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 which exhibit strong oscillations at ∼580 Hz. We show that combining the data from the first 0.75 seconds of each of the five bursts yields a signal at 290 Hz that is significant at the $4 \times 10^{-5}$ 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 an algorithm for combining time series data from the five bursts so that the phases of the 580 Hz oscillations are aligned, may be used in any source to search for weak oscillations that have frequencies related in a definite way to the frequency of a strong oscillation.

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

1. INTRODUCTION

Prior to the launch of the Rossi X-ray Timing Explorer (RXTE) in December 1995, many theorists argued that thermonuclear (Type 1) 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 et al. 1984; Bildsten 1995 ). The discovery with RXTE of high-frequency (∼300 – 600 Hz), nearly coherent high-amplitude brightness oscillations during Type 1 bursts from several sources 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. 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, Swank, & Zhang 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 X 1743–29 (589 Hz). In three of these sources oscillations have been observed in several bursts: 4U 1728–34 has had 17 such bursts, 4U 1636–536 has had five, and X 1743–29 has had 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, Zhang, & Swank 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 is roughly 290 Hz (see Miller, Lamb, & Psaltis 1998). 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 ~0.1c 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 has not yet been 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 where nuclear burning occurs, which implies that the subsurface fields are much stronger, perhaps ~10^{11} G or higher.

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 more compact a neutron star is (i.e., the larger its ratio of mass to radius), the greater the deflection of light near its surface and hence the larger an area on the star that is visible at infinity. This implies in turn that the maximum modulation in brightness produced by a rotating hot spot is lower when the neutron star is more compact, and therefore that an observed amplitude of modulation places an upper limit on the compactness (see Strohmayer 1997; Miller & Lamb 1998). These limits are much stronger for a given oscillation amplitude if there are two hot spots instead of one (Miller & Lamb 1998). Another difference of a 290 Hz spin frequency compared to a 580 Hz spin frequency is that it implies much lower surface velocities, and hence a much smaller amount of power at 1160 Hz due to Doppler shifts and aberration (Miller & Lamb 1998). It is therefore essential to analyze the data as sensitively as possible to determine if there is any detectable 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. Our approach is to use the strong signal at 580 Hz visible in all five bursts to combine the five time series datasets so that the signal at 580 Hz is maximized. This procedure is somewhat similar to the technique used by Méndez et al. (1998) 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 then analyze the initial second of the combined burst data, which is the interval during which any signal at 290 Hz is expected to be strongest, and find a prominent peak at 290 Hz. The significance of the peak at 290 Hz is $4 \times 10^{-5}$ 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. This technique of combining time series data in phase, using a strong signal, can also be used to search for weak oscillations in other sources, such as 4U 1728–34 with its 17 bursts exhibiting brightness oscillations.

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, which occurred on 28 December 1996 at 22:39:24 UTC, 28 December 1996 at 23:54:03 UTC, 29 December 1996 at 23:26:47 UTC, 31 December 1996 at 16:39:28 UTC, and 23 February 1997 at 09:42:49 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 in the initial portion 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 harmonics
and subharmonics of the frequency of the primary peak will be strongest near the start of the
burst. For each burst, we therefore constructed a time series of countrate data \( C_i(t) \), for the \( i \)th
burst, starting at the beginning of the burst as determined by when the countrate rises above the
persistent countrate.

Observations of 4U 1636-536 and other X-ray bursters show that the frequency of the strong
peak, in this case near 580 Hz, can vary in a complicated way that is different from burst to
burst, with frequency changes of a few Hertz in less than a second (Strohmayer et al. 1998a). The
power at the primary \( \sim 580 \) Hz peak is therefore spread significantly unless the temporal variation
of this frequency is modeled carefully and separately for each burst (see, e.g., Strohmayer et al.
1998a). Since the existence of the \( \sim 580 \) Hz peak is secure, models of its frequency variation can
be explored without increasing the number of trials.

After extensive exploration of functional forms for the frequency behavior, we find that
a sufficiently descriptive model has five parameters for each burst: frequency and frequency
derivative for an initial, short time; a different frequency and frequency derivative for the remainder
of the data; and a break time between the two. This is similar to the frequency behavior reported
for the brightness oscillations during bursts from several other sources (Strohmayer et al. 1998a).
Given this relatively simple description, there is a frequency jump at the break time, which is not
expected to be present in a more accurate representation of the frequency behavior. The break
time was searched over the range from 0.125 s to 0.625 s, and the frequency was constrained so
that nowhere in the interval was it less than 576 Hz or greater than 585 Hz, to exclude spurious
solutions produced by noise in the power spectrum. The model that we use for the behavior of the
frequency during a particular burst is therefore

\[
\omega(t) = \omega_1 + \dot{\omega}_1 t, \quad t < t_{\text{break}}
\]

\[
= \omega_2 + \dot{\omega}_2 t, \quad t \geq t_{\text{break}}.
\]

These parameters are then varied for each burst to maximize the power at 580 Hz. In the next
step, the data for the five bursts are time-shifted with respect to each other by times \( \delta t_i < 1/580 \) s,
so that the power

\[
P = \left| \int_0^T \sum_i C_i(t + \delta t_i) e^{i\omega_i(t)} dt \right|^2
\]

of the combined data is maximized at 580 Hz. We expect that this is equivalent to aligning the
phases of the strong oscillation in the bursts. Here \( \omega_i(t) \) is the frequency fit for the \( i \)th burst
defined by equations (1) and (2) above, and without loss of generality we can set \( \delta t_1 = 0 \). The
time \( T \) is the time interval of the data included; in general this time could be different for each
burst, but for simplicity we integrate over the same interval for all five bursts. In the final step, \( T \)
is varied so as to maximize the 580 Hz power. This maximum occurs for \( T=0.734 \) s. The fits and
the resulting characterization of the burst brightness oscillations in 4U 1636–536 will be described
in detail in a forthcoming paper.
Fig. 1.— Leahy-normalized power spectra above 100 Hz for the first 0.734 s of the combined data set of the five bursts. The probability of a peak in this graph occurring by chance is just $\exp(-P/2)$, where $P$ is the power of the peak. The power at 580 Hz is 136 and that at 290 Hz is 25.6; the latter has a chance probability of $2.8 \times 10^{-6}$. Taking into account the 16 trials required to phase-align the 290 Hz peaks in the five bursts, the significance of the peak at 290 Hz is $4.4 \times 10^{-5}$.

In total, we use 30 parameters to describe the frequency behavior of the $\sim$580 Hz peak in all five bursts: five for each of the five bursts, four for the relative phases between bursts, and the integration time. We emphasize again that the strength of this peak allows us to do such modeling without introducing any trials.

This procedure maximizes the power of the signal at 580 Hz and will also maximize the power of the signal at any integral multiple of 580 Hz (e.g., at the 1160 Hz overtone of this frequency). However, it is not guaranteed to maximize the phase coherence at subharmonics such as 290 Hz. For example, if the 580 Hz oscillations for two different bursts are in phase, then the 290 Hz oscillations are either in phase or $\pi$ radians out of phase. Therefore, after maximizing the signal at 580 Hz in two bursts as above, it is necessary to determine which of the two possible relative oscillation phases maximizes the signal at 290 Hz. For five bursts there are four such choices of relative phase, and hence there are $2^4=16$ trials. The difference between the power produced by
the two different phase choices in each of the four steps is so great that there are no ambiguities.

The 100–1200 Hz power spectrum constructed from the time series data combined in this way is shown in Figure 1. An indication of the success of this method in bringing out the power at the 580 Hz peak is that if a power spectrum is constructed for the initial 0.734 seconds of the individual bursts, and the frequency model is simply a constant frequency, then the highest Leahy et al. (1983) normalized power near 580 Hz for any burst is 37 whereas the power at 580 Hz in Figure 1 is 136. This difference occurs because of the large variation in the frequency of the oscillation near 580 Hz, which becomes rapidly dephased compared to any constant frequency signal. This figure also shows a strong peak at 290 Hz, with a Leahy-normalized power of 25.6. This means that, in the combined data, the amplitude at ∼290 Hz is only a factor of 2.3 less than the amplitude at ∼580 Hz, and hence there can actually be a substantial amount of asymmetry between the two main emitting spots. Taking into account the 16 trials performed for the 290 Hz peak, the significance of the peak is $4.4 \times 10^{-5}$. This significance estimate is likely to be conservative, because in order to bypass issues of multiple trials we have assumed not only that the ∼290 Hz signal is always at exactly half the frequency of the ∼580 Hz signal, but also that the relative phase between the 580 Hz oscillation and the 290 Hz oscillation is constant throughout a burst and is the same from burst to burst. In reality, the relative phase is not likely to be constant, and hence the true power at 290 Hz is probably greater than estimated here.

3. DISCUSSION AND CONCLUSIONS

The very significant peak 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. In addition, either the two spots or our line of sight must be nearly in the rotational equator, because otherwise we would see much stronger emission from one spot than from the other, and hence a strong signal at 290 Hz. Of the two possibilities it is more likely that it is the hot spots that are near the rotational equator, because if our line of sight were close to the rotational equator then it would probably be blocked by the accretion disk. Hence, this source is probably close to being an orthogonal rotator, which has interesting implications for the evolution of its magnetic field geometry.

(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, personal communication). Our analysis of the first burst in our sample shows that there is a significant oscillation at 580 Hz within 0.03 seconds of the onset of this burst. The distance between poles is approximately $3 \times 10^6$ cm, so the required velocity is in excess of
$10^8 \text{ cm s}^{-1}$. This velocity is significantly greater than even the largest velocities $\sim 3 \times 10^7 \text{ cm s}^{-1}$ estimated for deflagration waves. Hence, if the ignition at one pole is communicated to the other pole via propagation of a nuclear burning front, the front must be a detonation wave.

(3) The existence of a strong signal at 580 Hz in the tail of the burst (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 tail of the burst (F. K. Lamb, personal communication).

(4) The large amplitudes reported by Strohmayer et al. (1998c) near the beginning of one burst place strong constraints on the compactness of the neutron star. 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). Indeed, the 75%±17% peak-to-peak amplitude (50% rms) at 580 Hz reported for a 1/16 second interval near the beginning of one burst from 4U 1636–536 (Strohmayer et al. 1998c) is so large that Strohmayer et al. (1998c) used it as an argument that only one pole was emitting and hence that 580 Hz is the true spin frequency. An amplitude this large can, however, be produced by two antipodal spots if bandwidth corrections and surface beaming are taken into account (Miller & Lamb 1998). Moreover, the quoted amplitude applies to a countrate spectrum from which an estimated background (calculated using the 20 seconds prior to the burst) has been subtracted. This implicitly assumes that the background is constant during the initial phase of the burst. If this is not the case, the true amplitude could be significantly less. Nonetheless, the existence of such a high amplitude from two hot spots has excellent promise for constraining strongly the compactness of this neutron star.

(5) The establishment of 290 Hz as 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 290 Hz (see Miller et al. 1998), and 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 as a clock to align time series data in some bursts 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 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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