A Systematic Pulse Scan for Intermittent-AMXPs via Z^2 and Maximum Likelihood Techniques

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1. Introduction

We present a detailed systematic pulse search for three Intermittent-Accreting Millisecond X-ray Pulsars (Intermittent-AMXPs), HETE J1900.1-2455, SAX J1748.9-2021, Aql X-1, via Z^2 and maximum likelihood techniques by using 20 years data of Rossi X-ray Timing Explorer/Proportional Counter Array (RXTE/PCA) in the energy range of 3.0 – 30.0 KeV. We first performed pulse scan by using Z^2 technique for every 25s time interval by shifting 1s in millisecond sensitivities to cover all observation data set around the detected frequency given in the literature. We tracked the Z^2 power over time and flagged the time intervals exceeded defined threshold for each source as pulse candidates. We built the pulse profiles for the candidate segments and checked the amplitude of the pulses to better define pulsed regions. The pulse list throughout our scan has new discoveries while covering the pulsed regions presented in the literature for these three sources. For a deeper search, using the pulses obtained from Z^2 method as probability density function as input parameter, we rescanned the duration covering around the obtained pulse by using maximum likelihood technique. We checked a systematic phase shift pattern over search duration. In conclusion, we discuss the advantages and disadvantages of the timing methods in millisecond rages as well as identifying new pulsed regions in intermittent-AMXPs.

2. Timing Analysis

All RXTE data of the three Intermittent-AMXP sources in our sample were downloaded from the NASA-coordinated database HEASARC (*Richmond & White 1994; HEASARC 2016*) to the local server by preserving the data structure with the "Archive Downloader" program (*Güngör et al. 2022*) and made ready for data analysis. First, the FXBARY subprogram of the HEASOFT program was used to apply the "Sun center reduction process" to the time information in the raw data.

Preliminary analyses have allowed for time analysis of some strong pulse regions in the energy range (3.0 - 30.0 KeV) where the RXTE satellite is most sensitive. **Figure 1** shows the variation of the Z^2 power value for three different energy ranges. According to these results, scanning operations were performed in the range of 3.0 - 13.0 KeV for all sources in order to gain speed and to operate in the most sensitive range.

Table 1. Fundamental characteristics and RXTE observational details of the systems investigated.

Source	Pulse Frequency	Orbital Period	Accessible ObsID	Frequency
	ν (Hz)	P_{orb} (Hr)	Number (RXTE)	Range (Hz)
HETE J1900.1-2455	337[1]	1.4[2]	464	336.0 – 338.0
SAX J1748.9-2021	442[3]	8.8[3]	280	441.0 – 443.0
Aql X-1	550[4]	19[5]	927	550.0 – 550.5

References – [1]Morgan et al. (2005); [2]Kaaret et al. (2006); [3]Altamirano et al. (2008); [4]Casella et al. (2008); [5]Chevalier et al. (1998)

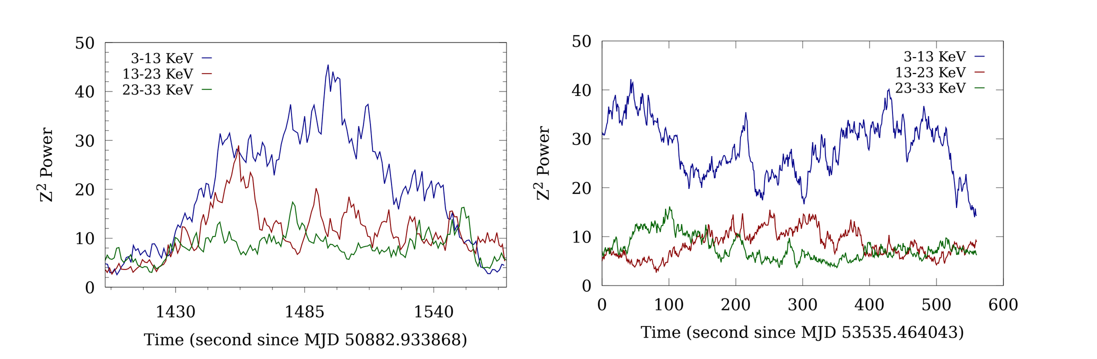

Figure 1. Variation of Z^2 power values with time in three different energy ranges. *Aql X-1*; ObsID: 30188-03-05-00 (left), *SAX J1748.9-2021*; ObsID: 91050-03-07-00 (right)

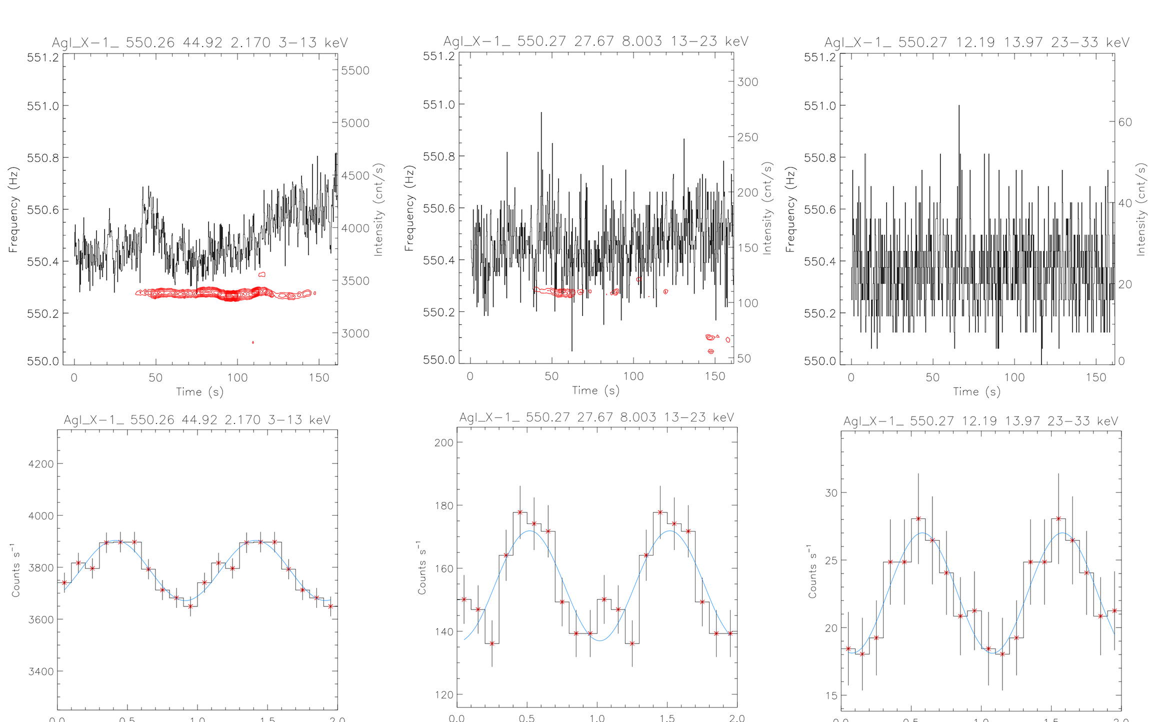

Figure 2. Scanning Z^2 pulses in three energy ranges for the pulse-open region of the *Aql X-1* source in approximately the last 150 seconds. The red regions on the light curve indicate the strength of the pulse (ObsID: 30188-03-05-00). The lower ones show the frequency excursion phases at the maximum power obtained from these regions.

2.1. Z^2 Technique

Using the arrival time and channel information of each photon in the RXTE/PCA raw data, we performed our analyses in the range of 3.0-13.0 keV, where the detector is most sensitive. The first method we used for time analysis, the Z2 method, is based on the calculation of the power value for a given spin frequency using the function Z^2,

$$Z^2 = \frac{2}{N}\sum_{k=1}^{n}\left[\left(\sum_{j=1}^{N}\cos k\Phi_j\right)^2 + \left(\sum_{j=1}^{N}\sin k\Phi_j\right)^2\right] \quad (1)$$

where $\boldsymbol{Z^2}$ is the calculated power value, N is the total number of photons, $\boldsymbol{\Phi}$ is the phase of the arrival times of the photons, and $\boldsymbol{k}$ is the number of orders of solution of $\boldsymbol{\Phi}$. The spin frequencies of these 3 sources were obtained in 10^{-4} Hz steps at ± 1 Hz intervals and the power spectra of each source are available in the literature. Using this as the central frequency for each source, the Z^2 power was generated. In this way, frequency variations can be detected with a resolution of one ten thousandth.

2.1. Maximum Likelihood Technique

Maximum likelihood technique allows the detection of the most probable phase shift in the presence of a variation like the pulse profile, using the beat frequency information obtained by the Z^2 technique, an initial time and a pulse profile. In order to apply the method, the pulse profile must first be obtained and calibrated so that the area under the pulse profile is equal to one, allowing the pulse profile to be used as a probability function.

$$\mathrm{Prob}(\Phi_{\mathrm{off}}) = \prod_{i=1}^{N} P(\Phi_i - \Phi_{\mathrm{off}}) \quad (2)$$

$\boldsymbol{P_{(\Phi)}}$ in **Equation 2** shows the probability function obtained from the throw profile. In the method, the phase values ($\boldsymbol{\Phi_i}$) should first be obtained by using the optimal start time ($\boldsymbol{T_0}$) and rotation frequency ($\boldsymbol{v}$) for each time information ($\boldsymbol{T_i}$). For an assumed phase shift ($\boldsymbol{\Phi_{off}}$) in the region under investigation, a probability is determined by using all $\boldsymbol{\Phi_i}$ values in the observation section.

3. Analysis Results

In our study, the results of the Z^2 method applied to all three sources are shown in subheadings. When identifying the regions that could be pulsed, we selected data that were at least a few sigma above the base value in the Z^2 power spectrum. At the same time, we also searched for a certain correspondence by using the RMS values showing the compatibility with the smoothed model added on the pulse phases generated using the frequency value with the highest power value. Accordingly, for example, in the diagram shown in **Figure 3**, we set a Z^2 value of 28 for the Aql X-1 source as the threshold. For the other sources, this value was set to 30.

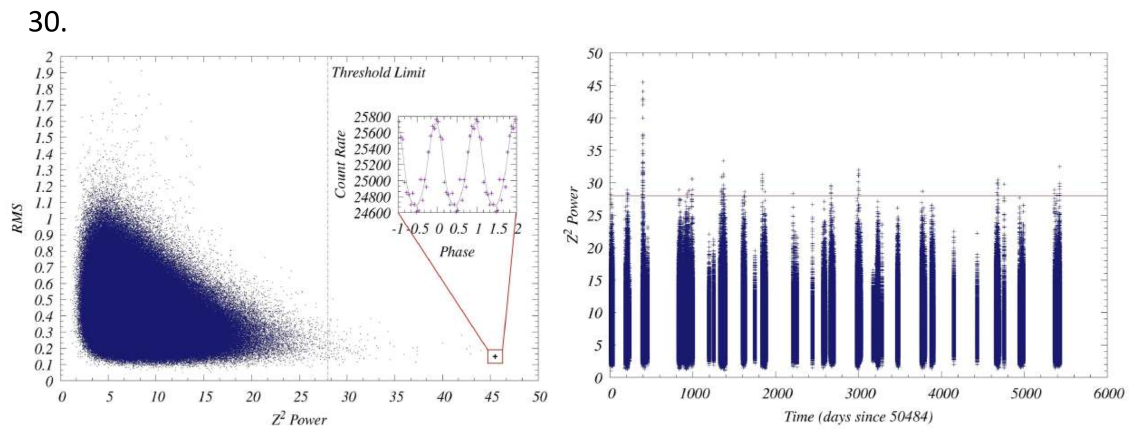

Figure 3. Diagram of the RMS value of the data-model relationship of the throw profile data-model and Z^2 power values obtained on all scanned data for the *Aql X-1*. The throw profile with the highest Z^2 power value is shown in the graph (left). Variation of Z^2 power values with respect to time. The threshold value is shown as red horizontal line. (right)

3.1. HETE J1900.1-2455

HETE J1900.1-2455 was discovered by the High Energy Transient Explorer (HETE). Morgan et al. (2005) detected the pulsations of this source using RXTE data and announced its spin frequency as 377 Hz. The pulsations observed in the X-ray light curve persisted for the first twenty days of the 2005 flare, but then abruptly disappeared and were occasionally detected again during the flare over the next 2.5 years. In our study, we applied rigorous time analyses to all the RXTE/PCA data for this source and some example dynamic spectra of the results are shown in **Figure 4.** In addition, the detected pulses are plotted on the long term ASM light curve in **Figure 5**.

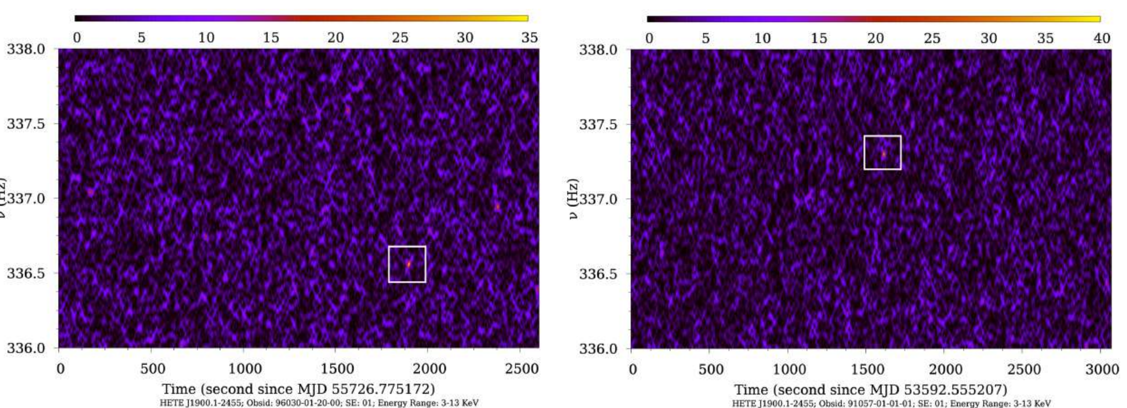

Figure 4. Example dynamic power spectrums of the HETE J1900.1-2455 source. Regions inside the white squares showing pulsing.

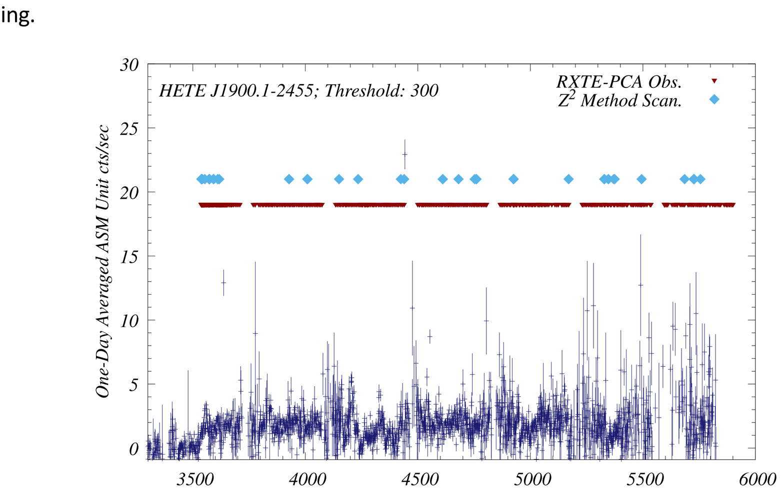

Figure 5. ASM light curve representation of the detected pulse areas of the *HETE J1900.1-2455.*

3.2. SAX J1748.9-2021

SAX J1748.9-2021 is an AMXP in the globular star cluster NGC 6440. The spin frequency of the source was found to be 442 Hz (Gavril et al., 2006). Since its discovery in 1998, it has not shown any pulsations, and the first pulsations were observed during its flare in 2005. Therefore, it is classified as a transient AMXP. Altamirano et al. (2008) investigated the transient pulsations of this source and found that the pulsations at 442.36 Hz occurred transiently during flares in 2001 and 2005 and discussed their relationship with thermonuclear explosions. In the present study, we present the results of the short pulsations of this source, excluding some periods of high amplitude pulsations. **Figure 6** shows some sample Z^2 power spectra. Finally, we show the pulsations detected on Swift-BAT observational data for the globular cluster NGC 6440.

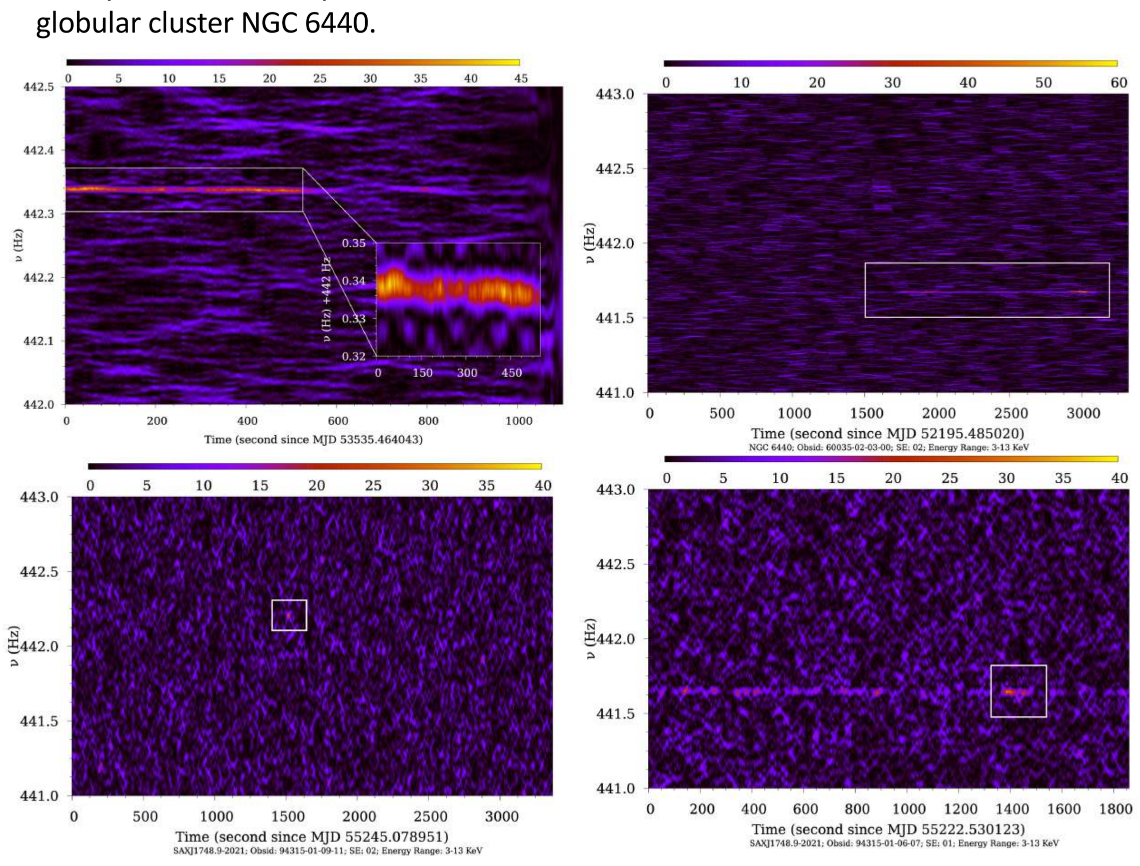

Figure 4. Example dynamic power spectrums of the SAX J1748.9-2021 source. Regions inside the white squares showing pulsing. (First one obsID: 91050-03-07-00)

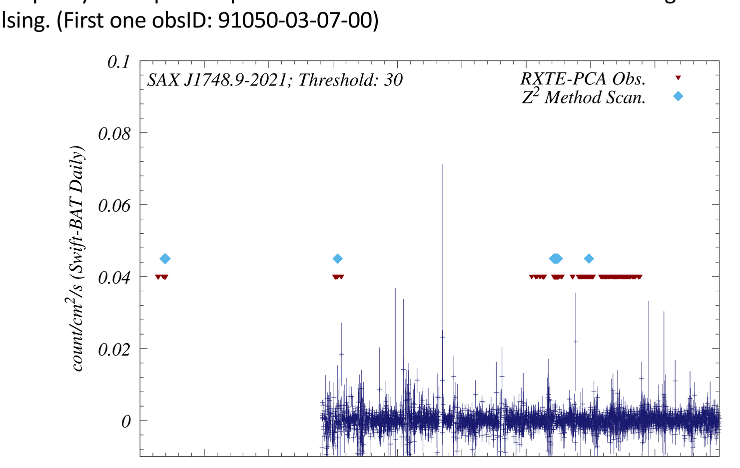

Figure 5. BAT(Swift) light curve representation of the detected pulse areas of the SAX J1748.9-2021.

3.3. Aql X-1

Aql X-1 is the second source where transient pulses were discovered. This source also shows burst-order oscillations, and the spin frequency of 550.27 Hz detected in the x-ray light curve is consistent with that obtained with burst-order oscillations. Although it has about 22 years of observational data, the pulsations were only discovered in the last 120 seconds of the RXTE observation with ObsID 30188-03-05-00 at the maximum of the 1998 flare. There have been more detailed studies, conducted by independent groups, scanning for pulsars from Aql X-1, but no other traces have been found. In our study, we have systematically scanned all the data from this source at 25-second time intervals, shifted by 1 second each, at a frequency of 0.5 Hz. We have listed the observational data with high pulse power, as shown in **Figure 6** shows some example dynamic power spectra, while **Figure 7** shows the pulse times we detected on the long-period light curve.

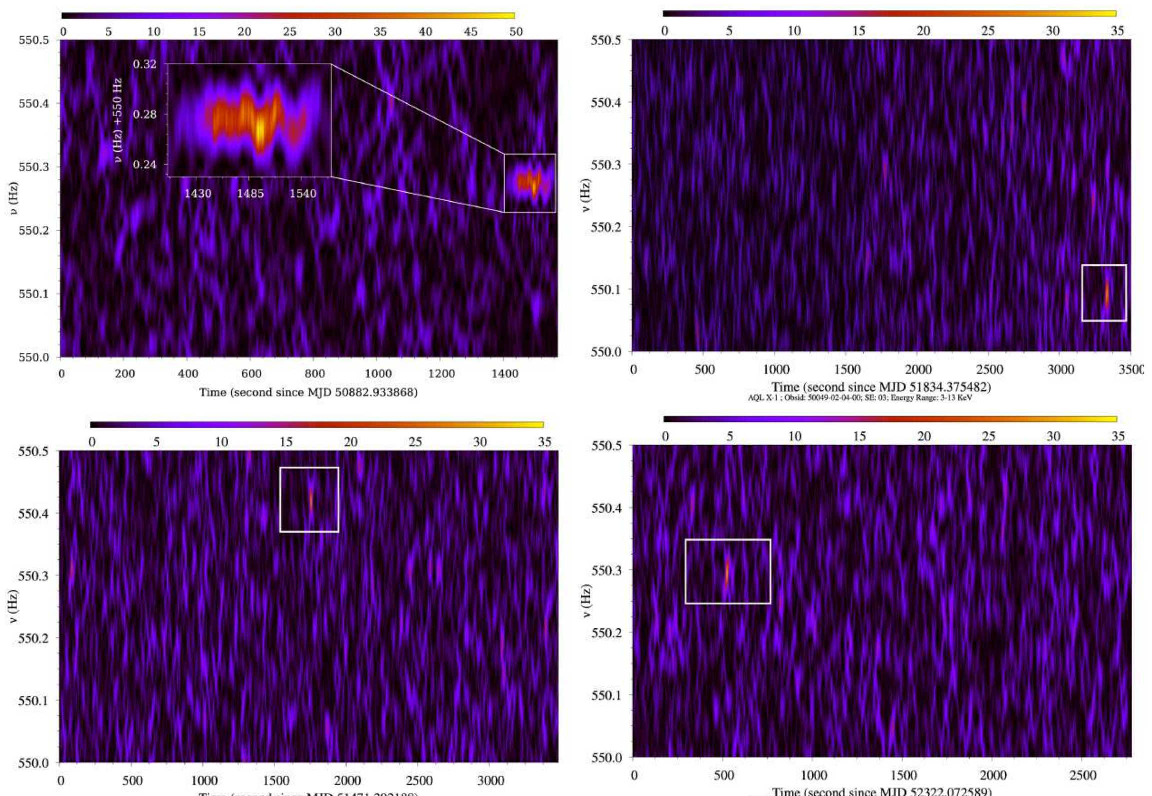

Figure 6. Example dynamic power spectrums of the Aql X-1 source. Regions inside the white squares showing pulsing. (First one ObsID: 30188-03-05-00)

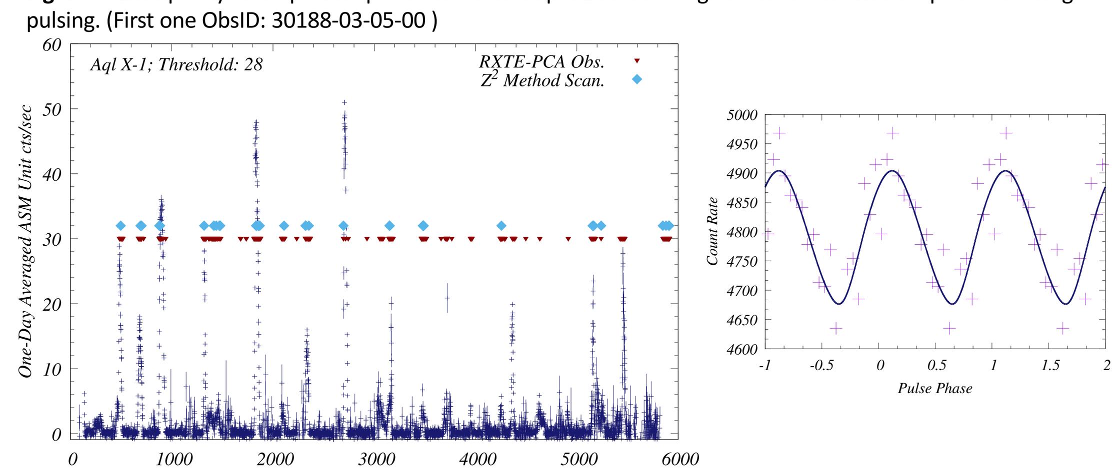

Figure 7. ASM light curve representation of the detected pulse areas of the Aql X-1 (left). Example pulse profile of Aql X-1 ObsID: 50049-02-04-00 (right).

3.3.1. Aql X-1 with Maximum Likelihood Technique

In addition, the maximum likelihood technique was applied on the observation data of the Aql X-1 source with ObsID number 30188-03-05-00, which is frequently mentioned in the literature. The discard model required for the technique was obtained by the Z2 method. After normalizing this model, the change between phase 0-1 was applied to 25-second observation intervals by shifting them by 1 second each. The possible phase value obtained and the variation of this phase value with time is shown in **Figure 9**.

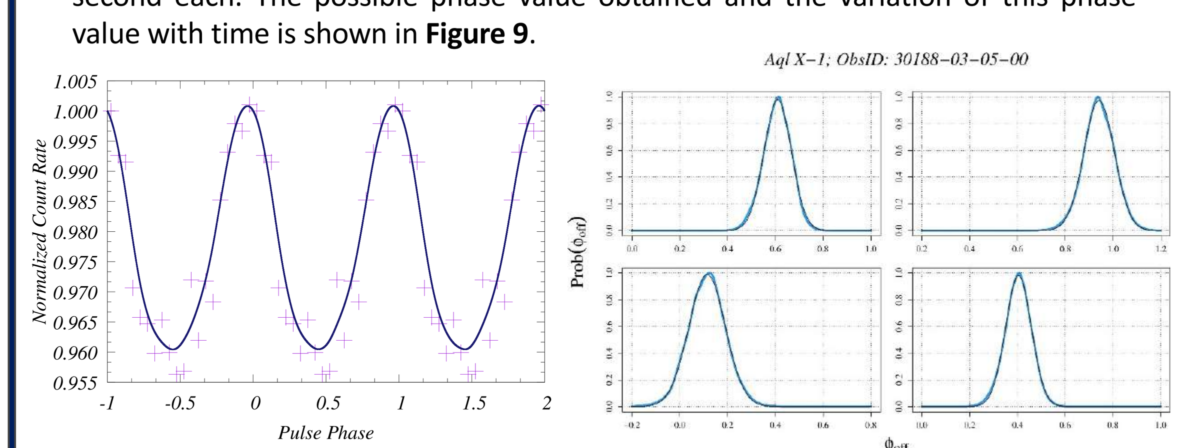

Figure 8. The pulse profile model used for the Maximum Likelihood technique (left) and the graph showing the probability distributions resulting from applying the model (right). ObsID selected for the pulse phase model: 30188-03-05-00, last 150 second.

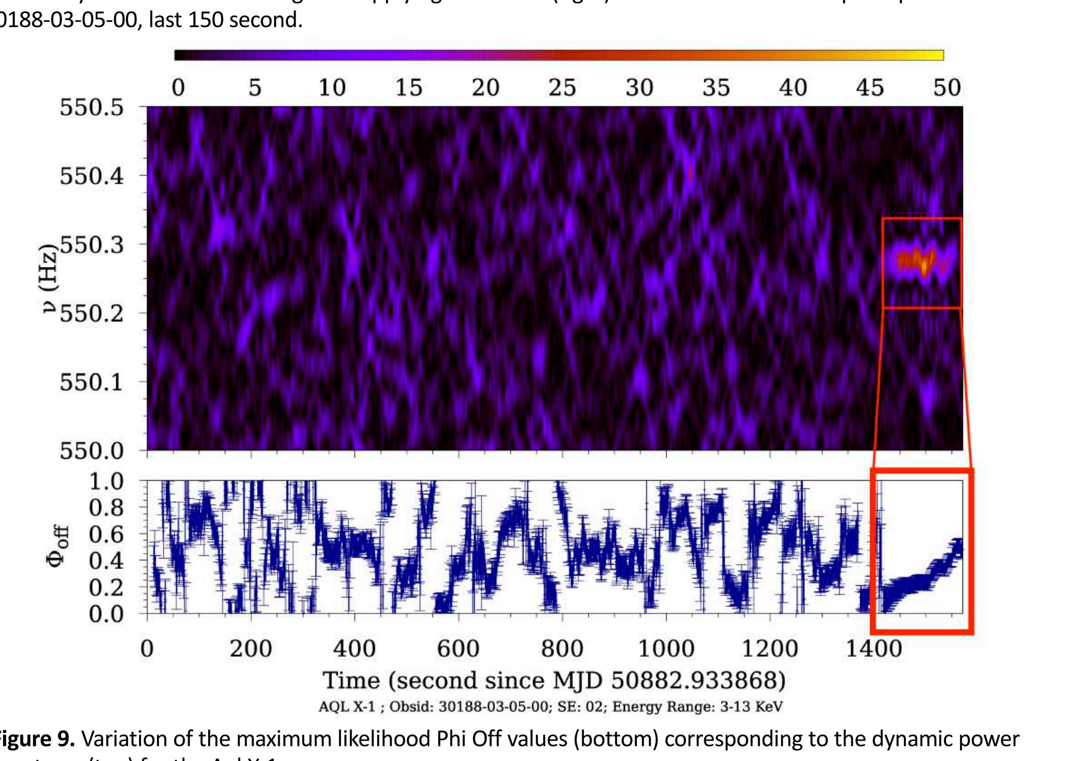

Figure 9. Variation of the maximum likelihood Phi Off values (bottom) corresponding to the dynamic power spectrum (top) for the Aql X-1.

4. Summary and Conclusions

In this research, we tested two different time analysis methods for three different millisecond X-ray pulsars. Not only were the data obtained from the analyses completely consistent with the values previously established in the literature, but we also determined new pulse durations. The Z^2 method is particularly useful for time analysis calculations on the order of milliseconds. In some cases where the Z^2 method is insufficient, we propose to use maximum likelihood method, a statistical approach that can be applied to observation sections with a small number of photons or short time intervals in rapidly changing sources. We believe that some of our results will be a step towards understanding why intermittent-AMXBs do not show continuous pulse thanks to the new pulse region.

5. References

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