

We looked for correlations between LFQPOs and spectral states. The bottom-left panel of Fig. 3 shows the LFQPO frequency versus the 5-30 keV count rate. All but one of the LFQPOs are detected in observations of the LS. For 4U1915-05, the LFQPO frequency seems to roughly correlate positively with the intensity, but the scatter is substantial.

The bottom-right panel of Fig. 3 shows the LFQPO RMS as a function of count rate. The RMS ranges from 5 to 20 %. For the HS, we have derived upper limits ranging between 3 and 10 % (see Table 1). No simple relation seems to connect the two quantities.

Recent works have shown that some timing features of similar systems were better correlated with the position on the color-color diagram than with the count rate (Méndez et al., 1999; Méndez and Van der Klis, 1999). We thus examined the QPO properties as a function of the position on the color-color diagram.

Color-color diagrams are sensitive to changes of a few percent in flux ratios between energy bands. Observations allowed to show that during these subtle changes, the X-ray intensity was not a measure of the accretion rate since both positive and negative correlations between the two quantities could occur (Hasinger and Van der Klis, 1983; Van der Klis, 1994). The position on the color-color diagram is a better indicator of the spectral state and hence the accretion rate than the count rate.

The direction of evolution of the accretion rate on the color-color diagrams was inferred from X-ray luminosities and confirmed by multiwavelength and bursts observations (Hasinger et al., 1990; Van der Klis et al., 1990). In the atoll sources, the accretion rate is believed to increase from the island to the lower and then to upper banana states. For our analysis, we refer to the color-color diagram shown in Fig. 3. The spline shows the approximated track followed by 4U1915-05 during the observations. The direction of evolution of the accretion rate along the track is derived from the X-ray luminosity which globally increases from the extremity located at the top of the dia-

![Fig. 8. PDS showing the LFQPO in a segment of the October 29th observation (persistent and dipping emissions combined). The solid line is the best fit of the QPO with a Gaussian.](image-url)
Table 4. Properties of the QPOs detected above 3 $\sigma$ (see text) in 4U1915-05 in the 5-30 keV energy range. We list the observation date (month/day) followed by the segment number or by an asterisk if all segments have been summed, the frequency, FWHM, RMS and significance of the LFQPOs (100-100 Hz) and HFQPOs (100-1400 Hz). The last column is the separation between the twin HFQPOs. All the values are inferred from Gaussians used to fit the QPOs. The reduced $\chi^2$ are close to 1. The error bars are given for the 90 % confidence level ($\Delta \chi^2=2.7$ for the variation of a single parameter). When no signal is present above our confidence threshold, we give a 3 $\sigma$ upper limit on the RMS of a signal of FWHM 10 Hz for the LFQPOs and 50 Hz for the HFQPOs. The significances quoted here are for a single trial only. A more detailed assessment of the significance of the detections taking into account the number of trials may be found in the text (see section 2.3.3). $^a$ flags detections at a significance level between 3 and 4 $\sigma$. The other signals have significance level greater than 4 $\sigma$. $^b$ The excess could not be fitted as a Gaussian (see text). Approximated values of the frequency, FWHM and RMS are given.
Fig. 9. Left: LFQPO (bottom panel) and HFQPO (top panel) frequency as a function of the 5-30 keV count rate (no background subtraction). Right: LFQPO (bottom panel) and HFQPO (top panel) RMS as a function of the 5-30 keV count rate. Small symbols are used for detections between 3 and 4 $\sigma$, big symbols for detections above 4 $\sigma$.

projecting the corresponding point of the color-color diagram (inset panel of Fig. 3, where one point corresponds to one segment) on the spline. This value of $S_a$ could then also be attributed to the LFQPO detected in the given segment. For LFQPOs detected in PDS averaged from several segments of the same observation day, we used the mean of the $S_a$ values found for each segment. The bottom-left panel of Fig. 10 shows the LFQPO frequency as a function of $S_a$. A positive correlation is now clearly visible. In the bottom-right panel of Fig. 10, we show that the LFQPO RMS anticorrelates with $S_a$. In both plots, the scatter is now much smaller than in the previous plots where the count rate was involved. Note that we have also studied the evolution of the LFQPOs as a function of the hard color (10-30 keV/5-10 keV). We concluded that the hard color was a worse indicator of the timing behaviour than $S_a$: the evolution of the soft color had to be taken into account.

3.3. Discovery of high frequency quasi-periodic oscillations

Now, we report on the discovery of HFQPOs from 4U1915-05. The analysis has been carried out in the 5 to 30 keV energy range because in other sources, it is known that HFQPOs are more easily detected in this energy band, as in, e.g. KS1731-260 [Wijmans and van der Klis, 1997]. The persistent and dipping emission were combined to increase the signal to noise ratio (see section 3.2.2).

The results are reported in Table 4 (either the observations or the segments). The HFQPOs frequency ranges
between $\sim 200$ and $1300$ Hz. Their FWHM is around 70 Hz and coherence around 50. Their RMS amplitude is high ($\sim 17 \%$). One of the strongest HFQPO signals is shown in Fig. 11.

We detect twin HFQPOs in 5 segments or observations (Table 4). For four of them, the frequency separation is consistent with being constant. The mean separation is $348 \pm 12$ Hz. For the fifth, the separation is $290 \pm 5$ Hz, thus inconsistent with the previous value. We note that this pair of QPOs occur at 514 and 224 Hz whereas the four other twin peaks occur above 550 Hz. The twin HFQPOs detected in a segment of the June 1st observation are shown in Fig. 12.

HFQPOs were not detected in observations with the largest count rates (February 2nd, March 13rd) with upper limits of $\sim 6 \%$ on the RMS (Table 4). HFQPOs were not detected either in the lowest count rate regime (May 18th to May 22nd); this might be due to a lack of sensitivity. Indeed, only 3 PCUs were working during these observations (see Table 2) and the upper limits on the RMS are not constraining ($\sim 20 \%$, see Table 4).

The top-left panel of Fig. 8 shows the HFQPO frequency as a function of count rate. In this diagram, we observe a branch between 700 and 1100 Hz where the frequency strictly correlates with the count rate. A second parallel branch seems to be drawn at lower frequencies. However, some of the HFQPOs of that branch do not have a simultaneous twin peak in the upper branch. In the lowest count rate regime, the frequency does not follow anymore a simple relation with the count rate.
Fig. 11. PDS for the September 6th observation. The HFQPO is fitted with a Gaussian.

The twin HFQPOs fitted with Gaussians detected in a segment of the June 1st observation. For display purposes, two different frequency binnings have been used.

The top-left panel of Fig. 10 shows the HFQPO frequency as a function of $S_a$. The frequency versus $S_a$ relation appears much simpler than the frequency versus count rate relation. We can now easily identify the upper and lower HFQPOs. The frequency of the upper HFQPO is now well correlated with $S_a$ within its full range. The four twin peaks above 550 Hz are detected within a narrow range of $S_a$ around 3. Their frequency separation is shown with an asterisk on Fig. 10. The pair of QPOs at 224 Hz and 514 Hz appears at the lowest $S_a$ and hence lowest inferred accretion rate. Concerning the HFQPO RMS, we show that, surprisingly, it is better correlated

Fig. 12. LFQPO frequency as a function of the upper HFQPO frequency. We report signals detected simultaneously above 4 $\sigma$. The solid line is the powerlaw of index 1.6 fitting the data. The dashed line is the precession frequency (Lense-Thirring and classical contributions (Stella and Vietri 1998)) assuming standard parameters for the neutron star (see text) and a spin frequency of 348 Hz.

(negatively) with the count rate than with $S_a$ (top-right panel of Fig. 8 and 10 respectively).

3.4. Correlation between low and high frequency quasi-periodic oscillations

Fig. 10 (left panel) shows the parallelism between HF and LF QPOs. Their frequency increases similarly with $S_a$. In Fig. 13, we show the relation between LFQPO and upper HFQPO frequencies when both QPOs are detected simultaneously and above 4 $\sigma$. The correlation between the two frequencies is obvious. It can be approximated with a power law of the form $\nu_{LFQPO} = a \nu_{HFQPO}^\beta$. The first attempt of fitting the data provided a high reduced $\chi^2$ because of the point representing the July 15th observation lying off from the fit. We thus made the fit taking out this point. We obtained $\alpha = (6 \pm 10) \times 10^{-4}$ and $\beta = 1.6 \pm 0.3$ (reduced $\chi^2$ of 1.1) as parameters of the power law drawn as the solid line on Fig. 13.

3.5. Search for oscillations in bursts

For the bursts recorded in the 122 $\mu$s resolution mode, we have computed thirty PDS of 1 second duration so that they covered the rising and decaying parts of the bursts. Each was individually searched for excess power. No such excesses were found either in individual PDS nor in their sum. We therefore conclude that no QPOs were found in those bursts. We have set upper limits on the RMS, assuming a 3 $\sigma$ signal of FWHM 1 Hz in the PDS. We
derive a 3σ upper limit of 3.2% for the October 29th burst, and of 2.8% for the August 16th burst.

For the burst catcher mode, the situation is slightly different. The data cover only the first 3.75 seconds of the bursts, and the Nyquist frequency is 256 Hz which is below the typical frequency of a burst oscillation (Van der Klis, 1999). Note however that coherent oscillations were found at 7.6 Hz in a burst from Aql X-1 (Schoelkopf and Kelley, 1999). For the burst that occurred on May 5th, no significant signals were found in PDS computed for different segments durations (ranging from 1.25 to 3.75 seconds). We have derived a 3σ upper limit of 2.8% (FWHM=1 Hz) for the 3.75 seconds burst duration.

For the June 1st burst, we have also computed an FFT from the 3.75 seconds data set. When the PDS so computed is rebinned by a factor of 4 (∆ν = 1 Hz), two signals are detected by our algorithm: 117.5 Hz (5.4σ, RMS=3.5±0.4%), 225.7 Hz (5.0σ, RMS=2.8±0.2%). However, in the case of these PDS, the corresponding significance detection level (taking into account the number of trials; see section 2.3.3) is only 85%, which is insufficient to claim a detection.

4. Discussion

4.1. The nature of 4U1915-05

The classification introduced by Hasinger and Van der Klis (1988) distinguishes two classes of LMXBs, the Z and the atoll sources. We list the main evidence suggesting that 4U1915-05 is an atoll source. First, 4U1915-05 has always been detected at X-ray luminosities below ~1.5 × 10^37 ergs s^{-1}, which is typical for atoll sources. The Z sources are roughly 10 times brighter. Second, the orbital period of 4U1915-05 (50 min) is among the shortest observed for LMXBs. Now, it is observed that Z sources have longer periods (more than 10 h) than atoll sources, consistent with the idea that their companions are giants or subgiants (Van der Klis, 1993). Furthermore, almost all persistent dippers and bursters belong to the atoll class (Cyg X-2 and GX 17+2 are the only Z sources to display type I bursts (Kahn and Grindlay, 1984; Smale, 1983; Sztajno et al., 1986)). Finally, no Z track in the color-color diagram has been observed neither in the GINGA data (Yoshida, 1992), nor in the RXTE data. Hence, this favors the idea that 4U1915-05 belongs to the atoll class, as suggested by Yoshida (1992).

4.2. The states of 4U1915-05

Identifying the different atoll states in 4U1915-05 is not straightforward. From the hardness-intensity diagrams, we can see that the emission, on average, varies along the observations from a HS to a LS that could correspond to banana and island states respectively. However, we do not observe clearly separated regions in the color-color diagram but rather a continuous banana shape. Furthermore, in its LS, 4U1915-05 does not display HFN which is the typical aperiodic variability of atoll sources in their island state: 4U1915-05 displays VLFN in its both states. This behaviour was observed in the GINGA data as well. Unlike Yoshida (1992) who associated the two regimes with island and banana states, we believe that, during our observations, the source was not in its island state; it probably remained on the banana branch and hence never reached the state which may be at even lower luminosity. Such a state may have been observed by BeppoSAX (Church et al., 1998) since extrapolating the spectral parameters reported by Church et al. (1998) into the 2-50 keV energy range gives a luminosity of 4.5 × 10^{36} ergs s^{-1} while the luminosity derived from the RXTE observations in the same energy band ranges between 5 × 10^{36} and 1.4 × 10^{37} ergs s^{-1} (Bloser et al., 2000).

The properties and presence of HFQPOs strongly depend on source states. For atoll sources, HFQPOs seem to occur at intermediate inferred accretion rates: they are generally not observed in extreme island or upper banana states corresponding respectively to the lowest and highest accretion rates in a given source, as in e.g. 4U1608-52 (Méndez et al., 1999). Twin simultaneous HFQPOs have now been detected in all atoll sources showing kHz variability but Aql X-1 (Van der Klis, 1999). They are always seen during banana states with the exception of 4U1728-34 (Ford and Van der Klis, 1998a; Strohmayer et al., 1996; Méndez and Van der Klis, 1999) and 4U1735-44 (Ford et al., 1998a). This gives further support to the idea that 4U1915-05 was in a banana state during our observation. The highest intensity state where no HFQPO is detected (February and March observations) was therefore more likely the upper banana state. The lowest intensity state was likely the lower banana state, although no HFQPO is detected during May 18th to 22nd observations where the count rate is the lowest; maybe due to a lack of sensitivity (the RMS upper limits corresponding to these observations and quoted in Table 4 are not really constraining).

4.3. Tracking the accretion rate with Sα

It has been shown that the relation between HFQPO frequency and intensity could be much more complex than a roughly one to one correlation as for example in 4U1820-30 (Smale et al., 1997). Numerous branches are clearly visible in the HFQPO frequency versus intensity diagram made with an extensive set of data from 4U1608-52 and 4U1728-34 (Méndez et al., 1999; Méndez and Van der Klis, 1999). Zhang et al. (1998) also showed that Aql X-1, observed in very distinct flux or count rate ranges, could display HFQPOs in the same frequency range. The absence of a simple correlation had previously been noticed in 4U1705-44 (Ford et al., 1998a). For 4U1608-52, the HFQPO frequency was reported to correlate well with the count rate but only on timescales of hours (Méndez et al., 1999). Thus, the relation between HFQPO frequency and intensity seems to differ from source to source; sometimes being complex. On the contrary, the position on color-
color diagram yields a more universal and unique relation as in, e.g. 4U1608-52, 4U1728-34 [Méndez et al., 1998; Méndez and Van der Klis, 1999]. Our study of 4U1915-05 confirms these results. The HFQPO frequency has a simpler relation with the position $S_a$ on the color-color than with the count rate (Fig. 3 and 10). The frequency is well correlated with $S_a$ within its full range.

Now, currently admitted models for HFQPOs, which are beat frequency models (BFM), involve a bright spot at a specified radius of the Keplerian disk, e.g. the sonic radius in the “sonic-point model” [Miller et al., 1998c] to produce the upper HFQPOs. As the accretion rate increases, the disk inner radius moves inwards until the innermost stable orbit is reached. Then, the HFQPO frequency is supposed to correlate with the accretion rate up to a saturation. Thus, the observed complex relations between HFQPO frequency and count rate show that the count rate is not as good as $S_a$ to track the accretion rate. This confirms the studies carried out with EXOSAT data which revealed the position on color-color diagrams as a better indicator of accretion rate than intensity [Hasinger and Van der Klis, 1989; Van der Klis et al., 1990; Hasinger et al., 1990].

However, the position on the color-color diagram may not be the only or the best indicator of the accretion rate or (and) of the timing behaviour. The properties of the HFQPO RMS amplitude found in 4U1915-05 (Fig. 8 and 10) may be new evidence for this. Indeed, in the sonic-point model, the HFQPO amplitude is expected to decrease as the accretion rate increases: the optical depth and electron density increase near the neutron star, and the oscillations generated there are more attenuated during their propagation [Miller et al., 1998c]. Therefore, one would expect the HFQPO RMS to be anticorrelated with the accretion rate. However, for 4U1915-05, the HFQPOs RMS does not seem to be anticorrelated with $S_a$ but rather may be anticorrelated with the count rate (Fig. 10 and 3). Thus, the timing properties do not probably depend only on the position $S_a$. Furthermore, it is not clear why the HFQPOs RMS amplitude and frequency would be driven by different parameters.

Moreover, we have shown that 4U1915-05 can display different timing behaviours (presence or absence of HFQPOs) during observations overlapping in the color-color diagram. The same situation occurs in other sources, e.g. 4U1636-53 [Méndez, 1998].

One explanation may be that these timing behaviours are in fact the same but seem different in appearance because of instrumental limitations. For example, a QPO may be present in two observations overlapping in the color-color diagram but not detected in one of them because one of the detectors has been switched off leading to a loss of sensitivity (see e.g. the RMS upper limits in Table 3).

A second explanation may be that within the timespan for which $S_a$ is computed, the source might have moved in and out the $S_a$ span, washing out temporal signals.

Another explanation is that the source has actually intrinsically different timing behaviours. In this case, this is evidence that the position in the color-color diagram is not the best indicator of the timing behaviour of a source. Then two different conclusions may be considered. First, assuming that the timing behaviour is governed by the accretion rate, then $S_a$ is not a good indicator of the accretion rate. This quantity may be better represented by a combination of parameters or by other parameters than $S_a$. Second, assuming that $S_a$ is a good indicator of the accretion rate, then the timing behaviour is not governed only by the accretion rate.

### 4.4. Low and high frequency quasi-periodic oscillations

LFQPOs between a few and $\sim 80$ Hz have now been observed in several atoll sources (see Table 1). In 4U0614+09 [Ford, 1997], 4U1608-52 [Yu et al., 1997], 4U1702-43 [Markwardt et al., 1999], 4U1728-34 [Strohmayer et al., 1995; Ford and Van der Klis, 1998], KS1731-260 [Wijnands and Van der Klis, 1997] and 4U1735-444 [Wijnands et al., 1998d], such LFQPOs are detected simultaneously with HFQPOs. In the case of 4U0614+09, 4U1728-34 and 4U1702-43, the LFQPO frequency is observed to increase with the HFQPO frequency and with the intensity of the source. First, this indicates that the LFQPOs detected in atoll sources are comparable to the horizontal branch QPOs (HBOs) detected in Z sources, suggesting that similar physical processes are at work in both kind of LMXBs. Second, this indicates that LF and HFQPOs are produced either by related mechanisms or by the same mechanism seen under different aspects or occurring at different locations in the disk. Our study of 4U1915-05 confirms both these conclusions. For the first time, we show a LFQPO in an atoll source varying in frequency and RMS amplitude as a function of the position on the color-color diagram (Fig. 10) the same way as HBOs in Z sources. We note however that in 4U1915-05, the LFQPOs are not strictly correlated with the source intensity, which is a characteristic of HBOs and also of the atoll sources mentioned above showing LFQPOs and HFQPOs. 4U1915-05’s behaviour is thus different in this respect. This may be explained by the fact that in 4U1915-05, the intensity is not correlated with the position in the color-color diagram over the entire range where LFQPOs are detected. On the contrary, the intensity is strictly correlated with the position in the color-color diagram in horizontal branches [Van der Klis, 1995] and probably in some portions of the track of atoll sources. In 4U1915-05, we clearly show (Fig. 10 and 3) that $S_a$, and not the count rate, is the key parameter of the quasi-periodic variability at low frequencies. Thus, the HF and LFQPOs frequencies depend the same way upon $S_a$. 
Psaltis et al. (1999a) have shown that the frequency of the QPOs detected between 0.1 and 100 Hz in numerous Z, atoll or black hole binaries, simultaneously with HFQPOs followed one of a small number of correlations with the lower HFQPO frequency. For 4U1915-05, we could detect simultaneously the LFQPO and the lower HFQPO only during three segments. On the diagram derived by Psaltis et al. (1999a), see their figure 2), these points would fall in the region where the two main correlations merge. Hence, our RXTE observation does not help to conclude about the unified picture suggested for QPOs.

The fact that HBOs and HFQPOs have now been observed simultaneously in Z sources, as in Cyg X-2 (Wijnands et al., 1998a) calls into question the models proposed for QPOs. Indeed, the magnetospheric BFM was first proposed to explain the HBOs in Z sources (Alpar and Shaham, 1985). Later, the same model was suggested to explain the HFQPOs (Strohmayer et al., 1996) observed both in atoll and Z sources. But simultaneous LFQPOs and HFQPOs are difficult to explain with the same model. This requires that the disk is still present inside the radius where the magnetosphere couples the disk and channels the matter (Miller et al., 1998c). In this case, HBOs and HFQPOs can be explained both with the magnetospheric BFM. Psaltis et al. (1999b) have shown that the correlations observed between HBO and HFQPO frequencies in Z sources were indeed consistent with this model. However, this result has been shown so far only for Z sources only. The striking similarities between the LFQPOs detected in 4U1915-05 and HBOs suggest that both phenomena could be interpreted within a same model. But the magnetospheric BFM may not be easily extrapolated to atoll sources because of their lower inferred magnetic fields and accretion rates.

Another possible interpretation comes from Stella and Vietri (1998) who proposed that the LFQPOs observed around 15-50 Hz in several atoll and Z (horizontal branch) sources could result from the precession of the innermost disk regions. In the first version of this model, the LFQPO frequency is the nodal precession ($\nu_{nod}$) of slightly tilted orbits in these regions. This precession frequency (relativistic -Lense-Thirring- and classical contributions) depends on the equation of state of the neutron star but also on its spin frequency and on the Keplerian frequency of the innermost accretion disk region. In the framework of BFM, these latter frequencies are inferred for LMXBs displaying twin HFQPOs, from the frequency separation of the peaks and the frequency of the upper peak respectively. The precession frequency is predicted to vary approximately as the square of the innermost Keplerian frequency. For 4U1915-05, the LFQPO frequency varies as $\nu_{K}^{1.5}$ where $\nu_{K}$ is the inferred Keplerian frequency (see Fig. 13). This is not far from the expected quadratic dependence within the errors. However, the observed LFQPO frequency is $\sim 2$ times greater than the expected precession frequency drawn as a dashed line on Fig. 13. We assumed a neutron star spin frequency of 348 Hz which is the mean peak separation between the twin HFQPOs detected in 4U1915-05. Furthermore, we used the same parameters as Stella and Vietri (1998) for the neutron star: mass $M = 1.97 M_{\odot}$, ratio $I_{45}/M = 1.98$ where $I_{45}$ is the moment of inertia in units of $10^{45}$ g cm$^2$. With these values, Stella and Vietri (1993) found that the precession frequency matched the LFQPO frequency for three different atoll sources (4U1728-34, 4U0614-09 and KS1731-260). Since the neutron star parameters used yield precession frequencies close to the maximum values that can be reached keeping the parameters in the ranges allowed in classical neutron star models, it is unlikely that the Lense-Thirring model can be pushed up to match the LFQPOs in 4U1915-05. The precession frequencies are actually lower than the observed LFQPO frequencies for any values of $M$ and $I_{45}/M$ within their reasonable respective ranges. This would also be the case if the spin frequency were lower than the one inferred from the twin peaks separation (348 Hz). On the opposite, the precession frequencies would roughly match the LFQPOs if the spin frequency were twice that value ($\sim 700$ Hz). With a spin frequency of 348 Hz, matching the observed LFQPO frequencies with precession frequencies would require a ratio $I_{45}/M$ of $\sim 3.5$ which is too large. Indeed, this ratio is inferred to be in the range $\sim 0.5-2$ for realistic rotating neutron star models (Stella and Vietri, 1998; Markovic and Lamb, 1998; Kalogera and Psaltis, 1999; Miller et al., 1998c).

Similar conclusions have been reached for 4U1728-34 (Ford and Van der Klis, 1998), from a larger set of data than the one used by Stella and Vietri (1998), 4U1735-44 (Wijnands et al., 1998c), 4U1702-42 (Marsinko and Stella, 1999), 4U1608-52 (Jonker et al., 1998; Psaltis et al., 1999b; Kalogera and Psaltis, 1999). For the atoll source 4U1608-52, the precession frequency model does not seem to apply either: the spin frequency predicted from the Lense-Thirring model (Yu et al., 1997) is inconsistent with the one inferred from the frequency separation of the twin HFQPOs later observed (Méndez et al., 1998a; Méndez et al., 1998c). In summary, the LFQPOs roughly follow the dependence upon the Keplerian frequency expected within the Lense-Thirring model but occur at a frequency lower than the precession frequency for a growing group of binaries that now includes 4U1915-05. Thus, in order to explain the LFQPOs with the Lense-Thirring effect, further hypothesis are required (Markovic and Lamb, 1998; Marsinko and Stella, 1999; Armitage and Natarajan, 1999; Kalogera and Psaltis, 1999; Schaab and Weigel, 1999). Another possibility is that the LFQPOs correspond to the second harmonics of the precession frequency $2\nu_{nod}$ instead of $\nu_{nod}$ as proposed in a second version of the Lense-Thirring model, maybe because of a modulation at twice the precession frequency generated at the two points where the inclined orbit of the blobs intersects the disk (Vietri and
tion $\Omega = \Omega$

reconstruct the $\Omega$ profile. We thus use the approxima-

tion, radiation forces in the disk could significantly affect
the precession frequencies and thus possibly challenge the
Lense-Thirring model as the explanation for the LFQPOs
(Miller, 1999). Thus, the LFQPOs origins and relations
with HFQPOs remain unclear.

Another model proposes to interpret both the LF and
HF QPOs within the same framework: the two-oscillator
model (Osherovich and Titarchuk, 1999a). In this
model, the lower kHz QPO is the Keplerian frequency
($\nu_K \sim 700$ Hz) at the outer edge of the boundary layer
between the Keplerian disk and the neutron star. Blobs
thrown out from this region into the magnetosphere osci-
llate in both radial and perpendicular modes to pro-
duce an upper kHz QPO (at $\nu_h \sim 1000$ Hz ) and a low
frequency QPO (at $\nu_L \sim 50$ Hz) respectively. Furth-
more, viscous and diffusive processes within the bound-
ary layer produce respectively a low frequency QPO (at
$\nu_L \sim 30$ Hz) and a break (at $\nu_b \sim 8$ Hz) in the PDS. In
this model, the angle $\delta$ between the rotational frequency $\nu = \Omega/2\pi$ of the magnetosphere and the normal to the
neutron star disk is not zero.

The various observed QPOs of Sco X-1, 4U1728-34
and 4U1702-42 have been successfully identified in the
framework of the two-oscillator model (Titarchuk et al.,
1999a). The angle $\delta$ derived is $8.3^\circ \pm 1.0^\circ$, $5.5^\circ \pm 0.5^\circ$ and $3.9^\circ \pm 0.2^\circ$ respectively
for each source. Furthermore, the predicted variation of
$\nu_L$ as $\nu_L = b$ has been checked for number of atoll and Z
sources (Titarchuk et al., 1999).

For 4U1915-05, the identification of the observed
QPOs is not straightforward. 4U1915-05 does not show
any break in its PDS. Only one LFQPO is detected in the
frequency range where QPOs are predicted to be present
at $\nu_L$, $\nu_L$ and $2\nu_L$.

We tried however to test the two-oscillator model. $\nu_L$
$\nu_K$ and $\nu_h$ follow the relation $\nu_K^2 = \nu_h^2 + (\Omega/\pi)^2$ (see
e.g., equation 2 in Osherovich and Titarchuk (1999a)), so
that the rotational frequency can be derived when twin
HFQPOs are detected simultaneously and interpreted as
$\nu_K$ and $\nu_h$.

The bottom panel of Fig. 14 shows the inferred rota-
tional frequency as a function of the lower HFQPO
frequency, for the four segments where twin HFQPOs
are detected above 550 Hz (see Table 1). Theoretically,
$\Omega$ depends on the magnetic structure of the neutron
star’s magnetosphere. In the case of 4U1915-05, there
are not enough simultaneous detections of $\nu_K$ and $\nu_h$
to reconstruct the $\Omega$ profile. We thus use the approxima-
tion $\Omega = \Omega_0 = \text{const}$, as was done also for 4U1702-42

(Osherovich and Titarchuk, 1999a). As shown in Fig. 14
(bottom panel), the rotational frequency is indeed consis-
tent with being constant with $\nu = \Omega_0/2\pi = 373 \pm 36$ Hz.
We note that the pair of QPOs at 224 and 514 Hz would
correspond to a rotational frequency of $231.2 \pm 1.3$ Hz
inconsistent with the previous value and not considered
here.

Knowing $\Omega$, the angle $\delta$ can be derived when $\nu_K$
and $\nu_L$ are measured simultaneously (see e.g. equation 5 in
Osherovich and Titarchuk (1999a)). The top panel of Fig.
14 shows the inferred angle $\delta$ for 4U1915-05, assuming
that the LFQPO frequency is $\nu_L$. $\delta$ is consistent with
being constant with a mean value $\delta = 4.6^\circ \pm 3.1^\circ$. It is in
the range of values found for the other sources, but the
error is particularly large.

We note however that the relation between $\Omega$, $\nu_K$
and $\nu_h$ written above requires $\nu_h > 2\nu$, which becomes $\nu_h > 746$ Hz in the case of 4U1915-05. Now, according to Fig.
14 (left) showing the HFQPO frequency as a function of $S_{\nu}$, when only one HFQPO is detected, it seems to be the upper HFQPO. If we assume that it is actually
the case and that its frequency is $\nu_h$, then the observed
frequency range of $\nu_h$ would begin at $\sim 500$ Hz. This
would be inconsistent with the condition $\nu_h > 746$ Hz
derived according to the assumptions considered above.
4.5. Implications for the neutron star in 4U1915-05

Observations of HFQPOs allow to derive constraints on the neutron star present in the system. In the framework of beat frequency models, the frequency difference between twin HFQPOs is interpreted as the spin frequency of the neutron star. For 4U1915-05, the mean frequency separation is 348 Hz for four segments of observations. This is consistent with values reported in other LMXBs and would imply a neutron star rotating with a 2.8 ms period. However, a frequency separation of 290 Hz is detected for a pair of QPOs at 514 and 224 Hz. The spin frequency detection at 348 Hz needs to be firmly confirmed.

5. Conclusions

We have analyzed the 1996 RXTE data of the X-ray burster and dipper 4U1915-05. We confirm that it is an atoll source that was probably in its lower and upper banana branch during the RXTE observations. We report the discovery of both LFQPOs (5-80 Hz) and HFQPOs (200-1300 Hz) and weak evidence for a 0.2 Hz QPO. We show a correlation between the LFQPOs and the HFQPO frequencies suggesting that both QPOs are produced either by related mechanisms or by the same mechanism seen under different aspects or occurring at different locations in the disk. Furthermore, the LF and HFQPO frequencies both positively correlate with the position $S_0$ of the source in the color-color diagram that is a key parameter of the timing behaviour though probably not the only one.

Four twin HFQPOs are detected above 550 Hz with a frequency separation consistent with being constant (348 ± 12 Hz) suggesting a spin frequency of 2.8 ms for the neutron star. A pair of QPOs below 550 Hz is also detected with a frequency separation of 290 Hz.

Many more observations have been performed by RXTE. They should help to confirm the picture of the aperiodic variability discovered from 4U1915-05. Especially, the 0.2 Hz QPO and signatures of the neutron star rotation should be searched for in the persistent, dipping and bursting emissions.

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