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# STUDY OF PERIOD VARIATION OF THE ECLIPSING BINARY SYSTEM W DELPHINI

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## ABSTRACT

A period study of the semi-detached eclipsing binary system W Delphini based on the extensive series of minimum timings covering more than a century (109 years) indicates a cyclic $(O-C)$ variation of the system. This variation can be explained as due either to (1) stellar magnetic activity cycles of the cool subgiant G5 secondary component of the binary with a subsurface magnetic field equals to 3 kG, or (2) a long-term orbital period increases with a rate of $1.68 \times 10^{-8}$ day/cycle caused by a mass transfer rate of $4.9 \times 10^{-8}$ $M_{\odot}yr^{-1}$ from the less to more massive component modulated by a light time effect due to a hypothetical third body with period of $53.4 \pm 1.06$ years. The former explanation is more recommended than the later one since the obtained third body mass value ($M_3 = 1.58$ $M_{\odot}$) is quite large but it can not manifest itself observationally and also it cannot be a white dwarf. In the contrary, from the magnetic activity point of view, the obtained characteristics are in good consistent when applying Applegate (1992) mechanism. However, further precise photometric and CCD observations for minima timings with brightness determinations are needed to confirm the present solution.

*Key words :* eclipsing binaries – sd-system – algol variable – period variation – LITE – magnetic activity – W Del

## I. INTRODUCTION

The eclipsing binary system W Delphini [$\alpha = 20^h 37^m 40^s.0857$, $\delta = +18^\circ 17' 03''.780$ (2000); HD 352682; BD+17°4367; $mag_v = 9.84$; Sp. B9.5 Ve + G5] has been discovered in 1895 by Miss Wells. W Delphini is a good example of the typical Algol variable, with a deep primary minimum, showing a constant phase, and little or no secondary minimum (Russell, 1912). Generally W Del is regarded in the literature as a sd-system.

Russell (1912) has discussed the well defined light curve which has been observed by, Professor Wendell, with a polarizing photometer and has been published in the Harvard Annals, 69, part I. He has deduced a "uniform" line elements with period of 4.8061 days.

Complete light curves in B and V of this semi-detached system observed 1964 were given by Walter (1970) who had found that the primary minimum strongly asymmetric while it was symmetric in the years near 1900.

Struve (1946) found an orbital eccentricity $e = 0.20$ and a longitude of periastron $\omega = 0°$. Lucy and Sweeney's (1971) re-discussion of Struve's (1946) data confirmed the same eccentricity value which in a contradiction with Walter's (1970) photoelectric observations which displayed a secondary eclipse centered at phase 0.5. Photometric disturbances probably due to the presence of gas streams were visible especially around the strongly asymmetrical primary minimum (Mezzeti et al., 1980). Walter (1970) also, from the light curves photometric solutions, showed that the effect of dissimilarity of the shape of the components might strongly influence the calculated value of the ratio of radii. He also found $i = 84°$ and that the fractional luminosity of the brighter star (in V) was 0.86.

The spectrum of W Del outside eclipse has been deduced by Struve (1946) to be B9 or A0, whereas Hill et al. (1975) have found it to be B9.5V. For the sub-giant secondary component, Struve (1946) has deduced a G5 spectral classification whereas Mezzetti et al. (1980) have deduced a late G spectral type.

Cisneros-Parra (1970) has used the evolutionary calculations of binary systems, given by Kippenhahn and Weigert (1967) and has concluded that the observed sd-systems have suffered a large mass exchange and that this mass exchange may still be going on.

## II. TIMES OF MINIMA AND LIGHT ELEMENTS

Graff (1930a) collected times of minima up to 1927 and gave the quadratic line elements:

$$JDHel(Min) = 18048.67900 + 4.80600 \cdot E - 0.6 \times 10^{-8} \cdot E^2$$

Horrocks (1941) has reduced (using the linear part of the light elements of Graff) the data given by Graff (1930a) together with other three times of minima given by Graff (1930b) & Piotrowski (1934a,b) and he has exhibited the results graphically as an $(O-C)$ diagram. The diagram indicates a strong oscillatory term having an amplitude of $0^d.046$ and a period of about 50 years. Horrocks, also, has given linear light ele-

TABLE 1.
THE EPHEMERISE OF W DEL FOUND BY DIFFERENT AUTHORS

| JD.+240000 | Period | Quadratic term | Periodic term | Cubic term | Reference |
|---|---|---|---|---|---|
| 12002.50000 | 4.806400 | | | | Pickering (1896) |
| 12002.55940 | 4.806211 | $-0.62 \times 10^{-7}$ | | | Russell et al. (1917) |
| 18048.67900 | 4.806000 | $-0.6 \times 10^{-8}$ | | | Graff (1930) |
| 18048.63100 | 4.806029 | | | | Horrocks (1941) |
| 18048.62200 | 4.806038 | | | | Tsessewich (1957) |
| 18048.61866 | 4.80604313 | | $A \sin(BE + C)^{\dagger}$ | | Plavec (1960) |
| 18048.61870 | 4.8060633 | | | | Agerer & Todoran (1992) |
| 18048.61870 | 4.80604313 | | | | Kukarkin et al. (1969) |
| 33283.76530 | 4.8061345 | $+0.7523 \times 10^{-7}$ | | $0.1284 \times 10^{-10}$ | Wood and Forbes (1963) |
| 38618.55810 | 4.8061380 | | | | Kukarkin et al. (1974) |
| 43328.54950 | 4.8061000 | | | | Mallama (1980) |
| 43328.52755 | 4.80610015 | $+0.7253 \times 10^{-8}$ | | | Borkovits & Hegedüs (1996) |
| 45933.41880 | 4.8060721 | | | | Kreiner et al. (2001) |

$\dagger A = 0^d.05550$, $B = 0^o.09303$ and $C = 81^o.08$

ments shown in Table 1 with a mean period value of $4^d.806029$.

Up to the end of 1956, 29 new times of minima have been observed. The period variation of W Del has been discussed by many authors [e.g., Tsessewich (1957), Plavec (1959&1960) and Borkovits & Hegedüs (1996)].

Tsessewich (1957) noted that $O - C$ to be cyclic, perhaps even periodic, and warning that the periodic elements often appears as invalid after some time. Plavec (1959), used the collected list of times of minima by Tsessewich's (1957) together with 13 minima from other literatures and started his study of the period change of W Del by a total of 116 times of minima. He calculated the deviations $(O - C)$ on the base of Graff's (1930) line elements and deduced new line elements (see Table 1) that strongly indicated a simple periodic term . He reported that the observed period of W Del undergos periodic change with a period of 50.9 years and amplitude of 0.0555 days. He did not reach to a conclusion - after detailed discussions according to data available in that time - concerning the cause of such periodic change and he reported that this periodic term could not be explained by apsidal motion or the presence of a third body. Plavec (1960) re-discussed the variation and argued it to be due to an apsidal line rotation of period 50.9 years. On the other hand, Borkovits and Hegedüs (1996) reported that the system showed an evidence for multiplicity of W Del and suggested a solution of four body LITE for its period variation. They also reported that the available data set, at that time, was not suited to compute a reliable solution.

## III. ORBITAL PERIOD VARIATIONS

### (a) PERIODIC VARIATION

To study the variation in the orbital period of W Del, all the available published visual (vis), photographic (pg), photoelectric (phe) and CCD times of minima from literature have been compiled. The main source of the older photographic and visual minima times has been the compilation provided by Plavec (1959). For the earlier 81 times of minima, in his list, Plavec has not recorded their type of observations. All other types of minima times are listed in Table 2. In the table, the original references are given except the four times of minima that have been taken from the "Cracow Eclipsing Binaries Minima Database (CEBMD)" since they are not included in the BBSAG Bull. 25&26 as have been recorded in the (CEBMD). These four times of minima are also listed and they are typed in italics in Table 2 with an asterisk symbol in Figure 1.

The residual values $(O-C)$ have been calculated using the light elements that are given by Kreiner (2001) as:

$$JDHel(Min.) = 2445933.4188 + 4.8060721\,E \quad (1)$$

and are listed in Table 2 together with the times of minima, type of observations and reference of each observation respectively. All the residuals are presented graphically versus cycles in Fig. 1. It can be seen from Figure 1 that the period of the system started to increase after JD. 2428756.418.

The semi-detached binary system W Delphini has a remarkable variation in its orbital period. This variation has been emphasized by eminent scientists and the cause of the periodic phenomenon is still under discussion. However, despite the deviation $(O - C)$ calculated for times of minima till 1957, i.e., between JD

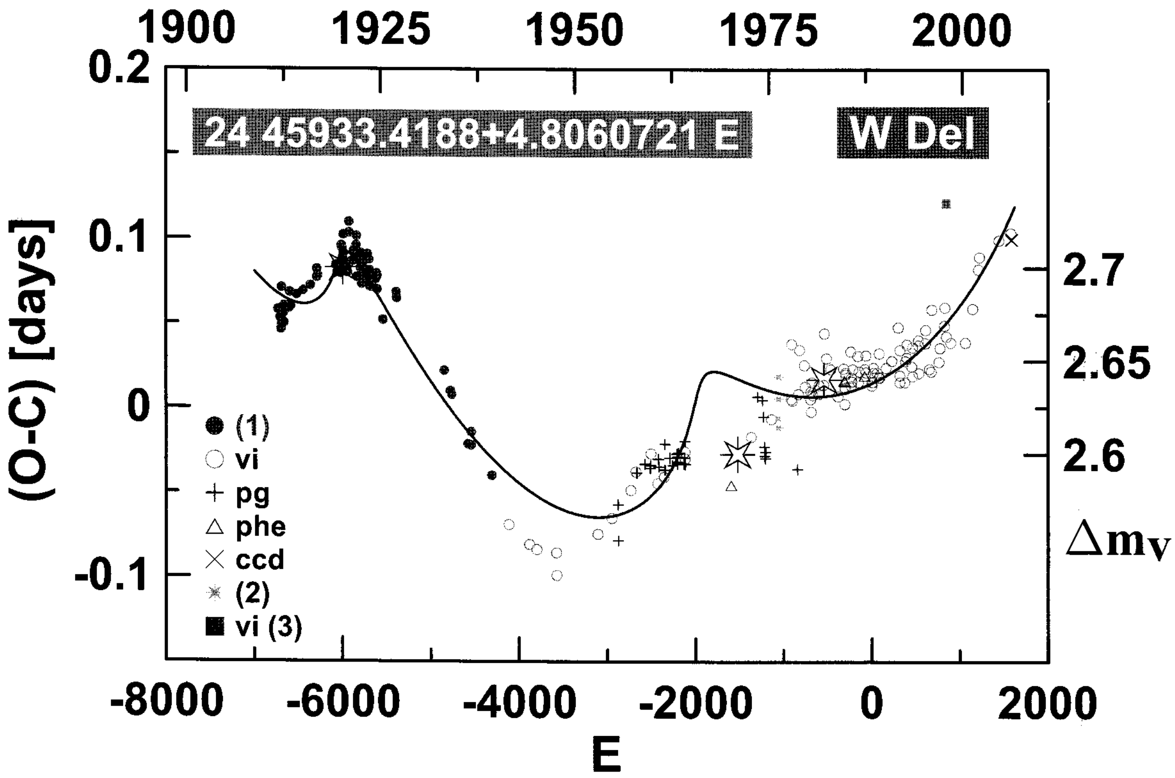


**Fig. 1.**— The $(O-C)$ diagram is given corresponding to Kreiner's (2001) ephemeris $JD_{minI} = 245933.4188 + 4.8060721 \times E$. The top label shows approximate calendar years of the observations. The solid line represents the light time effect best fit for an elliptical orbit. The numbers 1, 2 and 3 represent the set of data points in which the type of observations are not written in Table 2, the four points from the CEBMD and the excluded time of minima, respectively. The three big dark blue stars are correspond to the right coordinate scale of the brightness difference $\Delta m$.

2413564 and 2435749 nearly formed a complete cycle of about 50 years, Tsessewich (1957) has reported that $O-C$ variations to be cyclic, perhaps even periodic, and warning that the periodic elements often appears as invalid after some time, that is the reason he do not give any length of the period.

In Figure 1, where all $O-C$ differences for primary minima are displayed, a periodic character may be proposed. The use of a trigonometric term of the form

$$O - C = a_1 \ \sin(a_2 E + a_3)$$

implies a periodicity of a particular form in the times of minimum which may be spurious (Wood and Forbes 1963). For W Del if a periodic function is proposed it may be represented by the formula

$$O - C = 0.080^d \ \sin(0.089^\circ E + 49.4^\circ)$$

where the corresponding period is approximately 54 years.

However, when the current observed sinusoidal function $O-C = f(E)$ turns out to be periodic, the following two hypotheses must be taken into consideration:
i) The hypothesis of the apsidal motion, which is valid when the corresponding relative orbit is eccentric.
ii) The hypothesis of the presence of a third body which is rotating around the eclipsing pair.

Hegedüs (1988), in his paper, listed the binary W Del as an eclipsing Algol with an undoubted but weakly proved, or questionable apsidal motion. Also Petrova & Orlove (1999) included W Del into the list of systems which exhibited eccentric orbit with $e = 0.036$ and an apsidal motion with period of 50.9 years (according to Plavec 1960), shorter by 2.5 years than the period of our supposed third body.

TABLE 2.
TIME OF MINIMIUM LIGHTS FOR W DEL.

| HJD. (+2400000) | E | $(O-C)$ | Type | Ref. |
|---|---|---|---|---|
| 13564.581 | -6735 | 0.0577935 | | 1 |
| 13684.728 | -6710 | 0.0529910 | | 1 |
| 13713.564 | -6704 | 0.0525584 | | 1 |
| 13737.588 | -6699 | 0.0461979 | | 1 |
| 13761.643 | -6694 | 0.0708374 | | 1 |
| 13766.427 | -6693 | 0.0487653 | | 1 |
| 13804.882 | -6685 | 0.0551885 | | 1 |
| 13814.489 | -6683 | 0.0500443 | | 1 |
| 13833.722 | -6679 | 0.0587559 | | 1 |
| 13857.749 | -6674 | 0.0553954 | | 1 |
| 13886.590 | -6668 | 0.0599628 | | 1 |
| 13896.192 | -6666 | 0.0498186 | | 1 |
| 14107.668 | -6622 | 0.0586462 | | 1 |
| 14136.505 | -6616 | 0.0592136 | | 1 |
| 14179.759 | -6607 | 0.0585647 | | 1 |
| 14203.791 | -6602 | 0.0602042 | | 1 |
| 14213.411 | -6600 | 0.0680600 | | 1 |
| 14232.628 | -6596 | 0.0607716 | | 1 |
| 14256.657 | -6591 | 0.0594111 | | 1 |
| 14578.671 | -6524 | 0.0665804 | | 1 |
| 14948.741 | -6447 | 0.0690287 | | 1 |
| 15347.648 | -6364 | 0.0720444 | | 1 |
| 15693.690 | -6292 | 0.0768532 | | 1 |
| 15698.501 | -6291 | 0.0817811 | | 1 |
| 15746.558 | -6281 | 0.0780601 | | 1 |
| 15751.364 | -6280 | 0.0779880 | | 1 |
| 16741.421 | -6074 | 0.0841354 | | 1 |
| 16813.508 | -6059 | 0.0800539 | | 1 |
| 16962.501 | -6028 | 0.0848188 | | 1 |
| 16991.332 | -6022 | 0.0793862 | | 1 |
| 17034.603 | -6013 | 0.0957373 | | 1 |
| 17068.244 | -6006 | 0.0942326 | | 1 |
| 17082.656 | -6003 | 0.0880163 | | 1 |
| 17111.487 | -5997 | 0.0825837 | | 1 |
| 17111.492 | -5997 | 0.0875837 | | 1 |
| 17140.343 | -5991 | 0.1021511 | | 1 |
| 17145.138 | -5990 | 0.0910790 | | 1 |
| 17356.594 | -5946 | 0.0799066 | | 1 |
| 17409.465 | -5935 | 0.0841135 | | 1 |
| 17438.327 | -5929 | 0.1096809 | | 1 |
| 17462.351 | -5924 | 0.1033204 | | 1 |
| 17707.444 | -5873 | 0.0866433 | | 1 |
| 17707.450 | -5873 | 0.0926433 | | 1 |
| 17832.411 | -5847 | 0.0957687 | | 1 |
| 17861.253 | -5841 | 0.1013361 | | 1 |
| 17875.657 | -5838 | 0.0871198 | | 1 |
| 17880.453 | -5837 | 0.0770477 | | 1 |
| 18048.679 | -5802 | 0.0905242 | | 1 |
| 18053.486 | -5801 | 0.0914521 | | 1 |
| 18082.313 | -5795 | 0.0820195 | | 1 |
| 18149.589 | -5781 | 0.0730101 | | 1 |
| 18154.410 | -5780 | 0.0879380 | | 1 |
| 18173.631 | -5776 | 0.0846496 | | 1 |
| 18178.440 | -5775 | 0.0875775 | | 1 |
| 18183.237 | -5774 | 0.0785054 | | 1 |
| 18202.462 | -5770 | 0.0792170 | | 1 |
| 18245.718 | -5761 | 0.0805681 | | 1 |
| 18255.336 | -5759 | 0.0864239 | | 1 |
| 18447.583 | -5719 | 0.0905399 | | 1 |
| 18524.462 | -5703 | 0.0723863 | | 1 |
| 18529.283 | -5702 | 0.0873142 | | 1 |
| 18553.307 | -5697 | 0.0809537 | | 1 |
| 18572.526 | -5693 | 0.0756653 | | 1 |
| 18596.552 | -5688 | 0.0713048 | | 1 |
| 18625.396 | -5682 | 0.0788722 | | 1 |
| 18649.421 | -5677 | 0.0735117 | | 1 |
| 18894.533 | -5626 | 0.0758346 | | 1 |
| 18947.403 | -5615 | 0.0790415 | | 1 |
| 18952.208 | -5614 | 0.0779694 | | 1 |
| 18971.424 | -5610 | 0.0696810 | | 1 |
| 18971.432 | -5610 | 0.0776810 | | 1 |
| 19293.413 | -5543 | 0.0518503 | | 1 |
| 20009.534 | -5394 | 0.0681074 | | 1 |
| 20038.367 | -5388 | 0.0646748 | | 1 |
| 22619.185 | -4851 | 0.0219571 | | 1 |
| 22960.404 | -4780 | 0.0098380 | | 1 |
| 23037.299 | -4764 | 0.0076844 | | 1 |
| 23921.587 | -4580 | -0.0215820 | | 1 |
| 24099.411 | -4543 | -0.0222497 | | 1 |
| 24104.225 | -4542 | -0.0143218 | | 1 |
| 25219.208 | -4310 | -0.0400490 | | 1 |
| 26151.557 | -4116 | -0.0690364 | vis | 1 |
| 27271.360 | -3883 | -0.0808357 | vis | 1 |
| 27670.261 | -3800 | -0.0838200 | vis | 1 |
| 28732.401 | -3579 | -0.0857541 | vis | 1 |
| 28756.418 | -3574 | -0.0991146 | vis | 1 |
| 30991.266 | -3109 | -0.0746411 | vis | 1 |
| 31760.247 | -2949 | -0.0651771 | vis | 1 |
| 32096.680 | -2879 | -0.0572241 | pg | 1 |
| 32115.883 | -2875 | -0.0785125 | pg | 1 |
| 32793.569 | -2734 | -0.0486786 | vis | 1 |
| 33067.526 | -2677 | -0.0377883 | vis | 1 |
| 33115.586 | -2667 | -0.0385093 | pg | 1 |
| 33562.556 | -2574 | -0.0332146 | pg | 1 |
| 33855.724 | -2513 | -0.0356127 | pg | 1 |
| 33879.756 | -2508 | -0.0339732 | pg | 1 |
| 33889.375 | -2506 | -0.0271174 | vis | 1 |
| 34254.619 | -2430 | -0.0445970 | vis | 1 |
| 34302.694 | -2420 | -0.0303180 | pg | 1 |
| 34331.526 | -2414 | -0.0347506 | pg | 1 |
| 34605.466 | -2357 | -0.0408603 | vis | 1 |
| 34648.740 | -2348 | -0.0215092 | pg | 1 |
| 34653.531 | -2347 | -0.0365813 | pg | 1 |
| 34922.678 | -2291 | -0.0296189 | pg | 1 |
| 35076.468 | -2259 | -0.0339261 | pg | 1 |
| 35292.748 | -2214 | -0.0271706 | pg | 1 |
| 35340.803 | -2204 | -0.0328916 | pg | 1 |
| 35345.610 | -2203 | -0.0319637 | pg | 1 |
| 35345.613 | -2203 | -0.0289637 | vis | 1 |
| 35393.676 | -2193 | -0.0266847 | pg | 1 |
| 35691.646 | -2131 | -0.0331549 | pg | 1 |
| 35715.680 | -2126 | -0.0295154 | pg | 1 |
| 35739.720 | -2121 | -0.0198759 | pg | 1 |
| 35749.322 | -2119 | -0.0300201 | vis | 1 |
| 35749.326 | -2119 | -0.0260201 | vis | 1 |
| 35768.543 | -2115 | -0.0333085 | pg | 1 |
| 38253.270 | -1598 | -0.0455842 | phe | 2 |
| 39358.695 | -1368 | -0.0171672 | vis | 3 |
| 39709.562 | -1295 | 0.0065695 | pg | 4 |
| 39978.700 | -1239 | 0.0045319 | pg | 4 |

Continue Table 2.

| HJD. (+2400000) | E | $(O-C)$ | Type | Ref. |
|---|---|---|---|---|
| 40031.557 | -1228 | -0.0052612 | pg | 4 |
| 40079.600 | -1218 | -0.0229822 | pg | 4 |
| 40113.237 | -1211 | -0.0284869 | pg | 4 |
| 40137.266 | -1206 | -0.0298474 | pg | 4 |
| 40161.300 | -1201 | -0.0262079 | pg | 4 |
| 40459.296 | -1139 | -0.0066781 | vis | 5 |
| *40800.528* | *-1068* | *-0.0057972* | | *6* |
| *40853.389* | *-1057* | *-0.0115903* | | *6* |
| *40853.406* | *-1057* | *0.0054097* | | *6* |
| *40853.419* | *-1057* | *0.0184097* | | *6* |
| 41545.480 | -913 | 0.0050273 | vis | 7 |
| 41569.543 | -908 | 0.0376668 | vis | 8 |
| 41598.346 | -902 | 0.0042342 | vis | 8 |
| 41891.476 | -841 | -0.0361639 | pg | 9 |
| 41934.775 | -832 | 0.0081872 | vis | 10 |
| 41997.280 | -819 | 0.0342499 | vis | 11 |
| 42266.411 | -763 | 0.0252123 | vis | 12 |
| 42309.653 | -754 | 0.0125634 | vis | 13 |
| 42602.816 | -693 | 0.0051653 | vis | 13 |
| 42626.851 | -688 | 0.0098048 | vis | 13 |
| 42631.645 | -687 | -0.0022673 | vis | 13 |
| 42679.723 | -677 | 0.0150117 | vis | 13 |
| 42713.358 | -670 | 0.0075070 | vis | 14 |
| 43059.396 | -598 | 0.0083158 | vis | 15 |
| 43059.401 | -598 | 0.0133158 | vis | 15 |
| 43304.511 | -547 | 0.0136387 | vis | 16 |
| 43347.796 | -538 | 0.0439898 | vis | 17 |
| 43458.321 | -515 | 0.0293315 | vis | 18 |
| 43693.812 | -466 | 0.0227986 | vis | 17 |
| 44092.700 | -383 | 0.0068143 | vis | 17 |
| 44395.499 | -320 | 0.0232720 | vis | 18 |
| 44438.7465 | -311 | 0.0161231 | phe | 19 |
| 44462.763 | -306 | 0.0022626 | vis : | 17 |
| 44462.7765 | -306 | 0.0157626 | phe | 20 |
| 44472.384 | -304 | 0.0111184 | vis | 21 |
| 44486.803 | -301 | 0.0119021 | vis | 17 |
| 44496.423 | -299 | 0.0197579 | vis | 22 |
| 44496.424 | -299 | 0.0207579 | vis | 23 |
| 44784.801 | -239 | 0.0334319 | vis | 17 |
| 44823.229 | -231 | 0.0128551 | vis | 17 |
| 44823.234 | -231 | 0.0178551 | vis | 17 |
| 44842.456 | -227 | 0.0155667 | vis | 24 |
| 44895.330 | -216 | 0.0227736 | vis | 25 |
| 45164.478 | -160 | 0.0307360 | vis | 26 |
| 45207.717 | -151 | 0.0150871 | vis | 17 |
| 45241.366 | -144 | 0.0215824 | vis | 27 |
| 45544.146 | -81 | 0.0190401 | phe | 28 |
| 45553.762 | -79 | 0.0228959 | vis | 17 |
| 45611.433 | -67 | 0.0210307 | vis | 29 |
| 45611.443 | -67 | 0.0310307 | vis | 29 |
| 45933.432 | 0 | 0.0132000 | vis | 30 |
| 45933.434 | 0 | 0.0152000 | vis | 31 |
| 46000.719 | 14 | 0.0151906 | vis | 17 |
| 46029.561 | 20 | 0.0207580 | vis | 17 |
| 46029.564 | 20 | 0.0237580 | vis | 17 |
| 46221.804 | 60 | 0.0208740 | vis | 17 |
| 46332.341 | 83 | 0.0182157 | vis | 32 |
| 46332.355 | 83 | 0.0322157 | vis | 32 |
| 46356.371 | 88 | 0.0178552 | vis | 33 |
| 46707.220 | 161 | 0.0235919 | vis | 34 |

Continue Table 2.

| HJD. (+2400000) | E | $(O-C)$ | Type | Ref. |
|---|---|---|---|---|
| 47024.425 | 227 | 0.0278333 | vis | 35 |
| 47375.288 | 300 | 0.0475700 | vis : | 17 |
| 47466.575 | 319 | 0.0192001 | vis : | 17 |
| 47466.590 | 319 | 0.0342001 | vis | 17 |
| 47471.377 | 320 | 0.0151280 | vis | 36 |
| 47740.517 | 376 | 0.0150904 | vis | 37 |
| 47769.366 | 382 | 0.0276578 | vis | 37 |
| 47836.653 | 396 | 0.0296484 | vis | 17 |
| 47846.273 | 398 | 0.0375042 | vis | 38 |
| 48115.400 | 454 | 0.0244666 | vis | 39 |
| 48158.666 | 463 | 0.0358177 | vis | 17 |
| 48163.455 | 464 | 0.0187456 | vis | 39 |
| 48480.674 | 530 | 0.0369870 | vis | 17 |
| 48480.677 | 530 | 0.0399870 | vis | 17 |
| 48509.494 | 536 | 0.0205544 | vis | 40 |
| 48860.355 | 609 | 0.0382911 | vis | 41 |
| 48874.781 | 612 | 0.0460748 | vis | 17 |
| 49076.613 | 654 | 0.0230466 | vis | 42 |
| 49177.539 | 675 | 0.0215325 | vis | 43 |
| 49206.412 | 681 | 0.0580999 | vis | 44 |
| 49600.479 | 763 | 0.0271877 | vis | 45 |
| 49653.354 | 774 | 0.0353946 | vis | 46 |
| 49898.477 | 825 | 0.0487175 | vis | 47 |
| 49922.518 | 830 | 0.0593570 | vis | 47 |
| 49999.398 | 846 | 0.0422034 | vis | 47 |
| **50004.283** | 847 | 0.1211313 | vis : | 48 |
| 50244.504 | 897 | 0.0385263 | vis | 49 |
| 51037.506 | 1062 | 0.0386298 | vis | 45 |
| 51436.430 | 1145 | 0.0586455 | vis | 51 |
| 51758.460 | 1212 | 0.0818148 | vis | 52 |
| 51811.334 | 1223 | 0.0890217 | vis | 53 |
| 52873.486 | 1444 | 0.0990876 | vis | 54 |
| 53517.504 | 1578 | 0.1034262 | vis : | 55 |
| 53555.9487 | 1586 | 0.0995494 | CCD | 56 |

References: (1) Plavec (1959), (2) IBVS 35, (3) IBVS 180, (1967), (4) IBVS 775, (1973), (5) IBVS 795, (1973), (6) (CEBMD) (7) IBVS 779, (1973), (8) BBSAG Bull. 5, (9) AC 1162, (10) JAAVSO 5, 86, (11) BBSAG Bull. 13, (12) BBSAG Bull. 17, (13) JAAVSO 6, 1, 28, (14) AN (1980) 301,6,327, (15) BBSAG Bull. 30, (16) BBSAG Bull. 33, (17) AAVSO 3, (18) BBSAG Bull. 35, (19) BBSAG Bull. 48, (20) IBVS 1938.(1981), (21) BBSAG Bull. 49, (22) BBSAG Bull. 50, (23) BBSAG Bull. 51, (24) BBSAG Bull. 56, (25) BBSAG Bull. 57, (26) BRNO 26, (27) BBSAG Bull. 62, (28) IBVS 5675.(2006), (29) BBSAG Bull. 69, (30) BBSAG Bull. 73, (31) BAAVSS 61,14, (32) BBSAG Bull. 78, (33) BBSAG Bull. 79, (34) BBSAG Bull. 82, (35) BBSAG Bull. 85, (36) BBSAG Bull. 90, (37) BBSAG Bull.92, (38) BBSAG Bull. 93, (39) BBSAG Bull. 96, (40) BBSAG Bull. 99, (41) BBSAG Bull. 102, (42) BBSAG Bull. 103, (43) BBSAG Bull. 104, (44) BBSAG Bull. 105, (45) BBSAG Bull. 107, (46) BBSAG Bull. 108, (47) BBSAG Bull. 110, (48) BBSAG 119, (49) BBSAG Bull. 112, (50) (51) BBSAG Bull. 121, (52) BBSAG Bull. 123, (53) BBSAG Bull. 124, (54) BBSAG Bull. 130, (55) Not accepted by IBVS as part of BBSAG bulletin, (56) IBVS 5636.

### i) THE HYPOTHESIS OF APSIDAL MOTION

As it is known, the effect of the apsidal motion may be detected in binary systems with eccentric orbits. Having in view Struve's spectroscopic observations, Batten et al. (1989) have assumed for W Del an orbital eccentricity of $e = 0.2$. In Svechnikov's Catalogue (Svechnikov 1986), however it is mentioned that the corresponding spectroscopic observations have given too large value for orbital eccentricities. In his discussion, Plavec (1960) has postulated an eccentricity of 0.036. The accuracy of spectroscopic eccentricities is far inferior compared to photometric ones, where for the more close binaries spectroscopic accuracy tends to be only about ±0.04 (Hanna et al. 1998). However, Algol's orbit is believed to be circular (Söderhjelm 1980). There is no known Algol (semidetached system) with non-circular orbit. Non-zero eccentricities are reported for the semidetached systems RY Gem and $\delta$ *Lib* in the list of well-studied binaries compiled by Harmanec (1988). In both cases, there are no photometric indications of eccentricity. As has been mentioned by Mayer and Hanna (1991) that most probably, circumstellar matter is responsible for the spectroscopic indication of the eccentricity in RY Gem (Plavec and Dobias 1987). Even not considering this effect, Lucy and Sweeney (1971) have preferred the circular orbit for W Del that agree with Walter's (1970) light curve which shows secondary minimum exactly at phase 0.5.

On the other hand, Cisneros-Parra (1970) has calculated theoretically the apsidal motion coefficients for homogeneous main sequence model, both those in the middle of their main sequence phase and those in different stages of mass exchange in several close binary systems. He has concluded that the mass loss from a subgaint component can decrease the apsidal motion coefficient $k_2$ by a factor of 100, i.e., even below the values observed in semi-detached binary systems. Cisneros-Parra has concluded from his theoretical results that it is possible to understand the small observed $k_2$-values by means of a mass exchange mechanism.

In addition, Zahn (1977) has concluded that observational and theoretical studies strongly suggest that turbulent friction in convective stellar envelopes leads to rapid circularization of close binary orbits.

Very recently, for spectroscopic and visual binaries with known orbital elements and having B0-F0 IV or V primaries, Abt (2005) has concluded that those binaries with period of a few days have been circularized.

Consequently, it is not recommended to argue the periodic behaviour of the $(O-C)$ diagram to be due to the rotation of the apsidal line of the sd-Algol eclipsing binary system W Del.

### ii) THE HYPOTHESIS OF A THIRD BODY IN THE SYSTEM

Any mean light elements derived by the linear best fit for all the residual points are not suitable to estimate the minima times in future. So, for the study of period changes a standard approach has been used. It is assumed that the times of minima follow a quadratic ephemeris and are modulated by the LITE. The times of minima can be computed as follows:

$$\begin{aligned} Min\,I &= JD_0 + P \times E + Q \times E^2 \\ &+ \frac{a_{12}\sin i}{c}\left[\frac{1-e^2}{1+e\cos\nu}\times \right. \\ &\left. \sin(\nu+\omega) + e\sin\omega\right] \end{aligned} \quad (2)$$

where $a_{12}\sin i$ is the projected semi-major axis, $e$ is the eccentricity, $\omega$ is the longitude of the periastron passage, $\nu$ is the true anomaly of the binary orbit around the center of mass of the triple system. $JD_0 + P \times E + Q \times E^2$ is the quadratic ephemeris of the minima in an eclipsing binary and c is the velocity of light.

To obtain an optimal fit and corresponding elements of the light time effect orbit including errors, the damped differential correction method has been used for all the data. Only the minimum JD 2450004.283 (written in bold font in Table 2 with a square symbol in Figure 1) has been excluded due to its deviation from the general trend in the $(O-C)$ diagram. The resulting ephemerides of the binary and the elements of the elliptical orbit of the eclipsing pair around the center of mass of the triple system are given in Table 3. Corresponding fit is depicted in Fig. 1.

As it can be seen from the $(O-C)$ diagram shown in Fig. 1, the orbital period of W Del is changing as follows: There is a long-term period increase caused by the mass transfer between the components modulated by a periodic LITE term due to the existence of a proposed third body on a 53.4-year orbit.

To estimate the mass of the third body, the following well known equation, have been used;

$$\begin{aligned} F(M_3) &= \frac{(a_{12}\sin i)^3}{P_2^2} = \frac{1}{P_2^2}\times\left[\frac{173.15A}{\sqrt{1-e^2\cos^2\omega}}\right]^3 \\ &= \frac{(M_3\sin i)^3}{(M_1+M_2+M_3)^2} = 0.23017\ \mathrm{M}_\odot, \end{aligned} \quad (3)$$

where $P_2$ is the period of the third-body orbit and $M_i$ the masses of the components. Values of $a_{12}$ are in AU, $P_2$ in years and $A$ is the observed semi-amplitude in days.

Adopting for $M_1$ and $M_2$ the values 2.1 $\mathrm{M}_\odot$ and 0.44 $\mathrm{M}_\odot$, respectively (according to Kopal and Shapley, 1956), $M_3(i)$ can be plotted in a figure in the inclination range 20° to 90°. Among these values one can consider the value of inclination $i = 84°$ published by Walter

TABLE 3.
THE LIGHT-TIME EFFECT SOLUTION AND
CORRESPONDING QUADRATIC EPHEMERIS OF THE BINARY SYSTEM W DEL.

| Elements | Value |
|---|---|
| $P_3$ [days] | $19506 \pm 386$ |
| $e_3$ | $0.77 \pm 0.076$ |
| $\omega_3$ [rad] | $0.616 \pm 0.127$ |
| $T_0$ [JD] | $2455940 \pm 875$ |
| $a_{12} \sin i$ [AU] | $8.69 \pm 0.93$ |
| $f(m_3)$ | $0.23017 \pm 0.07408$ |
| $JD_0[JD]$ | $2445933.46125 \pm 0.00302$ |
| $P_{binary}[days]$ | $4.80612024 \pm 0.00000159$ |
| $Q$ [days] | $8.41 \pm 0.26\ 10^{-9}$ |
| $\sum(O-C)^2[days^2]$ | 0.04343 |
| Times of minima in the large orbit (the binary and 3rd body in conjunctions) | |
| $T_{sec}$ | $56213.63 \pm 887.26$ |
| $T_{prim}$ | $54442.56 \pm 1119.64$ |

(1970), and confirmed by Mezzetti et al. (1980), corresponding to the hypothesis that the third body is revolving in the same plane of the two close components. On this assumption a considerable third body of mass $M_3 = 1.58$ M$_\odot$ has been obtained. Having in view the fact that the mass of the postulated third body is large, the third body has been detected by photometric observation. On other words, in case the primary masses $M_1$ and $M_2$ are as given by Kopal and Shapley (1956), then the third body -if close to main sequence- will have luminosity about one third of the primary. However, during the primary minima, the brightness of the system is less than one tenth of maximum brightness, i.e. the third body cannot be a normal star; and it cannot be a white dwarf, since then its mass can not be more than 1.44 M$_\odot$. In such a case the hypothesis of a third body can be put in discussion and new problems can be studied in the connection with the structure of the triple stellar system.

This result has been confirmed by Lanza and *Rodonò* (1999). They have reported that, in Algols and RS CVn binaries, the mass derived for the third body is usually $1-5$ M$_\odot$ and therefore, it is very difficult to explain (the case of W Del) how it has systematically escaped detection.

Borkovits and Hegedüs (1996) have suggested two bodies orbiting the binary W Del system and they have calculated the orbital elements of both the third and fourth components and have obtained a quite large minimal masses for different values of the inclination $i$. But, comparing their $(O-C)$ diagram for the data available in that time and the present $(O-C)$ diagram including the newer data, one can not be able to decide if the system is quadruple or not.

## (b) CYCLIC MAGNETIC ACTIVITY VARIATION

As it has been seen above, apsidal motion is not an acceptable explanation for such period changes for Algols because circular orbits are expected in the systems where the two components are close enough for tidal interactions and/or mass transfer to rapidly damp out any eccentricity. Also, as it is discussed above, explaining the orbital period modulation to be due to LITE of a third and/or a fourth body is not preferable and still questionable.

Lanza and *Rodonò* (1999) have pointed the difficulties confronting the assumption of the presence of a third body because the light-time effect implies a strictly periodic variation, of the (O-C) residuals, which is not observed when data covering several cycles of the modulation are available. They have mentioned case examples of RW Tri, Algol as well as some other Algols and RS CVn systems (cf., Lanza and *Rodonò* 1999).

Accordingly, since the minima timings for the Algol binary W Del are spread over an almost 109 years which covers, in principal, two cycles of the present proposed 54.3 year cycle and the periodicity is explicitly absent (see Fig. 1), one should strongly turn to look for another mechanism and test the luminosity variation due to the magnetic activity of the secondary convective envelop star.

In order to explain the cyclic, but not strictly periodic, modulation of the O-C variation, several physical mechanisms have been proposed and have been suggested by many scientists (e.g., Matese & Whitmire 1983; Applegate & Patterson 1987; Warner 1988, Applegate 1992 and Lanza et al., 1998). In the following, we are going to apply the Applegate (1992) mechanism to the Algole binary W Del.

Applegate (1992) has proposed a model which explains the period changes of 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 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 duration may be present (Baliunas& Vaughan 1985 and Applegate 1992). Applegate's (1992) mechanism requires that the active star to be variable, and the period of the luminosity variation to be the same as the period of the orbital period modulation.

Since the secondary active components in the Algol-type systems are generally much fainter than the primaries, a reasonable way is a comparison of the O-C curve with the brightness variations of the center of the total primary eclipse.

Only three magnitude determinations of W Del have been given in the literature. The first has been obtained, for observations between 1895 to 1902, by Pickering (1896) and recalculated by Russell (1912), with secondary component magnitude in the visual band $m_{v\,sec.} = 12^m.10$ and variation range $\Delta\, m_v = 2^m.70$. The second has been photoelectrically observed in the year 1964 (Walter 1970) with secondary component magnitude $m_{v\,sec.} = 12^m.19$ and variation $\Delta\, m_v = 2^m.60$. The third has been given in the general catalogue of variable stars (Kholopov et al. 1985) with secondary component magnitude $m_{v\,sec.} = 12^m.33$ and variation $\Delta\, m_v = 2^m.64$ corresponding to a HJD=2443328.5495. However the minimum brightness variation (at $E \simeq -6000$) has been occurred at maximum O-C and the second and third magnitude variations (at $E = -1500$ and E=-542, respectively) have also occurred with a corresponding O-C value (see Fig. 1). The behaviour of these three points data are strongly in an excellent agreement with Applegate's mechanism.

Unfortunately, the available magnitude determination data are not sufficient to deduce the magnetic activity cycle and it is relatively not possible to say now whether the magnetic activity of the secondary convective envelop star varies in accordance with the course of period changes because long and dense series of photoelectric data are needed. In the following we can follow the procedure performed by Applegate (1992) (his Sects. 2.4 and 3) to examine if the observed changes in W Del could be explained by the magnetic activity or not.

Assuming the period $P_3 = 53.4$ yr to be the modulation period $P_{mod}$ of the stellar magnetic activity of the convective secondary star, with a semi-amplitude O-C=0.078 days, accepting the parameters given by Mezzetti et al. (1980) [$M_2 = 0.60$ M$_\odot$ and $R_2 = 4.62$ R$_\odot$] and the orbital semi-major axis $a = 18.7$ R$_\odot$ (Lanza and Rodonò, 1999) one can follow the procedure performed by Applegate (1992).

The observed amplitude of the period modulation $\Delta\, P/P = 2\pi(O-C)/P_{mod} = 3 \times 10^{-5}$ gives the variation of the orbital period $\Delta P = 11$ second. The angular momentum transfer is $\Delta\, J = 2.56 \times 10^{48}\ g\,cm^2\ s^{-1}$. If the mass of the shell is $M_{shell} = 0.1\ M_2$, the moment of inertia of the shell is $I_{shell} = 8.2 \times 10^{54}\ g\,cm^2$, and the variable part of the differential rotation of the active star is $\Delta\,\Omega/\Omega = 0.013$. The energy budget needed to transfer the $\Delta\, J$ is $\Delta\, E = 1.6 \times 10^{42}\ ergs$. The luminosity change is $\Delta L_{RMS} = 3 \times 10^{33}\ erg\,s^{-1}$, where the angular velocity of differential rotation $\Omega_{dr} = \Delta\,\Omega = 0.013\,\Omega$ has been assumed. This luminosity variation is $\Delta L_{RMS}/L = 0.7 \simeq 10\%$ of the luminosity of the active star. In addition, the mean subsurface field of 3 kG can be deduced. These quantities are consistent and very similar to those derived by Applegate (1992) model for similar Algol systems.

## IV. RATE OF MASS TRANSFER

As the quadratic term given by Table 3, the system has a secular period increase with a rate of $1.68 \times 10^{-8}$ day/cycle or $1.278 \times 10^{-6}$ day/year. Referring to the works of Kuiper (1941), Kruszewski (1966), Plavec (1968), Rucinski (1974), and many other papers, the rate of mass transfer can be estimated using the formula

$$\frac{1}{M}\frac{dM}{dt} = \frac{q}{3\,P\,(q^2-1)}\frac{dP}{dt}, \tag{4}$$

where $M = M_1 + M_2$ is the total mass of the binary in M$_\odot$, and $q$ is $M_2/M_1$, so that $dM/dt$ will always be positive. The index 2 belongs to the component star gaining mass (see Batten 1973). Thus, if $dP/dt < 0$ then $M_2 < M_1$, and if $dP/dt > 0$ then $M_2 > M_1$. For the applicability of the above mentioned expression, it may be supposed that no mass is lost from the system and there is no exchange between the orbital angular momentum and rotational ones.

Now, accepting the above-mentioned simplifications, we can estimate the possible mass-transfer rate from the smaller component to the larger one. Using the mass ratio $q = 0.21$, one can obtain a mass-exchange rate for this binary by the above equation as: $dM/dt = 6.3 \times 10^{-10}$ M$_\odot$ cycle$^{-1}$ or $4.9 \times 10^{-8}$ M$_\odot$ yr$^{-1}$ mass transfer from the less massive component to the more massive one. Thus there is a slow decrease of the mass ratio of W Del.

## V. CONCLUSION

W Del, similar to several other close binaries, displays an alternating pattern in its times for primary eclipse. If the current observed sinusoidal function $(O-C) = f(E)$ turns out to be periodic, the following two hypotheses have to be taken into consideration:

a) The hypothesis of the apsidal motion, which is valid when the corresponding relative orbit is eccentric. The sd binary system W Del has a circular orbit as it has been investigated in section III a(i). Accordingly, this hypothesis has been given up.
b) The hypothesis of a third body has been studied modulated by a long-term orbital period increase with rate of $1.68 \times 10^{-8}$ day/cycle caused by a mass transfer rate of $4.9 \times 10^{-8}$ $M_{\odot} yr^{-1}$ from the secondary to the primary component. This modulation leads to a third body mass equals to 1.58 $M_{\odot}$, which however cannot be a normal star since it has an escaped detection, and it can not be a white dwarf too.

Also, Borkovits and *Hegedüs* (1996) suggested four body system and they did not reach to a satisfactory solution.

The periodic variation of the $O - C$ residuals for the sd Algol binary system W Del seems to be problematic. Such changes may be argued to be as a result of the magnetic activity cycling which affects the surface brightness of the active late type evolved secondary component. Such magnetic activity cycles which are similar to those of the sun are not necessarily to be strictly periodic. Applegate's (1992) mechanisms can be considered as a strong possible explanation for this O-C variation for the following two reasons:
1) Generally, If the third body possesses an orbit with nonzero eccentricity, the waveform contains both fundamental and first harmonic terms. And if the third body period is of 53.4 yr (from $E \simeq -6000$ *to* $-2000$) forms the fundamental cycle we search for its first harmonic at twice the frequency of the fundamental. Looking for Fig. 1, the expected first harmonic term dose not behave as the fundamental. In other words, the residuals do not appear to be strictly periodic and it may be concluded that the third-body hypothesis fails to explain the observed O-C curve for W Del.
2) When applying Applegate's (1992) mechanism a good consistency, as explained above, has been found between the behaviour of the O-C variation of W Del and the idea of the magnetic activity cycles of the secondary active G5 component of W Del, and therefore the model fits the data well.

Future high detector photometric, spectroscopic and CCD observations of minima times and magnitude determinations of W Del are required to put a complete scenario for the cause of the orbital period variability in the well known algol type eclipsing binary sd system W Del.

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## REFERENCES

Abt, H. A., 2005, Observed Orbital Eccentricities, ApJ, 629, 507-511.

Agerer, F. & Todoran, I., 1992, W Delphini - Request for New Observations, IBVS, 3731.

Applegate, J. H. & Patterson, J., 1987, Magnetic activity, tides, and orbital period changes in close binaries, ApJ, 322, L99.

Applegate , J. H., 1992, A mechanism for orbital period modulation in close binaries, ApJ, 385, 621

Baliunas, S. L., & Vaughan, A. H., 1985, Stellar activity cycles, ARA&A, 23, 379.

Batten, A. H., 1973, Binary and multiple systems of stars *(New York, Pergamon)*, p.97.

Batten, A. H., Fletcher, J. M., MacCarthy, D. G., 1989, Catalogue of the orbital elements of spectroscopic binary systems : 8 : 1989, DAO, 17.

Borkovits, T. & Hegedüs, T., 1996, On the invisible components of some eclipsing binaries, A&AS, 120, 63-75.

Cisneros-Parra, J. U., 1970, Apsidal motion in close binaries with and without mass exchange, A&A, 8, 141-147.

Graff, K., 1930a, Atti Pont. Acc, Nuovi Lincei, 83, 104.

Graff, K., 1930b, B.Z., 12, 62.

Hanna, M. A., Mayer, P. & Hanna, Y., 1998, Circularization of Binary Orbits, Ap&SS, 262, 171-176.

Harmanec, P., 1988, Stellar masses and radii based on modern binary data, BAC, 39, 329.

Hegedüs, T., 1988, An Updated List of Eclipsing Binaries Showing Apsidal Motion, BICDS 35, 15.

Hill, G., Hilditch, R. W., Younger, F. & Fisher, W. A., 1975, MK classifications of some Northern Hemisphere binary systems, Mem. R. Astron. Soc. 79, 101.

Horrocks, H. A., 1941, Variations in the periods of certain eclipsing binaries , MNRAS, 101, 237.

Kholopov, P. N., et al., 1985, GCVS, V. I., Moscow: "Nauka".

Kopal, Z. & Shapley, M. B., 1956, Jodrell Bank Annals, 1, 141.

Kreiner, J. M., Kim, Chung-Hwey, Nha, & Il-Seong, 2001, An Atlas of O-C Diagrams of Eclipsing Binary Stars, Wydawnictvo Naukove AP, Krakow.

Kippenhahn, R. & Weigert, A., 1967, Entwicklung in engen Doppelsternsystemen I. Massenaustausch vor und nach Beendigung des zentralen Wasserstoff-Brennens, Z. Astrophys., 65, 251.

Kruszewski, A., 1966, An experimental four-colour photometry, Adv. Astron. Astrophys. 4, 233.

Kukarkin, B. V., et al., 1969, GCVS, Moscow: "Nauka".

Kukarkin, B. V., et al., 1974, GCVS, 2d supplement, Moscow: "Nauka".

Kuiper, G. P., 1941, On the Interpretation of beta Lyrae and Other Close Binaries, ApJ, 93, 133.

Lanza, A. F., *Rodonò*, M. and Rosner, R., 1998, Orbital period modulation and magnetic cycles in close binaries, MNRAS 296, 893.

Lanza, A. F.& *Rodonò*, 1999, Orbital period modulation and quadrupole moment changes in magnetically active close binaries , A&A 349, 887.

Lucy, L. B. & Sweeney, M. A., 1971, Spectroscopic binaries with circular orbits, AJ, 76, 544.

Mallama, A. D., 1980, New ephemerides for 120 eclipsing binary stars, ApJS, 44, 241-272.

Matese, J.J. & Whitmire, D. P., 1983, Alternate period changes in close binary systems, A&A, 117, L7.

Mayer, P. & Hanna M.A., 1991, Eclipsing binaries with eccentric orbits, BAC, 42, 98-108.

Mezzetti, M., Cester, B., Giuricin, G. & Mardirossian, F., 1980, Revised Photometric Elements of 9 Sd-Systems, A&AS, 39, 273.

Plavec, M., 1959, Period changes of the eclipsing binary W Delphini, BAC, 10, 185.

Plavec, M., 1960, Apsidal motion in systems with subgiant components, BAC, 11, 148.

Plavec, M., 1968, Evolution of Close Binaries of Shorter Period and Moderate Mass, Adv. Astron. Astrophys. 6, 202.

Plavec, M. J. & Dobias, J. J., 1987, The moderately interacting Algol binary RS Cephei, AJ, 93, 440.

Petrova, A. V. & Orlov, V. V., 1999, Apsidal Motion in Double Stars. I. Catalog, AJ, 117, 587-602.

Pikering, E. C., 1896, The Algol Variable B.D.+ 17 degrees 4367, ApJ, 3, 200.

Pikering, E. C., 1896, The algol variable +17 4367, W Delphini., ApJ, 4, 320.

Piotrowski, S., 1934a, AcA, 2, 61.

Piotrowski, S., 1934b, AcA, 2, 77.

Rucinski, S. M., 1974, Binaries. II. A- and W-type Systems. The W UMa-type Systems as Contact, AcA, 24, 119.

Russell, H. N, 1912, Elements of the eclipsing variables W Delphini, W Ursae Majoris, and W Crucis, ApJ, 36, 133.

Russell, H. N, Fowler, M. and Borton, M. C., 1917, Elements of the eclipsing variables W Delphini, W Ursae Majoris, and W Crucis, ApJ, 45, 306.

Söderhjelm S., 1980, Geometry and dynamics of the Algol system, A&A, 89, 100.

Struve, O., 1946, The Radial Velocity of 27 Canis Majoris, ApJ, 104, 253.

Svechnikov, M.A., 1986, Katalog Orbitalnikh Elementov.

Tsessewich, W.P., 1957, On the periods of twenty eclipsing variable stars, Peremennyje Zvezdy, 11, 403.

Walter, K., 1970, Lichtkurve und Dimensionsbestimmung des Bedeckungssystems W Delphini, Astron. Nachr. Bd., 292, 4.

Warner, B. W., 1988, Quasiperiodicity in cataclysmic variable stars caused by solar-type magnetic cycles, Nat 336, 129.

Wood, B. D. & Forbes, J. E., 1963, Ephemerides of eclipsing stars, AJ, 68, 257.

Zahn, J., 1977, Tidal friction in close binary stars, A&A, 57, 383.