MXB1659-298: The Fastest Spinning Millisecond Pulsar

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ABSTRACT

We present the discovery of strong nearly coherent oscillations (NCOs) at 890.44 Hz for the low mass X-ray binary MXB 1659-298. This is significant because the corresponding spin period of the neutron star in this system is 1.123 ms, faster than any millisecond pulsars detected so far. We analyzed data from 2015 and 2016 outburst observations of this source with NuSTAR by employing the $Z^2_n$ statistic. In our analysis, large $\chi^2$ values with two degrees of freedom were found at 890.44 Hz, which corresponds to extremely low levels of statistical significance and high degrees of confidence ($> 5\sigma$) for all of the data sets from these NuSTAR observations.

Keywords: MXB 1659-298, NuSTAR

1. INTRODUCTION

The low mass X-ray binary (LMXB) MXB 1659-298 was first found by the SAS-3 mission during outburst in October 1976 (Doty et al. 1977). A 15 minute eclipse of the neutron star by its companion and a 7.11 hour orbital period are, by now, well established (Cominsky & Wood 1984). In 1999 after 23 years of quiescence MXB 1659-298 went back into outburst which was well observed with RXTE (Markwardt et al. 1999). Since then this source would remain in a quiescent state until 2015 when it went back into outburst again (Negoro et al. 2015) which continued into 2016 and was observed quite often with Swift XRT and twice with NuSTAR, but in March of 2017 the burst ended (Parikh et al. 2017).

Analysis of the 1999 burst data from RXTE found nearly coherent oscillations (NCOs) at $\sim 567$ Hz which was interpreted as the detection of the spin of the neutron star in this binary (Wijnands et al. 2001). However, since then there has been no confirmation of this result. The best way to confirm this result would be to find the NCOs in a different epoch with better instruments. All Swift XRT data could be disregarded for this timing work as it does not provide fine enough timing resolution. However the two NuSTAR observations are excellent opportunities to do so, as NuSTAR provides adequate temporal resolution at 2$\mu$s for event mode recording relative to the on board clock (Harrison et al. 2013). With more than 20 ks of exposure time in each observation and the ability to use two detectors A and B per observation, these NuSTAR observations enabled our timing work to check this report. Our analysis yielded strong NCOs at 890.44 Hz, however not at $\sim 567$ Hz. The conclusion is that the statistical evidence for 890.44 Hz NCOs strongly suggests that it is the spin of the neutron star in this binary, not 567 Hz.

2. METHOD

We obtained the NCOs of MXB 1659-298 by adopting the $Z^2_n$ statistic method. It is effectively a Fourier space that has a probability density function equal to a $\chi^2$ with $2n$ degrees of freedom (Bendat & Piersol 2011), where:

$$Z^2_n = \frac{2}{N} \sum_{k=1}^{n} \left[ \left( \sum_{i=1}^{N} \cos 2\pi k \phi_i \right)^2 + \left( \sum_{i=1}^{N} \sin 2\pi k \phi_i \right)^2 \right]$$  (1)
\[ \phi_i = \nu(t_i - t_0) + \dot{\nu}(t_i - t_0)^2/2 + \ldots \] (2)

We calculated \( Z_i^2 \) with equations (1) and (2). \( t_0 \) was set to the first photon arrival time of our data set, while \( t_i \) is each subsequent photon arrival time. The spin frequency (\( \nu \)) was tested over a wide range, and then after examining the full range of test values, signals of interest were zoomed in on and examined over smaller intervals at finer resolutions. With testing at such fine intervals, there is a significant level of assurance that a strong signal will not be missed in the noise. This allows for much stronger \( Z_i^2 \) values, leading to a stronger degree of statistical significance, and thus stronger confidence in any results. Our search ran over entire observations as to ensure that a strong signal can be observed. After processing all photon arrival times through the \( Z_i^2 \) statistic, the results are distributed against the associated test spin frequencies. The spin frequency best fit to the source should then stand tall. If a single strong signal with a large enough \( Z_i^2 \) value is found, then we can conclude that the signal refers to the spin of the source.

The data used from NuSTAR is the event mode data which is capable of temporal resolution of 2\( \mu \)s (Harrison et al. 2013). With NuSTAR’s two detectors, A and B, for two observations there are effectively four data sets to test for all observations. The two detectors allow the opportunity to check if a signal is a false positive. We expect to see nearly the same signal with a strong degree of significance and confidence in both detectors A and B for a given observation. For the arrival times from the event files to be usable, the entire observation is first reduced in accordance with the NuSTAR Data Analysis Software Guide. A bary-center correction and clock correction are also made to the photon arrival times. This process of data reduction for NuSTAR allows for a point source extraction to ensure that we are getting as many counts as possible without any background contamination. Since our source in question is very faint, the point source extraction reduces the noise in our results and lets the signal stand out in much greater magnitude.

We also examined the earlier archival data from RXTE to try and reproduce the \( Z_i^2 \) values used previously to determine the 567 Hz result by Wijnands et al. (2001). To do so we collected the same PCA event mode data with 122\( \mu \)s of timing resolution which covers the full PCA range of 2-60 keV. The photon arrival times from this data was also bary-center corrected.

The frequency range for testing adopted by Wijnands et al. (2001) was only up to 1200 Hz at an interval of 0.25 Hz. However since that was found to be inadequate to account for the prediction of the possible existence of a sub-millisecond pulsar population (Bhattacharyya & Chakrabarty 2017), a Newtonian approximation was used to estimate the appropriate upper bound of the range for our calculation by setting the gravitational force equal to the centripetal force. Then, by estimating the mass and radius of the neutron star in MXB 1659-298 to be \( \sim 1.7M_\odot \) and \( \sim 11\, \text{km} \) (Tsuruta, S. 2017, Unver 2013) a maximum spin frequency of just under 2100 Hz was obtained. Therefore we set our spin frequency (\( \nu \)) test range as 0 to 2100 Hz. This test range was initially used at a step interval of 0.001 Hz to identify strong signals of interest. After a signal of interest was found we narrowed the test spin frequencies to a much smaller range around the signal of interest, and then we significantly refined the step interval. In our work the step interval became as small as 10^{-6} Hz, depending upon the Nyquist frequency available within the data.

We verified our \( Z_i^2 \) calculation by testing on several data sets of sources with well established spin frequencies (i.e. Crab, SAX J1808.4-3658, etc.). We replicated the results from these well established sources using NuSTAR data. Further details can be found in Paper II (Teter et al. 2020, in preparation).

There are a few key differences in our methodology compared with that used in the previous detection of 567 Hz NCOs by Wijnands et al. (2001). First and foremost we tested the entire observation’s given photon arrival times all in one trial. We do this because the quantity of observed oscillations is at the maximum for a given observation and that the longer observations give better frequency resolution. Thus, the \( Z_i^2 \) value best fit to the source will be magnified enough such that we strictly use the statistical interpretation of the corresponding \( \chi^2 \) value with 2 degrees of freedom, to see which spin frequency is the best fit to the source. On the other hand, Wijnands et al. (2001) instead adopted the simpler Leahy Normalized Power Spectrum Method where only a 20 seconds segment of data along the observation was tested at a time, and the \( Z_i^2 \) values are distributed as contours over the power spectrum.

3. RESULTS

1. We analyzed the \( Z_i^2 \) statistic for the NuSTAR observations. A signal was found at around 890.44 Hz. It appears in all 2015 and 2016 NuSTAR data sets from both detectors A and B. The results are summarized in Table 1. The largest signal was found at 890.4471 Hz with a \( Z_i^2 \) statistic of 466.92 in the 2016 B detector. The detected signal for the NuSTAR 2016 B observation is shown in Figure 1A, while the phase resolved light curve for this case is shown in Figure 1B. The confidence in the NuSTAR results is > 8\( \sigma \) for all the data sets except for the 2015 A detector, which is
Table 1. MXB 1659-298 Results from $\nu$ Model

| Date          | Detector | Photons       | $\nu$ (Hz) | $Z_2^1$  | $\delta \nu$ (Hz) | Significance | Confidence |
|---------------|----------|---------------|------------|----------|-------------------|--------------|------------|
| Sept. 8, 2015 | NuSTAR A | 200,629       | 890.43931  | 37.85    | $6.039 \times 10^{-09}$ | $5.7\sigma$  |            |
|               | NuSTAR B | 184,428       | 890.44523  | 76.15    | $2.912 \times 10^{-17}$ | $> 8\sigma$ |            |
| Apr. 21, 2016 | NuSTAR A | 468,202       | 890.44425  | 260.59   | $2.592 \times 10^{-17}$ | $> 8\sigma$ |            |
|               | NuSTAR B | 429,206       | 890.44710  | 466.92   | $4.07 \times 10^{-102}$ | $> 8\sigma$ |            |
| April 6, 1999 | RXTE PCA | 5,674,724     | 890.45185  | 25.006   | $3.72 \times 10^{-06}$ | $4.48\sigma$ |            |

the weakest but where the signal detected at 899.43931 Hz is still with a $Z_2^1$ statistic of 37.85 ($5.7\sigma$). Our conclusion is that the frequency of 890.44 Hz is consistent across all NuSTAR 2015 and 2016 data.

2. We were not able to find signals at or near 567 Hz in all of the four data sets from NuSTAR observations. We adopted both our method and the one used by Wijnands et al. (2001). Even the largest individual peak is nearly indistinguishable from nearby noise peaks. The conclusion is that the 567 Hz frequency reported by Wijnands et al. (2001) is not confirmed in our analysis of all NuSTAR observations.

3. The significance for the $\sim 890$ Hz NCO’s detections ranges from $10^{-8}$ to $10^{-102}$. The meaning of statistical significance is the probability of obtaining the result by random chance. So for these NuSTAR observations we find a maximum of approximately one in ten thousand that the result occurred by chance. If we take the sets together, the combined probability is better than $10^{-102}$. We conclude that the detection of 890.44 Hz by the combined collections of two detectors over two epochs is not a chance result in the data.

4. Next the earlier archival 1999 RXTE data set was examined. When their method was adopted we noted signals near 567 Hz at the limited specified short time intervals where Wijnands et al. (2001) found such NCOs. However with our current method the $\sim 567$ Hz NCOs are not detected in the 1999 RXTE data. Instead a $Z_2^1$ peak of 25.006 was found at 890.45185 Hz.

Figure 1.
A: Signal of 890.4471 Hz from NuSTAR detector B in 2016.
B: Phase resolved light curve at 25 bins of NuSTAR detector B in 2016 using our 890.4471 Hz result.
5. The 890 Hz peak of $25 Z^2_1$ found in the 1999 RXTE data is not really a detection with only 4.7σ confidence. However, when we combine the significance of this RXTE peak at 890 Hz ($3.2 \times 10^{-6}$) with the superior results obtained from all of more recent NuSTAR observations, we get a combined significance of $10^{-102}$. From this combined result from three epochs spread over 17 years, we conclude that the spin frequency of MXB 1659-298 is 890.44 Hz. That corresponds to a spin period of 1.123 ms.

4. DISCUSSION

To obtain the 567 Hz NCOs for MXB 1659-298, Wijnands et al. (2001) analyzed the 1999 RXTE outburst data by adopting the $Z^2_2$ statistic and the Leahy Normalized Power Spectrum method. Although we adopted a similar $Z^2_1$ statistic method, our approach and specific treatment of the procedure are different (see Section 2). We did not detect the 567 Hz NCOs for MXB 1659-298. Instead we found strong NCOs at 890.44 Hz, as the more statistically significant results from more recent and superior NuSTAR instruments. We found a weaker signal at this frequency in the 1999 RXTE data, too. Our results do show large $Z^2_1$ values corresponding to extremely low levels of statistical significance and quite high confidence. This can be considered enough evidence to drop the previous claims of a 567 Hz signal as corresponding to the spin period of the star. A major reason for this is that we obtained the contradictory results, especially from NuSTAR. These observations show a very strong degree of statistical significance and confidence of > 8σ.

Our new result may show that some previous approaches to pulsar timing and determination of its possible spin in X-ray astronomy have some aspects that may remain to be improved. First of all, a better approach moving forward is one of pure statistics. Jumping straight to the Leahy Normalized Power Spectrum without first finding statistical significance in the resulting $Z^2_1$ values may provide false positives. Because of this, pulsars timed only using the Leahy Normalized Power Spectrum method without the statistical evidence from $Z^2_1$ may be improperly timed. Second, when dealing with faint sources it is important to realize that long exposure times, with very fine timing resolution, is a requirement for building proper NCOs for spin measurement. Third, we must consider spin frequencies up to the breaking point of the pulsar, for the simple reason that the first signal we detect may be a harmonic. Lastly, there must be much more precision taken in testing spin frequencies of these pulsars. In obtaining the previous value of NCOs with 567 Hz, a test spin frequency interval of 0.25 Hz was used. Our analysis has shown that with advances in computational technology we can test spin frequencies at a much more refined interval.

Wijnands et al. (2001) also used all of the data from the 1999 outburst. Instead of our method where we analyzed all the data points simultaneously, they examined limited short time intervals along the evolution of the burst. This is most likely so that the Leahy Normalized Power Spectrum method could be used, which was the method of choice at the time due to computational limitations of the time. Note that these authors found $\sim$ 567 Hz NCOs during certain short intervals of time along the burst evolution. One possibility is that these NCOs refer to some transient local temporal instability events, but do not correspond to the star’s rotation period. We could not find the NCOs in the more recent and more superior NuSTAR data. Also note that the 567 Hz NCOs as the identification of star’s spin period have not been confirmed in the last $\sim$ 20 years.

5. CONCLUSION

Our work finds NCOs with a frequency of 890.44 Hz for the neutron star in the LMXB MXB 1659-298. The corresponding spin period is 1.123 ms. On the other hand the fastest spinning ordinary stable pulsar existing so far was PSR J1748-2446, with a spin frequency of 716 Hz (Hessels et al. 2006). That being said, with these results MXB 1659-298 is a new fastest spinning millisecond pulsar at 890.44 Hz.

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