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AO Psc TIME KEEPING

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AO Piscium (RA=$22^{\rm h}55^{\rm m}17\overset{\rm s}{.}99$ DEC=$-03°10'40\overset{''}{.}0$ J2000.) is an intermediate polar, that is a subclass of cataclysmic systems in which the white dwarf is magnetized enough to module the accretion. Furthermore, the period of rotation (or spin) of the white dwarf is shorter than the orbital period and there is an accretion disc. AO Psc is one of the brightest cataclysmic, with a V mag as high as 13.2.

The orbital period is $P_{\rm orb} = 3\overset{\rm h}{.}59$, the rotation period of the white dwarf is $P_{\rm rot} = 805\,{\rm s}$ and the accretion X-ray beam is reprocessed on the secondary star atmosphere, giving rise to a synodic modulation with the period $P_{\rm syn}$ such that:
$1/P_{\rm syn} = 1/P_{\rm orb} - 1/P_{\rm rot}$
i.e. $P_{\rm syn} = 859\,{\rm s}$ (Patterson & Price, 1981, Motch & Pakull, 1981, van Amerongen et al., 1985 (hereafter vA85), Taylor et al., 1997).

All these periodicities are visible by photometry as modulations in the light curves, the synodic modulation being usually the strongest one.

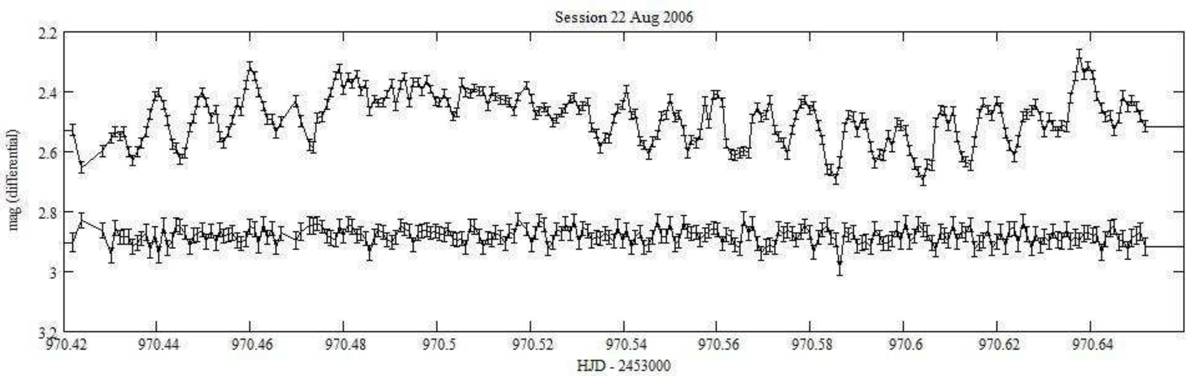

Figure 1. Upper light curve: AO Psc, Lower: the check star shifted by -0.2 mag. The error bars are the quadratic sum of the 1-sigma statistical uncertainties on the variable/check star and on the comparison star.

Photometric observations of AO Psc were carried out over eleven seasons, from 2004 to 2014, with a 203 mm f/6.3 Schmidt-Cassegrain telescope, a Clear filter and an SBIG

ST7E camera (KAF401E CCD). The exposures were 60 s long. The images were dark substracted (using master darks of the same duration than the images and at the same temperatures) and flat corrected (MaximDL software program). For the aperture differential photometry (AstroMB software package), the comparison star is GSC 5238-462. A check star, GSC 5238-347, is used to compare the standard deviations to the statistical uncertainties so as to make sure that the systematic errors are low. An example of a light curve is given Figure 1. A total of 8744 images were obtained over 74 nights.

Table 1: Results of the fits and cycle counts

Season	t_{syn}	N_{syn}	t_{rot}	N_{rot}	t_{orb}	N_{orb}	A_0	A_{syn}	A_{rot}	A_{orb}
2004	322.3748	(a)	323.2710	(b)	346.3534	(c)	2.614	-0.120	-0.054	0.033
	±10		±22		±68		±0.002	±0.001	±0.001	±0.002
2005	612.6533	29,209	612.6264	31,050	701.2596	2,372	2.488	-0.117	-0.051	0.063
	±7		±25		±40		±0.001	±0.001	±0.001	±0.001
2006	970.4400	36,002	970.4118	38,393	970.5857	1,800	2.530	-0.117	-0.063	0.068
	±12		±13		±49		±0.001	±0.001	±0.002	±0.001
2007	1301.5420	33,317	1356.4425	41,424	1296.6073	2,179	2.214	-0.044	-0.016	0.091
	±9		±36		±39		±0.001	±0.001	±0.001	±0.001
2008	1709.5149	41,052	1681.5259	34,884	1681.6001	2,573	2.271	-0.036	-0.038	0.062
	±18		±15		±9		±0.001	±0.001	±0.001	±0.001
2009	2041.5198	33,408	2041.5171	38,630	2041.5900	2,406	2.227	-0.029	-0.028	0.080
	±16		±21		±44		±0.001	±0.001	±0.001	±0.001
2010	2415.5229	37,634	2454.5989	44,327	2415.5044	2,499	2.292	-0.032	-0.040	0.075
	±30		±22		±33		±0.002	±0.002	±0.001	±0.001
2011	2744.5262	33,106	2748.5909	31,548	2744.5315	2,199	2.207	-0.041	-0.024	0.100
	±17		±16		±23		±0.001	±0.001	±0.001	±0.001
2012	3140.4698	39,842	3140.4705	42,052	3126.5269	2,553	2.218	-0.028	-0.020	0.063
	±38		±35		±13		±0.001	±0.001	±0.001	±0.001
2013	3489.5265	35,124	3489.4897	37,453	3559.3922	2,893	2.189	-0.049	-0.017	0.083
	±10		±51		±61		±0.001	±0.001	±0.001	±0.001
2014	3836.4857	34,913	3836.4863	37,236	3865.5218	2,046	2.173	-0.067	-0.007	0.087
	±11		±72		±72		±0.001	±0.001	±0.003	±0.001

the t_{xxx} are in HJD − 2,453,000 with the uncertainties in seconds,
the N_{xxx} for one season is the difference with the previous season,
the A_{xxx} are in mag.
(a) 819,882 cycles from the 0 of vA85, 83,170 cycles from the 2002 measurement of Williams (2003) (hereafter W03).
(b) 905,581 cycles from the 0 of vA85, 711,933 cycles from the 1986 measurement of Kaluzny & Semeniuk (1988) (hereafter KS88).
(c) 56,689 cycles from the 0 of vA85 + $P_{orb}/2$, 44,495 cycles from the 1986 measurement of KS88 + $P_{orb}/2$.

The magnitudes as a function of time t are fitted by the following $H(t)$ function:
$H(t) = A_0 + H_{syn}(t) + H_{rot}(t) + H_{orb}(t)$
where A_0 is a constant, $H_{syn}(t)$ is the synodic modulation:
$H_{syn}(t) = A_{syn}[\cos(\pi(t - t_{syn})/P_{syn}]^2$

$H_{\rm rot}(t)$ is the rotation modulation:
$H_{\rm rot}(t) = A_{\rm rot}[\cos(\pi(t - t_{\rm rot})/P_{\rm rot}]^2$
and $H_{\rm orb}(t)$ is the orbital modulation:
$H_{\rm orb}(t) = A_{\rm orb}[1 + \cos(2\pi(t - t_{\rm orb})/P_{\rm orb})]$

The $H(t)$ function is fitted to the observations owing to a Monte Carlo method to test the parameters relative to the timing and, for each trial, the amplitudes are determined by a least squares method. The magnitudes are weighted with the uncertainties.

Each Monte Carlo run is made of 10 millions trials. The averages and standard deviations for 10 runs are given in Table 1, along with the number of cycles, $N_{\rm xxx}$.

In 2007 the synodic and rotation modulations become fainter, especially the synodic one, and the orbital modulation and the non-modulated part A_0 become brighter, as shown Figures 2-5.

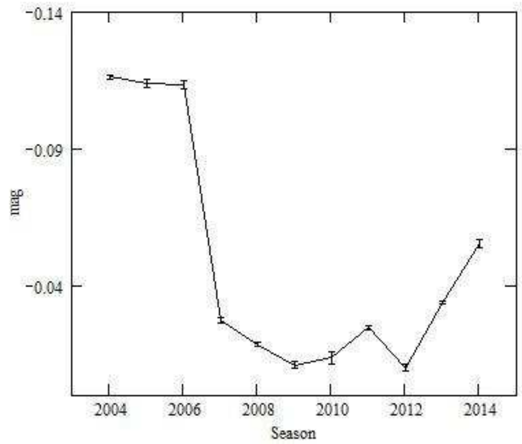

Figure 2. The amplitude $A_{\rm syn}$

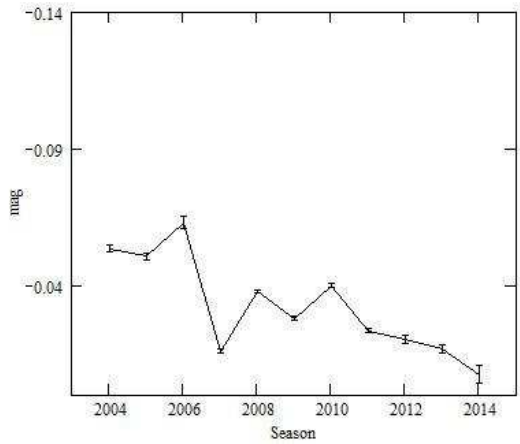

Figure 3. The amplitude $A_{\rm rot}$

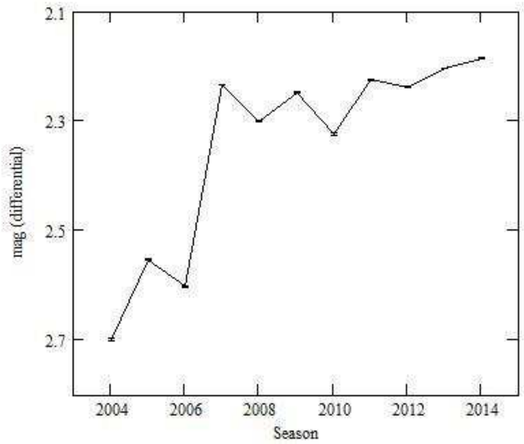

Figure 4. The amplitude A_0

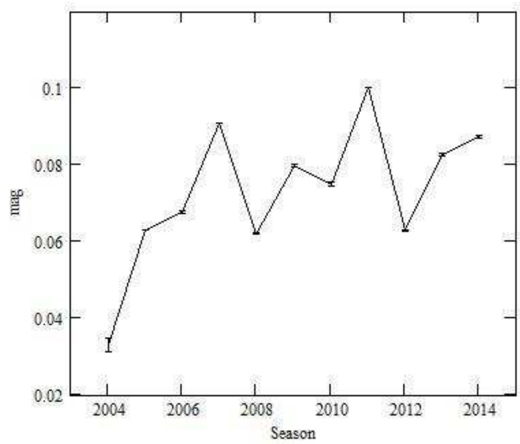

Figure 5. The amplitude $A_{\rm orb}$

The times of maxima of the synodic modulation may be fitted with the function $\mathrm{ToM}(n) = T_{\rm syn} + P_{\rm syn}n + b_{\rm syn}n^2$. There are 26 such maxima (9 from vA85, 1 from KS88, 5 from W03 and 11 from this paper). With only the data from vA85 and of W03, there is an ambiguity in the cycle count and two fits are possible (W03). Indeed, the residuals (weighted with the uncertainties) are then 8.1 s for the Fit 1 of W03 and 10.4 s for the

Fit 2. But adding the data presented here allow lifting the ambiguity: 8.9 s for the Fit 1, 15.6 s for the Fit 2. Adding the measurement of KS88 gives 9.2 s and 15.4 s respectively. Therefore, the cycle count of the Fit 1 of W03 is the right one.

The fit of the 2004-14 synodic maxima gives $b_{\rm syn} = -(2.544 \pm 0.043) \times 10^{-13}$ day. This is larger (smaller in absolute value) that the fits of W03, themselves larger than the ones of KS88 and of vA85. All the 26 maxima are then fitted with a supplementary term, $\gamma_{\rm syn} n^3$. Furthermore, they are corrected for the leap seconds due to the Earth rotation slowing down (Eastman et al., 2010). For $T_{\rm syn}$ in 1982 this correction is 21 s, for the first maximum the correction is 19 s, 35 s for the last one. $T_{\rm syn}$ is to be expressed in HJD, the corrections are then between −2 s and +14 s. The barycentric effect of Jupiter and Saturn is neglected as it is only ± 4 s and cyclic (unlike the leap seconds that keep accumulating), and the other general relativistic corrections are much smaller. The least squares method gives:
$b_{\rm syn} = -3.020 \times 10^{-13}$ day
$\gamma_{\rm syn} = 1.44 \times 10^{-21}$ day.

The fit is also done with a Monte Carlo method, so as to have a result that is independent of the least squares method and to evaluate the uncertainties. For a Monte Carlo run, $T_{\rm syn}$, $P_{\rm syn}$, $b_{\rm syn}$ and $\gamma_{\rm syn}$ are chosen each in its own range; for $\gamma_{\rm syn}$ the range is $[-10, +10] \times 10^{-21}$. 10 millions trials are computed for a run. The averages and standard deviations of 10 runs are:
$T_{\rm syn} = 2,445,174.181,13(2)$ HJD
$P_{\rm syn} = 0.009,938,498,0(4)$ day
$b_{\rm syn} = -3.031(8) \times 10^{-13}$ day
$\gamma_{\rm syn} = 2.13(44) \times 10^{-21}$ day.

Therefore the spinning up is slowing down. The derivative of the period is:
$\dot{P}_{\rm syn} = 2b_{\rm syn}/P_{\rm syn} = -6.10 \times 10^{-11}$
and the secondary derivative of the period is:
$\ddot{P}_{\rm syn} = 6\gamma_{\rm syn}/P^2_{\rm syn} = 1.30 \times 10^{-16}$ day^{-1}.
This gives the time scale:
$\tau = P_{\rm syn}/(2\dot{P}_{\rm syn}) = -223$ kyr
and the breaking index:
$n = P_{\rm syn}\ddot{P}_{\rm syn}/\dot{P}^2_{\rm syn} = 346$.
(By comparison, for FO Aqr, one has from W03: $\tau = 194$ kyr, $n = -6431$).

There are 7 orbital maxima from vA85 and one from KS88. In order to fit them with the 11 orbital minima presented here, they are corrected by adding $P_{\rm orb}/2$. A Monte Carlo method (rather than a least squares method, so as to evaluate the uncertainties) gives the ephemeris, for the orbital minima, taking into account the leap seconds:
$t(n) = T_{\rm orb} + P_{\rm orb} n$
with:
$T_{\rm orb} = 2,444,864.21809(1)$ HJD
$P_{\rm orb} = 0.149,625,502,2(1)$ day
This is within the error bars of the ephemeris of KS88, with a better precision. An ephemeris with a quadratic term was also searched for, but with no significant improvement.

As the rotation modulation is related to the synodic modulation and the orbital period, the number of rotations of the white dwarf may be calculated unambiguously. The results are given in Table 1 at (b).

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*This version of the paper contains corrections, and differs from the one appeared on-line originally. Date of last modification: Mar 13 2016