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RADIAL VELOCITY STUDIES AND ABSOLUTE PARAMETERS OF CONTACT BINARIES. II. OO AQUILAE

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ABSTRACT

New high-precision radial velocities of the contact binary OO Aql have been obtained using the cross-correlation technique. The orbital elements have been corrected for proximity effects, using an analysis of published light curves of the system. The spectroscopically determined mass ratio of 0.843 is in excellent agreement with the photometrically determined value. OO Aql thus has one of the largest mass ratios observed for a contact binary. In contrast to almost all other contact binaries of G spectral type, the primary minimum is due to a transit by the less massive component, and thus the system is classified as an A-type contact binary.

Absolute parameters are determined for OO Aql, which indicate that the primary component, although similar to the Sun in mass, is significantly more evolved. An age of about 8 Gyr and a metal abundance of one-half that of the Sun are determined. It seems that the system may have only recently evolved into contact, as suggested by Mochnacki, and that it is an important object for studies of the structure and evolution of contact binaries.

Subject headings: stars: eclipsing binaries — stars: individual (OO Aql) — stars: W Ursae Majoris

I. INTRODUCTION

OO Aquilae (BD +08°4224, HD 187183, SAO 125084) is a ninth-magnitude binary with a W Ursae Majoris–type light curve and relatively deep minima. Photoelectric blue and yellow light curves have been published by Binnendijk (1968), and *B* and *V* light curves by Lafta and Grainger (1985). Binnendijk found over several seasons that the shape of the light curves varied with time. Demircan and Gudur (1981) have published *B* and *V* observations, and have also gathered together a large number of times of minimum light as part of a period study. In addition, a number of other observers have published occasional times of minimum light. Mochnacki (1981) lists the results of an unpublished synthetic light curve analysis by Twigg, presumably of Binnendijk's light curves, and Lafta and Grainger analyzed their light curves using both Kopal's frequency domain technique and an optimization method.

A spectral type of G5 V has been assigned to the system by Roman (1956), and K0 by Hill *et al.* (1975) based upon classification spectra. The observed color indices are $(B-V) = 0.76$ (Eggen 1967) and $(b-y) = 0.46$ (Rucinski and Kaluzny 1981). The reddening is uncertain, and we will return to a discussion of it in the last section. Dereddened color indices indicate a spectral type of late F to late G, depending upon the estimated value of the reddening (Rucinski and Kaluzny 1981; Rucinski 1983). No previous radial velocity study has been published for this system.

Observations with the *International Ultraviolet Explorer* (*IUE*) satellite indicate a level of Mg II emission similar to that found for other contact binaries in the same general range of spectral types (Rucinski 1985). OO Aql has not been observed in the X-ray region with either the *Einstein* (Seward and Macdonald 1983) or *EXOSAT* (Sternberg *et al.* 1986) satellites. A radio survey of contact binaries with the VLA by Hughes and McLean (1984) yielded only an upper limit to the flux from OO Aql.

The binary stands out on a period-color diagram for contact binaries (see, for example, Rucinski 1985) in the sense that it has a long period for its color. Mochnacki (1981) argues that OO Aql has too much angular momentum to have existed as a zero-age contact binary, and that it must have evolved into contact. Binnendijk's analysis of his light curves led him to conclude that the primary minimum represented a transit, which is unusual in a W UMa of spectral type G, since in almost every other case the primary minimum is an occultation by the larger, more massive component. Mochnacki (1981), on the other hand, classified OO Aql as a W-type contact binary, in which case the primary minimum would be an occultation.

In this paper we present the results of a spectroscopic study of this interesting system. This represents a part of our ongoing program to determine new, high-precision radial velocity curves of contact binaries using the cross-correlation technique. These new velocity curves of OO Aql are analyzed together with published light curves to obtain the masses and other absolute properties of the components. The evolutionary state of the system is then discussed in the last section.

II. SPECTROSCOPIC OBSERVATIONS

OO Aql was observed on nine nights during the 1984 and 1985 seasons. The observations were obtained at the Dominion Astrophysical Observatory (DAO) with the 1.8 m telescope, using an image intensifier and either photographic plates (IIa-O) or an 1872 element Reticon. A total of 69 spectra of the binary were obtained, at a reciprocal dispersion of 15 Å mm^{-1} and with a resolution of about 0.8 Å.

A list of observations is given in Table 1. The heliocentric Julian Dates refer to the midpoints of the observations. Exposure times ranged from 3 to 12 minutes, depending upon seeing and transparency, and averaged 6 minutes, or $0.008P$. The ephemeris used to compute phases was

$$\text{Hel. Pri. Min.} = 2{,}445{,}185.2551 + 0.50678914E\ .$$

This is based on the published time of minimum light closest to the spectroscopic observations, that given by Lafta and Grainger (1985), and the period from the linear ephemeris of

TABLE 1

OBSERVATIONS OF OO AQUILAE

$JD_{\odot}$ − 2,440,000	Phase	Detector	V_P (km s^{-1})	V_S (km s^{-1})
5884.8356.........	0.417	R	−129	...
5899.9092.........	0.161	P	−157	142
.9168.........	0.176	P	−187	103
.9630.........	0.267	P	−192	141
.9699.........	0.280	P	−189	113
.9741.........	0.289	P	−205	81
5900.9460.........	0.206	P	−180	114
.9519.........	0.218	P	−220:	128
.9616.........	0.237	P	−202	112
5913.7547.........	0.481	P	−57	
.7644.........	0.500	P	−61	
.8908.........	0.749	P	107	−192
.8967.........	0.761	P	98	−207
5915.8514.........	0.618	R	43	−196
.8549.........	0.625	R	57	−197
.8577.........	0.630	R	56	−204
.8612.........	0.637	R	52	−202
.8646.........	0.644	R	78	−193
6269.9248.........	0.278	R	−181	145
.9352.........	0.299	R	−188	119:
.9428.........	0.314	R	−179	120
.9508.........	0.329	R	−170	117
.9592.........	0.346	R	−167	116
.9675.........	0.362	R	−164	94
6271.8772.........	0.131	R	−164	90
.8807.........	0.138	R	−170	97
.8845.........	0.145	R	−168	105
.8890.........	0.154	R	−181	99
.8942.........	0.164	R	−182	103
.8981.........	0.172	R	−188	113
.9015.........	0.179	R	−186	105
.9053.........	0.186	R	−179	118
.9092.........	0.194	R	−182	120
.9126.........	0.200	R	−187	114
.9168.........	0.209	R	−188	119
.9203.........	0.216	R	−193	130
.9234.........	0.222	R	−190	121
.9265.........	0.228	R	−183	133
.9307.........	0.236	R	−187	135
.9352.........	0.245	R	−190	132
.9401.........	0.255	R	−181	134
.9453.........	0.265	R	−185	127
.9491.........	0.272	R	−177	131
.9536.........	0.281	R	−185	123
.9581.........	0.290	R	−192	131
6283.8250.........	0.706	P	78	−206
.8407.........	0.737	P	94	−207
.8497.........	0.755	P	83	−210
.8615.........	0.778	P	107	−207
.8674.........	0.790	P	107	−206:
.8737.........	0.802	P	102	−190
.8799.........	0.814	P	87	−207
.8868.........	0.828	P	98	−174:
.8934.........	0.841	P	78	−186
.9004.........	0.855	P	70	−188
6285.8204.........	0.643	P	90	−195
.8239.........	0.650	P	73	−193
.8274.........	0.657	P	75	−211
.8312.........	0.665	P	80	−217
.8357.........	0.674	P	87	−200
.8402.........	0.682	P	90	−212
.8468.........	0.696	P	95	−211
.8496.........	0.701	P	90	−209
.8527.........	0.707	P	117	−192
.9072.........	0.815	P	92	−199
.9107.........	0.822	P	87	−193:
.9135.........	0.827	P	87	−229:
.9170.........	0.834	P	100:	−186:
.9208.........	0.842	P	87	−201

NOTES.—Photographic (P) spectra were given half-weight in the analysis, except for those values followed by colons, which were given zero weight. Reticon (R) spectra whose values are followed by colons were given half-weight in the analysis.

Rudnicki (1982). The type of detector, either Reticon (R) or photographic plate (P) is also given in Table 1. Approximately half of the spectra were recorded with each detector.

The spectral type of the system appears to be early to mid-G, with the Ca I λ4227/Hδ ratio indicating about G5 and the Fe I λ4046/Hδ ratio indicating early G. Although these spectra were not of classification dispersion, they clearly rule out a spectral type as late as K0 as given by Hill *et al.* (1975). The early to mid-G spectral type is in general agreement with the dereddened colors. No Ca II emission was obvious in these spectra of OO Aql, which included in all cases at least the H line and often the K line. We made no attempt, however, to measure possible infilling of these lines by emission.

A number of velocity standard stars were observed in this program and are used in the subsequent analysis.

III. SPECTROSCOPIC REDUCTION AND ANALYSIS

The general reduction procedures we have followed for obtaining the component velocities utilizing the cross-correlation technique have been discussed previously (Hrivnak *et al.* 1984; Hrivnak 1988) and will only be summarized here. The digitized spectra are wavelength calibrated and linearized in ln λ using the computer program REDUCE (Hill, Fisher, and Poeckert 1982). The program spectra were then cross-correlated with spectra of a standard star of similar spectral type, reduced following the same procedures. The program VCROSS (Hill 1982) was used, and the spectra were cross-correlated over the wavelength interval 4000–4270 Å, with the Hδ line excluded. Examples of the cross-correlation function (c.c.f.) profiles produced are displayed in Figure 1. These profiles were fitted simultaneously by two Gaussian functions with zero baseline, and the centers of the Gaussian functions were taken to represent the component velocities. The quality of the c.c.f. profiles produced by the higher signal-to-noise Reticon data was in almost all cases superior to that of the plate data, as is illustrated in Figure 1. In the subsequent analysis we assigned the plate data only half the weight of the Reticon data.

The velocities derived from the cross-correlation analysis are listed in Table 1. Uncertain values are followed by colons. The radial velocity standard was HD 217014 (G5 V, $V_r = -33.0$ km s^{-1}; Beavers *et al.* 1979). The actual templates used were composed of several co-added Reticon or photographic spectra of the star, for which we measured velocities of −33.3 and −31.7 km s^{-1}, respectively. A more detailed discussion demonstrating the accuracy of the standard star velocities is

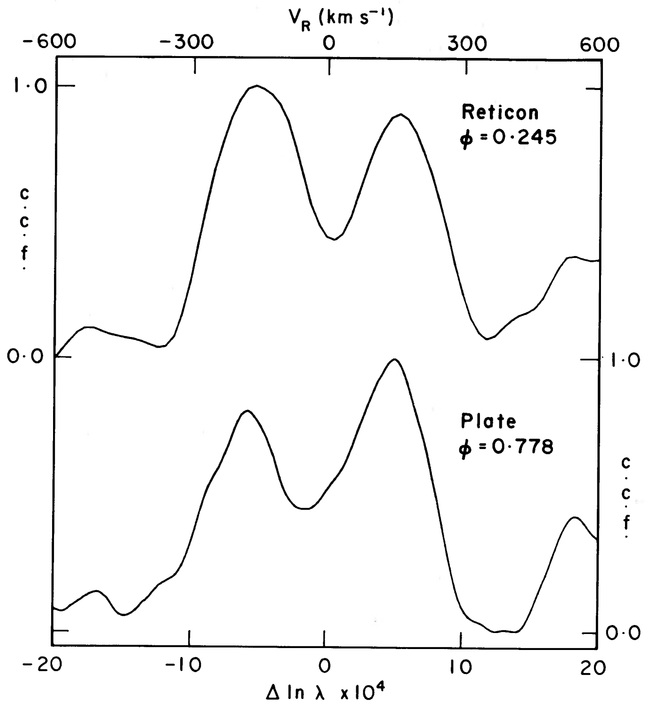

FIG. 1.—Examples of the cross-correlation function (c.c.f.) profiles obtained at the two quadratures of the orbit, using spectra recorded with a Reticon and a photographic plate. The exact phases are indicated.

contained in Hrivnak (1988). Uncertainties in the derived binary star velocities are estimated to be about 10 km s^{-1}.

The radial velocity curves were solved assuming a circular orbit, using the spectroscopic orbit program of C. L. Morbey. As noted earlier, the photographic data were assigned only half-weight in the analyses. The two observations near phase 0.5, during which one of the components was undergoing eclipse, displayed only single peaks in the c.c.f. profiles; these were not included in the analyses. The velocity curve of each component was first analyzed separately, and very good agreement was found between the systemic velocities of the components. Thus no distortion by gas streams or other large-scale complications are indicated. A combined analysis of the velocities of both components was made, with the constraint that they have the same V_0. The results are listed in Table 2, in columns (2)–(4). Also listed are the standard errors of the derived values. The resulting radial velocity curves are displayed in Figure 2. The fit to the data is very good for a contact system. The standard deviations for the radial velocity curves of the primary and secondary components are 9 and 14 km s^{-1}, respectively.

For OO Aql, the more massive (primary) component is the component eclipsed at primary minimum. Thus OO Aql should be classified as an A-type W UMa system, in contrast to what is typically found for the G and K spectral type contact binaries. This is in agreement with the classification by Binnendijk (1970) and in disagreement with the W-type classification by Mochnacki (1981). The values of the mass ratio found by Twigg (see Mochancki 1981) and Lafta and Grainger (1985) are quite similar to the radial velocity value of 0.825. This is one of the largest mass ratios observed for a contact binary, with only SW Lac and VZ Psc (Hrivnak and Milone 1989) possessing larger values.

The above analysis omits the corrections due to proximity effects, which require a model of the light distribution of the system. We discuss such an analysis of the velocity curves including tidal and eclipse effects, together with the light curves, in § V.

IV. LUMINOSITY RATIO FROM CROSS-CORRELATION FUNCTION ANALYSIS

Tests of the cross-correlation program indicated that reliable values for the luminosity ratio of the two components of the binary could be obtained from the c.c.f. profiles. Synthetic binary spectra were formed by adding together different spectra of the standard star, which were linearized in ln λ, with various specified velocity differences ranging from 150 to 400 km s^{-1} and also with a variety of specified light ratios from 1.0 to 0.4. These were then cross-correlated with the template. The area under the c.c.f. profile of each of the two components was determined in a manner analogous to that for determining an equivalent width, and the measured ratio of these was then compared with the specified input light ratio. The area of the c.c.f. profile is related to the strength of the absorption lines and the spectral match between the standard and program stars. In a contact binary, since the temperatures of the two stars are very similar, one would expect the ratio of these areas to be approximately equal to the light ratio. The agreement between the measured light ratios and the input light ratios

TABLE 2

ORBITAL ELEMENTS OF OO AQUILAE

	Proximity Effects			
	Not Included			Included
Element (1)	Primary (2)	Secondary (3)	Joint (4)	Joint (5)
V_0 (km s^{-1})	-46.3 ± 1.1	-47.0 ± 1.8	-46.6 ± 0.9	-45.2 ± 0.9
K_P (km s^{-1})	147.4 ± 1.2	...	147.3 ± 1.4	151.9 ± 1.2
K_S (km s^{-1})	...	178.6 ± 2.0	178.5 ± 2.0	180.2 ± 1.3
σ_P (km s^{-1})	8.5	...	8.5	7.7
σ_S (km s^{-1})	...	13.6	13.6	10.8
$a_P \sin i$ ($R_\odot$)	...	...	1.475 ± 0.014	1.521 ± 0.012
$a_S \sin i$ ($R_\odot$)	...	...	1.787 ± 0.020	1.804 ± 0.013
$M_P \sin^3 i$ ($M_\odot$)	...	...	0.995 ± 0.023	1.041 ± 0.018
$M_S \sin^3 i$ ($M_\odot$)	...	...	0.821 ± 0.019	0.877 ± 0.015
$q (= M_S/M_P)$	...	...	0.825 ± 0.012	0.843 ± 0.008

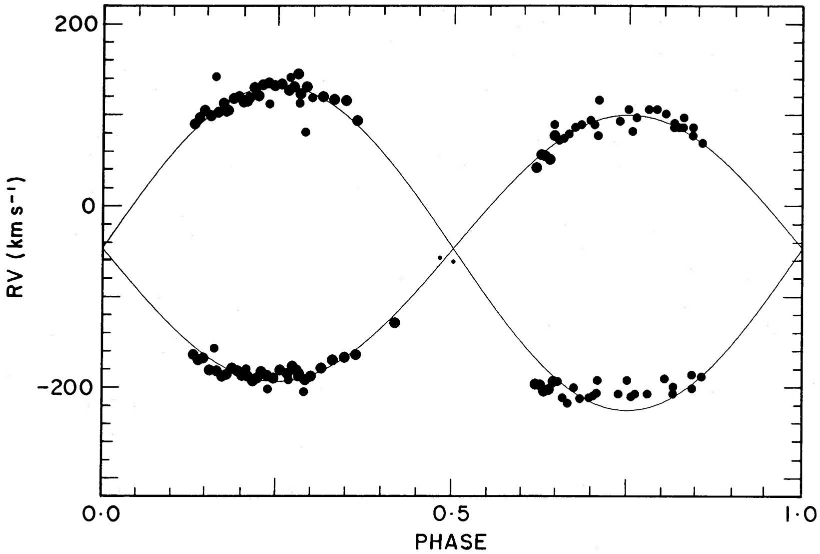

FIG. 2.—Radial velocity curves of OO Aql. The solid dots represent the observed velocities, and the solid lines the velocity curve solution, without the inclusion of proximity effects. The largest dots indicate data which received full weight, and the middle-sized dots indicate data which received half-weight, in the analysis. These are in most cases data obtained with the Reticon and photographic plates, respectively. The smallest dots, near eclipse, were not used in the analysis.

was found to be very good for values near unity, and then the difference between the two increased monotonically with decreasing light ratio, with the measured light ratio generally somewhat too large. At a light ratio of 0.6, the agreement is still good, with a deviation of 10%.

The ratio of the area of the c.c.f. profiles of the two components can serve as a check on the value of the light ratio determined from the light curve solution. This is particularly true for the W-type contact systems, which all have large light ratios near unity. Even at a light ratio of 0.4, the accuracy was found to be about 25%, which is still precise enough to provide a useful constraint on the light curve solution when nonunique solutions are found, as can be the case for partially eclipsing systems without a spectroscopic mass ratio. Similar tests of the light ratio were carried out independently by Hilditch and King (1986), who also found that reliable values of the light ratio could be obtained from the c.c.f. profiles. This method thus has the potential for providing a useful constraint on the light curve study of a contact binary from the analysis of only a few spectra obtained at quadrature.

This method was applied to the c.c.f. profiles of OO Aql. We calculated the ratios of the areas of the c.c.f. profiles for OO Aql, taking the ratio of the area of the secondary component to that of the primary for each of the spectra. Weighting the photographic data at half that of the Reticon data, we determined a ratio at the first quadrature (the phase interval around 0.25) of 0.80 and at the second quadrature of 0.75, and an average of 0.78. Thus we expect the light ratio (in the blue) to be near 0.78, with an uncertainty of perhaps ± 0.05. As we will later see, this value is very close to the blue-light ratio of 0.81 determined from the light curve analysis. Thus it gives us confidence in this method to see that the approximate light ratio determined from the c.c.f. profiles is in good agreement with the more precise light ratio determined from the light curve analysis.

V. CONSISTENT VELOCITY AND LIGHT CURVE ANALYSIS

The mass ratio and orbital elements determined from the radial velocity data do not include corrections for the proximity effects in the velocity curves. While these are most obvious during eclipse ingress and egress, they can also affect the velocity curves at the quadratures. At these later phases, the tidally distorted shapes and the nonuniform brightness distribution can cause the light-center velocities (which are suitably close to the absorption-line velocities) to differ from the mass-center velocities. To correct for these effects requires a model of the shape and light distribution of the components in the system. This can be obtained from an analysis of the light curves of OO Aql.

Published photoelectric light curves are those of Binnendijk (1968) from 1966 and of Lafta and Grainger (1985) from 1982. Unfortunately, those of Lafta and Grainger are incomplete in the phase interval 0.85–0.95. For our light curve study we have thus chosen to analyze the 1966 blue (b) and yellow (y) light curves of Binnendijk. These light curves contain 489 blue and 493 yellow light observations obtained over an interval of 80 days. These were not transformed to a standard system.

We gathered these individual observations into average points by averaging the observations within phase bins of 0.010, centered on phase 0.000, except within $0.020P$ of the two minima, where we used smaller phase bins of 0.005. These were used in the analysis, with the number of individual observations which composed each average point representing the weight of the point. The light curves of OO Aql are known to display some intrinsic variability, at least from season to season (Binnendijk 1968). They also show an asymmetry in the heights of maximum light, with the first maximum (following primary minimum) brighter than the second by about 0.02 mag in the light curves of Binnendijk and by 0.06 mag in the light curves of Lafta and Grainger. This asymmetry is due to some nonsymmetric light distribution in the system, perhaps attributable to starspots. Such asymmetries can be handled in various manners such as by subtraction of outside-eclipse sine terms, by fitting to only half of the light curve centered about the higher or lower maximum, or by the introduction of spots into the light curve program. In a previous study of the contact binary XY Leo (Hrivnak 1985), we found that the system possessed an asymmetry of 0.015 mag with a total light variation of one-half that of OO Aql. We first analyzed a sine-corrected light curve of XY Leo, determining the light curve parameters. Then we analyzed half of the light curve at a time, and in both cases arrived at parameters which were in all cases within 2 standard deviations of those determined from the sine-corrected analysis, and thus did not differ significantly from them. In the case of OO Aql, where the asymmetry in the Binnendijk light curves is an even smaller fraction of the overall light variation, we feel that the effect on the light curve parameters of correcting by some method to a symmetric light curve will not be significant. Thus we use the entire observed light curve, with no corrections to remove or model the asymmetry.

The light curves were analyzed with the programs of Wilson and Devinney (1971), modified by Wilson (1979) to include velocity curves according to the method of Wilson and Sofia (1976). To find a consistent set of light and velocity curve elements, we used the following strategy. With the mass ratio fixed at the radial velocity value of 0.825, we solved the light curves. Then, with this light model, we solved the velocity curves with explicit corrections for the proximity effects. We repeated this process until a consistent set of elements was found, in which all parameter adjustments were less than their probable errors.

The parameters which we permitted to adjust in the light curve analysis were the orbital inclination i, the temperature of the secondary component T_S, the modified equipotential surface of each component Ω_P and Ω_S (which are equal for a contact or overcontact system), and the light of the primary component in each bandpass $L_{P,b}$ and $L_{P,y}$. Since this is an A-type system, the primary, more massive component is the one eclipsed at primary minimum. For the light curve analysis we assumed the blue and yellow observations to have the effective wavelength of the standard B and V system. Initial values of these parameters were chosen by trial-and-error fits to these light curves, beginning with a detached configuration (mode 2).

The light curve parameters which were kept fixed included the bolometric albedos $A_P = A_S$ and the gravity darkening exponents $g_P = g_S$, which were fixed at the theoretical values of 0.50 (Rucinski 1969) and 0.32 (Lucy 1967), respectively. The temperature of the primary component, T_P, was set at 5700 K based upon the spectral type and color of the system; this value is uncertain by 200–300 K. Values for the wavelength-dependent limb darkening x_b and x_y were taken from the tabulation of Al-Naimiy (1978). There is no evidence of third light in the system, and we set $l_3 = 0.000$. The Carbon-Gingerich model atmosphere subroutine was used to represent the surface flux distribution. The relative weighting of the light curve average points was inversely proportional to the light level, and the curve-dependent weights for the blue and yellow light curves were set at the values of the mean standard deviations to the outside-eclipse Fourier analyses. A circular orbit was assumed.

While the mass ratio $q\ (=M_S/M_P)$ was held fixed in the light curve analysis, it was permitted to adjust in the velocity curve analysis, along with the semimajor axis of the orbit a and the systemic velocity V_0. These were initialized at the values determined in § III.

The initially detached configuration parameters immediately predicted adjustment to an overcontact configuration, and we proceeded in the analysis in mode 3. The light curves were first analyzed with $q = 0.825$, and all of the parameters except i converged to values in which their differential corrections were much less than their probable errors. The calculated values of the adjustments to i were such as to increase it to a value slightly greater than 90°, which is not permissible by definition. We then constrained i to a value less than or equal to 90°, and all of the other parameters converged to values in which their predicted adjustments were less than their probable errors. With these light curve parameters we again solved the velocity curves. They quickly converged to the mass ratio $q = 0.843$. With this slightly different value for the mass ratio, the light curve parameters then converged to their final values, with $i = 90°$.

The parameters of the velocity curve solution with proximity effects included are listed in Table 2, under column (5). This modified value of the mass ratio, $q = 0.843$, is not significantly different (2 σ) from that determined without the inclusion of the proximity effects. However, the theoretical velocity curve fit is significantly better, as is demonstrated quantitatively by the reduction in the standard deviations of the fits (σ) in Table 2. This improvement can be seen visually in Figure 3, where we have replotted the observations and the spectroscopic solution, together with the velocity curve solution including proximity effects. The shapes of the theoretical curves are noticeably distorted from those of sine curves by the proximity effects. This appears most obviously in those portions of the curve when the components are undergoing eclipse. However, in practice it is hard to resolve the components at these phases, and very near the eclipses the light of the eclipsed component becomes relatively small. The proximity effects cause the curves to be flatter near quadratures, where most of our observations were made, and this leads to the improved fit. This improvement is most evident in the fit to the secondary component in the phase interval 0.6–0.9. The mass-center semiamplitudes are slightly larger than the light-center amplitudes, and thus the calculated masses are accordingly larger. The consequence of these corrections for the proximity effects is to lead to calculated masses which are approximately 6% larger in this case.

The light curve parameters are listed in Table 3, along with their standard errors. Since the light and velocity curve parameters are actually coupled through q, the errors listed are those derived from a light curve solution including q as an adjustable parameter, which takes this correlation between parameters into account. The difference in temperature between the two components is small, with the secondary component (the less massive one) cooler by 65 K. The value of the degree of overcontact is 27%. The fit of the theoretical light curve to the observed average points is very good. The deviation is small, apart from the slight asymmetry in the heights of the two maxima and the asymmetric brightening in the observed light curve as compared with the theoretical one in the phase interval 0.3–0.4. These light curves are displayed in Figure 4. The theoretical light curve predicts a grazing total eclipse of $0.010P$ duration at secondary minimum. The fit to the color curve is also good, indicating that the determined temperature difference is accurate. The slight blueward increase in color seen in secondary minimum results from the eclipse of the reddened limbs of the smaller star. This effect is discussed more thoroughly for multicolor light curves of W UMa by Linnell (1987).

We also determined a solution to the light curve with the mass ratio q permitted to vary. We started with the parameters for the light curves obtained for the consistent light and velocity solution, with $q = 0.843$. The parameters which were permitted to vary were those which were adjusted in the previous light curve solution, plus q. The parameters were divided into

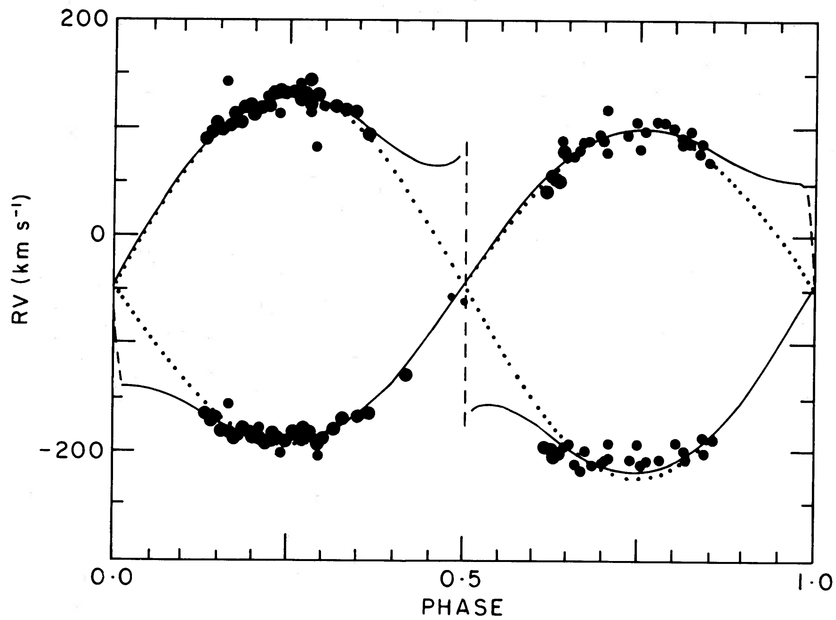

FIG. 3.—Radial velocity curves of OO Aql, modified to include proximity effects such as tidal distortion and eclipses (*solid lines*). The symbols have the same meanings as in Fig. 2. Also, the radial velocity curves without proximity effects from Fig. 2 are replotted for comparison (*dotted lines*). The dashed lines within eclipse indicate phases where the relative light ratio is less than 0.20.

subsets, to separate the strong correlation between q and Ω. The resulting light curve solution does not differ significantly from that determined in the consistent velocity and light curve solution as listed in Table 3, with all parameters differing by less than 1 standard error, and leads to $q = 0.834 \pm 0.005$.

The results of previous photometric solutions by Twigg (Mochnacki 1981) and Lafta and Grainger (1985) can be compared with values in Table 3. While the values of the mass ratio agree, these previous solutions obtained a lower inclination, 87°, and different radii. The solution of Twigg, using presumably the same data set and essentially the same analysis programs of Wilson and Devinney (1971), indicated the components to be significantly smaller in fractional radii, leading to a fill-out factor of only 6%. These differences may be due to incorrect analyses of the system as a W type, with the smaller, less massive component eclipsed at primary minimum, although details of this aspect of the analyses are not clear in these references. A correct analysis of the system requires the recognition that the more massive component is eclipsed at primary minimum, as demonstrated in this study.

TABLE 3

CONSISTENT LIGHT CURVE AND VELOCITY CURVE PARAMETERS FOR OO AQUILAE

Parameter	Light Curve[a]	Velocity Curve
$a\,(R_\odot)$	...	3.325 (18)
V_0 (km s^{-1})	...	−45.2 (9)
q	...	0.843 (17)[a]
i	90.0[b] (16)	...
$g_P = g_S$	0.32[c]	...
T_P (K)	5700[c]	...
T_S (K)	5635 (8)	...
$A_P = A_S$	0.50[c]	...
$\Omega_P = \Omega_S$	3.364 (27)	...
$L_P/(L_P + L_S)_V$	0.550 (4)	...
$L_P/(L_P + L_S)_B$	0.552 (4)	...
$x_{P,V} = x_{S,V}$	0.62[c]	...
$x_{P,B} = x_{S,B}$	0.77[c]	...
l_3	0.000[c]	...
$r_{P,\,\mathrm{pole}}$	0.388 (4)	...
$r_{P,\,\mathrm{side}}$	0.412 (5)	...
$r_{P,\,\mathrm{back}}$	0.451 (7)	...
$r_{S,\,\mathrm{pole}}$	0.359 (4)	...
$r_{S,\,\mathrm{side}}$	0.380 (5)	...
$r_{S,\,\mathrm{back}}$	0.422 (8)	...
f(% overcontact)	27 (6)	...

NOTE.—Standard errors in the last digits are given in parentheses (not probable errors, as are usually listed in Wilson-Devinney analyses).

[a] Errors listed are those appropriate to a light curve solution which includes q as an adjustable parameter.

[b] Constrained to be ≤90°.

[c] Not adjusted in the solution.

Thus the mass ratio determined from light curve analyses of the system is very close to that found from our radial velocity study. This good agreement between the spectroscopic and photometric mass ratio is what one would expect to find in a contact system with a high orbital inclination, owing to the strong correlation between the sizes of the stars as determined by their equipotential surface and the mass ratio.

VI. SUMMARY AND DISCUSSION

Absolute parameters for OO Aql can be calculated, based upon the parameters of the consistent light and velocity curve solution. These are listed in Table 4, along with the standard error of the last figure in each parameter, which is listed in parentheses. The radius is the mean volume radius. It and the mean surface gravity were calculated using the tables of Mochnacki (1984), which are based upon the Roche geometry. For the temperature of each component, we have assumed a standard error of 300 K, which is unfortunately rather large but is realistic. The luminosity is based upon the temperature and surface area of each component. Following Popper (1980), we have adopted for solar values $T_{\mathrm{eff}} = 5780$ K, $M_{\mathrm{bol}} = 4.69$, and BC $= -0.14$. The bolometric correction used for each component is from Popper's (1980) tabulation. The calculated visual magnitude difference between the two components

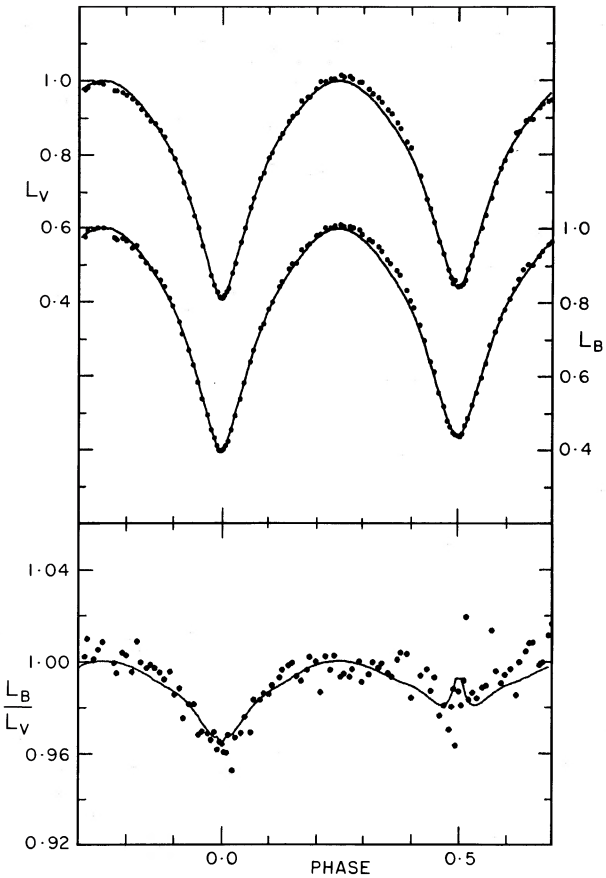

FIG. 4.—Light and color curves of OO Aql. The solid dots represent the observed average points by Binnendijk (1968), and the solid lines the results of the consistent light and velocity curve solution. Note the change in scale of the color curve.

agrees exactly with the light ratio determined from the light curve analysis. We used the value for the observed V-magnitude of 9.31 derived from the observations of Rucinski and Kaluzny (1981) and Eggen (1967) at maximum light. For reddening, we have utilized the study of Perry and Johnson (1982) to find the reddening for stars in the region of OO Aql. Based upon 10 stars within 4° of OO Aql in the sky and with distances between 90 and 200 pc, we determined an average reddening of $E(b-y) = 0.02$. This value transforms to $E(B-V) = 0.03$. Eggen (1967) had listed the uncertain value of $E(B-V) = 0.15$, based upon the deviation of OO Aql from his empirical period-color relation, but this is not to be regarded as a direct determination. Rucinski and Kaluzny (1981) used Eggen's value to deredden the color indices of OO Aql in their study of W UMa–type binaries in the *uvby* system. However, they note that OO Aql is one of the few systems which strongly deviates from the relationships which they find, and that a decrease in reddening to near zero would bring it into agreement. Thus we use the value of $E(B-V) = 0.03$, and assume that the reddening is uncertain by the same amount.

TABLE 4

ABSOLUTE PARAMETERS OF OO AQUILAE

Element	Primary	Secondary
Mass ($M_\odot$)	1.04 (2)	0.88 (2)
Radius ($R_\odot$)	1.39 (2)	1.29 (2)
log g (cgs)	4.14 (1)	4.13 (1)
log T	3.76 (2)	3.75 (2)
log ($L/L_\odot$)	0.26 (9)	0.17 (9)
M_{bol} (mag)	4.05 (22)	4.27 (22)
M_V (mag)	4.20 (22)	4.42 (22)
Distance[a] (pc)	136 (15)	

[a] Assumed reddening of 0.03 mag.

While the mass of the primary is similar to that of the Sun, the radius is larger than that of the Sun by approximately one-third. Thus it appears that the system is evolved on a nuclear time scale. Both components are significantly more luminous than the Sun. However, a significant fraction of the luminosity of the secondary is presumably due to energy transfer from the primary through the common envelope. Mochnacki (1981) develops a simple method to correct for this luminosity transfer, assuming a mass-luminosity relationship of $L(\text{internal}) \propto M^\gamma$. We began by using a value of $\gamma = 4.7$, appropriate for unevolved main-sequence stars. Such a correction leads to luminosities (bolometric magnitudes) of 2.27 $L_\odot$ (3.65 mag) and 1.02 $L_\odot$ (4.52 mag) for the primary and secondary components, respectively. These corrected values can be compared with stellar evolution models to see whether the models can represent the mass and luminosity of the components. In making this comparison with models, we are assuming that no significant amount of mass has been lost from the components. In Figure 5 the uncorrected and corrected bolometric magnitudes of the components of OO Aql are compared with isochrones from VandenBerg (1985) for three different metal abundance values, $Z = 0.0169$ (solar), $Z = 0.0100$, and $Z = 0.0060$. The model calculations are based upon a helium abundance $Y = 0.25$ and a ratio of mixing length to pressure scale height $\alpha = 1.6$. The secondary is highly overluminous compared with the models, even with the correction for $\gamma = 4.7$. However, this exponent is appropriate for unevolved main-sequence stars, and a steeper mass-luminosity relationship exists for evolved stars. Comparing values of mass and M_{bol} for 1.04 and 0.88 $M_\odot$ models of VandenBerg for ($Z = 0.0169$, age = 10.0 Gyr), (0.0100, 8.0 Gyr), and (0.0060, 6.0 Gyr) leads to a more appropriate exponent of $\gamma = 8.0$. With this revised correction for energy transfer from an evolved primary, the values of the luminosities (bolometric magnitudes) are 2.62 $L_\odot$ (3.50 mag) and 0.67 $L_\odot$ (4.98 mag) for the primary and secondary components, respectively. These are also shown in Figure 5. Very good agreement exists between these corrected magnitudes and the isochrone for $Z = 0.0100$, age = 8.0 Gyr. Although this is the best fit, a range in age from 6 to 11 Gyr, depending upon the metal abundance, is consistent with these corrected bolometric magnitudes to within 1 standard error. The primary component is near the turnoff of the main sequence. One can also make a correction to the temperature of the primary component by assuming that the energy transfer is shut off, with the primary radius remaining fixed (Mochnacki 1981). This increases the temperature of the primary by 10%, leading to a value in exact agreement with that predicted by the model for $Z = 0.0100$, age = 8.0 Gyr. Thus the observed parameters, when corrected consistently for energy transfer from primary to secondary, agree well with the models for stars with ages of approximately 8 Gyr and with a metal abundance of about one-half that of the Sun.

Only a few other contact binaries have such high-precision radial velocity studies, and consequently well-determined parameters. Among these, BV Dra, BW Dra (Kaluzny and

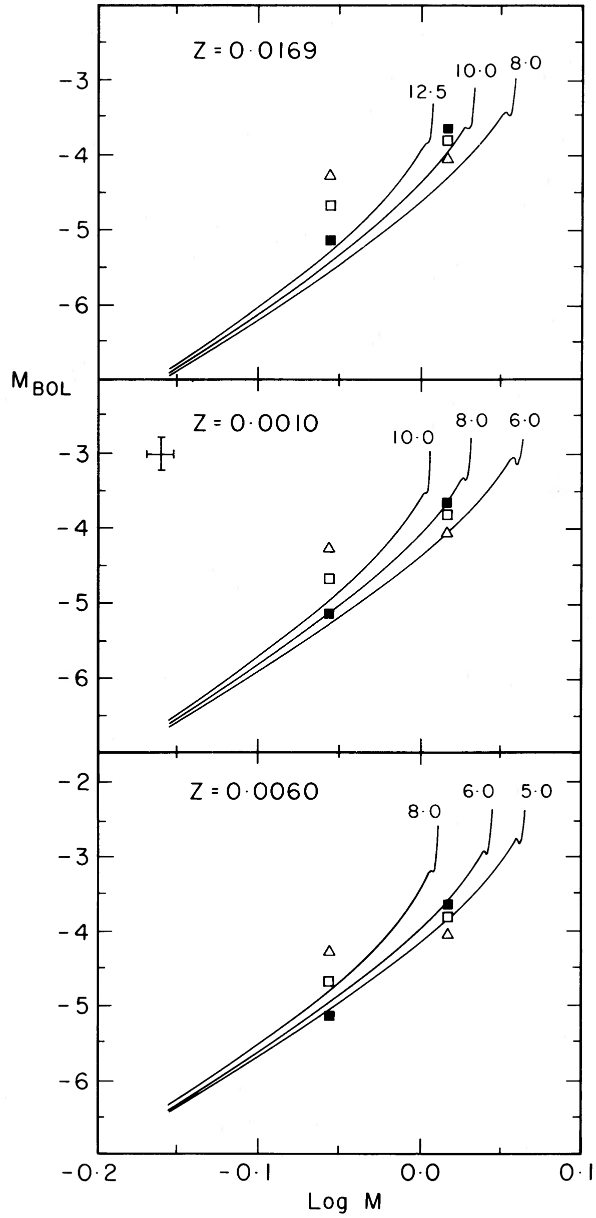

FIG. 5.—Observed and energy-transfer–corrected bolometric magnitudes of the components of OO Aql, compared with evolutionary model isochrones of VandenBerg (1985) for three different metal abundances. The ages of the isochrones in Gyr are listed. The observed values of M_{bol} are indicated by triangles, the initially corrected values with a mass-luminosity exponent of 4.7 are indicated by open squares, and the final corrected values with an exponent of 8.0 are indicated by filled squares. The size of the standard error bars for these values is shown in the middle panel. (Note that the values of M_{bol} for OO Aql are adjusted by +0.03 in the figure to account for the slight difference in the solar value used with the models.)

Rucinski 1986), and AB And (Hrivnak 1988) also have primary components with masses similar to that of the Sun, and all appear to be somewhat evolved and to possess metal abundances about one-third to one-half that of the Sun. However, none of these is as evolved as the components of OO Aql.

We note that Popper *et al.* (1986) urge caution in accepting the age and composition of binaries based upon comparison with stellar models. Their reason is due in part to differences between theoretical models of different investigators. However, some of these differences are due to the use of older opacity values, as compared with the newer values used by VandenBerg (1985). There does not appear to be a problem in the mass-luminosity plane (see Popper *et al.* 1986, Fig. 8), which is what we have used. In comparison with the G-type detached binaries which they investigated, OO Aql appears to be more evolved than either FL Lyr or EW Ori, and is perhaps comparable to HS Aur in age.

TABLE 5

GALACTIC MOTION OF OO AQUILAE

Element	Value
$u_\alpha \cos\delta$ (arcsec yr^{-1})	+0.065 ± 0.012
u_δ (arcsec yr^{-1})	−0.003 ± 0.009
U (km s^{-1})	48 ± 5
V (km s^{-1})	−24 ± 5
W (km s^{-1})	−31 ± 8
S (km s^{-1})	62 ± 6
U' (km s^{-1})[a]	38 ± 5
V' (km s^{-1})[a]	−14 ± 5
W' (km s^{-1})[a]	−25 ± 8
S' (km s^{-1})[a]	48 ± 6

[a] Primed quantities refer to the LSR.

The kinematics of the system also indicate an old age. Proper-motion components are listed in the SAO catalog. These were combined with the systemic velocity, calculated distance, and positional coordinates to yield the kinematic values listed in Table 5. The quantities U, V, W, and the space motion S refer to the motion relative to the Sun, U outward in the galaxy, V in the direction of galactic rotation, and W perpendicular to the plane. The primed quantities refer to motion relative to the local standard of rest (LSR). The space motion S' of 48 km s^{-1} is relatively large and is consistent with the system's belonging to the intermediate to old disk population. This would suggest an age on the order of that of the Sun or older on kinematic grounds. Large values of space motion appear to be common among the W UMa–type binaries (Guinan, Bradstreet, and Robinson 1987).

Mochnacki (1981) has suggested that OO Aql and a few systems similar to it have evolved into contact. OO Aql definitely has too much angular momentum to have existed as a contact binary on the zero-age main sequence with its present mass. A likely evolution of the components into contact occurred as the stars evolved separately on a nuclear time scale with the primary increasing in size and luminosity, while at the same time angular momentum loss through magnetic braking in stellar winds brought the components closer together. Vilhu (1982) has discussed the evolution of detached binaries into contact by gradual angular momentum loss. Using his formula for the rate of period change and an age of 6–8 Gyr for the system, one arrives at an initial period for the system of approximately 2.5 days, assuming that it has only recently come into contact. Examples of short-period systems which are good candidates to evolve in such a way into a contact binary are ER Vul and UV Leo. ER Vul consists of a pair of early G-type stars (G0 V and G5 V; Northcott and Bakos 1967) with a period of 0.698 days. Parameters for the components as listed in the recent study of Budding and Zeilik (1987) are (0.96 $M_\odot$, 1.03 $R_\odot$) and (0.89 $M_\odot$, 0.83 $R_\odot$), and the present angular momentum of the system is 25% greater than that of OO Aql. UV Leo consists of a pair of G2 V stars with parameters listed by Popper (1980) as (0.99 $M_\odot$, 1.08 $R_\odot$) and

($0.92\ M_{\odot}$, $1.08\ R_{\odot}$), with an orbital period of 0.600 days and with an angular momentum 7% greater than that of OO Aql. However, the components of neither of these systems would be expected to be as evolved on a nuclear time scale when the systems evolve into contact as the components of OO Aql presently are.

Evidence for a gradual change in the angular momentum of a binary can be sought in a study of the change in the orbital period of the system. However, for OO Aql, the period behavior appears to be dominated by a change from one constant period to another constant period, rather than by a continuously varying one. This is based upon an analysis of the times of minimum light as listed by Lafta and Grainger (1985), supplemented by the additional times listed by Scarfe *et al.* (1984), Pohl *et al.* (1987), and Hegedus (1987). Changes in the periods of contact binaries appear to be common, with about equal numbers of increasing and decreasing values, and in the case of OO Aql a change to a smaller constant period seems to be the dominant term.

Evidence that OO Aql has only recently evolved into contact is provided by its mass ratio. Discussions of the evolution of contact binaries indicate that, in response to the energy transfer from primary to secondary through the common envelope, the secondary expands and transfers mass to the primary to accommodate the evolutionary expansion of the primary (Webbink 1976). Thus the systems evolve toward lower mass ratio. Angular momentum loss appears capable of maintaining the contact during this phase of the evolution (Rahunen and Vilhu 1982; Rucinski 1982), although Mochnacki (1985) raises the concern that if the time scale of magnetic braking is too short, the contact phase will be too short. Some sort of self-regulating mechanism would need to operate, and suggestions have been made (Rucinski 1982). The high mass ratio of OO Aql thus suggests that the system has not yet evolved significantly while in contact. Note that had any significant exchange of mass from the secondary to the primary taken place, this would imply that the primary had evolved prior to contact as a lower mass star, and thus the age of the system would be even larger than that determined above. Thus our results support Mochnacki's (1981) suggestion that OO Aql has (recently) evolved into contact.

As has been noted by several authors, the division into A-type and W-type W UMa systems occurs around the same spectral type as the division between radiative and convective atmospheres, respectively, about F8. OO Aql is anomalous, as it is one of the few contact systems which deviates from this pattern. It is an A-type system, but its mass and spectral type indicate a convective atmosphere. This suggests that the cause of the separation into the A- and W-type systems involves another parameter in addition to the envelope energy transport mechanism. Note, however, that if mass is transferred conservatively from the secondary to the primary on a short time scale, before the primary has evolved much further, then OO Aql will in the future appear as a rather typical A-type system, with an early F primary when the mass ratio reaches a typical value of 0.3.

In summary, based upon our new radial velocity study, we have obtained precise absolute parameters for OO Aql. The primary component is similar to the Sun in mass, but is significantly more evolved. Comparison with theoretical models indicates that the system has an age of about 8 Gyr and a metal abundance about one-half that of the Sun. The space velocity of the system is consistent with such an age. The large mass ratio suggests that the system has only recently evolved into contact. In light of these precisely determined parameters and the evolved nature of the system, OO Aql appears to be an important system for detailed comparison with models of the structure and evolution of contact binaries. This study also illustrates the potential increase in our understanding of the contact binaries which can result from high-precision radial velocity observations and consistent light curve analyses.

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