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Orbital period variation study of the low-mass Algol eclipsing binary AI Draconis

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Abstract Orbital period changes for the Algol-type eclipsing binary AI Dra were studied based on the analysis of its observed times of light minimum. The period variation showed cyclic changes in the interval from JD. ≈ 2436000 to JD. ≈ 2447500 and a secular period increase rate ($dP/dt = 2.44 \times 10^{-7}$ d/year) starting from JD. ≈ 2448500 up to 2455262, in a time scale equals to 5×10^{6} year.

1. Introduction

The system AI Dra (HD 153345, SAO 30164, HIP 82884 BD = +52° 2009, $\alpha_{2000} = 16^{h}\,56^{m}\,18.15^{s}$ $\delta_{2000} = +52°\,41'.9$, $mag_{v} = 7.05–8.09$, $P = 1^{d}.988$, and Sp. type A0V + F9) is a detached–semi-detached (d–sd) eclipsing binary with an Algol type light curve. Its light variability was suspected by Schilt and Hill (1938) and its Algol type eclipsing nature was confirmed by Geyer et al. (1955).

As AI Dra is bright and of short period, many photoelectric observations have been carried out since 1959. The first light curve (no filter) was published by Cester (1959). Six other sets of light curves were published by Mauder (1962) (interference filters with half-width of 100 Å), Winiarski (1971) and Degirmenci et al. (2000) (B and V filters), Jassur et al. (2001) (U, B and V filters), Arevalo and Lazaro (2002) (infrared J, H and K bands), and Kiss (2002) (*uvby* bands). In addition, many time of minima have been determined by various observers.

Two single line radial velocity (RV) curves were observed and published by Ebbighausen (1967) and Duerbeck and Teuber (1978). The only double lined spectrum was observed by Khalesseh (1999). Degirmenci et al. (2000) tried to solve these given RV curves by the code of Wilson and Devinney (1971) (W–D). They did not find good agreement between the observed and theoretical values for the RV of the eclipsing pair's mass center.

2. Period variation

An essential method to study the period variation in the eclipsing binary systems is the analysis of the *O-C* diagram by the use of minima times determined throughout all the observational history of the binary.

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2.1. Data set

In order to study the period variation of AI Dra, all the available photoelectric (pe), ccd, photographic (pg) and visual (v) times of minima have been carefully collected from the literature.

2.2. Light elements

Since the light discovery of the variability of AI Dra (Schilt and Hill, 1938), the system attracted many observers and researchers to observe and study due to its brightness (mag_v = 7.05–8.09), and its short orbital period ($P = 1^d.988$). Several light elements were obtained; they are listed in Table 1.

In the present study we construct the *O-C* diagram (Fig. 1) using all the available times of minima data, with Kreiner's (2004) light elements:

$$HJD(Min.I) = 2437544.5092 + 1^d.198814892E. \quad (1)$$

Fig. 1 represents 631 data points by two sets of minima times. 534 visual and photographic minima times are in small (+) sign, while 97 photoelectric and ccd minima times are in big bold dot sign. As it is obviously seen, the gap in the data ranged from JD. 2429024.517 to JD. 2435337.498 is common between the two data sets (see, Fig. 1). Thus, due to the very large scatter in the (v) and (pg) data relative to the (pe) and ccd, we consider only the later set in the present analysis. Fig. 2 represents all the available (pe) and (ccd) minima times except the very early two minima JD. 2424638.07 and JD. 2440875.415 due to their uncertainty as remarked by the observers, and JD. 2441869.4263 for its large deviation from the general trend of the data. Using the last 27 pe and ccd minima time, the improved light elements has been obtained:

$$HJD(Min.I) = 2437544.48421 + 1^d.198818089E, \quad (2)$$

with standard deviation SD = 0.002, and a regression $r = 0.971$. When considering the quadratic fit, an orbital period increase rate $dP/dt = 8.03 \times 10^{-10}$ d/cycle ($= 2.44 \times 10^{-7}$ d/year), in a time scale equals to 4.9×10^6 year has been obtained.

New quadratic least-squares fit of the *O-C* values for all the pe and ccd minima times yields the following ephemeris:

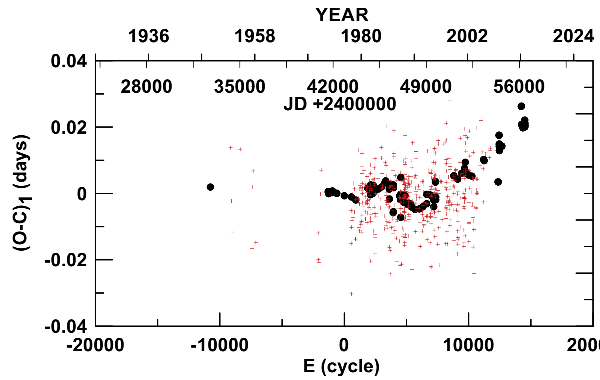

Fig. 1 The (*O-C*) diagram for all the data. The v and pg observations (+) show big scatter compared to the pe and ccd (•) observations. The gap around $E = -5000$ is nearly common between the two sets of data.

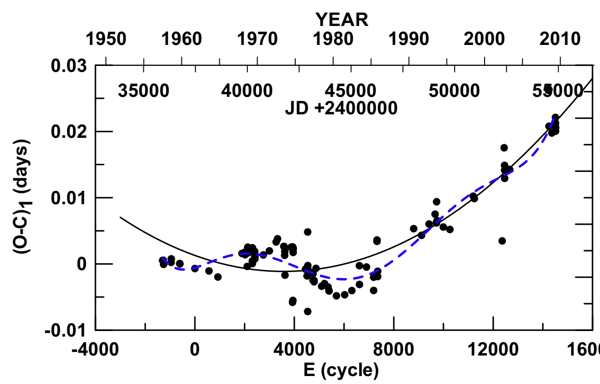

Fig. 2 The quadratic (solid curve) and six order polynomial (dashed curve) fits of the residual values for the pe and ccd observations.

$$HJD(Min.I) = 2437544.51048 + 1^d.198813541E + 1.89 \times 10^{-10}E^2, \quad (3)$$

with SD = 0.003 and $r = 0.921$, associated with an orbital period increase rate $dP/dt = 3.78 \times 10^{-10}$ d/cycle ($= 1.15 \times 10^{-7}$ d/year), in a time scale equals to 1.04×10^7 year.

Table 1 The ephemerides of AI Dra found by various authors.

JD. + 240000	Period	Quadratic term	Cubic term	References
24638.07000	1.19881359			Khlopov et al. (1958)
28656.47900	1.19881350			Geyer et al. (1955)
33282.70317	1.19881720.	2.598×10^{-9}	2.60×10^{-13}	Wood and Forbes (1963)
43291.62700	1.19881460			Khlopov et al. (1985)
37544.50950	1.19881520			Winiarski (1971)
36398.44240	1.19881470			Cester (1959)
48475.30860	1.19881750			Degirmenci et al. (2000)
52480.55810	1.19881450			Kiss (2002)
37544.50920	1.198814892			Kreiner (2004)
43291.62860	1.19881580	$6.24 \pm 1.15 \times 10^{-11}$		Zasche et al. (2010)
37544.48421	1.198818089			Present work[a]
37544.51048	1.198813541	1.89×10^{-10}		Present work[b]

[a] The period represented from the last 27 minima.
[b] For all pe and ccd data.

3. Orbital period variation studies

Two orbital period variation studies for the Algol semi-detached binary system AI Dra were carried out by Degirmenci et al. (2000) and Zasche et al. (2010).

Degirmenci et al. (2000) suggested a continuous period increase rate of about 1×10^{-7} d/year (0.91 s/century), which corresponds to a mass transfer from the less to the more massive component at a rate of 7.5×10^{-7} M⊙/year. They also suggested that there may be an unseen third body orbiting the system with a period of about 23 years and a mass $M_3 = 1.35$ M⊙, and determined its orbital period parameters.

Zasche et al. (2010) obtained 3.85×10^{-8} d/year orbital period increase rate due to a conservative steady mass transfer rate equal to 8.6×10^{-9} M⊙/year superimposed on alternative period variation of two hypothetical unseen companions orbiting the system with periods of about 18 and 43 years. They also calculated the orbital elements of both companions and determined minimal masses 0.02 M⊙ and 0.16 M⊙ for both with very low semi-amplitudes 0.0029 d and 0.0037 d, respectively. However they reported that their hypothesis could not be proved with the available data and more photometric and spectroscopic observations are needed to confirm or reject it.

To study the orbital period behavior of AI Dra, we are going to discuss the evolutionary status of the binary and the possibility of mass transfer via Lagrangian point L_1 considering the conservative and the non-conservative mass transfer case when the mass loss via stellar wind. To do such study we have to discuss the rotational velocity (RoV) of the primary component. Also the magnetic activity of the late type component has to be under the scope of the present study.

The *O-C* diagram constructed in Fig. 2 shows abrupt sine-like variation. A six order polynomial fit is the dashed curve in the figure. 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.

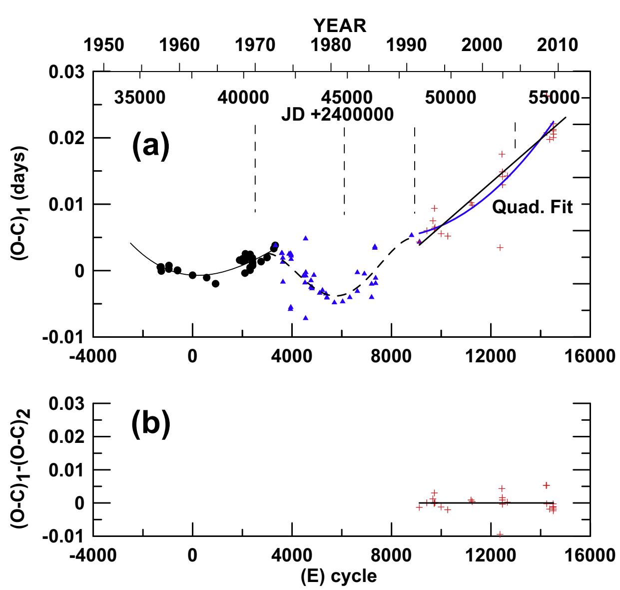

Fig. 3 The same *O-C* diagram. Cyclic and quadratic portions are explained in the text. Vertical dashed lines represent the epoch of the change in primary's RoV.

It is clearly seen that the *O-C* curve could not be described by only one least-square polynomial fit. 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-square polynomial. That is applied to Fig. 3.

Fig. 3(a) shows the same residual diagram as Fig. 2. The *O-C* diagram is divided into two portions. The first portion contains two cycles represented by dots (•) and filled triangles are fitted by two fourth order polynomials. The second represented by (+) signs is fitted via linear and quadratic least squares polynomial fits. The linear fit for deducing the expected ephemeris and the quadratic is for calculating the dP/dt and to obtain the rate of mass transfer expected in this interval. The lower panel (Fig. 3b) shows the residuals after subtracting the effect of mass transfer as explained in, e.g., Kalimeris et al. (1994) and Hanna (2010).

4. Discussion and results

4.1. Mass transfer and evolutionary status

Generally, orbital period increase can be interpreted as a result of mass transfer from the less massive evolved secondary star to the more massive primary one when considering conservative mass transfer, or an isotropic flow-out of matter (from one or both components) from the system is considered, in the none-conservative case (see, Pribulla 1998).

Both previous studies proposed the conservative mass transfer hypothesis for the system AI Dra. They considered that mass directly transfer from the secondary less massive evolved star to the more massive primary main sequence component via the Lagrangian point L_1. It seems that this is not strictly the case of the system under study. Many investigators tried to determine the evolutionary status of AI Dra from the light curve analysis, but their results were in contradiction. The secondary star sometimes fills or not-fills its Roche lobe (RL). Mezzetti et al. (1980) analyzed Cester's (1959) and Winiarski's (1971) light curves and found that the secondary components are actually undersized and not in contact with its RL. Brancewicz and Dworak (1980) classified the system as A0V + F9 and considered AI Dra as an Algol type detached binary. Khalesseh (1999) was not able, using his spectroscopic study, to define an acceptable evolutionary model for the system. Degirmenci et al. (2000) observed the system photoelectrically for 17 nights in 1993. Their study and analysis of the LC revealed a sd configuration.

Jassur et al. (2001) observed the system photoelectrically during July to October 1988 in the *UBV* bands. They analyzed their light curves, and used the spectroscopic results of Khalesseh (1999). They reached to the conclusion that, AI Dra should be classified as a d-system with main-sequence primary and evolved secondary stars. Their result was in agreement with the results obtained by Mezzetti et al. (1980) and Khalesseh (1999), but in disagreement with Cester (1959) and Mauder (1962). Kiss (2002) has fitted the mean *uvby* light curves of AI Dra to derive physical parameters of the components from his Stromgren photometry by using the Nightfall software of Wichmann (1998). He has reported that the results are consistent with previous parameter determinations, and the secondary is likely to fill its Roche-lobe, thus the system is in sd configuration as it has been proved earlier by, e.g. Degirmenci et al. (2000). Lazaro et al. (2004) observed the system photoelectrically in the *JHK* bands in different runs during 1996 and 1997 and reported that the secondary star fills its Roche lobe. Also they observed it spectroscopically. They classified the stellar components as A0V for the primary and F9.5V or it could reach as far as G4V, for the secondary. This classification shows that, the secondary component fills its Roche lobe while it is still a main sequence star.

As we have illustrated above, such late type low mass stars mostly lose matter via stellar winds, in analogy to the sun. In the following we shall calculate the rate of the stellar wind mass loss using the formula by Tout and Hall (1991):

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

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.

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. Adopting, parameters by Lazaro et al. (2002) with R/R_L varies from 0.85 to unity, one can deduce the rate of mass loss via stellar winds to be 1.3×10^{-8} to 3.5×10^{-8} $M_\odot$/year. Fig. 4 shows the effect of the intrinsic variability that can affect the *O-C* diagram.

The *O-C* diagram consists of a series of episodes of changes and the duration of the episode in which the period length is changing lies below the resolution limit of the data, due to the observational inaccuracies and intrinsic variability of the light curves. Such abrupt changes have been shown by Šimon (1998).

4.2. Rotational velocity

From the previous studies one can notice the confusion in specifying the evolutionary status of the secondary component. Is it filling or undersize its Roche lobe? In case the secondary star fills its *RL* completely, one can expect a continuous mass transfer through the Lagrangian point L_1. Otherwise, one can interpret the period increase to be due an isotropic flow-out of matter via magnetic stellar winds (see, Pribulla, 1998), and the cyclic variation can be tested by the dynamo theory represented by, e.g., the Applegate mechanism (1992) (see, Section 4.3). Recently, Ibanoglu et al. (2012) have reached to a conclusion that, there appear to be relationships between the Equivalent Widths (EWs) of CII λ 4267 Å line and the rates orbital period increase and mass transfer in some Algols. As the mass transfer rate increases the EW of CII line decreases, which indicates that accreted material has not been completely mixed yet in the surface layers of the gainers.

Among sd-binary systems, the hot gainer rotates more rapidly than the rate synchronous with orbital motion. Huang (1966) and Plavec (1970) suggested that oversynchronous rotations are results of mass transfer. Such a process should accelerate at least the surface rotation. Hence, the rotational velocity (RoV) studies may be considered as a clue in interpreting this indeterminacy of the evolutionary status in the AI Dra. Mass transfer from the secondary star that fills up its Roche lobe showed changes in the RoV of the primary component. It spins up its RoV. Determinations of the RoV have been carried out by Olson (1984) who searched for RoV changes among eclipsing binary stars. He observed a small decrease in the projected RoV of AI Dra during the time interval from 1970 ($v_r \sin i = 79 \pm 3$ km/s) to 1982 ($v_r \sin i = 78 \pm 3$ km/s). While Lazaro et al. (2004) observed a higher RoV in 2004 ($v_r \sin i = 83$ km/s), and Worek (1996) observed the system in 1991 and deduced $v_r \sin i = 85.6$ km/s. Dervisoglu et al. (2010) concluded that the slow rotation of the gainers in the classical Algol systems is explained by a balance between the spin-down by a stellar wind linked to a magnetic field and spin up by mass accretion falling on the primary star. For AI Dra, the balance and/or spin down RoV can be seen before 1982 since it decreases 1 km/s in twelve years, while the spin up RoV can be seen in 2004 when it increases by 3 km/s.

4.3. The cyclic magnetic activity behavior

The cyclic but not strictly periodic modulation of the *O-C* variation has been studied by several physical mechanisms (e.g., Matese and Whitmire, 1983; Applegate and Patterson, 1987; Warner, 1988; Applegate, 1992; Lanza et al., 1998). The alternative changes of the orbital period observed in the *O-C* diagram can be explained by the change in the magnetic activity of the active star in the system. Applegate (1992) has proposed a model which explains such variations and deduced that the active star variability has to be at the $\Delta L_{\mathrm{RMS}}/L \approx 0.1$ level. In the following we apply the Applegate (1992) mechanism to the Algol binary AI Dra.

The present *O-C* residual diagram of AI Dra (Fig. 3) contains two complete cycles of 15.2 and 17.7 years, which are corresponding to the intervals P_1 from JD 2435988.448 to 2441529.3737 and P_2 from JD 2441529.3737 to 2448475.3077, respectively. Assuming P_1 and P_2 to be the modulation periods, P_{mod}, of the stellar magnetic activity of the evolved convective secondary component, with amplitudes $O\text{-}C = 0.0036$ and 0.0066 days, respectively; and accepting the parameters by Jassur et al. (2001) ($M_2 = 1.28$ $M_\odot$, $R_2 = 2.15$ $R_\odot$, $L_2 = 3.24$ $L_\odot$) one can follow the Applegate procedure (see, Applegate, 1992).

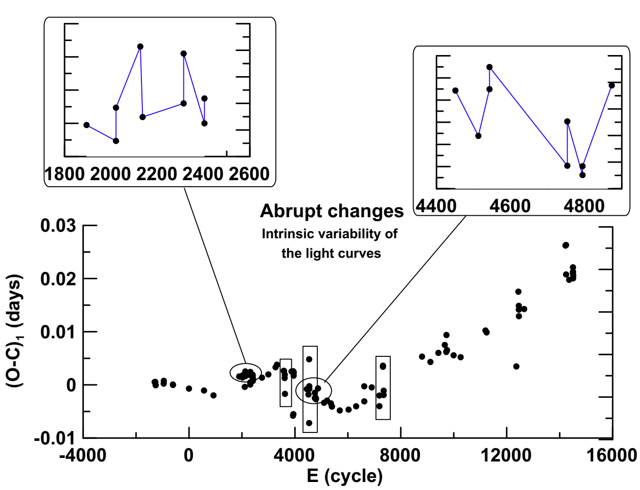

Fig. 4 The figure shows the pe and ccd minima times. The two windows show, e.g., the detailed description of the abrupt changes due to intrinsic variability in the secondary star that reflects on the LCs.

Table 2 Magnetic circulation elements from the Applegate mechanism for AI Dra.

	1st Cycle	2nd Cycle
$\Delta P/P$	3.06×10^{-6}	4.07×10^{-6}
ΔP (s)	0.37	0.42
ΔJ (g cm^2 s^{-1})	5.21×10^{47}	6.93×10^{47}
$\Delta\Omega/\Omega$	1.5×10^{-3}	2.0×10^{-3}
ΔE (ergs)	1.43×10^{41}	2.52×10^{41}
$\Delta L_{\rm RMS}$ (ergs s^{-1})	9.37×10^{32}	1.32×10^{33}
$\Delta L_{\rm RMS}/L$	0.07	0.105
B (kG) (the mean sub-surface field)	7.8	8.1

The required value for the angular momentum transfer ΔJ which produces the observed orbital period variations, the energy required to transfer this ΔJ, the 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 2.

Applegate's (1992) mechanism requires that the active star should be variable at the $\Delta L_{\rm RMS}/L \approx 0.1$ level. The quantities obtained for the two cycles in Table 2 are consistent with and close to those derived by Applegate's (1992) model for similar active stars.

5. Conclusion

As it has been emphasized, the system shows episodes of variability in the RoV of the primary star. This feature may be due to the observed alternative changes in the evolutionary status of the system between detached and semi-detached configurations. In other words the system passes through different episodes concerning the secondary component in which it is sometimes filling up it Roche lobe and sometimes it contracts to be undersize its lobe. When the secondary component fills its Roche lobe, it transfers matter to the primary one. Then it accelerates up the RoV of the primary star (showing a change in its RoV). In the contrary, when the secondary contracts to be undersize its Roche lobe, flow of matter through the Lagrangian point L_1 (mass transfer) stops and the RoV of the primary star goes down till reaching a state of constancy. Certainly, these processes occur gradually and there should be a phase shift between the two processes.

Due to such evolutionary behavior, we divided the *O-C* diagram into two parts, the first having two cycles (of 15.2 and 17.7 years) considering no mass transfer during this era, and the second showing a continuous increase in the orbital period of rate 2.44×10^{-7} d/year starting around epoch JD. 24 48096.0 up to the end of the present collected data. This orbital period increase can be interpreted to be due to a continuous mass transfer of rate $dM/dt = 1.52 \times 10^{-7}$ M$_\odot$/year during this era from the secondary less massive evolved to the more massive primary star via the Lagrangian point L_1.

The two cycles shown in Fig. 3 can be interpreted to be due to the intrinsic variability of the secondary star arising in the form of star spot activity in analogy to the sun. Applegate mechanism has been applied to check the magnetic activity process that can cause the cyclic period variability of AI Dra. The mechanism shows a good consistency with similar active binaries (see, Applegate 1992).

Due to great possibility of the presence of stellar wind that affects the light curves and consequently the *O-C* diagram as shown in Fig. 4, we have calculated the rate of mass loss via stellar wind. It is ranged from 1.3 to 3.5×10^{-8} M$_\odot$/year.

The present investigation cannot dismiss the study given by Zasche et al. (2010), suggesting the presence of two other companions orbiting AI Dra, but also more detailed studies have to be taken into consideration such as the aspects studied in this paper concerning the puzzling situation in determining the evolutionary status of the system, and the mutual change in the rotational velocity of the primary component which sometimes confirm the conservative mass transfer and sometimes not. In addition, more precise minima times and light curves together with high dispersion spectroscopic observations are strongly recommended indeed.

Acknowledgments

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