Timing of AB And eclipses

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Abstract

This study aims timing the eclipses of the short period low mass binary star AB And. The times of minima are taken from the literature and from our observations in October 2013 (22 times of minima) and in August 2014 (23 times of minima). We find and discuss an inaccuracy in the determination of the types of minima in the previous investigation by Li et al. (2014). We study the secular evolution of the central binary’s orbital period and the possibility of the existence of third and fourth companions in the system.

Keywords: binaries: eclipsing, binaries: close, stars: individual: AB And

1. Introduction

AB And is a W UMa type eclipsing binary star found by Guthnick and Prager (1927). The primary star’s mass and radius are nearly solar values, for the secondary they are approximately half the solar values (e.g., Pych et al., 2004, Hasanzadeh et al., 2008). Old photographic plates allowed to obtain times of minima of the AB And light curve since 1902, such that now there is a set of observations longer than one hundred years. It consists of more than 1600 points accord-
ing to the B.R.N.O. Eclipsing Binaries database, including photographic, visual and photoelectric (CCD and photomultiplier) observations.

The orbital period change in AB And was discovered by Oosterhoff (1950), later the amount of observational data was growing, and different researchers gave different descriptions of the \((O-C)\) diagram as a superposition of some pulsations (e.g., Binnendijk, 1959; Panchatsaram and Abhyankar, 1981; Demircan et al., 1994; Kalimeris et al., 1994; Borkovits et al., 2005). In the latest paper Li et al. (2014) found that there is a linear increase of the orbital period along with pulsations, and this increase was interpreted as mass transfer from the companion to the primary.

The evolution of low mass contact binaries was investigated by Iben and Tutukov (1984). It was shown that the evolution of low mass \((\leq 1.5M_\odot)\) binaries, components of which have convective envelopes, is driven mainly by loss of orbital angular momentum by the magnetic stellar wind. The initial separation of a main-sequence predecessor of W UMa has to be about \(6 - 10R_\odot\). The final product of the evolution of W UMa stars can be a blue straggler. Studies of the multiplicity of stellar systems also are very important for understanding the formation and evolution of stars (e.g., Tokovinin, 1999).

2. Observations of AB And and determinations of the times of minima

AB And was observed using the 50 cm AMT-1 telescope with an Apogee Alta-U16M 4Kx4K CCD camera at the Maidanak observatory of the Ulugh Beg Astronomical Institute, Uzbek Academy of Sciences in October 2013 and in August 2014. We obtained several tens of thousands images in the Bessell \(R\) filter with exposure times ranging from 8 to 20 seconds, the typical value was 10 seconds. The source was continuously monitored for 5-7 hours per night. Bias and dark frames with appropriate exposures were made every night before and after the observations. Flat field frames were recorded for the twilight sky.

To process the data we used the aperture photometry method with the C-Munipack program. The optimum aperture corresponded to the minimum of the standard deviation for differential magnitudes. We took 2Mass J15270686+3659270 and 2Mass J15272880+3647225 as reference stars. The aperture was constant during one night, its differences from night to night were insignificant. Maximum errors for a single exposure were in the range \(0.0024^m - 0.004^m\) for the different

\(^1\)http://var2.astro.cz/ocgate/?lang=en
\(^2\)http://c-munipack.sourceforge.net
nights. Standard dark and flat field corrections were made. Original fits files were
converted to text files that included the dependence of the AB And brightness with
respect to a reference star on the heliocentric Julian date (HJD). Light curves of
AB And were created on the basis of these data. In Figure 1 we show a sample
light curve of AB And from our observations. In order to achieve the highest pos-
sible precision of the times of minima we used only the full light curves between
their maxima.

We calculated 45 times of minima from our observational material, listed in
Table 1. Using this high precision homogeneous material without inner systematic
errors we attempted to find modulations with low amplitude in the same way as
we did for CV Boo (Bogomazov et al., 2016). The geometrical parameters of
the system were taken from Li et al. (2014). \((O - C)\) values were calculated for
the full set of times of minima (ours + the B.R.N.O. database). We found that
the \((O - C)\) values in our computations were different in comparison with the
\((O - C)\) values in the paper by Li et al. (2014) for the times of minima before
1930.

There is a difficulty in the determination of the primary and secondary times
of minima of W UMa type light curves, because the system’s orbit is circular,
and the shapes of the minima are comparable in their duration and depth. If the
system’s relatively short orbital period is changing with time, times of minima
can be calculated incorrectly. This is especially important for observations made
in the distant past. The earliest times of minima were obtained in 1902-1910, then
in 1926-1930, and since 1939 there is a continuous set of times of minima.

We computed the \((O - C)\) values for the times of minima and noticed that
we obtained a maximum value for the \((O - C)\) value at the beginning of the
observations (1902-1903) of \(\approx 0.22\) days. In the paper by Li et al. (2014) for this
time this value is much greater and can reach up to 0.6 days. Since we used the
same ephemerides as Li et al. (2014) this discrepancy can only be due to a wrong
determination of epoch of the minimum in comparison with the initial epoch.
Pribulla et al. (2001) obtained as ephemerides:

\[
\text{Min I} = \text{HJD}2451534.25045 + 0.33189106 \times E, \quad (1)
\]

where Min I is the epoch of the primary minimum, \(T_0 = \text{HJD}2451534.25045\) is
the initial epoch, \(P_0 = 0.33189106\) days is the orbital period, \(E\) is the number of

\(0.3318912\) days for AB And according to General Catalogue of Variable Stars (Samus et al.,
2017).
orbital cycles since the initial epoch.

In the older paper of Binnendijk (1959) information about the kind of minimum (primary or secondary) was included. The \((O-C)\) value calculated by Li et al. (2014) can be obtained if they took one orbital period more before the initial epoch in 1902-1910, and in addition in 1926-1930 confused a primary with a secondary minimum. If the \((O-C)\) values are recalculated using the ephemerides by Binnendijk (1959), our values of \(E\) do not coincide with those of Li et al. (2014). For the first minimum HJD2416103.925 we took for the epoch number \(E = -106753.5\), whereas Li et al. (2014) took for this \(E = -106754.5\).

3. Periodic (O-C) variations

We calculated the \((O-C)_1\) values by using all times of minima (ours + the B.R.N.O. database) and Equation 1. The obtained \((O-C)_1\) values were fitted by the equation:

\[
\text{Min I} = (T_0 + \Delta T_0) + (P_0 + \Delta P_0)E + \frac{\beta}{2}E^2 + A_3 \left( \sqrt{1 - e_3^2 \sin E^* \cos \omega_3 + \cos E^* \sin \omega_3} \right),
\]

(2)

with the equality

\[
\frac{2\pi}{P_3}(t - T_3) = (E^* - e_3 \sin E^*),
\]

here \(\Delta T_0\) is the correction for the initial epoch, \(\Delta P_0\) is the correction for the orbital period, \(A_3 = (a_3 \sin i_3)/c\), \(c\) is the speed of light, \(a_3 \sin i_3\) is the projected semi-major axis of the binary’s orbit around the center of masses of the assumed triple system, \(e_3\) is its eccentricity, \(\omega_3\) is its argument of periapsis, \(E^*\) is its eccentric anomaly, \(T_3\) is the time of the periastron passage by the third body, \(t\) is the time. The numerical values of these parameters are listed in Table 2. A graphical representation of the result is shown in Figure 2 by the green curve.

The mass function is \(f(M_3) = 0.048M_\odot\), so the lower limit of mass of the third companion is \(M_3 = 0.4 - 0.5M_\odot\). This value is much smaller than the lower mass limit obtained by Li et al. (2014), they estimated it as \(\approx 2.5M_\odot\).

The next step was to search for remaining smaller variations of \((O-C)\) relative to the green curve. The visual times of minima are not precise enough and
can make only noise for this purpose. So, we used the photoelectric and photographic times of minima starting from the epoch HJD2429000. The earlier points calculated using photographic observations can have systematic errors (see Figure 2). We calculated values \((O - C)\)_2 as the difference between observational times of minima and values calculated using Equation (2). The obtained quantities of \((O - C)\)_2 were fitted by a light equation\(^4\) with the parameters shown in Table 3. A graphic presentation of the result is shown in Figure 3. These then imply the presence of a fourth companion. The mass function for this 4th body is \(f(M_4) = 0.00035M_\odot\), and the lower limit of its mass is \(M_4 = 0.1M_\odot\).

To estimate the significance of our results we used a statistical method of Stellingwerf (1978) and calculated the value

\[
\theta = \frac{\sigma^2}{\sigma_0^2},
\]

where \(\sigma_0\) and \(\sigma\) are the standard deviations. The smaller the \(\theta\) the better is the agreement between the data and the theoretical fit.

For the “Theory, combined” curve in Figure 2: \(\sigma_0 = 0.0304\) corresponds to the values of \((O - C)\)_1, \(\sigma = 0.0037\) is corrected with the theoretical curve from Equation (2), and \(\theta = 0.015\). For the theoretical curve in Figure 3: \(\sigma_0 = 0.00160\) corresponds to the values of \((O - C)\)_2, \(\sigma = 0.00267\) is corrected with the light equation obtained using the parameters from Table 3, and \(\theta = 0.36\).

It is essential to note that an error in times of minima obtained using photographic observations can reach a value of up to \(\approx 0.01\) days, therefore if the binary’s orbital period is \(\approx 0.3\) days the derived difference of \((O - C)\) \(\approx 0.2\) days between modern and old observations is impossible, so the secular change is real.

We also tested possible variabilities for the data in Figure 3 with different periods and found that \(\theta\) for them is \(\geq 0.7\) (for the curve in Figure 3 this values is almost twice less). Nevertheless, future observations potentially are able to correct estimations of periods, especially after the next periastron passage.

4. Discussion and conclusions

We obtained 45 times of minima of AB And from our observations, and analysed them along with the times of minima from the B.R.N.O. database. Our work

\(^4\)See, e. g., Kozyreva, Kusakin and Khaliullin (2005). Formula (3) for the light equation, and Formula (5) for the mass function.
corrected claims made by Li et al. (2014), because we found an error in their determination of times of minima type for the old data. The results of the present study are similar in some respects with the results of Hasanzadeh et al. (2008): also in their paper there are two periodical modulations of the times of minima.

Using all available times of AB And minima we find that the central binary’s orbital period shows a secular increase and two periodical modulations. Recalculation of mass transfer rate using Equation (5) by Li et al. (2014) with our value of $\beta$ from Table 1 gives $\dot{M} \approx 5 \cdot 10^{-8} M_\odot$ per year. The mentioned modulations can be explained by the gravitational influence of a third and a fourth circumbinary bodies. The orbital periods and the lower limits of masses of these bodies are $P_3 \approx 106$ years, $M_3 \gtrsim 0.4 M_\odot$, $P_4 \approx 59$ years, $M_4 \gtrsim 0.1 M_\odot$ respectively.

The presence of two distant companions to the close binary AB And is not a great surprise. The empirical initial distribution of components of binary stars over separations was described by Equation (22) of Masevich and Tutukov (1988), page 110:

$$dN = 0.2d\log(a/R_\odot), 1 \leq \log(a/R_\odot) \leq 6,$$

To estimate the possible multiplicity we can treat this function as a probability to find a new companion in a multiple system. Selection effects could lead to missing of components of very close binaries or binaries with a faint companion, therefore binaries in reality can be triples/multiples. According to Tokovinin et al. (2006) more than 96% of binaries with orbital periods $\lesssim 3$ days have a tertiary companion. Our statements are in a good agreement with this radial velocity study.

Thus, the formation of several “additional” components to a close W UMa type system even with a significant eccentricity of their orbits can be a natural product of the collapse of a rotating protostellar gas cloud. The orbits of the two new components of AB And due to their large eccentricities (0.41 and 0.87) are very close to each other. The ratio of orbital periods is only about 1.8. The stability of such close orbits deserves now a special attention, e. g. (Orlov and Zhuchkov, 2005; Naoz, 2016).

Also a magnetic mechanism (Applegate, 1992) can be an explanation for a modulation of the binary’s orbital period. We re-calculated the values $\Delta L_1$ and $\Delta L_2$ (changes of the luminosity of components due the magnetic mechanism, we used Equations 6-10 by Li et al. (2014) using our value of $A$ and obtained $\Delta L_1 = 0.42 L_\odot$ and $\Delta L_2 = 0.17 L_\odot$. The values of Li et al. (2014) were inconsistent.
with the possible energy of the mechanism, whereas our values are significantly smaller. [Kalimeris et al. (1994)] already discussed this issue and found arguments in favour as well as against Applegate’s mechanism on a AB And. Their luminosity variation in long time scales was $\Delta(L_1 + L_2) = 0.18L_\odot$. [Hasanzadeh et al. (2008)] attributed the second modulation of the orbital period to the magnetic mechanism. The possible causes of orbital period modulations can be (at least, in principle) clarified using future CCD photometry, radial velocity, astrometric and direct observations.
Table 1: AB And times of minima obtained in this study.

| HJD-2400000 | Min | HJD-2400000 | Min | HJD-2400000 | Min |
|-------------|-----|-------------|-----|-------------|-----|
| 56567.2122  | II  | 56580.1555  | II  | 56875.2067  | II  |
| 56567.3783  | I   | 56580.3215  | I   | 56875.3728  | I   |
| 56568.3737  | I   | 56581.3168  | I   | 56876.2025  | II  |
| 56569.2032  | II  | 56589.2827  | I   | 56876.3683  | I   |
| 56569.3693  | I   | 56589.4486  | II  | 56884.3336  | I   |
| 56571.1944  | II  | 56590.2783  | I   | 56886.3251  | I   |
| 56571.3608  | I   | 56590.4443  | II  | 56886.4908  | II  |
| 56572.1904  | II  | 56871.2239  | II  | 56887.3206  | I   |
| 56573.1859  | II  | 56871.3902  | I   | 56887.4868  | II  |
| 56573.3518  | I   | 56872.2196  | II  | 56888.3165  | I   |
| 56574.1817  | II  | 56872.3858  | I   | 56888.4825  | II  |
| 56574.3474  | I   | 56873.2157  | II  | 56889.3125  | I   |
| 56577.1688  | II  | 56873.3818  | I   | 56889.4786  | II  |
| 56577.3343  | I   | 56874.2115  | II  | 56890.3077  | I   |
| 56578.3297  | I   | 56874.3776  | I   | 56890.4740  | II  |
Table 2: Values of the parameters in Equation 2.

| Parameter | Value     | Error     |
|-----------|-----------|-----------|
| $\Delta T_0$, d | 0.041 | $\pm 0.002$ |
| $\Delta P_0$, d | $1.1 \cdot 10^{-7}$ | $\pm 0.7 \cdot 10^{-7}$ |
| $\beta$, d/yr | $3.95 \cdot 10^{-8}$ | $\pm 2.5 \cdot 10^{-8}$ |
| $A_3$, d | 0.047 | $\pm 0.002$ |
| $e_3$ | 0.41 | $\pm 0.12$ |
| $P_3$, d | 38700 | $\pm 1990$ |
| $\omega_3$, ° | 290.0 | $\pm 0.6$ |
| $T_3$, HJD | 2434950.6 | $\pm 260.3$ |

Table 3: Values of the parameters for the second periodical variation.

| Parameter | Value     | Error     |
|-----------|-----------|-----------|
| $A_4$, d | 0.0062 | $\pm 0.0015$ |
| $e_4$ | 0.87 | $\pm 0.2$ |
| $P_4$, d | 21650 | $\pm 100$ |
| $\omega_4$, ° | 19.5 | $\pm 1.5$ |
| $T_4$, HJD | 2443047 | $\pm 50$ |
Figure 1: A sample light curve of AB And obtained in our observations in the Bessel $R$ filter.
Figure 2: \((O - C)\) diagram, calculated using Equation (1). Curves represent a secular change of the system’s orbital period, a periodical modulation of it, and the resulting combination of these two, represented by Equation (2). Circles depict photographic and photoelectric (CCD and PMT) observed times of minima, boxes depict visual data.
Figure 3: $(O-C)$ diagram for the smaller periodical variation after the subtraction of the combined theoretical modulation of Figure 2. The curve depicts the theoretical result; circles represent the photographic and photoelectric times of minima from HJD2429000.
References

Applegate J. H., 1992, ApJ, 385, 621

Binnendijk L., 1959, AJ, 64, 65

Bogomazov A. I., Kozyreva V. S., Satovskii B. L., Krushevskaya V. N., Kuznyetsova Y. G., Eghamberdiev S. A., Karimov R. G., Khalikova A. V., Ibrahimov M. A., Irsmambetova T. R., Tutukov A. V., 2016, Astrophys. Space Sci., 361, id. 390

Borkovits T., Elkhateeb M. M., Csizmadia Sz., Nuspl J., Bíró I. B., Hegedüs T., Csorvási R., 2005, Astronomy and Astrophysics, 441, 1087

Demircan O., Derman E., Akalin A., Selam S., Muyesseroglu Z., 1994, MNRAS, 267, 19

Guthnick P., Prager R., 1927, Astronomische Nachrichten, 231, 165

Hasanzadeh A., Jassur D. M. Z., Kermani M. H., 2008, Astrophys. Space Sci., 317, 71

Iben I. Jr, Tutukov, A. V., 1984, ApJ, 284, 719

Kalimeris A., Rovithis-Livaniou H., Rovithis P., Oprescu G., Dumitrescu A., Suran M. D., 1994, Astronomy and Astrophysics, 291, 765

Kozerva V. S., Kusakin A. V., Khaliullin Kh. F., 2005, Astronomy Letters, 31, 117

Li K., Hu S.-M., Jiang Y.-G., Chen X., Ren D.-Y., 2014, New Astronomy, 30, 64

Masevich A. G., Tutukov A. V., 1988, Evolution of Stars: Theory and Observations, Moscow, Nauka (in Russian)

Naoz S., 2016, Ann. Rev. Astron. Astrophys., 54, 441

Oosterhoff P. Th., 1950, Bull. Astron. Inst. Netherlands, 11, 217

Orlov V. V., Zhuchkov R. Ya., 2005, Astronomy Reports, 49, 201

Panchatsaram T., Abhyankar K. D., 1981, Bull. Astron. Soc. India, 9, 243

Pribulla T., Vanko M., Parimucha S., Chochoł D., 2001, IBVS, 5056, 1
Pych W., Rucinski S. M., DeBond H., Thomson J. R., Capobianco C. C., Blake R. M., Ogloza W., Stachowski G., Rogoziecki P., Ligeza P., Gazeas K., 2004, AJ, 127, 1712

Samus N. N., Kazarovets E. V., Durlevich O. V., Kireeva N. N., Pastukhova E. N., 2017, Astronomy Reports, 61, 80

Stellingwerf R. F., 1978, ApJ, 224, 953

Tokovinin A. A., 1999, ASP Conf. Ser., 185, 347

Tokovinin A., Thomas S., Sterzik M., Udry S., 2006, Astronomy and Astrophysics, 450, 681