A comparative timing analysis of *Suzaku* X-ray data of the nova-like variable system AE Aquarii.

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Abstract. The nova-like cataclysmic variable system AE Aquarii shows strong emission in the X-ray regime. Previous studies using data from *Ginga, ASCA, XMM-Newton, Suzaku, Chandra* and *Swift* were used to characterise the soft and hard X-ray components. The soft component was found to be multi-thermal whereas the hard component could possibly be non-thermal. Additional timing analysis of predominantly the soft X-ray data was used to update the white dwarf (WD) spin ephemeris, with discrepancies however still reported between different ephemerides determined at different epochs and data sets. For this study a comparative timing analysis of the available *Suzaku* data was considered. The timing analysis results was used in conjunction with results from previous studies to compare the current most accurate and excepted spin period for the WD as calculated by [14] and [5] to confirm the WD ephemeris. A very accurate WD ephemeris is critical for other studies, such as a possible correlation that has been reported between the WD spin period and possible pulsar-like emission towards higher energies. This study however found that the timing analysis results are highly dependant on the type of analysis process, and recommends further studies on the selection criteria of timing analysis processes to be used in similar and future timing analysis studies.

1. Introduction

The unique nova-like magnetic cataclysmic variable star AE Aqaurii consists of a fast rotating white dwarf (WD) primary star, and a K2-K5 type evolved secondary star [1]. The WD is in the ejector state, wherein a propeller mechanism drives the in-falling matter from the secondary star away from the WD in the form of interacting blobs [1]. The primary and secondary components orbit the centre of mass of the system at a $P_{orb} = 9.88$ h [2, 3], with the highly magnetized WD ($B_1 \sim 10^6$G) [4] having a spin period of $P_{spin} \approx 33$ s. The WD is also spinning down at a rate of $\dot{P}_{spin} = 5.64 \times 10^{-14}$ s s^{-1}, resulting in a spin-down luminosity of $-I\dot{\Omega}\Omega = 6 \times 10^{33} I_{50}$erg s^{-1} [5]. This large spin down power is ~ 120 times greater than the inferred accretion luminosities derived from UV [6] and X-ray emission [7]. This spin down power could act as a reservoir that drives non-thermal particle acceleration [8], explaining the radio synchrotron and possible high energy (γ-ray) emission [9, 10].

The discovery of the WD spin pulsations in *Einstein* data [11] led to further studies utilising data from *ASCA, XMM-Newton, Chandra, Swift* and *Suzaku* to detect, define and model the soft and hard X-ray emission components from the system. The soft X-ray emission ($\leq$ 10 keV) has been shown to be multi-thermal [12, 13], while the hard X-ray emission ($\geq$ 10 keV), could best be described through non-thermal emission from accelerated electrons, as inferred from a power-law model fit [12]. Correlations between the pulsations in the soft X-ray and the lower hard X-ray (10-25 keV) *Suzaku* data were also found [12]. The very strong 33 s pulsations in the soft X-ray data from *ASCA, XMM-Newton* and *Chandra* were used to update the WD spin ephemeris [14]. It was found that an additional $\dot{\mathrm{P}}_{\mathrm{spin}} = 2.0(1.0) \times 10^{-15}$ s s^{-1} term, explained as a modest increase in the accretion torques spinning down the WD, best fitted the discrepancy between the analysis and the earlier de Jager [5] ephemeris. Another ephemeris containing a $\ddot{\mathrm{P}}$ term was also proposed by [14], but was found to be inconsistent with the proposed models. Timing analysis of *Suzaku* data [12] correlated to measured results [14]. However a multi-wavelength campaign using optical, UV, X-ray (*Swift*) and gamma-ray (MAGIC) telescopes conducted in 2012 [15, 16], found a phase-offset to the proposed ephemeris by [14], but it has to be noted that the $\ddot{\mathrm{P}}$ version of the Mauche [14] ephemeris was used.

Because a very accurate WD ephemeris is critical for other studies, such as a possible correlation that have been reported between the WD spin period and possible pulsar-like emission towards higher energies, a comparative timing analysis of the available (0.2-12 keV) *Suzaku* soft X-ray instrument (XIS) data will be considered. The timing analysis results will be used in conjunction with results from previous studies to compare the current most accurate and accepted ephemerides for the WD as calculated by [14] and [5] to update and confirm the WD ephemeris.

This study utilised data from *Suzaku*. Additional information on the telescope and mission is available at `http://heasarc.gsfc.nasa.gov/docs/suzaku/`.

2. *Suzaku* XIS data analysis

Suzaku observed AE Aquarii on three separate occasions during October of 2005, 2006 and 2009. Although the 2005 (ID 400001010) and 2006 (ID 400001020) datasets were previously studied [12], they were revisited in addition to the 2009 dataset (ID 404001010). The datasets had on-source observation lengths of 180 ks, 96 ks and 299 ks respectively. Timing analysis of the XIS data were performed using "XSELECT" (Version 2.4c) available in the "Heasoft" (Version 6.15.1) software package available from the HEASARC site at `http://heasarc.gsfc.nasa.gov/`, the time-series analysis package "Period" (Version 5.0-2) available in the "Starlink" (Version 2015B) package, as well as custom Matlab scripts.

To utilize the latest available calibration data files, the raw uncleaned datasets were used. These datasets were run through the *Suzaku* "AE pipeline" (Version 1.1.0).

The filtered and calibrated datasets timing data were then corrected from telescope time to TDB (barycentric dynamic time) using "aebarycen" with source coordinates of RA = 310.038175 and Dec = -0.87085. Source and background (1 second resolution) light-curves were then extracted from the cleaned and time corrected datasets using "XSELECT", with the background data used to subtract the sky soft X-ray background from the source light-curves. The XIS instrument has 4 detectors, i.e. xis0, xis1, xis2 and xis3. Xis0, xis2 and xis3 are front illuminated (FI) CCD detectors, while xis1 is a back illuminated (BI) CCD detector. The recommendation is to combine the FI data to boost the signal to noise and thus reduce the uncertainty. The combined FI and singular BI data were then examined using standard FFT techniques to check signal strength and correlations between FI and BI data. A clear correlation was found between the FI and BI periodograms, with the only difference at the signal power levels, as can be seen in Figure 1. With the clear indication that the measured signal of the FI and BI detectors are the same, the FI and BI light-curves were combined incoherently with the errors recalculated as the $mean\ error/\sqrt{n}$ where n is the number of contributing values per bin (Figure 2).

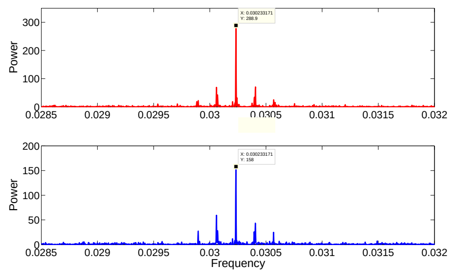

Figure 1. FFT periodograms of FI (top) and BI (bottom) data filtered between 0.0285 and 0.032 cycles per second. The side lobes are uncorrected residuals of the satellite orbital motion.

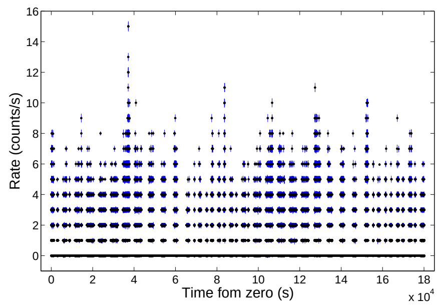

Figure 2. Incoherently combined light-curve for all XIS detectors for the 2005 dataset. The errors are scaled according to the combining process from the original errors in the count rates.

The final combined light-curves were analysed using the following process. The combined light-curves were entered into the "Period" package. The light-curves were de-trended using "Period-Detrend.option[M]". Lomb-Scargle periodograms were produced in "Period-Period" using a frequency selection of 0.01 Hz to 0.1 Hz with test for significance enabled over 200 iterations. Using "Period-Peaks" the clear 33 second period and error values were determined for the three data-sets. The determined periods for each dataset were used to fold the corresponding light-curve. Regression analysis was thereafter performed on the folded curves to determine the best fit parameters for the following equation:

$$y = B + Asin(2\pi(x - t_0)/P) \qquad (1)$$

With y the rate, B the shift in the rate, A the amplitude, P the test period, x the folded time vector and t_0 the shift in the time. See Figure 3, Figure 4 and Figure 5 for the folded light-curves as well as the best fit regression models. See Table 1 for the best fit parameter values.

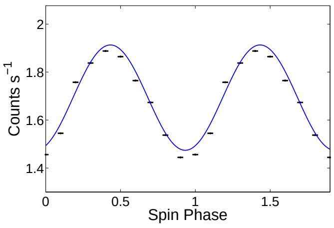

Figure 3. Folded light-curve for 2005 data for $P_{spin} = 33.07625245 \pm 0.001518$

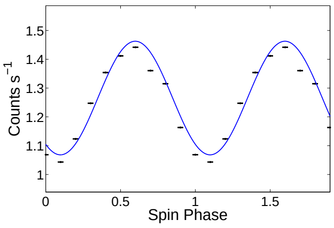

Figure 4. Folded light-curve for 2006 data for $P_{spin} = 33.07660634 \pm 0.002834$

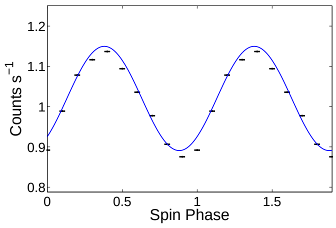

Figure 5. Folded light-curve for 2009 data for $P_{spin} = 33.07720393 \pm 0.000913$

Table 1. Best fit parameters for folded light-curves.

Parameters	2005	2006	2009
T0 (BJD)	2453674.45021604965	2454033.76738751408	2455121.26481127436
A (counts/s)	0.21956 ± 0.0002371	0.19724 ± 0.0002832	0.12943 ± 0.0003190
B (counts/s)	1.69354 ± 0.0001684	1.26540 ± 0.0002003	1.02024 ± 0.0002257
$t_0(s)$	6.03997 ± 0.047043	11.52168 ± 0.007249	4.31722 ± 0.095284
$P_{spin}(s)$	33.0762524 ± 0.001518	33.0766063 ± 0.002834	33.0772039 ± 0.000913

O-C diagrams were calculated using equations based on the results obtained by [5] and [14]. Figure 6 shows the three predicted ephemeris curves for the WD spin period with the de Jager et al (1994) ephemeris forming the baseline (black line). The blue dotted line is the predicted Mauche (2006) ephemeris with the additional $\dot{P}$ term, while the red dashed line is the predicted Mauche (2006) ephemeris with the additional $\ddot{P}$ term. The WD P_{spin} values determined in this study are included in Figure 7 (Green points). In addition the WD P_{spin} (black point) as determined by [12] is included as reference.

3. Discussion

The main focus of this study was to do a comparative timing analysis, and based on the significance of the results, to either update or confirm the WD spin ephemeris. The technique used to determine the WD spin period was a model independent approach

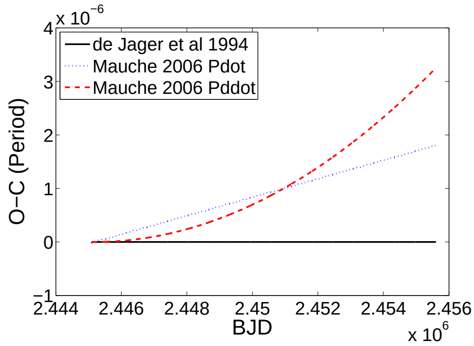

Figure 6. O-C diagram for the WD spin period showing the three different ephemeris models relevant to this study, with the de Jager et al (1994) [5] ephemeris (black line) forming the baseline. The blue dotted line is the predicted Mauche (2006) [14] ephemeris with the additional $\dot{P}$ term, while the red dashed line is the predicted Mauche (2006) [14] ephemeris with the additional $\ddot{P}$ term.

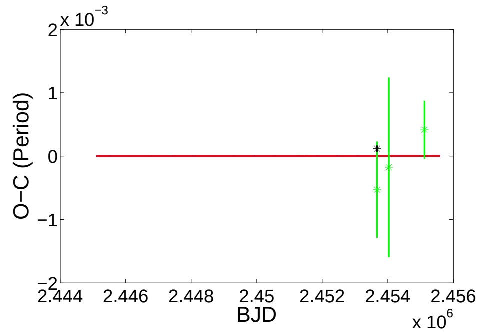

Figure 7. O-C diagram for the derived WD spin period showing the three different ephemeris models relevant to this study with the de Jager et al (1994) [5] ephemeris forming the baseline. The determined O-C derived spin periods and errors for the 2005, 2006 and 2009 datasets are indicated in green. In addition the O-C derived WD spin period and error for the combined 2005 and 2006 datasets investigated by [12] is indicated in black.

and only considered the data and standard time series analyses. The resultant WD spin period values, although compatible within error with the currently proposed WD spin ephemeris models, are not accurate enough to give a clear indication to which model is the unique model describing the evolution of the WD spin the best. The WD spin value as determined by [12] is not compatible within error with any of the three models, but does indicate a stronger spin-down rate. The technique used by [12] follows an epoch folding analysis as described in [17].

The trend of the WD spin period, based on the mean values of each dataset used, as determined in this study, does show a spin-down, but it is very dramatic, with a required spin-up in an epoch preceding this study to fit the general trends of the model ephemerides. This however would be unrealistic as the expected mechanisms in the system is dissipative, with the WD being in a long term spin-down phase. There are a couple of possible explanations for the results: Either the time series analysis technique is, although robust, too inaccurate in relation to the model requirements, or there might be an inherent variability in the WD spin period, or both. A recent study by [18] found that the secondary star is not tidally locked and has various starspots. This means that the mass transfer in the system is most probably variable in nature. This can result in variable accretion and rotational torque moments on the WD. The interactions between internal and external stellar structures might lead to a small variation in the WD spin-down rate, analogous to star-quakes experienced in pulsars but on a very small scale.

4. Conclusion

Based on the results and indicative inconsistencies between various studies and proposed models of the WD spin ephemeris, a new approach is required for the data analysed in this and similar studies. The analysis technique might have to be a lot more model dependant, such as used by [14], in that deviations in the model is determined and examined using the data in conjunction with the models.

The possible variation in the WD spin needs to be examined in greater detail, and new and extensive studies need to be conducted using both new observations as well as all available archival data. The analysis techniques must also be tested and standardised using Monte-Carlo simulations to exclude inconsistencies due to varying analysis methodologies. With Astrosat (India's first dedicated multi-wavelength space observatory) that was launched in September 2015, with its very large sensitivity range, applications can be made to study the emission from AE Aquarii in greater detail, thus facilitating the refinement of the models describing the system, specifically the evolution of the WD.

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