Discovery of a 584.65 Hz Burst Oscillation in the Low-mass X-Ray Binary 4U 1730–22

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ABSTRACT

Type-I X-ray burst oscillations are powered by thermonuclear energy released on the neutron star (NS) surface in low-mass X-ray binaries (LMXBs), where the burst oscillation frequencies are close to the NS spin rates. In this work, we report the detection of oscillation at 584.65 Hz during the cooling tail of a type-I X-ray bursts observed from the accreting NS LMXB 4U 1730–22 on 2022 March 20, by the Neutron star Interior Composition Explorer telescope. The oscillation signal showed a strong Leahy power, $P_m \sim 54.04$, around 584.65 Hz, which has single-trial and multiple-trials confidence levels of 7.05σ and 4.73σ, respectively. The folded pulse profile of the oscillation in the 0.2–10 keV band showed a sinusoidal shape with the fractional rms amplitude of (8.0 ± 1.1)%. We found the oscillation frequency showed insignificant upward drifting, i.e., less than 0.3 Hz, during the cooling tail, similar to the behavior appearing in accreting millisecond X-ray pulsars (AMXP), and indicate the source could be an AMXP spinning at 1.71 ms.

Keywords: X-ray bursts; Low-mass x-ray binary stars; X-ray sources; Neutron stars

1. INTRODUCTION

The X-ray source 4U 1730–22 was discovered by Uhuru during its X-ray outburst in 1972 (Cominsky et al. 1978; Forman et al. 1978). The quiescent state of the source has been observed by Chandra, which associates with the faint X-ray source CXOU J173357.5–220156 (Tomsick et al. 2007). Based on the persistent and quiescent X-ray spectra, 4U 1730–22 was classified as a probable neutron star low-mass X-ray binary (NS LMXB; Tanaka & Shibazaki 1996; Chen et al. 1997). On 2021 June 7, the MAXI/GSC team reported the activities of an X-ray transient, which is associated with 4U 1730–22 after 50 yr of being at a quiescent state as confirmed by Swift follow-up observations (Kennea et al. 2021a,b; Kobayashi et al. 2021; Iwakiri et al. 2021). The position of 4U 1730–22 has been identified in optical wavelengths (Kennea et al. 2021b; Russell et al. 2021), which is consistent with the localization by Chandra (Tomsick et al. 2007).

Type-I X-ray bursts are triggered from unstable thermonuclear burning of accreting material on the NS surface (Lewin et al. 1993; Galloway et al. 2008; Galloway & Keek 2021). The first type-I X-ray burst from the source was detected by Neutron star Interior Composition Explorer (NICER; Bult et al. 2021c), confirming definitively, that the source is a transient LMXB hosting an accreting NS. Moreover, the optical counterpart of 4U 1730–22 has been identified, which shows strong hydrogen and weaker helium emission lines indicating a companion star in the main sequence (Russell et al. 2021; Strader et al. 2021).

Besides type-I X-ray bursts, the detection of coherent pulsation can also confirm the compact object in an LMXB as an NS. In addition, measuring the NS spin periods are also important in many other aspects, such as studying the spin evolution during the accretion process, evaluating the broadening effects of spectral lines on the NS surface (Chang et al. 2006), measuring the orbit parameters (see, e.g., Strohmayer et al. 2018), determining the NS masses and radii from photospheric radius expansion bursts (Suleimanov et al. 2020), and constraining on the NS equation of state especially from ultrafast rotational NS (i.e., submillisecond pulsars, Haensel et al. 2009). The spin periods of a large fraction of NSs have
been measured from their coherent emissions observed in radio or X-ray bands or both (see e.g., Manchester et al. 2005; Liu et al. 2006, 2007; Walter et al. 2015; Patruno & Watts 2021).

During type-I X-ray bursts, an NS may produce inhomogeneous thermal emissions on the surface, which manifests as burst oscillations (Strohmayer et al. 1996). The type-I X-ray burst oscillations provide us with an indirect method to measure the NS spin periods, due to the fact that the oscillation frequencies measured in accreting millisecond X-ray pulsars (AMXPs) are very close to their coherent spin frequencies within a few hertz during the persistent emissions (e.g., Chakrabarty et al. 2003; see Watts 2012 and Bhattacharyya 2022 for reviews). Totally, five persistent AMXPs have been observed burst oscillations, and their oscillation frequencies usually showed negligible upward drifting during the cooling tails (Chakrabarty et al. 2003; Galloway et al. 2008; Bilous & Watts 2019).

NICER was launched and installed on the International Space Station on 2017 June 3, which has the capabilities to collect X-ray photons in the energy of 0.2–12 keV with absolute time resolution as high as 100 ns (Gendreau & Arzoumanian 2017). After 5 yr of operation, NICER has been observed ∼ 56% of all known NS LMXBs in the MINBAR catalog (Galloway et al. 2020; see also the webpage 1) that have exhibited type-I X-ray bursts, including 23 sources with the detection of burst oscillation (or candidates) previously by RXTE and Swift (see Bilous & Watts 2019, and references therein). Benefiting from its high timing accuracy and relatively large collecting area, NICER has detected burst oscillations from 4U 1728–34 at ∼362.5 Hz (Mahmoodifar et al. 2019) and SAX J1808.4–3658 at 401 Hz (Bult et al. 2019), which were previously found by RXTE (Strohmayer et al. 1996; Chakrabarty et al. 2003). Recently, the burst oscillation candidate from XTE J1739–285 has been observed at 386.5 Hz (Bult et al. 2021a), rather than 1122 Hz reported by Kaaret et al. (2007). However, most of the sources have not reported the detection of burst oscillations (see, e.g., Aql X–1 and 4U 1636–536; Li et al. 2021; Güver et al. 2022; Zhao et al. 2022).

In this work, we report the detection of the burst oscillation at the frequency ∼ 584.65 Hz from 4U 1730–22.

2. OBSERVATIONS

In this work, we analyzed all public archived NICER observations of 4U 1730–22 on Modified Julian Date (MJD) 59642.0–59775.0 that have a total unfiltered exposure of 447.37 ks. The observation IDs (ObsIDs) include 42022001aa, 52022001bb, and 46390101cc, where aa, bb and cc run from 01 to 43, 01 to 19, and 01 to 83, respectively. We processed the NICER data analysis using HEASOFT V6.30.1 and the NICER Data Analysis Software (NICERDAS). We adopted the default selection criteria by using nicer2 to filter the cleaned event data. We then applied barycentric corrections using the tool barycorr to all the event data employing the source coordinates R.A. = 263°.489792, decl. = −22°.032472 (Tomskic et al. 2007) and the JPL-DE430 ephemeris. The 1 s light curves in the energy of 0.5–10 keV of all observations were extracted. From the light curves, a total of 16 type-I X-ray bursts have been identified. The observation log and properties of all bursts are listed in Table 1.

3. RESULTS

3.1. Burst Oscillation

Since the spin period or burst oscillation was previously unknown in 4U 1730–22, we carried out blind searches of all type-I X-ray bursts in Table 1 for testing the presence of coherent burst oscillations, where the time interval of each burst starts −5 s prior to the burst trigger. To preserve as many photons as possible, the cleaned event files in the 0.2–10 keV energy range were used. We applied the fast Fourier transform (FFT) technique with Leahy normalization to calculate the power spectra. For a pure Poisson counting process without any deterministic signal, the Leahy power satisfies a χ² distribution with two degrees of freedom (Leahy et al. 1983). We adopt the slide window of ΔT = 4 s, each new window moving forward 0.5 s with respect to the previous one. For each window, the statistically independent Fourier frequencies between 50 and 2000 Hz with steps of 0.25 Hz 2 and the corresponding power were recorded (see, e.g., Bilous & Watts 2019; Bult et al. 2021a).

We found the cooling tail in burst #4 shows a strong oscillation signal at ∼ 584.65 Hz with the Leahy power peaked at Pm = 54.04, well exceeding Pm = 2 expected from white noise. It corresponds to a probability of 1.84 × 10⁻¹² produced by chance for a single trial, which converts to the confidence level of 7.05σ. If considering all the searched frequencies (N_Freq = 1950 × 4) and segments (N_seg = 160), the total trials are N =

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1 https://personal.sron.nl/~jeanz/bursterlist.html

2 In practice, however, if the duration between the first and last photons in a 4 s window is slightly smaller than 4 s, then the Fourier frequency bin is slightly larger than 0.25 Hz. It has a negligible effect for estimating the detection significance of burst oscillation.
Power Counts/s Rate [10⁻¹⁹⁸³; Huppenkothen et al. 2019) in the frequency range [7.5, 10.0] Hz (Buccheri et al. 1983). In order to search for the burst oscillations more accurately, we applied the Z²-statistics, in which the power also satisfies the χ² distribution with two degrees of freedom, based on Stingray (Buccheri et al. 1983; Huppenkothen et al. 2019) in the frequency range between 579.5–589.5 Hz with steps of 0.01 Hz. The cleaned event files in the 0.2–10 keV energy range are also used by applying a moving window method with the same window size and step as the above-mentioned FFT method. We also reproduced the oscillation signal for the burst oscillation around 584.61 Hz, in which the Z² power peaked at 56.37. It converts to a probability of 5.75 × 10⁻¹³ produced by a random process for a single trial, that is, 7.21σ. If considering the total searched frequencies (Nfreq = 1000) and segments (same as the FFT method), the probability of multiple trials is 9.19 × 10⁻⁸.

In the left panel of Fig. 1, we produced the light curve of burst #4, and showed the contours of Z² power with the power changing from 25 to 55. We found the upward drifting of the oscillation frequency smaller than 0.3 Hz. The fractional rms (root-mean-square) amplitude is calculated from the relation,

\[ A_{rms} = \left( \frac{P_s}{N_m} \right)^{1/2} \frac{N_m}{N_m - N_{bkg}}, \]

where \( P_s \) is the power of the signal, \( N_m \) and \( N_{bkg} \) are the total and background X-ray photons collected during the burst interval. Compared with the high count rate of the burst, the background contribution can be neglected (see also Mahmoodifar et al. 2019; Remillard et al. 2022).

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**Figure 1.** Left panel: the 1 s binned light curve of the burst from ObsID 5202200113 (burst #4). We search the time interval between −5 and 75 s. The contours mark the Z² power from 25 to 55 with the steps of 5. The insert zoomed-in panel shows the time interval where the oscillation was detected. Right panel, the Leahy and Z² power marked as vertical dashed lines, during the burst interval \( t \approx 8.5 - 12.5 \) s, in the left panel. The horizontal dashed lines represent the single-trial significance of 4σ and 6σ, respectively.

**Figure 2.** The folded pulse profile of the burst oscillation in the energy range of 0.2–10 keV during the interval marked as vertical dashed lines in the left panel of Fig. 1. The red dashed line represents the best fitted sinusoidal model, \( A + B \sin(2\pi ft - \phi_0) \). In order to clarity, two cycles are shown.

\[ N_{freq} \times N_{seg} = 1.248 \times 10^6. \] It should be noticed that the segments are highly overlapped and not independent. We conservatively estimated that the confidence level of multiple trials is \( 2.30 \times 10^{-6} \), i.e., 4.73σ. Finally, further adjusting the trial count to include all 16 bursts, we obtained \( 3.68 \times 10^{-5} \) and 4.13σ.

In order to search for the burst oscillations more accurately, we applied the Z²-test statistics, in which the Z² power also satisfies the χ² distribution with two degrees of freedom, based on Stingray (Buccheri et al. 1983; Huppenkothen et al. 2019) in the frequency range...
We obtained the fractional rms amplitude to be $(8.0 \pm 1.1)\%$.

Using the oscillation frequency at the highest $Z_1^2$ power, in Fig. 2, we folded the pulse profile of burst #4 in the 0.2–10 keV in 16 phase bins from the 4 s interval marked by vertical dashed lines in the left panel in Fig. 1. The sinusoidal model, $A + B \sin(2\pi\nu t - \phi_0)$, has been applied to fit the pulse profile, resulting in the best-fitted values and $1\sigma$ uncertainties, $A = 544.0 \pm 5.8$, $B = 61.1 \pm 8.2$ and $\phi_0 = -(0.56 \pm 0.02)\pi$, respectively. The goodness of fit has the minimum $\chi^2$ of 14.2 for 13 degrees of freedom, i.e., 16 phase bins minus three model parameters, indicating a good fit. The fractional rms amplitude from the folded profile, $B/\sqrt{2A}$, is consistent with the previous result.

We have also searched for the possible presence of the second harmonics related to the burst oscillation frequency. We have found no significant signal and put an upper limit of the fractional rms amplitude of 2.6% and the significance level of 1.3$\sigma$ for a single trial.

3.2. X-ray Burst light curve simulations

The significance of the burst oscillation is calculated from overlapped timing windows, which are statically independent. In order to estimate the probability of detecting the oscillation signal by chance, we performed a sophisticated method through numerical simulations to take into account the effectiveness of the nonstationary of the burst light curve and the skewing effects of using overlapping windows. We constructed a sample of artificial light curves by using a method similar to Bilous & Watts (2019) and Bult et al. (2021b); see also the webpage.\footnote{https://jmichaelburgess.com/lc/} For each simulated light curve, we applied exactly the same searching procedure as mentioned in Sec. 3.1, and then, the maximum FFT power in the frequency range between 50 and 2000 Hz is preserved. After running $5 \times 10^4$ simulations, we found that none of the simulated maximum powers were higher than $P_m$. We also found that the maximum powers satisfy a lognormal distribution (see Fig 3). The probability to obtain the power exceeding the measured value, $P_m = 54.04$, is $2.67 \times 10^{-6}$. This shows directly that the detected burst oscillation is unlikely to occur by random chance.

4. DISCUSSION

We detected 16 type-I X-ray bursts from 4U 1730–22 by analyzing its 2021 and 2022 NICER observations. For the first time, we found that one burst in 4U 1730–22 appears as a strong burst oscillation signal during the cooling tail. The maximum Leahy power is 54.04, corresponding to the significance of 7.05$\sigma$ for a single trial, 4.73$\sigma$ for multiple trials, and 4.13$\sigma$ with all 16 bursts included, which are more significant than the burst oscillation powers from 4U 1728–34 (Mahmoodifar et al. 2019) and XTE J1739–285 (Bult et al. 2021b) observed by NICER. Moreover, the single burst oscillation signal for 4U 1730–22 is stronger than detections from SAX J1750.8–2900, HETE J1900.1-2455 (Bilous & Watts 2019), and 4U 0614+09 (Strohmayer et al. 2008), but weaker than SAX J1810.8–2609 (Bilous et al. 2018). The folded pulsation of the burst oscillation showed a sinusoidal shape, with a fractional rms amplitude of $(8.0 \pm 1.1)\%$. Both features are typical characteristics shown in many other NS LMXBs (see, e.g., Galloway et al. 2008). The burst decay oscillation and the fractional rms amplitude shown in 4U 1730–22 can be explained by the surface mode model, where the oscillation waves are excited at the burst raise in the NS ocean and spread for a large fraction of the cooling tail, or the asymmetric cooling wake model, where different parts of the NS surface cool at different rates (see, e.g., Heyl 2004; Watts 2012; Mahmoodifar & Strohmayer 2016; Bhattacharyya 2022).

The oscillation frequency is around 584.65 Hz, which indicates a fast rotational NS in 4U 1730–22 with a spin period of around 1.71 ms. Moreover, the oscillation frequency showed small upward drifting, less than 0.3 Hz, during the cooling tail, similar to the behaviors appearing in AMXPs (see, e.g., Chakrabarty et al. 2003; Watts 2012; Bult et al. 2019). Hence, we suggest that 4U 1730–22 could be also an AMXP spinning at 1.71 ms. During the process of this work, 4U 1730–22 is still in outburst,
and more data will be collected. Our observed burst oscillation can be searched and verified from possible new triggered type-I X-ray bursts from this source in near future. The spectral studies of all type-I X-ray bursts will be published elsewhere. With an almost known spin period, it is helpful to perform exhaustive searching for the coherent pulsation from the persistent emissions with reduced parameter spaces when the outburst stops (e.g., Strohmayer et al. 2018). If the spin frequency is confirmed, 4U 1730–22 would be one of the fastest accreting NSs, which belongs to the subpopulation of LMXBs with a high spin frequency centered at ≈ 575 Hz (Patruno et al. 2017). Moreover, we note that the effective surface temperature of 4U 1730–22 during its quiescent state was hot, that is, $1.51 \times 10^6$ K (Tomsick et al. 2007).

Rather than a coincidence, a rapidly rotating NS tends to excite an r-mode instability to balance the spin-up torque, resulting in reheating the star (Gusakov et al. 2014a,b; Patruno et al. 2017).

In addition, radio observations are highly encouraged to be carried out, to search for the coherent radio pulsation and catch the possible transition from accretion-powered to rotation-powered states, when the source evolves into the X-ray quiescent state (see Papitto & de Martino 2022).

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**Facilities:** NICER (Gendreau et al. 2012).

**Software:** Stingray (Huppenkothen et al. 2019), HEASOFT (NASA High Energy Astrophysics Science Archive Research Center (Heasarc) 2014).

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Table 1. Summary of burst observations.

| Burst No. | NICER ObsID | Burst Trigger Time (TDB MJD) | ObsID Start Time (YYYY-MM-DD) | Peak Count Rate * (10^3 ct s^−1) |
|-----------|-------------|-----------------------------|-----------------------------|---------------------------------|
| 1         | 4202200125  | 59404.55780                 | 2021-07-09                   | 3.14                            |
| 2         | 5202200101  | 59639.33493                 | 2022-03-01                   | 3.67                            |
| 3         | 5202200112  | 59657.91327                 | 2022-03-19                   | 6.31                            |
| 4         | 5202200113  | 59658.96139                 | 2022-03-20                   | 6.29                            |
| 5         | 4639010102  | 59664.12261                 | 2022-03-26                   | 2.71                            |
| 6         | 4639010104  | 59666.95125                 | 2022-03-28                   | 2.98                            |
| 7         | 4639010113  | 59675.59719                 | 2022-04-06                   | 2.32                            |
| 8         | 4639010116  | 59678.77329                 | 2022-04-09                   | 6.99                            |
| 9         | 4639010131  | 59695.09694                 | 2022-04-26                   | 7.93                            |
| 10        | 4639010141  | 59718.3307                  | 2022-05-19                   | 5.45                            |
| 11        | 4639010146  | 59723.8250                  | 2022-05-24                   | 2.78                            |
| 12        | 4639010160  | 59739.4289                  | 2022-06-09                   | 5.79                            |
| 13        | 4639010160  | 59739.8745                  | 2022-06-09                   | 6.87                            |
| 14        | 4639010166  | 59747.6837                  | 2022-06-17                   | 5.91                            |
| 15        | 4639010175  | 59756.8607                  | 2022-06-26                   | 5.83                            |
| 16        | 4639010179  | 59762.7372                  | 2022-07-01                   | 5.59                            |

* The peak count rates are measured from the 1 s cleaned light curves in the energy range of 0.5–10 keV.
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