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# OO Aquilae: a solar-type contact binary with intrinsic light curve changes

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**Abstract** New multi-color photometry of the solar-type contact binary OO Aql was obtained in 2012 and 2013, using the 60 cm telescope at Xinglong Station of the National Astronomical Observatories, Chinese Academy of Sciences. From two sets of light curves $LC_1$ and $LC_2$, photometric models were performed by using the 2003 version of the Wilson-Devinney code. The overcontact factor of the binary system was determined to be $f = 37.0(\pm 0.5)\%$. The intrinsic variability of this binary occurs in light maxima and minima, which could result from a possible third component and magnetic activity of the late type components. Based on all available light minimum times, the orbital period may change in a complicated mode, i.e., sudden period jumps or continuous period variations. The period of OO Aql may possibly undergo a secular period decrease with a rate of $dP/dt = -3.63(\pm 0.30) \times 10^{-8}$ d yr$^{-1}$, superimposed by two possible cyclic variations in the $O - C$ curve. The long-term period decrease may be interpreted as conserved mass transfer from the more massive component to the less massive one. The 21.5-yr oscillation may be attributed to cyclic magnetic activity, and the 69.3-yr one may result from the light-time effect of an unseen tertiary body.

**Key words:** binaries: close — binaries: eclipsing — stars: individual (OO Aql)

## 1 INTRODUCTION

W UMa-type binaries surrounded by a common envelope are usually active systems with interaction between both components and strong chromospheric activities, which usually account for the brightness variation over a short time scale. It is common that these stars show complicated period variations (Maceroni & van't Veer 1996), which may be caused by several mechanisms, such as the magnetic breaking effect (Verbunt & Zwaan 1981; Rappaport et al. 1983), the light-time effect (Irwin 1959; Mayer 1990; Wolf et al. 1999) and the tidal effect (Zahn 1966). Except for the period variations, the relation between the two components, especially in late-type W UMa binaries (Webbink 2003), might oscillate between contact and semi-detached states, according to the theory of thermal relaxation oscillation (Lucy 1967; Flannery 1976; Robertson & Eggleton 1977).

OO Aql [$\alpha_{\rm J2000.0} = 19^{\rm h}48^{\rm m}12.653^{\rm s}$, $\delta_{\rm J2000.0} = +09^\circ18'32.38''$, $m_{\rm v} \sim 9.5$ mag] is a contact binary of A-subtype consisting of two late type stars. The mass ratio ($q = 0.844(8)$, İçli et al. 2013) and orbital period ($P \sim$0.506 d) of this system are unusual since most cool contact binaries have periods of 0.25–0.35 days and mass ratios of 0.3–0.5 (Hrivnak et al. 2001), suggesting that the components have only recently come into contact (Mochnacki 1981; Hrivnak et al. 2001). The age and distance of the binary are estimated to be approximately 8 Gyr and 136 pc respectively (Hrivnak 1989; İçli et al. 2013).

OO Aql has been observed extensively since its discovery by Hoffleit (1932). Binnendijk (1968) presented the first completely covered light curves in $B$ and $V$ bands. Over the past fifty years, the binary showed varying asymmetry between maxima in light curves (the so-called O'Connell effect, Milone 1968; Davidge & Milone 1984) from time to time. The different heights of maxima in light curves of Lafta & Grainger (1985) were interpreted by a single spot on the primary component, while those of Essam et al. (1992) were attributed to two bright active areas on the secondary (Djurašević & Erkapić 1998). On the other hand, chromospheric activity of OO Aql studied in ultraviolet wavelengths (Hrivnak et al. 2001) revealed that Mg II $h$ and $k$ emission varied with time. However, they also pointed out that the level of chromospheric activity in the binary was lower than those of other W UMa-type binaries with similar colors, which was possibly attributed to its early stage of contact binary evolution (Hrivnak et al. 2001).

The period variation of OO Aql was noticed almost half a century ago (Binnendijk 1968). Demircan & Gudur (1981) observed this system from 1968 to 1974. They found an abrupt decrease in the period of the system in the 1960s with plausible six-year periodic fluctuations and suggested the periodicity may be due to the presence of a third body or nodal regression. The third-body assumption was also made by Rafert (1982) who found a 13 yr oscillation in the $(O-C)$ curve. Demircan & Guerol (1996) showed that the $(O-C)$ data were well represented by two sloping straight lines or a large amplitude sinusoidal wave with $P = 89$ yr, a value which was already very close to that provided by recent researches (Borkovits et al. 2005; Zasche 2005; İçli et al. 2013). Still, the fluctuating periods for $O-C$ curves analyzed by these works were found to be different from each other. For Borkovits et al. (2005) and Zasche (2005), the period was estimated to be about 75 yr and 72 yr respectively, while a shorter period was given $(P = 52(\pm 2)\ \mathrm{yr})$ in the analysis of İçli et al. (2013).

Considering the peculiar properties of OO Aql, further detailed studies are needed. In this paper, we present comprehensive photometric observations of OO Aql, which are described in Section 2. Possible orbital period variations are investigated in Section 3. Photometric solutions are carried out in Section 4. The possible existence of a third body and evolutionary status for OO Aql are discussed in the last section.

## 2 NEW CCD PHOTOMETRY

New $BVR$ photometry of OO Aql was obtained from 2012 August to 2013 August, using a 0.6 m telescope located at Xinglong Station of National Astronomical Observatories, Chinese Academy of Sciences (NAOC). The telescope was equipped with a 1024×1024 Princeton Instruments (PI) CCD and standard Johnson $UBVRI$ filters (Li et al. 2009). Since 2013 August 23, a 512×512 PI CCD was used for technical reasons. The effective fields of view with the 1024-CCD and 512-CCD were $18' \times 18'$ and $16.6' \times 16.6'$ respectively. All photometric reductions were performed with IRAF[1] including bias and dark subtraction, and flat-field correction.

During the data reduction process, the star TYC 1058-289-1 was used as a comparison. We did not select TYC 1058-689-1 and TYC 1058-409-1 as comparison stars in the previous literature since they showed variations of about 0.02 mag while TYC 1058-289-1 that we selected was more stable (within 0.01 mag) during our observations in 2012 and 2013. In two observing seasons, we obtained two sets of light curves, $LC_1$ obtained in 2012 with 974 data points in $B$, 995 in $V$ and 993 in $R$ band, and $LC_2$ in 2013 containing 950 measurements in $B$, 957 in $V$ and 927 in $R$ band. The measurements are tabulated in Table 1 in the form of HJD versus differential magnitude (the full dataset is presented in the online version of the journal). The resulting differential photometric accuracy for OO Aql is estimated to be 0.01 mag in $B$, $V$ and $R$ bands. Two sets of complete light curves are displayed in Figure 1, in

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

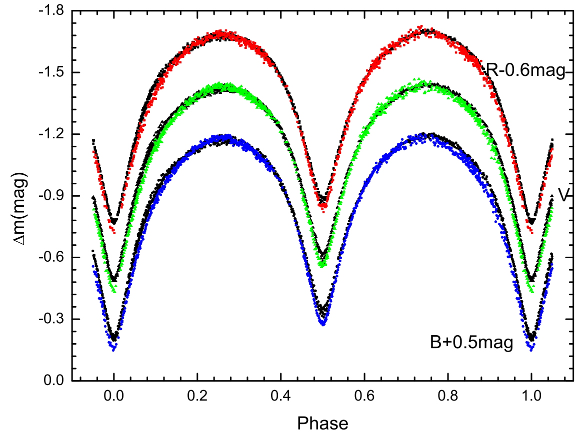


**Fig. 1** New photometric observations of the solar-type eclipsing binary OO Aql, obtained in 2012 and 2013 using the 60 cm telescope at Xinglong Station of NAOC.

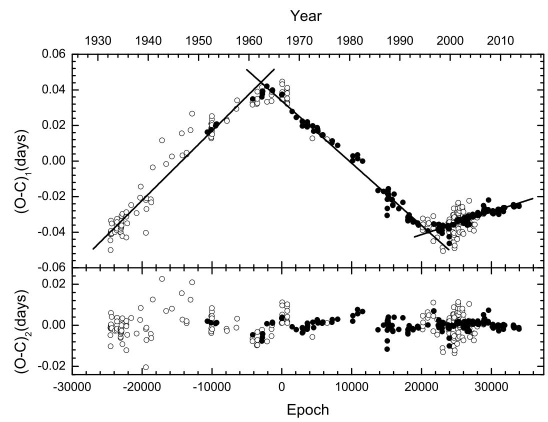


**Fig. 2** Residuals of $(O-C)_1$ (*upper panel*) and $(O-C)_2$ (*lower panel*) of OO Aql. The solid lines are plotted by using Equation (2). The open circles refer to plate, visual and photographic observations, while the filled circles represent photoelectric and CCD ones.

which phases are computed with a period of 0.50679190 d (Demircan & Guerol 1996). Photometric properties of $LC_1$ and $LC_2$ are listed in Table 2. As shown in this table, both maxima are approximately consistent, but both minima in $LC_2$ are fainter than those in $LC_1$ up to about 0.05 mag. The differences between Max.I and Max.II of $LC_1$ in 2012 are 0.022 mag, 0.019 mag and 0.022 mag in the different respective bands, while in 2013 Max.I and Max.II were of equal height. This is strong evidence for the existence of magnetic activity associated with OO Aql (Djurašević & Erkapić 1998). Additionally, the secondary eclipse time was monitored on 2013 August 30 using the 0.6 m telescope. From our new observations, 23 single-color minima and their standard errors, determined by using the K-W method (Kwee & van Woerden 1956), are given in Table 3.

## 3 REANALYZING PERIOD VARIATIONS

Based on different databases of light minimum times, the orbital period changes of OO Aql have been sub-

**Table 1** Photometric Observations of OO Aql in 2012 and 2013

| $LC1$ (2012) | | | | | | $LC_2$ (2013) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *B* band | | *V* band | | *R* band | | *B* band | | *V* band | | *R* band | |
| JD (Hel.) | $\Delta m$ | JD (Hel.) | $\Delta m$ | JD (Hel.) | $\Delta m$ | JD (Hel.) | $\Delta m$ | JD (Hel.) | $\Delta m$ | JD (Hel.) | $\Delta m$ |
| 154.9961 | −0.968 | 154.9966 | −0.618 | 154.9969 | −0.401 | 498.0722 | −1.248 | 498.0720 | −0.931 | 498.0719 | −0.698 |
| 154.9974 | −0.947 | 154.9992 | −0.618 | 154.9982 | −0.390 | 498.0727 | −1.245 | 498.0725 | −0.931 | 498.0724 | −0.699 |
| 155.0001 | −0.959 | 155.0007 | −0.618 | 154.9996 | −0.392 | 498.0739 | −1.228 | 498.0737 | −0.931 | 498.0729 | −0.703 |
| 155.0017 | −0.967 | 155.0023 | −0.618 | 155.0012 | −0.391 | 498.0744 | −1.204 | 498.0742 | −0.931 | 498.0741 | −0.670 |
| 155.0034 | −0.973 | 155.0040 | −0.618 | 155.0028 | −0.411 | 498.0749 | −1.209 | 498.0747 | −0.931 | 498.0746 | −0.668 |
| 155.0050 | −0.988 | 155.0073 | −0.618 | 155.0045 | −0.418 | 498.0755 | −1.195 | 498.0753 | −0.931 | 498.0751 | −0.650 |
| 155.0067 | −1.009 | 155.0093 | −0.618 | 155.0061 | −0.443 | 498.0760 | −1.190 | 498.0758 | −0.931 | 498.0756 | −0.647 |
| 155.0085 | −1.042 | 155.0113 | −0.618 | 155.0079 | −0.466 | 498.0765 | −1.183 | 498.0763 | −0.931 | 498.0762 | −0.636 |
| 155.0105 | −1.071 | 155.0133 | −0.618 | 155.0099 | −0.498 | 498.0770 | −1.169 | 498.0768 | −0.931 | 498.0767 | −0.622 |
| 155.0125 | −1.103 | 155.0152 | −0.618 | 155.0119 | −0.535 | 498.0775 | −1.156 | 498.0774 | −0.931 | 498.0772 | −0.603 |
| 155.0145 | −1.132 | 155.0169 | −0.618 | 155.0139 | −0.568 | 498.0781 | −1.158 | 498.0779 | −0.931 | 498.0777 | −0.611 |
| 155.0163 | −1.155 | 155.0185 | −0.618 | 155.0157 | −0.594 | 498.0786 | −1.141 | 498.0784 | −0.931 | 498.0783 | −0.587 |
| ... | ... | | | | | | | | | | |

Notes: JD (Hel.) of this table are expressed after the value HJD 2456000.0 was subtracted. This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online version of the journal. A portion is shown here for guidance regarding its form and content.

**Table 2** Photometric Properties of the Contact Binary OO Aql

| Parameter | $LC_1$ in 2012 | | | $LC_2$ in 2013 | | |
|---|---|---|---|---|---|---|
| | $B$ | $V$ | $R$ | $B$ | $V$ | $R$ |
| Min.I (mag) | −0.82 | −0.50 | −0.29 | −0.77 | −0.46 | −0.24 |
| Min.II (mag) | −0.94 | −0.61 | −0.38 | −0.89 | −0.57 | −0.35 |
| Max.I (mag) | −1.77 | −1.42 | −1.18 | −1, 78 | −1.43 | −1.18 |
| Max.II (mag) | −1.79 | −1.43 | −1.20 | −1.78 | −1.43 | −1.20 |

**Table 3** Newly Observed Eclipsing Times of OO Aql

| JD (Hel.) | Min | Error | Filter |
|---|---|---|---|
| 2456164.12105 | II | ±0.00025 | $B$ |
| 2456164.12104 | II | ±0.00022 | $V$ |
| 2456164.12150 | II | ±0.00026 | $R$ |
| 2456176.03080 | I | ±0.00026 | $B$ |
| 2456176.03054 | I | ±0.00028 | $V$ |
| 2456176.03084 | I | ±0.00028 | $R$ |
| 2456184.13916 | I | ±0.00015 | $B$ |
| 2456184.13923 | I | ±0.00014 | $V$ |
| 2456184.13942 | I | ±0.00017 | $R$ |
| 2456206.94486 | I | ±0.00015 | $B$ |
| 2456206.94530 | I | ±0.00013 | $V$ |
| 2456206.94532 | I | ±0.00015 | $V$ |
| 2456233.04483 | II | ±0.00020 | $B$ |
| 2456233.04517 | II | ±0.00023 | $V$ |
| 2456498.09738 | II | ±0.00010 | $B$ |
| 2456498.09749 | II | ±0.00009 | $V$ |
| 2456498.09755 | II | ±0.00008 | $R$ |
| 2456514.06188 | I | ±0.00013 | $B$ |
| 2456514.06161 | I | ±0.00012 | $V$ |
| 2456514.06162 | I | ±0.00014 | $R$ |
| 2456535.09300 | II | ±0.00009 | $B$ |
| 2456535.09289 | II | ±0.00013 | $V$ |
| 2456535.09279 | II | ±0.00023 | $R$ |

sequently analyzed by many authors. Several modulations were present including abrupt changes in period (Essam et al. 1992), secular decrease/increase (Binnendijk 1968), one sinusoidal curve (Demircan & Guerol 1996), two sinusoidal ones (Borkovits et al. 2005), and an upward/downward parabola with cyclic variations (Rafert 1982; İçli et al. 2013). Due to the inconsistent results, a complete database of eclipsing times for OO Aql is needed for analysis. Therefore, we compiled all available light minimum times, which are given in Table 4. Seventeen plate measurements, 2 photographic measurements, 164 visual measurements, 102 photoelectric measurements and 102 CCD data are included in the table. Using the following ephemeris given by Kreiner et al. (2001),

$$\text{Min.I} = \text{HJD } 2439322.6916 + 0.50679190 \times E\,, \quad (1)$$

we can compute the residuals $(O-C)_1$ for all eclipsing times, which are also listed in Table 4. During the following calculation process, the weights were defined as 1 for plate, visual or photographic observations (i.e., "pv," "vi" or "pg"), and 10 for photoelectric or CCD ones (i.e., "pe" and "CCD").

### 3.1 Possible Period Jumps

In the work Essam et al. (1992), possible discontinuous variation of orbital period was first considered. For the contact binary OO Aql, the $(O-C)_1$ curve is plotted against the epoch number in the upper panel of Figure 2. From this figure, the $(O-C)_1$ curve may be divided into three segments. A linear least-squares method with weights led to the following equation,

$$\text{Min.I} = \begin{cases} \text{HJD } 2439322.7474(19) + 0.50679580(10) \times E & \text{for } E < +3000\,, \\ \text{HJD } 2446980.3295(06) + 0.50678840(05) \times (E-15110) & \text{for } +3000 < E < +23000\,, \\ \text{HJD } 2456206.8782(26) + 0.50679317(10) \times (E-33316) & \text{for } E > 23000\,, \end{cases} \quad (2)$$

where the parenthesized numbers represent the standard errors in units of the last decimal place. From Equation (2), we can compute the residuals $(O-C)_2$, which are listed in Table 4, and are also shown in the lower panel of Figure 2. Although some small fluctuations exist, no regularity is apparent. The possible period jumps approximately occurred in 1970 (i.e., HJD$\sim$2440830) with a sudden period of $-0.64$ seconds, and in 1998 (i.e., HJD$\sim$2450970) with an abrupt period of $+0.41$ seconds. This kind of variation also exists in other contact binaries, such as AU Ser (Qian et al. 1999), EK Com and UX Eri (Li & Zhang 2006), which were interpreted as variation in the binary's structure, or rapid mass exchange between both components and their circumstellar matter.

### 3.2 Continuous Period Changes

Another possible characteristic that describes the $(O-C)_1$ curve for OO Aql is that the orbital period continuously changes, as previously suggested by several authors. İçli et al. (2013) recently analyzed the period variations. However, plate, visual and photographic data with relatively less accuracy were neglected in their study. These relatively less accurate data may also make a contribution to the complex behavior of OO Aql's $O-C$ curve. In our analysis, the shape of the $(O-C)_1$ curve can be described using a quadratic curve with two cyclic variations. In order to search the oscillating periods, Fourier analysis (Lenz & Breger 2005) was performed for the residuals of $(O-C)_1$. The results are displayed in the right panel of Figure 3. Two prominent peaks are $f_1 = 1.418 \times 10^{-4}\ \text{d}^{-1}$ and $f_2 = 3.882 \times 10^{-5}\ \text{d}^{-1}$, which correspond to two periods of $P_{\text{mod1}} \simeq 19.3$ yr and $P_{\text{mod2}} \simeq 70.5$ yr respectively. Therefore, a parabolic ephemeris with two sinusoidal variations was applied to fit the $(O-C)_1$ curve. A nonlinear least-squares method yields the following ephemeris,

$$\begin{aligned} \text{Min.I} \ =\ & \text{HJD } 2439322.6964(6) + 0.50679200(5)E - 2.52(21) \times 10^{-11}E^2 \\ & +0.0037(2) \times \sin[4.06(4) \times 10^{-4}E + 2.865(86)] \\ & +0.0309(8) \times \sin[1.26(2) \times 10^{-4}E + 1.980(28)]\,. \end{aligned} \quad (3)$$

The corresponding residuals of $(O-C)_3$ are given in Table 4 and are displayed in the lower left panel of Figure 3. The solid and dotted lines in the upper left panel are plotted by the contribution of Equation (3) and only its parabolic part, respectively. With the coefficient of the quadratic term, we can obtain a continuous period decreasing rate of $dP/dt = -3.63(\pm 0.30) \times 10^{-8}$ d yr$^{-1}$. Two modulated periods are

$$P_2 = 21.5(\pm 0.2)\ \text{yr} \quad \text{and} \quad P_1 = 69.3(\pm 0.9)\ \text{yr},$$

which approximate the searched values of $P_{\text{mod1}}$ and $P_{\text{mod2}}$ respectively.

From Equation (3), the orbital period is decreasing with a rate of $dP/dt = -3.63(\pm 0.30) \times 10^{-8}\ \text{d yr}^{-1}$. We noted that our result was different from that given by İçli et al. (2013). In their research, the orbital period was calculated to be increasing with $dP/dt = +1.27(\pm 32) \times 10^{-8}$ d yr$^{-1}$, combined with two periods of $P_1 = 20(\pm 1)$ yr and $P_2 = 52(\pm 2)$ yr derived for a third and a fourth body respectively. After further analysis, we found the discrepancy was caused by the data and the ephemeris used when doing the analysis. The data we collected started from 1932 as presented in Table 4, while those of İçli et al. (2013) were only since 1951. However, the ephemeris we used was taken from Kreiner et al. (2001), while that of İçli et al. (2013) was from Demircan & Guerol (1996). These discrepancies lead to different shapes of $O-C$ curves between our work and that of İçli et al. (2013), and hence different conclusions.

**Table 4** All Compiled Light Minimum Times of OO Aql

| JD (Hel.) | Epoch | Method | Min | $(O-C)_1$ (d) | $(O-C)_2$ (d) | $(O-C)_3$ (d) | Ref. |
|---|---|---|---|---|---|---|---|
| 2426892.0590 | −24528.0 | vi | I | −0.0409 | −0.0011 | +0.0020 | [1] |
| 2426893.8290 | −24524.5 | vi | II | −0.0446 | −0.0048 | −0.0017 | [2] |
| 2426897.8780 | −24516.5 | vi | II | −0.0500 | −0.0102 | −0.0071 | [2] |
| 2426920.4390 | −24472.0 | pg | I | −0.0412 | −0.0016 | +0.0015 | [3] |
| 2426920.4406 | −24472.0 | vi | I | −0.0396 | +0.0000 | +0.0031 | [4] |
| 2426921.7080 | −24469.5 | vi | II | −0.0392 | +0.0004 | +0.0035 | [2] |
| ...... | | | | | | | |
| 2456176.0307 | 33255.0 | CCD | I | −0.0255 | −0.0010 | +0.0001 | [119] |
| 2456184.1393 | 33271.0 | CCD | I | −0.0256 | −0.0012 | +0.0000 | [119] |
| 2456206.9452 | 33316.0 | CCD | I | −0.0253 | −0.0009 | +0.0002 | [119] |
| 2456233.0449 | 33367.5 | CCD | II | −0.0254 | −0.0011 | +0.0001 | [119] |
| 2456498.0975 | 33890.5 | CCD | II | −0.0250 | −0.0014 | −0.0002 | [119] |
| 2456514.0616 | 33922.0 | CCD | I | −0.0248 | −0.0012 | +0.0000 | [119] |

Notes: The entire table is only available on the website of the journal. [1] Florja & Kukarkin 1932; [2] Florja 1933; [3] Martynov 1933; [4] Martinoff 1938; [5] Miczaika 1937; [6] Lause 1935; [7] Martinov 1938; [8] Soloviev 1934; [9] Bush 1968; [10] Ahnert 1976; [11] Ashbrook 1952; [12] Ashbrook 1953; [13] Fitch 1964; [14] Binnendijk 1968; [15] Ahnert 1960; [16] Demircan & Guerol 1996; [17] Flin & Słowik 1967; [18] Czerlunczakiewicz & Flin 1968; [19] Pohl 1969; [20] Baldwin 1964; [21] Madej & Malas 1974; [22] Flin 1969; [23] Pohl & Kizilirmak 1970; [24] Kizilirmak & Pohl 1971; [25] Pohl & Kizilirmak 1972; [26] Klimek 1973; [27] Kizilirmak & Pohl 1974; [28] Pohl & Kizilirmak 1975; [29] Pohl & Kizilirmak 1976; [30] Pohl & Kizilirmak 1977; [31]Scarfe & Barlow 1978; [32] Ebersberger et al. 1978; [33] Scarfe et al. 1984; [34]Andrakakou et al. 1981; [35] Pohl et al. 1983; [36] Paschke et al. 1985; [37] Pohl et al. 1987; [38] Keskin & Pohl 1989; [39] Mavrofridis & Diethelm 1987; [40] Hübscher & Lichtenknecker 1988; [41] Hegedus 1987; [42] Hanzl 1990; [43] Hübscher et al. 1989; [44] Hübscher et al. 1990; [45] Wunder et al. 1992; [46] Hanzl 1991; [47] Brelstaff 1997; [48] Gurol 1994; [49] Paschke 1992; [50] Blättler 1992; [51] Diethelm & Acerbi 1994; [52] Barani 1995; [53] Acerbi 1994; [54] Saijo 1995; [55] Brno observers 2002; [56] Agerer & Hübscher 1996; [57] Hübscher et al. 1997; [58] Agerer & Hübscher 2000; [59] Baldwin & Samolyk Baldwin 1999; [60] Agerer & Hübscher 1998; [61] Borkovits & Biro 1998; [62] Hübscher et al. 1999; [63] Baldwin & Samolyk 2000; [64] Agerer & Hübscher 1999; [65] Biro & Borkovits 2000; [66] Agerer & Hübscher 2001; [67] Diethelm 2000; [68] Nagai 2000; [69] Nelson 2000; [70] Baldwin & Samolyk 2002; [71] Hübscher 2001; [72] Agerer & Hübscher 2002; [73] Borkovits et al. 2001; [74] Agerer & Hübscher 2003; [75] Baldwin & Samolyk 2004; [76] Hübscher et al. 2003; [77] Borkovits et al. 2002; [78] Selam et al. 2003; [79] Nagai 2003; [80] Demircan et al. 2003; [81] Gurol et al. 2003; [82] Diethelm 2003; [83] Bakis et al. 2003; [84] Bakis et al. 2005; [85] Biro et al. 2006; [86] Hübscher 2005; [87] Nagai 2004; [88] Kim et al. 2006; [89] Hübscher et al. 2012; [90] Hübscher et al. 2006; [91] Hübscher et al. 2005b; [92] Hübscher et al. 2005a; [93] Nagai 2005; [94 Nagai 2006; [95] Senavci et al. 2007; [96] Private communication with Prof. J.-M Kreiner; [97] Private communication with Prof. J.-M. Kreiner; [98] Nagai 2007; [99] Marchini et al. 2011; [100] Hübscher & Walter 2007; [101] Marino et al. 2010; [102] Baldwin & Samolyk 2007; [103] Dogru et al. 2007; [104] Baldwin & Samolyk 2006; [105] Samolyk 2008; [106] Nagai 2009; [107] Brát et al. 2008; [108] Hübscher et al. 2009; [109] Hübscher et al. 2010; [110] Samolyk 2010; [111] Erkan et al. 2010; [112] Brat et al. 2011; [113] Hübscher 2011; [114] Borkovits et al. 2011; [115] Samolyk 2011; [116] Hübscher 2011; [117] Nagai 2011; [118] İçli et al. 2013; [119] This Study.

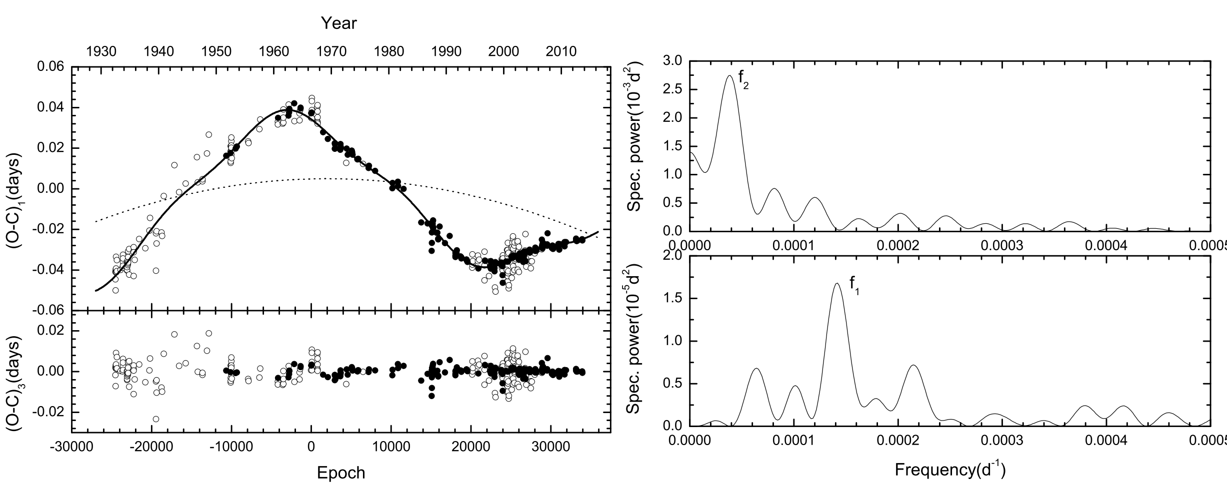


**Fig. 3** *Upper left panel*: the $(O-C)_1$ diagram of OO Aql. *Lower left panel*: $(O-C)_3$ diagram of OO Aql. The solid line was constructed by Equation (3). Other symbols are the same as Figure 2. *Right*: Fourier power spectra for the residuals of $(O-C)_1$, including two significant peaks $f_1$ and $f_2$.

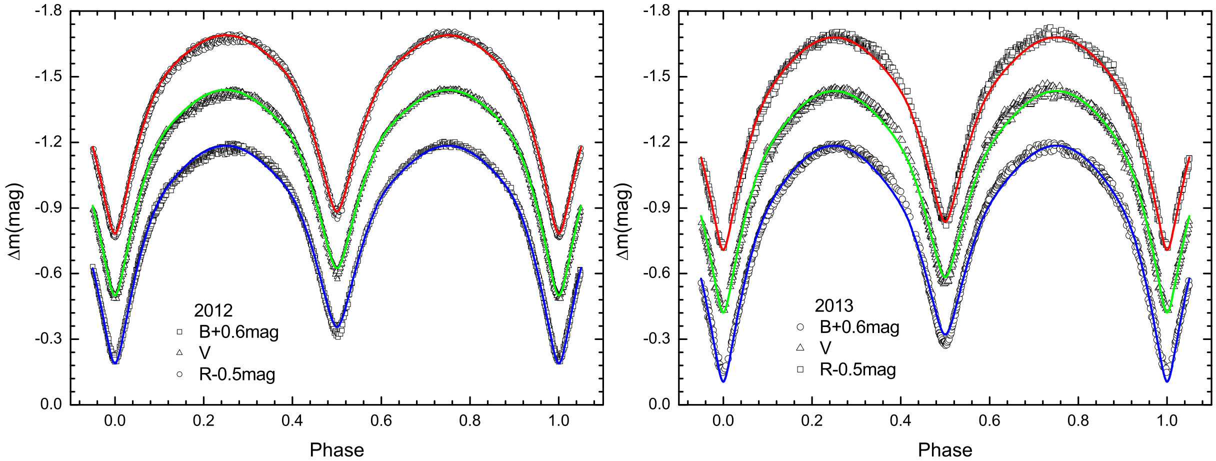


**Fig. 4** Comparison between observations and theoretical light curves in 2012 (*left panel*) and 2013 (*right panel*). The solid lines were constructed by Sol.1 for $LC_1$ and Sol.3 for $LC_2$.

## 4 MODELING LIGHT CURVES

Light curves in 2012 ($LC_1$) and 2013 ($LC_2$) of OO Aql were analyzed using the 2003 version of the Wilson-Devinney (W-D) program (Wilson & Devinney 1971; Wilson 1979), including a stellar atmosphere model (Kurucz 1993) and a detailed reflection treatment (Wilson 1990). The logarithmic bolometric/monochromatic limb-darkening coefficients (i.e., $X$ and $Y$; $x$ and $y$) were interpolated from tables published by van Hamme (1993). The gravity darkening coefficients and the bolometric albedo coefficients were taken at the values of $g_{1,2} = 0.32$ (Lucy 1967) and $A_{1,2} = 0.5$ (Ruciński 1973). In the calculation process, we adopted some adjustable parameters (i.e., $i$, $T_2$, $\Omega_1$ and $L_1$) as usual.

The spectral type of OO Aql is between F8V and G1V (Pribulla et al. 2007), corresponding to effective temperatures 6250 K and 5800 K respectively (Drilling & Landolt 2000). Thus we adopted a medium value with a sub-spectral-type error of $T_1 = 6100(\pm 150)$ K. The photometric solutions of the contact binary OO Aql were performed using Mode 3 of the W-D program, with a fixed mass ratio of $q_{sp} = 0.846$ (Pribulla et al. 2007). For $LC_1$ in 2012, the difference between both maxima is about $0.02$ mag. A tiny hump between phase $0.30$ and phase $0.42$ exists in the light curves. Considering the photometric error of $\sim 0.01$ mag, the distortions in light curves are too small to model. In addition, the depths of primary and secondary minima for $LC_1$ are brighter than those of $LC_2$ in 2013 by up to about 0.05 mag, which does not result from observing errors. A third light contribution was applied as a free parameter and no meaningful value was found. Therefore, the variation around both eclipses requires a reasonable interpretation. After several iterations, we obtained two sets of photometric elements (i.e., Sol.1 for $LC_1$ and Sol.2 for $LC_2$), which are listed in Table 5. The theoretical light curves in $B$, $V$ and $R$ filters are plotted in both panels of Figure 4 as solid lines.

## 5 RESULTS AND DISCUSSION

In the analysis above, we performed the photometric models for two sets of light curves. The distorted tiny humps may result from mass transfer from the primary component to the secondary one. Combining the spectral elements (Pribulla et al. 2007) with Sol.2, we redetermined the absolute parameters as follows:

$$
\begin{aligned}
M_1 &= 1.060(\pm 0.007)\, M_\odot\,, \\
M_2 &= 0.897(\pm 0.006)\, M_\odot\,, \\
R_1 &= 1.406(\pm 0.002)\, R_\odot\,, \\
R_2 &= 1.309(\pm 0.002)\, R_\odot\,, \\
L_1 &= 2.453(\pm 0.007)\, L_\odot\,, \\
L_2 &= 1.894(\pm 0.006)\, L_\odot\,.
\end{aligned}
$$

### 5.1 Intrinsic Light Variability

From the published literature, the difference between light maxima for OO Aql is varying. In most cases, the primary maximum light is brighter than the secondary one (Lafta & Grainger 1985; Demircan & Guerol 1996), except for a significant reverse around 1987, when a sharp increase of the system's brightness was observed after the secondary minimum (Essam et al. 1992).

Figure 5 displays this kind of light variation, whose values are determined from the published literature. As shown in Figure 5, some irregularity exists, which is similar with BX Peg (Lee et al. 2004). Such intrinsic light variability, i.e., the O'Connell effect, is probably caused either by cyclic magnetic activity of the late type components (Applegate 1992; Demircan & Guerol 1996) or by hot material hitting the surface of the secondary star during unstable mass transfer (Djurašević & Erkapić 1998). Moreover, the former may possibly result in the short-period oscillation of the $O - C$ curve, which will be investigated further in our future observation. This kind of variation occurs in other contact binaries, such as CK Boo (Yang et al. 2012),

**Table 5** Photometric Elements of the Contact Binary OO Aql

| Parameter | Hrivnak (1989) | İçli et al. (2013) | Sol.1 ($LC_1$ in 2012) | Sol.2 ($LC_2$ in 2013) |
|---|---|---|---|---|
| $i(°)$ | 90.0(16) | 85.6 | $86.49(\pm0.04)$ | $87.72(\pm0.09)$ |
| $T_1$(K) | 5700 | 5700 | 6100 | |
| $X_1, Y_1$ | | | $+0.648$, $+0.250$ | |
| $x_{1B}, y_{1B}$ | 0.77 | | $+0.824$, $+0.205$ | |
| $x_{1V}, y_{1V}$ | 0.62 | | $+0.740$, $+0.266$ | |
| $x_{1R}, y_{1R}$ | | | $+0.648$, $+0.272$ | |
| $T_2$(K) | 5635 | 5472(55) | $5954(\pm3)$ | $5926(\pm4)$ |
| $X_2, Y_2$ | | | $+0.649$, $+0.217$ | $+0.649$, $+0.218$ |
| $x_{2B}, y_{2B}$ | | | $+0.832$, $+0.179$ | $+0.831$, $+0.182$ |
| $x_{2V}, y_{2V}$ | | | $+0.752$, $+0.252$ | $+0.751$, $+0.254$ |
| $x_{2R}, y_{2R}$ | | | $+0.660$, $+0.263$ | $+0.659$, $+0.265$ |
| $\Omega_{1,2}$ | 3.364(27) | 3.391(1) | $3.4205(\pm0.0018)$ | $3.3477(\pm0.0071)$ |
| $L_1/(L_1+L_2)_B$ | 0.552(4) | | $0.5742(\pm0.0004)$ | $0.5801(\pm0.0006)$ |
| $L_1/(L_1+L_2)_V$ | 0.550(4) | | $0.5648(\pm0.0003)$ | $0.5690(\pm0.0004)$ |
| $L_1/(L_1+L_2)_R$ | | | $0.5596(\pm0.0002)$ | $0.5627(\pm0.0003)$ |
| $r_1$(pole) | 0.388(4) | | $0.3803(\pm0.0003)$ | $0.3907(\pm0.0005)$ |
| $r_1$(side) | 0.412(5) | | $0.4022(\pm0.0004)$ | $0.4154(\pm0.0006)$ |
| $r_1$(back) | 0.451(7) | | $0.4376(\pm0.0005)$ | $0.4571(\pm0.0009)$ |
| $r_2$(pole) | 0.359(4) | | $0.3524(\pm0.0003)$ | $0.3630(\pm0.0005)$ |
| $r_2$(side) | 0.380(5) | | $0.3713(\pm0.0004)$ | $0.3844(\pm0.0006)$ |
| $r_2$(back) | 0.422(8) | | $0.4085(\pm0.0005)$ | $0.4290(\pm0.0009)$ |
| $\Sigma(O-C)_i^2$ | | | 0.6596 | 0.6402 |
| $f(\%)$ | 27(6) | | $21.8(\pm0.1)$ | $37.0(\pm0.5)$ |

**Table 6** Model Parameters of Possible Magnetic Activities for OO Aql

| Parameter | $P_1 = 21.5(\pm0.2)$ yr | | $P_2 = 69.3(\pm0.9)$ yr | |
|---|---|---|---|---|
| | Primary | Secondary | Primary | Secondary |
| $\Delta P/P$ $(10^{-6})$ | $1.50(\pm0.08)$ | | $7.67(\pm0.20)$ | |
| $\Delta Q$ $(10^{50}$ g cm$^2)$ | $0.38(\pm0.02)$ | $0.83(\pm0.02)$ | $0.32(\pm0.02)$ | $0.83(\pm0.02)$ |
| $\Delta J$ $(10^{47}$ g cm$^2$s$^{-1})$ | $1.18(\pm0.06)$ | $1.05(\pm0.06)$ | $3.06(\pm0.08)$ | $2.71(\pm0.07)$ |
| $I_s$ $(10^{54}$ g cm$^2)$ | 1.35 | 0.99 | 1.35 | 0.98 |
| $\Delta\Omega/\Omega$ $(10^{-3})$ | $0.61(\pm0.03)$ | $0.74(\pm0.04)$ | $1.58(\pm0.04)$ | $1.91(\pm0.05)$ |
| $\Delta E(10^{41}$ erg$)$ | $0.21(\pm0.02)$ | $0.22(\pm0.02)$ | $1.39(\pm0.07)$ | $1.49(\pm0.08)$ |
| $\Delta L_{\rm rms}(10^{32}$ erg s$^{-1})$ | $0.96(\pm0.10)$ | $2.41(\pm0.11)$ | $1.03(\pm0.11)$ | $2.41(\pm0.11)$ |
| | $0.010\ L_p$ | $0.014\ L_s$ | $0.021\ L_p$ | $0.030\ L_s$ |
| $B$ (kG) | $5.91(\pm0.16)$ | $5.56(\pm0.07)$ | $6.20(\pm0.17)$ | $5.56(\pm0.07)$ |

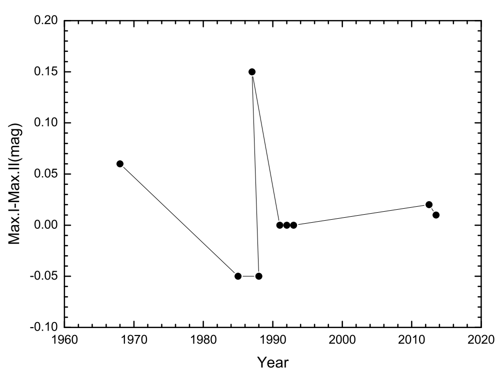


**Fig. 5** The variation of Max.I-Max.II for the eclipsing binary OO Aql.

DF CVn (Dai et al. 2011), KV Gem (Zhang et al. 2014), DZ Psc (Yang et al. 2013) and GSC 3576-0170 (Zhang et al. 2010), whose magnetic activity may possibly result in the short-period oscillation.

## 5.2 Interpreting Period Changes

Based on all available light minimum times, we derived two possible scenarios for the period changes, i.e., period jumps or continuous period variations. The identification of abrupt period changes is a very uncertain procedure. The $(O-C)$ modeling becomes ambiguous, since personal judgement plays an essential role (Kalimeris et al. 2002). Moreover, the sum of residuals of $\Sigma(O-C)_2^2 = 0.0082$ from Equation (2) is larger than that of $\Sigma(O-C)_3^2 = 0.0070$ from Equation (3), which can be seen directly from Figure 2 and Figure 3. Therefore, the continuous description of the $(O-C)$ curve modeled by Equation (3) may be a true case of period variation.

From Equation (3), there may exist two oscillations. Considering the late spectral types of both components, we try to explain the observed period oscillations with Applegate (1992)'s mechanism, which interprets the period modulation of some eclipsing binaries as a manifestation of stellar magnetic activity. Using the absolute dimensions, several of Applegate's model parameters were estimated from the related formulae (Lanza et al. 1998).

Table 6 lists the calculation results, including $\Delta P/P$, $\Delta Q$, $\Delta J$, $I_s$, $\Delta\Omega/\Omega$, $\Delta E$, $\Delta L_{\rm rms}$ and $B$. For the contact binaries, the typical values of $\Delta Q$ and $\Delta L_{\rm rms}$ are of the orders of $10^{51} \sim 10^{52}$ (Lanza & Rodonò 1999) and $0.1\ L_{p,s}$ (Applegate 1992), respectively. It can be seen that the values of $\Delta Q$ and $\Delta L_{\rm rms}$ for OO Aql are much smaller than the typical ones. The mean subsurface magnetic field strength $B$, however, is close to the predicted value of several kilo-gauss (Applegate 1992).

From Figure 5, the existence of intrinsic light variations implies that cyclic magnetic activity might play a role in the orbital period changes. Therefore Applegate's mechanism could not be excluded for the target. Another possible mechanism is the light-time effect via the presence of an additional body (Irwin 1952). According to the fitted parameters of Equation (3), we can derive the minimum masses of $M_{31} = 0.14(\pm 0.01)\ M_\odot$ and $M_{32} = 0.62(\pm 0.02)\ M_\odot$ corresponding to the periods of $P_1$ and $P_2$, respectively. Even if the additional component were a degenerate object, the mass of $M_{32}$ is so large that it has possibly been identified via reducing the depth of the light minima, which can be seen from Figure 1, although it is not a meaningful value of the third light given in Sol.1. Therefore, the long-term oscillation may be attributed to the light-time effect due to the additional tertiary body. Meanwhile, the 21.5-yr oscillation of the F8V-G1V-type binary OO Aql, close to the activity cycle of the Sun, may result from cyclic magnetic activity. In future work, high-precision photometry is needed to investigate the nature of period changes and the variability of light curves.

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## References

Acerbi F., 1994, BBSAG Bull., 107, 1
Agerer, F., & Hübscher, J. 1996, Information Bulletin on Variable Stars, 4382, 1
Agerer, F., & Hübscher, J. 1998, Information Bulletin on Variable Stars, 4606, 1
Agerer, F., & Hübscher, J. 1999, Information Bulletin on Variable Stars, 4711, 1
Agerer, F., & Hübscher, J. 2000, Information Bulletin on Variable Stars, 4912, 1
Agerer, F., & Hübscher, J. 2001, Information Bulletin on Variable Stars, 5016, 1
Agerer, F., & Hübscher, J. 2002, Information Bulletin on Variable Stars, 5296, 1
Agerer, F., & Hübscher, J. 2003, Information Bulletin on Variable Stars, 5484, 1
Ahnert, P. 1960, Zentralinstitut fuer Astrophysik Sternwarte Sonneberg Mitteilungen ueber Veraenderliche Sterne, 1, 513
Ahnert, P. 1976, Zentralinstitut fuer Astrophysik Sternwarte Sonneberg Mitteilungen ueber Veraenderliche Sterne, 7, 131
Andrakakou, M., Boistel, G., Boninsegna, R., et al. 1981, Bulletin der Bedeckungsveraenderlichen-Beobachter der Schweizerischen Astronomischen Gesellschaft, 56, 1
Applegate, J. H. 1992, ApJ, 385, 621
Ashbrook, J. 1952, AJ, 57, 259
Ashbrook, J. 1953, AJ, 58, 171
Bakis, V., Bakis, H., Erdem, A., et al. 2003, Information Bulletin on Variable Stars, 5464, 1
Bakis, V., Dogru, S. S., Bakis, H., et al. 2005, Information Bulletin on Variable Stars, 5662, 1
Baldwin, M. E. 1964, Sky and Telescope, 28, 244
Baldwin, M. E., & Samolyk G., 1999, Observed Minima Timings of Eclipsing Binaries: Number 5 (Cambridge, MA (USA): The American Association of Variable Star Observers)
Baldwin,M. E., & Samolyk G., 2000, Observed Minima Timings of Eclipsing Binaries: Number 6 (Cambridge, MA (USA): The American Association of Variable Star Observers)
Baldwin, M. E., & Samolyk G., 2004, Observed Minima Timings of Eclipsing Binaries: Number 9 (Cambridge, MA (USA): The American Association of Variable Star)
Baldwin, M. E., & Samolyk, G. 2002, Observed Minima Timings of Eclipsing Binaries: Number 7 (Cambridge, MA (USA): American Association of Variable Star Observers)
Baldwin, M. E., & Samolyk, G. 2006, Observed minima timings of eclipsing binaries: Number 11 (Cambridge, MA (USA): American Association of Variable Star Observers)
Baldwin, M. E., & Samolyk, G. 2007, The American Association of Variable Star Observers, 12, 1
Barani, C. 1995, Bulletin der Bedeckungsveraenderlichen-Beobachter der Schweizerischen Astronomischen Gesellschaft, 108, 3
Binnendijk, L. 1968, AJ, 73, 32
Biro, I. B., & Borkovits, T. 2000, Information Bulletin on Variable Stars, 4967, 1
Biro, I. B., Borkovits, T., Csizmadia, S., et al. 2006, Information Bulletin on Variable Stars, 5684, 1
Blättler, E. 1992, Bulletin der Bedeckungsveraenderlichen-Beobachter der Schweizerischen Astronomischen Gesellschaft, 101, 2
Borkovits, T., & Biro, I. B. 1998, Information Bulletin on Variable Stars, 4633, 1
Borkovits, T., Biro, I. B., & Kovacs, T. 2001, Information Bulletin on Variable Stars, 5206, 1
Borkovits, T., Biro, I. B., Hegedus, T., et al. 2002, Information Bulletin on Variable Stars, 5313, 1
Borkovits, T., Elkhateeb, M. M., Csizmadia, S., et al. 2005, A&A, 441, 1087
Borkovits, T., Biro, I. B., Hegedus, T., et al. 2011, Information Bulletin on Variable Stars, 5979, 1

Brat, L., Trnka, J., Smelcer, L., et al. 2011, Open European Journal on Variable Stars, 137, 1
Brát, L., Šmelcer, L., Kuèáková, H., et al. 2008, Open European Journal on Variable Stars, 94, 1
Brelstaff, T. 1997, British Astronomical Association Variable Star Section Circular, 91, 16
Brno Observers 2002, Open European Journal On Variable Stars, 32, 1
Bush, H. 1968, Hartha Mitt., 1
Czerlunczakiewicz, B., & Flin, P. 1968, Acta Astronomica, 18, 331
Dai, H.-F., Yang, Y.-G., & Yin, X.-G. 2011, New Astron., 16, 173
Davidge, T. J., & Milone, E. F. 1984, ApJS, 55, 571
Demircan, O., & Gudur, N. 1981, in Photometric and Spectroscopic Binary Systems, ed. E. B. Carling & Z. Kopal, 413
Demircan, O., & Guerol, B. 1996, A&AS, 115, 333
Demircan, O., Erdem, A., Ozdemir, S., et al. 2003, Information Bulletin on Variable Stars, 5364, 1
Diethelm, R. 2003, Information Bulletin on Variable Stars, 5438, 1
Diethelm, R., & Acerbi, F. 1994, Bulletin der Bedeckungsveraenderlichen-Beobachter der Schweizerischen Astronomischen Gesellschaft, 107, 1
Djurašević , G., & Erkapić , S. 1998, Ap&SS, 262, 305
Dogru, S. S., Donmez, A., Tuysuz, M., et al. 2007, Information Bulletin on Variable Stars, 5746, 1
Drilling, J. S., & Landolt, A. U. 2000, Normal Stars, ed. A. N. Cox, Allen's Astrophysical Quantities, ed. A. N. Cox (New York: AIP Press; Springer), 381
Ebersberger, J., Pohl, E., & Kizilirmak, A. 1978, Information Bulletin on Variable Stars, 1449, 1
Erkan, N., Erdem, A., Akin, T., Alicavus, F., & Soydugan, F. 2010, Information Bulletin on Variable Stars, 5924, 1
Essam, A., El-Bassuni, A. A., & Mahdy, H. A. 1992, Ap&SS, 188, 127
Fitch, W. S. 1964, AJ, 69, 316
Flannery, B. P. 1976, ApJ, 205, 217
Flin, P. 1969, Acta Astronomica, 19, 173
Flin, P., & Słowik, A. 1967, Acta Astronomica, 17, 59
Florja, N. F. 1933, Perem. Zvezdy, 4, 111
Florja, N. F., & Kukarkin, B. V. 1932, Tashkent Circular, 5
Gurol, B. 1994, Information Bulletin on Variable Stars, 4103, 1
Gurol, B., Gurdemir, L., Caglar, A., et al. 2003, Information Bulletin on Variable Stars, 5443, 1
Hanzl, D. 1990, Information Bulletin on Variable Stars, 3423, 1
Hanzl, D. 1991, Information Bulletin on Variable Stars, 3615, 1
Hegedus, T. 1987, Information Bulletin on Variable Stars, 3125, 1
Hoffleit, D. 1932, Harvard College Observatory Bulletin, 887, 9
Hrivnak, B. J. 1989, ApJ, 340, 458
Hrivnak, B. J., Guinan, E. F., DeWarf, L. E., & Ribas, I. 2001, AJ, 121, 1084
Hübscher, J., & Lichtenknecker, D. 1988, Berliner Arbeitsgemeinschaft fuer Veraenderliche Sterne - Mitteilungen, 50, 2
Hübscher, J., D., L., & Wunder, E. 1989, Berliner Arbeitsgemeinschaft fuer Veraenderliche Sterne - Mitteilungen, 52, 2
Hübscher, J., Lichtenknecker, D., & Wunder, E. 1990, Berliner Arbeitsgemeinschaft fuer Veraenderliche Sterne - Mitteilungen, 56, 2
Hübscher, J., Agerer, F., Hassforther, B., & Wunder, E. 1997, Berliner Arbeitsgemeinschaft fuer Veraenderliche Sterne - Mitteilungen, 101, 1
Hübscher, J., Agerer, F., Busch, H., et al. 1999, Berliner Arbeitsgemeinschaft fuer Veraenderliche Sterne - Mitteilungen, 122, 1
Hübscher, J. 2001, Berliner Arbeitsgemeinschaft fuer Veraenderliche Sterne - Mitteilungen, 143, 1
Hübscher, J., Agerer, F., Hassforther, B., Lange, T., & Pasch, A. K. 2003, Berliner Arbeitsgemeinschaft fuer Veraenderliche Sterne - Mitteilungen, 157, 1
Hübscher, J. 2005, Information Bulletin on Variable Stars, 5643, 1
Hübscher, J., Lange, T., Paschke, A., & Walter, F. 2005a, Berliner Arbeitsgemeinschaft fuer Veraenderliche Sterne - Mitteilungen, 174, 1
Hübscher, J., Paschke, A., & Walter, F. 2005b, Information Bulletin on Variable Stars, 5657, 1
Hübscher, J., Paschke, A., & Walter, F. 2006, Information Bulletin on Variable Stars, 5731, 1
Hübscher, J., & Walter, F. 2007, Information Bulletin on Variable Stars, 5761, 1
Hübscher, J., Steinbach, H.-M., & Walter, F. 2009, Information Bulletin on Variable Stars, 5889, 1
Hübscher, J., Lehmann, P. B., Monninger, G., Steinbach, H.-M., & Walter, F. 2010, Information Bulletin on Variable Stars, 5918, 1
Hübscher, J. 2011a, Open European Journal on Variable Stars, 131, 1
Hübscher, J. 2011b, Information Bulletin on Variable Stars, 5984, 1
Hübscher, J., Lehmann, P. B., & Walter, F. 2012, Information Bulletin on Variable Stars, 6010, 1
İçli, T., Koçak, D., Boz, G. Ç., & Yakut, K. 2013, AJ, 145, 127
Irwin, J. B. 1952, ApJ, 116, 211
Irwin, J. B. 1959, AJ, 64, 149
Kalimeris, A., Rovithis-Livaniou, H., & Rovithis, P. 2002, A&A, 387, 969
Keskin, V., & Pohl, E. 1989, Information Bulletin on Variable Stars, 3355, 1
Kim, C.-H., Lee, C.-U., Yoon, Y.-N., et al. 2006, Information Bulletin on Variable Stars, 5694, 1
Kizilirmak, A., & Pohl, E. 1971, Information Bulletin on Variable Stars, 530, 1
Kizilirmak, A., & Pohl, E. 1974, Information Bulletin on Variable Stars, 937, 1
Klimek, Z. 1973, Information Bulletin on Variable Stars, 779, 1
Kreiner, J. M., Kim, C.-H., & Nha, I.-S. 2001, An Atlas of O-C Diagrams of Eclipsing Binary Stars (An Atlas of O-C Diagrams of Eclipsing Binary Stars / by Jerzy M. Kreiner, Chun-Hwey Kim, Il-Seong Nha. Cracow, Poland: Wydawnictwo Naukowe Akademii Pedagogicznej. 2001.)

Kurucz, R. L. 1993, IAU Commission on Close Binary Stars, 21, 93
Kwee, K. K., & van Woerden, H. 1956, Bull. Astron. Inst. Netherlands, 12, 327
Lafta, S. J., & Grainger, J. F. 1985, Ap&SS, 114, 23
Lanza, A. F., & Rodonò, M. 1999, A&A, 349, 887
Lanza, A. F., Rodono, M., & Rosner, R. 1998, MNRAS, 296, 893
Lause, F. 1935, Astronomische Nachrichten, 257, 73
Lee, J. W., Kim, C.-H., Han, W., Kim, H.-I., & Koch, R. H. 2004, MNRAS, 352, 1041
Lenz, P., & Breger, M. 2005, Communications in Asteroseismology, 146, 53
Li, H.-L., Yang, Y.-G., Su, W., Wang, H.-J., & Wei, J.-Y. 2009, RAA (Research in Astronomy and Astrophysics), 9, 1035
Li, L., & Zhang, F. 2006, New Astron., 11, 588
Lucy, L. B. 1967, ZAp, 65, 89
Maceroni, C., & van't Veer, F. 1996, A&A, 311, 523
Madej, J., & Malas, Z. 1974, Astrophysics Reports Publications of the Beijing Astronomical Observatory, 1, 33
Marchini, A., Banfi, M., Cena, M., et al. 2011, Journal of the American Association of Variable Star Observers (JAAVSO), 39, 102
Marino, G., Arena, C., Bellia, I., et al. 2010, Information Bulletin on Variable Stars, 5917, 1
Martynov, D. Y. 1933, Perem. Zvezdy, 4, 115
Martinoff, D. I. 1938, Perem. Zvezdy, 5, 205
Mavrofridis, G., & Diethelm, R. 1987, BBSAG Bull., 84, 1
Mayer, P. 1990, Bulletin of the Astronomical Institutes of Czechoslovakia, 41, 231
Miczaika, G. R. 1937, Astronomische Nachrichten, 261, 301
Milone, E. E. 1968, AJ, 73, 708
Mochnacki, S. W. 1981, ApJ, 245, 650
Nagai, K. 2000, VSOLJ Var. Star Bull., 37, 2
Nagai, K., 2003, Var.Star Bull. Japan, 40, 1 *http://vsolj.cetus-net.org/no44.pdf*
Nagai, K. 2004, Variable Star Bulletin (Japan), 42, 1
Nagai, K., 2005, Var.Star Bull. Japan, 43, 1 *http://vsolj.cetus-net.org/no44.pdf*
Nagai, K., 2006, Var.Star Bull. Japan, 44, 1 *http://vsolj.cetus-net.org/no44.pdf*
Nagai, K. 2007, Variable Star Bulletin (Japan), 45, 1
Nagai, K. 2009, Variable Star Bulletin (Japan), 48, 1
Nagai, K. 2011, Variable Star Bulletin (Japan), 51, 1 *http://vsolj.cetus-net.org/no44.pdf*
Nelson, R. H. 2000, Information Bulletin on Variable Stars, 4840, 1
Paschke, A. 1985, Bulletin der Bedeckungsveraenderlichen-Beobachter der Schweizerischen Astronomischen Gesellschaft, 78, 6
Paschke, A. 1992, Bulletin der Bedeckungsveraenderlichen-Beobachter der Schweizerischen Astronomischen Gesellschaft, 99, 2
Peter, H., Martin, B., Peter, S., et al., 2000, BBSAG Bull., 121, 1
Pohl, E. 1969, Information Bulletin on Variable Stars, 391, 1
Pohl, E., Akan, M. C., Ibanoglu, C., Sezer, C., & Gudur, N. 1987, Information Bulletin on Variable Stars, 3078, 1
Pohl, E., Hamzaoglu, E., Gudur, N., & Ibanoglu, C. 1983, Information Bulletin on Variable Stars, 2385, 1
Pohl, E., & Kizilirmak, A. 1970, Information Bulletin on Variable Stars, 456, 1
Pohl, E., & Kizilirmak, A. 1972, Information Bulletin on Variable Stars, 647, 1
Pohl, E., & Kizilirmak, A. 1975, Information Bulletin on Variable Stars, 1053, 1
Pohl, E., & Kizilirmak, A. 1976, Information Bulletin on Variable Stars, 1163, 1
Pohl, E., & Kizilirmak, A. 1977, Information Bulletin on Variable Stars, 1358, 1
Pribulla, T., Rucinski, S. M., Conidis, G., et al. 2007, AJ, 133, 1977
Qian, S., Liu, Q., & Yang, Y. 1999, A&A, 341, 799
Rafert, J. B. 1982, PASP, 94, 485
Rappaport, S., Verbunt, F., & Joss, P. C. 1983, ApJ, 275, 713
Robertson, J. A., & Eggleton, P. P. 1977, MNRAS, 179, 359
Ruciński, S. M. 1973, Acta Astronomica, 23, 79
Samolyk, G. 2008, Journal of the American Association of Variable Star Observers (JAAVSO), 36, 186
Samolyk, G. 2010, Journal of the American Association of Variable Star Observers (JAAVSO), 38, 85
Samolyk, G. 2011, Journal of the American Association of Variable Star Observers (JAAVSO), 39, 94
Scarfe, C. D., & Barlow, D. J. 1978, Information Bulletin on Variable Stars, 1379, 1
Scarfe, C. D., Forbes, D. W., Delaney, P. A., & Gagne, J. 1984, Information Bulletin on Variable Stars, 2545, 1
Saijo K., 1995, Var. Star Bull. Japan, 23, 1 *http://vsolj.cetus-net.org/no23.pdf*
Selam, S. O., Albayrak, B., Senavci, H. V., et al. 2003, Information Bulletin on Variable Stars, 5471, 1
Senavci, H. V., Tanriverdi, T., Torun, E., et al. 2007, Information Bulletin on Variable Stars, 5754, 1
Soloviev, A. 1934, Tadjik Circ., 3, 1
van Hamme, W. 1993, AJ, 106, 2096
Verbunt, F., & Zwaan, C. 1981, A&A, 100, L7
Webbink, R. F. 2003, in Astronomical Society of the Pacific Conference Series, 293, 3D Stellar Evolution, ed. S. Turcotte, S. C. Keller, & R. M. Cavallo, 76
Wilson, R. E. 1979, ApJ, 234, 1054
Wilson, R. E. 1990, ApJ, 356, 613
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Wolf, M., Diethelm, R., & Šarounová, L. 1999, A&A, 345, 553
Wunder, E., Wieck, M., Kilinc, B., et al. 1992, Information Bulletin on Variable Stars, 3760, 1
Yang, Y.-G., Qian, S.-B., & Soonthornthum, B. 2012, AJ, 143, 122
Yang, Y.-G., Qian, S.-B., Zhang, L.-Y., Dai, H.-F., & Soonthornthum, B. 2013, AJ, 146, 35
Zahn, J. P. 1966, Annales d'Astrophysique, 29, 313
Zasche, P. 2005, in WDS'05 Proc. of Contributed Papers: Part III-Physics, ed. J. Safrankova (Prague:Matfyzpress), 446
Zhang, L., Jing, J., Tang, Y., & Zhang, X. 2010, New Astron., 15, 653
Zhang, L., Pi, Q., Yang, Y., & Li, Z. 2014, New Astron., 27, 81