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THE LONG-TERM STABILITY OF OSCILLATIONS DURING THERMONUCLEAR X-RAY BURSTS: CONSTRAINING THE BINARY X-RAY MASS FUNCTION

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ABSTRACT

We report on the long-term stability of the millisecond oscillations observed with the *Rossi X-Ray Timing Explorer* during thermonuclear X-ray bursts from the low-mass X-ray binaries (LMXBs) 4U 1728−34 and 4U 1636−53. We show that bursts from 4U 1728−34 spanning more than 1.5 yr have observed asymptotic oscillation periods that are within 0.2 μs of each other, well within the magnitude that could be produced by the orbital motion of the neutron star in a canonical LMXB. This stability implies a timescale to change the oscillation period of more than 23,000 yr in this system and suggests a highly stable process, such as stellar rotation, as the mechanism producing the oscillations. For 4U 1636−53, which has an orbital period of 3.8 hr, we show that the offsets in the asymptotic oscillation periods from three different bursts can be consistently interpreted as due to the orbital velocity of the neutron star with $v \sin i/c \approx 4.25 \times 10^{-4}$. An updated optical ephemeris for the epoch of maximum light from V801 Arae would provide a strong test of this interpretation. We discuss the constraints on the X-ray mass function, which in principle can be derived using this technique.

Subject headings: stars: individual (4U 1636−53, 4U 1728−34) — stars: neutron — stars: rotation — X-rays: bursts

1. INTRODUCTION

Millisecond oscillations in the X-ray brightness during thermonuclear bursts have now been observed from six low-mass X-ray binaries (LMXBs) with the *Rossi X-Ray Timing Explorer* (*RXTE*) (see Strohmayer et al. 1996, 1997a; Smith, Morgan, & Bradt 1997; Zhang et al. 1996, 1998; and Strohmayer, Zhang, & Swank 1997b). The presence of large-amplitude oscillations near burst onset, combined with spectral evidence for localized thermonuclear burning, suggests that the oscillations are caused by rotational modulation of thermonuclear inhomogeneities (see Strohmayer et al. 1997b).

The accretion-induced rate of change of the neutron star spin frequency in an LMXB is approximately

$$\frac{d\nu}{dt} \approx 1.8 \times 10^{-6} \frac{\dot{m}_{17}(M_x r_{\rm acc})^{1/2}}{2\pi I_{45}} \ \text{Hz yr}^{-1}, \qquad (1)$$

where $\dot{m}_{17}$, M_x, $r_{\rm acc}$, and I_{45} are the mass accretion rate in units of 10^{17} g s^{-1}, the neutron star mass in solar units, the characteristic radius of the inner accretion disk in kilometers, and the stellar moment of inertia in units of 10^{45} g cm^2, respectively. If the millisecond oscillations observed in the X-ray brightness from thermonuclear X-ray bursts with *RXTE* are produced by rotational modulation of the burst flux, then the Doppler-corrected frequencies should be stable at the better than $\Delta\nu = 0.001$ Hz level over a hundred years or so. The Doppler shift due to orbital motion of the binary can produce a frequency shift of magnitude

$$\frac{\Delta\nu}{\nu} = \frac{v \sin i}{c} = 2.05 \times 10^{-3} \frac{M_c \sin i}{P_{hr}^{1/3}(M_x + M_c)^{2/3}}, \qquad (2)$$

where M_x, M_c, $P_{\rm hr}$, v, and i are the neutron star mass, the companion mass (both in solar units), the orbital period in hours, the magnitude of the neutron star orbital velocity, and the system inclination angle, respectively. For canonical LMXB system parameters, this Doppler shift easily dominates over any possible accretion-induced spin change on orbital to several year timescales. Thus, the level of observed stability in oscillation periods from burst to burst provides a method to further test the rotational modulation hypothesis. For example, if oscillation period shifts larger than can plausibly be produced via orbital motion are observed, this would tend to cast doubt on the spin modulation interpretation. On the other hand, if the burst oscillation frequencies remain stable over long timescales, revealing a signature of binary motion, then it will both support the rotational interpretation and become possible to use the observed frequency shifts to constrain the neutron star binary mass function in systems that have observed burst oscillations.

In this Letter, we investigate the long-term period stability of burst oscillations in two LMXB sources, 4U 1728−34 and 4U 1636−53. We show that in 4U 1728−34 bursts separated in time by about 1.6 yr have the shortest observed oscillation periods, what we refer to as asymptotic periods, within 0.2 μs of each other, well within the range of shifts that could result from the system's binary motion. For 4U 1636−53, which has a known orbital period of 3.8 hr, our time baseline is shorter; however, the orbital period allows us to show that the oscillation period shifts observed from three different bursts can be consistently interpreted in terms of those produced by binary orbital motion with reasonable values for the component masses and system inclination. If the relative orbital phases when the bursts occurred can be converted to absolute phases, for example, with an updated optical ephemeris of the epoch of maximum light, then this would provide a test of the Doppler shift interpretation and, if confirmed, would enable constraints on $v \sin i/c$ and thus the X-ray mass function to be derived.

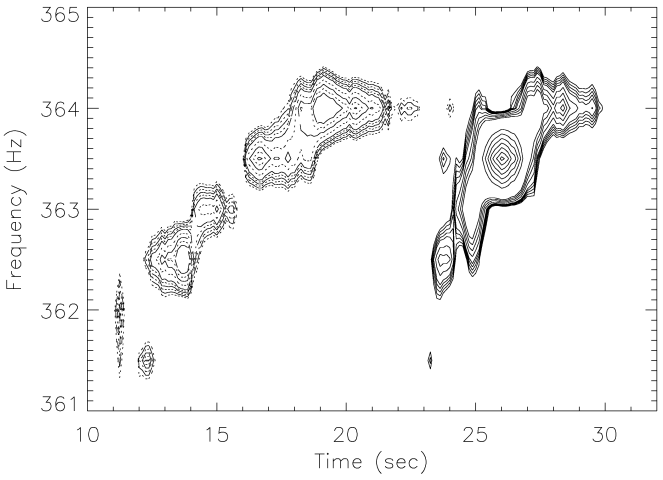


FIG. 1.—Dynamic power spectra computed from two different bursts from 4U 1728−34 separated in time by 1.6 yr. Shown are contours of constant power spectral density. The contours have been offset from each other for clarity. Note that the range in frequency of the oscillations and the highest observed frequency are very similar. The burst from 1996 February 16 at 10:00:49 UTC is on the left, that from 1997 September 22 at 06:42:56 UTC is on the right.

2. LONG-TERM FREQUENCY STABILITY IN 4U 1728−34

We had observations of 4U 1728−34 with *RXTE* in 1996 February and again in 1997 September (see Strohmayer et al. 1996 for a summary of the 1996 February observations). Using data from these two observations, we can compare the oscillation periods during bursts over a span of about 1.6 yr. For all the burst data reported here, we had either 125 μs (1/8192 s) resolution binned data or event mode data with the same temporal resolution.

The oscillations at 2.75 ms (363 Hz) observed during bursts from 4U 1728−34 are not strictly coherent (see Strohmayer et al. 1996). In some bursts, the period is observed to evolve from a high of about 2.762 ms near burst onset to about 2.747 ms during burst decay. Due to the episodic nature of the oscillations, not all bursts show detectable oscillations over this entire range. Strohmayer et al. (1997a) have argued that this frequency evolution is caused by the increase in the scale height of the thermonuclear burning layer on the neutron star surface and subsequent conservation of angular momentum of the thermonuclear shell. In many bursts that show oscillations, the oscillation period appears to reach a nearly coherent, asymptotic limit as the burst decays away. In the context of the spin modulation hypothesis, this limit represents the actual spin period of the bulk of the neutron star.

We selected for detailed comparison a pair of bursts from the 1996 February observations (bursts 4 and 5, respectively, from Strohmayer et al. 1997b) and one from the 1997 September data. Here we refer to these bursts as bursts 1, 2, and 3, in time order. We selected these bursts because they showed significant oscillations over the longest time intervals during the bursts and the oscillation period during the burst decay reached a stable, coherent limit. In Figure 1 we compare the dynamic power spectra of the bursts detected on 1996 February 16 at 06:51:07 UTC and 1997 September 22 at 06:42:51 UTC (bursts 2 and 3 in Table 1). We only show two of the three bursts since the pair of bursts observed on 1996 February 16 were nearly identical in their oscillation properties. The figure shows contours of constant power spectral amplitude, which have been shifted in time for clarity. The dynamic power spectra were computed from 2 s intervals with a new interval starting every $\frac{1}{8}$ s. The leftmost contours are for the 1996 February burst. The frequency evolution from low to high is clearly evident in both bursts, and the range of observed frequencies and the highest observed frequency are very similar. Note that the oscillation frequencies in both bursts reach a stable upper limit, which we will call the asymptotic frequency or period.

TABLE 1

ASYMPTOTIC OSCILLATION PERIODS IN BURSTS FROM 4U 1728−34 AND 4U 1636−53

Source	$T_{\rm burst}$ (UTC)	$P_{\rm cen}$ (ms)	σ_P (μs)	$\phi_{\rm rel}$ (TDB)
	4U 1728−34			
Burst 1	1996 February 16 06:51:13	2.74774	0.40	...
Burst 2	1996 February 16 10:00:49	2.74757	0.39	...
Burst 3	1997 September 22 06:42:56	2.74755	0.39	...
	4U 1636−53			
Burst 1	1996 December 28 22:39:24	1.71970	0.43	0.0
Burst 2	1996 December 28 23:54:03	1.71896	0.39	0.327
Burst 3	1996 December 29 23:26:47	1.71981	0.38	0.517

Since the rotational modulation hypothesis suggests that the shortest observed period is the underlying stellar spin period, we performed an epoch-folding period search analysis using only the portions of all three bursts after which the frequency has stabilized to see how closely these asymptotic frequencies agree. Figure 2 shows the resulting χ^2 plots from the folding analysis as a function of barycentric period. To estimate the oscillation periods and uncertainties from the epoch folding, we computed the centroids $P_{\rm cen}$ and standard deviations σ_P of each χ^2 peak using the relations

$$P_{\rm cen} = \frac{\sum_i \chi_i^2 P_i}{\sum_i \chi_i^2} \, \sigma_P^2 = \frac{\sum_i \chi_i^2 (P_i - P_{\rm cen})^2}{\sum_i \chi_i^2}, \qquad (3)$$

where i runs over each burst's χ^2 peak from the epoch-folding analysis. Table 1 summarizes the derived asymptotic periods and uncertainties for each burst. As can be seen from the inferred periods and uncertainties, there is no significant evidence that the observed asymptotic periods from the three bursts are different. Using the measured centroids as the best estimator

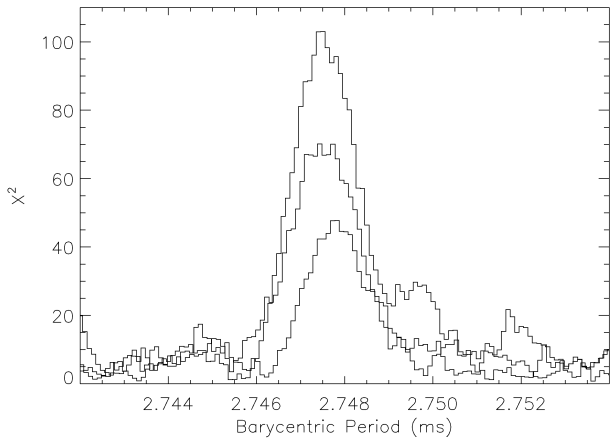


FIG. 2.—Results from the χ^2 epoch-folding analysis for the three bursts from 4U 1728−34. The bursts are arranged in time order from bottom (burst 1) to top (burst 3). See Table 1 for the measured period centroids and uncertainties.

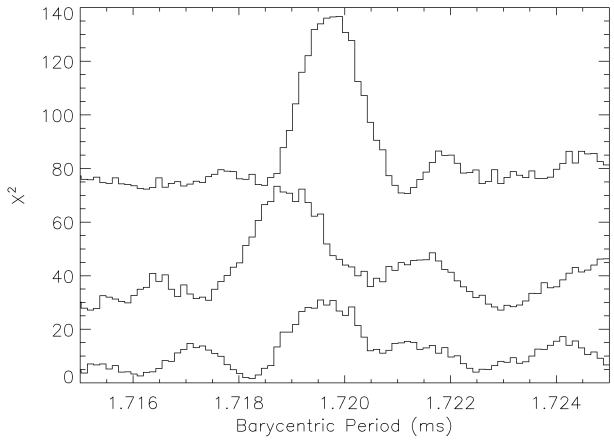


FIG. 3.—Results from the χ^2 epoch-folding analysis for the three bursts from 4U 1636−53. The bursts are arranged in time order from bottom (burst 1) to top (burst 3). See Table 1 for the measured period centroids and uncertainties.

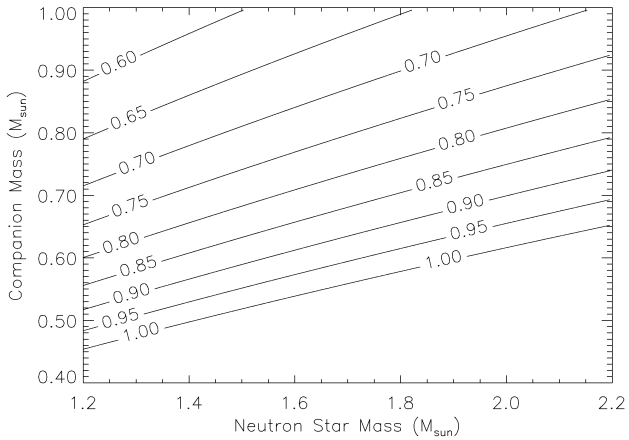


FIG. 4.—Contours of constant sin i for a binary system with orbital period 3.8 hr and $v \sin i/c = 4.25 \times 10^{-4}$, as suggested by the observed period offsets in bursts from 4U 1636−53. This result should not yet be taken as a constraint on the system masses in 4U 1636−53; rather, it only suggests that the orbital motion is a plausible explanation for the observed period shifts.

of the periods for each burst, the implied period difference over the 1.6 yr timespan is about 0.19 μs. In terms of a timescale to change the period, this corresponds to $\tau > P/\dot{P} = P\Delta T/\Delta P = 2.3 \times 10^4$ yr and implies a limit on any orbital Doppler shift $\Delta P/P = v_{\rm orb} \sin i/c < 6.9 \times 10^{-5}$, well within the shift that could be produced by orbital motion of the neutron star in a typical LMXB.

3. BURST OSCILLATION FREQUENCIES IN 4U 1636−53

X-ray brightness oscillations during X-ray bursts at 1.72 ms (581 Hz) were discovered in 4U 1636−53 by Zhang et al. (1996). The 3.8 hr orbital period of 4U 1636−53 is known from the observed optical periodicity of the optical companion V801 Arae (see van Paradijs et al. 1990; Smale & Mukai 1988; and Pedersen, van Paradijs, & Lewin 1981). Since the orbital period is known, the *relative* phases at which bursts occurred can be determined. One can then compare the observed oscillation periods from different bursts and determine if any observed changes can be consistent with an orbitally induced Doppler shift. In particular, if at least three bursts are available with measured oscillation periods, then one can try to solve the following set of equations:

$$P_{t_j} = P_0 - \Delta P \cos(\phi_{t_j} + \phi_0). \quad (4)$$

Here P_{t_j} and ϕ_{t_j} are the observed asymptotic oscillation periods and relative orbital phases, respectively, for bursts which occurred at t_j, and P_0, ΔP, and ϕ_0 are the barycentric oscillation period when the neutron star transits the line of sight, the magnitude of the Doppler-induced period change, and an initial phase offset, respectively. With at least three different oscillation period measurements during bursts, it may be possible to determine a set of values for the three parameters P_0, ΔP, and ϕ_0 that are consistent with binary motion. The orbital velocity v and system inclination i are related by $\Delta P/P_0 = v \sin i/c$.

For 4U 1636−53, we now have three different bursts spanning a time interval of slightly more than a day. To determine the asymptotic oscillation periods for each burst, we performed a similar epoch-folding analysis on these bursts as those from 4U 1728−34 described above. Table 1 summarizes information on the occurrence times, relative orbital phases (from burst 1) measured at the solar system barycenter of 4U 1636−53 at the time of occurrence, and the barycentric asymptotic period observed during the decaying portion of each burst. Figure 3 displays the resulting χ^2 plots from the epoch-folding analysis for each of the three bursts.

Bursts 1 and 3 occurred approximately half an orbit apart from each other; note that these bursts had asymptotic periods that are, within the uncertainties, consistent with each other. Burst 2 occurred roughly midway in orbital phase between bursts 1 and 3 but had a significantly shorter period by about 0.74 μs. Thus, a plausible scenario is that burst 1 occurred near the time of superior conjunction of the neutron star (inferior conjunction of the secondary). At this phase, as well as half an orbit away, the neutron star is near transit and the orbital component of its velocity along the line of sight is nearly zero. This can explain the consistent periods measured during bursts 1 and 3. Finally, burst 2 occurred 0.327 in phase from burst 1 and thus with a significant fraction of its total orbital velocity along the line of sight to produce the strong blue shift to shorter period.

This scenario gives $v \sin i/c \approx 4.25 \times 10^{-4}$ to account for the observed period shift between burst 2 and bursts 1 and 3. The current understanding of the mechanism underlying the optical modulations at the orbital period suggests that the epoch of maximum light be identified with superior conjunction of the optical secondary (see Smale & Mukai 1988). Van Paradijs et al. (1990) give an ephemeris for the epoch of maximum light for V801 Arae based on a compilation of observations from as early as 1980 July to as late as 1988 May. However, the uncertainties in projecting this ephemeris forward to the epoch of burst 1 are such that it does not provide a significant test of the orbital Doppler interpretation, but with an updated optical ephemeris, a much more restrictive test can be made.

Since the orbital motion hypothesis cannot be rejected with the present data, we show in Figure 4 the contours of constant sin i in the mass plane for the appropriate orbital period of 3.8 hr and the $v \sin i/c$ suggested by the period shifts in the bursts. For the 3.8 hr orbital period and a main-sequence companion, empirical mass-radius relations would suggest a mass of about 0.36 $M_\odot$ for V801 Arae (see Patterson 1984; Smale & Mukai 1988). This is a bit lower in mass than that suggested by the inferred $v \sin i/c$ from the bursts (see Fig. 4), but given the uncertainties in the period measurements as well as the un-

certain effects of X-ray heating on the secondary, it is still within a reasonable range for the observed shifts to be plausibly produced by orbital motion. Both the observation of additional bursts as well as an updated optical ephemeris for V801 Arae can provide a careful test of the orbital hypothesis for the observed burst oscillation period shifts.

4. DISCUSSION

The episodic nature of the oscillations during bursts does introduce some uncertainty into our understanding of what is the "highest" observed frequency during a burst. It is possible that in some bursts the oscillations are not strong enough to be detected at late times in the burst, and therefore the highest frequency may not be observed in all bursts. Partly this can be mitigated by comparing bursts that show similar overall oscillation properties, as we have endeavored to do here, but in order to fully overcome this, one simply needs the weight of evidence from a larger sample of bursts. In particular, with a large enough sample to cover most of the orbital phase space, the signature of orbital Doppler shifts should become fairly transparent, or not, since the magnitude of the frequency offsets should be limited by the magnitude of the binary orbital velocity, and an approximately equal number of redshifts and blueshifts should be observed.

The long-term stability of the highest millisecond oscillation frequencies observed in thermonuclear bursts from 4U 1728−34 and 4U 1636−53 provides a strong argument in favor of a highly stable clock, such as stellar rotation, setting the observed oscillation frequency. Regardless of the mechanism, any oscillation period will suffer orbital Doppler effects. The limits on the period offsets from bursts spanning 1.6 yr in 4U 1728−34 indicate that the intrinsic period that sets the asymptotic period during bursts can change on a timescale no shorter than $\tau = P\Delta T/\Delta P \approx 2.3 \times 10^4$ yr. This timescale is longer than similar timescales for many known X-ray pulsars and is also longer than the characteristic time to change the thermal state of the neutron star surface ocean (see Bildsten et al. 1998). Thus, if oscillation modes sensitive to the thermal state, such as *g*-modes, were the cause of the oscillations, they would not be expected to be stable over such a long timescale. If analysis of additional bursts continues to support this interpretation, then it will become possible to use oscillation periods observed in different bursts to place constraints on the masses of the components in LMXBs; thus, long-pointed observations that collect many bursts are well-justified given that they could lead to a determination of the mass function for a larger sample of systems. In addition, constraints on $v \sin i/c$ derived from different bursts provide a method of conducting more sensitive searches for the millisecond X-ray pulsar in the persistent, accretion-driven flux, which should be present at some level in most LMXBs.

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