AN ACTIVE TRIPLE SYSTEM 44i BOOTIS

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ABSTRACT. The long-term *UBVR* photoelectric monitoring of 44i Boo performed at the Skalnaté Pleso, Stará Lesná and Kryonerion observatories is presented. The orbital period changes are discussed including light-time effect caused by the visual companion. The radial velocity of the visual companion as well as observed period change conclusively determine the ascending node of the visual orbit to be in the first quadrant. The light curve of the system was found to be quite stable but asymmetric: maximum in the phase 0.25 has always been fainter than maximum in the phase 0.75. Light-curve analysis of the V observations since 1998 provided new inclination angle i =73.66±0.14°. Combination of the inclination angle with the published spectroscopic elements gave reliable masses of the components: m_1=0.861±0.008 $M_\odot$ and m_2 = 0.419±0.11 $M_\odot$.

Key words: Stars: binary: contact; stars: individual: 44i Boo

1. Introduction

Triple system 44i Boo (V = 4.76, sp. K2V) composed of a W-type contact binary star and a main sequence companion forms a visual double star ADS9494 (P_{123}= 206 years). The system is unique since it has precisely known astrometric orbit and it is our closest W UMa neighbour (π = 0.0784"). The contact pair shows enhanced photospheric activity displayed as the differences in the maxima heights and brightenings in the UV region. Because of its brightness the system has been subject to numerous photometric observations. Unfortunately, the precise determination of the photometric elements is complicated not only by the photospheric activity but also low inclination angle (≈69-73°) and considerable third light making the amplitude of the light variation as small as ΔV = 0.17 mag.

Lu et al. (2001) performed extensive high-dispersion spectroscopic observations of the system. A thorough analysis of the broadening functions resulted in new reliable spectroscopic elements of the contact pair (see Table 1). Söderhjelm (1999) used all Hipparcos and Earth-bound astrometry and re-computed the relative visual orbit (Table 1).

Table 1: Spectroscopic elements of the contact pair (Lu et al., 2001) and the orbital elements of the relative 12-3 orbit (Söderhjelm, 1999). Errors are given in the parentheses.

Spectroscopic orbit 12		Visual orbit 12-3	
V_0 [km.s^{-1}]	-17.9(4)	$\sum m$ [$M_\odot$]	2.70(16)
K_2 [km.s^{-1}]	231.3(6)	P_{123} [year]	206(2)
K_1 [km.s^{-1}]	112.7(5)	a ["]	3.8
q_{12}	0.487(6)	e	0.55
$m_{12}\sin^3 i$ [$M_\odot$]	1.132(11)	i [°]	84
P_{12} [day]	0.267818	ω [°]	45
		T_0 [year]	2013
		Ω [°]	57

2. New observations

In our paper we present three sets of *UBVR* photoelectric observations. In all three cases the combined light of the visual pair was measured. The first set of data are *UBV* observations obtained at the Skalnaté Pleso (SP) observatory of the Astronomical Institute of SAS in 1968 (3 nights) and in 1969 (4 nights only in *V*). The second set of data was obtained with the 1.2m Cassegrain reflector at the Kryonerion Astronomical Station (KAS) of the Athens National Observatory on 5 nights from May 1994 to May 1996. Standard *BV* filters and a two-beam, multi-mode, nebular-stellar photometer was used. 54 Boo served as the comparison star. The system was also observed on 18 nights from

Table 2: New times of the primary (p) and secondary (s) minima. The standard errors are given in parentheses

JD_{hel} 2400000+	Fil.	JD_{hel} 2400000+	Fil.
p 39222.5889(2):	B	p 50204.4309(1)	V
p 39222.5851(3)	V	s 50204.5613(1)	V
p 39887.5749(4)	U	s 50204.5620(2)	B
p 39887.5755(2)	B	s 50205.3654(1)	B
p 39887.5744(1)	V	s 50205.3645(1)	V
s 39940.4618(5):	U	p 50205.4996(1)	B
s 39940.4650(3)	B	p 50205.5017(1)	V
s 39940.4651(5)	V	s 52001.3670(8)	B
p 39995.4973(3):	U	s 52001.3675(5)	V
p 39995.5000(8)	B	p 52097.3817(1)	B
p 39995.5021(7)	V	p 52097.3816(1)	V
p 40286.6217(3)	V	p 52123.3557(1)	B
p 50204.4286(2)	B	p 52123.3572(6)	V

February 1998 to August 2001 at the Stará Lesná (SL) and SP observatories of the Astronomical Institute of the SAS. At both observatories a single-channel photoelectric photometer installed at the Cassegrain focus of the 0.6m reflector was used. The standard *UBV* and *UBVR* filters were employed at SL and SP, respectively. 47 Boo was used as the comparison star.

Our observations led to the determination of 31 minima times. They have been calculated separately for each passband using Kwee & van Woerden's (1956) method. Twelwe previously unpublished minima times are listed in Table 2.

3. Period Analysis

The orbital period of the system was analysed by many investigators. Part of them correctly included the light-time effect (hereafter LITE) caused by the presence of the third component, others ignored the LITE in their analysis entirely. Hill et al. (1989) tried to re-analyse the times of the minima including the LITE. The authors, however, computed the scale factor s erroneously.

The analysis of the orbital period changes of the contact pair has no meaning without proper subtraction of the LITE. The mass ratio $q_{123} = m_3/(m_1 + m_2 + m_3)$, necessary for the determination of the semi-amplitude of the LITE, can be determined from the total mass of the system determined from the visual orbit (Söderhjelm, 1999) and the simultaneous spectroscopic (Lu et al., 2001) and photometric analysis of the contact pair. From Table 1 we have $m_1 + m_2 + m_3 = 2.70\pm0.16$ $M_\odot$ and $(m_1 + m_2)\sin^3 i = 1.132\pm0.011$

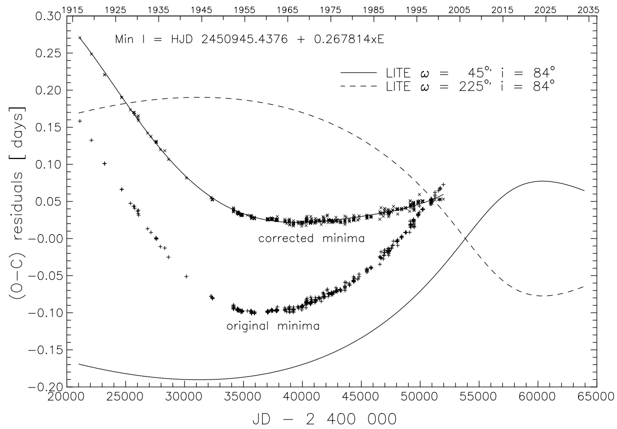

Figure 1: $(O-C)$ diagram of 44i Boo from the mean linear ephemeris. The theoretical LITE curve corresponds to the visual orbit and parallax given in Table 1 and $q_{abc} = 0.52$

$M_\odot$. If we take the orbital inclination $i = 73.7°$ (see Section 4), we get $q_{123} = 0.52\pm0.03$.

The theoretical LITE correction with respect to the center of the mass of the triple system can be computed as follows:

$$\Delta T = \frac{a" q_{123}}{c\pi} \sin i_{123} \frac{1 - e^2}{1 + e\cos\nu} \sin(\nu + \omega), \quad (1)$$

where $a"$ is the semi-major axis in arcsec, e eccentricity, ω longitude of the periastron, ν true anomaly and i_{123} inclination of the relative orbit, c is the velocity of light and π is the parallax of the system.

The contact pair revolves the third component in the direct orbit. Unfortunately, the positional measurements do not allow to distinguish between two possible positions of the ascending node [1]: either in the first or third quadrant. Both cases computationally differ in the longitude of the periastron ω. If the ascending node is positioned in the first quadrant, then $\omega = 45°$. In the second case $\omega = 45 + 180 = 225°$.

To analyse the orbital period changes of the contact pair we have gathered all available minima mainly from Hill et al. (1989) and Kreiner et al. (2001). The minima were weighted according to Kreiner et al. (2001): photographic and photovisual $w = 3$, photoelectric $w = 10$. The $(O-C)$ diagram from the mean weighted linear ephemeris $Min\ I = 2\,450\,945.4376 + 0.26781558 \times E$ is presented in Fig. 2. The general course of the observed times of minima (mainly since 1955) as well radial velocity of the third component indicates that the ascending node is in the first quadrant i.e., the contact pair is now receding from the Sun. Although the LITE correction to the minima cannot be

[1] where the fainter component (contact pair) crosses the plane of the sky while receding from the observer

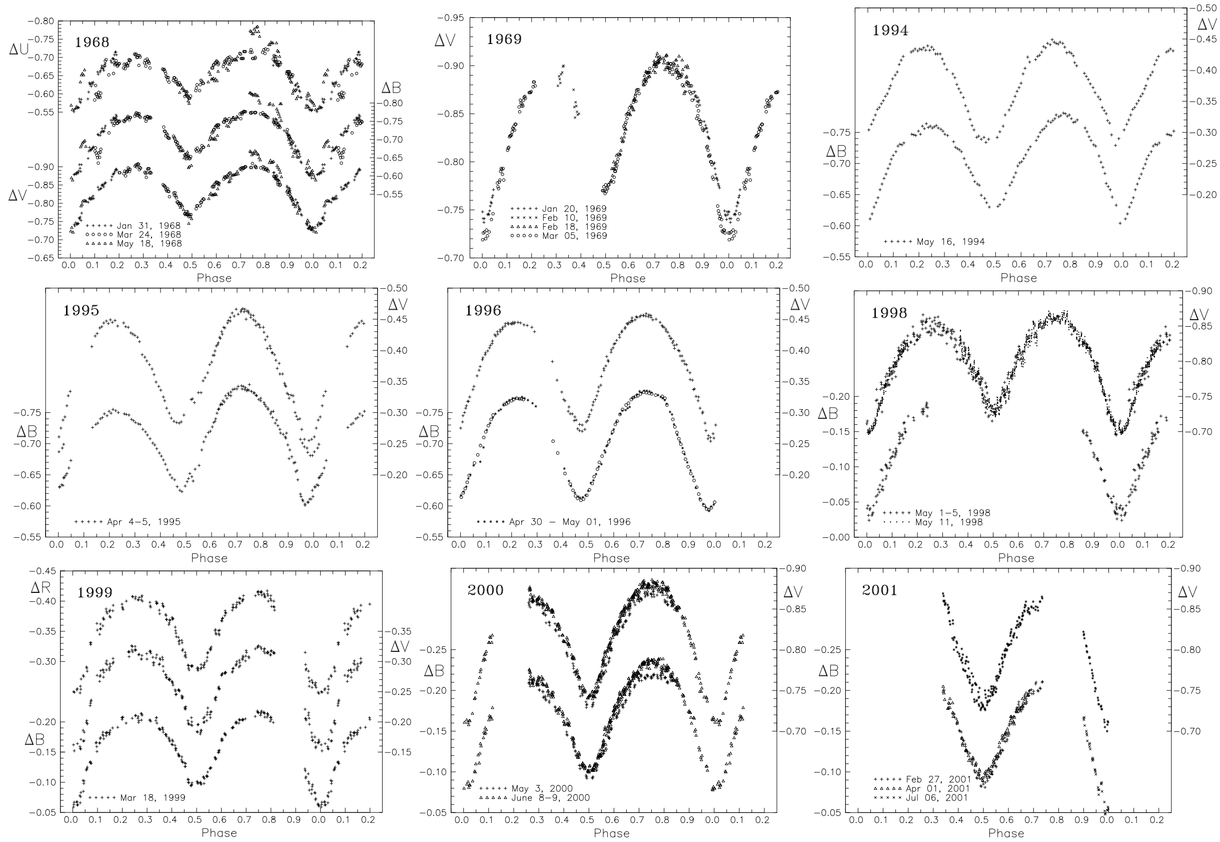

Figure 2: Selected $UBVR$ photoelectric light curves of 44i Boo

neglected, the corrected $(O-C)$ residuals still show steady period increase.

The $(O-C)$ diagram for the corrected times of the minima can be divided into two parts (i) till $\approx$ JD 2 431 000 when the orbital period seemed to be constant: $Min\ I = 2\,450\,945.078(6) + 0.26780838(7)\ E$ and (ii) since JD 2 431 000 when the orbital period is increasing at an approximately constant rate: $Min\, I = 2\,450\,945.4910(5){+}0.26781565(3)\,E{+}2.21(5)\ 10^{-11}\ E^2$. Although the ephemerides describe the general trend well, the individual minima show large scatter (caused most probably by the photosheric activity) and small intermittent period changes. Hence our light curves (hereafter LCs) were phased using minima in short intervals around observations.

4. Light-curve analysis

In the present paper we have aimed at the determination of the geometrical elements necessary for the absolute parameters determination. Hence we tried to remove the photometric disturbances caused by the activity on the surface of the contact pair. The most stable and best covered is the V passband LC. U and B passband observations are negatively influenced by the chromospheric, flare and spot activity on the surface. R passband observations are rather scanty. Hence we have analysed only the V LC.

It is interesting to note that all V LCs observed at the SP and SL observatories since 1998 are very similar and stable (see Fig. 2). Therefore, we used them for the determination of the photometric elements. These LCs only slightly differ mainly in the maxima heights. The maximum I (phase 0.25) has been always observed to be fainter by 0.004 - 0.017 mag than maximum II (phase 0.75). If we assume that the component 3 is not variable and we correct the LCs for its light, the corresponding maxima differences are 0.012 - 0.052 mag. The most stable part of the LC was around the maximum I. Assuming the presence of dark starspots on the surface we have used only the brighter half of the LC around the maximum II. All V passband observations in this phase interval were used to form 89 normal points by the running parabolae method.

For the determination of the photometric elements we have used the 1992 version of the differential corrections code developed by Wilson & Devinney (1971) (W&D). Since the spectroscopic elements are reliably known, we have fixed the mass ratio $q = 0.487$ (Lu et al., 2001). Mode 3 of the W&D code appropriate for the contact binaries was employed. For the computation of the monochromatic luminosities we have used the approximate atmospheric model option of the

W&D program. Coefficients of the gravity darkening $g_1 = g_2 = 0.32$ and bolometric albedo $A_1 = A_2 = 0.5$ were fixed as appropriate for the convective envelopes. The limb darkening coefficients were interpolated from Table 1 of Al-Naimiy (1978). The mean temperature of the primary (the more massive and cooler component) was taken 4830 K corresponding to the $(B - V)$ colour of the contact pair. Fabricius & Makarov (2000) give $V_{12} = 6.12$ (average) and $V_3 = 5.28$. The corresponding maximum V magnitude of the contact pair is 6.05 and the third light is $l_{3V} = 0.676$. The resulting geometrical elements are: $i = 73.66° \pm 0.14°$, $\Omega = 2.8020 \pm 0.0038$ (fill-out = 0.167±0.013). The temperature of the secondary (hotter and smaller component) is $T_2 = 5174 \pm 10$ K. The corresponding fit of the V LC is depicted in Fig. 3 by the solid line.

Using "clean" geometric elements we have tried to solve the whole V LC assuming that the cool circular spot is positioned on the primary component. Due to the fact that the spot is not eclipsed we have fixed its latitude on the stellar equator. The best fit was obtained for the spot positioned at the longitude $l = 68°$ with radius $r_{spot} = 20°$ and the temperature factor $k = 0.937$. Fitting the one-passband photometry we must be aware that the radius and temperature factor of a spot are quite correlated. The resulting spot fit is depicted in Fig. 3 by the dashed line in the residuals.

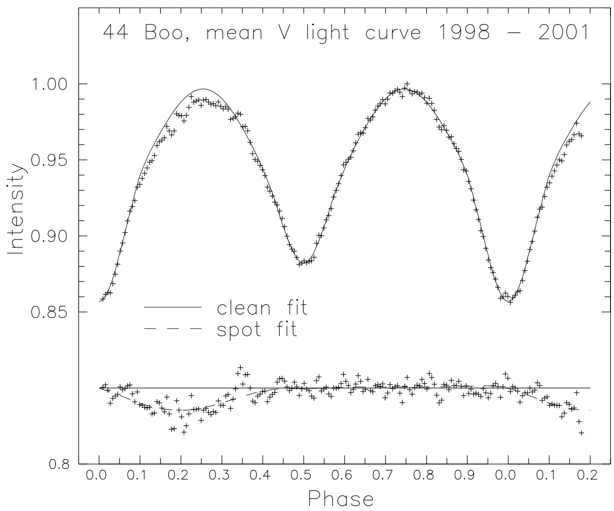

Figure 3: Best fit of the mean V LC constructed from observations since 1998. The spot fit corresponds to a dark spot positioned on the primary component.

5. Absolute parameters of the components and conclusion

Using our new determination of the inclination angle $i = 73.7°$, new spectroscopic elements of the contact pair (Lu et al., 2001) and the elements of the visual orbit, we have computed masses of the components $m_1 = 0.816 \pm 0.008 M_\odot$ and $m_2 = 0.419 \pm 0.003 M_\odot$. If we accept the total mass of the system as 2.70±0.16 $M_\odot$ (Söderhjelm, 1999) we have the mass of the third component $m_3 = 1.42 \pm 0.16\ M_\odot$. As this component is much more massive than expected for its spectral type (G5V), it can be a binary system.

Including the semi-major axis $a_{12} = 1.898 \pm 0.006$ in the W&D code we have obtained the absolute visual magnitude of the contact pair as $M_{12}^{bol} = 5.31$. Using the appropriate bolometric correction BC = -0.46 we obtained absolute visual magnitude $M_{12} = 5.77$. Since the distance to the system is precisely known, we can determine the absolute magnitude from the observed maximum visual brightness $V_{12} = 6.05$ assuming zero interstellar absorption. The resulting absolute visual magnitude 5.52 is much lower than that obtained from the spectroscopic and photometric data. The luminosity of the contact pair increases with the semi-major axis (and masses) of the components. Hence, it is possible that the most recent determination of the spectroscopic elements (Lu et al., 2001) is still negatively influenced by the third component.

Our monitoring of the eclipsing system 44i Boo shows that the system's LC suffers small seasonal variations but the general shape of the LC remains stable. It is interesting to note that the asymmetry in the maxima heights (maximum II brighter) was persistent during our observations since 1968.

The orbital period of the system is variable. Apart from the LITE caused by the third component on the 206 years orbit, the orbital period of the system continuously increases. The large scatter of minima times, highly exceeding the standard errors of the minima, is probably caused by the LC disturbances.

The detailed analysis and revision of both LC and period changes is under preparation.

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