

A NEW PHOTOMETRIC ANALYSIS OF U OPHIUCHI

ROBERT H. KOCH AND CLAIRE A. KOEGLER

Department of Astronomy, University of Pennsylvania, Philadelphia

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ABSTRACT

The history of the short-period eclipsing pair, U Oph, reveals several misinterpretations and evidences of intrinsic variability that have heretofore been ignored. It is shown here that the period variability cannot have a single explanation and that familiar causes, such as light-time effects in a triple system and a rotating eccentric orbit, cannot be proved at the present time. Numerous 50 Å wide scanner observations have been assembled into four light curves that themselves reveal complexities. These light curves have been solved on the basis of assorted assumptions. For no case is the historical photometric solution confirmed, and one new analysis is presented in considerable detail. It is prudent to reconsider the use of this binary for delineating the mass-radius and mass-luminosity relations.

Subject headings: stars: eclipsing binaries — stars: individual

I. HISTORY

Among bright eclipsing binaries, U Oph (HD 156247, BD +1°3408, ADS 10428 A, HR 6414), is reputed to be very well known and uncomplicated, lacking for instance, the evident effects of fast and slow mass exchange which characterize β Lyr and β Per, respectively. One purpose of this paper is to demonstrate that U Oph must really be described as a complicated pair. This cannot be done without a detailed recital of the photometric history of the star. In this paper, primary eclipse is established at phase 0.0000.

The first complete light curve, based on meridian photometer observations by Wendell and Pickering, appears in Bailey (1903), refers to the year 1882, and shows secondary minimum to occur at phase 0.496. This light curve was first solved by Shapley (1915*a*), who gave three limiting solutions and who also remarked on the similar observations of Wendell (1909) for 1902. These latter are few in number but, according to Shapley (1915*b*), show stellar ellipticity. In fact, this seeming ellipticity is only observational scatter. Shapley did not treat Wendell's (1913) polarizing photometer measurements accumulated from 1906 to 1912, which are very numerous, which show no evident ellipticity, and for which the secondary eclipse falls at phase 0.497. The next significant contribution was made by Viola (1928). Viola mistakenly believed that Shapley's remark concerning ellipticity referred to orbital eccentricity, but the main interest in his work is the treatment of 244 wedge photometer (Guerrieri 1914) observations made by Bemporad from 1918 through 1921. Although neither Bemporad nor Viola ever published the individual observations, the light curve of normal points looks quite satisfactory and the secondary minimum occurs at phase 0.441, from which Viola derived an impossible combination of e and ω . Thereafter, Magalashvili

(1949) obtained yellow and blue photoelectric light curves for 1944 and 1945 with the secondary eclipse at phase 0.498, but she treated the observations for $\omega = 90^\circ$. Huffer and Kopal (1951) reported unfiltered photoelectric observations obtained over the intervals 1939-1941 and 1947-1948, and emphasized the care taken to ensure that no seasonal differences would exist among the 434 observations. Within the minima, however, the observations are not homogeneous. In the primary eclipse there is a well-defined lower envelope to the data, but the observations of three nights scatter upward by differing amounts approaching 0.2 mag. A similar effect occurs in the secondary minimum, with two nights brighter than the rest by about 0.2 mag. Nothing in the Washburn data, however, suggests a displaced secondary eclipse. The precision claimed by Kopal and Shapley (1956) for the solution of this light curve clearly cannot have resulted from the use of all the observations with their full scatter. Finally, Eaton and Ward (1973) treated OAO-2 fluxes from 1970 in numerous bandpasses, and all secondary eclipses fall at phase 0.5012.

All of these efforts involved different comparison stars, which might not have been equally satisfactory. For example, Abt (1973) has shown HD 154895 to be a conspicuous velocity variable, and Gould (1879) suspected slight variations for HD 156208, which might be a low amplitude δ Scuti-type variable because of its spectral classification. None of the comparison stars is as hot as U Oph itself. However, none of the U Oph light curves shows effects on the order of hours which would implicate short-period variable comparison stars or inappropriate differential extinction corrections. Rather, the photometric changes seem to be longer-term ones.

Some miscellaneous topics may now be summarized. It may first be noted that U Oph is neither 38 Oph (Hoffleit 1964) nor 31 Sco. These mistakes of attribution apparently appeared first in Pickering (1908).

Batten (1967) and Popper and Carlos (1970) give appreciations of the assorted radial velocity studies. Coyne (1970) has shown that the p -parameter of linear polarization sometimes varies for certain bandpasses as the eclipses are approached but that the θ -parameter remains constant at about the interstellar value. The agreement of the reddening values for the components of ADS 10428 strongly suggests this to be a true visual binary with a very long period since there has been no change in the relative positions of the stars over 150 years. The unreddened UBV indices suggest a spectral type for U Oph that is very slightly earlier than that given by Koch, Olson, and Yoss (1965) which, in turn, is earlier than any previous classification. This discrepancy might indicate U Oph to be an unresolved triple system in which the third star would be a hot, degenerate object in order to ensure that its absorption lines would remain invisible in the net spectrum. The compatibility of this possibility with long-term period variations and with the photometric solution will be examined.

II. THE OBSERVATIONS

The present observations were made during the summers of 1963 and 1964 with the photoelectric scanner (Oke 1964) attached to the Cassegrain focus of the 152 cm Mount Wilson reflector. The comparison star (HD 156208, BD +2°3283) and the variable were alternately centered in a diaphragm typically subtending 23" in the focal plane. Poor seeing, however, sometimes required the use of a 31" diaphragm, but ADS 10428 B was always excluded from the measurements. During all measurements of both the variable and comparison stars the telescope was guided by centering on the image reflected from a microscope cover slip placed behind the diaphragm and viewed by a high magnification eyepiece. The width of the exit slot of the scanner permitted 50 Å of radiation to pass to the photocell, and the central wavelength of the bandpass was set by rotating the scanner grating. On each night the zero point of the grating dispersion was determined by observation of the core of the H γ line of α Lyr. The present paper reports data taken at central wavelengths of $\lambda\lambda 4026, 4230, 4476$, and 4750. For the longest wavelength, a Wratten K2 gelatin filter eliminated the violet of the overlapping order. Either of two cold boxes surrounding 1P21 photocells with crushed CO₂ was used and the photocurrent was amplified and recorded in a conventional way. During the present observations, the comparison star shows no evidence of variation with respect to 109 Vir, which was also observed every night.

Because the character of the light curve was clearly not simple, all observations were reduced with the utmost care. For relatively long nights the extinction coefficients were constrained to the values associated with Rayleigh scattering-ozone-aerosol standard atmospheres computed by Blitzstein (1975) for the altitude of Mount Wilson. For short nights which encompass only a small air-mass range the extinction coefficients were calculated from tables by Elterman

(1970) for a horizontal meteorological range of about 75 km at the altitude of the observatory.

The central wavelengths for these bandpasses were chosen to isolate two domains ($\lambda\lambda 4750, 4230$) of pure continuum and two intervals ($\lambda\lambda 4476, 4026$) containing weak absorption lines in the hope that the independent determinations of limb darkening would reveal something of the atmospheric structure of the component stars. The weaknesses of the helium and magnesium lines and the complicated nature of the eclipses prevented realization of this intention. Three additional light curves, which are dominated by hydrogen line and continuum absorption, will be discussed in a separate paper to be published later. Economy forbids publication of the journal of the present 1400 observations, but the data may be obtained from the IAU Commission 27 depository at the RAS library by requesting File IAU (27) RAS-41.

III. PERIOD VARIATIONS

From the present observations and those obtained at other stations but still unpublished, several times of minimum light have been calculated by bisecting chords across the minima. These epochs appear in Table 1. Plavec, Pěkný, and Smetanová (1960) presented the last comprehensive period study incorporating all timings from the discovery of the variability of the system. For a star so bright, it is to be expected that numerous meridian observations would have been made, and the observers' estimates might reveal some of these to occur at or near minimum light because the period is relatively short. A search of 18th and 19th century catalogs confirms the former expectation. Among these sources, however, there appears to be only one which merits consideration: Bessel's (1823) brightness estimation with a meridian circle at JD 2,386,717.38 must be quite close to primary minimum. This observation permits the conclusions that no secular quadratic ephemeris term is detectable through the 33,000 cycles elapsed over the past 150 years and that a suitable period for long-term prediction is $P = 1.67734523$ days. The determinacy of this period is probably limited by the variations in the Earth's rotation rate.

Before about 1940 it was unclear whether the period of U Oph was variable, but subsequent photoelectric minimum timings show this to be the case. The most conspicuous variations for both eclipses are of essentially the same amplitude and in phase with each other. Thus, the cause for this effect must be either intrinsic

TABLE 1
TIMES OF MINIMUM LIGHT FOR U OPHIUCHI

Minimum	Heliocentric JD
Primary.....	2,438,196.7862
Primary.....	2,438,201.8160
Secondary.....	2,438,227.815
Primary.....	2,442,621.6212

TABLE 2
PARAMETERS FOR A LIGHT TIME
ORBIT IN A POSSIBLY TRIPLE
U OPHIUCHI SYSTEM

$e' = 0.3$
$\omega' = 120^\circ$
$T_0' = \text{JD } 2,408,421$
$P' = 9200P = 42.2 \text{ years}$
$\tau' = 0^{\text{d}}0135$
$A_1' \sin i' = 3.53 \times 10^8 \text{ km}$
$F'(\mathcal{M}) = 0.0087 \mathcal{M}_\odot$

period variation or revolution about the barycenter of an unresolved triple system. Because of the scatter of the early visual estimates and observations, it is not certain that the variation is truly periodic, but one cycle was convincingly completed from the early 1930s through the early 1970s. All residuals from a constant ephemeris were analyzed by Irwin's (1959) procedure for the light time parameters of the hypothetical orbit. The results from a graphical fitting procedure appear in Table 2, primed symbols being used to avoid confusion with the orbit of the eclipsing system. These results essentially forbid a mass smaller than $1 \mathcal{M}_\odot$ for the hypothetical third object but place no upper limit on its mass. Three of the four determinations of the γ -velocity show no evidence for its variation. The fourth and most divergent evaluation of the γ -velocity is associated with the smallest evaluations of the semi-amplitudes of the velocity curves and the smallest dispersion on the plates.

A period of 1.67734119 days best represents the present minima and was used to compute phases for

the observations. As Figure 1 shows, primary minimum at $\lambda 4230$ is satisfactorily symmetrical about zero phase but the secondary eclipse is displaced to phase 0.4985. The same displacement occurs for all the new light curves. The relative displacements of the secondary eclipse appear as a function of time in Figure 2. Those derived from complete light curves have already been described in §§ I and III; the remaining determinations are of relatively high weight if they result from photo-electric timing, but otherwise they are of low weight. Relative to the primary minimum, there seems to be a clear preference for secondary eclipse to occur before the half-period moment, and this alone suffices to rule out an explanation founded on an eccentric orbit rotating with a period less than a few centuries. Even if there is a very long apsidal period, the orbital eccentricity cannot be evaluated from all the history of the minima. More forcefully, for massive stars moving in orbits as small as those of the U Oph components, all theories predict apsidal periods counted in a few decades, so that we should now have observed numerous secondary eclipses displaced past the half-period instant. One additional possibility should be considered: the rotation of the apse of an eccentric orbit of the eclipsing pair caused by perturbations from the hypothetical third star. Slavenas (1937) presented a first-order analog to the lunar theory for the triple stellar case, and this may be applied to a possible triple U Oph system for a lower limit of $1 \mathcal{M}_\odot$ for the hypothetical third star. Over a century, the theoretically accumulated motion of the hypothetical U Oph apse would be less than $0^\circ.1$, a value so small that it would be consistent with the persistently advanced secondary eclipse. For a larger third mass, the apse would rotate

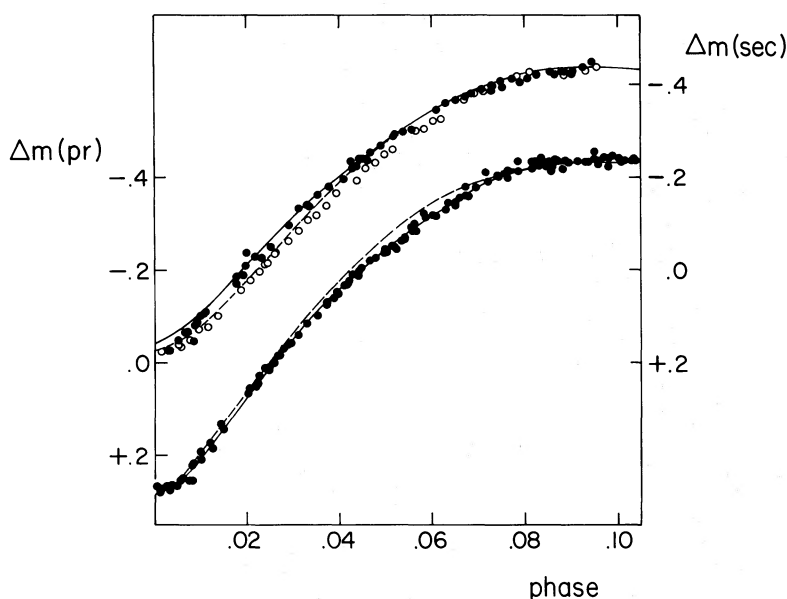


FIG. 1.—The primary (*below*) and secondary (*above*) eclipses at $\lambda 4230$. The asymmetry of the secondary eclipse is shown by the phase difference between the filled and open circles. The latter observations were not used in developing the solution of Table 3, which is shown by the continuous curves. The dashed curves show the Huffer and Kopal solution calculated by the code used for the theoretical continuous curves.

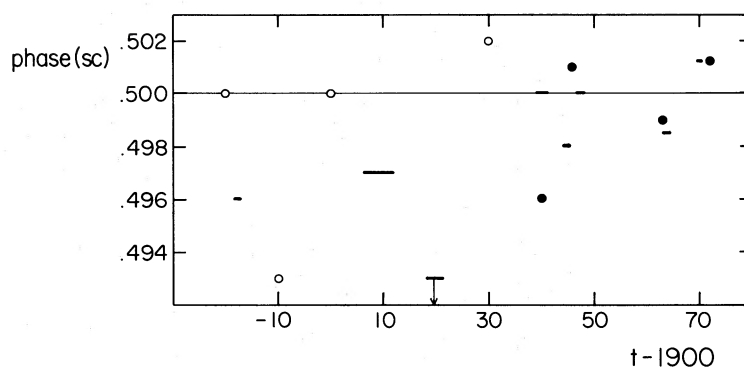


FIG. 2.—The phase displacement of secondary eclipse as a function of time. The horizontal bars give the displacements derived from complete light curves whose time bases extend over months or years. The displacement for the measurement of about 1920 is described in the text. Open circles show average displacement (typically at decade intervals) derived from visual or photographic estimations or observations of minimum light. Filled circles are average displacements derived from photoelectric timings of minimum light.

faster. A more positive statement is presently impossible.

Figure 2 shows clearly that shorter-term fluctuations also occur in the timings of the secondary eclipse relative to the primary minimum. There is a suggestion of a cycle on the order of 20 years in these variations, but they cannot be represented by a single period. Although such a short interval is suggestive of apsidal motion for an eccentric orbit, the lack of rigorous periodicity for the variations prohibits this possibility. Even if this explanation were true, it would lead to an eccentricity much smaller than any value spectrographically detectable, and the effects upon the photometric analysis of the eclipses would be very small as Wilson (1970) has shown.

The presentation just completed is one of two special cases. It would be equally satisfactory to fix the secondary eclipse at phase 0.5000 and study the variable behavior of the timings of primary minimum. There appears to be no way to decide the more likely of the two cases, and, in fact, it is probable that the timings of both eclipses are time-variable. The uncertainty of interpreting the longer-term period variation is the most troublesome impediment at the present time.

IV. THE PHOTOMETRIC ANALYSIS

The observations were compiled into normal points at intervals of phase 0.01 and assigned weights proportional to the number of observations divided by the average normal luminosity. The symmetry of the primary minimum permitted the use of all its normals. Similarly, all data between the eclipses were used. The two branches of the complicated secondary eclipse were tested individually, and it was instantly clear that the descending branch was inconsistent with the remaining observations. At the beginning of the analysis, then, only the ascending half of secondary was used. Initial values for the geometric and photometric parameters were based on previously published solutions. Improvement of the starting values was

accomplished by the differential correction program of Wilson and Devinney (1971) which varies any or all of 15 model parameters in order to produce a least-squares fit to the weighted observational data. All computing was performed on the IBM 360/65 at the University of Pennsylvania.

One trial solution showed that the models were insensitive to the gravities and albedos of the component stars. Therefore, these elements were fixed at unity throughout the computations. A second trial showed there to be no hope of improving the mass ratio, which was accordingly fixed at the spectroscopic value of 0.90. A third trial confirmed the conclusion of Eaton and Ward that the stellar temperatures made little impact on the solution. These were chosen to be appropriate for the spectral classifications. Numerous iterations established the wavelength-independent values for the orbital inclination and the surface potentials of the two stars. This was an extremely tedious process, for it proved impossible to converge upon the accepted geometry of a hot, large, massive star accompanied by a cool, small, less massive companion. Fourteen trials using different initialized data sets all led to unacceptably large and systematic runs of residuals. A better representation of the observations was finally achieved by permitting the hot and massive star to be the small one. It was first surmised that this result was an artifact of the choice of the ascending half of the secondary minimum. Subsequent trials permitted only the descending half of that minimum, but they failed to represent the data as well as the previously successful one. Therefore, the conclusion is quite strong that the present observations require a geometry which is nearly the inverse of the commonly accepted one. Olson (1975) has noted that the absorption equivalent widths are consistent with either geometry.

At $\lambda 4750$ a test was made with symmetry imposed, as well as possible, on the secondary eclipse so that the two branches of the primary eclipse diverged from each other. This analysis neither represented the observations well nor sustained the historical geometry.

After the wavelength-independent parameters had been determined, the individual observations between phases 0.9851 and 0.0150 and between phases 0.5000 and 0.5150 replaced the corresponding normal points in order to avoid smearing the detail within the minima. For each bandpass, the luminosities and the limb darkening coefficients for each eclipsing member and the luminosity of a third source were subjected to differential correction until the magnitudes of their corrections remained smaller than the associated errors through several iterations. As convergence for the wavelength-dependent parameters was approached, final differential corrections to the stellar potentials were also evaluated.

Following each differential correction, theoretical light curves were computed for each wavelength by the Wilson-Devinney (WD) light curve code for comparison with the observations. The $\lambda 4230$ observations and theoretical light curves for both minima are shown in Figure 1. The best solution appears in Table 3, the notation being that of Wilson and Devinney. All errors cited are probable errors, and parameters which are not assigned errors are those which were tested as described above and whose values were found to be

impossible to improve significantly. It is worth noting that the derived geometry is not a consequence of the method of analysis. For instance, the $\lambda 4750$ data were subjected to the classical Princeton methods (e.g., Russell and Merrill 1952) which require similar ellipsoids similarly oriented. The new geometry emerged, and the previous geometry was denied.

Figure 1 also displays the theoretical light curves for the Huffer and Kopal (HK) solution computed by the WD light curve code. This solution is a useful reference, not only because it is the one most frequently cited in the literature but also because it is the only one to rest upon photoelectric measures which show an undisplaced secondary eclipse. Their (HK) theoretical light variations do not represent the present observations adequately. The Huffer and Kopal geometry was also used for theoretical light curves (not shown in Fig. 1) calculated by the Princeton method, and these failed as badly as those from the Tampa program.

It was next decided to test the new geometry on historical observations. Only the Wisconsin OAO-2 data are of precision comparable with those treated here, and the Wisconsin geometry was determined by the 151 observations at $\lambda 4250$. The light curves from

TABLE 3
Photometric Solution for U Ophiuchi

			$T_h = 16500^\circ\text{K}$	$i = 87.6 \pm 0.1$		
			$T_c = 15500 \text{ K}$	$r_{h,\text{point}} = 0.2421 \pm 0.0006$		
			$g_h = 1.0$	$r_{h,\text{side}} = 0.2366 \pm 0.0006$		
			$g_c = 1.0$	$r_{h,\text{back}} = 0.2404 \pm 0.0006$		
			$A_h = 1.0$	$r_{h,\text{pole}} = 0.2336 \pm 0.0005$		
			$A_c = 1.0$	$r_{c,\text{point}} = 0.2804 \pm 0.0008$		
			$q = 0.90$	$r_{c,\text{side}} = 0.2679 \pm 0.0007$		
			$\Omega_h = 5.16 \pm 0.01$	$r_{c,\text{back}} = 0.2760 \pm 0.0007$		
			$\Omega_c = 4.449 \pm 0.008$	$r_{c,\text{pole}} = 0.2627 \pm 0.0006$		
λ	x_h	x_c	L_h	L_c	J_h/J_c	L_3
4750 Å	0.04 ± 0.09	0.22 ± 0.07	0.471 ± 0.003	0.529 ± 0.003	1.15 ± 0.01	-0.001 ± 0.007
4476	0.02 ± 0.09	0.30 ± 0.06	0.466 ± 0.003	0.534 ± 0.003	1.12 ± 0.01	$+0.002 \pm 0.008$
4230	0.01 ± 0.08	0.17 ± 0.07	0.468 ± 0.003	0.532 ± 0.003	1.13 ± 0.01	-0.001 ± 0.007
4026	0.04 ± 0.09	0.34 ± 0.06	0.469 ± 0.003	0.531 ± 0.003	1.14 ± 0.01	-0.000 ± 0.008
3330	0.3 ± 0.1	0.53 ± 0.08	0.474 ± 0.003	0.526 ± 0.003	1.16 ± 0.01	0.000
2980	0.4 ± 0.2	0.4 ± 0.1	0.474 ± 0.005	0.526 ± 0.006	1.21 ± 0.01	0.000
2460	0.5 ± 0.1	0.82 ± 0.06	0.484 ± 0.003	0.516 ± 0.003	1.21 ± 0.01	0.000
1920	0.3 ± 0.1	0.94 ± 0.06	0.497 ± 0.003	0.503 ± 0.003	1.27 ± 0.01	0.000
1550	0.5 ± 0.1	0.82 ± 0.05	0.494 ± 0.003	0.506 ± 0.003	1.32 ± 0.01	0.000
1380	0.5 ± 0.2	0.75 ± 0.09	0.502 ± 0.005	0.498 ± 0.005	1.30 ± 0.02	0.000

$\lambda 3330$ to $\lambda 1380$ were subjected to the same analysis as the Mount Wilson data, with the new geometry imposed upon them. No effort was made to evaluate third light from these data, but the stellar luminosities and limb darkenings were permitted to differ from the evaluations by Eaton and Ward. In terms of fitting the observational data, the Eaton and Ward results are clearly superior for the $\lambda 1550$ primary while our trials are better for the $\lambda 1920$ secondary. Additionally, our fit for the $\lambda 4230$ primary is clearly better than the Wisconsin fit for the $\lambda 4250$ primary, whereas for the remaining 11 minima no clear preference can be established. This result expresses once again the familiar recognition that, for a limited number of observations, the distinction between a partial transit and a partial occultation is subtle for component stars of similar size. The results of these analyses also appear in Table 3.

V. DISCUSSION

In Table 3, the values of L_3 are all smaller than their assigned errors. It appears that 0.01 may safely be considered as the upper limit for the contribution to the systemic light by a third source. It may easily be calculated that the bright limit to such a source would be of the order of $M_{\text{bol}} = +2$. Were the supposed third source a white dwarf, it could be no hotter than about 50,000 K. Evolution to this stage would require the original mass of the third object to be significantly greater than that of the eclipsing components which are apparently still on the H-burning main sequence. It follows that the total mass loss necessary to result in an eventual white dwarf could only have been accomplished by a cataclysmic event, and at present there is no evidence for this. A less extreme post-main-sequence evolution would still require the third star to have a mass greater than $5 M_{\odot}$, while the upper limit to its luminosity implies that its mass is surely less than $2 M_{\odot}$. Two possibilities remain: a main-sequence or a pre-main-sequence object. The evolutionary stage of the two eclipsing components sets an upper limit of 6.8×10^7 years for the age of the system. Stars between $2 M_{\odot}$ and $1 M_{\odot}$ reach the zero-age main sequence between 10^7 and 5×10^7 years (Iben 1964). Without more definite values for the age of the system and for the mass of the third star, no final decision can be made on its evolutionary stage. If indeed there is a third star unresolved in the U Oph system, the most likely interpretation favors a pre-main-sequence object or a main-sequence star between spectral types mid-A and early G. Detection of such a star would be extremely difficult.

It has been known for a long time (e.g., Irwin 1947) that the evaluations of the radius and limb darkening of an eclipsing binary component are strongly correlated. There arises, therefore, the question of whether the geometry newly developed here is associated with significant, and perhaps inadmissible, changes in the accepted darkening values. Eaton and Ward's analysis provides the most useful comparison. For every bandpass, the darkenings derived for the present cool,

bright star (whose radius differs by 10% for the two studies) are within two probable errors of the Wisconsin coefficients which are mean values assigned to both stars. There is, therefore, no significant discrepancy in the independent evaluation of the cool star's darkening. The darkenings derived here for the hot, small member (whose radius evaluations also differ by 10%) are all significantly different from the mean Wisconsin values. The changes in radius and darkening for the hot star are in the appropriate algebraic sense to be explained as a correlation artifact. However, the magnitudes of the changes are discordant by a factor of about 5, and this possible explanation cannot be sustained.

Figure 3 shows the darkening coefficients of Table 3 as a function of wavelength. The coefficients for the cool star are in reasonable agreement with theoretical predictions by Klinglesmith and Sobieski (1970), but those for the hot component are too low in the blue-green. Very small, or even negative, darkenings are not unknown for hot stars. Recent examples appear in the analyses of MR Cyg by Wilson and Devinney (1971) and by Proctor and Linnell (1972). These separate analyses do not converge on identical results, and each has been challenged by other workers using different methods on the same material. Furthermore, the Mount Wilson and OAO-2 observations were made at different times, so the difference of the darkening values perhaps expresses long-term variability and complexity of the U Oph system. Additionally, J. A. Eaton has privately suggested that some contribution to these differences may be traced to the blackbody flux used in the Tampa code and the model atmosphere used for the Wisconsin analysis.

It is possible that, at least at times, the atmospheric structure of the hot member differs significantly from much of the atmosphere of the cool star and does not conform to any theoretical hot, main-sequence atmosphere for a star. Alternately, it is possible that the entire binary is beset by many photometric complications, of which some are readily detectable as eclipse asymmetries, while others are more subtle and appear only as fallacious darkenings of seemingly credible determinacy coupled with biased stellar radii. The diversely complicated natures of the eclipses favor the latter interpretation.

It might be supposed that the spectrographic evaluation of ΔM_v would provide a useful control on the light ratios given in Table 3. This may be seen not to be the case from the sequence of results published for ΔM_v : -1.0 (Petrie 1952); -0.5 , an average derived by us from Petrie's (1964) recalibration; -0.2 (Koch, Olson, and Yoss 1965); and essentially 0.0 (Olson 1968) since only a mean M_v can be determined. In addition, Olson (1975) has commented privately that ΔM_v is very small. Any interpretation of these results is probably irrelevant to those of Table 3, for the H γ line is contained in none of the four bandpasses studied here and the He I lines noted in § II above are so weak as to have only minute effects on the 50 Å wide flux isolated by the scanner. As was also noted above, there exist three additional 50 Å wide light curves obtained at the same time as those studied here. These

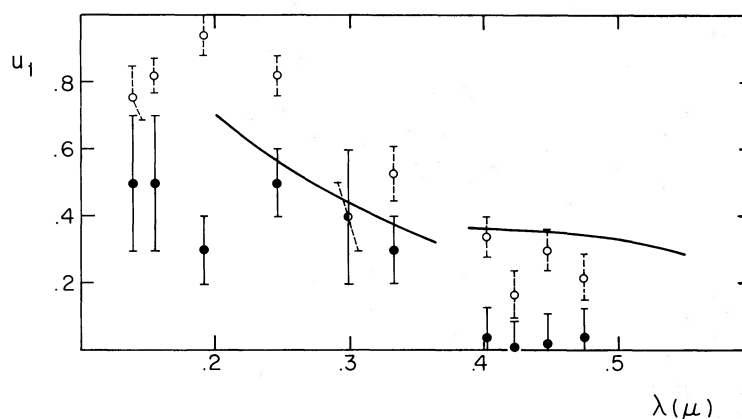


FIG. 3.—The coefficients of limb darkening of Table 3 as a function of wavelength. The filled circles refer to the hot star and the open circles to the cool companion. The error bars are twice the errors of Table 3. The curve segments give Klinglesmith and Sobieski's theoretical darkening for $T_e = 16,000$ K and $\log g = 4.0$.

three light curves are very complicated and show evidence of variability of H γ , H10, and H11 on time scales of days. These light curves will require very extended study to see if eclipses can be photometrically analyzed in any sense, but the conjecture may be offered that line variability of U Oph is not necessarily accompanied by variability of the continuum.

The greatest accomplishment of the program, without doubt, has been to demonstrate that critical scrutiny fails to confirm this binary as a simple one. This is not the first close binary for which repeated investigations have yielded different interpretations, but it is particularly troublesome because U Oph has always been accepted as a stable and informative pair. A realistic approach requires analysis of each data set on its own merits while maximizing external consistency. At present it is impossible to determine if any of the photometric and spectrophotometric observations have been made in the absence of systemic complications.

From the beginning of this program it was apparent that discussion of the observations would be very lengthy and expensive. The continuing NSF support through grants NSF GP-1343, 6774, 7884, 25227 and MPS 74-01656 is most gratefully acknowledged. R. H. Koch wishes to express his gratitude to the Director of the former Mount Wilson and Palomar Observatories for generous allocation of telescope time and to J. B. Oke for instruction in the use of the photoelectric scanner. We are also grateful to E. J. Devinney and R. E. Wilson for providing their code and continual direction on its use and to W. Blitzstein, J. A. Eaton, E. C. Olson, and the referee for valuable advice. At one time or another, F. C. Hall, D. Ives, P. Langford, and P. Torres assisted in the data reduction. Mrs. F. Jamieson prepared the typescript.

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ROBERT H. KOCH and CLAIRE A. KOEGLER: Department of Astronomy, University of Pennsylvania, Philadelphia, PA 19174