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MILLISECOND OSCILLATIONS IN THE PERSISTENT AND BURSTING FLUX OF AQUILA X-1 DURING AN OUTBURST

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ABSTRACT

The *Rossi X-Ray Timing Explorer* observed the soft X-ray transient Aquila X-1 during its outburst in 1997 February and March. We report the discovery of quasi-periodic oscillations (QPOs) in its persistent flux with frequencies in the range of 740–830 Hz, a *Q*-value of over 100, a fractional rms amplitude of 6.8% ± 0.6%, and nearly coherent oscillations (NCOs) during a type I burst with a frequency of 549 Hz. The frequency of the QPOs in the persistent flux is correlated with the mass accretion rate on a timescale of hours, but not on a timescale of days. This is most likely the manifestation in a single source of the kilohertz QPO puzzle observed among many sources, i.e., on the one hand, individual sources show a correlation between the QPO frequency and the inferred mass accretion rate, and on the other hand, the dozen or so sources with luminosities spanning two decades have essentially the same QPO frequencies. We propose that this multivalued QPO frequency and mass accretion rate correlation indicates the existence of many similar regimes of the accretion disk. These regimes, with a very similar energy spectrum and QPO frequency, are distinguished from each other by the mass accretion rate or the total X-ray flux. The NCOs during the burst can be made almost perfectly coherent by taking into account a large $\dot{\nu}$. This strongly suggests that this frequency is related to the neutron star spin frequency. The large $\dot{\nu}$ is attributable to the expansion or contraction of the neutron star photosphere during the burst.

Subject headings: stars: individual (Aquila X-1) — stars: neutron

1. INTRODUCTION

The launch of the *Rossi X-Ray Timing Explorer* (*RXTE*) in 1995 December marked a new beginning for the study of compact objects and their accretion disks. Since then, quasi-periodic oscillations (QPOs) in the kilohertz range (hereafter kHz QPOs) have been discovered in the persistent flux of a number of low-mass X-ray binaries (LMXBs), including both the Z and atoll sources, as well as sources that have not been classified. For a comprehensive review of the literature on this subject, see van der Klis (1997). Although questions about the detailed physical mechanism for the generation of these oscillations has not been settled, it is clear that the kHz QPOs are related to the dynamic timescale near the neutron star surface and the nearly coherent oscillations (NCOs) likely to be the neutron star spin.

One of the puzzling characteristics of the kHz QPOs is their similarity across the large number of sources that cover two decades in luminosity and probably also two decades in magnetic field. This characteristic raises a serious question as to what roles the overall accretion rate and the neutron star magnetic field play in determining the QPO frequencies and other characteristics. It places a severe constraint on any potential model for their generation mechanism. Another puzzling characteristic of both the kHz QPOs and the NCOs is that the inferred neutron star spin frequencies of these LMXBs are in a very narrow range in the vicinity of 300 Hz (White & Zhang 1997). Both of these puzzles are hard to understand in the context of the standard disk magnetodynamic interactions (Ghosh & Lamb 1991) without invoking some kind of correlation between the magnetic field and the mass accretion rate across these sources (White & Zhang 1997), unless we accept the possibility that either the inferred frequencies from the burst oscillations are not directly related to the neutron star spins or the disk magnetodynamic interactions picture we have at the present is significantly incomplete.

In this Letter, we report *RXTE* observations of Aquila X-1 during its 1997 February outburst. We present analysis results of the kHz QPOs in the persistent flux and the NCOs during a type I burst. We believe that the data strongly indicate that there exist new regimes characterized by different branches in the relationship between the kHz QPO frequency and the total source luminosity.

2. OBSERVATIONS

The data analyzed for this Letter result from 12 separate *RXTE* observations or pointings at Aql X-1 covering the calendar period from 1997 February 16 through March 10. Each observation is typically two *RXTE* orbits in duration and results in about 8000 s of good data segmented into two to three pieces because of *RXTE* passages through the South Atlantic Anomaly and Earth occult of Aql X-1. The typical time gap between two consecutive observations is 2 days. The first observation took place approximately a week after Aql X-1 passed the peak luminosity, and the last took place when the source had essentially reached its quiescent state. Two type I X-ray bursts occurred during these observations, only one of which has data with good time and energy spectral resolution. The other one occurred shortly after an Earth occult, before the instrument was completely ready to take the data. In addition to the standard one and two data sets, we have event-mode data with 64 energy channels and a $128\mu t$ ($\mu t = 2^{-20}$ s) time resolution, and a burst-catcher mode with 1 energy channel and a $128\mu t$ time resolution. During the type I burst, the event-mode data exceeds the bandwidth between the proportional counter array (PCA)

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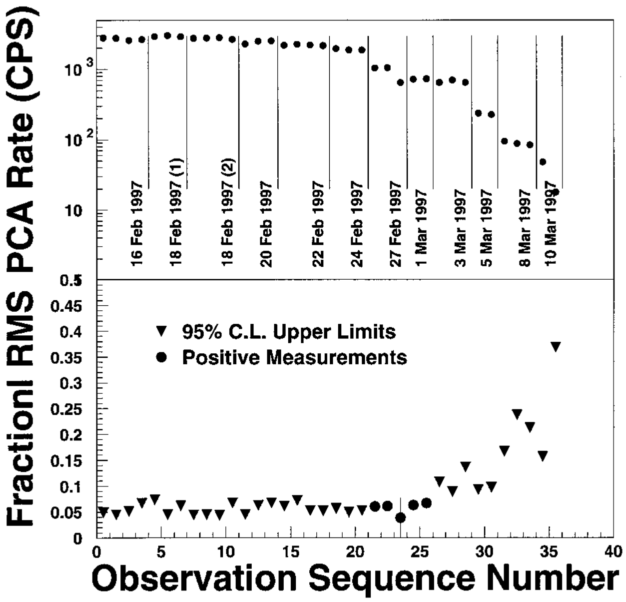

FIG. 1.—*Top panel*: the light curve from the data reported for this Letter. *Bottom panel*: fractional rms for data from each of the 36 *RXTE* orbits. The four filled circles have error bars too small to show. In deriving the upper limits, we have assumed that the QPO frequency can spread over the range of 700–900 Hz.

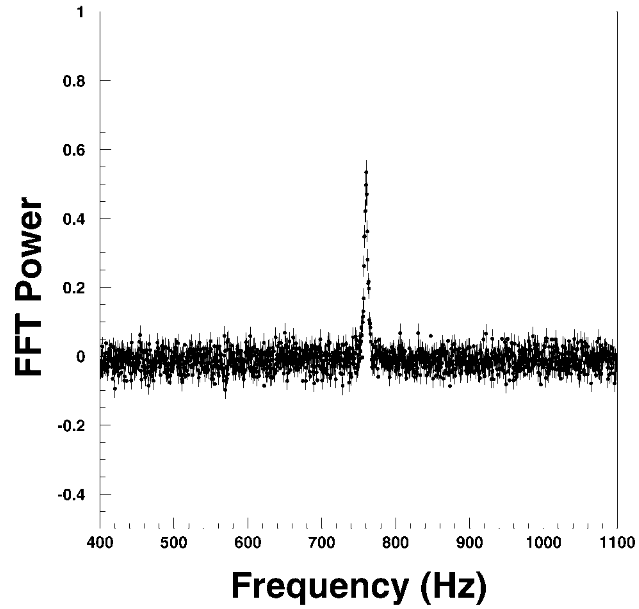

FIG. 2.—Power spectrum lined up with the detected QPO peak as the fiducial mark. The peak is at 760 Hz and has a fractional rms amplitude of 6.8% ± 0.6% and an FWHM of 6.3 Hz. There are no peaks at any other frequencies. The 95% confidence level upper limit is 1%.

and the spacecraft, and therefore it has gaps. We have used the burst-catcher data to perform the timing analysis reported below.

3. DATA ANALYSIS AND RESULTS

3.1. *Characteristics of kHz QPOs in the Persistent Flux*

The top panel of Figure 1 shows the light curve from the entire data set. Each point represents data from one *RXTE* orbit. The 12 intervals bracketed by the vertical lines represent the 12 pointings. We have fitted the energy spectrum with a model consisting of a blackbody component and a power-law component with an absorption column density fixed at $n_{\rm H} = 0.5 \times 10^{22}$ cm^{-2} (Christian & Swank 1997). Hereafter, flux values are calculated using the fitted model and parameters.

We have constructed an average fast Fourier transform (FFT) power spectrum for data from every orbit of the 12 pointings using event-mode data. Only two pointings have shown clearly detectable kHz QPO peaks in their power spectra, the seventh and the eighth, which took place on February 27 and March 1, respectively. The bottom panel of Figure 1 shows the corresponding upper limits for those days when kHz QPOs are not positively detected. The overall average fractional rms amplitude in the *RXTE*/PCA band is 6.8% ± 0.6%. The width of the QPO peak varies with time but does not correlate with any other variable. It has an overall average of 6.23 Hz (FWHM) (see Fig. 2). Figure 3 shows the correlation between the QPO centroid frequency and the measured flux in the 2–10 keV band. The correlation between the frequency and the count rate is very similar, except that there appears to be more scatter among the points. In particular, we have also examined the correlation between the QPO frequency and the flux in the blackbody component and found that the correlation is much worse. This is in contrast to the case of 4U 0614+091 (Ford et al. 1997), where the correlation between the two seem to be rather good over a long timescale. We note that on each day individually, the QPO frequency appears to be correlated with the flux, but there is a shift between the 2 days. The seven points toward the lower left part of the graph that stand away from the rest of the points are there because there was a 10% drop in overall flux right after the type I burst. This kind of correlation on a short timescale, i.e., from minutes to hours, and the apparent lack of it on a longer timescale, i.e., days, between the QPO frequency and the overall flux or count rate have been observed before in other sources, e.g., in 4U 1608−52 (Berger et al.

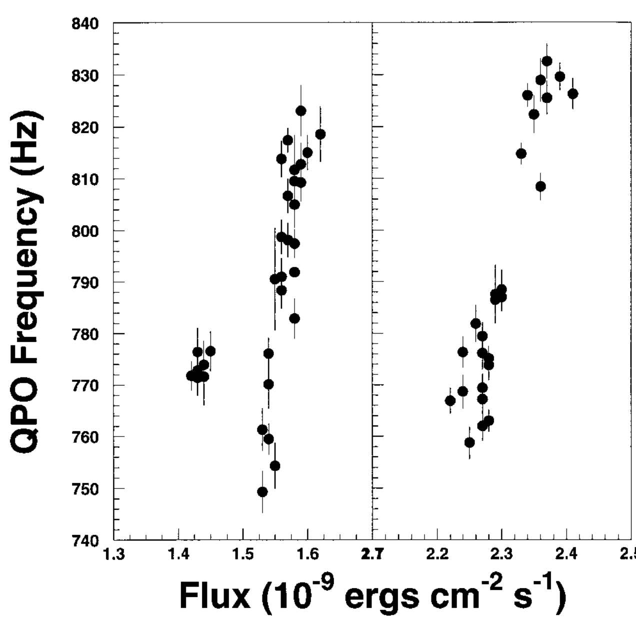

FIG. 3.—QPO frequency vs. flux in the 2–10 keV band. The two clearly separated groups come from data collected on 1997 February 27 (*right*) and March 1 (*left*), respectively.

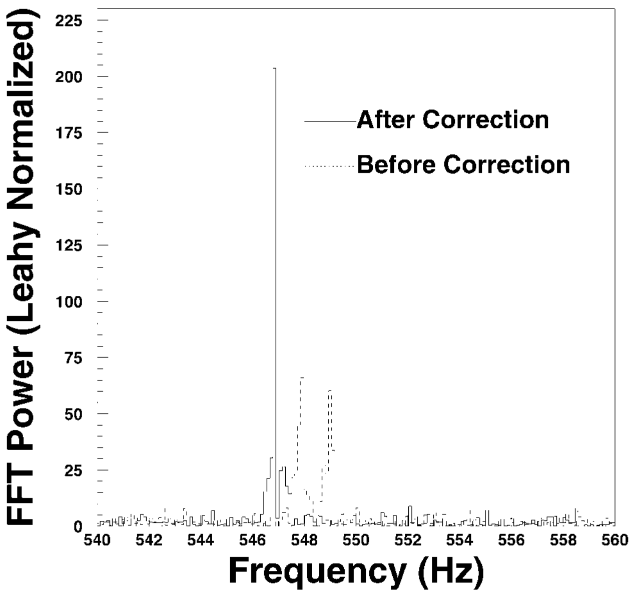

FIG. 4.—Power spectra obtained from the burst. *Dashed histogram*: power spectrum obtained with the original times. *Solid histogram*: power spectrum obtained after correcting the original times with the $\dot{\nu}$.

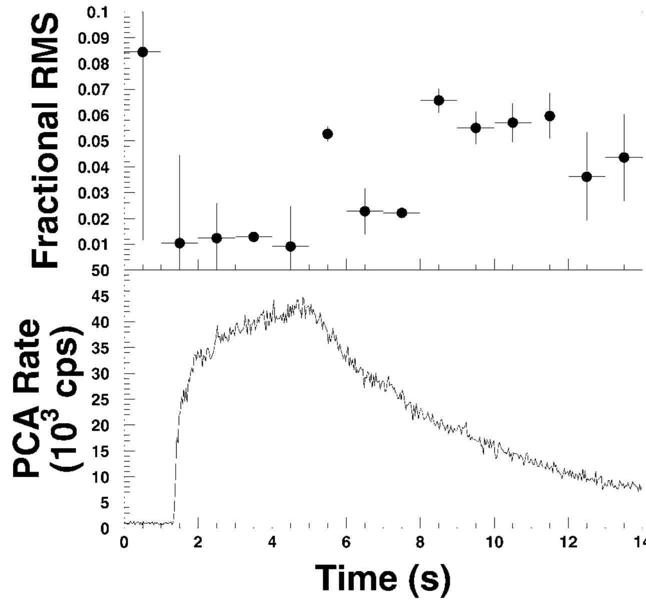

FIG. 5.—*Top panel*: fractional rms amplitude of the 549 Hz oscillations in the burst vs. time. *Bottom panel*: light curve of the burst. The time 0 in the plot corresponds to UTC 23:27:39 on 1997 March 1.

1996; Yu et al. 1997) and 4U 0614+091 (Ford et al. 1997). It shows up very dramatically in these observations of Aql X-1. The rms amplitude varies with energy. They are 5% ± 1% and 9% ± 1% in the 2–5 and 5–10 keV bands, respectively.

Since only one QPO peak is observed on each of the 2 days, it is possible that, even though they cover a similar range in frequency, they could be the manifestations of the two QPO peaks that have been commonly observed in other sources, e.g., 4U 1728−34. To investigate this possibility, we have compared the dynamic FFT power spectrum of 4U 1728−34 obtained over a 2 day period in 1996 February with that of Aql X-1 on 1997 February 27 and March 1. We have found that in the case of 4U 1728−34, the QPO with the lower frequency is always much narrower in width than the QPO with the higher frequency. They can be distinguished on power spectral width alone. On the other hand, the QPO peaks of Aql X-1 during the 2 days look indistinguishable in width. In particular, their widths are very similar to the widths of the lower frequency QPO peak of 4U 1728−34. Therefore, we conclude that most likely the Aql X-1 QPOs we have observed during the 2 days are the same QPO peak.

Following Méndez et al. (1998), we have also searched for a second QPO peak by fitting the power spectrum from every 64 s of data and using the frequency from the fit to align all the power spectra. As shown in Figure 2, we have found no indication of a second peak anywhere in the resulting power spectrum. In particular, we have examined the part of the power spectrum where one would expect a second peak, namely, 275 Hz above or below the existing QPO peak, and found no statistically significant enhancement at all. The 95% confidence level upper limit is 1%.

3.2. *Oscillations during the Burst*

An FFT of the 14 s time series of the burst-catcher data reveals that its intensity oscillates at frequencies near 549 Hz, as shown by the dashed histograms in Figure 4. To investigate the frequency and its amplitude variation with time, we have constructed power spectra for each of the 14 s of data, as shown in Figure 5. It can be seen that, statistically speaking, the oscillations do not start until after the peak of the light curve, which is shown in the bottom panel.

To investigate whether or not the oscillation during the burst is coherent, we have performed a search in ν-$\dot{\nu}$ space for optimal values of ν and $\dot{\nu}$ in order to minimize the width of the FFT peak. The detailed procedure is that, given a trial pair of $(\nu, \dot{\nu})$, we first transform the original arrival time t_0 of each photon to $t_1 = t_0 + \dot{\nu}t_0^2/\nu$ and then construct the FFT power spectrum using the new time series of t_1. Using the 8 s of data right after the peak of the light curve, we have found that when $\nu_0 = 547.8$ Hz and $\dot{\nu} = 0.14$ Hz s^{-1}, we obtain the power spectrum with the minimal width, as shown by the solid histogram in Figure 4. The amount of power in the peaks of the dashed and solid histograms is 418 ± 9 and 425 ± 9, respectively. In other words, we have gathered all the powers from a much larger frequency region into a much smaller region by taking into account a $\dot{\nu}$. The width of the resultant peak is such that, although it is not consistent with perfect coherence, it is fairly close. Therefore, we conclude that this is strong evidence to support the interpretation that the observed oscillations are due to the spin of the neutron star photosphere. The large $\dot{\nu}$ indicates that the photosphere is probably mostly decoupled from the rest of the star and therefore conserves its own angular momentum in the course of contraction (Strohmayer et al. 1997). The inclusion of a $\ddot{\nu}$ does not decrease the width of the peak.

4. DISCUSSION

Since the energy spectrum of the source changed very little, if any, from February 27 to March 1, it is quite reasonable to assume that the measured flux and the true mass accretion rate are positively correlated. Figure 3 clearly indicates that it is not possible that, given a mass accretion rate or, for that matter, given an X-ray flux level, the QPO frequency is uniquely determined. On the contrary, Figure 3 clearly indicates that at least two flux levels can give the same QPO frequency. We believe this is a clear manifestation in a single source of the puzzle we discussed in § 1; i.e., on the one hand, there appears to be a correlation between the QPO frequency and the source luminosity for individual sources; on the other hand, despite the vast difference in mass accretion rates, the QPO frequencies are essentially the same among all those sources. It is therefore reasonable to conclude that, in LMXBs, regimes with essentially identical QPO frequency and energy spectrum can exist at very different fluxes or mass accretion rates.

This conclusion is inevitable when one examines Figure 3 further. For example, on 1997 February 27, as the flux decreased, the QPO frequency also decreased. Had the observation been carried out continuously from February 27 through March 1, we would have had to observe one of the following three possibilities: (1) at some point, the kHz QPOs cease being observable for some time and then become observable again at a higher frequency; (2) at first, the QPO frequency is positively correlated with the flux until the frequency reaches a smaller value than 750 Hz, then they become anticorrelated for some time so that as the flux decreases, the QPO frequency increases until it reaches above 830 Hz and the anticorrelation changes back to the positive correlation; and (3) as the flux decreases, there is a sudden and discontinuous jump in the QPO frequency from below 750 Hz to above 830 Hz. In all likelihood, the first possibility probably would have been observed. The reason is that, to our knowledge, the anticorrelation required by the second possibility has never been observed in any source at any time. Nor has the sudden and discontinuous change in QPO frequency of the third possibility.

The data we have presented have naturally led us to the conclusion that the total X-ray flux, and therefore the total mass accretion rate, of a source cannot uniquely determine the frequency of the kHz QPOs. Moreover, we infer from the data that there exist many similar regimes for the inner region of the accretion disk. In each of these regimes, the kHz QPO frequency is more or less tightly correlated with the mass accretion rate or the total X-ray flux. The QPO frequency ranges of these regimes are rather similar. They are all in the vicinity of 1000 Hz. The disk can make a transition from one regime to another with change in the overall mass accretion rate.

This transition of a LMXB from one state to another with change in mass accretion rate is not new. For example, the Z source GX 5−1 is believed to move along its Z track on the X-ray color-color diagram as the mass accretion changes (Hasinger & van der Klis 1989). This motion along the Z track, however, involves significant changes in the energy spectral shape. What is new with Aql X-1 is that, even though the mass accretion rate and the energy spectral state can be different from time to time for a given source, the geometric location (as inferred from the kHz QPO frequency) of the disk with respect to the neutron star does not seem to change by much. This is just another way of saying that the mass accretion rate does not directly determine the QPO frequency. It is the disk regime that determines the large scale of the kHz QPO frequency, and the mass accretion rate affects it in the smaller scale in between regime changes.

We conclude by noting that a possible scenario explaining the observed two regimes on the QPO frequency versus flux plane is that the disk structure changed during the decay of the outburst. The different regimes correspond to different vertical scale heights. Therefore, kHz QPOs can be used to probe the accretion disk structure evolution.

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