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EVIDENCE FOR ANTIPODAL HOT SPOTS DURING X-RAY BURSTS FROM 4U 1636−536

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ABSTRACT

The discovery of high-frequency brightness oscillations in thermonuclear X-ray bursts from several neutron star low-mass X-ray binaries has important implications for the beat frequency model of kilohertz quasi-periodic brightness oscillations, the propagation of nuclear burning, the structure of the subsurface magnetic fields in neutron stars, and the equation of state of high-density matter. These implications depend crucially on whether the observed frequency is the stellar spin frequency or its first overtone. Here we report an analysis of five bursts from 4U 1636−536 that exhibit strong oscillations at ∼580 Hz. We show that combining the data from the first 0.75 s of each of the five bursts yields a signal at ∼290 Hz that is significant at the 4×10^{-5} level when the number of trials is taken into account. This strongly indicates that ∼290 Hz is the spin frequency of this neutron star and that ∼580 Hz is its first overtone, in agreement with other arguments about this source but in contrast to suggestions in the literature that ∼580 Hz is the true spin frequency. The method used here, which is similar to matched filtering, may be used for any source to search for weak oscillations that have frequencies related in a definite way to the frequency of a strong oscillation.

Subject headings: dense matter — equation of state — gravitation — relativity — stars: neutron — X-rays: bursts

1. INTRODUCTION

Prior to the launch of the *Rossi X-ray Timing Explorer* (*RXTE*) in 1995 December, many theorists argued that thermonuclear (type I) X-ray bursts on neutron stars are almost certainly caused by ignition at a single point followed by the spread of nuclear burning around the star, as opposed to simultaneous ignition over the entire stellar surface (e.g., Fryxell & Woosley 1982; Nozakura, Ikeuchi, & Fujimoto 1984; Bildsten 1995). The discovery with *RXTE* of high-frequency (∼300–600 Hz), nearly coherent high-amplitude brightness oscillations during type I bursts from several sources (for reviews see, e.g., Strohmayer, Zhang, & Swank 1997; Strohmayer, Swank, & Zhang 1998a) is of great significance because it provides for the first time a wealth of observational data on the propagation of nuclear burning in dense matter, which has implications for all phenomena involving such propagation, including novae and Type Ia supernovae as well as X-ray bursts. The properties of these oscillations may also yield important information about the strength and nature of subsurface magnetic fields in these stars and even about the equation of state of the dense matter in their cores (Strohmayer 1997; Miller & Lamb 1998). The conclusions drawn depend strongly on whether the frequency of the burst oscillation from a particular source is the stellar spin frequency or its first overtone.

The brightness oscillations during bursts from a given source always have approximately the same frequency. There are six sources for which such oscillations have been reported (see Strohmayer et al. 1998a for a more detailed summary): 4U 1728−34 (363 Hz), 4U 1636−536 (580 Hz), 4U 1702−43 (330 Hz), KS 1731−260 (526 Hz), Aql X-1 (549 Hz), and X1743−29 (589 Hz). In three of these sources, oscillations have been observed in more than one burst. In 4U 1728−34, there have been 17 observed bursts with oscillations, in 4U 1636−536 there have been five such bursts, and in X1743−29 there have been three. In no burst from any source has an oscillation been detected at any other frequency. The extreme stability and coherence of these burst oscillations provide compelling evidence that the burst oscillation frequency is the stellar spin frequency of the neutron star or an overtone (see Strohmayer et al. 1997; Strohmayer et al. 1998b). It is thought that the oscillations themselves are produced by the rotation of one or two "hot spots" on the star that are brighter than the surrounding surface.

The source 4U 1636−536 is a low-mass X-ray binary (LMXB) with an orbital period of 3.8 hr (see, e.g., Pederson, van Paradijs, & Lewin 1981). The beat-frequency model of the kilohertz quasi-periodic brightness oscillations (QPOs) observed in the accretion-powered X-ray emission from this source predicts that the spin frequency of the neutron star cannot be 580 Hz (Miller, Lamb, & Psaltis 1998), but should be approximately equal to the kilohertz frequency separation (although not exactly equal; Lamb, Miller, & Psaltis 1999). For 4U 1636−536, this separation has been measured to be 250.6 ± 3.5 Hz (Méndez, van der Klis, & van Paradijs 1998b) and 276 ± 10 Hz (Wijnands et al. 1997) in two different observations. Hence, the beat-frequency model implies that 580 Hz must be the first overtone. However, the power spectra of each of the five bursts from 4U 1636−536 show a significant peak only at ∼580 Hz, and as a result it has been suggested that the spin frequency is 580 Hz (Strohmayer et al. 1998b). The ∼0.1*c* surface velocity implied by a 580 Hz spin frequency is expected to generate significant power at the 1160 Hz first overtone because of Doppler shifts and aberration (see Miller & Lamb 1998), but this is not observed.

If instead 580 Hz is the first overtone of the spin frequency, as required by the beat-frequency model, then in this source we must be seeing enhanced X-ray emission from two similar and nearly antipodal hot spots, which are therefore likely to be the locations of fuel accumulation, e.g., due to magnetic funneling. In addition, the accumulated fuel must be confined to a relatively small surface area. The dipolar magnetic fields of ∼10^8–10^9 G inferred for these sources from spectral modeling (e.g., Psaltis, Lamb, & Miller 1995) and from the sonic-point model of kilohertz QPOs (Miller et al. 1998) are insufficient to confine the accreted fuel at the depths at which nuclear burning occurs, which implies that the subsurface fields are much stronger, perhaps ∼10^{11} G or higher (see, e.g., Woosley

& Wallace 1982; Hameury et al. 1983; Bildsten & Brown 1997).

If the strong ∼580 Hz oscillation observed in 4U 1636−536 can be shown to be the first overtone of the spin frequency, this would also have important implications for the compactness of neutron stars and their high-density equation of state. The maximum modulation in brightness produced by a rotating hot spot is lower when the neutron star is more compact, and therefore an observed amplitude of modulation places an upper limit on the compactness (see Strohmayer 1997; Miller & Lamb 1998). This limit is much stronger for a given oscillation amplitude if there are two hot spots instead of one (Miller & Lamb 1998). A ∼290 Hz spin frequency rather than a ∼580 Hz spin frequency also implies much lower surface velocities and hence a much weaker signal at ∼1160 Hz due to Doppler shifts and aberration (Miller & Lamb 1998). It is therefore very important to analyze the data using the most sensitive possible methods to determine if there is any oscillation at ∼290 Hz in addition to the strong oscillation at ∼580 Hz.

Here we present a new analysis that combines data from five bursts from 4U 1636−536. We determine approximately the count rate waveform at ∼580 Hz for each of the five bursts in a manner similar to that of Zhang et al. (1998a). We then use this waveform to predict the waveform at ∼290 Hz. Our method is a form of "matched filtering" (see Helstrom 1960, pp. 84–95; Wainstein & Zubakov 1962, pp. 80–91), which has previously been used or proposed in other astrophysical contexts, such as the search for gravitational waves from coalescing binaries (see, e.g., Lobo 1990). The procedure is somewhat similar to the technique used by Méndez et al. (1998a) to detect weak signals in the persistent emission from 4U 1608−52, except that they shifted and added power spectra to maximize a strong peak (and hence added the data incoherently), whereas we combine the time series data coherently, which improves the sensitivity significantly. We cross-correlate the predicted count rate waveform with the time series of the data from an initial segment of all five bursts and detect a prominent signal at the half-frequency oscillation. The significance of this oscillation is 4×10^{-5} when the number of trials is taken into account. Therefore, a significant signal is present at ∼290 Hz in one or more of the bursts, implying that ∼290 Hz is the true spin frequency. Data from other bursts from 4U 1636−536, when combined in the same way, are expected to enhance the signal.

In § 2 we describe the data analysis method that we use and our results in more detail. In § 3 we discuss the implications of the results and summarize our conclusions.

2. METHOD AND RESULTS

We acquired public domain data from the High-Energy Astrophysics Science Archive Research Center archives for five bursts from 4U 1636−536. We define the start time t_{0i} of the ith burst by the beginning of the first 1/16 s interval in which the count rate was significantly in excess of the quiescent count rate. The start times were 1996 December 28 at 22:39:24.188 UTC, 1996 December 28 at 23:54:02.876 UTC, 1996 December 29 at 23:26:46.813 UTC, 1996 December 31 at 17:36:52.941 UTC, and 1997 February 23 at 09:42:48.938 UTC. We used the data in event mode and analyzed all of the counts together (i.e., we did not select by energy channel). We focused on data during the initial portions of the bursts because if the oscillations are caused by the rotation of expanding hot spots (see, e.g., Strohmayer et al. 1997), it is expected that the amplitudes of harmonics and subharmonics of the strong oscillation will be greatest near the starts of the bursts.

We use the standard signal processing method of matched filtering, which is also called "matched waveform filtering" or "template filtering" (see Helstrom 1960 or Wainstein & Zubakov 1962 for details). In this approach, we construct a statistic H by cross-correlating an expected waveform $s(t)$ with the count rate time series $C(t)$. For the reasons described below, we define H to be proportional to the squared modulus of the cross-correlation:

$$H \propto \left| \int_{T_1}^{T_2} s(t)C(t)dt \right|^2 . \tag{1}$$

Here T_1 and T_2 are, respectively, the beginning and ending times of the interval analyzed. Detection occurs when H exceeds a chosen threshold H_0, which depends on the normalization and which is determined according to the significance at which one declares a detection.

For the question we addressed, which is whether there is a subharmonic of the strong ∼580 Hz oscillation, the expected waveform at ∼290 Hz can be derived from the waveform at ∼580 Hz, given the prediction that there is a weaker oscillation whose phase advances in time at exactly half the rate of the phase advance of the ∼580 Hz oscillation (that is, a "half-frequency" oscillation). There are four steps in the algorithm we used to detect the weaker ∼290 Hz oscillation: (1) construct an approximate waveform for the ∼580 Hz oscillation, (2) use that waveform to predict the waveform of the ∼290 Hz oscillation, (3) compute the statistic H for the ∼290 Hz oscillation, and (4) calculate the probability that the measured value of H occurred by chance. We emphasize that the modeling of the ∼580 Hz oscillation does not have to be exact to produce a large increase in the sensitivity to the ∼290 Hz half-frequency oscillation.

To determine approximately the waveform of the ∼580 Hz oscillation, we need to choose a functional form for the waveform and then determine the parameters in that functional form that give the best fit to the count rate time series. The waveform we considered for the strong ∼580 Hz oscillation is not a sinusoid but is nearly sinusoidal and therefore can be described by the expression $\sin(\omega t)$, where ω varies slowly in time compared to $1/\omega$. The primary task in this approach is to determine the frequency behavior of the ∼580 Hz oscillation. Our model of this behavior has five parameters for each burst i: the oscillation frequency $\omega_{i,1}$ and frequency derivative $\dot{\omega}_{i,1}$ during an initial, short time interval; a different frequency $\omega_{i,2}$ and frequency derivative $\dot{\omega}_{i,2}$ for the remainder of the time interval included in H; and the break time $t_{\mathrm{bk},i}$ between the two. The frequency behavior described by this model is similar to the frequency behavior reported for the brightness oscillations during bursts from several other sources (Strohmayer et al. 1998a).

To determine the parameter values that give the best fit of this model waveform to the ∼580 Hz oscillation during each burst, we varied the five parameters for each burst to maximize the quantity

$$H_{580,i} = \left| \int_{t_{0i}}^{t_{0i}+T_i} C_i(t)e^{i\omega_i(t)t}dt \right|^2 , \tag{2}$$

where t_{0i} is the start time of the ith burst, T_i is the total inte-

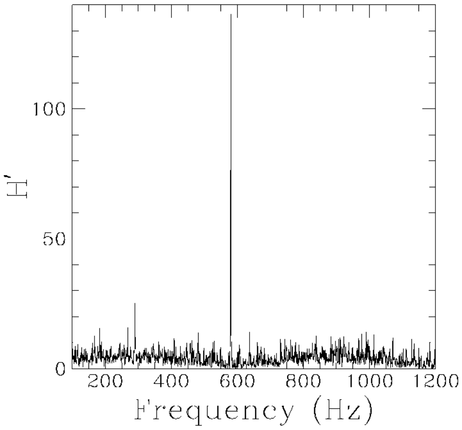

FIG. 1.—Statistic H' (defined in the text) as a function of frequency. In order to compare with the value of H' at 290 Hz, there have been four binary choices of phase at every frequency to maximize H'. These are choices between two consecutive crests of the ~580 Hz oscillation (see text). There are therefore $2^4 = 16$ trials per frequency to select relative phase. As is apparent from the figure, this procedure increases H' most for frequencies near odd harmonics of 290 Hz. The chance probability of $H' > H'_0$ near 290 Hz is approximately $16 \exp(-H'_0/2)$ and is 4×10^{-5} for 290 Hz, for which $H' = 25.6$.

gration time of the ith burst, $C_i(t)$ is the count rate time series of the ith burst, and $\omega_i(t)$ is the parameterized frequency as a function of time of the ith burst. In the initial analysis $T_i = 0.75$ s for all five bursts, but in the final step T_i was changed to 0.734 s to maximize the signal (see below). The frequency was constrained to be between 576 and 585 Hz everywhere in the full time interval analyzed to exclude spurious solutions produced by noise. Given the form of the statistic $H_{580,\,i}$, the phase of the ~580 Hz oscillation during each burst did not have to be determined. The best-fit parameters were found by a grid search. For the first burst, $\omega_1 = 581.2$ Hz, $\dot{\omega}_1 = -7.6$ Hz s^{-1}, $\omega_2 = 578.0$ Hz, $\dot{\omega}_2 = 6.4$ Hz s^{-1}, and $t_{\rm bk} = 0.344$ s; for the second burst, $\omega_1 = 579.0$ Hz, $\dot{\omega}_1 = 8.0$ Hz s^{-1}, $\omega_2 = 579.6$ Hz, $\dot{\omega}_2 = 3.2$ Hz s^{-1}, and $t_{\rm bk} = 0.344$ s; for the third burst, $\omega_1 = 578.6$ Hz, $\dot{\omega}_1 = 7.6$ Hz s^{-1}, $\omega_2 = 578.0$ Hz, $\dot{\omega}_2 = 0.8$ Hz s^{-1}, and $t_{\rm bk} = 0.406$ s; for the fourth burst, $\omega_1 = 578.0$ Hz, $\dot{\omega}_1 = -0.4$ Hz s^{-1}, $\omega_2 = 582.6$ Hz, $\dot{\omega}_2 = -5.2$ Hz s^{-1}, and $t_{\rm bk} = 0.25$ s; and for the fifth burst, $\omega_1 = 582.0$ Hz, $\dot{\omega}_1 = -8.0$ Hz s^{-1}, $\omega_2 = 585.0$ Hz, $\dot{\omega}_2 = -0.4$ Hz s^{-1}, and $t_{\rm bk} = 0.406$ s.

Having constructed the candidate waveform of the ~580 Hz oscillation in each of the five bursts individually, we then maximized the quantity

$$H_{580} = \left| \Sigma_i \int_{t_{0i}}^{t_{0i}+T_i} C_i(t) e^{i(\omega_i t + \delta\phi_i)} dt \right|^2 \quad (3)$$

over the relative phases $\delta\phi_i$, which were searched in phase increments of 0.1π. Without loss of generality, we can set $\delta\phi_0 = 0$. In general, T_i could be different for each burst, but for simplicity we integrated over the same interval T for all five bursts. In the final step, T was varied to maximize H_{580}; this occurred for $T = 0.734$ s. The best-fit parameters and the implied waveforms of the ~580 Hz burst brightness oscillations will be described in detail in a forthcoming paper.

The procedure just described completes the first of the four steps listed above, namely the construction of the waveform of the ~580 Hz oscillation. In the second step, we used the ~580 Hz waveform to construct the expected ~290 Hz waveform based on a model that relates the two oscillations to each other. Here we adopt a simplified model for the oscillations, in which the phase advance of the ~290 Hz oscillation in each burst is precisely half the phase advance of the ~580 Hz oscillation. Because the ~290 Hz oscillation is assumed to be a subharmonic of the ~580 Hz oscillation, we assume that the phase relation of the crests of the ~290 Hz oscillation to the crests of the ~580 Hz oscillation is always the same in each burst. However, there is an ambiguity between which of the two possible crests of the ~580 Hz oscillation is to have the given phase offset from the ~290 Hz oscillation. For each pair of bursts, we must therefore choose between two possible phases, which we do by maximizing the quantity

$$H_{290} = \left| \Sigma_i \int_{t_{0i}}^{t_{0i}+T} C_i(t) e^{i[(1/2)(\omega_i t + \delta\phi_i) + b_i]} dt \right|^2 , \quad (4)$$

where $b_i = 0$ or π and the other variables were fixed in the construction of the ~580 Hz waveform. We may set $b_1 = 0$ without loss of generality. There are therefore four binary choices, for a total of $2^4 = 16$ trials.

The third step is to determine the statistic H'_{290}, which is the significance statistic for the cross-correlation of the expected waveform at ~290 Hz with the count rate data. Our normalization is $H'_{290} = 2H_{290}/(\Sigma_i N_i)$, where N_i is the number of photons in the pertinent segment of the count rate data from burst i. This normalization is chosen for convenience and familiarity to resemble the Leahy et al. (1983) normalization of power density spectra. We emphasize that this particular normalization has no other consequences and that any other normalization could have been used. We find that $H'_{290} = 25.6$. This implies that, on average, the rms amplitude of the ~290 Hz oscillation is a factor of 2.3 less than the rms amplitude of the ~580 Hz oscillation.

The last step in our analysis is to estimate the probability of finding this value of H' by chance and hence its significance. When $H'_{290} > 20$, Monte Carlo simulations of the chance probability are fit well by the simple expression $16 \exp(-H'_{290}/2)$, or 4×10^{-5} for $H'_{290} = 25.6$. Figure 1 shows H' as a function of frequency using the binary phase choice procedure described above.

We note that, although the procedure described above is a more sensitive way to detect the weak oscillation at ~290 Hz, a hint of this signal is evident when standard constant-frequency power spectra are constructed. For example, the sum of the Leahy-normalized power densities at 290 Hz in the initial 0.75 s of each burst is 30.7, with a chance probability of 7×10^{-4}.

3. DISCUSSION AND CONCLUSIONS

The very significant oscillation at ~290 Hz indicates that this is the spin frequency of the neutron star in 4U 1636−536 and that ~580 Hz is the first overtone. Several major consequences follow:

1. From the strength of the 580 Hz signal compared to the 290 Hz signal, there are two very similar and nearly antipodal hot spots on the surface, and they are almost equally visible to us. This almost certainly implies that accreting gas is being funneled to the two hot spots by an external magnetic field.
2. The rapidity with which the signal at the ~580 Hz first

overtone of the spin frequency appears indicates that thermonuclear ignition must be communicated quickly from one pole to the other (F. K. Lamb 1998, private communication). Our analysis of the first burst in our sample shows that there is a significant oscillation at 580 Hz within 0.03 s of the onset of this burst. The distance between poles is approximately 3×10^6 cm, so the required velocity is in excess of 10^8 cm s^{-1}. This velocity is significantly greater than the velocities of $\sim 1 \times 10^6$ cm s^{-1} discussed in the literature for turbulent deflagration waves (see, e.g., Fryxell & Woosley 1982; Nozakura et al. 1984) and hence may imply a detonation wave.

3. The existence of a strong signal at ∼580 Hz in the tails of the bursts (see Strohmayer et al. 1998c) indicates that fuel is not only *funneled* toward the magnetic poles, but is *confined* there before the start of the X-ray burst. If the fuel were not confined (e.g., if the magnetic field were too weak to prevent the fuel from spreading), then the fuel would spread almost evenly over the entire surface, so that even if ignition occurs almost simultaneously at the two poles, there would be no strong oscillation at ∼580 Hz in the burst tails (F. K. Lamb 1998, private communication).

4. The large amplitude of the oscillation at ∼580 Hz reported by Strohmayer et al. (1998c) near the beginning of one burst from 4U 1636−536 places strong constraints on the compactness of the neutron star because the maximum modulation amplitude produced by rotation is much less when there are two emitting spots than when there is only one (see Strohmayer 1997; Miller & Lamb 1998). The precise constraints depend on details such as surface beaming and bandwidth corrections (see Miller & Lamb 1998), but the establishment of ∼580 Hz as the first overtone strengthens these constraints dramatically.

5. The determination that ∼290 Hz is the spin frequency of 4U 1636−536 provides further support for the beat-frequency model of the kilohertz brightness oscillations detected in the persistent accretion-powered X-ray emission from many neutron star LMXBs (Strohmayer et al. 1996; Miller et al. 1998; see van der Klis 1998 for an observational overview of these oscillations). In the beat-frequency model, the spin frequency of 4U 1636−536 is predicted to be approximately equal (but not exactly equal; Lamb et al. 1999) to the separation frequency of the kilohertz oscillations, which has been measured as 250.6 ± 3.5 Hz (Méndez et al. 1998b) and 276 ± 10 Hz (Wijnands et al. 1997) in two different observations. Therefore, the detection of a signal at 290 Hz strengthens confidence in the inferences drawn from the beat-frequency model. For example, observations of 4U 1820−30 interpreted using this model provide good evidence for the detection of an innermost stable circular orbit (a key prediction of strong-gravity general relativity) and for the existence of a 2.2–2.3 $M_\odot$ neutron star (Zhang et al. 1998b), which have profound implications for our understanding of gravity and nuclear forces.

In conclusion, the results presented here show that the use of a strong oscillation in some bursts to construct the predicted waveform of a weaker related oscillation is an effective method to search for weaker oscillations at related frequencies. This procedure is especially powerful when a single source has more than one burst with a strong oscillation (e.g., 4U 1728−34, for which 17 bursts exhibiting brightness oscillations have been observed; see Strohmayer et al. 1998a), because coherent addition of data is then possible. It can also be used to improve signal detection during a single burst (as, for example, was done by Zhang et al. 1998a using data from a burst from Aql X-1). The method may also be used to characterize the properties of a peak whose existence has been demonstrated, such as either the 580 Hz peak or the 290 Hz peak in 4U 1636−536. In a future paper, we will report in detail the frequency and amplitude behavior of the ∼580 Hz oscillations in this source. Such characterization and detection holds outstanding promise as a sensitive probe of the properties of nuclear burning in X-ray bursts and of neutron stars themselves.

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