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FO Aqr TIME KEEPING

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FO Aquarii (RA=$22^{\rm h}17^{\rm m}55\overset{\rm s}{.}39$ DEC=$-08°21'03\overset{''}{.}8$, J2000) is an intermediate polar, that is a subclass of cataclysmic systems in which the white dwarf is magnetized enough to modulate the accretion. Furthermore, the period of rotation (or spin) of the white dwarf is shorter than the orbital period. FO Aqr is one of the brightest of its kind.

The orbital period of FO Aqr is $P_{\rm orb} = 4.85$ hr, the rotation period of the white dwarf is $P_{\rm rot} = 1254$ s (Patterson et al., 1998, hereafter P98). They are visible as modulations in optical photometry, the rotation modulation being fairly strong with an amplitude of 0.2 mag. Some faint and random sideband modulations may show up; however, following e.g. P98 and Williams (2003 hereafter W03), they will be neglected in the analysis that will follow.

Twelve seasons of photometric monitoring, from 2004 to 2015, are to be presented and compared with previous observations. The analysis is similar to the one in Bonnardeau (2015) for AO Psc.

Observations

The observations were carried out with a 203 mm f/6.3 Schmidt-Cassegrain telescope, without filter and an SBIG ST7E camera (KAF401E CCD, which is mostly red sensitive). The exposures were 60 s long. For the differential photometry, the comparison star is UCAC4 409-138153 (or GSC 5803-398) with $r' = 10.596 \pm 0.02$. A total of 5328 useful images were obtained over 49 nights. Figure 1 shows an example of a light curve.

Analysis of the modulations

The magnitudes as a function of time t are fitted by the following $H(t)$ function:

$$H(t) = A_0 + H_{\rm rot}(t) + H_{\rm orb}(t)$$

where A_0 is a constant, $H_{\rm rot}(t)$ is the rotation modulation:

$$H_{\rm rot}(t) = A_{rot}[\cos(\pi(t - t_{\rm rot})/P_{\rm rot}]^2$$

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 using 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 fits are weighted with the uncertainties on the observations. This is done season by season and the results are listed in Table 1.

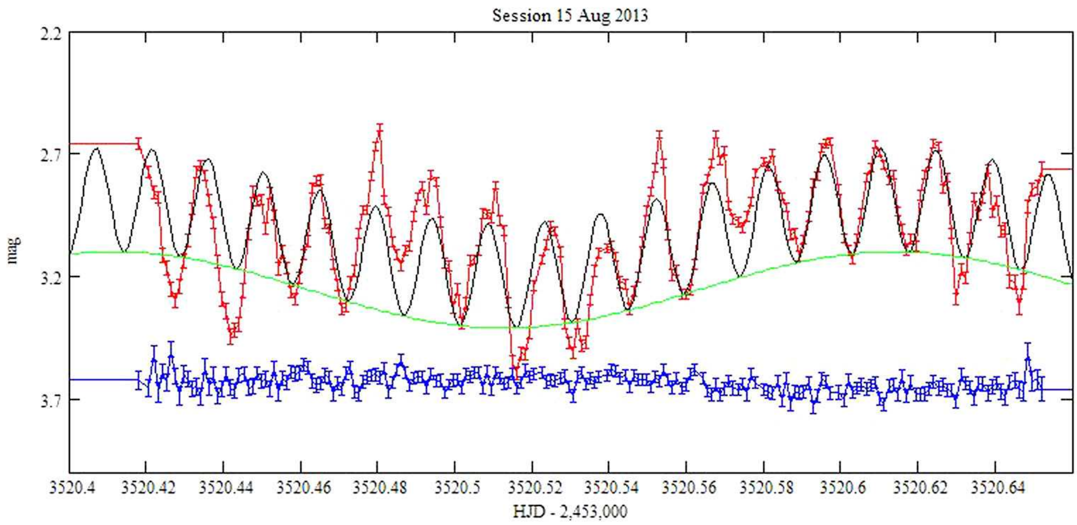

Figure 1. Upper light curve: FO Aqr, lower one: the check star UCAC4 409-138161. The error bars are the quadratic sum of the 1-sigma statistical uncertainties on the comparison star and, respectively, on the variable star or the check star. Dark line: $H(t)$ function, green line: $H_{\rm orb}(t) + A_0$ function.

Table 1: Results of the fits and cycle counts

Season	$t_{\rm orb}$	$\Delta N_{\rm orb}$	$t_{\rm rot}$	$\Delta N_{\rm rot}$	A_0	$A_{\rm orb}$	$A_{\rm rot}$
2004	249.55091	(a)	245.48796	(b)	2.828	0.103	−0.194
	±0.00069		±0.00007		±0.029	±0.001	±0.004
2005	695.29533	2206	695.37821	30988	2.864	0.126	−0.213
	±0.00042		±0.00008		±0.039	±0.008	±0.008
2006	916.5548	1095	999.44714	20944	2.932	0.058	−0.237
	±0.0012		±0.00006		±0.044	±0.001	±0.009
2007	1294.6062	1871	1350.43570	24176	2.887	0.059	−0.242
	±0.0013		±0.00009		±0.032	±0.004	±0.006
2008	1682.56750	1920	1682.55057	22876	2.763	0.137	−0.234
	±0.00061		±0.00005		±0.016	±0.001	±0.002
2009	2058.60433	1861	2058.59430	25902	2.864	0.148	−0.194
	±0.00056		±0.00010		±0.022	±0.003	±0.003
2010	2478.49376	2078	2416.51837	24654	2.749	0.147	−0.220
	±0.00030		±0.00010		±0.013	±0.006	±0.003
2011	2745.5946	1322	2794.59157	26042	2.835	0.083	−0.209
	±0.0035		±0.00015		±0.020	±0.001	±0.003
2012	3125.4822	1880	3167.42265	25681	2.887	0.102	−0.261
	±0.0014		±0.00005		±0.019	±0.001	±0.003
2013	3520.5132	1955	3520.43653	24316	2.900	0.121	−0.331
	±0.0014		±0.00010		±0.023	±0.002	±0.005
2014	3830.4561	1534	3887.58892	25290	2.957	0.021	−0.288
	±0.0069		±0.00005		±0.020	±0.001	±0.004
2015	4214.5996	1901	4327.40413	30295	2.903	0.100	−0.359
	±0.0015		±0.00005		±0.020	±0.001	±0.004

$t_{\rm xxx}$ in BJD − 2,453,000
$\Delta N_{\rm xxx}$ number of cycles from the previous season
(a) 12,478 cycles from the last observation of P98, 41,902 cycles from the origin of P98.
(b) 582,866 cycles from the origin of W03, see text.

Analysis of the orbital minima

The orbital modulation gives orbital minima t_{orb} (Figure 1 shows one of them). There are 70 orbital minima available: 54 from P98, 3 from Kruszewski & Semeniuk (1998), 1 from Kennedy et al (2016), and 12 from this work. They span 34 yr and 61,525 orbits.

These minima are converted in BJD using the on-line tool of the University of Ohio. They are fitted with the linear ephemeris $t_{\mathrm{orb}}(e) = T_{\mathrm{orb}} + P_{\mathrm{orb}} \cdot e$ using a Monte Carlo method. The results are:

$$T_{\mathrm{orb}} = 2444782.870469 \pm 0.000056 \text{ BJD}$$

$$P_{\mathrm{orb}} = 0.2020594932 \pm 0.0000000025 \text{ day}$$

This is compatible with the ephemeris of P98, with an improved precision. The resulting $O - C$ diagram shows only noise.

Analysis of the rotation maxima

The rotation modulation gives rotation maxima t_{rot} (Figure 1 shows a number of them). The last observations of rotation maxima before my measurements are the ones from W03 in 1992, 1997, 1998, 2001 and 2002. The cycle count for these measurements can be computed from the ephemeris of W03: 281,276 for 1992, 405,380 for 1997, 433,342 for 1998. For 2001 the cycle count is ambiguous, it is either 510,202 or 510,203. The number of cycles between 2001 and 2002 is 21,089.

The number of cycles between the 2002 observation of W03 and my first measurement, in 2004, is also ambiguous: it is either 51,574 or 51,573.

I fit together the W03 observations and mine with a quadratic ephemeris $t_{\mathrm{rot}}(e) = T_{\mathrm{rot}} + P_{\mathrm{rot}} \cdot e + b_{\mathrm{rot}} \cdot e^2$. Because of the ambiguities in the cycle counting, there are 4 different ways to do the fit. The residuals of the 4 fits are shown in the $O - C$ diagram of Figure 2.

The fit that gives the least residuals and the smoothest ones is for the 2001 measurement of W03 at cycle number 510,203 and for 51,574 cycles between the 2002 measurement and my 2004 measurement.

Actually, W03 considered 3 different values for the cycle count for the 2001 measurement (and not 2). So I also considered the 2001 measurement with the cycle count numbers 510,201 and 510,204. The 4 extra fits give residuals that are larger than the ones shown in Figure 2.

So, by interpolation, the ambiguities of the cycle count are lifted.

There are 140 rotation maxima available:

- 114 from P98 and 7 from Kruszewski & Semeniuk (1998) whose cycle numbers can be calculated from the ephemeris of W03;
- 1 from Andronov et al. (2005) (there are a V measurement and a R measurement and a combination of both; I used this last one), at −1259 cycles from my 2004 observation and 581,607 cycles from the origin of W03;
- 1 from Kennedy et al. (2016) at 8,601 cycles from my 2014 observations and 842,336 cycles from the origin of W03;

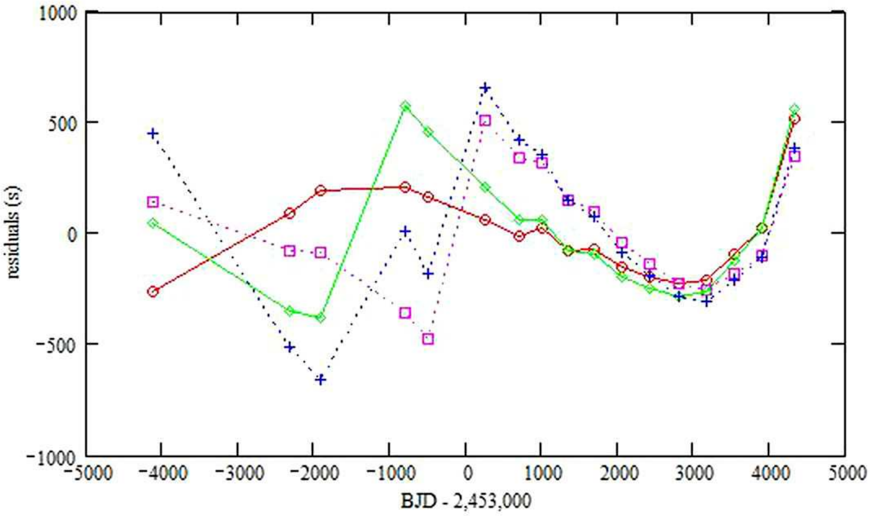

Figure 2. Red circles: the residuals for 2001 at cycle number 510,203 and 2004 at 51,574 cycles from 2002, magenta squares with dotted line: same for 2001 and 2004 at 51,573 cycles from 2002, green diamonds: 2001 at cycle number 510,202 and 2004 at 51,574 cycles from 2002, blue crosses with dotted line: same for 2001 and 2004 at 51,573 cycles from 2002.

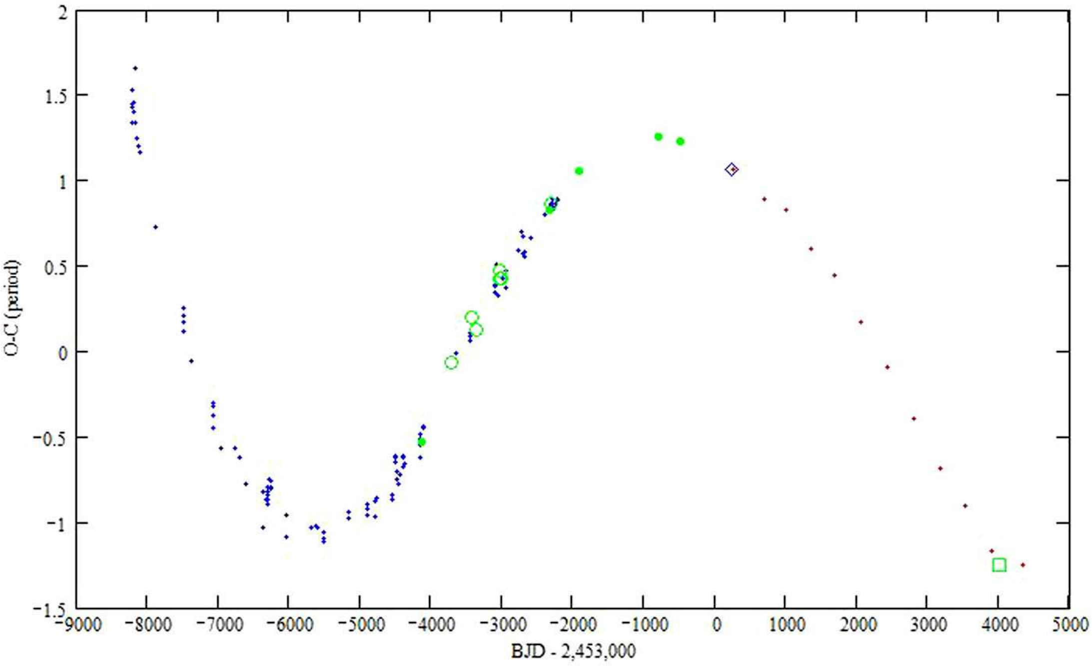

Figure 3. Blue dots: the data from P98, green dots: the W03 observations, green circles: Kruszewski & Semeniuk (1998), blue diamond: Andronov et al. (2005), green square: Kennedy et al. (2016), red dots: this work.

- 5 from W03 and 12 from this work, whose cycle numbers have been determined above. These data span 34 years and 864,030 rotations.

The 140 times of maxima are converted in BJD and are fitted with the same quadratic ephemeris as above. The results of the Monte Carlo are:

$$T_{\rm rot} = 2444782.8967 \pm 0.0016 \text{ BJD}$$

$$P_{\rm rot} = 1254.48379 \pm 0.00092 \text{ s}$$

$$b_{\rm rot} = -1.002 \cdot 10^{-12} \pm 0.021 \cdot 10^{-12} \text{ day}$$

The resulting $O - C$ diagram is shown in Figure 3.

The period of rotation of the white dwarf is decreasing at a rate $P'_{\rm rot} = 2b_{\rm rot}/P_{\rm rot} = -1.380 \cdot 10^{-10} \pm 0.029 \cdot 10^{-10}$, over a time scale $P_{\rm rot}/2P'_{\rm rot} = -144$ kyr (about the same as for AO Psc, see Bonnardeau, 2015). The $O - C$ diagram may suggest an oscillation with a time scale of about 25 yr; this is not due to a third body as the residuals for the orbital ephemeris show no modulation.

Amplitude variations

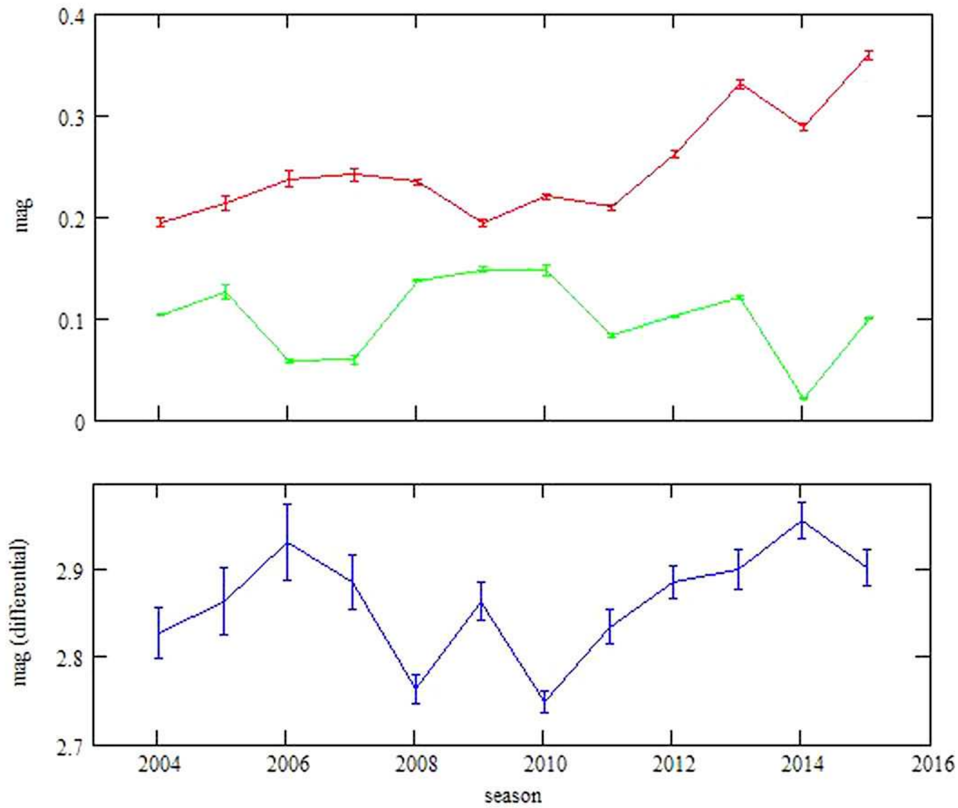

Figure 4. Red: $-A_{\rm rot}$, green: $A_{\rm orb}$, blue: A_0 (may be approximatively transformed into r' non-differential mag by adding the r' mag of the comparison star).

The variations of the amplitudes do not show any obvious trend or correlation, except for $A_{\rm rot}$ which stayed nearly constant at -0.2 mag from 2004 to 2011, then reached -0.35 mag in 2015, as shown in Figure 4.

However, a preliminary result for the season 2016 is that FO Aqr has fainted by about 1.5 mag; see also Littlefield et al. (2016a,b,c).

Acknowledgment: The use of the on-line tool of the University of Ohio to convert HJD to BJD, at `http://astroutils.astronomy.ohio-state.edu/time/hjd2bjd.html`, is acknowledged.

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