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S EQUULEI: A LOW MASS RATIO ALGOL-TYPE ECLIPSING BINARY AT THE ACTIVE PHASE OF MASS TRANSFER

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ABSTRACT

Orbital period change of a low mass ratio ($q = 0.13$) Algol-type eclipsing binary, S Equulei, is presented based on the analysis of its century-long times of light minimum. Alternate period changes are discovered to superimpose on a rather rapid period increase with rate of $dP/dt = +1.27 \times 10^{-6}$ days yr^{-1}. The alternate period changes can be explained either by the variation in the gravitational quadruple momentum via the cyclic magnetic activity of the G-type secondary or by the light-time effect via the presence of a third body. Since the third-body assumption is in good agreement with Zola's photometric solution, S Equ may be a truly triple system. The third body is rotating in an eccentric orbit ($e' = 0.37$) with an orbital inclination of $i' = 16°$, which is rather smaller than that of the eclipsing binary system ($i = 88\overset{\circ}{.}3$). This indicates that the third body may be captured by the eclipsing pair. New accurate photometric and spectroscopic data over the next decade are very important to verify this conclusion. The rapid period increase suggests that S Equ is a low mass ratio Algol-type binary system in an active phase of mass exchange. To satisfy such a period increase, a conservative mass transfer from the less massive to the more massive components would be of the order $dm/dt = 4.94 \times 10^{-8}\ M_\odot$ yr^{-1}.

Subject headings: binaries: close — binaries: eclipsing — stars: evolution — stars: individual (S Equulei) — stars: variables: other

1. INTRODUCTION

S Equ (BD 4°4584=HD 199454) was discovered to be a variable by Mackie in 1916 on Harvard patrol plates. Subsequently, the Algol-type light variation of the binary star was found by O'Reilly (Plavec 1966). Photoelectric observations of the eclipsing binary were obtained by Plavec (1966), Catalano & Rodono (1968), and more recently by Zola (1992). A detailed analysis of the spectroscopic data of S Equ observed at Victoria Observatory was carried out by Plavec (1966), who classified the two components as B9.5+F7 IV and later as B7 V+G8 III (Plavec 1983). Combining the spectroscopic elements with the photometric solutions he obtained the absolute parameters of the system. His investigation showed that S Equ is an Algol-type eclipsing binary system with an extremely low mass ratio ($q \sim 0.11$–0.15). The photoelectric light curve published by Catalano & Rodono (1968) was analyzed by Piotrowski et al. (1974) and by Cester et al. (1979), and absolute dimensions were also determined. By the analysis of his photoelectric light curves in *U*, *B*, and *V* with the Wilson-Devinney method, a significant third light in the system was found by Zola (1992). The extremely low mass ratio and the presence of a third body in the system both made S Equ a very interesting system to study.

2. $O - C$ CURVE FOR S EQUULEI

S Equ is a relatively bright Algol-type variable (8.2 mag) with a rather deep primary minimum (about 2 mag), which made it a suitable object for times of light minimum even with visual or photographic methods. After its discovery, many times of light minimum were published. The period variation of the binary star was first noticed by Cesevic (1958), who suggested that the change may have occurred suddenly sometime in the early thirties. Plavec (1966) collected all timings published before 1966 and presented an $O - C$ diagram. It was showed that the period was variable but properties of the period change were not clear. After Plavec's study, 36 yr have elapsed. Many times of light minimum have been compiled at the Eclipsing Binaries Minima Database (EBMD),[3] and recently one timing observed by Kohl and two times of light minimum observed by Meyer and by Lange have been published in BBSAG No. 122 and in BAV Mitteilungen No. 143. A detailed period investigation of the systems is absolutely required.

All available times of light minimum are shown in Table 1. Those listed in the second and the seventh columns of the table are the observed methods where "vp" refers to visual or photographic observations, "pe" to photoelectric, and "CCD" to charge-coupling device data. The $(O - C)_1$ values of these timings based on the following linear ephemeris (Plavec 1964),

$$\text{Min. I} = \text{HJD } 2,437,968.345 + 3.4360726 \times E\ , \quad (1)$$

are computed and are listed in Table 1. The first time of light minimum, HJD 2,410,002.337, published by Cannon (1916), is not listed in the table and not used for this present period study, since the time intervals between the minimum and the others are very large and its accuracy is uncertain (Plavec 1966). During the computation, some eclipse times with the same epoch have been averaged. Three times of minimum light, HJD 2,442,138.420, 2,442,524.552, and 2,447,053.368, are discarded since their $(O - C)_1$ values show large deviations compared with the general trend

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[3] Available at http://www.oa.uj.edu.pl/ktt/krttk_dn.html.

TABLE 1

$O-C$ DATA FOR S EQUULEI

HJD +2400000	Meth.	E	$(O-C)_1$ (days)	$(O-C)_2$ (days)
23334.165	vp	−4259	+0.053	+0.003
23990.446	vp	−4068	+0.044	+0.001
24100.403	vp	−4036	+0.047	+0.005
24282.514	vp	−3983	+0.046	+0.006
24385.583	vp	−3953	+0.033	−0.006
24430.260	vp	−3940	+0.041	+0.003
24746.362	vp	−3848	+0.024	−0.011
25093.402	vp	−3747	+0.021	−0.011
25474.800	vp	−3636	+0.015	−0.013
25708.459	vp	−3568	+0.021	−0.005
25866.512	vp	−3522	+0.015	−0.010
26581.208	vp	−3514	+0.008	−0.016
27409.307	vp	−3073	+0.013	+0.001
27670.440	vp	−2997	+0.005	−0.005
27756.331	vp	−2972	−0.006	−0.016
27962.514	vp	−2912	+0.012	+0.004
28072.449	vp	−2880	−0.007	−0.015
32807.360	vp	−1502	−0.004	+0.009
33178.465	vp	−1394	+0.005	+0.018
33539.241	vp	−1289	−0.006	+0.008
34226.447	vp	−1089	−0.015	−0.001
34604.432	vp	−979	+0.002	+0.016
36133.480	vp	−534	−0.002	+0.011
37188.3613	pe	−227	+0.004	+0.0148
37559.445	vp	−119	−0.007	+0.003
37559.456	vp	−119	+0.004	+0.014
37968.3438	pe	0	−0.001	+0.0075
38253.5397	pe	83	+0.001	+0.0085
38284.4641	pe	92	0.000	+0.0074
38315.377	vp	101	−0.011	−0.004
38315.3877	pe	101	−0.001	+0.0062
38607.4530	pe	186	−0.001	+0.0051
39009.476	vp	303	+0.001	+0.005
39394.304	vp	415	−0.011	−0.008
39710.428	vp	507	−0.006	−0.005
40088.401	vp	617	−0.001	−0.002
40150.249	vp	635	−0.002	−0.003
40806.538	vp	826	−0.003	−0.008
40844.333	vp	837	−0.005	−0.010
40930.239	vp	862	−0.001	−0.007
41222.3021	pe	947	−0.0037	−0.0116
41246.353	vp	954	−0.005	−0.013
41507.492	vp	1030	−0.008	−0.018
41569.344	vp	1048	−0.005	−0.015
41593.402	vp	1055	0.000	−0.010
41830.497	vp	1124	+0.006	−0.006
41916.404	vp	1149	+0.012	−0.001
42201.587	vp	1232	+0.001	−0.014
42318.418	vp	1266	+0.005	+0.009
42524.592	vp	1326	+0.015	−0.003
42672.334	vp	1369	+0.006	−0.013
42727.313	vp	1385	+0.007	−0.012
42957.522	vp	1452	0.000	−0.021
42988.463	vp	1461	+0.016	−0.005
43012.509	vp	1468	+0.009	−0.012
43043.441	vp	1477	+0.017	−0.005
43311.445	vp	1555	+0.007	−0.017
43483.253	vp	1605	+0.012	−0.014
43689.423	vp	1665	+0.017	−0.010
43713.484	vp	1672	+0.026	−0.002
43723.789	vp	1675	+0.022	−0.005
43830.307	vp	1706	+0.022	−0.007
44122.378	vp	1791	+0.027	−0.005
44146.418	vp	1798	+0.015	−0.017
44153.293	vp	1800	+0.017	−0.015
44208.281	vp	1816	+0.028	−0.004
44438.487	vp	1883	+0.017	−0.017
44448.805	vp	1886	+0.027	−0.008
44469.418	vp	1892	+0.024	−0.011
44472.853	vp	1893	+0.023	−0.012
44479.730	vp	1895	+0.027	−0.008
44524.393	vp	1908	+0.022	−0.014
44555.322	vp	1917	+0.026	−0.010
44586.248	vp	1926	+0.027	−0.009
44847.387	vp	2002	+0.025	−0.014
44878.313	vp	2011	+0.026	−0.013
44902.367	vp	2018	+0.028	−0.012
44933.293	vp	2027	+0.029	−0.011
45077.615	vp	2069	+0.036	−0.005
45163.512	vp	2094	+0.031	−0.011
45173.825	vp	2097	+0.036	−0.006
45541.496	vp	2204	+0.047	+0.001
45544.9246	pe	2205	+0.0395	−0.0067
45603.344	vp	2222	+0.046	−0.001
45905.726	vp	2310	+0.053	+0.003
45929.775	vp	2317	+0.050	−0.001
45960.699	vp	2326	+0.049	−0.002
46266.515	vp	2415	+0.055	0.000
46290.558	vp	2422	+0.045	−0.010
46321.487	vp	2431	+0.050	−0.006
46328.3635	pe	2433	+0.0539	−0.0013
46328.366	vp	2433	+0.056	+0.001
46352.415	vp	2440	+0.053	−0.003
46359.286	vp	2442	+0.052	−0.004
46644.490	vp	2525	+0.062	+0.003
47087.741	vp	2654	+0.059	−0.005
47431.359	vp	2754	+0.070	+0.001
47778.410	vp	2855	+0.078	+0.004
48094.538	vp	2947	+0.087	+0.009
48187.316	vp	2974	+0.091	+0.012
48448.460	vp	3050	+0.094	+0.011
48479.3804	pe	3059	+0.0893	+0.0063
48503.440	vp	3066	+0.096	+0.013
48922.639	vp	3188	+0.095	+0.005
49214.711	vp	3273	+0.100	+0.007
49228.457	vp	3277	+0.102	+0.008
49929.4221	pe	3481	+0.1084	+0.0040
50262.727	CCD	3578	+0.1142	+0.0045
50276.480	vp	3582	+0.123	+0.013
50341.764	vp	3601	+0.122	+0.011
50719.736	vp	3711	+0.126	+0.009
50726.605	vp	3713	+0.122	+0.005
51097.715	vp	3821	+0.137	+0.014
51434.452	vp	3919	+0.139	+0.010
51757.428	vp	4013	+0.124	−0.011
51812.409	vp	4029	+0.128	−0.008

formed by other data. The corresponding $(O-C)_1$ diagram is displayed in Figure 1, which indicates that the period change of S Equ is very complex. As shown in the figure, the general $(O-C)_1$ trend can be described by an upward parabolic curve, suggesting a secular period increase in the system. With weights 1 to the VP data and 8 to the photoelectric or CCD observations, a weighted least-squares solution leads to the following quadratic ephemeris

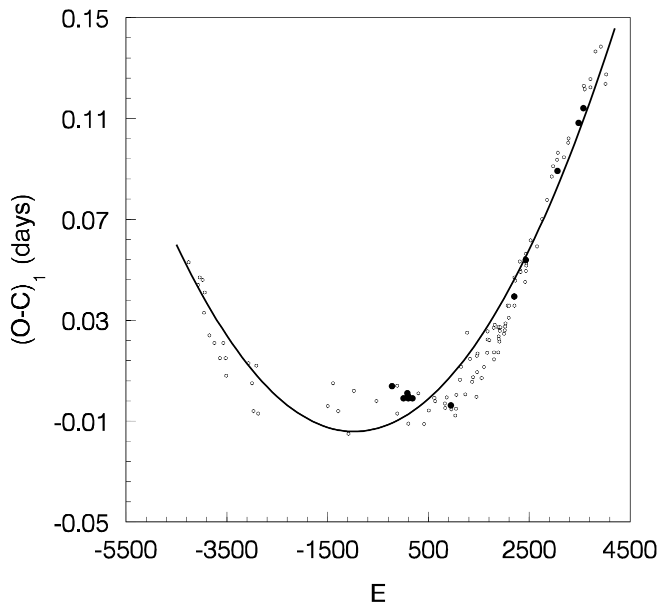

FIG. 1.—$(O - C)_1$ plot for S Equ with respect to the ephemeris of Plavec (eq. [1]). The solid line represents the best fit parabola to the data (eq. [2]). Solid dots refer to photoelectric or CCD and circles to visual or photographic data.

with the mean error for each term:

$$\text{Min. I} = \text{HJD } 2,437,968.3365(13) + 3.43608425(37) \times E + 5.97(17) \times 10^{-9} \times E^2 , \quad (2)$$

which can give a good fit to the general $(O - C)_1$ trend (Fig. 1, *solid line*).

3. DISCUSSION OF THE $O - C$ CURVE OF S EQUULEI

The long-term general trend in Figure 1 indicates an increasing period. With the quadratic term of equation (2), a period increase rate, $dP/dt = +1.27 \times 10^{-6}$ days yr^{-1}, is obtained. This trend can be interpreted as a mass transfer from the less massive to the more massive components. This is in agreement with the semidetached configuration of the binary system. Assuming that the period increase is due to a conservative mass transfer (with no magnetic effect), then putting $M_1 = 2.21\ M_\odot$ and $M_1 = 0.30\ M_\odot$ given by Zola (1992) to the following equation (Kwee & van Woerden 1958),

$$\Delta P/P = 3(M_1/M_2 - 1)\Delta M_1/M_1 , \quad (3)$$

a mass transfer rate is estimated to be $dm/dt = 4.94 \times 10^{-8}\ M_\odot\ \text{yr}^{-1}$.

A careful examination of the $(O - C)_1$ curve in Figure 1 shows that S Equ possesses an alternating period change superimposed on the secular increase. This behavior is more easily seen in Figure 2 where the residuals computed from the parabolic fit are displayed. The corresponding $(O - C)_2$ residuals from the quadratic ephemeris are also listed in Table 1. Since the $(O - C)_2$ residuals of two times of light minimum, given in BAV Mitteilungen No. 143, shows large scatters when compared with the general trend formed by other data, the two values are not displayed in Figure 2 and are not used for the following period analysis.

The $O - C$ residuals in Figure 2 may suggest a cyclic oscillation in the orbital period which may result from the orbital motion of the system around the center of mass of an assumed triple system. This model has been used to explain the cyclic period changes in Algols and other short-period binaries by Frieboes-Conde & Herczeg (1973), Chambliss (1992), and recently by Borkovits & Hegedüs (1996). The not strictly sinelike change of the $(O - C)_2$ curve indicates that the third body is moving in an elliptical orbit. However, the nearly sinusoidal shape of the $(O - C)_2$ curve indicates that the orbital eccentricity of the eclipsing pair around the common center of the gravity of the three bodies is very small. The following formula,

$$(O - C)_2 = a_0 + \sum_{i=1}^{2} [a_i \cos(i\omega E) + b_i \sin(i\omega E)] , \quad (4)$$

can be used to express those $(O - C)_2$ values where $a_{1,2}$ and $b_{1,2}$ are the Fourier coefficients and ω is the fundamental frequency. By various numerical trials with different value of ω, a best solution of equation (4) was determined: $a_0 = 0.0002(4)$, $a_1 = 0.0060(9)$, $b_1 = -0.0090(8)$, $a_2 = 0.0021(11)$, $b_2 = 0.0002(8)$. Putting the ephemeris period $P_e = 3.4360726$ to the formulae,

$$\omega = 360^\circ P_e/T , \quad (5)$$

the period of the eclipsing binary around the center of mass of the triple system was derived to be $T = 42.8$ yr.

The orbital parameters of the third body were derived from the formula given by Kopal (1959, p. 112),

$$a'_{12} \sin i' = c\sqrt{a_1^2 + b_1^2} , \quad (6)$$

$$e' = 2\sqrt{\frac{a_2^2 + b_2^2}{a_1^2 + b_1^2}} , \quad (7)$$

$$\omega' = \arctan\frac{(b_1^2 - a_1^2)b_2 + 2a_1a_2b_1}{(a_1^2 - b_1^2)a_2 + 2a_1b_1b_2} , \quad (8)$$

$$\tau' = t_0 - \frac{T}{2\pi}\arctan\frac{a_1b_2 - b_1a_2}{a_1a_2 + b_1b_2} , \quad (9)$$

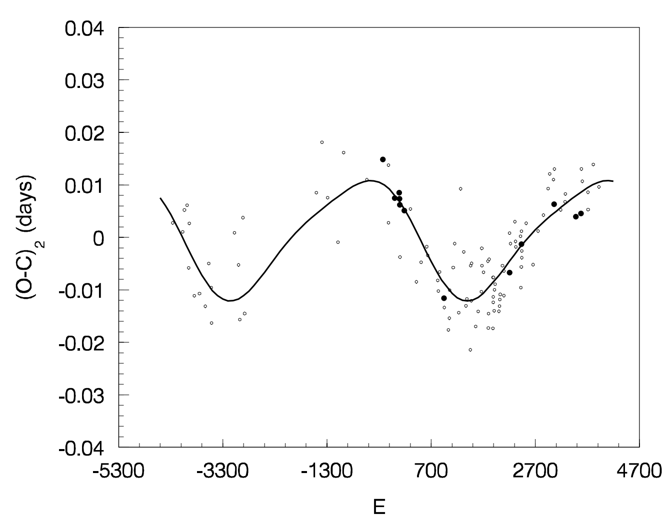

FIG. 2.—The $(O - C)_2$ residuals in days for S Equ after subtracting of the best-fit parabola given in eq. (2). Solid line represents the theoretical solution of an assumed third body.

where c is the speed of light, a'_{12} is the semimajor axis of the eclipsing binary around the common center of the gravity of the triple system, i', e', w', and τ' are the usual orbital parameters of the third body. The results are $a'_{12}\sin i' = 1.87(14)$ AU, $e' = 0.39(20)$, $w' = 62°(11)$ and $\tau' = 2440649^d(923)$. Then using the values of the semiamplitude of $a'_{12}\sin i' = 1.87$ AU and the period of $T = 42.8$ yr together with the following equation,

$$f(m) = \frac{(M_3 \sin i')^3}{(M_1 + M_2 + M_3)^2} = \frac{4\pi^2}{GT^2} \times (a'_{12}\sin i')^3 , \qquad (10)$$

the mass function for the additional body is determined to be $f(m) = 3.59(\pm 0.83) \times 10^{-3}$ $M_\odot$. With the masses $M_1 = 2.21$ $M_\odot$ and $M_2 = 0.30$ $M_\odot$ given by Zola (1992), the values of the masses and the orbital radii of the third body for different orbital inclinations (i') are calculated and are listed in Table 2. If the third body is coplanar to the orbit of the eclipsing pair (i.e., $i' = 88.^\circ3$), the mass and the orbital radius would be $m_3 = 0.31(\pm 0.03)$ and $a_3 = 15.4(\pm 1.7)$ AU, respectively. However, the $(O-C)_2$ values in Figure 2, especially those of VP data, show large scatters (up to $0.^d010$), the properties of the period changes are not clear at present. In order to check whether the $O-C$ variation is strictly periodic or not, more times of light minimum are required.

Apart from the presence of the additional body, the oscillation of the orbital period of a close binary containing at least one late-type star is usually explained as a consequence of possible magnetic cycle in the active component. In an important study of Hall (1989) comparing RS CVn to Algol binaries, he found a correlation between the alternating period change and the spectral type of the secondary, which has recently reproduced by Zavala et al. (2002). When the spectral type of the secondary is earlier than F5, alternating period change is never been found. Hall explained this finding as strong evidence of magnetic activity cycle in the secondary. This theory was first suggested by Matese & Whitmire (1983) and developed by Applegate & Patterson (1987) and Warner (1988), who attempted to interpret the $O-C$ patterns by assuming deformations of the star away from hydrostatic equilibrium via magnetic pressure or tidal.

TABLE 2
The Values of the Masses and the Orbital Radii for the Third Body in S Equulei

Parameters	Values	Units
$\sqrt{a_1^2 + b_1^2}$	0.0108 (±0.0008)	days
T	42.8 (assumed)	yr
e'	0.39 (±0.20)	No.
$a'_{12}\sin i'$	1.87 (±0.14)	A.U.
$f(m)$	3.59 (±0.83) × 10^{-3}	$M_\odot$
$m_3(i' = 90°)$	0.31 (±0.02)	$M_\odot$
$m_3(i' = 70°)$	0.33 (±0.03)	$M_\odot$
$m_3(i' = 50°)$	0.41 (±0.03)	$M_\odot$
$m_3(i' = 30°)$	0.66 (±0.06)	$M_\odot$
$m_3(i' = 10°)$	2.62 (±0.31)	$M_\odot$
$a_3(i' = 90°)$	15.4 (±1.8)	A.U.
$a_3(i' = 70°)$	15.3 (±1.7)	A.U.
$a_3(i' = 50°)$	15.0 (±1.7)	A.U.
$a_3(i' = 30°)$	14.2 (±1.7)	A.U.
$a_3(i' = 10°)$	10.3 (±1.4)	A.U.

However, this model was ruled out by Marsh & Pringle (1990) based on energetic considerations. In 1992, a detailed improvement on the theory was made by Applegate, who proposed that a quasi-periodic exchange of angular momentum between the inner and the outer parts in the convection zone may induce a modulation of stellar oblateness and consequently its quadruple moment. Therefore, the orbital period will be changed. Recently, the details of Applegate's mechanism have been studied by Lanza, Rodonò, & Rosner (1998). They pointed out that apart from the redistribution of the internal angular velocity, the change in the azimuthal field intensity can likewise produce a change in the oblateness of the active component, and the stability of the azimuthal magnitude field was discussed by considering a more general magnetic field geometry (Lanza & Rodonò 1999). For S Equ, its secondary is a G-type giant which contains a deep convective envelope and rotates very fast (several times as the Sun does). The periodic change in the period can also be plausibly interpreted as the result of the variation of the quadruple momentum via the magnetic activity of the cooler component as other Algol-type systems discussed by Zavala et al. (2002). With the equation given by Applegate (1992) and by Lanza et al. (1998),

$$\frac{\Delta P}{P} = -9\left(\frac{R}{a}\right)^2 \frac{\Delta Q}{MR^2} , \qquad (11)$$

the required change in the quadruple moment ΔQ in order to reproduce an orbital period change $\Delta P = 1.51 \times 10^{-5}$ days is calculated to be $\Delta Q = 2.27 \times 10^{50}$ g cm^{-2}. However, since the secondary is a giant with an extremely small mass of 0.30 $M_\odot$, the properties of magnetic activity cycle in this kind of stars are not clear.

4. CONCLUSIONS

Many photometric and spectroscopic studies have shown that S Equ is a very low mass ratio Algol-type binary star ($q = 0.13$) (e.g., Plavec 1966; Cester et al. 1979; Zola 1992). The rapid period increasing suggests that S Equ is a low mass ratio Algol-type binary in the active phase of mass transfer. According to the evolutionary theory of binary stars, Algol-type eclipsing binaries with very low mass ratio should be in a slow mass transfer stage on nuclear timescale. The present investigation may indicate that a rapid mass exchange still occurs in some of this kind of binaries. Thus, S Equ is a very important binary for understanding the evolution of Algol-type variables.

By the analysis of the photoelectric data, a significant third light in the systems was found by Zola (1992). This indicates that the alternating period change of S Equ may be cyclic, which is caused by the presence of a third body. These findings suggest that S Equ may be a truly triple system. In the previous section, the orbital parameters of the third body are determined and are listed in Table 2. Zola's photometric investigation shows that the amount of the third light is comparable to the contribution of the cooler component to the total flux of the system. If we assume that the third body is a main-sequence star and with Boehm's (1989) mass-luminosity relation, the mass of the third body is estimated to be $m_3 = 1.4$ $M_\odot$. Therefore, the orbital inclination of the third body should be $i' \sim 16°$, which is rather smaller than that of the eclipsing binary system ($i = 88.^\circ3$). If this is true, we can conclude that the third body is captured by the eclipsing pair. The triple system is not like planetary systems (and galaxies) as formed by contracting spinning gaseous clouds. However, it should be noted that, in the solution of the W-D code, THIRD LIGHT may be the result of a numerical artifact, since it is usually strongly correlated with many parameters. New accurate photometric and spectroscopic observations and a careful analysis of those data are needed. On the other hand, the secondary of S Equ is a late-type giant as in other Algols. The alternate period change may also be resulted from the variation of the gravitational quadruple momentum from periodic magnetic activity of the G-type component. Since the third body would produce exactly periodic variations in the $O - C$ curve, more determinations of eclipsing times over next decade are very important to settle the question.

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