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# The puzzling orbital period evolution of the LMXB AX J1745.6-2901

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## ABSTRACT

The orbital period evolution of X-ray binaries provides fundamental clues to understanding mechanisms of angular momentum loss from these systems. We present an X-ray eclipse timing analysis of the transient low mass X-ray binary AX J1745.6-2901. This system shows full eclipses and thus is one of the few objects for which accurate orbital evolution studies using this method can be carried out. We report on *XMM-Newton* and *ASCA* observations covering 30 complete X-ray eclipses spanning an interval of more than 20 years. We improve the determination of the orbital period to a relative precision of  $2 \times 10^{-8}$ , two orders of magnitudes better than previous estimates. We determine, for the first time, a highly significant rate of decrease of the orbital period  $\dot{P}_{orb} = -4.03 \pm 0.32 \times 10^{-11}$  s/s. This is at least one order of magnitude larger than expected from conservative mass transfer and angular momentum losses due to gravitational waves and magnetic breaking, and might result from non-conservative mass transfer. Imprinted on the long term evolution of the orbit, we observe highly significant eclipse leads-delays of  $\sim 10 - 20$  s, characterised by a clear state dependence in which, on average, eclipses occur earlier during the hard state.

**Key words:** Neutron star physics, X-rays: binaries, accretion, accretion discs, methods: observational, techniques: timing

## 1 INTRODUCTION

Eclipse timing provides us with powerful fiducial marks to investigate the orbital period evolution in low mass X-ray binaries (LMXBs; e.g. Chou 2014). This observable is closely associated with angular momentum variations of the system. In fact, any physical mechanism modifying the system angular momentum will inevitably modify the binary orbital period. The orbit can evolve as a consequence of mass transfer between the two stars (e.g. due to Roche lobe overflow), gravitational wave radiation (Landau Lifschitz 1958; Paczynski 1967; Faulkner 1971; Verbunt 1993), magnetic breaking (Eggleton 1976; Verbunt & Zwaan 1981; Rappaport et al. 1983), mass loss from the companion, accretion disc winds, jets or other types of outflows (e.g. Fender et al. 2004; Ponti et al. 2012), and tidal interactions between the components of the binary system (Lear et al. 1976).

The theory of angular momentum evolution due to mass transfer via Roche lobe overflow and gravitational wave radiation is well established and leads to quantitative predictions (Landau Lifschitz 1958; Paczynski 1967; Faulkner 1971; Verbunt 1993). However, angular momentum losses due to emission of gravitational waves only dominate at short orbital period ( $P_{orb} \lesssim 2$  hr), while other mechanisms, such as magnetic breaking, are invoked to explain the orbit evolution at longer periods. The theory at the heart of

the magnetic breaking model is based on the same physical principles through which magnetic stellar winds are known to decelerate the rotation of low-mass stars (e.g. Kraft 1967; Skumanich 1972; Sonnerblom 1983). In synchronised binaries (typically the case of LMXBs), the angular momentum loss from the companion star is continuously re-distributed to the angular momentum of the whole binary system, therefore affecting its orbital period and binary separation (e.g. Taurus 2001). Large uncertainties are involved in the extrapolation of magnetic breaking from isolated low-mass stars to the case of synchronised companion stars in LMXBs (e.g. see discussion in Knigge et al. 2011). Indeed, despite the large allowed range of model parameters (possibly translating into more than one order of magnitude on efficiency of angular momentum removal), magnetic breaking often fails to reproduce measured values of the orbital period derivative, at least in the case of conservative mass transfer (Di Salvo et al. 2008; Hartman et al. 2008; 2009; Hu et al. 2008; Burderi et al. 2010; Jain et al. 2010; Gonzalez-Hernandez et al. 2012; 2014). Additional mechanisms, typically involving outflows, are generally necessary to explain these discrepancies (Di Salvo et al. 2008; Hartman et al. 2008; 2009; Burderi et al. 2010).

Up to now, there are only a handful of LMXBs showing full eclipses for which a determination of the orbital period evolution has been possible (e.g. EXO 0748-676 Wolff et al. 2009;

MXB 1659-29 Watcher et al. 2000; XTE J1710-281 Jain et al. 2011; GRS J1747-312 in't Zand et al. 2003; Her X-1 Staubert et al. 2009).

AX J1745.6-2901 is a dipping and eclipsing neutron star LMXB, showing type I bursts, discovered in *ASCA* data during the 1993-1994 outburst (Maeda et al. 1996). It is one of the brightest X-ray transients of the Galactic centre region, located only  $\sim 1.5$  arcmin away from the supermassive black hole at the Galactic centre (Maeda et al. 1996; Kennea & Skinner 1996; Hyodo et al. 2009; Deegenar et al. 2012; Ponti et al. 2015a,b). During outburst it reaches a brightness of 1–30% the Eddington luminosity, alternating the hard (power-law dominated) and soft (thermal) states typically seen in 'atol' sources (Ponti et al. 2015; Muñoz-Darias et al. 2014; Gladstone, Done & Gierlinski 2007; see section 6.3).

The high column density of absorbing material ( $N_H \sim 2 \times 10^{23} \text{ cm}^{-2}$ ) and the study of the black body radius during type I X-ray bursts suggest that AX J1745.6-2901 is located at or beyond the Galactic centre (Maeda et al. 1996; Ponti et al. 2015b). The first determination of the orbital period was performed by folding eclipses detected in the 1994 *ASCA* data, yielding  $P_{orb} = 8.356 \pm 0.008$  hr ( $30082 \pm 29$  s; Maeda et al. 1996, see also Sakano et al. 2001). Using *Suzaku* and *Chandra* observations taken between July and September 2007, Hyodo et al. (2009) measured an orbital period of  $P_{orb} = 30063.74 \pm 0.14$  s, consistent with the previous result. Due to its transient nature, crowding and high extinction (preventing detection below  $\sim 3$  keV), the orbital evolution of AX J1745.6-2901 has not been measured yet.

Here we study for the first time the evolution of the orbital period of AX J1745.6-2901 over an interval of more than 20 years by using data from 15 years of *XMM-Newton* monitoring campaign of the Galactic centre as well as data from the *ASCA* archive.

## 2 OBSERVATIONS AND DATA REDUCTION

### 2.1 *XMM-Newton*

We analysed all *XMM-Newton* (Jansen et al. 2001) observations of AX J1745.6-2901 over the period November 2001 - April 2015. In addition to the observations analysed in Ponti et al. (2015a), we include ten new *XMM-Newton* observations, taken during outburst (see Table 1 for a full list of *XMM-Newton* observations considered in this work). The EPIC pn camera aboard *XMM-Newton* occasionally experiences time jumps. We checked that all the positive and negative jumps are properly corrected by the EPIC pn reduction pipeline<sup>1</sup>. This is further confirmed by the fact that similar results are obtained with the EPIC MOS camera that is not affected by these time jumps. The arrival times of all events were corrected to the Solar system barycentre, applying the BARYCEN task of SAS.

<sup>1</sup> We checked that all time jumps as well as the unverified deltas and premature increments (see *XMM-Newton* User Handbook, Ebrero et al. 2015) are properly accounted for. During OBSID 0402430401, 7 frames (from 4318574 until 4318580) are repeated, however this does not produce any time shift. During OBSID 0505670101, two telemetry gaps of 3 s and one of 10 s are observed. Moreover, the quadrant with CCD 4 experienced a negative jump of 3 s, which is corrected. None of these produce any time shift. During OBSID 0723410501, three gaps of 634.2, 253.2 and 187.8 s, most probably due to telemetry gaps, happened in all CCDs. We manually checked that these intervals are very close to multiple integers of the frame time and that adding or subtracting a one full second time jump would not be multiple integer anymore. Therefore also these gaps do not produce any time shift.

We processed the data sets using the latest version (14.0.0) of the *XMM-Newton* Science Analysis System (SAS) and applied the most recent (July 2015) calibrations. We use all the EPIC (Struder et al. 2001) cameras. Having higher effective area, our prime instrument is the EPIC-pn (Turner et al. 2001), but we also analysed the EPIC-MOS, for a consistency check. All observations have the medium filter applied and are in Full Frame mode, therefore the EPIC-pn and EPIC-MOS light curves have minimum time resolutions of 73.4 ms and 2.6 s, respectively.

Since the main focus of this work is to measure the ingress/egress times and durations of the eclipses, increasing the number of source photons would provide a more accurate determination of the location of the transition points. Therefore, even if photon pile-up significantly affects the brightest observations we decided to retain all source photons (e.g. by not removing photons from the central part of the point spread function as in Ponti et al. 2015b). Pile-up is expected to have a negligible effect on the determination of the eclipse timing. The source and background photons are extracted from circular regions with 40 arcsec and 160 arcsec radii, respectively. The former centred on AX J1745.6-2901, while the latter covers a region free from bright point-like sources and low levels of diffuse emission.

For each observation we identified periods of enhanced particle-induced background activity by inspecting the 6-15 keV source and background light curves binned with 5 s resolution. We filtered out periods with a background level 25 % brighter than the average source count rate during the observation. Type I bursts have been removed, if clearly detected in 1 s source light curves. We note that type I burst were not detected either at the start, during or at the end of any eclipse.

To establish the X-ray state of the source (see section 6.3), we used the hardness intensity diagram shown in Fig. 2 of Ponti et al. (2015b), based on fluxes in the 3-6 and 6-10 keV bands. When present, pile-up can significantly affect these measurements. To mitigate this we removed (only for this specific analysis) the central 9.25 arcsec in the source extraction region, such as done by Ponti et al. (2014; 2015). Using the EPIC pn data with a time resolution of 73.4 ms we searched for the presence of pulsations during observation OBSID: 0402430301 and 0690441801 (the longest observations where the source is bright in the soft and hard state, respectively) but did not detect any significant pulsed signal.

### 2.2 *ASCA*

To significantly extend the time interval probed by the *XMM-Newton* pointings, we also examined *ASCA* observations. Data were obtained from the HEASARC database online, and screened event files were used in our analysis. As reported by Maeda et al. (1996), the source was found in outburst in 1993 and 1994. However, no eclipses were found in the 1993 data due to the short duration of the observation (additionally the source flux was about 5 times fainter than in 1994). Maeda et al. (1996) reported the discovery of eclipses with a 8.4 hr periodicity in the 1994 data. We thus analysed this dataset, extracting photons from a radius of 0.8 arcmin as done by Maeda et al. (1996) and combining data from the two GIS instruments, which have a higher time resolution than the SIS. We filtered photons so as to include only those in the 3 - 10 keV range. Photon arrival times were corrected to the Solar system barycenter using the TIMECONV task of FTOOLS. Finally, we found one eclipse fully covered by the observation, in the constructed light curve, which we used for our timing analysis.

Sakano et al. (2001) also reported a detection of the source by

ASCA in 1997. However, the source flux was significantly weaker in this observation (similar to the levels in 1993), and only a hint of an eclipse was present in their folded light curve. Therefore we did not include the 1997 data in our analysis.

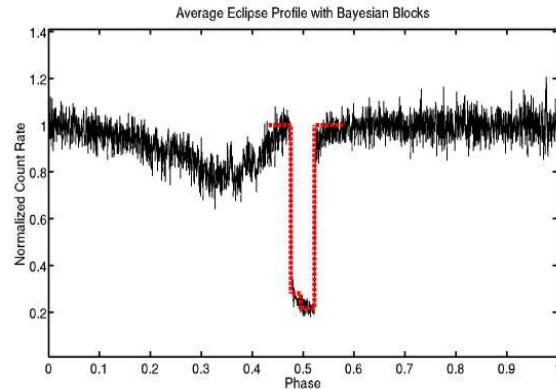
### 3 ECLIPSE TIMING

The determination of the eclipse times in all data sets was done using the Bayesian Block technique (Scargle et al. 2013; Ponti et al. 2015c). The technique allows us to detect statistically significant changes in count rates for time-tagged event data, along with a determination of the corresponding times. We first selected the source photons from the cleaned event files and then we applied the Bayesian Block code on the photon arrival times. We performed this on all the data sets. We typically ran the Bayesian Block code over an entire observation, except for observations with intense dipping activity and long exposures, where we split the event files into smaller segments, each containing one orbital period so that the routine converges in a reasonable amount of time. The eclipse ingress and egress times are singled out without ambiguity by using this technique.

Figure 1 shows the average source light curve during one orbit (obtained by averaging over all orbits, after removing type I bursts); phases are defined so that the centre of the eclipse is at 0.5. At the time of eclipse ingress, the source flux abruptly decreases and then it sharply increases again by a similar amount at the time of the egress. Note that during the eclipse, a residual flux is present which displays a gradual decay near ingress. It has been suggested that this behaviour is due to a dust scattering halo (Hyodo et al. 2009). In agreement with this interpretation, we observe that the amplitude of this effect steeply decreases at higher energies and is of the same order of magnitude as expected for the large column density of material toward the source ( $N_H \sim 2 \times 10^{23} \text{ cm}^{-2}$ ; Ponti et al. 2015b). A detailed study of this effect is beyond the scope of this paper.

At low fluxes, most of the observed eclipses are well described by a single block. In these cases we define ingress and egress times as the start and end times of the block. However, for observations with higher source count rates, the presence of the slow decay during the eclipse induces one additional significant block at the start of the eclipse. Whenever an additional block appears, we define as ingress time, the start of the first block marking the eclipse and as egress time, the end of the last block marking the eclipse (see Fig. 1). By using this method, we determined the start and end times of the 30 eclipses in the datasets that we analysed. Table 1 gives the measured times using this technique.

As a consistency check, we implemented the Bayesian Block technique on event files from the three EPIC cameras separately. Thus, for each eclipse we got three independent measurements of the eclipse times and their Bayesian Block uncertainties. A comparison between the uncertainties determined via the Bayesian Block approximation and those derived directly from the observed scatter (determined considering 12 measurements obtained by the EPIC cameras) suggests that the latter are more reliable (see Appendix and Fig. A1 for details) and were therefore used. In the case of the ASCA eclipse, where such a scatter measurement was not possible, we used the uncertainty as inferred from the Bayesian Block algorithm. For measuring the orbital evolution of the system, we



**Figure 1.** Average, normalised count rate orbital profile in the 3-10 keV band Bins are 10 s long. Individual profiles were aligned by using the eclipse centre time (which correspond to phase 0.5) as determined through the analysis described in the text. The red dotted line shows the results of the Bayesian blocks decomposition, at the time of the eclipse, determined during a bright soft state observation. After eclipse ingress a slow residual decay of the flux is observed. The average profile shows that the dipping phenomenon is more intense around phase 0.1-0.5, inducing a significant trough (up to  $\sim 30\%$ ) of the average source flux, with a minimum around phase 0.3. Dipping events are sometimes observed just before the start of the eclipse, making the determination of the ingress time less reliable than that of egress time in some orbital cycles.

used a weighted average<sup>2</sup> of the eclipse times obtained from the three *XMM-Newton* instruments (apart from the eclipse observed by *ASCA*, where we directly used the measured eclipse time from the GIS instrument).

On at least three occasions (cycle numbers -101, -1665 and -1666), we observe that the source was still dipping at the time of the eclipse ingress. Therefore, in order to proceed only with accurate measurements of the transition points, we used only the eclipse egress times to derive the orbital period evolution of the system. We note, however, that the analysis of the ingress times (after rejection of the cycles affected by dipping) provide results which are consistent within the errors of those obtained from egress times.

### 4 ORBITAL EVOLUTION

The eclipse times determined using the method described above allows us to measure the evolution of the orbital period over a period of more than 20 years. We fitted the eclipse egress times with a curve of the form (consistent with a constant orbital period derivative model):

$$T_N^e - T_0^e = \delta T_0^e + P_{orb\ 0} N + \frac{1}{2} \dot{P}_{orb\ 0} P_{orb\ 0} N^2 \quad (1)$$

where  $T_N^e$  is the eclipse egress time,  $T_0^e$  is the reference eclipse egress time,  $\delta T_0^e$  is the error in the determination of  $T_0^e$ ,  $P_{orb\ 0}$  is the orbital period at the epoch  $T_0^e$ ,  $\dot{P}_{orb\ 0}$  is the constant period derivative and  $N$  is the (integer) number of orbital cycle counting from  $T_0^e$ . We choose  $N$  to be the closest integer to  $(T_N^e - T_0^e)/P_t$ , where  $P_t$  is the orbital period estimate given by Hyodo et al. (2008). In each case, we have verified that  $|T_N^e - (T_0^e + NP_t)| \ll P_t$  to

<sup>2</sup> The weights have been taken as the average count rate of the source in the respective instrument during the orbital cycle under consideration.

Obs-ID	Cycle Number	PN-Count rate counts/sec	Eclipse Ingress Time† MJD	Eclipse Egress Time MJD	Error sec
ASCA					
52005000	-21561	-	49612.31079	49612.32854	5.1
<i>XMM-Newton</i>					
0402430701	-8405	9.33	54190.05919	54190.07556	2.2
0402430301	-8400	8.48	54191.79898	54191.81542	2.3
0402430301	-8399	7.52	54192.14693	54192.16335	2.6
0402430301	-8398	6.34	54192.49482	54192.51129	3.0
0402430401	-8394	8.39	54193.88681	54193.90319	2.4
0402430401	-8393	7.95	54194.23470	54194.25111	2.5
0402430401	-8392	6.22	54194.58267	54194.59912	3.0
0505670101	-7374	6.58	54548.80454	54548.82097	2.9
0505670101	-7373	6.46	54549.15253	54549.16899	2.9
0505670101	-7372	6.94	54549.50045	54549.51691	2.8
0724210201	-1666	8.87	56534.95316*	56534.96964	2.2
0724210201	-1665	10.54	56535.30115*	56535.31763	1.9
0700980101	-1636	10.18	56545.39197	56545.40833	2.0
0724210501	-1599	7.41	56558.26641	56558.28280	2.6
0723410301	-1143	1.18	56716.93537	56716.95191	12.3
0723410301	-1142	1.17	56717.28312	56717.29972	12.4
0723410401	-1115	0.81	56726.67793	56726.69466	16.9
0723410401	-1114	0.87	56727.02603	56727.04243	15.9
0723410501	-1050	0.76	56749.29538	56749.31187	17.7
0723410501	-1049	0.89	56749.64329	56749.65972	15.5
0690441801	-1047	0.90	56750.33916	56750.35564	15.4
0690441801	-1046	0.93	56750.68719	56750.70372	15.0
0690441801	-1045	1.02	56751.03514	56751.05157	13.9
0743630201	-617	1.26	56899.96128	56899.97786	11.7
0743630301	-614	1.14	56901.00544	56901.02190	12.7
0743630501	-533	1.18	56929.18989	56929.20639	12.3
0743630601	-101	9.25	57079.50762*	57079.52486	2.2
0743630801	-3	10.59	57113.60843	57113.62483	1.9
0743630901	0	10.91	57114.65233	57114.66868	1.9

**Table 1.** Measured eclipse times of the 29 *XMM-Newton* eclipses and 1 *ASCA* eclipse. The cycle number has been determined with respect to the reference time  $T_0^c$  (see Section 4), which is considered to be cycle 0. † Note that some of the ingress times (those marked with \*) are affected by the dipping phenomenon, and thus may not be reliable (see discussion in Section 3); we do not provide uncertainties for these measurements, but we expect them to be of the same order as those estimated for the egress times.

ensure that the number of each orbital cycle is determined without ambiguity.

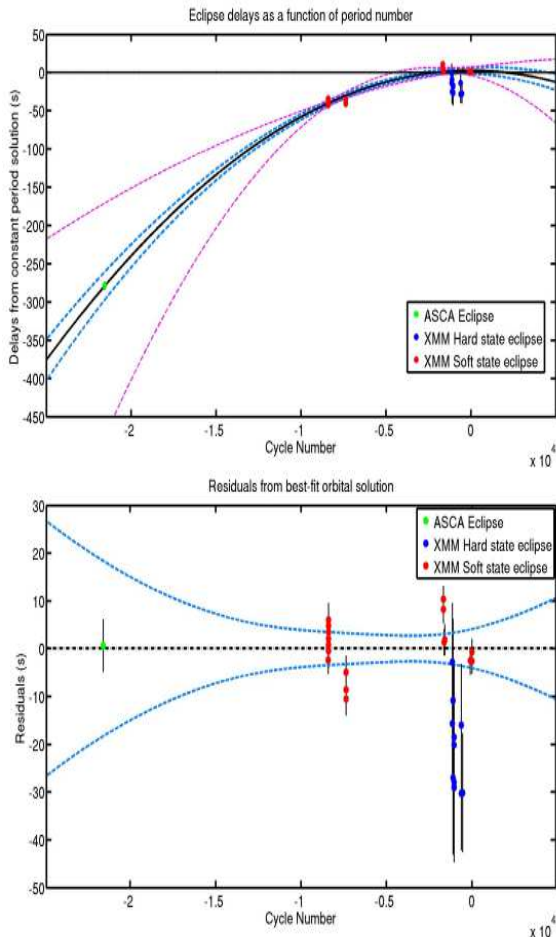
We first test the possibility of a constant orbital period ( $\dot{P}_{orb\ 0} = 0$ ) through a linear fit. This yields an unacceptable solution with  $\chi_\nu^2 = 29.1$ , indicating that evolution of the orbital period is required by the data. We then used only the eclipse times obtained from *XMM-Newton* observations to determine the ephemeris, and, in particular, to search for an orbital period derivative. We obtain:  $P_{orb\ 0} = 30063.628 \pm 0.003$  s, and  $\dot{P}_{orb\ 0} = (-5.1 \pm 1.9) \times 10^{-11}$  s/s. The reduced  $\chi_\nu^2$  was found to be 3.30 for  $\nu = 25$ . Thus, a non-zero orbital period derivative for the system was found by using the *XMM-Newton* observations spanning an interval of  $\sim 8$  years (see magenta lines in Fig. 2). We then extended our baseline by more than 10 years by including now also the *ASCA* observation. The best fit parameters are (see also Tab. 2):  $P_{orb\ 0} = 30063.6292 \pm 0.0006$  s, and  $\dot{P}_{orb\ 0} = (-4.03 \pm 0.27) \times 10^{-11}$  s/s. We now obtain a reduced chi-squared value of  $\chi_\nu^2 = 3.21$  with  $\nu = 26$ . We find that the eclipse egress time obtained from the *ASCA* observation, and the best-fit parameters using all eclipses, agree very closely with the values expected from the orbital solution obtained using solely *XMM-Newton* data (see Figure 2). This suggests that this orbital solution has been valid for more than 20 years. We also test the possibility of a variable

$\dot{P}_{orb\ 0}$ , by fitting the eclipse times with a constant  $\ddot{P}_{orb\ 0}$ . This results in a  $\ddot{P}_{orb\ 0}$  value consistent with 0, and a reduced chi-square value of  $\chi_\nu^2 = 3.22$ , larger than that from the quadratic fit.

The upper panel of Fig. 2 shows the eclipse time delays with respect to a constant orbital period model as a function of the orbital cycle. The solid black line shows the best fit solution with constant period derivative and the light blue dotted lines the corresponding one sigma uncertainty (the magenta dashed lines show the one sigma uncertainty for the *XMM-Newton* data only). The orbital period of AX J1745.6-2901 clearly evolves in time, shortening by  $\sim 25$  ms and producing a delay of  $\sim 300$  s over the past twenty years.

The bottom panel of Fig. 2 shows the residuals compared to the best fit model with a quadratic term. Significant residuals, as large as 10 – 20 s, are observed (see § 5). In fact the best solution we obtained, with a  $\chi_\nu^2 = 3.21$  for  $\nu = 26$ , could be formally rejected because it does not reproduce all the scatter observed in the data. The presence of residual jitter with amplitude comparable to that observed here is typical of eclipsing LMXBs (e.g. Wolff et al. 2009; Jain et al. 2011). This is discussed further in the next section.

We investigated the reliability of the eclipse timings by applying a different technique to determine the eclipse ingress and egress



**Figure 2.** (Top panel) Eclipse time delays (egress times) with respect to a constant orbital period model plotted versus the orbital cycle.  $T_0$  (therefore cycle one) corresponds to MJD=57114.66871. The red and blue circles show the eclipse egress delays corresponding to soft and hard states of the source respectively, which were observed with *XMM-Newton* whereas the green circle shows the eclipse egress delay derived from the single eclipse in the *ASCA* data (1994). The black solid and blue dashed lines show the best fit orbital solution of the combined *XMM-Newton* and *ASCA* data and the 68% confidence region. The magenta dashed lines show the 68% confidence uncertainty on the best fit orbital solution obtained fitting the *XMM-Newton* data only. (Bottom panel) Residuals compared to the best fit orbital solution. Significant scatter is observed.

time. We constructed a model light curve consisting of three blocks, corresponding to pre-eclipse, in-eclipse and post-eclipse regions, each with a constant count rate. We then used out a  $\chi^2$  minimization routine to fit each of the eclipse light curves (binned to a time resolution of 5 seconds) to get the corresponding eclipse ingress and egress times for each eclipse. The start and end times of the in-eclipse region would then correspond to the eclipse ingress and egress times. We confirm that the eclipse timings, the orbital solution obtained and the residuals are consistent with that determined using the Bayesian Block analysis.

## 5 RESIDUAL JITTER

Both the residuals in Fig. 2 and the results of the best fit with a quadratic orbital solution, clearly shows the presence of residual jitter in the eclipse egress time with an amplitude as large as ~

Parameter	Value	Units
$T_0^e$	$57114.66871 \pm 0.00005$	MJD
$P_{orb\ 0}$	$30063.6292 \pm 0.0006$	s
$\dot{P}_{orb\ 0}$	$-4.03 \pm 0.27$	$10^{-11}$ s/s

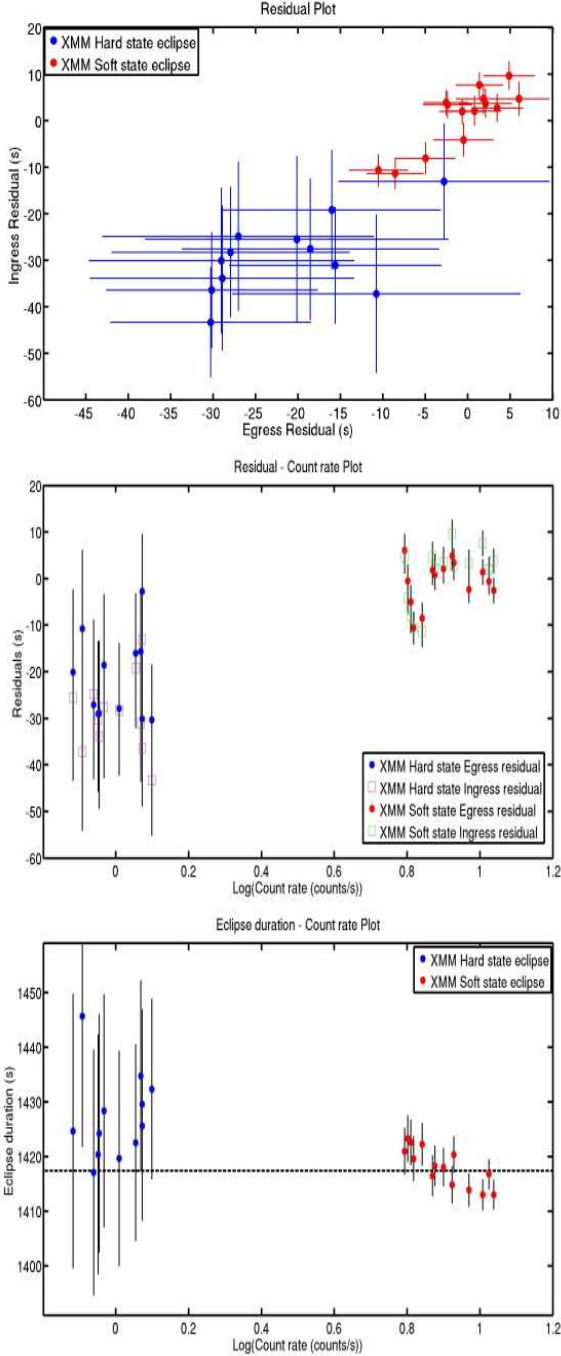
**Table 2.** Best fit orbital solution for AX J1745.6-2901 derived from the analysis of the eclipse arrival times from 1994 to 2015. Errors are at 1 sigma confidence level on the last digit. The value of  $P_{orb\ 0}$  refers to  $T_0^e$ .

10 – 20 s. We observe even higher residuals in the ingress time, about ~ 50 – 100 s, when dips are still in progress immediately before the eclipse onset (clearly observed in at least three cases; see Tab. 1). We interpret them as due to the dipping activity. The smaller jitter in the eclipse egress time is most likely unrelated to dips, because: i) it is present also during orbits when no dips are detected; ii) dipping activity is very rarely observed shortly after the eclipse egress; iii) it is present also during orbits when no dips are detected. The *XMM-Newton* calibrating team is excluding that the observed jitter has an instrumental origin.

### 5.1 State dependence

The top panel of Fig. 3 shows the eclipse ingress as a function of eclipse egress residuals. Note that, in all panels of Fig. 3, the blue (magenta) and red (green) points refer to the eclipses egress (ingress) time when the source was in the hard and soft state, respectively. A clear correlation between these quantities is observed. Kendall’s correlation coefficient is  $r = 0.91$ , with a null hypothesis probability of  $NHP \sim 10^{-6}$ . The presence of such a correlation suggests that the jitter is generated by the eclipses being either delayed or advanced, while their duration remains approximately constant. Indeed, as shown by the bottom panel of Fig. 3, a fit to the observed eclipse durations with a constant provides a reasonable fit ( $\chi^2_\nu = 0.774$  for 24 dof; with an average duration of ~ 1419.1 s, calculated for eclipses unaffected by dipping). However, we note a trend of decreasing eclipse duration with brightness in the soft state. Considering the duration and count rates during the soft state only, we do indeed observe a hint for a correlation (Kendall’s correlation coefficient is  $r = -0.65$ , with a null hypothesis probability of  $NHP \sim 7 \times 10^{-4}$ ). We also note that the eclipse ingress residuals show a higher scatter and span a larger range of values as compared to the egress residuals.

The top panel of Fig. 3 shows a clear separation between the soft and hard state points. A Kolmogorov-Smirnov test of the distribution of soft and hard state delays (based on the eclipse egress times), indicates that the null hypothesis probability of the two residuals being extracted from the same population is  $8 \times 10^{-7}$ . The state dependence is such that the hard state eclipses in average occur at earlier times (~ 29 s) than expected on the basis of the orbital solution. On the other hand, the eclipses happen roughly at the expected time (with an average delay of ~ 0.69s) when the source is in the soft state. This is not surprising because the source is typically brighter (having therefore smaller error bars) during the soft state. The middle and bottom panels of Fig. 3 shows that, indeed, the source is brighter in the soft state and the observed residuals are very well correlated with the source count rate (the Kendall’s correlation coefficient is  $r = 0.5123$ , with a null hypothesis probability  $NHP \sim 5 \times 10^{-5}$ , corresponding to a significance of ~ 4 sigma). We note that using the  $\chi^2$  minimization technique to determine the eclipse timings also reproduces a clear state dependence



**Figure 3.** (*Top panel*) Ingress versus egress time residuals, compared to the best fit orbital solution shown in § 2. Shown here are the twenty six eclipses not significantly affected by the dipping phenomenon. The red points show the soft state observations, while the blue points indicate the hard state observations. The residuals in the ingress and egress time are well correlated. (*Middle panel*) Egress and ingress time residuals as a function of the source count rate with filled circles and open squares, respectively. Soft and hard state observations are shown in red and blue (green and magenta) for the egress (ingress) times, respectively. Ingress residuals show higher amplitude of variations. (*Lower panel*) Eclipse duration (defined as eclipse egress time minus eclipse ingress time) as a function of the observed count rate. The variation of the eclipse egress counterbalance the variation of the eclipse ingress, generating an almost constant duration of the eclipse. However, a small, but significant, shortening of the eclipse is observed at high fluxes.

of the residuals (KS nul 1 hypothesis probability of  $\sim 10^{-4}$ ), with the residuals being correlated with the source count rate (Kendall's coefficient 0.567, corresponding to a null hypothesis probability of  $\sim 10^{-5}$ ).

## 6 DISCUSSION

Fifteen years of *XMM-Newton* monitoring of the Galactic centre joined with archival *ASCA* data allowed us to time the eclipses and measure the evolution of the orbital parameters of AX J1745.6-2901. We fitted the eclipse timing data with a parabolic function, finding a solution valid for more than two decades. In particular, we determined the orbital period of AX J1745.6-2901 with a precision of 1 over  $5 \times 10^7$ , that is an improvement of over two orders of magnitudes compared to the previous best estimate (Hyodo et al. 2009). We also determine, for the first time, a highly significant derivative of the orbital period, which indicates that the system is shrinking and the orbital period decreasing at a rate of  $-4.03 \pm 0.27 \times 10^{-11}$  s/s.

We note that, in the best monitored eclipsing LMXB (EXO 0748-676), eclipse timings obtained within different time intervals do produce inconsistent orbital solutions (Parmar et al. 1986; 1991; Asai et al. 1992; Corbet et al. 1994; Hertz et al. 1995; 1997; Wolff et al. 2002; 2009). In particular, detailed *RXTE* monitoring of the eclipse timing properties in EXO 0748-676 show that a unique orbital solution can be rejected at high significance and the orbital period evolution can be divided into at least three periods with abrupt changes between these (Wolff et al. 2002; 2009). Interestingly, other eclipsing systems have been suggested to undergo the same erratic behaviour (e.g. XTE J1710-281; Jain et al. 2011). To check if this is the case for AX J1745.6-2901, we fitted first the *XMM-Newton* data alone, and then extrapolated the best fit orbital solution obtained within the period from 2007 to 2015, to the *ASCA* data accumulated  $\sim 12$  years before (see § 4). We observe that the same orbital solution fitting the *XMM-Newton* data, with a constant orbital period derivative, intercept the *ASCA* data (see the magenta dashed lines in Fig. 2). This suggests the presence of a unique orbital solution in AX J1745.6-2901 and that the physical mechanism changing the angular momentum in AX J1745.6-2901 is most probably different from that at work in EXO 0748-676.

### 6.1 Constraints on companion star

By combining the Paczynski (1971) approximate formula for the Roche-lobe radius with Kepler's third law, it is possible to derive the average density of the companion star from the system orbital period. Assuming that the companion is a main sequence star, this would correspond to K0V companion of  $M_2 \simeq 0.8 M_\odot$  (indeed such a star would fill the Roche lobe). As often observed in LMXBs, the companion star might be slightly evolved, implying  $M_2 \lesssim 0.8 M_\odot$ . Therefore, the mass ratio is constrained to  $q = M_2/M_1 \lesssim 0.57$  for  $M_{NS} \geq 1.4 M_\odot$ .

A low mass main sequence star, loosing mass on a timescale much longer than the timescale on which the thermal equilibrium is established, is expected to have a mass-radius index  $\zeta \simeq 0.8$  ( $R \simeq M^{0.8}$ ). When the mass loss is fast (adiabatic), the effective mass-radius index is  $\zeta \simeq -1/3$  (Rappaport et al. 1982).

## 6.2 Conservative mass transfer

Conservative mass transfer induced by emission of gravitational waves and magnetic braking can be approximated by

$$\dot{P}_{orb} = -1.4 \times 10^{-14} m_1 m_{2,0.1} m^{-1/3} P_{8hr}^{-5/3} \times [1.0 + T_{MB}] \quad (2)$$

$$\times [(n - 1/3)/(n + 5/3 - 0.2m_{2,0.1}m_1^{-1})] s s^{-1} \quad (3)$$

(see Burderi et al. 2010; Di Salvo et al. 2008; Verbunt 1993; Rapport et al. 1987), where  $P_{8hr}$  is the orbital period in units of 8 hr;  $m_1$ ,  $m_{2,0.1}$  and  $m$  are the mass (in Solar masses) of the primary and secondary and binary system ( $m_1 + m_2$ ), respectively (the secondary is expressed in units of  $0.1 M_\odot$ );  $n$  is the index of the mass-radius relation of the secondary  $R_2 \propto M_2^n$ , that is assumed to be in the range  $0.6 - 0.8$ ;  $T_{MB}$  represents the effects of magnetic braking (Eggleton 1976; Verbant & Zwaan 1981; Tauris 2001; Burderi et al. 2010).

Following Burderi et al. (2010; see also Verbunt & Zwaan 1981; King 1988; Verbunt 1993; Tauris 2001) we express the magnetic braking term as

$$T_{MB} = 49.4(f/k_{0.277})^{-2} m_{2,0.1}^{1/3} m_1^{-4/3} P_{8hr}^2, \quad (4)$$

where  $k_{0.277}$  is the radius of gyration of the star  $k$  in units of 0.277 (we assume  $k_{0.277} = 1$ );  $f$  is a dimensionless parameter of order unity with preferred values of  $f = 0.73$  (Skumanich 1972) or  $f = 1.78$  (Smith 1979). We chose here the value that maximises the effect of magnetic braking ( $f = 0.73$ ), which results in  $T_{MB} = 129$ .

We observe that in a conservative scenario the orbital period derivative induced by gravitational radiation alone would be  $\dot{P}_{orb} = -1.6 \times 10^{-14} s s^{-1}$ , while it would be  $\dot{P}_{orb} = -5.1 \times 10^{-12} s s^{-1}$ , if magnetic braking were at work<sup>3</sup>. We note that even the latter estimate is about one order of magnitude smaller than the observed value. We thus conclude that a conservative mass transfer scenario does not reproduce the behaviour of the source. Therefore, non conservative mass transfer appears to be required.

## 6.3 Connection with accretion state

Superposed on the long-term evolution of the orbital period, highly significant jitter ( $\sim 10 - 20$  s) is observed. It is unlikely that the residual jitter originates from geometry variations of either the central X-ray source or the inner accretion disc, since these are small and get rapidly eclipsed by the rim of the companion star. In fact, at a velocity of  $\sim 230 \text{ km s}^{-1}$ , the companion star would swipe through the region where the bulk of the X-ray luminosity is produced, say  $\sim 100 r_g$  in less than  $\sim 1.2$  s (here  $r_g$  is the gravitational radius defined as  $r_g = GM/c^2$ , where  $c$  is the speed of light,  $G$  is the gravitational constant and  $M$  is the mass of the compact source).

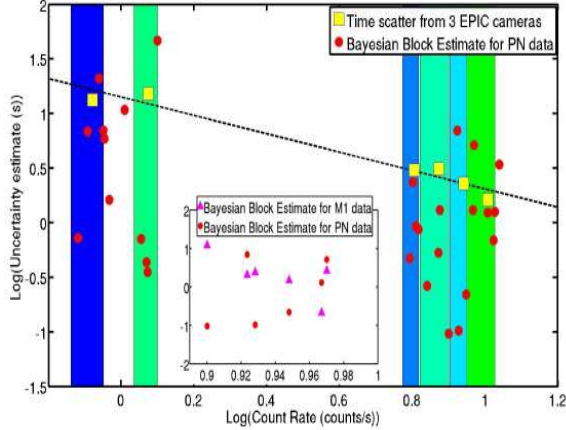
It is in theory possible that part of the observed jitter is associated to oscillations of the companion star atmosphere. For example, tidal forces could induce oscillations of the companion star. It is also well known that the magnetic activity in the Sun generates coronal loops extending several thousands kilometers above the photosphere. The presence of such structure on the surface of

the companion star would explain the amplitude of the observed jitter. One such event has been claimed in EXO 0748-676 (Wolff et al. 2007). However, were such effects at work in AX J1745.6-2901, they would either modify the ingress and egress time in a random fashion (in the case of coronal loops), or in an anti-correlated way (i.e., ingress delayed and egress advanced or vice-versa, in case of oscillations of the companion star atmosphere). Therefore, in all these cases, a variation of the duration of the eclipse, with comparable amplitude to the observed jitter, would be expected. On the contrary we observe a nearly constant eclipse duration in AX J1745.6-2901.

The correlation between ingress and egress residuals suggest that jitter is caused by the whole companion star being either "delayed" or "advanced" with respect to the expected long term orbital period evolution. In particular, the hard state eclipses arrive, on average,  $\sim 29$  s before the expected time, while the soft state eclipses arrive very close to the expected time with an average delay of  $\sim 0.69$  s. A possibility would be the displacement of the center of mass of the system, by the presence of a third body. To investigate this, we fitted Doppler shifts in the time of arrival due to the orbital velocity in the presence of a third body in an elliptical orbit (adapting equations from Schreier et al. 1972 and Mukherjee et al. 2006). The sparse sampling of the orbital evolution allows several possible solutions. However none of these solution is completely satisfactory. Indeed, they either provide an unlikely high eccentricity (higher than 0.999) or they predict (unlikely) large residuals ( $\Delta t > 60$  s) during the unsampled periods. Moreover, the observed periodicities are multiples of half a year and likely arise from the *XMM-Newton* observing window of the Galactic centre (observable for  $\sim 1.5$  months with a cadence of six months): therefore they might be spurious. Moreover, the connection between the eclipse timing and the X-ray source accretion state remains to be explained in the third body interpretation. We can also exclude that the center of mass could be modified by an asymmetric disc with a state dependent geometry, even though the outer disc bulge, generating dips, is observed to have a state-dependent behaviour. This would require an unrealistically high amount of mass ( $\sim 10^{-3} M_\odot$ ) to be stored in the bulge to produce the observed jitter.

We note that LMXB typically show durations of the eclipse transitions (i.e. duration of ingress and egress) of the order of 5-20 s (Cominsky & Wood 1989; Wachter et al. 2000; Wolff et al. 2009). Interestingly, these are comparable to the jitter observed in AX J1745.6-2901. Transition time scales are related to the atmospheric scale height of the companion star (indeed they correspond to  $\sim 1 - 4 \times 10^3$  km at a velocity of  $\sim 250 \text{ km s}^{-1}$ ). AX J1745.6-2901 shows the presence of a highly ionised plasma above the disc, with turbulent velocities of the order of  $\sim 500 \text{ km s}^{-1}$ , temperatures of  $kT \sim (4 - 10) \times 10^6$  K and densities of order  $10^{12-13} \text{ cm}^{-3}$  (Ponti et al. 2012; 2014; 2015). If such plasma travels to the orbit of the companion star without gaining additional angular momentum (i.e. maintaining the angular momentum characteristic of the outer parts of the accretion disc) it will not be in corotation with the companion star, which orbits at a speed of  $\sim 130 \text{ km s}^{-1}$ . If so, this plasma will exert a ram pressure on the atmosphere of the star of the order of:  $P_{ram} \sim 4 \times 10^2 (n/10^{13} \text{ cm}^{-3})(\Delta v/50 \text{ km s}^{-1})^2 \text{ dy cm}^{-2}$ , where  $n$  is the plasma density and  $\Delta v$  the velocity difference (assumed to be  $10^{13} \text{ cm}^{-3}$  and  $50 \text{ km s}^{-1}$ , respectively). This pressure is comparable to the pressure in the upper layers of a K type star atmosphere. Therefore, it could displace the position of the companion star atmosphere delaying both the ingress time and the egress time (although to a lesser extent, compared to the ingress time). The

<sup>3</sup> We note that for a lower index of the mass radius relation (e.g.  $n = 0.6$  instead of  $n = 0.8$ ), the orbital period evolution is slower,  $\dot{P}_{orb} = -3.4 \times 10^{-12} s s^{-1}$ . In the same way, if the companion is partly degenerate and thus has a lower mass (e.g.  $m_2 = 0.4$ ), a slower evolution would be expected,  $\dot{P}_{orb} = -1.5 \times 10^{-12} s s^{-1}$ .



**Figure A1.** (*Main panel*) The red circles show the uncertainties on the eclipse egress change times, as observed with the EPIC pn camera, determined through the Bayesian method described in Scargle et al. (2013). The yellow squares show the uncertainties derived from the scatter between the eclipse egress times measured by the different EPIC cameras averaged over orbits with similar sources flux. The coloured vertical regions indicate the flux intervals over which the average is performed. The black dashed line shows the best fit relation to the yellow points. (*Inset*) The red circles and magenta triangles show the uncertainties determined through the Bayesian block method for the EPIC pn and MOS1 cameras, respectively, over a narrow range of observed fluxes. The axes report the same quantities as the main panel.

eclipse might appear therefore delayed and shortened during the soft state, with the ingress time being more affected than the egress time. No such effect would be present during the hard state, when the disc ionised atmosphere is not present (Ponti et al. 2015). We note that, in this scenario, during the soft state, the ram pressure would act on the companion star, slowing down its motion, and therefore affecting the orbital evolution of the system. This would correspond to an additional contribution to the orbital period evolution of  $\dot{P} \sim -1.5 \times 10^{-11}$  s/s (during the soft state only).

Finally we note that both the source luminosity and spectral energy distribution change significantly between the two canonical states. In particular, the bottom panel of Fig. 3 shows a correlation between the source count rate and the observed delay. Different levels of irradiation might affect the atmospheric layers of the companion star enhancing mass transfer rate and/or mass loss (e.g., Tavani 1991).

Moreover, the geometry and physical conditions of the accretion disc are known to be significantly different in the two states. The hard state being characterised by a jet component and an inefficient disc, while the soft state showcasing a standard disc and an ionised atmosphere (Fender et al. 2004; Done et al. 2007; Ponti et al. 2012). It appears plausible that different types of outflows, potentially driving away significant amounts of angular momentum and kinetic power, are present in the different states (e.g. jets in the hard state, winds in the soft state; Ponti et al. 2012; Fender & Muñoz-Darias 2015). It is possible that either through irradiation, outflows or other mechanisms the system might lose angular momentum in a different way along the different accretion states.

## APPENDIX A: UNCERTAINTIES ON BLOCK CHANGE TIMES

The uncertainty on the block change times (i.e. the eclipses) was first determined using the method suggested in Scargle et al. (2013). This method allows us to compute the probability of change times for each block as a function of the photon arrival times, which peaks at the best fit block time. Since the probabilities thus obtained is a discrete distribution, we construct confidence intervals for change times by calculating the smallest symmetric interval around the best fit time which, in total, contains a given confidence level. The reported uncertainties, in all cases, are at a confidence level of 68%. The red circles in Fig. A1 (both in the main figure and in the inset) show these uncertainties obtained from the EPIC pn data. The magenta triangles in the inset of Fig. A1 show, instead, the Bayesian block estimates for the MOS1 data. We observe that, for similar source brightness, the uncertainty determined in this way span a range from 0.1 – 7 s, that appears relatively large. In particular, unreliably small uncertainties, as small as  $\sim 0.1 - 0.3$  s, are often observed. We note that, as clearly stated in Scargle et al. (2013), this method to determine the uncertainties on the block change times is approximate.

We also estimated the uncertainties based on the observed scatter on the simultaneous observation of the eclipse change points (e.g. egress time) with the three EPIC cameras. The observed scatter (difference between the three measurements of the change times) will be equal or larger than the intrinsic uncertainty. For each eclipse we define as ingress and egress time the weighted average of the measurements obtained by the three EPIC cameras and we measure the scatter compared to this average. We then sort the eclipses in source mean flux (over the orbital period) and group the eclipses in order to have at least 4 eclipses in each bin. We finally average the observed scatter over the 4 eclipses (therefore over a total of 12 data points). The yellow squares in Fig. A1 show the averaged uncertainties obtained in this way. The vertical coloured stripes show the width of the bin over which the scatter has been averaged.

We observe an overall good agreement between the two estimates of the uncertainties. However, we note that the uncertainties derived through the method suggested by Scargle et al. (2013) show a too large scatter. In particular, the inset of Fig. A1 reports a comparison between the uncertainty measured by the Bayesian block method from the EPIC pn and MOS1 data (the axes report the same quantities as the main panel). We observe that in several occasions the MOS1 camera has uncertainties about one order of magnitude smaller than the pn camera, for the same eclipse, despite the smaller effective area. Therefore, we prefer to be conservative and use the second estimate of the uncertainty. We also note that, as expected, the uncertainties become smaller when the source is brighter. We then fit this trend, so that we can associate to any observed source flux an uncertainty on the determination of the change point and use the latter as uncertainties.

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