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Solution of the Asymmetric Light Curve of OO Aquilae

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Abstract

The variability of the binary star system OO Aquilae was discovered by Hoffleit (6). Since that time, a number of its published photoelectric light curves show a definite asymmetry with a pronounced difference in maximum light (at elongation). The suggestion by Naqvi and Grønbech (21) of the hot region (to account for the asymmetry) on the binary star system TY Mensae, whose light curve is similar to OO Aquilae, has been incorporated into the light-curve modeling program by Nagy (18) used in the analysis of OO Aquilae. The results of this modeling with be presented and compared with solutions presented by other authors.

Introduction

The analysis procedure assumes a geometry based on the centrally condensed Roche model formulated in circular-cylindrical coordinates and second-order, limb-darkening fits to the model stellar-atmosphere calculations of Carbon and Gingerich (5). These assumptions have been applied to Lucy's model (12, 13), a common convective envelope for the W Ursae Majoris systems, and have been incorporated into the model developed by Nagy (18), which includes calculation of the reflection effect (second order). The gravity-darkening exponent (g) and the effective albedo (A) values are drawn from theoretical calculations by Lucy (11) and Rucinski (24, 25), respectively.

The light-curve synthesis procedure by Nagy (18) has been applied to the Johnson (7) V photoelectric light curve of Lafta and Grainger (10) of the W Ursae Majoris type eclipsing binary system OO Aquilae. The results of this analysis yield the relative sizes of the binary stars, their mass ratio (q) and the inclination of the orbital plane of the binary system (i). A comparison with analyses by other authors (Johnson (7) B and V bandpasses only) for photoelectric light curves at different epochs is presented.

Present Work

Tables of gravity coefficient values have been given by several authors in the past (Russell (26); Binnendijk (3) and Kopal (8)) using different assumptions at selected wavelengths. The generating expression utilizes a graybody assumption given to the first order by Kopal (8):

$$y = c_2/(4\lambda T_0\ (1\text{-}\exp(\text{-}c_2/\lambda T_0)))$$

where y is the monochromatic gravity coefficient, $c_2 = 1.438 \times 10^8$ angstroms/degree (second radiation constant), λ is the wavelength in angstroms, and T_0 is the effective temperature in degrees Kelvin. Essentially, the quantity y is used to convert the Stefan bolometric surface brightness to a Planck monochromatic surface brightness. The most common bandpasses used for light curve photometry are the Johnson (7) UBVRI and Stromgren (27) ubvy systems. The effective temperatures of the hotter stars (O and B) as given by Bohm-Vitense (4) tend to be higher than those by Johnson (7), but those stars are rarely of interest in binary star light-curve modeling. The modeling program used here is fairly insensitive to small variations in the values of the monochromatic gravity coefficient and to temperatures as a function of the spectral class.

The W Ursae Majoris eclipsing binary system OO Aql is a Binnendijk (2) A-type system. A summary of the adopted astrophysical parameters for the binary system is given in Table 1. The adopted model stellar-atmosphere parameters used in the computation of the synthetic light curve are given in Table 2. The limb-darkening

TABLE 1. Adopted Physical Parameters for OO Aquilae.

Quantity	*Value*	*Reference*
spectral type (Sp)	G5V	Roman (23)
effective temperature (T_{eff}) (primary star)	5660K	Böhm-Vitense (4)
period (P) in days	0.50678914	Lafta and Grainger (10)
bolometric albedo	0.5	Ruciński (25)

coefficients are derived values from the model stellar-atmosphere grids of Carbon and Gingerich (5). These derived values result from a second-order fit of the data in a least-squares reduction of the grid data values. The monochromatic gravity coefficients are from the generating expression given above. A summary of catalogue data for the system is presented in Table 3. This table provides other catalogue identifiers, spectral type and magnitude ranges for OO Aql. The synthetic light curve shown in Figure 1 was computed at 47 normal points (plotted as asterisks). Each of the normal points represents approximately 20 individual observations.

TABLE 2. Adopted Model Atmosphere Parameters for OO Aql.

wavelengths (angstroms)	limb-darkening coefficients u_1	u_2
B = 4400	0.864 ± 0.004	−0.063 ± 0.003
V = 5500	0.799 ± 0.006	−0.125 ± 0.004
		monochromatic gravity coefficient (y)
B = 4400		1.49
V = 5500		1.20

TABLE 3. Catalogue Data for OO Aql.

Reference	*Identifier*	*Sp*	*Magnitude Range*
Wood et al. (29)	2844	G5V	8.4 - 9.2
	BD +08°4224		
	HD 187183		
	HV 5468		

The individual data points are the individual observed points of Lafta and Grainger (10) plotted as phase vs. magnitude. In the plot, the magnitude has been zero-point shifted from the published data so that maximum light is plotted at approximately zero magnitude. The zero-point adjustment was 0.80 magnitude for the V data values (e.g., this value was added to the observed data). Computer modeling of physical systems permits the modeler the option of picking from a grab bag of parameters. Great restraint must be exercised to prevent too many parameters from varying since the solution parameters then begin to lose their physical meaning. It is important also to apply physical limits to parameters (e.g., the mass ratio should be permitted only inclusive values between zero and unity). The present analysis solves

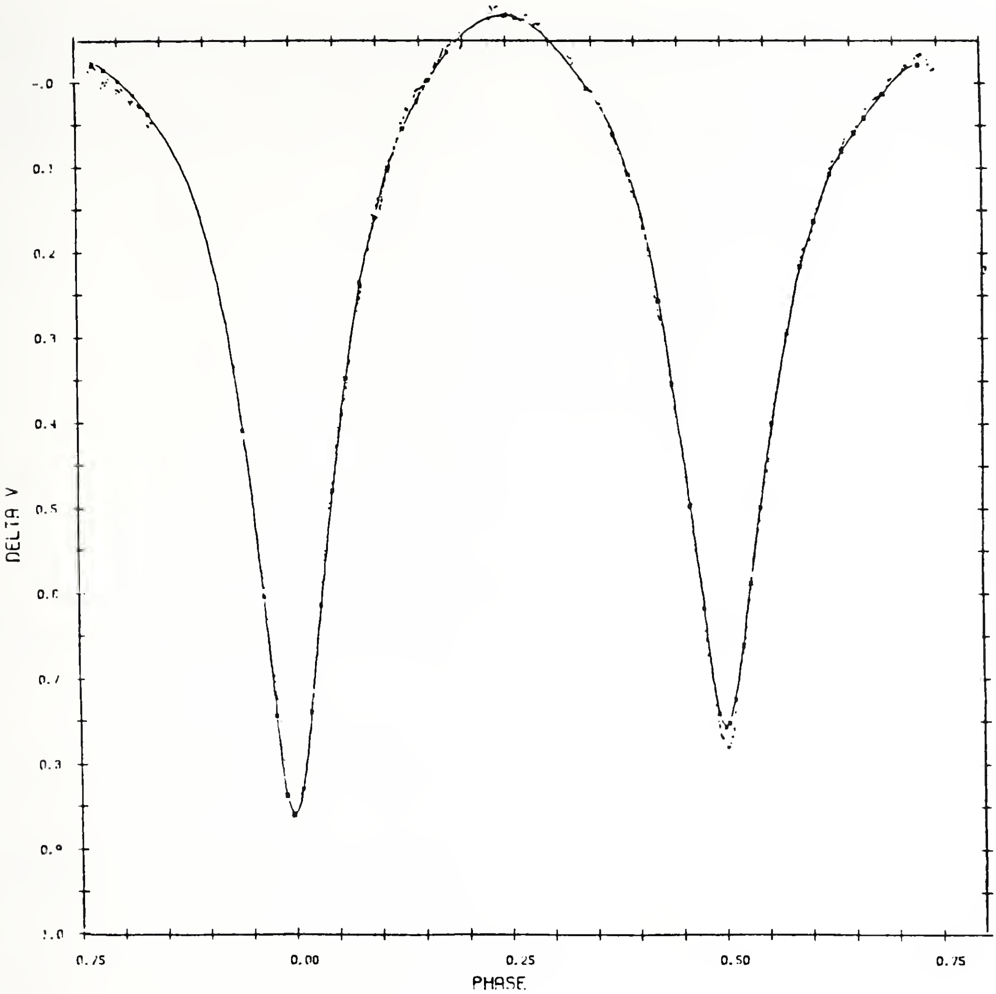

FIGURE 1. The relative V light curve of the binary star system OO Aql. The observations (small dots) are those of Lafta and Grainger (10) and the synthetic light curve has the parameters as given in Table 5. The computed values of the modeled light curve are plotted as asterisks and the solid curve is the spline fit through the computed values.

directly for three parameters: surface potential (C), inclination (i) as mass ratio (q). From these parameters a number of secondary parameters are computed (e.g., temperature differences and the relative sizes of the component stars).

Hot Spot

As shown in Figure 1, the *V* light curve of OO Aql is asymmetric as can be seen by comparing the amount of light at the two elongations of the system (i.e., phases 0.25 and 0.75). A number of the W UMa binary star systems exhibit this behavior but only recently have modeling programs been constructed to deal with it. Mullan (17) has proposed magnetic starspots to explain the asymmetry in the light curves of the W UMa class eclipsing binary stars. The presence of a hot spot (i.e., an area with a higher relative temperature than the surrounding area) on the primary manifests itself as an increasing effect from longer to shorter wavelengths (21). However, for the system OO Aql, as the wavelength decreased, the effect of the hot spot decreased. This is opposite the effect of a hot spot on the primary, which leads to the conclusion that the hot spot is on the secondary component of the system. Table 4 summarizes the analyses of three different eclipsing binary star systems exhibiting asymmetric light curves. Two have low mass ratios, with the hot spot on the primary (AG Vir and TY Men). The other has a high mass ratio with a hot

TABLE 4. Summary Comparison of Asymmetrical W UMa Stars.

Star	AG Vir (20)	TY Men (19)	OO Aql
λ	V, B	y, b	V
Inclination	$78^\circ.9 \pm 0^\circ.3$	$76^\circ.9 \pm 0^\circ.3$	$86^\circ.3 \pm 0^\circ.2$
Mass Ratio	0.277 ± 0.005	0.211 ± 0.005	0.819 ± 0.009
Fillout	1.39 ± 0.01	1.20 ± 0.01	1.01 ± 0.01
Primary: a b c	.55 .52 .48	.56 .53 .49	.42 .39 .37
Secondary: a b c	.33 .28 .27	.29 .25 .25	.39 .36 .34
Spot latitude	$75^\circ \leq \beta \leq 115$	$75^\circ \leq \beta \leq 120^\circ$	$-85^\circ \leq \beta \leq 175^\circ$
Area of spot	7.6%	6.7%	33.1%
T_p	7900°K	7560°K	5660°K
T_s	5200°K	6875°K	6475°K
Period	$0^d.64265$	$0^d.46166$	$0.^d50679$
Depth in Minima			
I	$0^m.55$	$0.^m48$	$0.^m92$
II	$0^m.45$	$0^m.40$	$0^m.82$

spot on the secondary component (OO Aql). Mochancki (15) has proposed that contact binaries be divided into three classes: the traditional W- and A-type systems of Binnendijk (2) and a new class the 'B-type systems', after Lucy and Wilson (14). The premise is that the B-type systems have evolved into a contact binary (evolved systems of large mass ratio and low mean density possess too much angular momentum to have existed as contact systems at age zero).

In a period study of OO Aql, Lafta and Grainger (10) found that, in a plot of frequency versus time, after about a 20 year consistency, the period starts decreasing with a sudden change around 1960. This change perhaps represents the onset of contact of the stars' the photospheres. If the trend of the plot continues, the binary system will increase its fillout, thus decreasing the period of the binary system.

Intercomparison of Analyses

A tabulated summary of the analyses of this system is given in Table 5. The Lafta and Grainger (10) analysis utilized the optimization method (a distorted spherical model). The results quoted for Niarchos (22) are based on the method of Kopal (9) which analyzes the light curves of close eclipsing binaries by transforming the data into the frequency domain. This method is quite different from the others used in the analysis of this system and hence some of the published results do not map directly into the standard set of parameters. In terms of the physical sizes, shapes of the components, mass ratio and degree of fillout for the binary system, the present results are very similar to those of Twigg (28). The Lafta and Grainger (10) solution compares favorably with present results in terms of mass ratio and inclination. Although there is similarity between the present analysis and the other solutions listed in Table 5, the difference is manifest in the parameter k, which is the ratio of the average radii of the smaller star with respect to the larger star.

The degree of fillout has been defined by Mochancki and Doughty (16) in terms of the surface potential (C), the innermost potential surface (C_1) and the outermost potential surface (C_2). When the fillout is less than unity ($O < F < 1$), the system is detached. In this case the surface potential of the system is greater than the inner-

TABLE 5. Comparison of Light Curve Analyses of the System OO Aql.

Analysis (Data)	Wynne and Nagy (10)	Lafta and Grainger (10) (10)	Niarchos (22) (1)	Twigg (28) (1)
λ	B, V	B, V	B, V	V
q	0.819 ± 0.009	V: 0.849 ± 0.002	V: 0.73	0.825
		B: 0.821 ± 0.003	B: 0.66	
C	3.989 ± 0.006	——	——	3.965
i (degrees)	86.34 ± 0.19	V: 87.8 B: 87.5	V: 77.2 B: 77.9	87.2
k	0.912	V: 0.829 ± 0.002	V: 0.81	0.915
		B: 0.841 ± 0.005	B: 0.80	
g	0.32	——	——	——
u_1	V: 0.799 ± .006	V: 0.6	V: 0.60	——
	B: 0.864 ± .004	B: 0.7	B: 0.70	——
u_2	V: -.125 ± .004	——	——	——
	B: -.063 ± .003	——	——	——
L_g	V: 0.550 ± .002	V: 0.650 ± 0.008	V: 0.690	——
	B: ——	B: 0.690 ± 0.007	B: 0.679	——
L_s	V: 0.450 ± .002	V: 0.350 ± 0.008	V: 0.310	——
	B: ——	B: 0.310 ± 0.007	B: 0.321	——
T_g	5660 K	——	5660 K	——
T_s	V: 6475 K	6336 K	——	——
a_g, b_g, r_g	.424 .393 .397	r_g: .417	r_g: .377(V) .393(B)	r_g: .402
a_s, b_s, r_s	.389 .357 .362	r_s: .345	r_s: .304(V) .316(B)	r_s: .368
A_1	0.5	V: 1.36 B: 1.20	——	——
A_2	0.5	V: 1.32 B: 1.47	——	——
F	1.01 ± 0.01	——	——	1.060
Y	V: 1.20	V: 1.22	——	——
	B: 1.49	B: 1.42	——	——

most potential surface, $C > C_1$ (q). When the fillout is less than unity, the fillout is computed as the ratio of the innermost potential surface to the surface potential ($F = C_1/C$).

A system is *overcontact* when the fillout has a value between one and two ($1 \leq F \leq 2$). In this case the surface potential has a value which is greater than that of the outermost potential surface and less than that of the innermost potential surface, $C_1 \geq C \geq C_2$ (q). In this case on fillout is defined as:

$$F = (C_1 - C)/C_1 - C_2) + 1.$$

If the surface potential is less than that of the outermost potential surface (C_2) then the surface is no longer bounded and thus is not a region of interest in defining the surfaces of binary star systems. Table 5 shows that the two solutions having fillouts are very similar and just slightly overfill their inner Roche lobe.

Summary

Comparison of the solutions of the light curves of OO Aquilae shows some correlation, but there are also distinct differences in some of the parameters of the solutions. Part of the difference comes from the fact that the hot spot was included in only two of the solutions (present work and (28)), which also turn out to be the two most similar. Another reason for differences is that the solutions are based on different epoch light curves, some of which exhibit more asymmetry than others. The Binnendijk (1) data are approximately 20 years older than the data of Lafta and Grainger (10). The hot spot for the present solution covers 33.1% of the visible area of the binary system at elongation (phase 0.75). In addition, the hot spot is 30% intrinsically brigher than the surrounding area. This leads the authors to conclude that the secondary component is hotter than originally believed.

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