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DETECTION OF THE SECONDARY OF ALGOL

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ABSTRACT

We have detected the Na D lines of the secondary of Algol (β Persei). The velocity curve obtained from 10 measurements of the velocity of the secondary has a semiamplitude of 201 ± 6 km s^{-1}. A mass ratio, m_A/m_B, of 4.6 ± 0.1 and masses m_A, m_B, and m_C of 3.7 ± 0.3, 0.81 ± 0.05, and 1.7 ± 0.2 $m_\odot$, respectively, are derived. The results are in agreement with indirect determinations of the masses. The secondary fills its Roche lobe.

Subject headings: stars: eclipsing binaries — stars: individual

I. INTRODUCTION

The well-known eclipsing binary Algol consists of three stars. The brightest member of the system, Algol A (B8 V), is eclipsed every 2.8673 days by its faint companion Algol B, which is a cool low-mass subgiant. Primary eclipse is 1.2 mag deep in V and is partial. Near the middle of primary eclipse sharp lines from the spectrum of the third star, Algol C, are visible. It orbits Algol A and B in 1.862 years and has a late A or early F, luminosity class IV or V, spectral type (Struve and Sahade 1957).

The large light ratio of Algol A to Algol B has prevented spectroscopic detection of Algol B. The probability that, as a result of rotation, the B spectrum lines are broad and shallow has also hindered its detection. Beer and Kopal (1954) and Sahade and Wallerstein (1958) made unsuccessful searches for the near-infrared spectrum of Algol B. In the absence of spectroscopic data for Algol B, a direct determination of the mass ratio, m_A/m_B, and thence the individual masses of Algol A, B, and C has not been possible.

In this *Letter* we report the first spectroscopic detection of Algol B. The Na D lines of Algol B are identified on low noise spectra. Measurements of these lines have been used to determine the mass ratio, m_A/m_B, and the individual masses.

II. OBSERVATIONS

The McDonald Observatory 2.7 m reflector, coudé spectrograph, and a 1024-element self-scanned silicon photodiode array Reticon (Vogt, Tull, and Kelton 1978) were used to observe the Na D lines. Grating B was used in first order to provide coverage of 100 Å of spectrum centered on the Na D lines. The signal-to-noise ratio of the observations, which are detailed in Table 1, was typically 500 to 1. The resolution of the first five observations was 0.2 Å (10 km s^{-1}); for the remainder it was 0.4 Å (20 km s^{-1}).

The standard stars η Tau (B7 III, $V = 2.86$) and α Ari (K2 III, $V = 2.00$) were observed immediately after each observation of Algol. The Algol spectrum was then divided by the η Tau spectrum instead of the customary flat field lamp so as to remove not only the small variations in diode response and vignetting but also the telluric water lines, which, in the vicinity of the Na D lines, are sufficiently strong to be troublesome. To make sure that the Na D lines of Algol (A, B, and C) are not affected by the division, the star used to divide out the water lines would, ideally, have no stellar Na D lines of its own. The early spectrum and rapid rotation ($V \sin i = 216$ km s^{-1} [Uesugi and Fukuda 1970]) of η Tau ensure that its Na D lines are very weak and also broad and shallow; thus it is a good choice for this purpose. Inspection of the data showed no sign that the Na D lines of Algol had been disturbed by Na D lines of η Tau as a result of the division. The star α Ari was observed for later use as a radial-velocity standard.

Inspection of expanded intensity scale plots of the spectra shows the Na D lines of both the primary and secondary. Figure 1 shows observations at phase 0.716 (secondary blueshifted) and phase 0.306 (secondary redshifted). The central depths of the broad secondary 5890 and 5896 Å Na D lines are 2.0% and 1.7%, respectively. The weakness of these lines, which are the strongest secondary lines in the red and near-infrared that are unblended in the composite spectrum, explains the failure to detect the secondary in photographic spectra. Note the presence of the very weak Fe I line at 5883.8 Å from Algol C. Other Algol C lines which we have been able to identify are Ba II (5853.7 Å), Ca I (5857.5 Å), Fe I (5859.6 Å), Fe I (5862.4 Å), and Fe I (5914.2 Å). Hitherto lines from Algol C have not been detectable except near the middle of primary eclipse.

The width of the secondary Na D lines is consistent with their being broadened by synchronous rotation of the secondary. The equivalent width of the secondary 5890 Å Na D line is 64 mÅ (measured at phase 0.716) and that of the secondary 5896 Å Na D line is 58 mÅ (measured at phase 0.306). The 5:1 light ratio of Algol A to B at 6600 Å (Koch 1973) and a 12% contribution from Algol C to the total light at 6600 Å (Cristaldi, Fracastoro, and Sobieski 1966) are used to estimate that, at the Na D lines, Algol B contributes 12% of the total light. The measured equivalent widths of the Algol B 5890 and 5896 Å Na D lines in the

TABLE 1

OBSERVATIONS OF ALGOL

Time of Observation (UT) Start	Finish	Date (1977)	HJD (2,443,000+)	Phase*	Velocity of Algol B† (km s^{-1})	
9^h46^m	9^h50^m	Sep 30	416.912	0.150	+163	+155
7 22	7 32	Nov 2	449.816	0.625	−136	−141
7 34	7 44	Nov 2	449.824	0.628	−142	−147
6 21	6 29	Nov 24	471.773	0.283	+194	+191
5 52	5 56	Nov 28	475.751	0.670	−187	−189
5 48	5 52	Nov 30	477.748	0.367	+145	+143
5 41	5 44	Dec 1	478.743	0.714	−199	−201
3 22	3 25	Dec 20	497.646	0.306	+179	+180
3 58	4 06	Dec 21	498.673	0.664	−169	−168
4 24	4 27	Dec 24	501.689	0.716	−201	−199

* Calculated from the ephemeris: time of primary minimum = 2,440,953.4657 + 2.8673075 E (*Sky and Tel.* 1976, **52**, 48).

† Measured heliocentric velocities are listed in the first velocity column. Velocities after subtraction of the contribution from the motion of Algol AB are listed in the next column.

composite spectrum are then converted to 530 and 480 mÅ, respectively, in the spectrum of Algol B. These Na D line strengths are consistent with what one would expect for the spectral type of Algol B, which Koch (1973) estimates as G2.

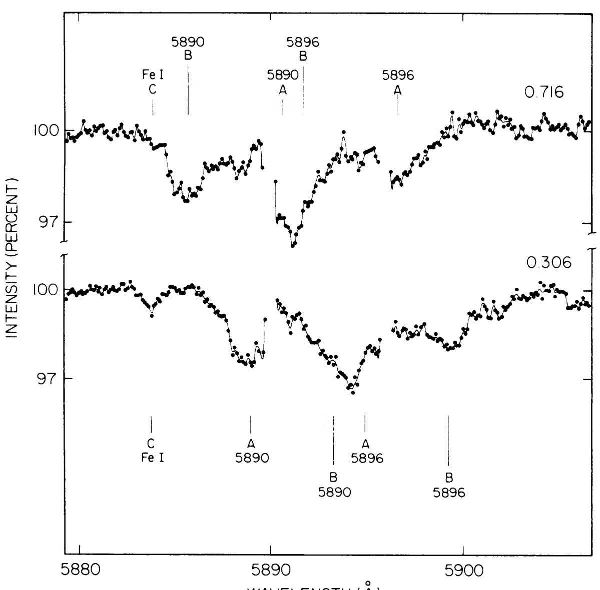

FIG. 1.—Observations of the Na D lines (5889.97 and 5895.94 Å) in Algol at phase 0.306 (03^h22^m UT, 1977 December 20) and phase 0.716 (04^h24^m UT, 1977 December 24) plotted on an expanded intensity scale. At phase 0.306 the Algol B lines are redshifted and the Algol A lines are blueshifted. The Algol B 5896 Å Na D line is resolved, while the Algol B 5890 Å Na D line is blended with the 5896 Å line of Algol A. At phase 0.716 the Algol B lines are blueshifted and the Algol A lines are redshifted. The Algol B 5890 Å Na D line is resolved, while the Algol B 5896 Å Na D line is blended with the 5890 Å line of Algol A. The wavelength of the 5883.8 Å Fe I line from Algol C does not change significantly. The Na D lines of Algol C are obscured by the interstellar Na D lines and blending with the Na D lines of Algol A. The wavelength scale is set by the interstellar Na D lines which are marked by the breaks.

In our search for the spectrum of the secondary, we had originally looked for the Ca II infrared triplet lines at 8498, 8542, and 8662 Å. Secondary lines were detected. However, all three Ca II lines are blended with Paschen lines from the primary. In the investigation of δ Lib (Tomkin 1978), which used the Ca II infrared triplet lines, the problem was overcome by correcting the observed spectrum for the Paschen lines of the primary. In Algol the observed spectrum is complicated by the presence of Algol C, which contributes Paschen lines and Ca II lines of its own. There appears to be no reliable way to solve these blending problems; therefore we chose to prosecute our investigation via the Na D lines instead of the Ca II infrared triplet lines.

III. MEASUREMENT OF RADIAL VELOCITIES

When the phase is between 0.0 and 0.5 the spectrum of the secondary is redshifted, and thus the 5896 Å Na D line is the most suitable for measurement of the secondary radial velocity. For observations in this phase interval, the secondary radial velocity was measured by cross-correlating the profile of the secondary 5896 Å Na D line with the associated α Ari spectrum. The Na D lines in α Ari are sharper and deeper than those in Algol. Therefore, prior to the cross-correlation, the α Ari spectrum was broadened and diluted so the profiles of its Na D lines matched those of the secondary of Algol. When the phase is between 0.5 and 1.0 the spectrum of the secondary is blueshifted, so the 5890 Å Na D line is most suitable for measurement. For observations in this phase interval, the profile of this line was used to measure the secondary radial velocity. We estimate that the uncertainty of an individual measurement is two channels (0.22 Å, 11 km s^{-1}).

The accuracy of this cross-correlation technique of radial-velocity measurement has been checked in an investigation of the eclipsing binary δ Lib (Tomkin 1978). The primary semiamplitude and γ velocity of δ Lib determined by this method were in good agreement with the results of previous investigations. The radial velocities of standard stars were also checked and found to be in good agreement with the published velocities.

These measurements provided the radial velocity of the secondary with respect to α Ari. Allowance for the geocentric radial velocity of α Ari and the geocentric correction of Algol gave the heliocentric velocity.

IV. ANALYSIS AND RESULTS

Before the velocities of Algol B were analyzed, the contribution from the motion of Algol AB in its 1.862 year orbit around the center of mass of Algol ABC was removed. The elements $K_{AB} = 12$ km s^{-1}, $e = 0.23$, $\omega = 133°$, and $T = 1952.05$ from Table 6 of Hill *et al.* (1971) were used to calculate the orbital motion of Algol AB. In their table T is erroneously entered as T_0. Velocities of Algol B after subtraction of the calculated Algol AB contribution are listed in Table 1.

These velocities were analyzed to determine the semiamplitude of the Algol B velocity curve, K_B, and the systemic velocity, γ. In the solution the other four elements, e, ω_B, P, and T, which have been reliably determined by the spectroscopic and photometric investigations of the primary, were fixed with the values in Table 2. The solution yielded $K_B = 201 \pm 6$ km s^{-1} and $\gamma = -9 \pm 11$ km s^{-1}. The computed velocity curve for Algol B is shown in Figure 2.

The value of K_A, which is 44 km s^{-1} and is accurately determined, combined with K_B gives a mass ratio, m_A/m_B, of 4.6 ± 0.1. Hill *et al.* (1971), who considered three indirect lines of evidence (synchronous rotation of Algol A, the minimum mass of Algol A + B, and the assumption that Algol B fills its Roche lobe) for the value of m_A/m_B, concluded that the best value is 4.6, a result that is the same as our own. The agreement of these two independent determinations of the mass ratio indicates that the mass ratio is now fairly well established.

TABLE 2

ELEMENTS AND MASSES OF ALGOL A AND B

P (days)	2.8673075
T (HJD)	2440954.0471
e	0.015±0.008
ω_B	343°±32°
K_A (km s^{-1})	44.0±0.4
K_B (km s^{-1})	201±6
γ (km s^{-1})	−9±11
$a_A \sin i$ (km)	1.73×10^6
$a_B \sin i$ (km)	7.93×10^6
f_A (m) ($m_\odot$)	0.0254±0.0008
f_B (m) ($m_\odot$)	2.42±0.22
i	82°42±0°04
m_A/m_B	4.6±0.1
m_A ($m_\odot$)	3.7±0.3
m_B ($m_\odot$)	0.81±0.05
r_A (pole)	0.220±0.001
r_B (pole)	0.231±0.002
R_A (pole) ($R_\odot$)	3.08
R_B (pole) ($R_\odot$)	3.23

NOTE.—The period is from the ephemeris used to calculate the phases in Table 1, T is calculated from the time of primary minimum in the same ephemeris. The values of e, ω_B, K_A, $a_A \sin i$, and f_A (m) are from Hill *et al.* (1971). To allow for the apsidal motion (period 32 years) ω_B has been increased to its present value. The inclination and fractional polar radii are from Wilson *et al.* (1972).

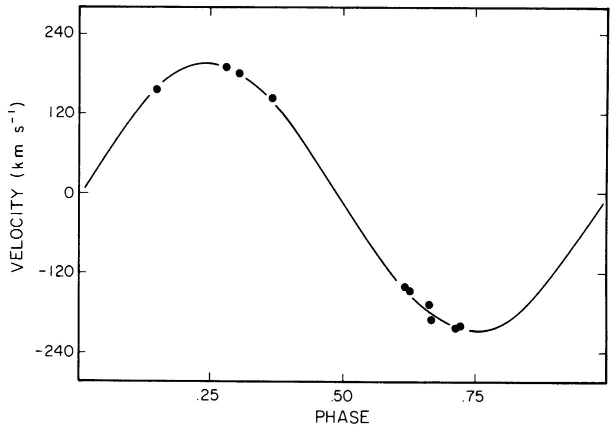

FIG. 2.—The velocity curve of Algol B

Our value of γ (−9 ± 11 km s^{-1}) is in reasonable agreement with previous results (Ebbighausen 1958; Ebbighausen and Gange 1962; Hill *et al.* 1971), which range from +1 to +6 km s^{-1}, based on analysis of the motion of Algol C and Algol AB.

Hill *et al.* (1971) derived a value of 2.6 for the mass ratio m_{AB}/m_C. Their result, combined with our determination of m_{AB}, leads to an Algol C mass of 1.7 ± 0.2 $m_\odot$. This Algol C mass should, perhaps, be viewed with caution. Because the semiamplitude, K_{AB}, is small it is difficult to determine accurately, and the mass ratio m_{AB}/m_C is therefore similarly difficult to determine. We note that a mass ratio m_{AB}/m_C of 3.57, which was determined by Ebbighausen and Gange (1962), would require an Algol C mass of 1.3 $m_\odot$.

Wilson *et al.* (1972) and Hill and Hutchings (1970) have made photometric analyses of Algol. The inclination derived by Wilson *et al.* (1972), who used a program that treats tidal distortion and other effects of importance in close binaries explicitly, is used to calculate the masses (Table 2). The use of the Hill and Hutchings (1970) value (81°6) would not alter the masses significantly.

In the solution of Wilson *et al.* (1972) the mass ratio is not solved for, but is fixed at $m_A/m_B = 5.0$. Therefore, to see whether Algol B fills its Roche lobe, we turn to the results of Hill and Hutchings (1970). Hill *et al.* (1971) used the assumption that Algol B fills its Roche lobe and the Algol B fractional radii of Hill and Hutchings (1970) to estimate a mass ratio, m_A/m_B, of 4.6. That this is the same as the actual mass ratio means that Algol B does indeed fill its Roche lobe. This conclusion supports models that use mass transfer from Algol B to Algol A to explain the radio (Wade and Hjellming 1972; Clark *et al.* 1976) and X-ray (Schnopper *et al.* 1976; Harnden *et al.* 1977) emission from Algol.

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