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THE SPECTROSCOPIC ORBIT OF ALGOL C*

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ABSTRACT

The following orbital elements for Algol C have been derived from the measures of the metallic lines which are observed in the spectrum of Algol during primary eclipse: $P = 1\,862$ years, $\gamma = +1\,4$ km/sec, $e = 0\,211$, $\omega = 308°1$, $K = 33\,6$ km/sec, and $T = 1952\,007$

I. A BRIEF HISTORY OF THE PROBLEM

Until recently, almost all the information concerning the third body in the Algol system has been obtained spectroscopically from the variations with time of the systemic velocity of the center of mass of the eclipsing pair. The first work on this problem was done by Belopolsky (1906, 1908, 1909, 1911), who was followed by Curtiss (1908), Schlesinger (1912), and McLaughlin (1937). The periods of the motion as found by these four investigators are, respestively, 1.733, 1.899, 1.874, and 1.873 years. McLaughlin was able to show that the 1.733-year period determined by Belopolsky must be ruled out as a result of errors in the latter's reductions. It should be pointed out that all this work suffers to some degree from systematic errors in the radial velocities.

In recent years Eggen (1948) and Pavel (1950) have examined the differences between the observed times of primary minima and those computed using a constant period. Both investigators find residuals that are satisfied by a period of about 1.873 years, the value determined by McLaughlin; the spectroscopic elements for the motion of the center of mass of AB and those derived by Eggen from photometric observations are given in Table 2.

II. THE RADIAL VELOCITIES FROM THE SPECTRUM OF ALGOL C

a) The Work of Miss Barney

During the course of his investigation of the orbit of Algol based on spectra taken at the Allegheny Observatory in the interval from 1908 to 1912, Schlesinger observed at times the presence of a large number (as many as ninety) of sharp, faint lines. These lines were particularly prominent and numerous at the times of primary minima. Miss Ida Barney (1923) measured and identified these lines and discussed the radial velocities obtained from twenty-two spectra. The spectra are fairly well distributed in phase in the 2.867-day period of the eclipsing pair. Her evidence seems to show that the velocities obtained from the sharp lines vary with the same period and are in phase with the variations in velocity of the B8 component, except that the amplitude is only about one-third that of the B8 star. Miss Barney concluded that the sharp lines are due mainly to the B8 star but with a contribution from the darker eclipsing component Algol B. She also concluded that these lines did not originate in Algol C because her velocities showed no variation with the period of that object. This conclusion will be commented upon in the next section.

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b) Recent Work

Beginning in 1953, the author began to make measures of the sharp lines in the Algol spectrum on grating spectra taken at the Mount Wilson Observatory by Dr. Otto Struve and Dr. J. Sahade which were made available to the author. The spectra were all taken with the 100-inch reflector and have dispersions of either 2.8 or 4.5 A/mm. The spectra were obtained at five different primary eclipses from 1952 to 1956.

In addition to the usual rotationally broadened lines of the B8 star, these spectra frequently show as many as one hundred sharp lines of metallic origin (mostly iron). The visibility of these lines is the greatest at the times of mid-primary eclipse and is sharply reduced outside an interval of about 1 hour on either side of mid-eclipse. The total duration of the eclipse is nearly 10 hours. On some spectra taken well outside eclipse and scattered throughout the period it is possible to see a few of these same lines, although they are relatively faint and much broader. Struve and Sahade (1957) class the spectrum as late A or early F.

Measures of the velocities of the sharp lines on eclipse spectra show very clearly that they do not originate either from Algol A or B or from an optical companion but rather from Algol C. Struve and Sahade (1957) and the author show that the radial velocities derived from these lines exhibit no change with a probable error of about 1 km/sec within a few hours on either side of mid-primary eclipse. During this interval the velocity of A would have changed by about 50 km/sec (rotation effect), and B would also have shown a large change. The sharp lines are not derived from an optical companion because their radial velocity changes from one eclipse to another when observed over a period of time. This effect has also been observed by Meltzer (1958) on the basis of the measurement of three spectra taken at two epochs 1 month apart. As will be shown later, these eclipse velocities are satisfied by a period close to that obtained by McLaughlin from the study of the motion of the center of mass of AB. In addition, the systemic velocity derived from the measures of these lines is very close to that obtained by McLaughlin from the motion of the AB system.

It now appears that Miss Barney's conclusion is in error. Most probably this resulted from the use of low-dispersion spectra (40 A/mm at $H\gamma$), uncertainties in line identifications and wave lengths, and a limited number of spectra (twenty-two). Only half of these were obtained during eclipse.

Eight "normal" velocities were available for the determination of the spectroscopic elements. The observations are spread over an interval of nearly 5 years or somewhat less than three periods. Five of these velocities were obtained by the author's measures of the spectra obtained at the Mount Wilson Observatory. While a summer visitor at the Dominion Astrophysical Observatory in 1957, the author obtained, through the courtesy of Dr. R. M. Petrie, the director, and with the assistance of Dr. McKellar, a series of spectra during one eclipse from which one velocity was obtained. The author measured only the best-quality iron lines in the range from about 3900 to 4400 A. The number of lines measured on an individual plate varied from five to a maximum of about twenty. Two more velocities were taken from Meltzer's paper, and these were also obtained from Mount Wilson grating spectra. Meltzer's spectra were taken in the red region with a wave-length range of from 5890 to 6550 A. Most of his measures were made on iron lines, together with a few other lines of metallic origin. Table 1 lists these eight observations.

To begin with, a provisional set of orbital elements was derived, and then a least-squares solution was performed for differential corrections using the method of Lehmann-Fihlés. Because the range of time covered by the observations was less than three periods, the term in the solution corresponding to the period correction was omitted. An effort to derive a period correction was made possible by Dr. McLaughlin of the Observatory of the University of Michigan, who kindly made available to the author a considerable number of eclipse spectra obtained in the course of his own investigations. From these eclipse spectra, six were selected with a dispersion of 19 A/mm at Hγ. From measures of the sharp iron lines, two velocities were obtained as follows: 1927.667, +5.9 km/sec (two spectra), and 1927.785, +25.9 km/sec (four spectra). With these two velocities and the velocity-curve obtained from the least-squares solution a period correction of −0.011 year was obtained, resulting in the new period of 1.862 years with a p.e. of not more than ±0.001 year. With this new and final period, new phases were obtained, and two least-squares solutions were performed, which resulted in a convergence of the solution. The final adopted elements and their probable errors are given in Table 2. The two Michigan velocities were not used in the least-squares solution. Figure 1 is a plot of the velocity-curve from the final set of elements and also the observations themselves. The largest deviation from the curve is 0.6 km/sec.

TABLE 1

SUMMARY OF OBSERVATIONAL DATA

No (1)	Date (2)	Source* (3)	No of Spectra (4)	A/mm (5)	Wt (6)	Phase† (P) (7)	$V\odot$ (km/sec) (8)	O−C‡ (km/sec) (9)
1	1952 939	MW,EE	7	2 8	3	0 501	−15 1	−0 1
2	1953 636	MW,EE	2	2 8	2	875	− 9 6	+ 1
3	1954 195	MW,EE	2	2 8	2	175	+33 4	0
4	1955 581	MW,Me	1	6 7	1	919	+ 2 0	− 3
5	1955 762	MW,Me	2	6 7	2	017	+31 2	+ 6
6	1956 723	MW,EE	3	4 5	2	533	−18 3	+ 1
7	1956 896	MW,EE	4	4 5	3	626	−25 6	0
8	1957 655	DAO,EE	5	3 5	3	0 033	+33 6	−0 3

* This column gives the initials of the observatory from which the spectra were obtained and also the measurer, thus "EE" is the author and "Me" is Meltzer

† The phases in this column are computed from T = 1952 007 and P = 1 862 years

‡ The residuals in this column are from the author's final set of spectroscopic elements given in column 5 of Table 2

TABLE 2

SUMMARY OF ORBITAL ELEMENTS FOR ALGOL

Element	AB about Center of Mass of Triple System			Algol C
	McLaughlin (Spectroscopic)	Eggen (Light-Time)		Ebbighausen (Spectroscopic)
		Original	Revised	
(1)	(2)	(3)	(4)	(5)
T	1903.38	1903.20	1952 299	1952 007±0 010 p e.
P	1 873 years	1 873 years (assumed)	1 862 years	1 862 years
e	0.26	0.14	0.47	0.211±0.005
ω	93°	90°	188°	308°.1±3°.3
γ	+2 2 km/sec	. . . .	−0 0010 day*	+1 4 km/sec±0 2
$a \sin i$	88×10⁶ km	78×10⁶ km	87×10⁶ km	307×10⁶ km
K	9 7 km/sec	8 4 km/sec	10 6 km/sec	33 6±0 2 km/sec

* The γ given in this column is the constant term in the light-time equation

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III. DISCUSSION OF THE RESULTS

a) Comparison of the Results of McLaughlin, Eggen, and the Author

Table 2 is a tabulation of the elements of the motion of the center of mass of the AB system as derived by McLaughlin and Eggen and by the author for C. The correspondence between McLaughlin's value of the systemic velocity of the triple system and that of the author is close. The two values of ω should differ by 180°; while the actual value is 215°. McLaughlin gave no probable errors for his elements, but it is apparent from an inspection of the fit of his data to his computed velocity-curve that the p.e. of his ω is considerably larger than that obtained by the author, and hence the difference of 35° is probably not far from three times the p.e. of the difference. The agreement between the two values of the eccentricity is satisfactory.

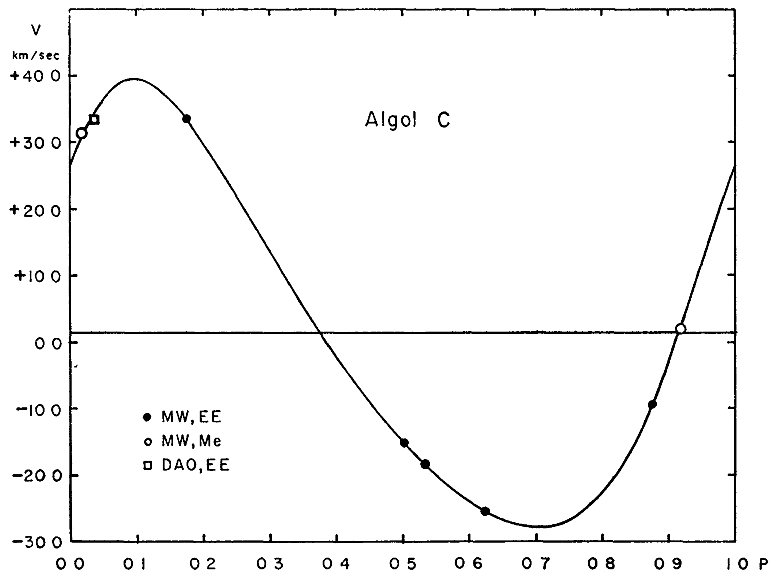

FIG. 1.—Velocity-curve for Algol C computed from elements in column 5, Table 2, and the observed velocities from Table 1

The situation represented by the results from Eggen's photometric data is a difficult one. Column 3 of Table 2 gives his results for the motion of the AB system derived from the times of light-minima. It will be seen that, although the agreement with McLaughlin's value of ω is good, considerable differences appear in the comparison of e and K. In the course of an examination of Eggen's data it was found that the phases in column 5 of his Table 1 of observations numbered 4, 8, and 13 are in error. This has been confirmed by correspondence with Dr. Eggen, who also states that the JD's are correct. In addition, note 5 to this table should read that the phases are computed from 1903.20 instead of 1902.70, as stated. Accepting the JD's as correct and computing new phases with the new period of 1.862 years, two successive least-squares solutions were performed on the data from observations 4 through 19. The resulting elements are given in column 4 of Table 2 of this paper. It is now seen that the new elements are radically different from those originally derived by Eggen and also from those obtained by McLaughlin and the author. The average deviation of the sixteen points from the new light-time-curve is 0.0004 day. The computed semiamplitude of the light-time variation is 0.0026 day. Although no probable errors were computed for the elements, they are relatively large. Nevertheless, the eccentricity (0.47) seems unreasonably large, and the same can be said for ω and K. The author feels that, because of the quality of his own observational data, considerable reliance can be placed on his own results. It is possible that Eggen's data are affected by systematic variations that, by the nature of the problem, have not been entirely removed. The residuals from the solution have been examined as a function of the time, but they exhibit only random fluctuations. Figure 2 is a plot of the light-time-curve obtained from the revised set of elements given in column 4 of Table 2, together with Eggen's observations numbered 4 through 19 in column 6 of Table 1 of his paper.

b) The Mass Relations in the Triple System

At the present time the masses of Algol A, B, and C are subject to considerable uncertainty. The ratio of K_C/K_{AB} would give the mass ratio of AB to C, but the best that can be said at this time is that K_C is rather well determined and K_{AB} is not. The author is more inclined to accept McLaughlin's value of $K_{AB} = 9.7$ km/sec than that of Eggen. The

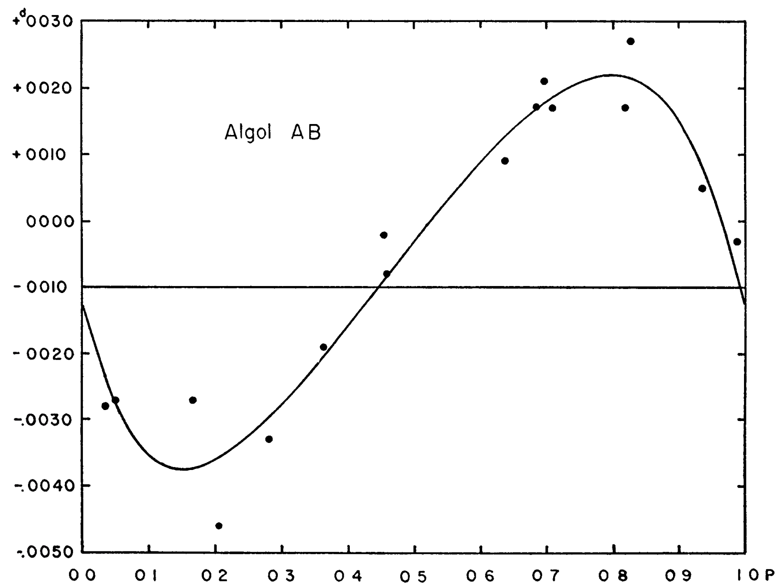

FIG. 2.—Light-time-curve from the revised set of elements of column 4, Table 2, and the times of minima given by Eggen

resulting mass ratio $m_{AB}/m_C = 3.5$. This is still subject to some uncertainty and awaits a better determination of K_{AB}. The author is now in possession of some data for such a determination and hopes to obtain more in the near future.

The determination of the masses of A and B (and therefore of C) is also subject to great uncertainties. Up to the present, all attempts to determine the masses of A and B rest upon the determination of the rotation effect at primary eclipse or the equatorial rotational velocity of A from line broadening as observed outside eclipse. As far as the author knows, the only data on the rotation effect are those obtained by McLaughlin and given in his original paper. After appropriate treatment, Kopal (1942) derives an equatorial rotational velocity of 48 km/sec for star A. If synchronism is assumed between rotation and revolution, then, from this value and the photometric and spectroscopic elements, Kopal obtains $m_A/m_B = 3.8$, $m_A = 2.3\ \odot$, and $m_B = 0.6\ \odot$. With slightly different elements Meltzer obtains very nearly the same values. If $m_{AB}/m_C = 3.5$, these values give $m_C = 0.8\ \odot$. If one adopts the rotational velocity of 60 km/sec, as determined by Struve and Elvey and also Slettebak, then Meltzer obtains $m_A = 5.0\ \odot$ and $m_B = 1.0\ \odot$. If $m_{AB}/m_C = 3.5$, then $m_C = 1.7\ \odot$. In Meltzer's discussion he used $m_{AB}/m_C = 4.5$, derived from his own data on Algol C and Eggen's original value of

$K_{AB} = 8.4$ km/sec. In this author's opinion this value of K_{AB} is seriously open to question. Meltzer also discusses the possibility that the rotation of Algol A is not synchronous with orbital motion, and he arrives at $m_A/m_B = 5.3$, which agrees well with 5.0 found from a rotational velocity of 60 km/sec.

More information about this system would be obtained if the inclination of the orbit of Algol C were known. The investigation of van de Kamp *et al.* (1951) on the astrometric orbit gives $65° \pm 16°$, but this value is too rough to be used for conclusive results. Because of the very small size of the astrometric orbit, the elements cannot be derived with a good deal of accuracy in spite of the large number of observations which were used.

It must also be mentioned here that McLaughlin found that the rotation effect is not always symmetrical with respect to the time of primary minimum. Kopal discusses this in detail and suggests that it results from the fact that the axis of rotation of the B8 star is not perpendicular to the orbital plane of AB. He points out that if this inclined axis of rotation is precessing about the perpendicular to the orbital plane and if the precessional period and axial inclination can be determined, this constitutes another method of determining the mass ratio of A to B. To date, this problem has not been attacked with sufficient observational data.

The most obvious method of obtaining the masses of A and B would be to record the spectrum of B and determine the ratio from the radial velocities of both components. Thus far the spectrum of B has not been observed because of the relative faintness of B to A. Two attempts have been made to photograph the spectrum in the infrared region. The first of these by Beer and Kopal (1954) with the aid of quite low-dispersion spectra was not successful, although the authors suggested that the change in the equivalent widths of certain lines was due to the presence of lines of Algol B. The second and latest attempt by Sahade and Wallerstein (1958) was made with spectra of a dispersion of 20 A/mm taken during eclipse but gave no evidence for the existence of the spectrum of the secondary component.

In conclusion, it would appear that, although the orbital elements of Algol A about the center of mass of AB and those of C about the center of mass of the triple system are rather well known, very little reliable information is known about the masses of A, B, and C.

The author wishes to express his gratitude to Dr. Otto Struve for having suggested this problem and for supplying the author with the major part of the observational data. Thanks are due to Dr. Dean McLaughlin for the loan of the Michigan spectra and to Dr. R. M. Petrie, director of the Dominion Astrcphysical Observatory, for the courtesies extended to the author during the summer of 1957 and for the opportunity of securing spectra at Victoria.

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