DISCOVERY OF NEARLY COHERENT OSCILLATIONS WITH A FREQUENCY OF ~567 Hz DURING TYPE I X-RAY BURSTS OF THE X-RAY TRANSIENT AND ECLIPSING BINARY X1658−298

RUDY WINANDS,1,2 TOD STROMHAYER,3 AND LUCÍA M. FRANCO4

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ABSTRACT

We report the discovery of nearly coherent oscillations with a frequency of ~567 Hz during type I X-ray bursts from the X-ray transient and eclipsing binary X1658−298. If these oscillations are directly related to the neutron star rotation, then the spin period of the neutron star in X1658−298 is ~1.8 ms. The oscillations can be present during the rise or decay phase of the bursts. Oscillations during the decay phase of the bursts show an increase in frequency of ~0.5–1 Hz. However, in one particular burst the oscillations reappear at the end of the decay phase at about 571.5 Hz. This represents an increase in oscillation frequency of about 5 Hz, which is the largest frequency change seen so far in a burst oscillation. It is unclear if such a large change can be accommodated by present models used to explain the frequency evolution of the oscillations. The oscillations at 571.5 Hz are unusually soft compared to the oscillations found at 567 Hz. We also observed several bursts during which the oscillations are detected at much lower significance or not at all. Most of these bursts happen during periods of X-ray dipping behavior, suggesting that the X-ray dipping might decrease the amplitude of the oscillations (although several complications exist with this simple picture). We discuss our discovery in the framework of the neutron star spin interpretation.

Subject headings: accretion, accretion disks — stars: individual (X1658−298) — stars: neutron — stars: rotation — X-rays: stars — X-rays: bursts

1. INTRODUCTION

Of the more than 50 low-mass X-ray binaries (LMXBs) that exhibit type I X-ray bursts, only in six1 systems have nearly coherent oscillations (NCOs) during X-ray bursts been detected (Strohmayer et al. 1996, 1997b, 1998a; Smith, Morgan, & Bradt 1997; Zhang et al. 1998; Markwardt, Strohmayer, & Swank 1999; these oscillations are also called “burst oscillations”). Their high coherence (e.g., Strohmayer & Markwardt 1999; Muno et al. 2000), their strength (Strohmayer, Zhang, & Swank 1997a; Strohmayer et al. 1998a), and their frequency stability over many years (Strohmayer et al. 1998b) suggest that they are due to the spin of the neutron star. Their observed frequencies (300–600 Hz) are also consistent with the spin periods of other known rapidly rotating neutron stars, for example, the millisecond radio pulsars and the 401 Hz accreting X-ray pulsar SAX J1808.4−3658 (Wijnands & van der Klis 1998). Four of the burst oscillation systems are persistent sources and can be studied extensively so that the properties of their bursts (i.e., the NCOs) can be correlated with the overall behavior of the source (i.e., the variations in the mass accretion rate), although this has so far been done for only two systems (Muno et al. 2000; Franco 2001; van Straaten et al. 2001). The other two sources are transients, and the NCOs can be studied only when these sources are in outburst. Such outbursts occur infrequently, and only a limited number of X-ray bursts from them have been observed. Because of the limited amount of published results, the phenomenology of how the properties of NCOs relate to source state and mass accretion rate is not yet well understood.

The LMXB X1658−298 is an X-ray transient and was discovered by Lewin, Hoffman, & Doty (1976). They reported type I X-ray bursts from the system and thus demonstrated that the compact object is a neutron star. Cominsky & Wood (1984, 1989) found that the source displays deep X-ray dips and eclipses every ~1.1 hr, which most likely is the orbital period. After an outburst in 1978 the source remained in quiescence until 1999 April, when it was again found to be active (in ’t Zand et al. 1999). The Rossi X-Ray Timing Explorer All Sky Monitor (RXTE/ASM) light curve4 shows that as of the time of resubmission of this Letter (2000 December 15) the source is still active. An updated ephemeris for the orbital period was obtained by Wachter, Smale, & Bailyn (2000), using public TOO observations of X1658−298, performed with the proportional counter array (PCA) on RXTE. We searched the archival RXTE data (public TOO observations and proprietary data which have become publicly available) of X1658−298 for type I X-ray bursts, and we then searched the bursts we found for the presence of NCOs. Here we report the discovery of NCOs at a frequency of ~567 Hz during X-ray bursts from X1658−298. A preliminary announcement of this discovery was already made by Wijnands, Strohmayer, & Franco (2000).

2. OBSERVATIONS, ANALYSIS, AND RESULTS

Since its reappearance, X1658−298 has been observed on many occasions with the RXTE/PCA, both as a result of proprietary Cycle 4 observations and also via public TOO observations (Cycles 4 and 5). We searched all the currently public archival data for X-ray bursts using the Standard 1 data mode. Besides this mode and the Standard 2 mode, data were collected using an event mode with a time resolution of 122 μs in 64 energy channels (E_125us_64M_0_1s; covering the full RXTE/ASM light curve of X1658−298 can be found at http://xte.mit.edu/ASMlc.html.

1 Center for Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307; rudy@space.mit.edu.
2 Chandra Fellow.
3 Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771.
4 University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637.
5 After submission of our Letter, NCOs were also reported in 4U 1916−053 (Galloway et al. 2001), 4U 1608−52 (Chakrabarty et al. 2000), and possibly SAX J1808.4−3658 (in ’t Zand et al. 2001), bringing to 10 the number of systems now known to exhibit NCOs.
PCA energy range of 2–60 keV). These event mode data were used to search for and study oscillations during the type I bursts.

We found 14 bursts (Table 1), five of which occurred during intervals of dipping activity (bursts 1, 5, 9, 10, and 12), and one of which occurred during an eclipse (burst 14) and only the end of its decay phase could be studied. Of the bursts which occurred outside the dips, one burst was only about half as bright as the others (burst 6). Only during five bursts (bursts 1, 2, 3, 4, and 7) were all five PCA detectors on; for the others only four (eight bursts; bursts 5, 6, 8, 9, 11, 12, 13, and 14) or three (one burst; burst 10) detectors were active.

We searched the bursts for NCOs by using the $Z_n^2$ statistic (i.e., the $Z_n^2$ statistic because NCOs are highly sinusoidal) which was first used for analyzing the timing properties of X-ray bursts by Strohmayer & Markwardt (1999). We computed $Z_n^2$ throughout the bursts using overlapping 2 s intervals with a new interval defined every $\frac{1}{3}$ s. The $Z_n^2$ statistic has the same statistical properties as a Leahy normalized power spectrum. Thus, for a purely random Poisson process it is distributed as a $\chi^2$ distribution with 2 degrees of freedom. We searched the frequency range from 100 to 1200 Hz (for the range 2–22 keV) and discovered that highly significant NCOs were present at a frequency range from 564–568 Hz.

The strength of the NCOs is typically between 8% and 20% rms amplitude, and discovered that highly significant NCOs were present at a frequency range from 564–568 Hz (Table 1; including the persistent source count rate which varied typically in the range of 100–150 counts s$^{-1}$ PCU$^{-1}$), and the folded light curves of the oscillations are very sinusoidal (e.g., Fig. 2). For two of these bursts the NCOs were present only during the rising phase of the bursts (e.g., Fig. 1a); for the other four bursts (including burst 9) NCOs were present in the tail of the bursts (e.g., Fig. 1b). The properties of the method used for

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### TABLE 1

**Properties of the X-Ray Bursts**

| Burst | Observation ID | Time of Burst (UTC 1999) | Orbital Phase$^e$ | PCUs On | Count Rate$^c$ (counts s$^{-1}$ PCU$^{-1}$) | Oscillation? | Amplitude$^e$ (567 Hz; % rms) | Single Trial Probability$^d$ | Amplitude$^e$ (571.5 Hz; % rms) |
|-------|---------------|--------------------------|------------------|--------|-----------------------------------------|-------------|-------------------------------|-----------------------------|-------------------------------|
| 1     | 40036-10-01-00| Apr 6 12:12:46           | 0.80 0, 1, 2, 3, 4 | 2120   | No                                       | <4.6        | ...                           | <6.9                        | ...                           |
| 2     | 40050-04-01-00| Apr 9 14:46:30           | 0.28 0, 1, 2, 3, 4 | 2060   | Tail                                     | 19.6        | 1.1 × 10$^{-8}$              | <9.1                        | ...                           |
| 3     | 40050-04-02-00| Apr 10 09:48:33          | 0.95 0, 1, 2, 3, 4 | 2190   | Rise                                     | 8.5         | 1.5 × 10$^{-6}$              | <4.7                        | ...                           |
| 4     | 40050-04-04-00| Apr 14 11:47:52          | 0.73 0, 1, 2, 3, 4 | 1580   | Tail                                     | 8.7         | 2.2 × 10$^{-6}$              | 12.3 ± 1.5                  | ...                           |
| 5     | 40050-04-08-00| Apr 18 16:37:09          | 0.90 0, 2, 3, 4    | 2400   | No                                       | <7.4        | ...                           | <9.2                        | ...                           |
| 6     | 40050-04-08-00| Apr 18 18:26:14          | 0.15 0, 2, 3, 4    | 950    | No                                       | <6.1        | ...                           | <14.5                       | ...                           |
| 7     | 40050-04-10-00| Apr 20 16:24:19          | 0.61 0, 1, 2, 3, 4 | 1840   | No                                       | <4.9        | ...                           | <11.1                       | ...                           |
| 8     | 40050-04-11-00| Apr 21 11:44:53          | 0.33 0, 2, 3, 4    | 1800   | Tail                                     | 8.0         | 1.3 × 10$^{-3}$              | <7.7                        | ...                           |
| 9     | 40050-04-13-00| Apr 24 14:42:08          | 0.86 0, 1, 2, 3    | 275    | Tail                                     | 12.6        | 1.0 × 10$^{-6}$              | <9.1                        | ...                           |
| 10    | 40050-04-16-00| Apr 29 14:50:32          | 0.75 0, 2, 4       | 1380   | No                                       | <7.0        | ...                           | <10.9                       | ...                           |
| 11    | 40050-04-20-00| May 5 11:08:47           | 0.46 0, 1, 2, 3    | 1385   | Rise                                     | 12.0        | 1.8 × 10$^{-3}$              | <8.9                        | ...                           |
| 12    | 40050-04-21-00| May 9 17:23:12           | 0.83 0, 1, 2, 3    | 1625   | No                                       | <9.2        | ...                           | <20.9                       | ...                           |
| 13    | 40050-04-23-00| Jun 2 07:41:29           | 0.42 0, 2, 3, 4    | 1520   | No                                       | <4.9        | ...                           | <8.9                        | ...                           |
| 14    | 50410-01-05-00| Aug 8 09:32:22           | 0.02 0, 2, 3, 4    | 575    | No                                       | <14.1       | ...                           | <8.6                        | ...                           |

$^a$ As determined using the ephemeris of Wachter et al. 2000. Mid-eclipse time is phase 0.0.

$^b$ The peak count rate for the 2–60 keV RXTE/PCA energy range.

$^c$ For 2–60 keV. The amplitude is the maximum amplitude of the oscillations throughout the bursts. The errors on the amplitudes are between 1% and 1.5% rms. The 90% confidence upper limits are calculated for the beginning of the bursts to 20 s after the start in the frequency range 564–568 Hz.

$^d$ The single trial probability for chance detections.

$^e$ For 2–60 keV. The amplitude for burst 4 is the maximum amplitude of the oscillations. The 90% confidence upper limits are calculated for the peak of the bursts to 20 s after the start in the frequency range 570–573 Hz.

$^f$ In the year 2000. Approximate start time of this burst; it started when the source was still eclipsed by the companion star.

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**Fig. 1.**—Dynamical power spectra in the energy range 2–22 keV of the bursts on (a) 1999 April 9, 14:46 UTC (burst 2), and on (b) 1999 April 10, 9:48 UTC (burst 3), which clearly show the oscillations near 567 Hz. The lowest contour plotted is $Z_n^2 = 14$, and the contours increase in steps of 2. The burst count rate profiles (for five PCUs) are overplotted. The times given correspond to the start of the plots.
the analysis of the NCOs and their transient nature cause the broad distribution in frequency of the contours near the burst rise in Figure 1a. It is still not clear what determines the time or times during the bursts when oscillations are present. We are in the process of analyzing the bursts' behavior and the source behavior in detail in order to determine if the properties of the NCOs are correlated with any of the other burst properties (e.g., burst profile, episodes of photospheric radius expansion) or with the source properties (e.g., mass accretion rate). In a forthcoming paper we will discuss our results (R. Wijnands et al. 2001, in preparation).

When the NCOs are found in the tail of the bursts, their frequency increases slightly by 0.5–1 Hz (Fig. 1b). However, in one burst we found a very interesting evolution of the oscillation frequency. The frequency during the burst decay phase increased slightly by ~1 Hz, after which the oscillation died away. However, about 4 s later the oscillation reappeared but at a frequency of 571.5 Hz (12.3% ± 1.5% rms amplitude; 2–60 keV; Fig. 3, top panel). These NCOs near 571.5 Hz have similar peak power ($Z_i^2 \sim 32$) as the ones earlier on and the single trial probability of detecting such a power by chance is $1.1 \times 10^{-7}$. When taking into account a conservative estimate of the number of trials involved (the frequency range searched was 564–574 Hz for a 20 s interval after the burst peak), this probability increases to $2.2 \times 10^{-5}$. Including the total number of bursts (14) in our sample, we find a probability of $3.1 \times 10^{-4}$ that the signal is due to chance. However, when taking into account only the six bursts which show NCOs, the probability decreases to $1.3 \times 10^{-3}$. We conclude from these numbers that the signal we see at 571.5 Hz is real. Similar oscillations were not present in the other bursts with typical amplitude upper limits of 5%–11% rms (2–60 keV; Table 1).

The 5 Hz change in frequency represents the largest increase in any burst oscillation reported to date. To study this behavior further we decided to examine the energy dependence of the oscillations. We found that the oscillations at 571.5 Hz are most clearly visible below 6 keV (Fig. 3, middle panel), whereas when the frequency is close to 567 Hz the oscillations are stronger above 6 keV (Fig. 3, bottom panel). This demonstrates that the oscillation had a different energy dependence at different times during the burst.

3. DISCUSSION

We have discovered highly significant nearly coherent oscillations at a frequency of ~567 Hz during five type I X-ray bursts observed from the X-ray transient and eclipsing binary X1658–298. This makes this source the seventh source for
which highly significant NCOs have been found. The properties of these oscillations (their coherence, strengths, and long-term stability) make it likely that they are directly related to the spin frequency of the neutron star (or its first overtone as in 4U 1636–53; Miller 1999). In this interpretation, the spin period of the neutron star in X1658–298 would be ~1.8 ms. This is well within the range of what has been observed for the other sources which exhibit NCOs.

The frequency of the oscillation in the tail increases slightly by about 1 Hz (see Fig. 1b), similar to what has been observed before (e.g., Strohmayer et al. 1996, 1998a; Markwardt et al. 1999; Muno et al. 2000) in all of the other burst oscillation sources (although in some bursts a frequency decrease has been observed; Strohmayer 1999; Miller 1999; Muno et al. 2000). However, for one burst we observed a frequency increase of ~5 Hz (Fig. 3 top panel), the largest increase so far observed for any system. During this burst the oscillations have a different energy dependence at different frequencies: the oscillations are considerably harder when the frequency is observed near 567 Hz than when it reached 571.5 Hz. Usually the burst oscillations are hard (e.g., Smith et al. 1997; Strohmayer et al. 1997b; Muno et al. 2000); the 571.5 Hz signal is the first clear detection for which the burst oscillations are soft. The physical mechanism behind this sudden change in hardness is unclear, although it might be related to the softening of the burst spectrum in the decay phase of the burst.

In the interpretation that the burst oscillations are due to the rotation of the neutron star, the evolution of the frequency of the oscillations (usually an increase of the frequency) observed in the tail of the bursts has been explained by assuming that the bursting layer on the neutron star surface expands by several tens of meters (e.g., Strohmayer et al. 1997b; Cumming & Bildsten 2000). This height increase causes the layer to slow down and the frequency of the oscillations to decrease, only to spin up again when the layer settles back on the neutron star surface. To explain the large (5 Hz) increase in frequency we observed for X1658–298, a simple estimate indicates that the burning layer would have to expand by about 40–45 m. Cumming & Bildsten (2000) recently investigated the amount of hydrostatic expansion expected from bursts over a range of conditions. They find that Δz/Δz(90%), the increase in the height of the layer which contains 90% of the mass, can be as large as about 40 m, so it may be possible to account for such a change in the frequency. However, it is unclear if this “expanding bursting layer” model can account for the erratic increase of the frequency during this particular burst. It is possible that the asymptotic frequency, assumed to be very close to the spin frequency, is actually a few Hz lower than the true spin frequency. This might be the case not only for X1658–298 but for all the other sources as well. It is however not clear why the large frequency increase is observed only for one burst for X1658–298 and not for the others in this source or for the bursts in the other sources. In order to study this behavior in more detail, additional bursts are needed which show a similar large frequency increase.

Besides the five bursts which exhibit the very significant NCOs, we found a significant detection (although at lower significance) of the NCOs in one other burst (burst 9) but only nonsignificant indications in the other bursts with rms amplitude upper limits significantly lower than the NCOs strengths (see Table 1). Four of the bursts without NCOs occurred during orbital phase interval 0.75–0.02 (as determined using the ephemeris provided by Wachter et al. 2000; including the burst during an eclipse). The absence of NCOs might be due to the fact that during this orbital phase interval the source exhibits strong dipping behavior which is most likely caused by matter coming in to the line of sight. This matter (partly) obscures our view of the inner system and will also attenuate the NCOs. The density of the obscuring matter is highly variable, and if the density decreases significantly, it is possible that the NCOs can become undetectable, similar to what we observe.

However, the above simple picture does not hold for all bursts. Three bursts outside the dipping phase (bursts 6, 7, and 13; orbital phases of 0.15, 0.61, and 0.42) do not exhibit these oscillations. The reason why these bursts do not show NCOs might be because they behaved differently from the bursts with oscillations in other respects. Burst 6 was only about half as bright as the other bursts, indicating that the physical process behind the lower flux of this burst might also have inhibited the oscillations to be produced. The burst profiles of bursts 7 and 13 were different from those of the other bursts. Burst 7 exhibited an excess of burst flux several (2–4) seconds after the peak of the burst, just when oscillations are expected to be present (as judged from the other bursts which do have NCOs), and the rise phase of burst 13 lasts 2–4 times as long (~4 s) as the rise phases of the bursts showing NCOs (typically 1–2 s). The physical processes involved in producing these unusual burst profiles might also have caused the inhibition of the NCO mechanism.

Although the above picture can explain why NCOs might not have been present during all bursts which occur outside the dipping episodes, it cannot explain the two bursts at phases 0.86 (burst 9) and 0.95 (burst 3) which do show NCOs. The NCOs in burst 3 can be explained by assuming that although the source has not entered the eclipsing phase yet, the dipping activity has already subsided and we are able to observe the inner system again. This is consistent with the absence of any clear dipping activity in the persistent emission before and after this burst (but before the eclipse). However, the NCOs in burst 9 cannot be explained in this way. From the light curve it is clear that this burst happened during a period of extremely heavy dipping activity, which should have attenuated the oscillations. Instead, the NCOs we observe in the tail of this burst are even stronger than the oscillations in the tail observed for other bursts. If we assume that the oscillations are indeed partly attenuated, then these oscillations should have been even stronger. It is unclear what causes these strong oscillations in burst 9 and why they are not strongly attenuated.

X1658–298 is the first X-ray dipping and eclipsing binary for which NCOs have been discovered, and in this system the binary inclination is well constrained (i ~ 75°–80°) compared to the other systems. Because the other systems do not exhibit X-ray dips, their inclination is lower than ~70°, and most likely the range of inclination angles for these systems is large (based on statistical grounds). It seems likely that system inclination is an important factor in determining whether a source will show burst oscillations. In order for rotational modulation to be effective, the line of sight must not be too close to the spin axis of the neutron star. Since this axis is almost certainly perpendicular to the orbital plane, systems with high inclination have the most favorable geometry for producing rotational modulation. The fact that burst oscillations are seen in X1658–298 is at least consistent with this simple argument. Unfortunately, the inclinations of other burst oscillation sources are not so tightly constrained, so it is not possible at present to state that inclination is the primary factor in burst oscillation observability. Indeed, it may be that other factors are as important as inclination in producing observable burst oscillations.
tions. For example, the magnetic field strength may be important in pooling fuel at the magnetic poles, as suggested by Miller (1999) in the context of 4U 1636−53, or the oscillations might be detectable only above certain values of the mass accretion rate, as shown for KS 1731−260 (Muno et al. 2000) and 4U 1728−34 (Franco 2001; van Straaten et al. 2001). At the moment, however, it is still unclear why only a few sources exhibit these burst oscillations.

Because of its high inclination and hence the strong constraints on the binary parameters, X1658−298 could be an excellent source to try to determine the X-ray mass function from the burst oscillations as proposed by Strohmayer et al. (1998b). The bursts which exhibit the oscillations during the tail of the bursts (four bursts in our sample of bursts) are the most promising bursts to perform such a measurement if one assumed that the asymptotic frequency observed is the neutron star spin frequency. However, the observation of a burst frequency several Hz higher than the asymptotic frequency in the other three bursts casts doubt on the validity of this assumption.

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