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AC BOOTIS – AN UNEVOLVED W-TYPE OVERCONTACT ECLIPSING BINARY WITH A HIGH MASS TRANSFER RATE

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The variability of AC Boo (= BD +46°2004 = TYC 3474-905-1 = HIP 73103, Sp. F8V) was discovered by Geyer (1955, as reported in Mauder, 1964). Zessewitsch (1956) first identified the system as a W-UMa-type and attempted to determine its period, getting values of 0.38514 and 0.4278192 days. Mauder (1964) secured light curves in B and V photoelectrically and determined the correct period of 0.352429 days. He went on to do an analysis of the light curves using the rectification method. Lacking radial velocities, he was forced to estimate the mass ratio by indirect methods. Binnendijk (1965) used the 28-inch reflector at the Flower and Cook Observatory to secure a photoelectric light curves in two colours and derived orbital elements from the rectification method. Mancuso et al. (1974, 1977, 1978) determined times of minima and full light curves photoelectrically. They classified the system as W-type and went on to use the methods of Wood (1971) and Wilson-Devinney (1971, 1990, hereafter WD) to analyze their light curves, taken in 1972 and 1973, and also those of Binnendijk (1965). Assuming a spectral type of F0 (attributed to Mauder, 1964), they used fixed parameters $i = 85\overset{\circ}{.}47$, $\Omega_1 = 7.330$, $T_1 = 6100$ K, and mass ratio $q = M_2/M_1 = 3.57$. (The temperature was estimated from the colour index, and the others indirectly from Russell-Merrill (1952) analysis.) Noting the variation in the light curves over time, they obtained temperatures of the secondary varying from $T_2 = 5735$ to 6055 K. Schieven et al. (1983) secured further light curves photoelectrically, analyzed some period changes, and performed a light curve synthesis using the methods of Rucinski (1976a, b, and c). They also noted the variability of the light curves (on a time scale of days) and also the presence of an asymmetry in the portion of the light curve following the primary (flat-bottomed) minimum. They attributed the latter to the presence of starspots. They obtained two values of the mass ratio: 0.31 and 0.28. (Note that these values <1 imply an A-type system.) Linnell, et al. (1990) report modelling with their (unpublished) photometric data and the mass ratio of 0.41 (A-type) = 2.44 (W-type) of Hrivnak (1993) requiring a complex set of dark spots and third light. No error estimate was provided. Finally, Hrivnak (1993), using cross-correlation techniques, derived RV values which fit a double sine curve somewhat poorly, resulting in an rms deviation of 16.7 km/s and the above reported mass ratio.

With improved versions of the WD code that support star spots, and the opportunity to obtain new radial velocities (RVs) using analysis by the modern broadening functions due to Rucinski (1976a, 1976b, 1976c, 1992, 2004), an updated study was deemed important.

Table 1. New times of minima for AC Boo

Minima	Error (days)	Cycle	Type
55300.8561	0.0002	28893	I (occultation - flat bottom)
55301.7380	0.0005	28895.5	II (transit)
55312.8395	0.0002	28927	I (occultation - flat bottom)

This system has shown significant period change since 1929 when the first visual observations were recorded. Altogether 246 times of minimum have been entered into the Excel worksheet that is part of the "Eclipsing Binary $O-C$ Files" (observed minus calculated) database at the AAVSO site that is maintained by the author (Nelson, 2010 – updated annually). These include three new times of minimum determined during light curve acquisition and reported here – see Table 1.

Throughout the years, a total of 10 elements (epoch, period) have been used by various authors; some give the (incorrect) phase 0.5 of the deeper, or flat-bottomed minima (and of course, 0.0 for the shallower minima). The elements of Schieven et al. (1983) seem to give the best results (but note that there seems to have been a typo in HJD_0 – the correct value, as determined from his data, is given in Equation 1). As corrected, the elements give correct phases for the minima of Mauder (1964) and Binnendijk (1965), (subject to the requirement to adjust the cycle counts by $+$ or $-$ 0.5 for various ranges to obtain a contiguous relationship):

$$\text{J.D. Hel. min I} = 2445117.781(1) + 0.3524321(2)E \tag{1}$$

The results are plotted in Figure 1. The reader will note, as mentioned by various authors, that the period seems to have been constant from 1929 to 1982 (cycle counts from -54880 to 0); the best-fit period in this interval was 0.3524294 (1) days. Close to cycle 0 there was a sudden rise in the period; after that, the period displayed a slow, steady increase over time. The abrupt change of period can be explained by an episodal mass interchange, possibly as the two stars established contact (but see below). The portion of the curve after cycle 200 (and especially after cycle 1400) can be fitted closely by a parabola – denoting a constant rate of change. (Assuming no other cause, this implies a constant mass transfer rate; this is calculated later.) The elements best describing the curved section are given in Equation 2. (Then $\mathrm{d}P/\mathrm{d}E = 2\times$ the quadratic coefficient $= 8.13 \times 10^{-10}$ days/cycle.)

$$\text{J.D. Hel. min I} = 2445117.8019(1) + 0.3524305(1)E + 4.1(3) \times 10^{-10}E^2 \tag{2}$$

During September of 2008 and 2009, the author took six spectra (10 Å/mm reciprocal dispersion, resolving power 10,000) at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia, Canada; he then used the Rucinski broadening functions (Rucinski, 2004) to obtain radial velocity (RV) curves (see Nelson et al., 2006 for details). The spectral range was 5014-5261 Å. A log of DAO observations and RV results is presented in Table 2. An anonymous referee has pointed out that – due to the short period of the system – the one hour exposures represent a significant fraction of a period (0.118) and that excessive "phase smearing" of RVs might occur. A simple analysis reveals that, for circular orbits and assuming that neither star is undergoing an eclipse during any part of the exposure, the derived (averaged) RV values are reduced by a factor $f = \sin X/X$ from the instantaneous values (where $X = \pi t/P$, with $t =$ exposure time and $P =$ period).

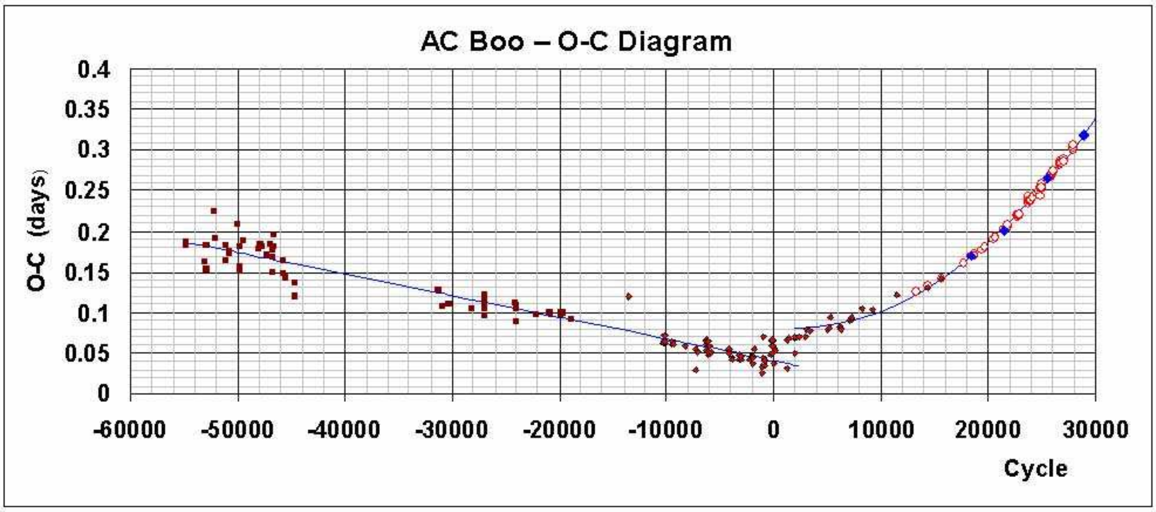

Figure 1. Observed - Computed ($O-C$) plot for AC Boo

Table 2.

DAO Image #	Mid Time (HJD-2400000)	Exposure (sec)	Phase at Mid-exp	V_1 (km/s)	V_2 (km/s)
4786*	54568.8890	3600	0.192	−275.7	50.2
4854*	54571.9030	3600	0.743	232.1	−109.9
5369	54927.8462	3600	0.655	200.6	−96.9
5381	54928.0313	1693	0.180	−266.4	32.5
5402	54928.9480	1800	0.781	221.2	−95.6
5420	54929.8189	3600	0.252	−278.2	56.6

*Taken in 2008

Note that factor f is independent of phase (subject to the above conditions). Therefore, corrected RVs were obtained by simply dividing all the derived RVs by f. (Note that, for $t = 3600$ seconds, $f = 0.977$. Note also that neglecting this correction factor cannot affect the derived value for the mass ratio but does affect the derived values of mass, etc.; therefore this correction is needed.)

On seven nights April of 2010, the author took a total of 241 CCD images of the field in V, 266 in R_C and 238 in I_C (both Cousins) at his private observatory in Prince George, British Columbia, Canada. The telescope was a 33 cm f/4.5 Newtonian on a Paramount ME mount; the detector was a SBIG ST-7XME CCD cooled to −20°C. Reduction software was MIRA by Mirametrics, Inc., and light-box flats were used. A list of the Variable, Comparison and Check stars appears in Table 3.

The following elements were used for phasing the light curves (see Nelson, 2010 for the $O-C$ relation):

$$\text{JD Hel Min I} = 2455312.8409(1) + 0.3524320(1)E \quad (3)$$

The author used the 2004 version of the Wilson-Devinney (WD) light curve and radial velocity analysis program with the Kurucz atmospheres (Wilson and Devinney, 1971, Wilson, 1990, Kallrath, et al., 1998) as implemented in the Windows software WDwint (Nelson, 2009) to analyze the data. To get started, a spectral type F8 V (SIMBAD

Table 3.

Type	TYC 3474–	R.A. J2000	Dec. J2000	V Mags	$B-V$ Mags
Variable	905	$14^{\rm h}56^{\rm m}28.341$s	$46^\circ21'44''.1$	10.0–10.62	0.592
Comparison	835	$14^{\rm h}56^{\rm m}07.846$s	$46^\circ21'26''.2$	11.18	0.549
Check	966	$14^{\rm h}56^{\rm m}26.300$s	$46^\circ26'50''.7$	9.39	0.358

Table 4.

Quantity	Value	
—	Star 1	Star 2
g	0.500	0.500
A	1.000	1.000
$x_{\rm bol}$	0.137	0.137
$y_{\rm bol}$	0.581	0.581
$x_{\rm V}$	0.148	0.148
$y_{\rm V}$	0.665	0.665
$x_{\rm Rc}$	0.049	0.049
$y_{\rm Rc}$	0.696	0.596
$x_{\rm Ic}$	−0.018	−0.018
$y_{\rm Ic}$	0.678	0.678

- no reference given) and a temperature $\mathbf{T_1} = \mathbf{6250 \pm 240}$ K were used; interpolated tables from Cox (2000) which gave $\log g = 4.368$ were used; an interpolation program by Terrell (1994) gave the (van Hamme, 1993) limb darkening values; and finally, a square root (LD=3) law for the limb darkening coefficients was selected, appropriate for hotter stars (Bessell, 1979). (The logarithmic LD=2 coefficients were tried but gave identical results.) Radiative envelopes were chosen for both stars, again appropriate for hotter stars (convective envelopes were tried but gave much poorer results.) The parameters are listed in Table 4.

Mode 3 (for overcontact binaries) was chosen, based on the general appearance of the light curves.

Because of the asymmetry of the light curves (unequal maxima and distorted light curve from about phase 0.25 to 0.50), noted by other authors, it was necessary to add a bright spot (a plage) on the more massive star (star 2). After a number of adjustments, the computed curved fit the observed values very closely indeed. The fit for the same spot put on star 1 was poorer, and a dark spot anywhere on the system did not give any kind of fit at all. It was also necessary to add third light; the values of l_3 are well above the 3 sigma values – see Table 4.

Convergence by the method of multiple subsets was reached in a large number of iterations (owing to the many parameters to adjust – 17). It was noted that identical values (to 3 figures) for the mass ratio were obtained from the photometric only WD solution, RV curve-fitting (alone), and the combined solution. This agreement reinforces the validity of the solution.

A plot of the VR_CI_C light curves and WD fit are shown in Figure 2; the RVs are shown in Figure 3 (the rms deviation from the fitted curve was 3.7 km/s). A three dimensional representation from Binary Maker 3 (Bradstreet, 1993) is shown in Figure 4.

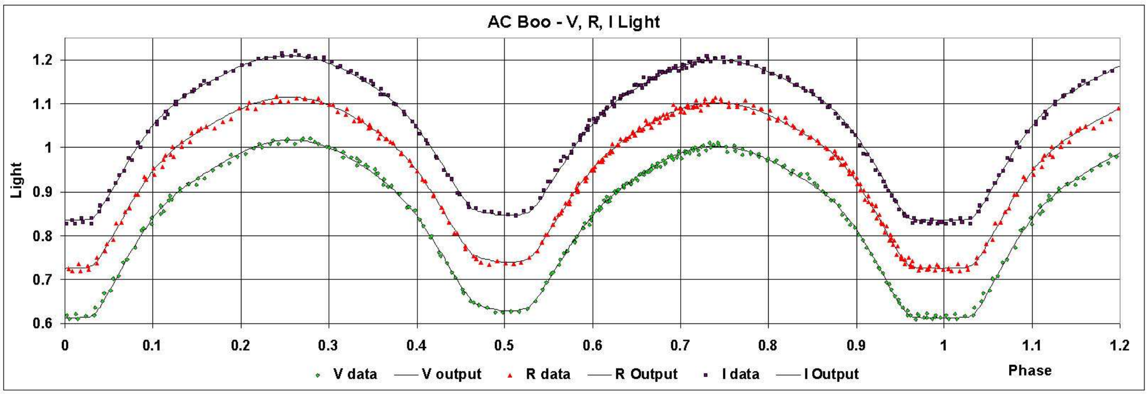

Figure 2. AC Boo: V, R, I Light Curves – Data and WD Fit

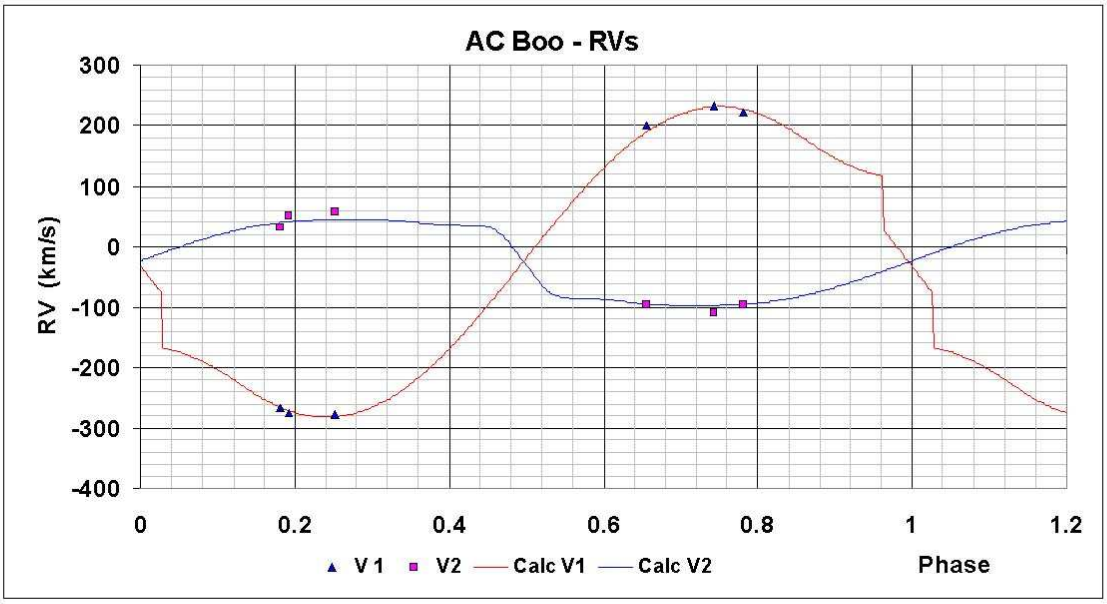

Figure 3. AC Boo: Radial Velocity Curves – Data and WD Fit.

Table 5.

Quantity.	Value	Error	Quantity	Value	Error
T_1 (K)	6250	—	a (solar radii)	2.43	0.04
T_2 (K)	6241	6	V_γ (km/s)	-25.8	0.1
$\Omega_1 = \Omega_2$	7.034	0.004	Spot Co-latitude	75	40
$q = M_2/M_1$	3.340	0.004	Spot Longitude	31	4
i (deg)	86.3	0.5	Spot Radius	40	2
$L_1/(L_1+L_2)(V)$	0.251	0.0006	Spot Temp. Factor	1.019	.007
$L_1/(L_1+L_2)(R)$	0.250	0.0005	R_1 (pole)	0.263	0.001
$L_1/(L_1+L_2)(I)$	0.250	0.0004	R_1 (side)	0.274	0.001
$l_3/(L_1+L_2)(V)$	0.0013	0.0001	R_1 (back)	0.308	0.001
$l_3/(L_1+L_2)(R)$	0.0012	0.0001	R_2 (pole)	0.458	0.001
$l_3/(L_1+L_2)(I)$	0.0009	0.0001	R_2 (side)	0.493	0.001
$\Sigma\omega^2_{\rm res}$	0.00665	—	R_2 (back)	0.518	0.001

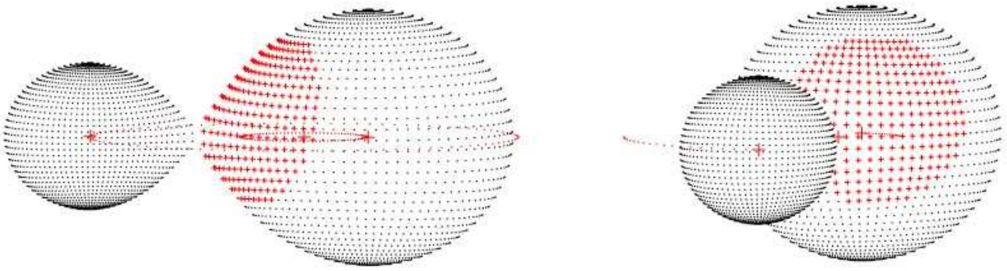

Figure 4. Binary Maker 3 representation of the system – at phases 0.24 and 0.44.

Final WD output parameters are listed in Table 5 with formal errors; the real error of the temperatures are around $\pm 250K$ as noted above.

The WD output fundamental parameters are listed in Table 6 along with those from the properties of zero age main sequence stars (ZAMS; Cox, 2000). The more massive star's mass and radius correspond closely to the tabular values (confirming its spectral type and its unevolved status), but it's overluminous by 3%. This may be due to the hot spot, or just to random error. In estimating the distance, galactic extinction was ignored, owing to the high galactic latitude (58°).

In an effort to understand the period behaviour of this system, the author scanned the data of Binnendijk (1965) [early data only – later data required a spot] and Schieven (1983), and ran the same WD package, starting at the above solution set of parameters. The results were (somewhat gratifyingly) almost identical with the above. The system in 1965 and 1983 was overcontact then as well. However, that does nothing to explain why the period could be constant for so long, suffer some kind of jump around cycle 0 (1982) and then display a constant rate of increase after that.

The calculation of the mass transfer rate for the curved part of the $O-C$ curve (i.e. after cycle 0) proceeded as follows:

It is not difficult to show that, under the assumptions of mass and angular momentum conservation of the system as a whole, and using basic physics:

Table 6.

Fundamental Quantity	Star 1 Tabular	Star 1 WD	Star 1 error	Star 2 Tabular	Star 2 WD	Star 2 Error
Sp. Type	F8 V	—	—	F8 V	—	—
Mass ($M_\odot$)	—	0.36	0.03	1.18	1.20	0.05
Radius ($R_\odot$)	—	0.69	0.01	1.18	1.19	0.01
$\mathrm{M_{bol}}$	—	5.26	0.17	3.84	4.07	0.17
Log g (cgs)	—	4.32	0.004	4.388	4.36	0.004
Luminosity ($L_\odot$)	—	0.65	0.09	1.89	1.94	0.28
Distance (pc)	—	182	13	—	—	—

$$(M_1 M_2)^3 P = \text{constant} \qquad (4)$$

where M_1 and M_2 = masses (any units), and P= period. Taking the natural logarithm of both sides of the equation and differentiating by time, and using the fact that $\mathrm{d}M_2 = -\mathrm{d}M_1$, one gets:

$$\frac{\mathrm{d}M_1}{\mathrm{d}t} = \frac{1}{3P}\left(\frac{1}{M_2} - \frac{1}{M_1}\right)^{-1} \frac{\mathrm{d}P}{\mathrm{d}t} \qquad (5)$$

Substituting the values from Table 5, and using the derived value of $\mathrm{d}P/\mathrm{d}t = +8.16(6) \times 10^{-7}$ days/year (taken from fitting the $O-C$ curve with a parabola), one gets a value of $-3.9(3) \times 10^{-7}$ solar masses/year for the mass transfer rate of the primary (less massive) star (i.e., mass is transferred from the less to the more massive star). This value is consistent with those of a number of other overcontact binaries (Schieven et al., 1983; Pribulla and Vanko, 2002).

In conclusion, AC Bootis is a subtype W overcontact binary comprised of unevolved stars. A full solution for its fundamental parameters has been obtained. It has been shown that it is undergoing mass transfer from the less massive to the more massive star at a rate of 3.9×10^{-7} solar masses per year.

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