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U B V R_C I_C photometry and modelling of AO Ser

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Abstract. AO Ser is an eclipsing binary of the Algol type. We aim to present a new model of AO Ser and to justify the presence and the mode of pulsations of its primary component. We achieved these objectives by modelling our original U, B, V, R_C, I_C light-curves. Pulsations were investigated by means of the periodic analysis. In this way we determined fundamental (L, R, T) parameters of the binary components, their masses and the distance $d = 671^{+3}_{-4}$ pc to AO Ser. Our mass-ratio $q = 0.396$ of the components is not consistent with previous estimates. We also argue that a suspected third component is not present in this system. Finally, we confirmed pulsations of the primary component and derived its more accurate period $P_{\rm puls} = 0.040$ d. The primary pulsates in the first non-radial mode $l = 3$.

Key words: techniques: photometric – binaries: eclipsing – stars: individual: AO Ser

1. Introduction

AO Ser (BD+17 2942, TYC 1496-3-1) is a faint star with magnitudes $B = 11\overset{\rm m}{.}26$, $V = 11\overset{\rm m}{.}04$ (Høg *et al.*, 1998), $J = 10\overset{\rm m}{.}287$, $H = 10\overset{\rm m}{.}093$, and $K = 10\overset{\rm m}{.}031$ (Cutri *et al.*, 2003) at coordinates $\mathrm{RA}_{2000} = 15\,58\,18.408$, $\mathrm{Dec}_{2000} = +17\,16\,09.958$ (Høg *et al.*, 1998). The variability of AO Ser was first published by Hoffmeister (1935) and classified as an Algol-type eclipsing binary (EA) without the determination of the orbital period. Soloviev (1939) published the first ephemeris of AO Ser Min I = HJD2 428 005.294 + 0.879 440 4 × E. There were several attempts to find the intrinsic orbital period of the system, e.g. Koch (1961) with the ephemeris Min I = HJD2 434 133.464 + 0.879 347 45 × E; and Wood and Forbes (1963) with a cubic ephemeris of the primary minimum,

$$\begin{aligned}\text{Min I} = &\ \text{HJD}\ 433\,283.330\,54\ +\ 0.879\,404\,2 \times E \\ &-\ 0.231\,9 \cdot 10^{-7} \times E^2\ -\ 0.462 \cdot 10^{-11} \times E^3\ .\end{aligned}$$

The period of variability of AO Ser was also investigated by ROTSE-I and found to be $P = 0.879\,347\,45$ d. Later, Ahnert (1974) showed that the orbital period is constant, satisfying the ephemeris Min I = HJD2 433 283.330 54 + 0.879 404 20 × E. The first model was published by Brancewicz and Dworak

(1980) using iterative methods. They approximated the surface temperature of the secondary component from the depths of minima of the light-curve. Their solution lead to a mass-ratio $q = 0.45$ with radii of the components $R_1 = 1.80\,\mathrm{R}_\odot$ and $R_2 = 1.79\,\mathrm{R}_\odot$ separated at $a = 5.98\,\mathrm{R}_\odot$. They also measured the parallax $\pi = 0\farcs0013$ of the system, leading to the distance $d \approx 769$ pc. The star was neglected until Kim *et al.* (2004) discovered pulsations of the primary component with $P_{\rm puls} = 21.5$ cycles per day and amplitude $\Delta B \sim 0\fm2$. Lately Yang *et al.* (2010) modelled AO Ser based on their two-colour (B, V) photometry and arrived at the mass-ratio $q = 0.22$. They used the O-C analysis and a quadratic ephemeris with a sinusoidal cyclic oscillation and found the orbital period $P_3 = 17.32$ years of a supposed third body. Recently, Alton and Prša (2012) modelled AO Ser based on (B, V, I_C) photometry and suggested a different spectral classification A7V+K1-3III. The system has never been observed spectroscopically, nor with an interferometer. In this paper we investigate pulsations of the primary component and model absolute parameters and the shape of the binary.

2. Observations and data reduction

Observations were obtained from January 2008 to July 2009 at Stará Lesná Observatory using a 508/2500 Newtonian telescope on a German mount fitted with an SBIG ST-10XME CCD camera equipped with Johnson-Cousins U, B, V, R_C, I_C photometric filters. The device was cooled by a thermoelectric cooler to 30°C below the outer temperature. The CCD chip was binned to 2×2 in order to get faster readouts at the expense of the spatial resolution, giving an effective frame of $1\,092 \times 736$ pixels. With the pixel size of $6.8\,\mu$m the image scale is $1\farcs12$ per pixel, resulting in a field of view of $20\farcm3 \times 13\farcm7$. We have also used public data from the ASAS survey (Pojmanski *et al.*, 2005) made in Johnson V, I filters. All our CCD observations were reduced in the usual way by a bias and dark subtraction, and a flat-field correction using the `MuniWin` package (Motl, 2012). Due to the small angular distance between all the stars in the observed field, we did not apply corrections for the atmospheric extinction. AO Ser was observed totally during 22 nights. The five-colour photometry was obtained during 19 nights. The measured differential (u, b, v, r, i) magnitudes were converted to the international (U, B, V, R_C, I_C) magnitudes using transformation coefficients we derived for our optical system.

$$\begin{aligned} V - I_C &= +1.281(v - i) \\ V - R_C &= +1.467(v - r) \\ V &= v \\ B - V &= +0.834(b - v) \\ U - V &= +1.036(u - v). \end{aligned} \tag{1}$$

The comparison and check stars are shown in Tab. 1.

Table 1. Comparison (C) and check stars (Ch1, Ch2, Ch3) used for a differential photometry of AO Ser. Superscripts: ^{U} values from the USNO A2.0 catalogue (Monet, 1998); ^{T} values from the Tycho catalogue (Høg *et al.*, 1998).

Star	Name	α_{J2000} [h m s]	δ_{J2000} [° ' "]	B [mag]	V [mag]	Sp. Type
V	AO Ser	15 58 17.78	+17 15 16.3	$< 11.26^{T}$	$< 11.04^{T}$	A2 D
C	BD+17 2940	15 57 59.51	+17 19 26.3	10.70^{U}	10.50^{U}	F0 D
Ch1	GCS1496.227	15 58 02.42	+17 21 13.5	12.47^{T}	11.79^{T}	
Ch2	GSC1496.1071	15 58 19.89	+17 19 45.5	12.52^{T}	11.68^{T}	
Ch3	GSC1496.919	15 58 23.48	+17 18 40.5	13.00^{U}	12.10^{U}	

3. Light-curve modelling

Even though the orbital period of AO Ser is shorter than one day, the light-curve corresponds to an EA-type binary. The level of the brightness outside eclipses is not constant due to a reflection effect. We tested the model solution of Yang *et al.* (2010) and the presence of the possible third body in the system of AO Ser. We have used combinations of our light-curves with ASAS data complemented with public data from Yang *et al.* (2010). Our various models we obtained by using the `ROCHE` code (Pribulla, 2004) converged to a higher mass-ratio $q = \mathcal{M}_2/\mathcal{M}_1$ than that from previous papers (e.g. Yang *et al.*, 2010). We also tried to determine the initial value of the mass-ratio q_0. Since AO Ser belongs to EA-type binaries, the evolution status of both components is unknown. Let us suppose that both components satisfy the mass-luminosity relation that can be expressed in solar units as $L_\star \sim \mathcal{M}_\star^\alpha$, where

$$\begin{array}{lrcl} \alpha = 2.3; & & \mathcal{M}_\star & \leq\ 0.43\,\mathrm{M}_\odot, \\ \alpha = 4.0; & 0.43\,\mathrm{M}_\odot\ < & \mathcal{M}_\star & \leq\ 2.00\,\mathrm{M}_\odot, \\ \alpha = 3.5; & 2.00\,\mathrm{M}_\odot\ < & \mathcal{M}_\star & \leq\ 20.00\,\mathrm{M}_\odot. \end{array} \qquad (2)$$

We can define the luminosity ratio of the secondary eclipse as $\Delta l_{\mathrm{II}} = l_1/(l_1 + l_2)$, where $l_1 = L_1/(L_1 + L_2)$ and $l_2 = L_2(L_1 + L_2)$ are the dimensionless luminosities of the primary and secondary component; and L_1, L_2 are the luminosities of the primary and secondary component, respectively. Assuming the total eclipse scenario and the orbital inclination $i \sim 90°$, we can get an estimate of the initial mass-ratio as

$$q_0 = \left(\frac{1}{\Delta l_{\mathrm{II}}} - 1\right)^{1/\alpha}. \qquad (3)$$

We have applied the bolometric correction $BC = -0\overset{\mathrm{m}}{.}2$ for the A2V spectral type (Cox, 2000) and found the value of Δl_{II} and the corresponding value of the

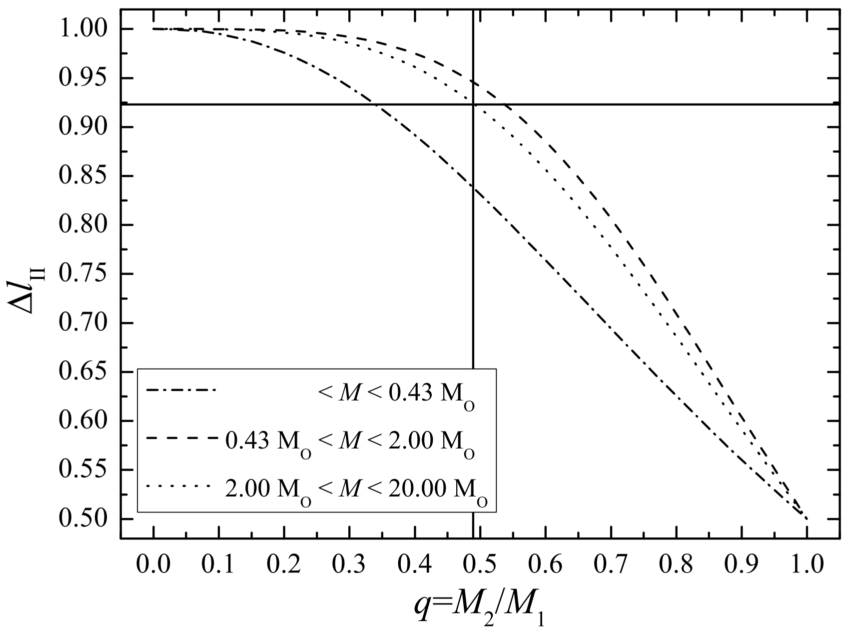

Figure 1. Initial mass-ratio q_0 of the AO Ser binary components according to the three mass-luminosity functions (Eq. 2). Solid lines denote the drop of brightness in the secondary minimum and the corresponding mass ratio for $\alpha = 3.5$.

initial mass-ratio $q_0 = 0.489 \pm 0.142$ (see Fig. 1). From our average colour index $B - V \simeq 0\overset{\mathrm{m}}{.}066$ we interpolated the spectral type of the primary component to be A3 and its effective temperature being equal to $T_1 = 8\,718\,\mathrm{K}$ by using tables of Cox (2000). We used the average temperature of spectral types A2V and A3V, $T_1 = 8\,860\,\mathrm{K}$, for further modelling. The initial model temperature of the secondary component $T_2 = 4\,870\,\mathrm{K}$ was estimated by using the approximation of Brancewicz and Dworak (1980),

$$T_2 \approx T_1 \left(\frac{1 + 0.4\Delta m_1}{1 + 0.4\Delta m_2} \right)^{1/4} , \tag{4}$$

where Δm_1 and Δm_2 are the observed depths of the primary and secondary minima, respectively. We have used the ephemeris Min I = HJD2 452 500.404 4 + 0.879 339 8 $\times$ E. The gravity darkening coefficient was fixed to $\gamma_1 = 1.0$ (von Zeipel, 1924) and to $\gamma_2 = 0.32$ (Lucy, 1967) for the primary and secondary component, respectively. We have fixed the bolometric albedo as $A_1 = 1.0$ and $A_2 = 0.56$ (Rucinski, 1969). For the next series of models we have used differential corrections for the mass-ratio q, orbital plane inclination i, potentials

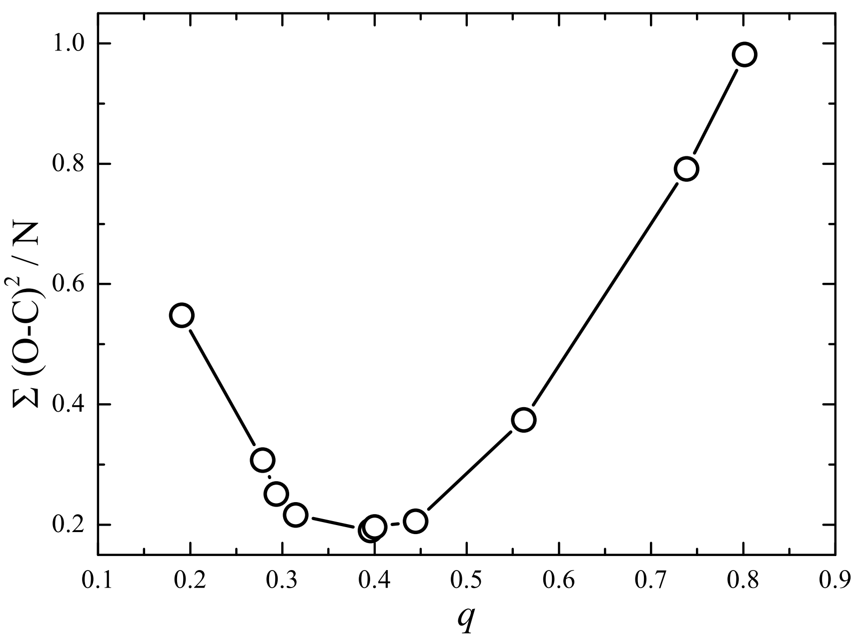

Figure 2. Sum of squared residuals of our photometric data and our models as a function of the mass ratio q.

$\Omega_{1,2}$, the effective temperature of the secondary component T_2, and the scaling parameters of relative fluxes in all observed colours. We have used interpolated bolometric coefficients for the logarithmic limb darkening law (see Tab. 4) based on the van Hamme tables (van Hamme, 1993). We have used various datasets combining our own photometric U, B, V, R_C, I_C data, available electronic data from Yang *et al.* (2010), and ASAS V, I data. Outside the estimated initial mass-ratio $q_0 = 0.489$ we have used other discrete values $q_0 \in \langle 0.1, 1.0 \rangle$. All datasets were converging to a higher mass-ratio than $q = 0.220$ (Yang *et al.*, 2010) (see Fig. 2). Our final solution is shown in Fig. 3 and the corresponding parameters are given in Tab. 2.

From the photometric model we can calculate the physical parameters of AO Ser. Under the assumption that the stars did not undergo significant mass transfer, we can estimate the mass of the primary from the assumed spectral type A2-A3V (Cox, 2000) to be $\mathcal{M}_1 = 2.4\,\mathrm{M}_\odot$. The mass of the secondary component, the semi-major axis calculated using Kepler's third law, luminosity according to the Stefan-Boltzmann law, and other derived parameters are introduced in Tab. 3.

The temperature of the secondary component ($T_2 = 4\,547 \pm 512$ K) suggests

Table 2. Model parameters of AO Ser for the best solution without the third light. Note: Value of T_1 was fixed.

Parameter	Primary	Parameter	Secondary
T_1 [K]	8 860	T_2 [K]	4 547(512)
Ω_1	3.690 9(284 1)	Ω_2	2.896 1(256 9)
$r_{1,\mathrm{back}}$	0.312	$r_{2,\mathrm{back}}$	0.266
$r_{1,\mathrm{side}}$	0.308	$r_{2,\mathrm{side}}$	0.250
$r_{1,\mathrm{pole}}$	0.302	$r_{2,\mathrm{pole}}$	0.244
$r_{1,\mathrm{point}}$	0.316	$r_{2,\mathrm{point}}$	0.276
i [deg]		87.00(13)	
$q = \mathcal{M}_2/\mathcal{M}_1$		0.395 7(81 6)	
$\Sigma(O-C)^2/N$		0.954	

Table 3. Other derived parameters of AO Ser.

Parameter	Primary	Parameter	Secondary
$\mathcal{M}_1$ [$\mathrm{M}_\odot$]	2.40	$\mathcal{M}_2$ [$\mathrm{M}_\odot$]	0.95
R_1 [$\mathrm{R}_\odot$]	1.78	R_2 [$\mathrm{R}_\odot$]	1.47
L_1 [$\mathrm{L}_\odot$]	17.48	L_2 [$\mathrm{L}_\odot$]	0.83
M_1^{bol} [mag]	1.63	M_2^{bol} [mag]	4.95
M_{V1} [mag]	1.83	M_{V2} [mag]	5.56
$\log g_1$	4.296 2	$\log g_2$	4.055 5
$l_1/(l_1+l_2)_U$		0.989(42)	
$l_1/(l_1+l_2)_B$		0.987(16)	
$l_1/(l_1+l_2)_V$		0.959(18)	
$l_1/(l_1+l_2)_R$		0.931(16)	
$l_1/(l_1+l_2)_I$		0.888(17)	
a [$\mathrm{R}_\odot$]		5.781	
d [pc]		671(+3/−4)	

its spectral type to be K4, with the uncertainty from K1 to K8. After applying the bolometric correction to bolometric magnitudes of both components for A3 and K4 spectral types, respectively, we get absolute visual magnitudes of the components: $M_{V,1} = 1\overset{\mathrm{m}}{.}83$ and $M_{V,2} = 5\overset{\mathrm{m}}{.}56$. Using the relation

$$M_V = -2.5\log(10^{-0.4M_{V,1}} + 10^{-0.4M_{V,2}}), \tag{5}$$

we get the bolometric magnitude of the system as $M_V = 1\overset{\mathrm{m}}{.}80$. The value of the colour excess of the target section of the sky is $E_{B-V} = 0\overset{\mathrm{m}}{.}038 \pm 0\overset{\mathrm{m}}{.}013$[1], which leads to the value of the interstellar reddening $A = 0\overset{\mathrm{m}}{.}119$ for $R_V = 3.240$. Thus the true distance of AO Ser is $d = 671^{+3}_{-4}$ pc.

[1] from http://irsa.ipac.caltech.edu/applications/DUST/

Table 4. Logarithmic law coefficients for both components of AO Ser in all photometric filters interpolated from van Hamme (1993).

Coefficient	U	B	V	R_C	I_C
x_1	0.512	0.780	0.647	0.501	0.244
y_1	0.131	0.309	0.278	0.229	0.153
x_2	0.832	0.838	0.815	0.712	0.609
y_2	−0.379	−0.160	0.023	0.125	0.170

Table 5. Selected model parameters of AO Ser of a solution including the third light in the system.

Parameter	AO Ser	Parameter	AO Ser
i' [deg]	87.43(16)	$l_3/(l_1+l_2)_U$	6.6%
Ω_1'	3.662 4(384 7)	$l_3/(l_1+l_2)_B$	5.5%
Ω_2'	2.654 1(290 3)	$l_3/(l_1+l_2)_V$	4.2%
$q' = \mathcal{M}_2/\mathcal{M}_1$	0.334 3(77 6)	$l_3/(l_1+l_2)_R$	2.9%
T_2' [K]	4 620(492)	$l_3/(l_1+l_2)_I$	1.1%

We have tried to model the light-curves of AO Ser with an unknown amount of third light l_3. Light-curves are affected by the change of the ratio of minima depths, which leads to lower values of the final mass-ratio for all initial mass-ratios used. Some cases lead to physically non-consistent solutions, e.g. negative $l_3/(l_1 + l_2)$. The best convergence was achieved for the solution listed in Tab. 3 which is, with respect to parameter uncertainties, consistent with a solution without the third (illusive) light. The black-body temperature of its star should be about $T_3 \sim 8\,983$ K (Fig. 4). Due to a small luminosity (of a few per-cent of the AO Ser system; see Table 3), the radius cannot be larger than $R_3 \sim 0.4\,\mathrm{R}_\odot$.

4. Pulsations of the primary component

According to Kim *et al.* (2004), the expected frequency of pulsation is $f_{\rm puls} =$ 21.5 cycles per day ($P_{\rm puls} \sim 1.12$ hours), with the amplitude of pulsations $\Delta B =$ $0\overset{\rm m}{.}02$. Although pulsations are present also during the secondary minimum, we have selected data outside of eclipses with a duration of at least two hours. The longest run (3.6 hours) in the B-filter from April 21, 2009 was analysed with the `PERANSO` code (Vanmunster, 2012). We have de-trended the data using the mean phase light-curve model. To determine the period of pulsations we have used the Discrete Fourier Transform (DFT) method (Deeming, 1975) and the Phase Dispersion Minimization (PDM) method (Stellingwerf, 1978). Both

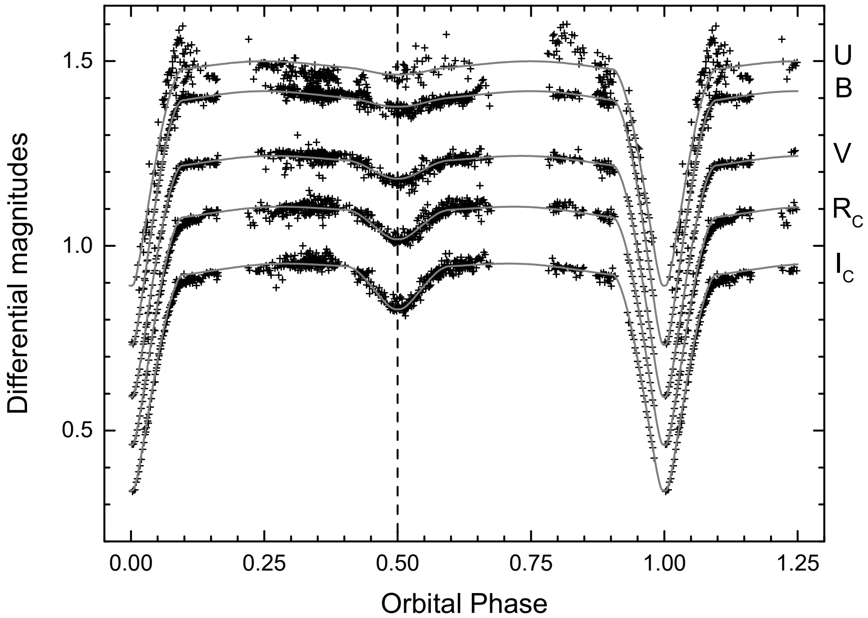

Figure 3. Our differential U, B, V, R_C, I_C observations of AO Ser folded in the phase diagram according to the ephemeris Min I = HJD2 452 500.40180 + 0.879 339 80 × E. For a better visualization, the data are shifted by a constant. Solid lines represent our best solution without the third light. Corresponding parameters are given in Table 2.

analyses were compared to the spectral window, and spurious periods and their aliases were removed. The results are presented in Tab. 6.

The maximum of DFT and the minimum of PDM converged to the same frequency $f_{\rm puls} = 24.944$ cycles per day for the longest data set, so we used the corresponding period, $P_{\rm puls} = 0.040\,089\,8$ d, to fold the pulsation curve (Fig. 5) with a sinusoidal function $f(\varphi) = A \sin[2\pi(\varphi - \varphi_0)]$, where the amplitude A depends on the used pass-band and the phase φ_0 corresponds to the minimum. We used the B magnitudes because of their low uncertainties ($< \pm 0\overset{\rm m}{.}0025$).

Based on the model temperature of the primary ($T_1 = 8\,860$ K), we estimated the mass of the pulsating component to be $\mathcal{M}_1 \simeq 2.4\,{\rm M}_\odot$. We used our model radius $R_1 = 1.78\,{\rm R}_\odot$ (Tab. 3) to compute the mean density $\rho_1 \simeq 0.427\,\rho_\odot$. The pulsation constant $Q = P_{\rm puls}\sqrt{\rho_1} = 0.026\,2 \pm 0.001\,0$ corresponds to a non-radial pulsation mode p_1 with the radial degree $l = 3$ for a star with mass $\mathcal{M}_\star = 2.5\,{\rm M}_\odot$ (Fitch, 1981). There are four possible solutions of pulsations (Fig. 6). Using the Doppler tomography, we found that the primary component pulsates in the first non-radial mode $l = 3$.

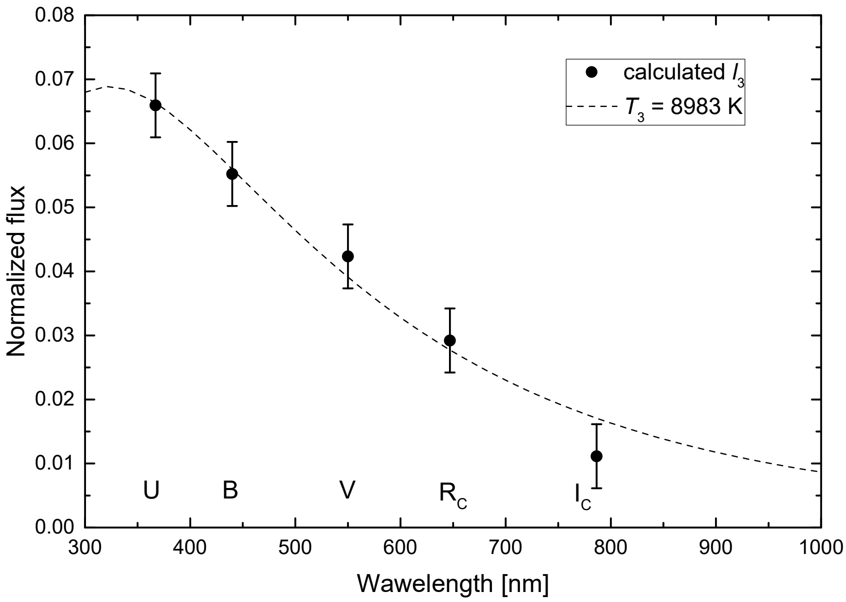

Figure 4. The third light (points) modelled in AO Ser compared to a black body radiating at the temperature $T_3 = 8\,983\,\mathrm{K}$ (dashed line).

Table 6. Results of our period analysis using DFT and PDM for all selected nights. The uncertainty value corresponds to the position of the extremum.

Night	DFT [c/d]	PDM [c/d]	# of data
2008-01-25	32.911 ± 0.014	34.712 ± 0.025	20
2008-03-18	21.972 ± 0.016	20.796 ± 0.017	54
2008-03-31	24.821 ± 0.050	24.675 ± 0.033	32
2009-04-21	24.944 ± 0.013	24.944 ± 0.012	90

5. Discussion and conclusion

We have acquired first five-colour CCD photometry for the neglected Algol-type binary AO Ser.

Photometric solution of Yang *et al.* (2010) was revisited and a new mass-ratio $q = 0.395\,7 \pm 0.081\,6$ was found. Absolute parameters of the components were determined on the assumption that both stars did not undergo a distinct

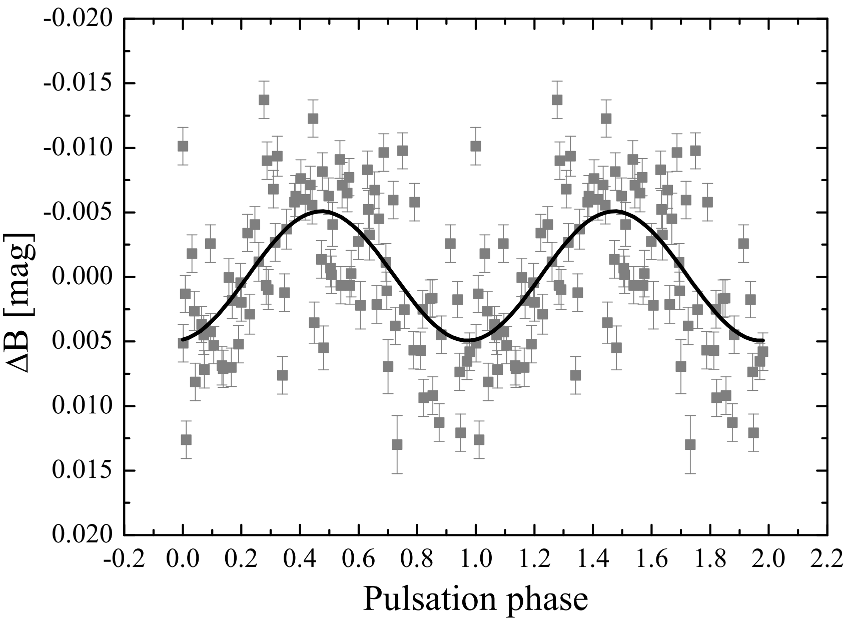

Figure 5. Residual B magnitudes of AO Ser folded in the phase diagram with the pulsation frequency 24.944 cycles per day. The solid thick line represents the best fit with a sinusoidal function (see the text).

mass transfer. If the mass loss was occurring, this would lead to the decrease of the orbital period and the separation. Yang *et al.* (2010) argue that a third body with an orbital period of $P_3 = 17.32 \pm 0.01$ years is present in the system. However, our photometric model suggests that due to the small luminosity (Tab. 3) the radius of this body is $R_3 \approx 0.4\,\mathrm{R}_\odot$, radiating at the black-body temperature $T_3 \sim 8\,983\,\mathrm{K}$. Such stars probably do not exist. This is in favour of attributing the $O - C$ change to some magnetic activity on the secondary (less massive) component.

According to Yang *et al.* (2010), the separation $a_{12} = 9.24 \pm 0.35$ AU between the supposed third body and the eclipsing pair is seen almost perpendicular to the plane of the sky, with $a_{12} \sin i_3 = 0.883\,0 \pm 0.017\,3$ AU (i_3 being the orbital inclination of the outer component to the close binary). Thus, the maximum angular separation of the supposed third body from the centre of gravity of the inner binary is 1.32 ± 0.03 mas. This is too small a value for the current interferometric observations.

Comparison of recent models of AO Ser is given in Table 5. Zavros *et al.* (2008) obtained V, R, I photometry, but modelled the light-curves in various fil-

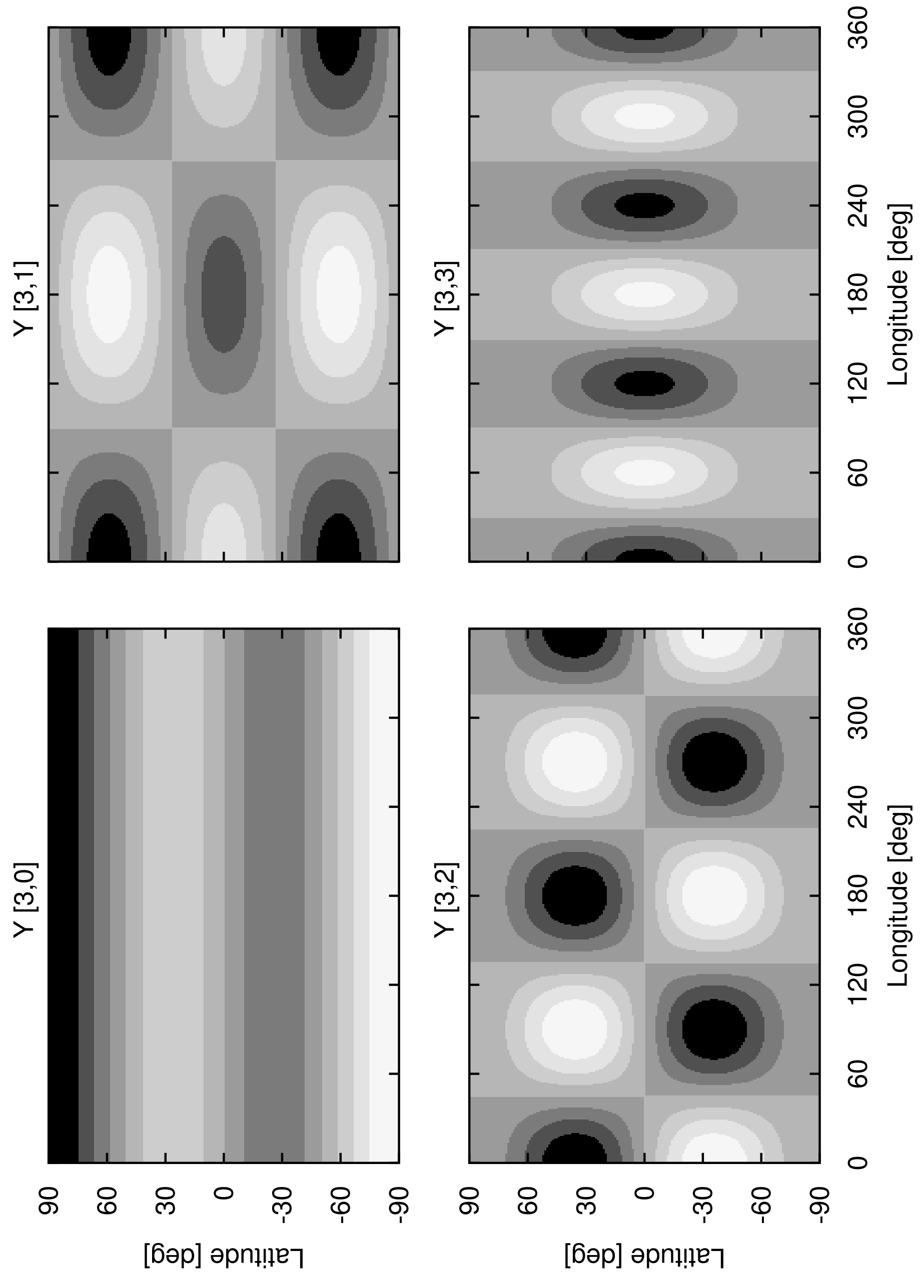

Figure 6. Basic modes of non-radial pulsations for four harmonic functions $Y(l, m)$ in polar coordinates θ, φ. Light grey and dark grey regions are pulsating contrary to each other. The primary component pulsates in the first non-radial mode $l = 3$.

Table 7. Comparison of selected photometric elements of AO Ser obtained from the Roche model curve fitting. Values in columns are taken from I - this work, II - Zavros *et al.* (2008), III - Yang *et al.* (2010), and IV - Alton and Prša (2012). Note: Zavros *et al.* (2008) did not use a simultaneous light-curve fitting.

Parameter	I	II	III	IV
T_1 [K]	8 860	8 770	9 480	7 800
T_2 [K]	4 547	4 858 − 5 137	4 786	4 412
$q = \mathcal{M}_2/\mathcal{M}_1$	0.396	0.450	0.220	0.235
Ω_1	3.691	4.625 − 4.936	2.597	3.560
Ω_2	2.896	2.778	2.282	2.318
i [deg]	87.00	80.12 − 81.18	87.62	86.80

ters separately. The mass-ratio values in papers by Yang *et al.* (2010) and Alton and Prša (2012) are lower than our value $q = 0.396$. Both were obtained assuming a model with an unknown third light. When the third light was included in our modelling, the final solutions for q converged to a smaller value $q' = 0.334$. The unknown amount of the third light decreases depths of the primary and secondary minima, which correlates with lower values of the orbital inclination i and the mass ratio q of the binary. The fact that AO Ser is a total eclipsing binary puts a lower limit on i'. Hence, modelling the system with a third light always results in $q' < q$.

From our model parameters, we calculated bolometric magnitudes of both components of AO Ser, and the absolute visual magnitude $M_V = 1\overset{\mathrm{m}}{.}80$ of the system. The distance $d = 671^{+3}_{-4}$ pc of the system was calculated from the distance modulus and corrected for the interstellar reddening. Previous determination of the distance $d = 769^{+659}_{-242}$ pc of AO Ser was based on computing the photometric parallax (Dworak, 1975) based on assumed spectral types of the components of the binary and mean stellar masses of stars according to their spectral type.

We have confirmed the pulsation of the primary component as discovered by Kim *et al.* (2004), and found its more accurate frequency $f_{\mathrm{puls}} = 24.944$ cycles per day by using the DFT and PDM methods. The pulsation constant $Q = 0.026\,2 \pm 0.001\,0$ corresponds best to a non-radial p-mode with $l = 3$ (Fitch, 1981). In their paper, Alton and Prša (2012) used the B, V, I_C photometry acquired by a telescope with the diameter of only 20 cm. Thus, the pulsations of the primary component were under their detection limit.

Our model (Tables 2 and 3) represents a small step ahead in our understanding of the system of AO Ser. However, without using a combined photometric and spectroscopic multi-dataset modelling we cannot make any final decisions.

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