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The triple system AO Monocerotis*
(Research Note)

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ABSTRACT

The variable star AO Mon is a relatively bright but seldom investigated early-type eccentric eclipsing binary. Thirty new eclipses were measured as a part of our long-term observational project or derived from previous measurements. Based on a new solution of the current O–C diagram, we found for the first time a rapid apsidal advance superimposed with a light-time effect caused by a third unseen body in the system. Their short periods are 33.8 years and 3.6 years for the apsidal motion and the third-body circular orbit, respectively. The observed internal structure constant was derived to be $\log k_{2,\mathrm{obs}} = -2.23$, which is close to the theoretically expected value. The relativistic as well as the third-body effects on the apsidal advance are negligible, as they are only about 3% of the total apsidal motion rate.

Key words. binaries: eclipsing – binaries: close – stars: individual: AO Mon – stars: fundamental parameters

1. Introduction

The detached and double-lined eclipsing binary AO Monocerotis (HD 53883, BD−4°1822, HIP 34299, FL 740, Sp. B3+B5, $V_{\max} = 9.6$ mag) is a seldom studied early-type binary with a slightly eccentric orbit and a short orbital period of about 1.88 days. It was discovered to be a variable star by Hoffmeister (1931). The first photographic light curve was presented by Lause (1933) with an incorrect period of 0.9423 days. The first spectroscopic analysis was presented by Struve (1945), who obtained the radial velocity curve and spectroscopic elements. The next photographic light curve was obtained by Gaposchkin (1953). The photoelectric photometry and photometric elements was published by Kandpal (1976), who also found that the orbit of AO Mon is slightly eccentric ($e \simeq 0.05$) and derived the absolute dimensions of components. Later, Giuricin et al. (1980) recalculated the photometric elements by means of the Wood's WINK code. To our knowledge, no modern period, photometric or spectroscopic study of this early-type eclipsing binary exists so far.

2. Observations

Our photoelectric and CCD photometry of AO Mon was obtained at four observatories:

- Ondřejov Observatory, Czech Republic: the 0.65-m ($f/3.6$) reflecting telescope with the CCD camera SBIG ST-8 or Apogee AP7 and Johnson's *VR* filters,
- South African Astronomical Observatory (hereafter SAAO), Sutherland, South Africa: the 0.50-m Cassegrain reflector ($f/18$) equipped with modular photometer utilizing a Hamamatsu EA1516 photomultiplier and Johnson *UBV* filters; during two weeks in April 2004.
- Johann Palisa Observatory and Planetarium Ostrava, Czech Republic: 0.2-m or 0.3-m telescopes with the CCD camera SBIG ST-8XME and *R* filter,
- Observatory Valašské Meziříčí, Czech Republic: the 0.3-m Celestron Ultima telescope with the CCD camera SBIG ST-7 and *R* filter.

The new CCD observations were reduced in a standard way. The APHOT, synthetic aperture photometry software developed by M. Velen and P. Pravec at the Ondřejov observatory and C-MUNIPACK[1] were routinely used for reduction of these CCD images. The data were dark-subtracted and flat-fielded and the heliocentric correction was applied. The new times of primary and secondary minima and their errors were determined by the well-known Kwee-van Woerden (1956) algorithm.

Photoelectric measurements at SAAO were done with the Johnson photometric system *UBV* filters with a 10 s integration time. The nearby star HD 296318 (spectral type A2, V = 10.5 mag) – used also in our CCD photometry – served as a primary comparison star. All observations were carefully reduced to the Cousins E-region standard system (Menzies et al. 1989) and corrected for differential extinction with the reduction program HEC 22 rel. 16.1[2]. The standard errors of these measurements were about 0.009, 0.007 and 0.005 magnitude in *U*, *B* and *V* filters respectively.

The original photometric data of Kandpal (1976) were recalculated and three new times of minima in *B* and *V* filters were obtained. Using the *Hipparcos* photometry (ESA 1997) and the ASAS-3 photometric database (Pojmanski 2002) we were

* Partly based on observations secured at the South African Astronomical Observatory, Sutherland, South Africa, in April 2004.

[1] http://c-munipack.sourceforge.net/
[2] http://astro.troja.mff.cuni.cz/ftp/hec/HEC22/

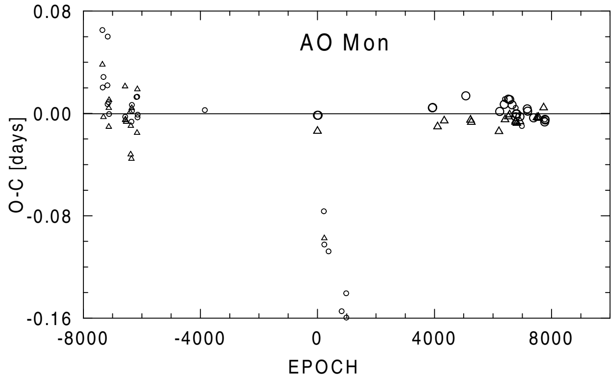

Fig. 1. Complete O–C graph for AO Mon. The individual primary and secondary minima are denoted by circles and triangles, respectively. Larger symbols correspond to the photoelectric or CCD measurements, which were used in our calculations. Visual timings between epochs 0 and 1000 with large negative deviations were omitted.

able to derive numerous additional times of minimum light with lower accuracy. The light-curve profile fitting method was used. All these new times are collected in Table A.1, where the epochs were calculated according to the linear light elements given in the GCVS catalogue[3]:

Pri. Min. = HJD 2 440 588.3272 + $1^{d}_{.}884660 \cdot E$.

3. Apsidal motion and light-time effect

As was mentioned in the previous section, AO Mon has a small but significant orbital eccentricity. Both the classical theory of tides and the General Relativity predict that a close system like this should show a certain degree of periastron advance.

Analysing the preliminary O–C diagram in Fig. 1, we tried to solve the apsidal motion and the light-time effect (hereafter LITE) simultaneously. In this case the deviation of the observed values $(\mathrm{O-C})_{\mathrm{obs}}$ from the linear ephemeris is given by a superposition of the apsidal advance of the eccentric orbit and by the LITE caused by a third star:

$$(\mathrm{O-C})_{\mathrm{obs}} = (\mathrm{O-C})_{\mathrm{aps}} + (\mathrm{O-C})_{\mathrm{LITE}}.$$

For the apsidal motion the method described by Giménez & García-Pelayo (1983), which is a weighted least-squares iterative procedure, including terms in the eccentricity up to the fifth order, was routinely used. The periastron position ω at epoch E is defined by the linear equation

$$\omega = \omega_0 + \dot{\omega}\, E,$$

where $\dot{\omega}$ is the rate of the periastron advance, and the position of periastron for the zero epoch T_0 is denoted as ω_0. The relation between the sidereal and the anomalistic period, P_s and P_a, is given by

$$P_s = P_a\,(1 - \dot{\omega}/360°),$$

and the period of apsidal motion by

$$U = 360° P_s/\dot{\omega}.$$

The theory of the third body motion and the LITE analysis in eclipsing binaries was reviewed several times in the literature, see e.g. Mayer (1990). The light travel time is given by

$$\mathrm{O-C} = \frac{A}{\sqrt{1 - e_3^2 \cos^2 \omega_3}} \left[\frac{1 - e_3^2}{1 + e_3 \cos v} \sin(v + \omega_3) + e_3 \sin \omega_3 \right],$$

where e_3 is the eccentricity of the third-body orbit, ω_3 the longitude of periastron and v the mean anomaly. The observed semi-amplitude A of the light-time curve (in days) is

$$A = \frac{a_{12} \sin i_3}{173.15} \sqrt{1 - e_3^2 \cos^2 \omega_3},$$

where a_{12} is semi-major axis of the relative orbit of the eclipsing pair around the common centre of mass (in AU), i_3 is the inclination of the third-body orbit, e_3 is the eccentricity and ω_3 the longitude of periastron of the third-body orbit. There are ten independent variables to be determined in this procedure:

$(T_0, P_s, e, \dot{\omega}, \omega_0)$, for the apsidal motion and
$(A, T_3, P_3, e_3, \omega_3)$ for the LITE.

The orbital eccentricity of the eclipsing pair was taken as a free parameter in our calculations. The resulting values of e have smaller intrinsic errors compared to those determined independently from the light curve analysis. This procedure gives us a better result for this important element.

Many eclipse timings for AO Mon have been reported in the literature using a variety of techniques, photoelectric or CCD measurements have greater precision and were used in this study. Besides the minima given in Table A.1, we have also added the minima obtained by Zejda (2004), Nakajima (2006, 2007)[4], Dvorak (2006), and Hübscher et al. (2006, 2009, 2010).

A total of 42 reliable times of minimum light were used in our dataset, with 17 secondary eclipses among them. The old visual timings of Lause (1933, 1936, 1949) and those of BBSAG observers were not used due to large scatter. The orbital inclination was assumed to be $i = 86^{\circ}_{.}2$ as a mean value of the B and V light-curve solution of the last photometric analysis of Giuricin et al. (1980). We minimized a quality function, which describes the difference between the observed and calculated times of minima:

$$\chi^2 = \sum_{i=1}^{N} \frac{(\mathrm{O}_i - \mathrm{C}_i)^2}{\sigma_i^2},$$

where σ_i is the corresponding error of a minimum estimation. The computed apsidal motion and LITE parameters and their internal errors of the least-squares fit (in brackets) are given in

Table 1. Apsidal motion and LITE elements of AO Mon.

Parameter	Unit	Value
T_0	HJD	2 440 588.3277 (8)
P_s	days	1.88476297 (7)
P_a	days	1.88505049 (7)
e	–	0.0177 (6)
$\dot{\omega}$	deg cycle^{-1}	0.0549 (8)
$\dot{\omega}$	deg yr^{-1}	10.6 (0.2)
ω_0	deg	238.9 (0.7)
U	years	33.8 (0.5)
A	days	0.0061 (2)
P_3	years	3.56 (3)
e_3	–	0.0 (0.05)
ω_3	deg	54 (1)
T_3	JD	2 452 820 (5)
$f(m)$	$M_\odot$	0.093
$M_{3,\mathrm{min}}$	$M_\odot$	2.5
K	km s^{-1}	8.8

[3] GCVS: http://www.sai.msu.su/groups/cluster/gcvs/

[4] http://vsolj.cetus-net.org/

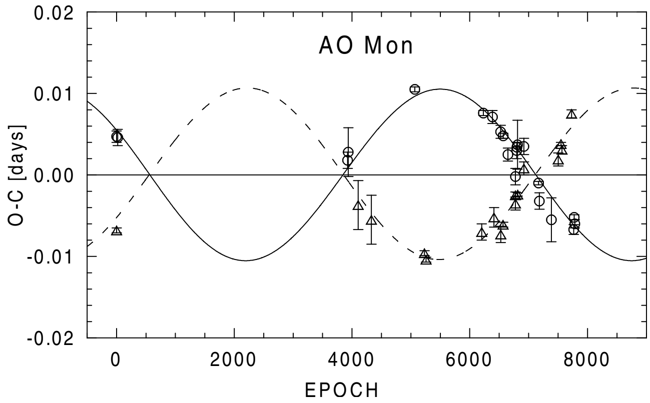

Fig. 2. Rapid apsidal motion in AO Mon with period of about 34 years. The continuous and dashed curves represent predictions for the primary and secondary eclipses, respectively. For clarity, the LITE terms were subtracted and error bars of individual times are indicated.

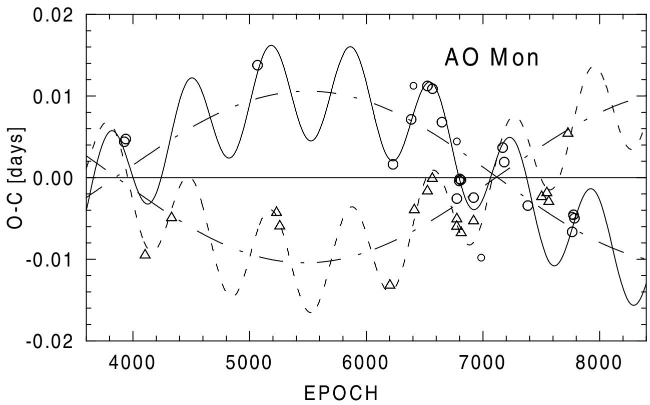

Fig. 3. O–C diagram of AO Mon in detail since the *Hipparcos* mission. The continuous and dashed curves represent the combination of the apsidal motion and LITE with the period of 3.6 years. The dash-dotted curves illustrate the apsidal motion (see Fig. 2). Symbols are as in Fig. 1.

Table 1, the O–C diagram illustrating the apsidal advance is shown in Fig. 2. The detailed O–C diagram in Fig. 3 is the resulting combination of the apsidal motion and LITE with the very short orbital period of the third body. The value of $\chi^2 \simeq 150$ is substantially higher than the number of degrees of freedom $N = 42{-}10 = 32$.

Assuming a coplanar orbit ($i_3 = 90°$) and the total mass of the eclipsing pair $M_1 + M_2 = 10.7\ M_\odot$, we can obtain a lower limit for the mass of the third component $M_{3,\min}$. This value, as well as the mass function $f(m)$, and the amplitude of the systemic radial velocity K are also given in Table 1. The third component may be a main-sequence star of a spectral type B9 with a bolometric magnitude of about +0.4 mag (Harmanec 1988) producing the third light of $L_3 \simeq 3\%$.

4. Internal structure constant

Observations of eccentric binary systems allow us to determine the internal structure constant (ISC), k_2, which is related to the variation in density within the star and is an important parameter of stellar evolution models. It is best studied in binary systems with eccentric orbits that show apsidal motion. The observed average value of $\overline{k}_{2,\mathrm{obs}}$ is given by

$$\overline{k}_{2,\mathrm{obs}} = \frac{1}{c_{21}+c_{22}}\frac{P_a}{U} = \frac{1}{c_{21}+c_{22}}\frac{\dot\omega}{360},$$

where c_{21} and c_{22} are functions of the orbital eccentricity, fractional radii, the masses of the components, and the ratio between rotational velocity of the stars and Keplerian velocity (Kopal 1978). The rotation of the stars was assumed to be synchronized with the maximum angular orbital velocity achieved at periastron.

Taking the value of the eccentricity and the masses of the components into account, a relativistic correction $\dot\omega_{\mathrm{rel}}$ (Giménez 1985) is subtracted

$$\dot\omega_{\mathrm{rel}} = 5.45\times10^{-4}\,\frac{1}{1-e^2}\left(\frac{M_1+M_2}{P}\right)^{2/3},$$

where M_i denotes the individual masses of the components in solar units and P is the orbital period in days. The values of $\dot\omega_{\mathrm{rel}}$ and the resulting mean internal structure constants $\overline{k}_{2,\mathrm{obs}}$ are given in Table 2. The theoretical value $k_{2,\mathrm{theo}}$ was taken as a mean value from the tables of the Granada stellar models (Claret 2004) according to the adopted masses ($\log m = 0.7{-}0.8$) and chemical composition $(X, Z) = (0.70, 0.02)$.

The acceleration of the rate of the apsidal motion $\dot\omega_3$ could also be caused by the third body in the system (Brown 1936; Martynov 1971)

$$\dot\omega_3 = \frac{3}{4}\lambda m^2 + \frac{225}{32}\lambda^2 m^3 + \ldots,$$

where

$$\lambda = \frac{M_3}{M_1+M_2+M_3}, \quad \text{and} \quad m = \frac{P_s}{P_3}.$$

The resulting value of $\dot\omega_3$ for the derived minimal mass $M_{3,\min}$ and the third-body orbital period P_3 is also given in Table 2. This correction for the apsidal motion rate is also negligible, as it is only 0.2% of the observed apsidal motion rate.

Table 2. Astrophysical parameters of AO Mon.

Parameter	Unit	Value
M_1	$M_\odot$	5.5 (0.1)
M_2	$M_\odot$	5.2 (0.1)
r_1	–	0.25 (0.01)
r_2	–	0.22 (0.01)
i	deg	86.2 (0.6)
Source		Giuricin et al. (1980)
$\dot\omega_{\mathrm{rel}}$	deg cycle^{-1}	0.00173
$\dot\omega_{\mathrm{rel}}/\dot\omega$	%	3.2
$\dot\omega_3$	deg cycle^{-1}	0.000125
$\dot\omega_3/\dot\omega$	%	0.23
$\log k_{2,\mathrm{obs}}$	–	−2.23 (0.01)
$\log k_{2,\mathrm{theo}}$	–	−2.27 (0.03)

5. Summary

We completed a new apsidal motion study of AO Mon by performing an O–C diagram analysis and adopting a complete list of published and observed times of minimum light. Our results indicate that AO Mon is an interesting triple and eccentric eclipsing system showing the rapid apsidal motion as well as the LITE caused by a third body orbiting with the short period of 3.6 years. The combination of the apsidal advance with a LITE in this multiple system serves as an excellent laboratory of celestial mechanics for other effects (e.g. precession of orbital planes, Söderhjelm 1975). We also calculated the internal structure constant of AO Mon and found that it is close to its theoretical value. The slight difference will probably be removed in the future with more precise masses. Moreover, AO Mon probably belongs to the important group of other early-type and triple eclipsing systems with a very short third-body orbital period (e.g. IM Aur, IU Aur, FZ CMa).

New high-accuracy timings of this eclipsing binary are necessary to improve the LITE parameters derived in this paper. It is also highly desirable to obtain new, high-dispersion and high-S/N spectroscopic observations for this system and to apply modern disentangling methods to obtain the radial-velocity curves of all components and, therefore, derive accurate masses for this important system. This massive system with its relatively short orbital period could be attractive for spectroscopists. The radial velocity curve should have a semi-amplitude of more than 200 km s^{-1}.

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Appendix A: Table of minima

Table A.1. Times of minimum light of AO Mon.

JD Hel.- 2 400 000	Error [day]	Epoch	Method filter	Source observatory
26 735.385	0.01	–7350.0	vis	Lause (1933)
26 736.301	0.01	–7349.5	vis	Lause (1933)
26 752.303	0.01	–7341.0	vis	Lause (1933)
26 800.342	0.01	–7315.5	vis	Lause (1933)
26 801.315	0.01	–7315.0	vis	Lause (1933)
27 059.521	0.01	–7178.0	vis	Lause (1933)
27 061.391	0.01	–7177.0	vis	Lause (1933)
27 076.522	0.01	–7169.0	vis	Lause (1933)
27 129.244	0.01	–7141.0	vis	Lause (1933)
27 143.376	0.01	–7133.5	vis	Lause (1933)
27 145.246	0.01	–7132.5	vis	Lause (1933)
27 159.391	0.01	–7125.0	vis	Lause (1933)
27 160.345	0.01	–7124.5	vis	Lause (1933)
28 191.321	0.01	–6577.5	vis	Lause (1936)
28 204.488	0.01	–6570.5	vis	Lause (1936)
28 207.317	0.01	–6569.0	vis	Lause (1936)
28 208.258	0.01	–6568.5	vis	Lause (1936)
28 257.260	0.01	–6542.5	vis	Lause (1936)
28 517.365	0.01	–6404.5	vis	Lause (1949)
28 547.488	0.01	–6388.5	vis	Lause (1949)
28 566.358	0.01	–6378.5	vis	Lause (1949)

Table A.1. countined.

JD Hel.- 2 400 000	Error [day]	Epoch	Method filter	Source observatory
28 599.344	0.01	–6361.0	vis	Lause (1949)
28 600.258	0.01	–6360.5	vis	Lause (1949)
28 621.030	0.01	–6349.5	pg	Gaposchkin HA 113.75
28 631.398	0.01	–6344.0	vis	Lause (1949)
28 633.278	0.01	–6343.0	vis	Lause (1949)
28 927.312	0.01	–6187.0	vis	Lause (1949)
28 960.268	0.01	–6169.5	vis	Lause (1949)
28 976.316	0.01	–6161.0	vis	Lause (1949)
28 977.265	0.01	–6160.5	vis	Lause (1949)
28 991.378	0.01	–6153.0	vis	Lause (1949)
29 008.343	0.01	–6144.0	vis	Lause (1949)
33 330.108	0.01	–3851.0	pg	Kaho BTOK 30
40 588.3263	0.0007	0.0	pe, BV	Kandpal (1976)
40 589.2572	0.0003	0.5	pe, BV	Kandpal (1976)
40 622.2520	0.0010	18.0	pe, BV	Kandpal (1976)
40 995.360	0.01	216.0	vis	Diethelm BBSAG29
41 027.375	0.01	233.0	vis	Locher BBSAG29
41 028.323	0.01	233.5	vis	Bosshard BBSAG29
41 302.545	0.01	379.0	vis	Locher BBSAG1
42 139.333	0.01	823.0	vis	Diethelm BBSAG15
42 433.370	0.01	979.0	vis	Locher BBSAG20
42 450.289	0.01	988.0	vis	Locher BBSAG21
42 450.314	0.01	988.0	vis	Diethelm BBSAG21
47 987.9115	0.001	3926.0	H	*Hipparcos*
48 010.529	0.003	3938.0	H	*Hipparcos*
48 324.328	0.003	4104.5	H	*Hipparcos*
48 750.289	0.003	4330.5	H	*Hipparcos*
50 140.3202	0.0003	5068.0	CCD, *R*	Ondřejov
50 446.5763	0.0003	5230.5	CCD, *R*	Ondřejov
50 499.34803	0.0003	5258.5	CCD, *R*	Ondřejov
52 278.557	0.0010	6202.5	CCD, *R*	Ondřejov
52 330.4026	0.0003	6230.0	CCD, *R*	Ondřejov
52 658.361	0.002	6404.0	CCD, –	Ostrava
52 622.5464	0.0008	6385.0	CCD, *V*	ASAS-3
52 886.4173	0.0008	6525.0	CCD, *V*	ASAS-3
52 887.347	0.001	6525.5	CCD, *V*	ASAS-3
52 964.6238	0.0003	6566.5	CCD, –	Ostrava
52 967.4618	0.0003	6568.0	CCD, –	Ostrava
53 118.2387	0.0008	6648.0	pe, UBV	SAAO
53 358.5334	0.0008	6775.5	CCD, *V*	ASAS-3
53 359.479	0.001	6776.0	CCD, *V*	ASAS-3
53 360.4191	0.0004	6776.5	CCD, *R*	Ondřejov
53 425.448	0.003	6811.0	CCD, *R*	Ondřejov
53 630.885	0.001	6920.0	CCD, *V*	ASAS-3
53 631.8247	0.0008	6920.5	CCD, *V*	ASAS-3
54 126.582	0.001	7183.0	CCD, *V*	ASAS-3
54 730.6445	0.0008	7503.5	CCD, *V*	ASAS-3
54 815.4593*	0.0002	7548.5	CCD, *R*	Ostrava
55 156.60868	0.0005	7729.5	CCD, *R*	Ostrava
55 223.5055	0.0005	7765.0	CCD, *R*	Valašské Meziříčí
55 244.2400	0.0003	7776.0	CCD, *R*	Ostrava
55 259.3177	0.0005	7784.0	CCD, *I*	MUO Brno

Notes. (*) Presented also in Brát et al. (2009).

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