A Fresh Look at the Algol-like Eclipsing Binary, AO Ser

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Abstract

CCD images acquired in B, V, and I_c passbands between July and August 2008 and from June to August 2010 were used to revise the ephemeris and update the orbital period for AO Ser. Analysis of the O-C diagram using all available time-of-minima data revealed a continually increasing orbital period for at least 68 years. Thereafter, a sudden decrease in orbital period (~0.84 sec) most likely occurred during the first few months of 1998; potential causes for this abrupt jump and other alternating changes in period are discussed. Although the spectral classification of the primary star has been long considered A2V (T_{eff} ~8800 K), B-V data from this study as well as color index estimates from several other recent survey catalogs suggest a significantly cooler A7V (T_{eff} ~7800 K) primary. A semi-detached Roche model of the binary produced theoretical fits matching light curve data in all passbands. AO Ser is reported to be an oscillating Algol-type variable star referred to as an oEA system. Using Fourier methods, lightcurve analysis in this study did not convincingly reveal any underlying periodicity other than that expected from the dominant orbital period.

1. Introduction

AO Ser is a short period (<1 day) and bright Algol-type binary suitable for study by amateur and professional astronomers alike. After its discovery in 1935 by the prolific observer Cuno Hoffmeister, the publication record for AO Ser was very sporadic with only a handful of times-of-minima (ToM) available for each of the next three decades. These mostly included photographic as well as visual timings. Only since 1969 has a steady flow of ToM values been available but no full light curve had been published until Zavros *et al*. (2008). AO Ser not only varies extrinsically by mutual eclipses but evidence is mounting that it also varies intrinsically by δ Sct-type pulsation of its primary component (Kim *et al*., 2004; Zavros *et al*., 2008). This new class of oscillating Algol-type variable stars is now designated as an oEA variable (Mkrtichian *et al*., 2004). More recently, the multiband (V and R) photometric properties and period variations of AO Ser were published by Yang et al (2010).

AO Ser (BD+17°2943) varies in magnitude (V) between 10.8 and 12.2; the first modern orbital period (0.87934745 d) was reported by Koch (1961). This target is favorably positioned (α_{J2000} = 15^{h}58^{m}18^s.408, δ_{J2000}= +17°16'9.96") for mid latitude backyard observers in the Northern Hemisphere with a clear view of Serpens Caput. Its spectral type (A2) reported by Brancewizc and Dworak (1980) is consistent with what would be expected for an Algol-like binary system, however, evidence from this study and several survey catalogs (eg. Tycho-2, USNO-A2.0, USNO-B1.0, and 2MASS) suggest a much cooler A7 system. This difference from all other published reports on this binary system will be discussed herein.

2. Methods, Observations and Data Reduction

2.1 Astrometry

Images of AO Ser were matched against the UCAC3-based standard star fields provided in MPO Canopus (V10.3.0.2 Bdw Publishing, Inc.). This "automatch" feature generates a star chart centered on the putative center of the image and then matches the chart's center, rotation, and scaling to the image. Plate constants are internally calculated which convert X/Y coordinates of a detected object to a corresponding RA and declination.

2.2 Photometry

CCD observations at UnderOak Observatory span from 2008 July 25 to August 22 and then again from 2010 June 19 to August 31. Equipment included a 0.2-m catadioptric telescope with an SBIG ST 402ME CCD camera mounted at the primary focus. The KAF 0402ME camera array (765×510) comprised of square pixels (9 µm) produces a ~9×14 arcmin field-of-view (FOV) with an image scale of ~1 arcsec/pixel with this optical assembly. The CCD camera was maintained at 0°C with thermoelectric cooling. Automated multi-bandwidth (B, V, and I_c) imaging was performed with SBIG photometric filters manufactured to match the Bessell prescription. During each 2008 session, an image in each bandpass was sequentially collected every 45 s; data acquisition and reduction (raw lights, darks, and flats) for this camera system has been described elsewhere (Alton, 2010). The other campaign which started in 2010 employed essentially the same equipment except that the acquisition time for each filter was increased to 60 s. Instrumental readings were reduced to catalog-based magnitudes using the MPOSC3 reference star fields built into MPO Canopus. The MPO Star Catalog (MPOSC3) is a hybrid assemblage which includes a large subset of the Carlsberg Meridian Catalog (CMC-14) as well as from the Sloan Digital Sky Survey (SDSS). Almost all stars in MPOSC3 also have BVRI magnitudes derived from 2MASS J-K magnitudes; these have an internal consistency of ±0.05 mag for V, ±0.08 mag for B, ±0.03 mag for I_c, and ±0.05 mag for B-V (Warner, 2007).

2.3 Lightcurve Analyses

Light curve modeling was performed using Binary Maker 3 (Bradstreet and Steelman, 2002), PHOEBE 0.31a (Prša and Zwitter, 2005), and WDwint Version 5.6a (Nelson, 2009), all of which employ the Wilson-Devinney (W-D) code (Wilson and Devinney, 1971; Wilson, 1979). Geometric renderings were produced by Binary Maker 3 (Bradstreet and Steelman, 2002).

3. Results and Discussion

3.1 Ensemble Photometry

Five comparison stars in the same field of view with AO Ser were used to calculate the relative change in flux and standard magnitudes (Table I). Over the duration of each session, comparison stars did not exhibit any variable behavior so Comp Cavg values remained constant over each observation period (Figure 1). The mean standard magnitude for each comparison star varied between ±0.015 (V and I_c) and ±0.03 (B) mag. During the entire campaign the airmass for all observations was kept under 2 to minimize error due to differential refraction and color extinction.

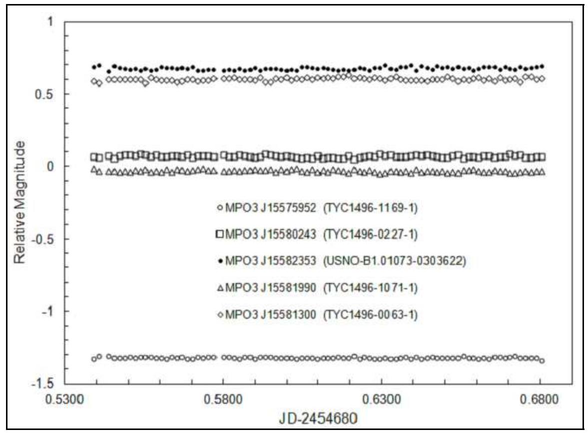

Figure 1. Constant relative magnitude (I_c-band) exhibited by comparison stars during a typical AO Ser photometric session (2008 Aug 02).

3.2 Folded Light Curves and Ephemerides

Individual photometric values in B (n = 1573), V (n = 1598), and I_c (n = 1580) were combined by filter to produce light curves that spanned 4 weeks of imaging in 2008 and 10 weeks in 2010. A period solution from all folded 2008 and 2010 datasets was calculated by MPO Canopus. Accordingly, the linear ephemeris (Eq. 1) for the heliocentric primary minimum was initially determined to be:

$$\text{Min I} = \text{HJD } 2454664.54963 + 0.8793429\ (\pm 0.0000013) \cdot E \qquad (1)$$

This result is in general agreement with the orbital period reported over the past 5 decades from other investigators. The period determination was confirmed with periodograms produced (Peranso v 2.1, CBA Belgium Observatory) by applying periodic orthogonals (Schwarzenberg-Czerny, 1996) to fit observation and analysis of variance (ANOVA) which was used to evaluate fit quality.

ToM values were estimated by Minima (V24b, Nelson, 2007) using a simple mean from a suite of six different methods including parabolic fit, tracing paper, bisecting chords, Kwee and van Woerden (1956), Fourier fit, and sliding integrations (Ghedini, 1981). Four new secondary (s) and two new primary (p) minima were detected during this investigation. Since no obvious color dependencies emerged, the timings from all three filters were averaged for each newly determined ToM. Residual values (O-C) were estimated from a complete set of visual (vis), photographic (pg), photoelectric (pe) and CCD timings reported over the past 80 years. Calculations were

MPOSC3[1] Star Identification	RA	DEC	B mag	V mag	I_c mag	(B-V)
MPO3 J15575952	$15^h57^m59^s.52$	+17°19′26.3″	10.843	10.41	9.889	0.433
MPO3 J15580243	$15^h58^m02^s.43$	+17°21′13.4″	11.985	11.547	11.021	0.438
MPO3 J15581300	$15^h58^m13^s.00$	+17°16′42.5″	12.852	12.158	11.391	0.694
MPO3 J15581841	$15^h58^m18^s.41$	+17°16′10.0″	11.667	11.208	10.661	0.459
MPO3 J15581990	$15^h58^m19^s.90$	+17°19′45.4″	12.518	11.50	10.445	1.018
MPO3 J15582353	$15^h58^m23^s.53$	+17°18′39.8″	12.876	12.214	11.474	0.662

[1]MPOSC3 is a hybrid assemblage which includes a large subset of the Carlsberg Meridian Catalog (CMC-14), the Sloan Digital Sky Survey (SDSS), and 2MASS Catalog.

Table I. Astrometric Coordinates and Estimated Color of AO Ser (MPO3 J15581841) and Five Comparison Stars in Same Field of View

initially based upon the linear elements (Eq. 2) defined by Kreiner (2004):

$$\text{Min I} = \text{HJD } 2452500.3991\ (\pm 0.0007) + 0.8793410\ (\pm 0.0000004) \cdot E \qquad (2)$$

The O-C diagram (Figure 2) for AO Ser is complex and characterized by parabolic and possibly alternating changes exhibited by many other late type Algol-like binary systems such as U Cep (Manzoori, 2008), Y Leo (Pop, 2005), TY Peg (Qian, 2002), and X Tri (Qian, 2002). Regression analysis using a scaled Levenberg-Marquardt algorithm (Press *et al*., 1992) as implemented in QtiPlot (v0.9.8 2010) revealed that the O-C data from the initial timing in 1930 until the last twelve years could be fit ($r^2 > 0.99$) by a quadratic expression (Eq. 3) modulated with a sinusoidal term:

$$c + a_1x + a_2x^2 + a_3\sin(a_4x + a_5) \qquad (3)$$

Accordingly, the coefficients (± error) for each solved term in the above (Eq. 3) are provided in Table II. From the parabolic component ($c + a_1x + a_2x^2$) it is apparent that the orbital period has been slowly increasing linearly with time as suggested by the positive coefficient (a_2) for the quadratic term, x^2. Algol-type binaries typically consist of a hot main-sequence massive primary well within its Roche lobe and a less-massive subgiant companion filling its Roche lobe. Gas streams from the secondary to the primary result in mass exchange and barring any other competing phenomena, the net effect is a change in the orbital period. In this case, the orbital period rate of increase ($\Delta p/p = 2a_2 = 1.25 \times 10^{-10}$) of this system, which is equivalent to a period increase rate of $dP/dt = +0.004479$ sec yr^{-1}, lasted for at least 68 years but suddenly slowed to a standstill as judged by the break in O-C residuals (Figure 2) around cycle -1855. The intersection of Q+S and L1 suggests this change which is centered at the beginning of 1998 probably occurred sometime between mid 1996 and mid-1999. This cannot be attributed to the shift from vis-pg to ccd-pe recordings since instrument-derived ToMs regularly reported after cycle 118.5 continue in a similar fashion until another break is observed near cycle 2000. This characterization of AO Ser is in contrast to that described by Yang et al. (2010) who only report a period decrease since 1981. This obvious difference from our findings is dis-

Curve	c	a_1	a_2	a_3	a_4	a_5
L1a	1.593×10-3 (±0.290×10-3)	-8.679×10-7 (±0.228)	-	-	-	-
L2a	-6.503×10-3 (±1.088×10-3)	3.046×10-6 (±0.4189×10-6)	-	-	-	-
Q+Sb	1.667×10-2 (±0.136×10-2)	+8.911×10-6 (±0.237×10-6)	+6.240×10-11 (±0.760×10-11)			
Q+Sc	1.667×10-2 (±0.136×10-2)	+8.911×10-6 (±0.237×10-6)	+6.240×10-11 (±0.760×10-11)	+3.748×10-3 (±0.593×10-3)	4.249×10-4 (±0.206×10-4)	3.209 (±0.244)

a: Linear least squares fit: $(O\text{-}C) = c + a_1x$
b: Non-linear regression fit $(O\text{-}C) = c + a_1x + a_2x^2$
c: Non-linear regression fit $(O\text{-}C) = c + a_1x + a_2x^2 + a_3\sin(a_4x + a_5)$

Table II. Coefficients (±error) From Regression Analysis of O-C vs Cycle Number Data for AO Ser

cussed further on in this section along with the potential for a light time effect which they also had proposed.

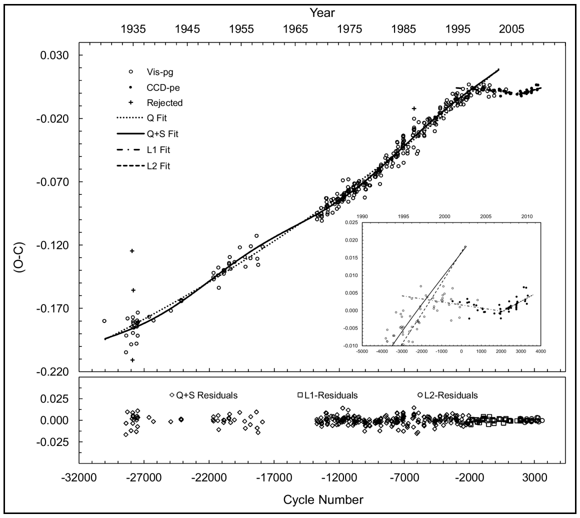

Figure 2. Nonlinear quadratic+sine term fit (Q+S) of residuals (O-C) vs cycle number for AO Ser observed from 1930 March to 1998 June 17. The inset figure shows a breakpoint centered near cycle -1855 (1998 Feb-March) and the straight line linear fit of data (L1) through cycle 1983.5 (mid-2007). Near term data (L2) were also fit using simple linear least squares analysis. The bottom panel represents a composite plot of all $(O-C)_2$ residuals from fitting Q+S, L1, and L2. All ToM values and references used to prepare this figure can be obtained by request (mail@underoakobservatory.com).

Calculations based on linear coefficients from the quadratic + sine term (Eq. 4) and simple least squares (Eq. 5) fits resulted in the following ephemerides, respectively:

Min I = HJD 2455666.9548 (± 0.0013)
+ 0.8793499 (± 0.0000002) · E (4)

Min I = HJD 2455666.9045 (± 0.0003)
+ 0.8793401 (± 0.0000002) · E (5)

The orbital period difference (-9.7788×10^{-6} days) between equations (Eq. 4) and (Eq. 5) corresponds to a rather large decrease (0.844 sec) over a relatively short period of time. The two most likely causes for a decrease in period are mass exchange between the components and/or angular momentum loss from the binary system. A rate of conservative mass transfer can be predicted (Eq. 6) as follows from Kwee (1958):

$$dm/dt = m\left[\frac{q}{3P(1-q^2)}\right]dP/dt \qquad (6)$$

where

$$m = M_1 + M_2 \text{ and } q = M_2/M_1$$

The abrupt change in orbital period likely took place within a 3 year window as suggested by the O-C diagram (Figure 2). Assuming the solar mass of a putative A7V primary approximates 1.82 M⊙ (Harmanec, 1988), then from the mass ratio (q_{ph}=0.235) determined herein, the calculated mass loss is 6.851×10^{-7} M⊙ y^{-1}. Averaged over three years this translates into nearly two-thirds of the Earth's mass. Alternatively from Mikuž *et al*. (2002), the associated change in angular momentum can also be estimated from the equations for total angular momentum (L) and Kepler's law:

$$\frac{dL}{L} = \left[\frac{2}{3} + \frac{q}{3(1+q)}\right]dm_1/m_1 + \left[1 - \frac{q}{3(1+q)}\right]dm_2/m_2 + \frac{1}{3}dP/P,$$

where $q = m_2/m_1$ and P is the period of AO Ser.

Assuming that the angular momentum change dL can only be zero or a negative value, then in order to produce a period change of $dP/P = 1.11\times10^{-5}$ the total mass lost from the system had to be at least 3.23 $\times10^{24}$ kg or slightly more than one half (~54%) of Earth's mass. The corresponding magnitude of mass loss estimated by either equation 6 or 7 is significant but nonetheless not unprecedented (1.626×10^{-4} to 9.5×10^{-8} M⊙ y^{-1}) for semi-detached binaries (van Rensbergen *et al.*, 2011).

Due to the continually changing nature of the O-C diagram, a new ephemeris equation (Eq. 8) based upon a linear least squares fit (L2) of near-term data (Table III) collected over the past four years (cycle 1905 to 3601) was calculated:

Min I = HJD 2455,666.9105(± 0.0011)
+ 0.8793441 (± 0.0000004) · E (8)

As such, if the complex O-C behavior of this system continues unabated, revised ephemerides for AO Ser will need to be calculated on a more regular basis. The composite residuals from the quadratic + sine term fit (Q+S) and simple least squares fit (L1 and L2) are shown in the bottom panel of Figure 2. No additional underlying periodicity in the $(O-C)_2$ diagram was uncovered with Peranso using Fourier (Lomb-Scargle) and statistical (ANOVA) methods.

In a recent publication, Yang *et al*. (2010) attempted to make a case for decreasing period and a third body with an incomplete set of data which excluded all pg and visual (n = 300) plus other CCD readings (n = 10) published from 1941 through the middle of 2008. It is unfortunate that this rich set of

Time of Minimum (– 2,400,000)	Type	Cycle Number	$(O-C)_1$	$(O-C)_2$	Reference
54175.5429	p	1905	-0.000805	-0.000700	3
54186.5371	s	1917.5	0.001632	-0.000662	3
54201.4835	s	1934.5	-0.000765	-0.000610	3
54211.5959	p	1946	-0.000786	-0.000575	3
54213.3545	p	1948	-0.000868	-0.000569	3
54220.3893	p	1956	-0.000826	-0.000545	2
54220.3906	p	1956	0.000494	-0.000545	2
54224.7859	p	1961	-0.000901	-0.000529	1
54242.3741	p	1981	0.000459	-0.000469	2
54244.5717	s	1983.5	-0.000274	-0.000461	3
54491.6646	s	2264.5	-0.002195	0.000395	4
54574.7651	p	2359	0.000581	0.000683	5
54581.3604	s	2366.5	0.000823	0.000706	6
54599.3865	p	2387	0.000433	0.000768	7
54610.8172	p	2400	-0.000300	0.000808	5
54612.5770	p	2402	0.000818	0.000814	8
54614.3375	p	2404	0.002636	0.000820	8
54628.4051	p	2420	0.000780	0.000869	8
54685.5625	p	2485	0.001015	0.001067	9
54696.5546	s	2497.5	0.001353	0.001105	9
54926.5017	p	2759	0.000781	0.001901	10
54928.2612	p	2761	0.001599	0.001907	11
54928.2614	p	2761	0.001799	0.001907	11
54929.1397	p	2762	0.000758	0.001911	11
54929.1400	p	2762	0.001058	0.001911	11
54932.2170	s	2765.5	0.000364	0.001921	11
54932.2181	s	2765.5	0.001464	0.001921	11
54939.6925	p	2774	0.001466	0.001947	12
54952.8851	p	2789	0.003951	0.001993	13
54968.7113	p	2807	0.002013	0.002048	12
54974.4272	s	2813.5	0.002196	0.002067	9
55259.7737	p	3138	0.002542	0.003056	14
55316.4953	s	3202.5	0.006647	0.003252	15
55327.4831	p	3215	0.002685	0.003290	15
55366.6142	s	3259.5	0.003157	0.003426	9
55395.6358	s	3292.5	0.006504	0.003526	9
55436.5206	p	3339	0.001938	0.003668	9
55666.9103	p	3601	0.004259	0.004466	16

(1) Baldwin and Samolyk, 2007 (2) Brát *et al.,* 2007 (3) Borkovits *et al.,* 2008 (4) Parimucha *et al*., 2009 (5) Samolyk, 2008 (6) Brát *et al*., 2008 (7) Hübscher *et al*., 2010 (8) Lampens *et al*., 2010 (9) Present study (10) Doğru *et al*., 2009 (11) Yang *et al*., 2010 (12) Samolyk, 2010 (13) Diethelm, 2009 (14) Samolyk, 2011 (15) Doğru *et al*., 2011 (16) Diethelm, 2011.

Table III. Near Term Recalculated Residuals $(O-C)_2$ for AO Ser Following Simple Linear Least Squares Fit of $(O-C)_1$ and Cycle Number Between 2007March16 and 2011April15.

data was not considered since out of 300 additional visual and pg observations, we found that only four values needed to be rejected as spurious. In contrast when all data are evaluated, residuals for the first seven decades clearly describe an upwardly turned parabola (Q), namely behavior consistent with conservative mass transfer and a continually increasing period. Additionally on this quadratic curve, there is evidence for underlying cyclical changes based upon non-linear regression analysis (Eq. 3). The amplitude (0.003748 ± 0.000593 d) of the periodic oscillation is defined by a_3, the coefficient of the sine term. Assuming for the moment that this behavior is associated with a third body, then according to the relationship:

$$P_3 = 2\pi P/\omega,$$

where the angular frequency, ω, corresponding to $a_4 = 4.249\ (\pm 0.206)\times 10^{-4}$, its Keplerian orbital period would be ~36 y. This estimate is more than twice as long as the periodic value (~17 y) reported by Yang *et al*. (2010) using an incomplete dataset covering the time span between 1981 and 2009.

Analysis of the complete set O-C residuals available between 1930 and 2011 paints a very different behavioral picture for this binary system. We agree there is a modicum of evidence that suggests cyclic, if not sinusoidal behavior in the O-C diagram but only up to 1998. Thereafter, between 1998 and 2011 the O-C trace is curvilinear but not necessarily sinusoidal for this system. It is possible that the event(s) responsible for the sudden change in orbital period in 1998 have masked our ability to tease out the putative 36 year periodicity observed during prior epochs.

Nonetheless, since the gravitational influence of a third body cannot be simply turned off, we believe that evidence for the presence of a third body in this system is inconclusive. Moreover, during attempts to fit light curve data to a Roche type model with our data, neither the orbital eccentricity (e) nor third light (l_3) rose above a level different than zero when included as variable parameters.

This begs the question as to what other phenomena might lead to cyclic, but not necessarily, persistent sinusoidal behavior. Hall (1989) noted that Algol-like systems which exhibit alternating variability in their O¬C diagrams are almost exclusively those possessing a late-type secondary which to a high degree of certainty are chromospherically active. Furthermore, earlier type Algols composed of two radiative-envelope companions yield much simpler O-C diagrams rarely demonstrating cyclic behavior (Budding and Demircan, 2007). The secondary in AO Ser is likely a rapidly rotating late type subgiant and therefore possesses a dynamically active lobe-filling convection envelope.

A plausible alternative to the light travel time effect (LITE) from additional unseen mass involves cyclic variability arising from magnetic activity of the secondary (Applegate, 1992). In addition, Biermann and Hall (1973) proposed a model where the secondary experiences abrupt episodes of mass transfer which orbits the primary as a disk. This leads to a temporary reservoir of orbital angular momentum where P decreases but at later time, angular momentum is returned by accretion during which P increases.

This scenario may have played out with AO Ser starting with the sudden break observed in the O-C diagram in early 1998 followed by a period decrease which begins to reverse direction around cycle 2000 (mid-2007). At this time in the absence of any supporting data from a spectroscopic study or speckle interferometry it would be speculative to assign any single reason or combination of phenomena that would unequivocally include LITE as an explanation to this very complex O-C diagram for AO Ser.

3.3 Light Curve Synthesis

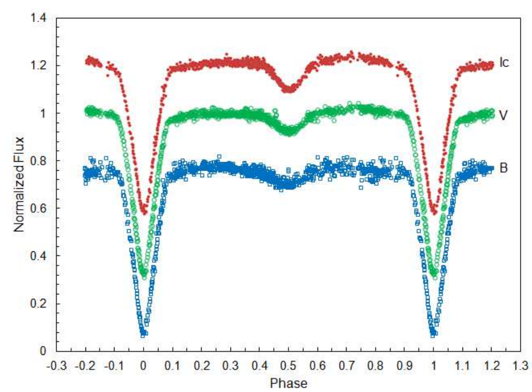

Figure 3. Folded (2008 July-August and 2010 June-August) CCD light curves for AO Ser captured in B, V, and I_c bandpasses.

Folded light curves (Figure 3) comprised of all observations (relative magnitude) in B, V, and I_c, show that minima are separated by 0.5 phase. Collectively, mode 5 (semi-detached; secondary fills Roche lobe), synchronous rotation and circular orbits were selected for modeling by PHOEBE. Each model fit incorporated individual observations assigned an equal weight of 1. Bolometric albedo ($A_1 = 1$) and gravity darkening coefficients ($g_1 = 1$) for the primary component were based on theoretical considerations for radiative stars reported by Eddington (1926) and von Zeipel (1924), respectively. As mentioned previously, third light (l_3) did not rise above a value different than zero when adjusted. Bolometric albedo (A_2=0.5) and gravity darkening coefficients (g_2 = 0.32) for cooler stars with convective envelopes were assigned as determined by Rucinski (1969) and Lucy (1967), respectively. After any change in Teff, logarithmic limb darkening coefficients (x_1, x_2, y_1, y_2) for both stars were interpolated from PHOEBE (Van Hamme, 1993). Once an approximate fit was obtained, differential corrections (DC) were applied simultaneously to photometric data in all filters.

3.3.1. Binary Model

As mentioned earlier the spectral type reported by Brancewizc and Dworak (1980) was A2 while the color index (B-V = –0.1) listed by Kreiner *et al.* (2004) suggests an even hotter primary star. Yet, evidence from this study which is the first to simultaneously acquire AO Ser light curves in B and V passbands, as well as data from multiple survey catalogs point to a much cooler system (Table IV).

The B-V value (0.247) observed in this study was taken during Min II when spectral contamination by the secondary was least likely to bias the result. In addition, maximum galactic reddening ($E_{(B-V)}$ = 0.0381) in this region of the sky (Schlegel *et al.*, 1998) is unremarkable and therefore no adjustment has been made to obtain the associated intrinsic color index for AO Ser.

On balance, we adopted an A7 spectral classification for AO Ser which is considerably cooler than that reported by all previous investigators; the effective temperature of the primary was estimated to be 7800 K based on the tables from Flower (1996). Values for q, Ω_1, Ω_2, and i reported by Zavros *et al.* (2008) were used as a starting point for an unspotted fit (V bandpass) using Binary Maker 3. A_1, A_2, g_1, g_2, q, and T_1 were fixed parameters whereas Ω_1, T_2, phase shift, x_1, x_2, and i were iteratively adjusted until a reasonable fit of the observed relative flux by the model was obtained.

Thereafter, the model fit was refined with PHOEBE while using DC to achieve a simultaneous minimum residual fit of all (B, V, and I_c) photometric observations. In mode 5, Ω_2 is constrained and as such is automatically calculated with any change to this parameter. The initial W-D model fit was marginally acceptable in all passbands which led to further adjustment of variable parameters. Early investigators of this Algol like system had used a mass ratio (q = m_2/m_1) of 0.45, presumably based on a tabulation of computed parameters for eclipsing binaries published by Brancewicz and Dworak (1980). However, in the absence of any radial velocity data for this binary system, it was deemed appropriate to allow this physical element to also vary freely.

An improved solution quickly emerged at a significantly different value, so it was decided to carefully examine this parameter under more controlled conditions. Mass ratio (q) was fixed over a range of 0.1 to 0.8 and a series of fits allowed to converge. The curve generated by plotting $\chi 2$ as a function of the putative mass ratio showed a shallow minimum between q = 0.220 and 0.260 (Figure 4). The mid-point (0.240) was nominally assigned as the starting q-value during Roche modeling.

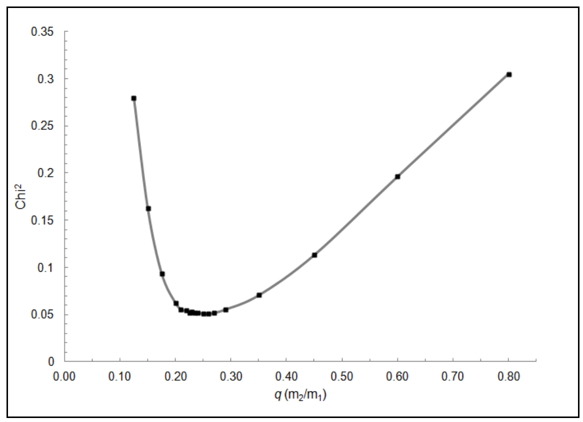

Figure 4. Search for mass ratio (q) providing the best simultaneous light curve fit (Chi^2) using data from all passbands (B, V, and I_c). The shallow minimum is essentially the same between 0.22 and 0.26 q.

Elements for AO Ser obtained using PHOEBE are provided in Table V while light curve fits for each filter band (B, V, and I_c) are respectively illustrated in Figures 5, 6, and 7. A 3-dimensional rendering produced using Binary Maker 3 depicts a spatial

Survey	Tycho-2	USNO-B1.0	USNO-A2.0	2MASS	ASCC-2.5 V3	Present Study
(B-V)[a]	0.219	0.195	0.235	0.459	0.266	0.247
Spectral Class[b]	A7	A7	A7	F5	A8	A7

a: Not corrected for galactic reddening – $E_{(B-V)}$ ~ 0.0381
b: Estimated from Fitzgerald (1970)

Table IV. AO Ser Color Index (B-V) From Several Survey Catalogs and the Present Study

Parameter	Present Study	Zavros *et al.* 2008	Yang *et al.* 2010
T_1 (K)[a]	7800	8770	9480
T_2 (K)[b]	4412 (33)	4858-5137[c]	4786 (11)
q (M_2/M_1)[b]	0.235 (3)	0.45	0.220 (2)
A_1[a]	1.0	1.0	1.0
A_2[a]	0.5	0.5	0.5
g_1[a]	1.0	1.0	1.0
g_2[a]	0.32	0.32	0.32
Ω_1[b]	3.56 (3)	4.625-4.936[c]	2.597 (11)
Ω_2	2.318	2.778	2.282
i^{o}[b]	86.8 (4)	80.12-81.18[c]	87.62 (17)

a: Fixed elements during DC
b: Error estimated from heuristic scanning of the $\Delta\chi^2$ surface (Prša and Zwitter, 2005)
c: Range since V, R, and I not simultaneously fit during W-D modeling

Table V. A Comparison of Selected Photometric Elements for AO Ser Obtained Following Roche Model Curve Fitting

model for AO Ser (Figure 8). As might be expected from adopting an A7 primary for AO Ser instead of a hotter A2, most of the physical and geometric elements determined in this study are quite different from those most recently reported by Yang et al. (2010) and Zavros *et al*. (2008). One other revealing difference is related to using a theoretical q value (0.45) from the literature (Zavros *et al*. 2008), as opposed to empirically determining a photometric *q*. As such, our value (q_{ph} = 0.235) agrees reasonably well with the value reported by Yang *et al*. (2010) of q_{ph} = 0.220). Based upon a compilation of absolute dimensions of eclipsing binaries (Harmanec, 1988), the mean stellar mass for an A7 main sequence binary star (1.82 M⊙) was used to estimate the mass of the secondary and the semi-major axis (a = 5.055) in solar units. The associated mass (0.428 M⊙) of the secondary and best fit temperature for T_2 (4412 K; log 3.645) of the putative sub-giant suggested a spectral type between K1 and K3 (Harmanec, 1988; İbanoğlu *et al*., 2006; Surkova and Svechnikov, 2004). Clearly, further spectroscopic analyses will be necessary to solidify the spectral classification of this Algol-like system.

3.3.2. Oscillating Frequencies of the Primary Star

Recent evidence suggests that AO Ser not only varies extrinsically by mutual eclipses but also intrinsically by δ Sct-type pulsation of its primary component (Kim *et al.*, 2004; Zavros *et al.*, 2008). To this end, we investigated the possibility that such oscillation could be detected in our data. Frequency analysis by classical Fourier methods with Period04 (Lenz and Breger, 2005) and Peranso did not convincingly expose any underlying periodicity other than that expected from the dominant orbital period. The spectral window (Figure 9) exhibits strong side-bands offset by 1 cycle per day and likely result from daily sampling aliases; results are shown for B-band, however, similar findings were observed in V and I_c. Data subsets intentionally stripped of measurements around the primary minimum or residuals remaining after Roche modeling were no more revealing of any underlying pulsations. Successive pre-whitening did not expose any other statistically meaningful (s/n > 4) oscillations in the frequency range (5-80 d^{-1}) expected for δ Sct-type pulsations (Breger, 2000) according to the criterion proposed by Breger *et al.* (1993). It is entirely possible, however, that intrinsic oscillations were not detected due to insufficient precision during photometric sampling given that low amplitude δ Sct-type pulsations may not exceed 0.06 mag (Christiansen, 2007).

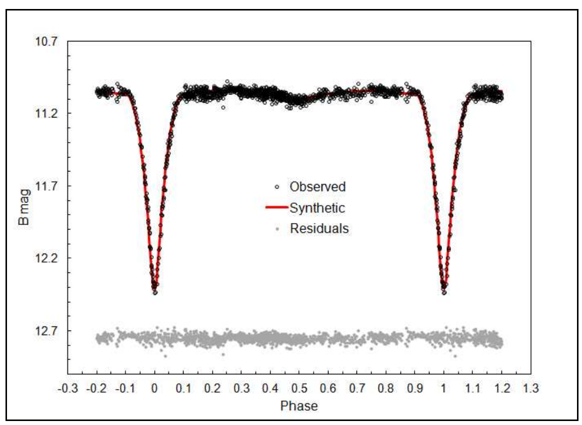

Figure 5. AO Ser light curve (B-band) synthesis determined by PHOEBE after simultaneous fit of all photometric data from three passbands (B, V, and I_c). Roche model residuals are adjusted by a fixed amount to display them in the same chart.

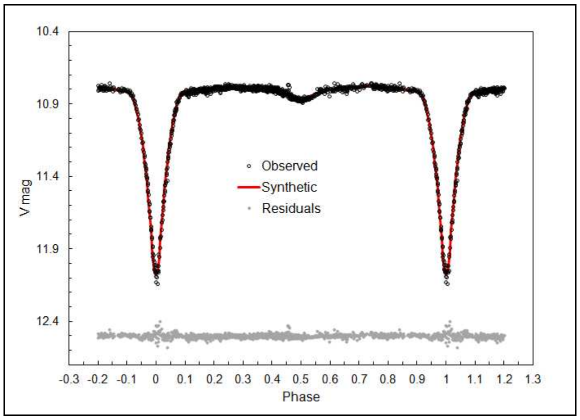

Figure 6. AO Ser light curve (V-band) synthesis determined by PHOEBE after simultaneous fit of all photometric data from three passbands (B, V, and I_c). Roche model residuals are adjusted by a fixed amount to display them in the same chart.

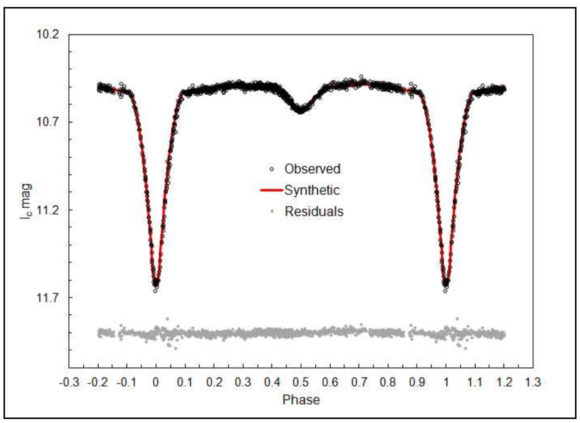

Figure 7. AO Ser light curve (I_c-band) synthesis determined by PHOEBE after simultaneous fit of all photometric data from three passbands (B, V, and I_c). Roche model residuals are adjusted by a fixed amount to display them in the same chart.

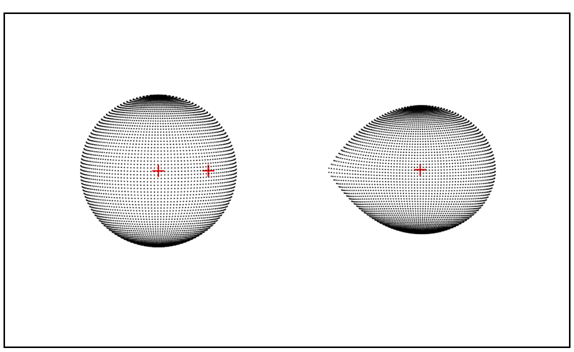

Figure 8. Three-dimensional rendering of the AO Ser binary system at phase 0.25.

4. Conclusions

CCD (B, V, and I_c filters) photometric readings were used to revise the orbital period for AO Ser and calculate an updated ephemeris. A detailed period analysis using O-C residuals generated from observations spanning 80 years revealed a very complex pattern of changes. Following at least seven decades of a constantly increasing orbital period, a sudden decrease (0.844 s) probably occurred around the beginning of 1998. Assuming no mass loss from the system and conservation of angular momentum, on average the minimum amount of stellar material transferred during that period exceeded 50% the mass of Earth.

Since then, the O-C residuals suggest that AO Ser is presently undergoing further changes caused by a yet to be determined phenomena or combination of effects. Evidence points to cyclic, if not sinusoidal behavior in the O-C diagram but only up to 1998; however, this same cyclic periodicity (~36 y) is not obvious within subsequent O-C residuals available for this system between 1998 and 2011.

At this time in the absence of any supporting data from a spectroscopic study or speckle interferometry it would be too early to assign any single reason or combination of phenomena that would unequivocally include the light travel time effect as an explanation to this very complex O-C diagram for AO Ser.

A Roche model based on the W-D code provided a simultaneous theoretical fit of light curve data in three colors (B, V, and I_c). The photometric mass ratio estimated (q = 0.235) from W-D analyses is at odds with a theoretically computed value (0.45) published in 1980 (Brancewicz and Dworak), but consistent with that recently published by Yang *et al*. (2010). Despite lacking critical spectroscopic or radial velocity data for this binary system, the light curve analysis herein based on a revised B-V color-index value for AO Ser provide strong evidence for an Algol-type binary system composed of an A7V main-sequence primary and K1 to K3 subgiant secondary. This classification is much cooler than previously considered by all other investigators. Finally, Fourier analysis did not convincingly reveal any underlying periodicity other than that expected from the dominant orbital period. However, it is possible that the magnitude of any putative δ Sct-type pulsation is below the limits of detection for the equipment used in this investigation.

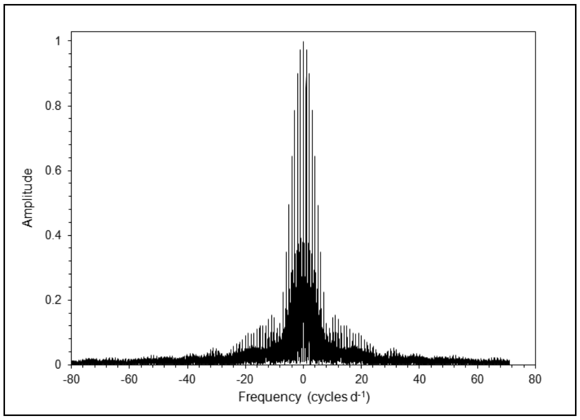

Figure 9. Spectral window for AO Ser exhibits strong side-bands offset by 1 cycle per day resulting from daily sampling aliases; results are shown for B-band residuals following Roche modeling, however, similar findings were observed in V and I_c.

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