DISCOVERY OF A SECOND KILOHERTZ QUASI-PERIODIC OSCILLATION PEAK IN 4U 1608−52

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ABSTRACT

Using a new technique to improve the sensitivity to weak quasi-periodic oscillations (QPOs), we discovered a new QPO peak at about 1100 Hz in the March 1996 outburst observations of 4U 1608−52, simultaneous with the ∼600–900 Hz peak previously reported from these data. The frequency separation between the upper and the lower QPO peaks varied significantly from 232.7 ± 11.5 Hz on March 3 to 293.1 ± 6.6 Hz on March 6. This is the first case of a variable kilohertz peak separation in an atoll source. We discuss to what extent this result could be accommodated in beat-frequency models such as proposed for the kilohertz QPOs. We measured the rms fractional amplitude of both QPOs as a function of energy, and we found that the relation is steeper for the lower than for the upper frequency peak. This is the first source where such a difference between the energy spectrum of the two kilohertz QPOs could be measured.

Subject headings: accretion, accretion disks — stars: neutron — stars: individual (4U 1608−52) — X-rays: stars

1. INTRODUCTION

Recent observations with the *Rossi X-Ray Timing Explorer* (*RXTE*) have led to the discovery of kilohertz quasi-periodic oscillations (kHz QPOs) in about a dozen low-mass X-ray binaries (LMXB; see van der Klis 1997a for a review). In most cases the power spectra of these sources show twin kHz peaks that move up and down in frequency together, keeping a constant separation (e.g., Strohmayer et al. 1996a; Wijnands et al. 1997; Ford et al. 1997a). Sometimes a third kHz peak is detected near a frequency equal to the separation frequency of the twin peaks (Strohmayer et al. 1996a) or twice that (Wijnands & van der Klis 1997; Smith, Morgan, & Bradt 1997), indicating a beat-frequency interpretation, with the third peak near the neutron star spin frequency (or twice that value) (Strohmayer et al. 1996b). However, in Sco X-1 the twin peak separation varies, which is not consistent with a simple beat-frequency interpretation (van der Klis et al. 1997a).

The transient atoll source (Hasinger & van der Klis 1989) 4U 1608−52 was observed with *RXTE* on 1996 March 3, 6, 9, and 12 during an outburst (Berger et al. 1996). In the first three pointings a single QPO peak was detected in the power spectra, with a frequency that changed from ∼570 to ∼890 Hz, while on March 12 no QPO peak was detected at frequencies ≳100 Hz. After the outburst, further observations were per-

formed by *RXTE* on 1996 August 1, October 24, and 1997 July 18.

In this Letter we report on the results obtained from a reanalysis of the data discussed by Berger et al. (1996), including more data from March 6 not analyzed in that paper, and an analysis of the new observations of 4U 1608−52 carried out by *RXTE* since then. Using a new technique to increase the sensitivity to weak QPOs, on March 3 and 6 we detected a second peak near 1100 Hz, simultaneous with the ∼600–900 Hz peak, which previously went unnoticed.

2. OBSERVATIONS AND DATA ANALYSIS

We describe four *RXTE* observations of 4U 1608−52 in outburst on 1996 March 3, 6, 9, and 12 (see Berger et al. 1996), plus three additional ones spanning 3, 3.8, and 6 ks starting UTC 1996 August 1 12:13:20, 1996 October 24 22:30:24, and 1997 July 18 02:04:16, respectively.

High time resolution data were collected on March 6 only from channels 0 to 49 (∼2–12.7 keV) and at all other times in the 2–60 keV range. In all cases there were simultaneous 16 s time resolution data in 129 bands covering the full energy range of the Proportional Counter Array (PCA).

We used the 16 s data to produce X-ray spectra for all the observations, which we fitted with a blackbody plus a power-law model (see Ford et al. 1997b for a detailed analysis of the energy spectra of these observations). From these fits, we find that the unabsorbed 2–20 keV fluxes on 1996 March 3, 6, 9, 12, August 1, October 24, and 1997 July 18 were 10.56, 7.54, 1.62, 1.61, 1.04, 0.65, and 0.04 × 10^{-9} ergs cm^{-2} s^{-1}, respectively, corresponding to full PCA source count rates (background subtracted) of ∼2785–3265, ∼1980–2480, ∼640–670, ∼620–780, ∼370–410, ∼210–260, and ∼5–50 counts s^{-1}, respectively (notice that the count rates quoted by Berger et al. 1996 for the March 6 observation were for 6–12.7 keV). We observed no X-ray bursts.

For each individual observation we calculated power spectra using 64 s data segments and averaged them. We renormalized all power spectra to fractional rms squared per Hertz (see van der Klis 1995) using background measurements from slew and Earth occultation data.

On March 3 and 6 the very strong peak previously reported by Berger et al. (1996) was obvious. Its frequency varied from

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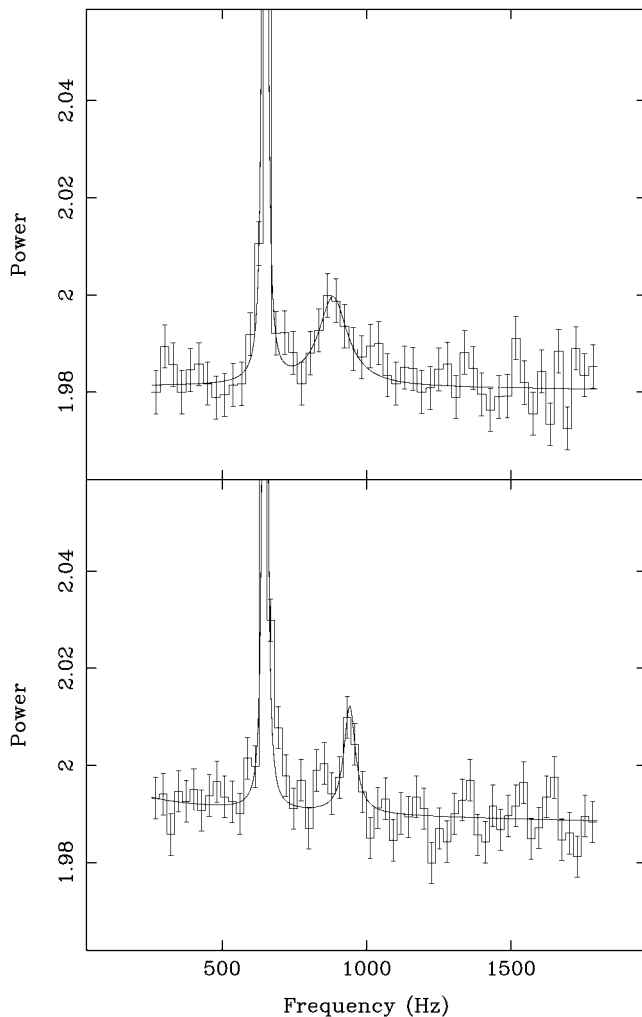[9] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

FIG. 1.—Power spectra for the observations of 1996 March 3 (*upper panel*) and March 6 (*lower panel*). The frequency of the strong peak was arbitrarily shifted to be the same in both power spectra (see text for details). On March 3 the data cover the full PCA energy band (2–60 keV), while on March 6 only data from 2 to 12.7 keV were available.

∼820 to ∼890 Hz (see Figs. 1 and 2 of Berger et al. 1996) on March 3 and between ∼650 and ∼870 Hz on March 6, extending the range seen by Berger et al. (1996) by ∼200 Hz due to our current more complete data set. Close inspection of these power spectra suggested to us the presence of a second QPO at a frequency ∼200–300 Hz higher than that of the strong peak. However, in both cases this peak was very broad and only marginally significant. Scrutiny of a dynamical power spectrum of March 6 further suggested that the second peak matched the frequency variations of the first one.

In order to investigate the reality of this second peak, we divided the data in segments of 64 s and calculated a power spectrum for each segment. The strong peak was well detected in each segment. We then fitted the centroid frequency of the strong peak in each individual power spectrum and shifted the frequency scale of each spectrum to a frame of reference where the position of the strong peak was constant in time. Finally, we averaged these shifted power spectra.

If the frequency separation between the two peaks were constant, then this "shift and average" procedure to compensate for the frequency change of the strong peak would also compensate for the frequency change of the weak peak, optimizing

chances to detect it. The improvement in the sensitivity comes from the fact that the signal-to-noise ratio, S/N, of a QPO peak of given rms amplitude is inversely proportional to the square root of its width (van der Klis 1989), and the motion of the peak, if uncorrected, makes it much wider, reducing the S/N.

3. RESULTS

In Figure 1 we show the power spectra of 1996 March 3 and 6 calculated using the above method. In both power spectra a second QPO peak can be seen at a frequency ∼200–300 Hz above that of the strong peak of Berger et al. (1996). We fitted the 256–3750 Hz range of each power spectrum with a function consisting of a constant level, representing the Poisson noise, the very large event contribution (Zhang et al. 1995; Zhang 1995), and two Lorentzians. On March 6 we also included a power law to account for the broadband noise component at low frequencies. The results are in Table 1; we do not quote the peaks' centroid frequencies, which were arbitrarily shifted, but only the peak separation, $\Delta\nu$. Frequencies of the lower peak are reported below (Fig. 2). The 1 σ error bars from the fits indicate the second peak to be 4.3 σ and 4.4 σ significant on March 3, and March 6, respectively. An F-test to the χ^2 of the fits with and without this peak yields a probability of 7.1 × 10^{-10} on March 3 and 5.3 × 10^{-8} on March 6, for the null hypothesis that the peak is not present in the data. Considering the number of trials implied by the number of independent frequencies analyzed (van der Klis 1989), these probabilities increase to 1.4 × 10^{-7} and 1.1 × 10^{-5}, respectively.

Interestingly, $\Delta\nu$ changed from 232.7 ± 11.5 Hz on March 3 to 293.1 ± 6.6 Hz on March 6, a change of 60.4 ± 13.3 Hz. We tested the significance of this result by fitting both power spectra simultaneously, but forcing the distance between the peaks to be the same in both of them. Applying an F-test to the χ^2 of this fit and the fit where all parameters were free we get a probability of 2.4 × 10^{-3} for the hypothesis that the peak separation did not change between the two observations: the difference in the frequency separation between March 3 and 6 is significant at the 3.2 σ level.

The FWHM of the low-frequency peak in the shifted and averaged power spectrum is 4.8 Hz on March 3 and 4.7 Hz on March 6. The high-frequency QPO peak was broader. It did not vary significantly between the two observations (Table 1). The only other source where the upper peak was measured to be significantly broader than the lower one is 4U 1728−34 (Strohmayer et al. 1996a). Although the upper QPO might be intrinsically broader, it might also have been blurred in the shift process due to small changes in the frequency separation during each observation. We tried to test this by dividing the data into shorter segments, but the lower statistics prevented us from getting a significant result.

On March 9 we only detected a single QPO, moving from ∼570 to ∼735 Hz, with upper limits to the rms of a second QPO below the March 3 and 6 values (Table 1).

On 1996 March 12, August 1, and October 24, and 1997 July 18 we detected no QPO above 100 Hz. The 95% confidence upper limits for a ∼10 Hz FWHM peak were 4.1%, 7.0%, 7.4%, and 7.8% rms, respectively, and about twice those values for a ∼200 Hz FWHM peak. On March 12 the flux was similar to that on March 9, but no QPOs were detected, implying that the amplitude of the QPO was ∼3 times smaller, or its FWHM was much broader, on March 12 than on March 9. This shows that the properties of the kHz QPOs do not depend only on flux.

TABLE 1

PROPERTIES OF THE KILOHERTZ QPOs IN 4U 1608−52

START TIME (UTC)	EXPOSURE (s)	LOWER FREQUENCY PEAK		HIGHER FREQUENCY PEAK		$\Delta\nu$ (Hz)[a]	χ_ν^2/dof[b]
		rms (%)	FWHM (Hz)	rms (%)	FWHM (Hz)		
1996 Mar 3 19:18:24	6784	7.37 ± 0.04	4.83 ± 0.08	3.14 ± 0.40	100^{+43}_{-32}	232.7 ± 6.6	1.04/2229
1996 Mar 6 03:20:32	8320	7.93 ± 0.04	4.72 ± 0.07	2.82 ± 0.37	49^{+23}_{-16}	293.1 ± 11.5	1.08/2227
1996 Mar 9 18:02:56[c]	5696	<4 to <7[d]	...	15.31 ± 0.54	129^{+13}_{-12}	...	1.02/2227

NOTE.—Quoted errors represent 1 σ confidence intervals.

[a] $\Delta\nu$ is the separation between both peaks. As the QPO peaks were arbitrarily shifted (see text), we do not quote their centroid frequencies.

[b] Reduced χ^2 and degrees of freedom of the fit.

[c] Only one QPO is seen. From our data we cannot establish if it is the upper or the lower peak.

[d] 95% confidence, for FWHM 10 and 200 Hz, respectively.

In Figure 2 we plot QPO frequency versus count rate for 1996 March 3, 6, and 9. We also plot results of March 15 and 22 (Yu et al. 1997). In nearly all cases frequency is positively correlated to the source count rate. On March 3 it remains more or less constant below 3090 counts s^{-1}, and then increases linearly above that value, while on March 6 there is a linear relation (a correlation in the data of March 6 was already reported by Berger et al. 1996). On March 9 there is a marginal indication of an anticorrelation of frequency with count rate. On March 15 and 22, at lower count rates, the frequency seems to be correlated with count rate (Yu et al. 1997).

We also measured the photon energy dependence of the new higher frequency QPO. On March 3 we divided the data into four energy bands, 2–4–6–8.1–31.8 keV, and found rms fractional amplitudes of less than 2%, 2.4% ± 1.0%, 6.1% ± 0.8%, and 4.5% ± 1.0%, respectively. On March 6, due to the constraints of the observing mode, we could only divide the data into two energy bands, 2–6–12.7 keV. The rms fractional amplitudes were then 2.1% ± 0.5% and 3.8% ± 0.5%, respectively, consistent with those of March 3. The rms amplitude of the high-frequency QPO seems to increase with energy, but significantly less steeply than in the low-frequency QPO (Berger et al. 1996). On March 9, for the same energy bands as on March 3, the rms amplitudes of the only QPO seen in the data were 12.9% ± 1.4%, 11.5% ± 1.4%, 18.4% ± 1.6%, and 21.3% ± 1.3%, compatible with both the upper and lower peak

on March 3 and 6. This does not allow us to establish which peak we detected on March 9.

4. DISCUSSION

We have found, for the first time, the second peak in 4U 1608−52 expected on the basis of comparison to other kHz QPO sources. Compared to the lower frequency peak, the amplitude of the higher frequency QPO increases less steeply with energy. We see, for the first time in a source with a luminosity far below Eddington, the separation between the two peaks vary. The dependence of the QPO frequency on count rate is complex.

Figure 2 shows that while for most observations the QPO frequency is correlated to count rate, there is no simple function that fits all the observations simultaneously. The changes in peak separation are only moderate, so this is true for both QPO.

A similar effect has been observed when different sources, spanning a very large range of luminosities, are plotted together in a single frequency-luminosity diagram: each source shows a positive correlation, along lines which are more or less parallel (van der Klis 1997a, 1997b; van der Klis et al. 1997b). A similar behavior as we see in 4U 1608−52 was also observed in 4U 0614+091 (Ford et al. 1997a; Méndez et al. 1997). The fact that this is observed in individual sources shows that a difference in neutron star properties such as mass or magnetic field strength cannot be the full explanation for the differences observed in the frequency-luminosity relations.

As noted by Berger et al. (1996), on March 6 frequency and count rates are correlated—we now see that the higher count rate data on March 3 also show a correlation. There is therefore no evidence for the frequency hitting a ceiling toward higher count rates, although the frequency did not decrease much when the count rate dropped from 3000 to 2400 counts s^{-1}.

We now turn to the behavior of the peak separation. It has been proposed that the higher frequency kHz QPO represents the Keplerian frequency, ν_K, of the accreting material in orbit around the neutron star at some preferred radius (van der Klis et al. 1996), while the lower frequency peak, at ν_B, is produced by the beating of ν_K with another frequency, ν_S, identified as the spin frequency of the neutron star (Strohmayer et al. 1996b; Miller, Lamb, & Psaltis 1997). As $\nu_S = \nu_K - \nu_B$, these models predict that the difference in frequency $\Delta\nu$ of the twin kHz peaks should remain constant, although ν_K and ν_B may vary in time. Obviously, the neutron star spin can not change by 26% in 3 days, as would be required by our observed change in $\Delta\nu$.

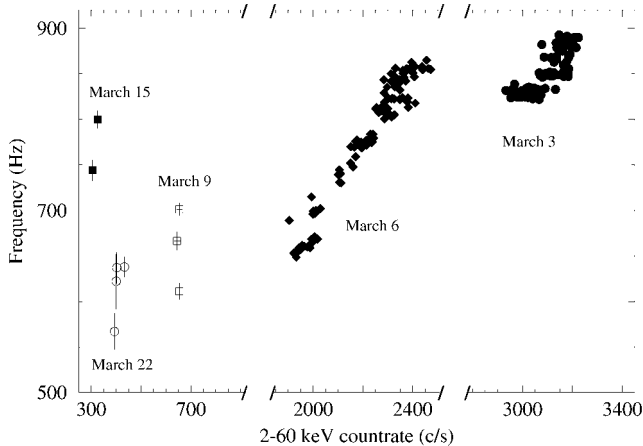In the case of Sco X-1, where $\Delta\nu$ also varies (van der Klis

FIG. 2.—The QPO frequency vs. count rate. The data for March 3, 6, 9, 15, and 22 are plotted using filled circles, filled diamonds, open squares, filled squares, and open circles, respectively. The points for March 15 and 22 are from Yu et al. (1997).

et al. 1997a), it has been argued that the variations can be attributed to near-Eddington accretion. White & Zhang (1997) propose a 35% expansion of the neutron star photosphere with conservation of angular momentum; F. Lamb (1996, private communication) suggests that in near-Eddington accretion the height of the inner disk increases, and that the different values of $\nu_K - \nu_B$ are due to the different values of ν_K at different heights in the disk. These explanations can not apply to 4U 1608−52, as at 3.6 kpc (Nakamura et al. 1989) its luminosity was 1.3×10^{37} ergs s^{-1} and 9.4×10^{36} ergs s^{-1} on March 3 and March 6, respectively, less than 10% of L_{Edd}.

One possible way out might be time-variable scattering. In the beat-frequency model the lower frequency peak is expected to be at least as broad as the higher frequency one, as it is generated by a beat between the higher frequency QPO and the (coherent) neutron star spin. Both on March 3 and 6 we observe the opposite. This might be due, in our shift and average technique, to a change in $\Delta\nu$ during each observation. Alternatively, a rapidly variable scattering medium around the neutron star could cause the broadening, and perhaps even a frequency shift. The QPO at ν_K (which in the sonic model is a beaming oscillation), would be more sensitive to this than the (luminosity oscillation) peak at ν_B. It remains to be seen if scattering can explain all the phenomenology: the varying $\Delta\nu$, the different peak widths at ν_K and ν_B, the energy dependences of the peak widths and amplitudes, and the ~27 μs time lags between the high- and low-energy photons in the lower frequency peak (Vaughan et al. 1997).

We therefore reconsider the idea of a layer at the surface of the neutron star that does not corotate with the body of the star, but has its own rotation frequency $\nu_L \geq \nu_S$, and that it is this frequency ν_L that beats with ν_K (White & Zhang 1997).

The observations of frequency drifts in burst QPO (Strohmayer et al. 1997) strongly suggest that such noncorotating layers, at least at some times, exist. However, the situation in 4U 1608−52 (and Sco X-1) differs from that in X-ray bursts, in that the timescales over which particular values of ν_L persist are hours to days, not seconds as in bursts. Therefore, in these cases, ν_L can not be estimated by only considering changes in the moment of inertia I_L of the layer as proposed by White & Zhang (1997) for Sco X-1, but must involve an estimate of, and may well be dominated by, the changes in its angular momentum, J_L. The layer will gain angular momentum from the accreting matter, which comes in with a higher angular velocity than that of the layer, and it will lose angular momentum through friction with the underlying neutron star body. The layer will rotate differentially, and it will depend on the precise nature of the beat-frequency interaction which frequency is picked out to interact with the Keplerian frequency.

If the beat-frequency interaction takes place via beamed emission from a certain radius in this layer out to the Kepler radius, such as, for example, in the sonic point model (Miller et al. 1997), then the photospheric radius will be the radius whose frequency we see.

Now consider the situation of 4U 1608−52 in our observations. Previous to the outburst there was little accretion for a considerable amount of time, and the layer may well have settled down to near-corotation with the body of the star. The onset of the outburst produces a sudden increase in $\dot{M}$, and high angular momentum matter is deposited in the existing layer that consequently spins up. Ignoring friction, we find that for a total mass of the layer of order 10^{-9} $M_\odot$, we can reproduce the observed frequency changes.

We note, that in Sco X-1 it is observed that ν_L decreases when $\dot{M}$ increases, and vice versa. Large changes in radius, and therefore moment of inertia of the layer, with $\dot{M}$, as proposed by White & Zhang (1997), would initially change ν_L in the sense observed, but it depends on the balance between angular momentum gained in accretion and lost to friction what would happen next. In general, we would expect in such scenario that, after its initial rapid spin down in response to an $\dot{M}$-induced increase in R, the layer would gradually spin up again due to the angular momentum deposited in it by the accreting matter, up to the point where friction and accretion are in equilibrium. It remains to be seen if the data confirm this.

Finally, we note that the beat-frequency interpretation requires some kind of pattern on the surface of the star that can interact with the Keplerian blobs. As for a noncorotating layer this pattern can not be attached to the magnetic field lines (in fact, such layers would be likely to smear out the hot spots at the magnetic poles into rings around the star, and therefore could explain the absence of strong pulsations in the persistent emission) some other origin is required for it. Perhaps magnetic loops or turbulent cells (prominences or granulation) could fulfill this role.

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