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Orbital period changes and possible stellar wind mass loss in the algol-type binary system AT Pegasi

Magdy A. Hanna *

National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Cairo, Egypt

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Abstract An analysis of the measurements of mid-eclipse times of AT Peg has been presented. It indicates a period decrease rate of $dP/dt = -4.2 \times 10^{-7}$ d/yr, which can be interpreted in terms of mass loss from the system via stellar wind with a rate between (1 and 2) $\times 10^{-8}$ $M_{\odot}$/yr. The O–C diagram shows a growing sine wave covering two different cycles of 13 yr and 31.9 yr with amplitudes equal to 0.026 and 0.032 day, respectively. These unequal durations of the cycles may be explained by magnetic activity cycling variations due to star spots. The obtained characteristics of the second cycle are consistent with similar systems when applying Applegate's mechanism.

1. Introduction

The Algol type system AT Peg (HD = 210892, BD + 07° 56, $\alpha_{2000} = 22^h\ 13.4^m$, $\delta_{2000} = +8°25'.5$, $mag_v = 9.5–10.3$, Sp. type A4V + G) is a semidetached-detached (sd-d) binary with early-type dwarf primary and late-type subgiant secondary components.

The light curve of the eclipsing binary AT Peg was observed three times till now. The first was by Cristaldi and Walter (1963) who obtained a photoelectric light curve (in integral light) at wavelength of 4540 Å. The second set of light curves in B- and V-bands was observed by Güdür et al. (1987). Later on, Gülmen et al. (1993) analyzed these light curves with the two well known methods of Wood (1972, 1973–78) and Wilson and Devinney (1971). They calculated the absolute elements of the system and deduced that the system might be an Algol type sd-binary with an orbital period decrease. Recently, Liakos et al. (2011) observed the system in the B and R Bessel photometric filters. They analyzed their light curves with the PHOEBE software, and derived new geometric and photometric elements.

Giuricin et al. (1981) analyzed the photoelectric light curve of Cristaldi and Walter (1963) by means of Wood's model. They obtained a mass ratio $q_{ph} = 0.48$ and deduced that AT Peg should be classified as a sd-d system.

The first spectroscopic study for AT Peg was done by Hill and Barnes (1972). They observed the system as a single-line eclipsing binary and obtained its orbital elements. They determined the low orbital eccentricity $e_{sp} = 0.024$, the mass function f(m) = 0.0793 $M_{\odot}$, and the spectral type A7V for the primary component. They also determined the system's physical parameters and the mass ratio $q_{sp} = 0.423$.

Maxted et al. (1994) studied the first double line spectra for AT Peg obtained by Hill between 1985 and 1992 and found that the system had zero orbital eccentricity. They also found

* Tel.: +20 2 24719149.
E-mail address: magdyh_nriag06@yahoo.com.
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the first direct measure of the mass ratio ($q = M_s/M_p = 0.473$) and determined the following absolute parameters:

$M_p = 2.22 \pm 0.065\,M_\odot$, $M_s = 1.05 \pm 0.025\,M_\odot$, $R_P = 1.86 \pm 0.025\,R_\odot$, $R_s = 2.15 \pm 0.03\,R_\odot$, $T_p = 8400 \pm 100$ K, $T_s = 4900 \pm 200$ K, $\log L_p = 1.19 \pm 0.025\,L_\odot$, and $\log L_s = 0.38 \pm 0.07\,L_\odot$.

2. Data and light elements

2.1. Data set

In order to study the period variation of AT Peg, all the available photoelectric (pe), ccd, photographic (pg) and visual (v) times of minima have been carefully collected from the literature. They are listed in Tables 8 and 9 of the Appendix and available via the electronic edition of the Journal.

2.2. Light elements

The 1st light elements of AT Peg was obtained by Wood and Forbes (1963) using 42 minima times, which were available up to approximately the end of 1960. They determined the cubic ephemeris:

$$\text{HJD(Min.I)} = 24\,33283.33022 + 1^d.14609576\,E - 0.25\,10^{-9}\,E^2 + 0.976\,10^{-13}\,E^3 \quad (1)$$

Later on, Cristaldi and Walter (1963) observed the system photoelectrically and gave the linear light elements:

$$\text{HJD(Min.I)} = 24\,37479.5211 + 1^d.146096\,E. \quad (2)$$

In the present study we construct the O–C diagram (Fig. 1) using all available minima times and Kreiner's (2004) light elements:

$$\text{HJD(Min.I)} = 24\,45640.459 + 1^d.14609013\,E. \quad (3)$$

Fig. 1 shows linear and quadratic least-squares fittings of the O–C values, with standard deviations (SD) 0.022 and 0.0151, and regressions (r) 0.849 and 0.9348, respectively. The figure shows big scatter concerning the v and pg data.

Due to the gaps found in the (O–C) diagram, constructed from the pe and ccd minima, we have used visual and photographic minima times. Only 68 v and pg minima (out of 97) were used in this study to fill these gaps. The pe minimum at JD = 24 42712.2435 was excluded due to its uncertainty as it has been remarked by the observer himself. Moreover, it is highly deviated from the common trend of the $(O–C)_2$ diagram. Table 1 compares the number of minima times used in the previous and present studies.

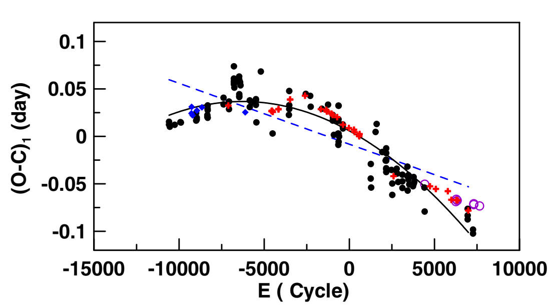

Fig. 1 Linear and quadratic fits of the residual values for all the data. The v (dots) and pg (squares) observations show big scatter compared to the pe (+) and ccd (o) observations.

We use the least squares method to fit the (O–C) curve which consists of 34 pe, 7 ccd minima together with a series of 13 averages of some visual and pg minima. These averaged minima (Table 2) are shown in Fig. 2 as dots with error-bars according to Poisson's distribution, while the pe and ccd minima are shown as (+) signs.

Two new linear and quadratic least-squares fitting of the O–C values yield the following two ephemerides. The linear ephemeris is:

$$\text{HJD(Min.I)} = 24\,45640.4506 + 1^d.146082853\,E, \quad (4)$$

with a standard deviation $SD = 0.020$, and regression $r = 0.881$. The quadratic ephemeris is:

$$\text{HJD(Min.I)} = 24\,45640.4671 + 1^d.146082105\,E - 6.58 \times 10^{-10}\,E^2, \quad (5)$$

with $SD = 0.010$, and $r = 0.973$, associated with the period decrease rate $dP/dt = -1.32 \times 10^{-9}$ d/cycle ($= -4.2 \times 10^{-7}$ d/yr). All the light elements given by various authors, together with the light elements obtained in this work are listed in Table 3.

3. Orbital period variation studies

Few orbital period variation studies for the Algol sd-binary system AT Peg were carried out by Margrave (1979), Güdür et al. (1987), Borkovits and Hegedüs (1996), and Liakos et al. (2011) (see, Table 7).

Margrave (1979) calculated a continuous period decrease rate of -14.03×10^{-9} d/cycle, while Güdür et al. (1987) obtained two period decrease rates equal to -2.0×10^{-9} d/cycle, when using all minima, or -3.84×10^{-9} d/cycle when using pe minima only. Borkovits and Hegedüs (1996) have used the pe and pg minima only, and obtained a decrease rate of -2.10×10^{-9} d/cycle. Liakos et al. (2011) obtained a decrease rate of -1.12×10^{-9} d/cycle close to our obtained value of -1.32×10^{-9} d/cycle.

Borkovits and Hegedüs (1996) have studied the (O–C) diagram and suggested, after removing a least squares parabola, an invisible hypothetical third white dwarf component orbiting the binary in 28.7 years with the mass (M_3) equals to 0.54, 0.63 or 1.20 $M_\odot$ corresponding to an orbital inclination (i_3) equals to 90°, 60° or 30°, respectively. Their hypothetical third body solution was obtained by using the observational interval data set of about 37.2 years. However, two cycles of equal durations are needed, at least, to propose the system tertiary. It is problematic to prove the existence of a third body due to a light time effect (LITE) via data covering only one cycle on the (O–C) diagram. One alternative cycle of the O–C residual diagram may be considered enough for calculating the third body orbital parameters if it is supported by spectroscopic evidences, in which the spectra shows spectral lines of the third body, together with spectral lines of the binary components – as it is seen in the study of, e.g., SZ Cam by Mayer et al. (1994). Recently, similar study by Liakos et al. (2011) has been done. They have suggested a third body of period 49.7 years which is a rather long period (∼173%) compared to that obtained by Borkovits and Hegedüs (1996).

Table 1 Comparison between number of minima times collected and used in previous and present studies for AT-Peg.

	v	pg	pe	ccd	Total
Güdür et al. (1987)	42	7	23	–	72
Borkovits and Hegedüs (1996)	150	26		–	176
Liakos et al. (2011)					276
Present work	97†	6	34‡	7	144

† Only 68 (v) minima have been used after grouping in 13 groups and averaged (see Table 2).
‡ Only one (pe) minima (24 42712.2435) has not been used due to its uncertainty, as remarked in its original source.

Table 2 Averaged groups of the selected visual & pg minima times of AT-Peg.

Interval (E)	$N^{\dagger}$	E	(O–C)	σ
−10589 to −10542	3	−10573.3	0.012641	±0.058
−10254 to −9892	3	−10021.7	0.013919	±0.058
−9267 to −8945	8	−9071.9	0.022898	±0.035
−8650 to −8317	7	−8371.3	0.026075	±0.038
−7386 to −7064	4	−7225.0	0.034939	±0.050
−6462 to −5744	10	−5937.7	0.036865	±0.032
−5483 to −5196	4	−5476.3	0.031324	±0.050
−2293 to −2266	2	−2279.5	0.036951	±0.071
1259 to 1608	5	1393.0	−0.021951	±0.045
1936 to 2170	9	2140.2	−0.025343	±0.033
2786 to 3122	7	2948.4	−0.043170	±0.038
3416 to 3524	6	3455.7	−0.044626	±0.041
3745 to 3819	4	3782.6	−0.048428	±0.050

† N is the number of minima in each group.

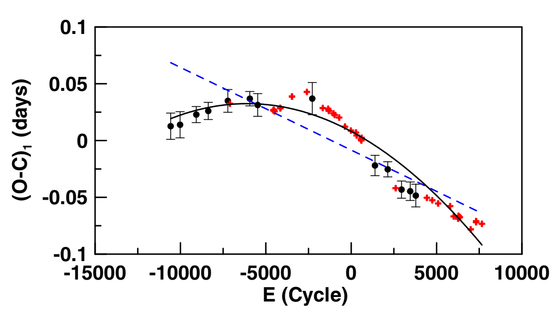

Fig. 2 Same as Fig. 1 for pe and ccd minima. Only some v and pg minima were used for filling up the gaps in the (O–C) diagram. The v and pg minima have been divided into 13 groups, and averaged in order to minimize the scattering. The length of the error-bars denote errors resulting from sampling statistics, in accordance with Poisson's distribution ($= 1/\sqrt{N}$), where N is the number of minima used in the density estimation at that point.

In a radio emission study on a sample of Algol binaries including AT Peg, Umana et al. (1998) have concluded that the systems detected at radio wavelengths show, in other spectral regions, the same features of magnetic activity as observed in RS CVns. This suggests that, sd-Algols and RS CVns not only show the same level of radio emission, but also the radio flux is strongly related to the magnetic activity of the late type component. This is because the primary, an early-type star without external convective layers, is not expected to be magnetically active (Umana et al., 1998).

Sarna et al. (1998) studied magnetic activity through the evolution of Algol-type stars. They examined the possibility of probing dynamo action in mass-losing stars. For this purpose, they selected systems of a typical Algol-type with different phases of mass transfer, and with measured X-ray fluxes. AT Peg was included among the systems TV Cas, AF Gem, HU Tau, RW Tau and X Tri, which are characterized by enhanced X-ray luminosities. They reported, that Algol-type binaries that transfer matter on a thermal time-scale have a thick convection zone, and therefore one can expect that cyclic magnetic dynamo operates efficiently in these stars. The occurrence of the hot corona and enhanced X-ray stellar activity should be characteristic of these stars (Sarna et al., 1998).

For studying the orbital period behavior of AT Peg, we are going to:

(1) discuss the effect of mass transfer and/or mass loss from the system, (2) subtract the parabolic term to obtain the $(O–C)_2$ residual curve, and to discuss the cyclic changes of the $(O–C)_2$ plot using the two methods by Qian (2000a) and by Kalimeris et al. (1994). Finally, we apply the Applegate's (1992) mechanism as an expected mechanism for interpretation of the cycling variation as a result of quadrupole moment changes due to the magnetic induced deformations of the active component.

3.1. Mass transfer

Semi-detached Algol binaries are systems where the less massive component is filling its Roche volume, transferring mass to its companion. The smaller component was initially more massive one, since it is more evolved. The initial mass ratio was reversed to its present value.

The evolution of Algol binaries has been investigated extensively (e.g., Refsdal and Weigert, 1969; Paczynski, 1971; Nelson and Eggleton, 2001; De Loore and van Rensbergen, 2005). It is generally thought that conservative mass transfer in Algol binaries causes their orbits to be wider due to the transfer of matter from the evolved less massive secondary star to its more massive main sequence companion. This is in agreement with the semidetached configuration of the binary system (e.g., S Equ in Qian and Zhu, 2002; AK Ser and VV Vul in Qian, 2000b). In contrast, many Algols show period decrease during their evolution (e.g., RW CrB and TU Her in Qian, 2000a; TU Cnc, FH Ori, IU Per, AY Gem, and XZ Per in Qian, 2001a). In this case, non-conservative evolution scenario, with mass and orbital angular momentum loss (AML), is required for agreement of theories with observations (e.g., Thomas, 1977; Refsdal et al., 1974; Sarna et al., 1997).

Giannuzzi (1981) has proved a correlation between the total mass and the angular momentum as a function of mass ratio

Table 3 Ephemerides of AT Peg by various authors.

JD. + 240000	Period	Quad. term	Periodic term	Cubic term	References
27030.226	1.1460969				Whitney (1957)
33283.33022	1.14609576	-0.25×10^{-9}		0.976×10^{-13}	Wood and Forbes (1963)
37497.5211	1.14609600				Cristaldi and Walter (1963)
37497.542	1.14608000				Hill and Barnes (1972)
40407.4368	1.14611077	-7.0158×10^{-9}			Margrave (1979)
40438.383	1.14608200				GCVS (1974) 3rd Ed.
40438.3946	1.14608840	-1.00×10^{-9}			Güdür et al. (1987)[a]
40438.3898	1.14609380	-1.92×10^{-9}			Güdür et al. (1987)[b]
45219.85614	1.14607960	-1.05×10^{-9}			Borkovits and Hegedüs (1996)
45615.2541	1.14607660				Güdür et al. (1987)[c]
45640.4590	1.14609013				Kreiner (2004)
38030.4470	1.14609050	-5.59×10^{-10}			Liakos et al. (2011)
45640.4506	1.146082853				Present Work
45640.4671	1.146082105	-6.58×10^{-10}			Present Work
45640.4671	1.146082105	-6.58×10^{-10}	a sin (bE + c)[†,‡]		Present Work

[a] Ephemeris obtained by using all minima times between HJD 24 33504.524 and 24 46334.419.
[b] Ephemeris obtained by using pe minima times of the same interval of note (a).
[c] Ephemeris obtained with primary minima during the time interval from 1975 to 1985.
[†] $a = 0^d.0129$, $b = 0°.087$, and $c = 129°.0$ (for 1st cycle).
[‡] $a = 0^d.0158$, $b = 0°.035$, and $c = 0°.0$ (for 2nd cycle).

for semi-detached Algol binaries. He has deduced the decrease in the total mass during mass transfer. However, authors have investigated such orbital period decrease to be due to one or a combination of the following causes: (1) Mass loss through the Lagrangian point L_2 and AML during the evolution (Pribulla, 1998). (2) AML via magnetic stellar winds (MSW) (Verbunt and Zwaan, 1981). (3) Magnetic braking (MB) of the stars occurs by the dynamo action in mass-losing stars which produce large-scale magnetic fields (Sarna et al., 1997, 1998). (4) Formation of a circumbinary disk surrounding the binary system due a small fraction of the flow-out material (see, van den Heuvel, 1994; Chen et al., 2006a). Chen et al. (2006a) have indicated that the circumbinary disk significantly influence the orbital evolution, and cause the orbit to shrink on a sufficiently long time scale. (5) Rapid mass transfer in low mass Algol binaries can be accounted for this scenario (Chen et al., 2006b).

In a survey of H_α mass transfer structure, Vesper et al. (2001) observed 37 classical Algol-type binaries and presented information on the prevalence of their mass transfer activity, disk presence, and system states associated with particular mass transfer structures. They identified AT Peg to have mass transfer activity by observing emission from the region between the two stars (central emission), due to star-stream interaction or stream-disk interaction, and a disk viewed out of eclipse with rapid rotation.

Stars in close binary systems suffer two kinds of mass change: (1) conservative mass transfer, in which one of the stars fills its Roche lobe and overflows its material to the companion star through the Lagrangian point L_1, (2) mass loss completely from the system via stellar wind; or a mixed situation in which a portion of the ejected matter is transferred to the companion star, and the other portion is lost from the system (non-conservative case). When both mechanisms exist together, observational estimates indicate that the mass-transfer and the mass-loss rates are of the same order (Tout and Hall, 1991).

Tout and Eggleton (1988) have proposed

$$\dot{M} = -4\times10^{-13}\frac{R\times L}{M}\left[1+10^4\left(\frac{R}{R_L}\right)^6\right], \quad (6)$$

with R, the radius of the star, L, its luminosity, and R_L, the Roche lobe overflow radius (RLOF) are in solar units, and time in years, as a simple model for enhanced stellar wind mass loss (see also, Popper and Ulrich, 1977; Hall and Kreiner, 1980). They have estimated, for semi-detached Algol-type system, an enhanced wind losing mass at a rate of $10^{-8}\ M_\odot$/yr (if a subgiant), or $10^{-7}\ M_\odot$/yr (if a giant). Following the same estimates, with lobe-filling factors (R/R_L) range from 0.9 to near unity, the enhanced wind mass-loss rate, for AT Peg, ranges from $1\times10^{-8}\ M_\odot$/yr to $2\times10^{-8}\ M_\odot$/yr. This result is in agreement with their deduced enhanced wind losing mass rate of the order $10^{-8}\ M_\odot$/yr for subgiant, and also agrees with the system configuration deduced by Giuricin et al. (1981), that AT Peg is a sd-d system. If we assume the conservative mass transfer case, according to the formula by Kreiner and Ziolkowski (1978), the rate of mass transfer equals to $2.43\times10^{-7}\ M_\odot$/yr. So, the rate of the enhanced mass loss via stellar wind differs only one order of magnitude from a conservative case and may be considered comparable to the rate of mass transfer (for a giant) in the non-conservative case.

Tout and Hall (1991) has deduced that the evolved star in a binary, just before becoming a semi-detached Algol-type system, is losing mass in an enhanced wind by the rate two or three orders of magnitude greater than in the conservative case. Hence, it is worthy to notice that, AT Peg may undergo an intermediate situation that combines together both of stellar wind mass loss and a portion of the mass flows from the less massive component to form a circumbinary disk around the primary component. However, the presence of both processes, the mass transfer and the mass loss, may be confirmed by the study of Dervişoğlu et al. (2010). They have registered, for AT Peg, a projected equatorial velocity for the gainer star if it were synchronous ($v_{syn}\ i = 80$ km/s) less than the measured

Table 4 Six linear fit sections, intervals, and period variations of AT Peg.

	Incomplete cycle		1st Cycle		2nd Cycle	
	(1) E_o–E_1	(2) E_1–E_2	(3) E_2–E_3	(4) E_3–E_4	(5) E_4–E_5	(6) E_5–E_6
Interval (in cycles)	−10573.3 to −10021.7	−10021.7 to −7105	−7105 to −4566	−4566 to −2599	−2599 to 2948.5	2948.5 to 7652
SD (Stand. Div.)	0.002	0.0014	0.0035	0.0017	0.0029	0.003
r (regression)	0.839	0.9636	0.5963	0.9846	0.9711	0.9626
Res. sum of sq.10^{-6}	4.50	6.28	0.25	0.17	0.015	0.015
ΔE (cycle)	551.6	2916.7	2539	1967	3934	10251
ΔT (day)	−0.0392	0.0279	−0.0116	0.0537	0.0003	−0.0442
ΔP (day) $\times 10^{-6}$	−3.009	3.645	−2.016	1.282	−7.30	7.600

projected rotational velocity (v_{eq} sin i = 82 km/s). Also, this can be supported by previous studies for similar systems (e.g., Olson, 1984), which showed that mass transfer from the less evolved secondary star via L_1 could spin up the equatorial rotational velocity of the primary massive main sequence star.

Subtracting off the effect of mass transfer and/or mass loss from the system, we obtain the $(O–C)_2$ residual plot in Fig. 3, which shows a significant quasi-sinusoidal variation. The solid curve represents the 8th order polynomial fit with standard deviation SD = 0.0034 and correlation coefficient r = 0.9453. In spite of using such a high degree polynomial, the data are not well-fitted. Hence, more details in studying such behavior have to be considered.

3.2. Qian's method

The $(O–C)_2$ values in Fig. 3 clearly suggest a non-continuous variation. Following Qian's (2000a) method, five clear jumps have taken place in the period of AT Peg within a time interval of about 64 years between the middle of May 1945 (or JD = 24 31587.7617) and the middle of June 2009 (or JD = 24 54998.4554). Between these jumps, the period is assumed to have undergone a steady decrease. Similar systems, such as BO Mon, Y Psc, UU and, and Z Per have been studied by Qian (2000c, 2001b). Using the least squares method, a linear function in each portion is used to obtain the best fit to the $(O–C)_2$ values:

$$(O - C)_2 = \Delta T + \Delta P \times E; \quad (7)$$

the values ΔT and ΔP in each portion are listed in Table 4. The period at any cycle E has been computed with the following equation:

$$P_{\rm Re}(E) = P_{Eph} + \Delta P + \frac{dP}{dE} \times E; \quad (8)$$

results are shown in Fig. 4, where we have plotted the difference between the real period $P_{\rm Re}$(E) and the ephemeris period P_{Eph} (1^d.146082853) – in units of 10^{-6} day – as a function of time.

3.3. Kalimeris et al.'s (1994) method

It is clearly seen that the description of the (O–C) curve cannot be fitted well by only one least-squares polynomial (Fig. 3). In dealing with similar case (X Tri), Rovithis-Livaniou et al. (2000) have followed a procedure by Kalimeris et al. (1994). They cut up the (O–C) curve into a number of segments. Each segment describes separately a least-squares polynomial. Segment boundaries can be chosen where the (O–C) diagram implies abrupt inclination changes, or even where approximating functions fail to describe properly the observed points.

For this purpose, Fig. 5 describes the $(O–C)_2$ diagram by applying a piece-wise least-squares approximation with two high-order weighted polynomials, for the two parts (cycles, 13 and 31.9 yr) connected together by a spline conjunction at E = −2500. Each one of the polynomials has the form:

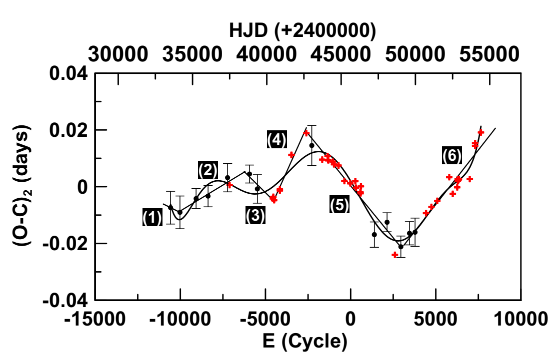

Fig. 3 Residuals of AT Peg from the quadratic ephemeris, and their description by several linear ephemerides. The solid curve represents the 8th order polynomial fit with SD = 0.0034 and r = 0.9453.

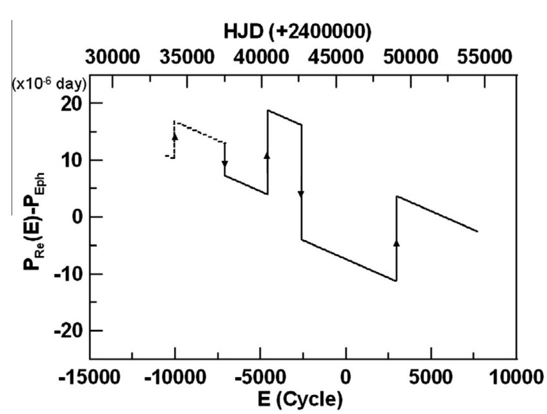

Fig. 4 Variations in the orbital period of AT Peg. Several jumps in the period are clearly visible. The dashed lines present the incomplete cycle.

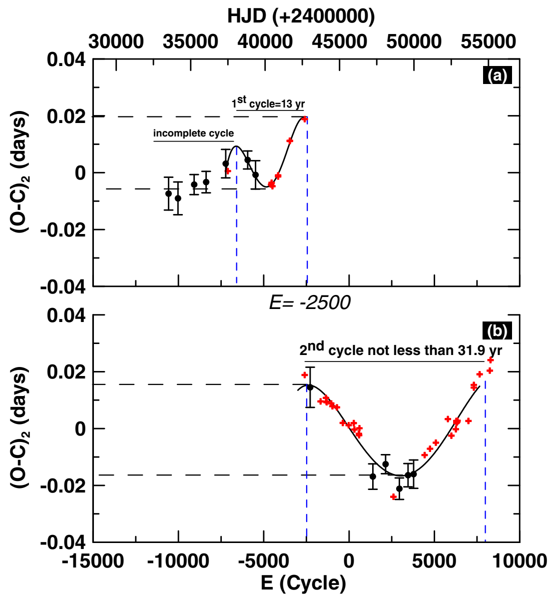

Fig. 5 The same (O–C)$_2$ curve as in Fig. 3, but dividing it into cycles in the upper and lower panels. The solid curves represent two separate 4th order best polynomial fits. The vertical and horizontal dashed lines show the duration and amplitude limits of each cycle.

Table 5 Elements of the best fitted polynomials shown in Fig. 5, for each of the two panels. All quantities are in days, except S_c which is dimensionless.

	Upper panel	Lower panel
a_o	−0.461	0.0003
a_1	−4.584	−0.1000
a_0	−1.828	0.0140
a_3	−26.757	0.0610
a_4	−27.469	−0.5230
S_c	10000	10000
Res. sum of Squ.	0.229×10^{-4}	3.856×10^{-4}

$$P(E) = \sum_{K=0}^{N} a_k \left(\frac{E}{S_c}\right)^K. \quad (9)$$

The used elements of the polynomials are listed in Table 5, while the solid curved lines in Fig. 5 represent them.

A reasonable fit, to the times of minimum light, can be obtained by adding a sinusoidal term to the quadratic ephemeris to get a good fit to the observations:

$$C = T_\circ + PE + 0.5\left(\frac{dP}{dE}\right)E^2 + a\sin(b_i E + c_i) \quad (10)$$

where, $i = 1, 2,\ldots,n$ is the cycle number. For the first and second complete cycles ($i = 1, 2$) in Fig. 5, we obtain the following two terms and include them in Table 3:

(1) for the 13 year cycle, $(O - C)_2 = 0.0129 \cdot \sin \cdot (0^\circ.087 \cdot E + 129^\circ)$; (11)
(2) for the 31.9 year cycle, $(O - C)_2 = 0.0158 \cdot \sin \cdot (0^\circ.035 \cdot E + 0^\circ.0)$. (12)

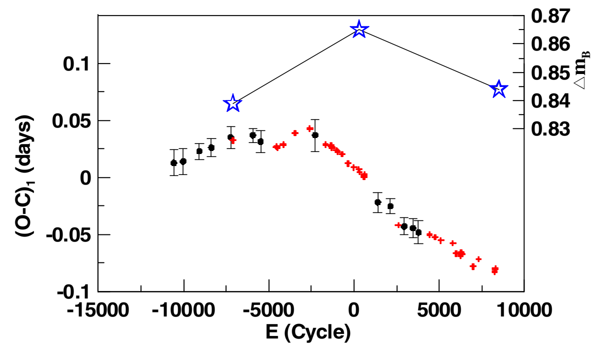

Fig. 6 Variations in the orbital period of AT Peg. The change in brightness (Δm_B) correlates the orbital period variation. Increasing (decreasing) brightness shows a decreasing (increasing) in the orbital period (Hall, 1991).

Table 6 Magnetic circulation elements from the Applegate mechanism.

	1st Cycle	2nd Cycle
$\Delta P/P$	1.71×10^{-5}	0.85×10^{-5}
ΔP (Sec.)	1.69	0.84
ΔJ (g cm^2 s^{-1})	1.73×10^{48}	0.87×10^{48}
$\Delta\Omega/\Omega$	5.83×10^{-3}	2.9×10^{-3}
ΔE (ergs)	1.926×10^{42}	0.48×10^{42}
ΔL_{RMS} (ergs s^{-1})	14.76×10^{33}	1.497×10^{33}
ΔL_{RMS}/L	1.58	0.16
B (kG) (the mean sub-surface field)	15	6.9

3.4. Cyclic behavior and the magnetic activity variation

As it is well known apsidal motion is not an acceptable explanation for such period variation in semi-detached Algols because circular orbits are believed to be the expected property in these systems, where the two components are close enough for tidal interaction and/or mass transfer to rapidly damp out any eccentricity. On the other hand, explaining the orbital period modulation, for AT Peg, to be due to LITE of a third body is still questionable, because if the third body possesses an orbit around the binary, the waveform contains the fundamental and first harmonic terms with equal durations, which is not the present case (see Fig. 5). However, Lanza and Rodonò (1999) have pointed the difficulties confronting the assumption of the presence of a third body. They have mentioned case examples of many Algols and RS CVn systems.

Various studies (e.g., Matese and Whitmire, 1983; Applegate and Patterson, 1987; Warner, 1988; Applegate, 1992; Lanza et al., 1998) have proposed and suggested, by several physical mechanisms, the cyclic but not strictly periodic modulation of the O–C variation. Many authors, e.g., Hall (1991), Šimon (1996), Zavala et al. (2002), Hanna (2006, 2010), and Hanna and Awadalla (2011) have suggested the magnetic activity cycling affecting the (O–C) behavior by applying the Applegate's (1992) mechanism. In the following we apply the Applegate (1992) mechanism to the Algol binary AT Peg.

Applegate (1992) has proposed a model which explains the period variation of the alternating sign as a consequence of magnetic activity in one of the stars in the binary. These orbital period modulations can be explained by the gravitational coupling of the orbit, due to the rotational oblateness, to

Table 7 Previous period variation studies and this work.

	Margrave (1979)	Güdür et al. (1987) †	Borkovits and Hegedüs (1996) †	Liakos et al. (2011)	Present work
Parabolic behavior related:					
dP/dE (d/cycle)	$-1.40\ 10^{-8}$	$-3.84\times10^{-9*}$ $-2.00\times10^{-9**}$	-2.10×10^{-9}	-1.12×10^{-9}	-1.32×10^{-9}
ΔM_2 ($M_\odot$/yr) (Conservative Mass Transfer)					2.43×10^{-7}
($M_\odot$/yr) (Stellar Wind)					$1\text{–}2\times10^{-8}$
3rd Body related:					
Remarks			††		
P_3 (period in yr.)			28.8 (≈9169 cycle)	49.7	
a (semi-amplit. in days)				0.018	
e_3 (eccentricity)			0.39	0.1	
ω_3 long. preias. Pass.(in rad)			6.05	3.57	
f(M_3) ($M_\odot$)			0.012‡‡	0.0129	
$M_3\_i = 90°\ M_\odot$			0.54	0.57	
$i = 60°$			0.63		
$i = 30°$			1.20		
a_3 (semi-major axis) (AU)					
a sini (projection of semi-major axis (AU)			291		
Magnetic activity related:					
Remarks					††
ΔJ (g cm^2 s^{-1})					‡
$\Delta\Omega/\Omega$					‡
$L_{\rm RMS}$ ($L_\odot$)					‡
B (kG)					‡
$P_{\rm cycle}$ (yr.)					1st cycle ≈13 2nd cycle ≈ 31.9

† Using only photoelectric and photographic minima.†† Results obtained by subtracting quadratic ephemeris.‡‡ The invisible component may be a white dwarf.
‡ See Table 6.
* Using only pe minima times.
** Using all primary minima times.

variations in the shape of a magnetically active star in the system. By analogy to the sun, magnetic activity should be expected to produce regular, but not strictly periodic, changes in an active star, and several cycles of different durations may be presented (Baliunas and Vaughan, 1985; Applegate, 1992).

Applegate's (1992) mechanism requires that the active star be variable at the $\Delta L/L \approx 0.1$ level. Also, Applegate has expected that the changes in the period owing to stellar magnetic activity may be accompanied by changes of the brightness of the active star (Hall, 1991; Šimon, 1997). The evolved secondary stars in Algol binaries are fainter than the early-type primaries and shallow secondary minima are considerably inaccurate in searching for the brightness variations assumed by Applegate (1992). In a similar study, for VV UMa, Šimon (1996) has suggested to overcome this problem by measuring the brightness of the system at the moment of the primary minima because the light contribution of the active secondary star is the most prominent there. In the orbital period variation study of CG Cyg, Hall (1991) found good agreement with the Applegate's theory with a cycle length of 50 years correlated with variations of brightness with the same cycle-length. He reported that maximum brightness occurring at minimum O–C. For AT Peg, we have measured primary minima depths (Δm_B) of all light curves observed by Cristaldi and Walter (1963) (Lambda = 4540 ~ B), Güdür et al. (1987), and Liakos et al. (2011) in the B-band. The three values have been plotted against their corresponding epochs of observation with the same abscissa scale of the O–C diagram as shown in (Fig. 6). Despite of the three values resulted from the available light curves are not enough to match about 59 years of observations, their trend shows a relatively quit correlation with the O–C variation. Unfortunately, the data points are not enough to cover all the observational history of AT Peg to match the two cycles obtained above independently (Eqs. 11 and 12). More light curves and brightness determinations for the secondary star are necessarily needed.

In analogy with the Algol system which shows an oscillation with two modulation periods of $P_{\rm mod} = 32$ yr, and $P_{\rm mod} = 180$ yr, we apply the same procedure as given by Applegate (1992). The present (O–C)$_2$ residual diagram for AT Peg contains two complete cycles of 13 and 31.9 years, which are corresponding to the interval from JD 24 37175 to 24 42662 and from JD 24 42662 to 24 54410, respectively. Assuming these two long periods P_1 and P_2 to be the modulation periods, $P_{\rm mod}$, of the stellar magnetic activity of the convective secondary star, with semi amplitudes O–C = 0.0129 and 0.0158 days, respectively; and accepting the parameters given by Maxted and Hilditch (1996) ($M_2 = 1.05\ M_\odot$, $R_2 = 2.15\ R_\odot$, $L_2 = 2.4\ L_\odot$), Giuricin et al. (1981) (the inclination $i = 78°.9$, and Gülmen et al. (1993) (a sin $i = 6.64\ R_\odot$, orbital semi-major axis $a = 6.77\ R_\odot$) one can follow the Applegate procedure (see, Applegate, 1992).

The required value for the angular momentum transfer ΔJ which produces the observed orbital period variations, the energy required to transfer this ΔJ, the root mean squares (RMS) luminosity variations $\Delta L_{\rm RMS}$ yield by the energy transfer, and the magnetic field strength B that sustains the whole mechanism have been computed for both cycles; these are given in Table 6.

The quantities obtained for the 2nd cycle in Table 6 are consistent with and close to those derived by Applegate's (1992) model for similar chromospherically active stars. The big value of $\Delta L_{\rm RMS}/L$ for the 1st cycle is in disagreement with Applegate's mechanism. This may be due to: (1) an inaccuracy in determining the amplitude and $P_{\rm mod}$ for the 1st cycle, which includes the most majority of the scattered visual and photographic minima times, (2) the angular momentum transfer and energy budget of the 13 yr cycle are virtually not identical to those of the 31.9 yr cycle because the two cycles have not the same $\Delta P/P$ as seen in Table 6. Hence, the model can plausibly explain the orbital period modulation in AT Peg, for the second cycle starting at JD = 24 42662. Table 7 summarizes the results obtained in previous orbital period variation studies and this work.

4. Discussions and conclusion

The period variation study of AT Peg leads us to the following conclusions:

(1) The nonexistence of the apsidal motion in the system AT Peg is confirmed by photoelectric observations of the secondary minima (Güdür et al., 1987).
(2) The pure parabolic approximation of the O–C curve yielding the light elements of Eq. (5) is not acceptable for the whole observational interval. If the secular period decrease exists, it needs mass flow (in the case of conservative mass transfer) from the more massive primary component, filling its Roche lobe, to the less massive secondary component. This is not valid for the system configuration obtained by various authors (e.g., Gülmen et al., 1993, and Maxted and Hilditch, 1996).
(3) The period variation observed in the sd-Algol AT Peg can be explained by stellar magnetic activity cycling on the cool secondary evolved less massive component (with sub-surface magnetic field equals to 6.9 kG for cycle number 2). This magnetic activity cycling may be superimposed on long term orbital period decrease with rate of $dP/dt = -4.2 \times 10^{-7}$ d/yr, corresponding to a timescale of 2.73×10^{6} years.
(4) The long term orbital period decrease can be interpreted in terms of (i) an enhanced wind mass-loss of rate ranges from $1 \times 10^{-8}\ M_\odot$/yr to $2 \times 10^{-8}\ M_\odot$/yr, or (ii) a portion of the ejected matter is transferred to the companion star, and the other portion is lost from the system, (iii) the ejected matter through the Lagrangian point L_1 can form a circumbinary disk around the primary component which affects the period behavior.
(5) The obtained two unequal alternative cycles (13 and 31.9 yr) shown in Fig. 5 may not reinforce the presence of the hypothetical third body assumed by Borkovits and Hegedüs (1996) and Liakos et al. (2011) (see Table 7), and may suggest the cyclic magnetic activity scenario. Also, the tertiary of the system is not confirmed till now by any spectroscopic evidences. However, one can not dismiss completely the possibility of a light-time effect due to the third body, and high dispersion spectroscopic observations are strongly recommended and/or more accurate pe and ccd times of minima are required to prove or disprove the presence of a third body.
(6) It is not excluded that more than one process is responsible for the period variation. The (O–C) curve could be approximated by a few shorter straight segments which correspond to the intervals of constant period, and by an abrupt change between two successive intervals of the constant period. According to this interpretation sudden period variation occurred near the dates: JD 24 37500, JD 24 40400, JD 24 42600 and JD 24 49200, referring to the 1st and 2nd cycles (Fig. 5). For the 2nd and 4th jumps the period decrease was observed and in the other two jumps (3rd and 5th) the period increase was observed (Table 4 and Fig. 4). Similar period variations are observed in W UMa-type systems (e.g., Qian and Liu, 2000; Hanna, 2010, and Hanna and Awadalla, 2011); also observed in Algols (e.g., Qian, 2000a,c).
(7) The X-ray emission of the stellar coronae is directly related to the presence of magnetic field and consequently gives information about the efficiency of the stellar dynamo. Sarna et al. (1998) have studied magnetic activity through the evolution of Algol-type stars. They reported that AT Peg is among the Algol systems, which have enhanced X-ray luminosities and one can expect that the dynamo operates efficiently in it. We have applied the Applegate's (1992) model. The quantities obtained for the 2nd cycle are consistent with and close to those derived by Applegate (1992) for similar chromospherically active stars.
(8) The photospheric activity of the late stars is demonstrated mainly by the O'Connell effect and distorted light curves. They can be reproduced by surface temperature inhomogenities caused by the existence of cool spots in analogy with our sun. Unfortunately, insufficient light curves for AT Peg have been observed in order to study the O'Connell effect. More light curves are needed to put a complete scenario for the orbital period variability of this interesting semi-detached system.

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Appendix A

Table 8 Photoelectric and CCD minima times for AT Peg.

HJD(Min)	Refs.	HJD(Min)	Refs.	HJD(Min)	Refs.	HJD(Min)	Ref.	HJD(Min)	Refs.
37497.5211	[1]	43728.8093	[6]	46000.3358	[12]	46334.4190	[12]	*52904.31070*	[19]
40407.4380	[2]	44089.8270	[6]	46298.3155	[12]	48620.2514	[13]	52928.37870	[21]
40438.3830	[2]	44128.7925	[6]	46315.5062	[12]	50716.4418	[14]	53657.28130	[22]
40493.3940	[3]	44136.8149	[6]	46334.4190	[12]	51077.4580	[15]	*54018.30596*	[23]
40877.3368	[4]	44442.8188	[8]	48620.2514	[13]	51469.4180	[16]	*54019.45297*	[23]
40877.3372	[4]	44520.7515	[8]	*50716.4418*	[14]	52276.2631	[17]	*54410.26738*	[24]
41661.2728	[5]	44826.7553	[9]	51077.4580	[15]	52512.3486	[18]	55093.3274	[25]
41661.2729	[5]	45219.8562	[10]	51469.4180	[16]	*52811.4762*	[19]	55141.4661	[25]
42661.8136	[6]	45615.2538	[11]	46298.3155	[12]	*52842.4231*	[20]		
42712.2435	[7]	45957.3600	[11]	46315.5062	[12]	52850.4449	[21]		

CCD minima times are in Italic font.

Refs.: [1] Cristaldi, S., Walter, K.: 1963, AN 287, 103, [2] Pohl, E., Kizilirmak, A.: 1970, IBVS 456, [3] Kizilirmak, A.: 1971, Publ. Ege Univ. Obs. No. 11–16, [4] Kizilirmak, A. & Pohl, E.: 1971, IBVS 530, [5] Kizilirmak, A., Pohl, E.: 1974, IBVS 937, [6] Margrave, T.E.: 1980, IBVS 1869, [7] Pohl, E. and Kizilirmak, A.: 1976, IBVS 1163, [8] Margrave, T.E.: 1981, IBVS 1930, [9] Margrave, T.E.: 1982, IBVS 2086, [10] Margrave, T.E.: 1983, IBVS 2292, [11] Pohl, E., Tunka, Z., Gülmen, O., Evren, S.: 1985, IBVS 2793, [12] Güdür. N., Sezer, C., Gülmen, O.: 1987, IBVS 2978, [13] Diethelm, R.: 1992, BBSAG Bull. 99, [14] Agerer, F., Hübscher, J.: 1998, IBVS 4606, [15] Agerer, F., Dahm, M. and Hübscher, J.: 1999, IBVS 4712, [16] Agerer, F., Dahm, M., Hübscher, J.: 2001, IBVS 5017, [17] Agerer, F., Hübscher, J.: 2002, IBVS 5296, [18] Demercan, O. et al.: 2003, IBVS 5364, [19] Bakis, V. et al.: 2003, IBVS 5464, [20] Bakis, V. et al.: 2005, IBVS 5662, [21] Hübscher, J.: 2005, IBVS 5643, [22] Hübscher, J., Paschke, A., Walter, F.: 2006, IBVS 5731, [23] Brat, L., Zejda, M., Svoboda, P.: 2007, B.R.N.O. Contribution 34, [24] Brat, L., Smelcer, L., Kucerkova, M. et al.: 2008, OEJV 94, 1. [25] Hübscher, J. et al.: 2010, IBVS 5941.

Table 9 Visual and photographic minima for AT Peg.

HJD(Min)	Refs.	HJD(Min)	Refs.	HJD(Min)	Refs.	HJD(Min)	Refs.	HJD(Min)	Refs.
33504.523	[1]	37544.515	[7]	39685.443	[14]	45200.373	[25]	49218.505	[31]
33504.526	[1]	37872.315	[8]	40477.326	[15]	45216.414	[25]	49218.512	[31]
33558.387	[1]	37872.317	[8]	41576.446	[15]	47083.342	[26]	49555.461	[31]
33888.463	[1]	37872.318	[8]	41599.374	[16]	47091.380	[26]	49555.471	[31]
34272.406	[2]	37872.321	[8]	41599.378	[15]	47114.277	[27]	49571.491	[33]
34303.350	[2]	37873.480	[9]	41599.393	[16]	47412.319	[28]	49618.497	[34]
35019.666	[3]	37904.402	[8]	43012.517	[17]	47483.385	[29]	49625.369	[34]
35034.572	[3]	37911.287	[8]	43043.450	[18]	47859.273	[30]	49679.230	[34]
35097.598	[3]	38226.462	[10]	43795.283	[19]	48088.482	[31]	49932.514	[34]
35332.541	[4]	38226.465	[10]	44211.318	[20]	48127.437	[31]	49974.356	[34]
35332.549	[4]	38234.466	[10]	44525.336	[21]	48127.440	[31]	49978.360	[35]
35370.363	[4]	38234.467	[10]	44526.476	[21]	48127.441	[31]	50017.329	[34]
35370.365	[4]	38234.469	[10]	44541.378	[21]	48127.449	[31]	50700.393	[36]
35388.710	[5]	38288.347	[8]	44603.249	[22]	48127.450	[31]	50716.413	[36]
35726.810	[5]	38288.348	[8]	44878.312	[23]	48127.457	[31]	53611.42839	[37]
36085.526	[4]	38319.289	[10]	44886.348	[23]	48127.462	[31]	53611.43255	[37]
36085.528	[4]	*38642.458*	[11]	44902.368	[23]	48480.435	[31]	53611.43950	[37]
36100.434	[4]	38940.447	[12]	44910.432	[23]	48535.421	[31]	53972.43184	[38]
36108.447	[4]	38940.454	[12]	44917.279	[23]	48535.433	[31]	53972.43604	[38]
36108.455	[4]	39057.353	[12]	44917.294	[23]	48833.432	[31]	55070.393	[39]
36108.460	[4]	39356.480	[6]	44925.293	[23]	48841.450	[32]		
37175.471	[6]	39356.485	[6]	44925.331	[23]	48872.394	[32]		
37175.478	[7]	39356.486	[6]	44956.243	[24]	48934.274	[32]		
37544.507	[7]	39387.406	[13]	45200.371	[25]	49218.498	[31]		

Photographic minima are in Italic font.

Refs.: [1] Domke, K., Pohl, E.: 1953, AN 281, 113, [2] Pohl, E.: 1955, AN 282, 235., [3] Whitney, D.S.: 1957, AJ 62, 371., [4] Rudolph, R.: 1960, AN 285, 161., [5] Whitney, D.S.: 1957, AJ 62, 371., [6] Czerlunczakiewicz, D. & Flin, P.: 1968, AcA. 18, 331., [7] Flin, P. & Slowik, A.: 1967, AcA 17, 59., [8] Pohl, E. & Kizilirmak, A.: 1964, AN 288, 69., [9] Oburka, O.: 1964, BAICz, 15, 26., [10] Oburka, O.: 1964, BAICz. 15, 250., [11] Oburka, O.: 1965, BAICz 16, 212., [12] Braune, W. & Hübscher, J.: 1967, AN 290, 105., [13] Braune, W. et al.: 1970, AN 292, 185., [14] Kizilirmak, A., Pohl, E.: 1969, AN 291, 111., [15] Braune, W. & Mundry, E.: 1973, AN 294, 225., [16] Diethelm, R. et al.: 1972, BBSAG Bull.6., [17] Braune, W. et al.: 1979, AN 300, 3., [18] Diethelm, R.: 1976, BBSAG Bull. 30., [19] Braune, W. et al.: 1981, AN 302, 53., [20] Diethelm, R.: 1980, BBSAG Bull. 46., [21] Locher, K.: 1980, BBSAG Bull. 51., [22] Locher, K.: 1981, BBSAG Bull. 52., [23] Locher, K.: 1981, BBSAG Bull. 57., [24] Locher, K.: 1982, BBSAG Bull. 58., [25] Locher, K.: 1982, BBSAG Bull. 62., [26] Locher, K.: 1988, BBSAG Bull. 86., [27] Locher, K.: 1988, BBSAG Bull. 88., [28] Locher, K.: 1988, BBSAG Bull. 89., [29] Paschke, A.: 1989, BBSAG Bull. 90., [30] Locher, K.: 1990, BBSAG Bull. 93., [31] Kundera, T., Cracow Eclipsing Binaries Minima Database, BRNO 31, [32] Paschke, A.: 1992, BBSAG Bull. 102., [33] Hübscher, J. et al.: 1995, BAV-M 79, [34] Molik, P.: 2007, Oejv 60, 1, [35] Hübscher, J. & Agerer, F.: 1996, BAV-M 93, [36] Hübscher, J. et al.: 1998, BAV-M 113, [37] Brat, L. et al.: 2007, B.R.N.O. Contr. 34, [38] Brat, L. et al.: 2008, OEJV 94, 1, [39] Hübscher, J.:2011, BAV-Mitt 213.

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