THE ASTROPHYSICAL JOURNAL, 194:L147–L151, 1974 December 15

SPECKLE INTERFEROMETRY. III. HIGH-RESOLUTION MEASUREMENTS OF TWELVE CLOSE BINARY SYSTEMS*

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Received 1974 August 30

ABSTRACT

Twelve binary star systems with angular separations between 0".049 and 0".290 have been resolved. The systems δ Sco, σ Her, and β Cep were found to have previously unknown stellar companions; and β Cep, β Per, and τ Per show features at the limit of resolution which may be due to circumstellar material. The masses of seven stars in four binary systems have been calculated, and the results are generally consistent with the empirical mass-luminosity relation.

Subject headings: binary stars — mass-luminosity relation

I. INTRODUCTION

This is the third in a series of articles describing the results of speckle interferometry observations. The theory of speckle interferometry was discussed by Labeyrie (1970), and more recently by Korff, Dryden, and Miller (1972), Dainty (1973), Liu and Lohmann (1973), Knox and Thompson (1974) and others. Paper I (Gezari, Labeyrie, and Stachnik 1972) and Paper II (Bonneau and Labeyrie 1973) dealt with the determination of seven stellar diameters and measurements of two close binary systems. In Paper III we present the results of a search for close binary star systems chosen from among 110 candidates which were noted for their peculiar spectra or for their variability, or which were known spectroscopic or astrometric binaries. Twelve binary systems have been resolved, including the astrometric companions to β Per (Algol C), χ Dra, and τ Per, the spectroscopic companions to γ Per and β CrB, and the previously unknown companions to δ Sco, σ Her, and β Cep.

II. INSTRUMENTATION AND DATA REDUCTION

Observations were made at the 200-inch (5 m) Hale telescope of the Hale Observatories, and an additional program was carried out by the Stony Brook group at the 84-inch (2.1 m) and the 150-inch (4 m) Mayall telescope of the Kitt Peak National Observatory, during the interval from 1971 March to 1973 October.

The SIT vidicon system used at the prime focus of the 200-inch telescope has been described by Labeyrie (1974), and the film system used at the 200-inch Cassegrain, 150-inch prime, and 36-inch Cassegrain foci was described in Paper I. Data recorded with the SIT system was optically processed from kinescoped films of the television recordings. The optical Fourier transform and data reduction techniques are described in Paper I, and examples of the speckle images and their optical transforms are shown in figures 1 and 2 (plates L11 and L12).

Error estimates do not appear in the Table of Observations (table 1) but are defined here. Based on several observations of α Aur and β Cep made during short time intervals (see § III), the statistical errors of measurement (1 σ) for all of the observations listed in table 1 are estimated to be $\pm$0".002 in separation and $\pm 3°$ in position angle. The systematic calibration error in separation is estimated to be less than 10 percent. The errors cited in table 2 are derived solely from the observational errors.

III. DISCUSSION

Among the 110 candidate stars, 12 were resolved as binaries and several others require further observation. Within the resolution (0".020) and contrast ($\Delta m < 5$) limits of the present system the unambiguously unresolved stars observed between 1972.22 and 1973.45 were: γ Peg, β Ari, α UMi, γ Ori, γ Gem, α CMa, κ Dra, α Lyr, γ Equ, δ Cap, and VV Cep.

The observational results appear in table 1 with spectral type, visual magnitude and parallax taken from the Bright Star Catalog (Hoffleit 1964).

1. *Tau Persei* is a well-known double-lined spectroscopic binary, but only the spectrum of the bright component (G0 III ?) was used by Colecevich (1941) to compute dynamical elements. Orbital elements were later computed by van de Kamp (1969) from astrometric studies. The position angle $\theta = 48°$ calculated from the astrometric orbit does not agree with our observation of $\theta = 94°$ (fig. 2). In the Fourier transform τ Per shows unsual structure which could be due to material surrounding the stars.

* This article is based on observations made by the authors as guest investigators at the Hale Observatories.

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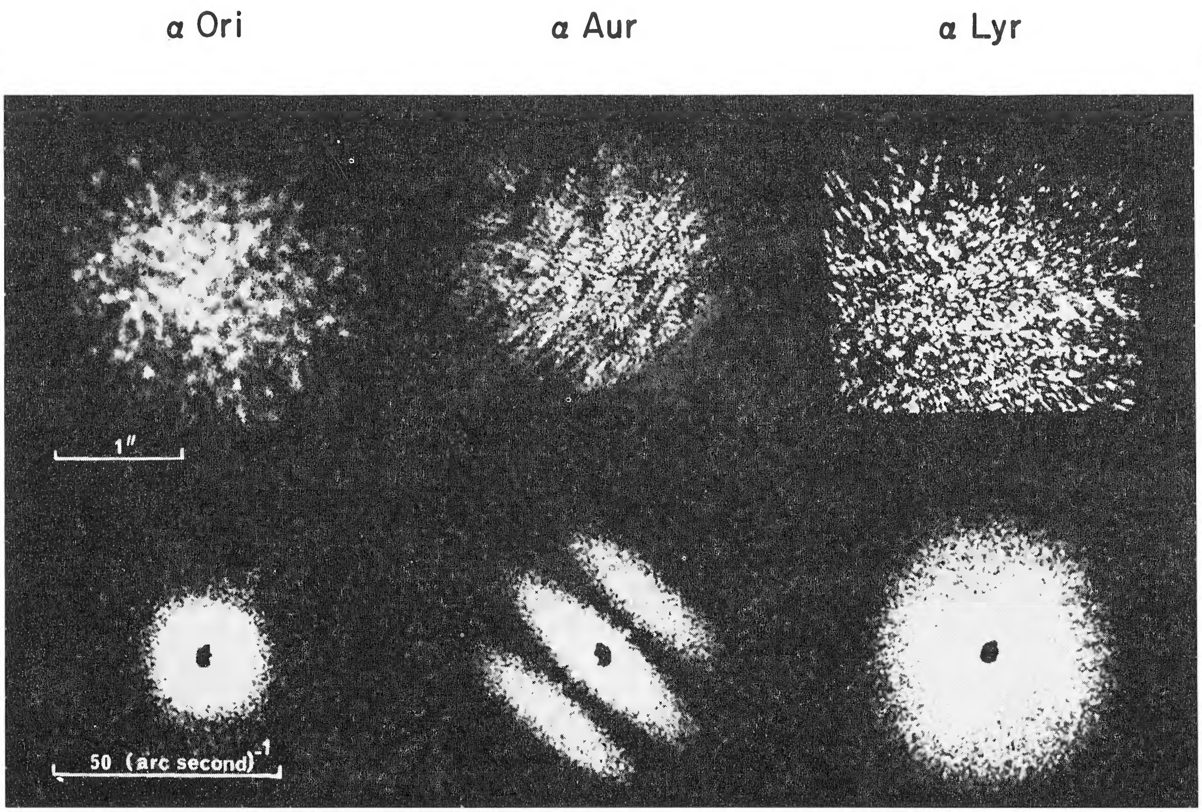

FIG. 1.—*Top row*, direct highly magnified photographs of the stars α Ori, α Aur, and α Lyr, taken with the 200-inch (5 m) Hale telescope using a focal ratio of f/200, exposure times of 0.010 s, and $\Delta\lambda = 200$ Å at $\lambda = 5000$ Å. The seeing during the observations was about 2″. Vega is not resolved, and the granular detail or "speckle" in the image is caused by atmospheric turbulence and the telescope optics. Betelgeuse is resolved by the telescope, with enlarged speckle arising from the convolution of its true image (diameter about 0″.06) with a point spread function which is illustrated by the image of an unresolved star such as α Lyr. In the photograph of α Aur a doubling of the image detail is clearly evident due to its binary structure. Each pair of speckles can be thought of as a distorted, diffraction limited image of the two stars in Capella. The separation of the two components is about $\rho = 0''.055$, and the stellar discs are not resolved. *Bottom row*, co-added optical Fourier transforms of the stellar images in the top row. The transform of α Lyr is typical of an unresolved star. Betelgeuse is well resolved, as indicated by an absence of high spatial frequencies in its Fourier transform. The transform of Capella shows a fringe pattern which defines the position angle and separation of the binary system. The optical transform and data reduction techniques are described by Gezari *et al.* (1972).

LABEYRIE *et al.* (*see* page L147)

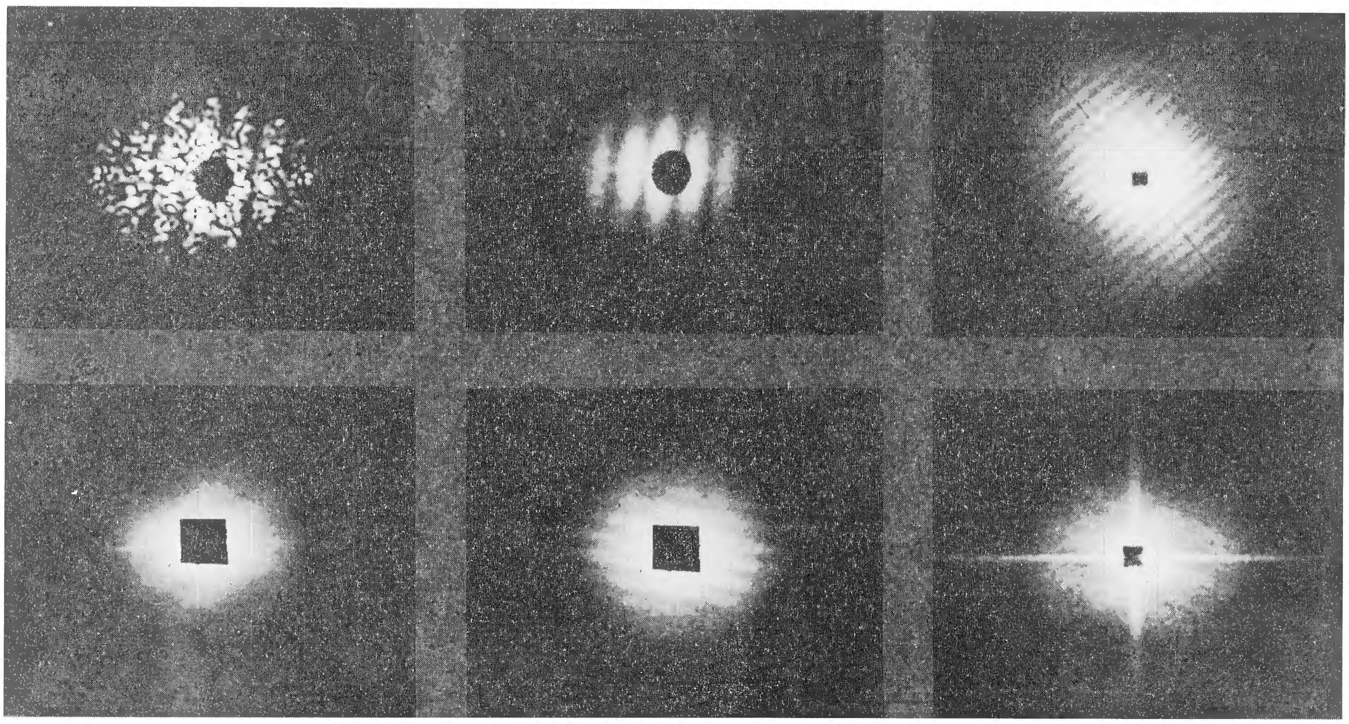

FIG. 2.—Intensity Fourier transforms of (*top, left*) ι Ser single frame; (*middle*) 20 co-added frames of ι Ser showing an improvement in the signal-to-noise ratio in the transform; (*right*) β Cep. *Bottom, left,* β Per; *middle,* γ Per; *right,* τ Per.

LABEYRIE *et al.* (*see* page L147)

TABLE 1

SUMMARY OF BINARY STAR OBSERVATIONS

BSC No.	Object	Spectral Type	Combined Visual Magnitude	Parallax $\pi('')$	Date of Observation (1971.0+)	Position Angle $\theta(°)$	Binary Separation $\rho('')$	Magnitude Difference Δm	Mean Wave-length λ (Å)
854.......	τ Per	G5 III+A5	3.09	+0.012	2.45	94	0.080	3–4	6300
915.......	γ Per	G8 III?+A3?	2.90	+0.011	2.45	59	0.193	1–2	6750
936.......	β Per	B8 V	2.2	+0.031	2.45	123	0.086	2–3	6750
1708.......	α Aur	G8 III?+F	0.09	+0.073	0.23	162	0.054	0	5500
					0.23	164	0.053	0	5500
					0.23	172	0.055	0	5500
					0.23	167	0.056	0	5500
					0.23	163	0.055	0	5500
					0.23	164	0.057	0	5500
					0.23	170	0.056	0	5500
					0.49	192	0.054	0	5400
					0.79	201	0.058	0	5500
					1.27	276	0.049	0	4550
2124.......	μ Ori	Am	4.12	+0.027	1.96	158	0.290	1	5450
					2.20	157	0.274	1	5450
5747.......	β Cr B	Fp	3.66	+0.031	2.22	158	0.240	1–2	6200
					2.45	157	0.250	1–2	6200
5842.......	ι Ser	A1 V	4.52	+0.005	2.22	84	0.102	~0	4700
					2.45	85	0.094	~0	5000
5953.......	δ Sco	B0 V	2.32	+0.003	2.22	171	0.180	~2	5500
					2.45	170	0.181	~2	4750
6168.......	σ Her	B9 V	4.23	+0.003	1.28	179	0.115	3–4	5450
					2.45	191	0.065	3–4	6200
6377.......	c Her	A5	5.26	+0.016	2.45	42	0.077	~1	5500
6927.......	χ Dra	F7 V	3.58	+0.120	2.21	61	0.096	~2	6000
					2.45	71	0.077	~2	4100
					2.76	39	0.115	~3	6750
8238.......	β Cep	B2 III	3.18	+0.005	0.48	47	0.255	3–4	5500
					0.48	48	0.256	3–4	5500
					0.78	48	0.264	3–4	5600
					1.27	47	0.258	3–4	5300
					1.27	47	0.262	3–4	5500
					1.46	47	0.252	3–4	5500
					1.46	47	0.258	3–4	5500
					2.45	49	0.244	3–4	6650

TABLE 2

ORBITAL ELEMENTS*

Parameter	γ Per	β Per (AB–C) (Orbit 1)	β Per (AB–C) (Orbit 2)	β CrB	χ Dra
P(y), period..................	*14.648*	*1.862*	*1.862*	*10.496*	*0.768*
T, epoch......................	*1947.21*	*1952.007*	*1952.05*	*1938.20*	*1923.425*
e(°), eccentricity................	*0.72*	*0.211*	*0.23*	*0.406*	*0.419*
ω(°), periastron................	*164*	*308*	*313*	*185.4*	*126*
Ω(°), line of nodes..............	52±18	134±9	131±15	159±5	237±4
i(°), inclination................	60±17	80±13	83±18	77±12	74±7
$\pi('')$, parallax..................	*0.011*	*0.039*	*0.039*	*0.031*	*0.120*
a(a.u.), semimajor axis..........	13.5±2.3	2.67±.11	2.67±.10	7.49±.85	0.965±.062
$a \sin i$ (a.u.)..................	*11.725*	*2.627*	*2.654*	7.30±.12	...
$a_A \sin i$ (a.u.).................	...	...	...	*2.955*	*0.402*
M_A/M_B.......................	*1.724*	*3.57*†	...	...	*1.31*
M_A+M_B ($M_\odot$)................	11.47±5.86	5.47±.70‡	5.51±.65‡	3.8±1.3	1.52±.18
$M_C \sin^3 i$ ($M_\odot$).................	...	...	*1.48*	...	...

* Numbers in italics are adopted values referenced in the text. The remaining data are new results based on the adopted values and the observations listed in table 1.

† $(M_A + M_B)/M_C$.

‡ $M_A + M_B + M_C$.

2. *Gamma Persei* is a double-lined spectroscopic binary for which McLaughlin (1948) obtained dynamical elements. The parallax of the system is sufficiently small for the combined magnitude and observed magnitude difference to be consistent with spectral types of G8 III and A3 V, or G8 II and A3 III.

3. *Beta Persei* (*Algol*).—The existence of a third star (Algol C) in the well-known eclipsing system has been inferred from spectroscopic, (Ebbighausen 1958), astrometric (van de Kamp, Smith, and Thomas 1951), and photometric light time evidence (Eggen 1948). We believe it likely that the component we have resolved is Algol C, based on the measured separation and the agreement between our magnitude difference $\Delta m = 2.5 \pm 0.5$ mag and the spectrophotometric determination of $\Delta m = 2.6 \pm 0.28$ mag (Fletcher 1964). We have computed preliminary elements of the relative orbit (table 2) assuming a parallax $\pi = 0\overset{''}{.}039$ (Frieboes Conde, Jerczerg, and Høg 1970) and using the dynamical elements of Ebbighausen (1958) (orbit 1) and Glushneva and Esipov (1968) (orbit 2). The orbital inclination we find is appreciably higher than that given by Bachmann (1973) and Frieboes Conde *et al.* (1970) in their recent reviews.

We note that our observations show only one fringe frequency in the Fourier transform (fig. 2). However, the large separation and magnitude difference of the postulated D and E components would not be detectable with the present system. The slightly anomalous attenuation of the outer fringes of the Fourier transform of β Per could be due to circumstellar material associated with the observed radio (Wade and Hjellming 1972) or Hα (Struve and Sahade 1957; Andrews 1967) emission.

4. *Alpha Aurigae* (*Capella*) was previously observed by Merrill (1922) using the Mount Wilson 100-inch (2.5 m) telescope as a Fizeau interferometer (see Paper I for a brief summary) and has been extensively studied spectroscopically. Data were taken during four observing runs covering three 104-day orbital periods. The average results of four observations made on the night of 1971 March 23 are $\langle\rho\rangle = 54.5 \pm 1.3$ milliseconds of arc, $\langle\theta\rangle = 166\overset{\circ}{.}3 \pm 4\overset{\circ}{.}3$, where the errors are the 1 σ statistical error of measurement only. We compared our observational results with an orbit we computed using elements P, T, e, and ω obtained spectroscopically by Struve and Kilby (1953) and elements a (arc seconds), Ω, and i obtained by Merrill (1922) with the stellar interferometer (fig. 3). The mean difference between 10 observations and the orbit was $+9.8 \pm 1.3$ milliseconds in separation and $+3\overset{\circ}{.}8 \pm 4\overset{\circ}{.}3$ in position angle. Plate measurement errors were estimated at no more than 2 percent in separation and $\pm 2°$ in position angle, for a good transform in this series. With the exception of the semimajor axis, the orbital elements that are implied by our observations appear to be consistent with those above.

5. *Mu Orionis*.—Two observations of μ Ori made 91 days apart at Kitt Peak by the Stony Brook group have been compared with positions computed from the orbit obtained by Bougeois (1929). The separations are very nearly those predicted, but the position angles of both observations are about 35° smaller than expected. A 25° rotation of the line of apsides could produce the observed angles, but the separations would then be about half the observed values.

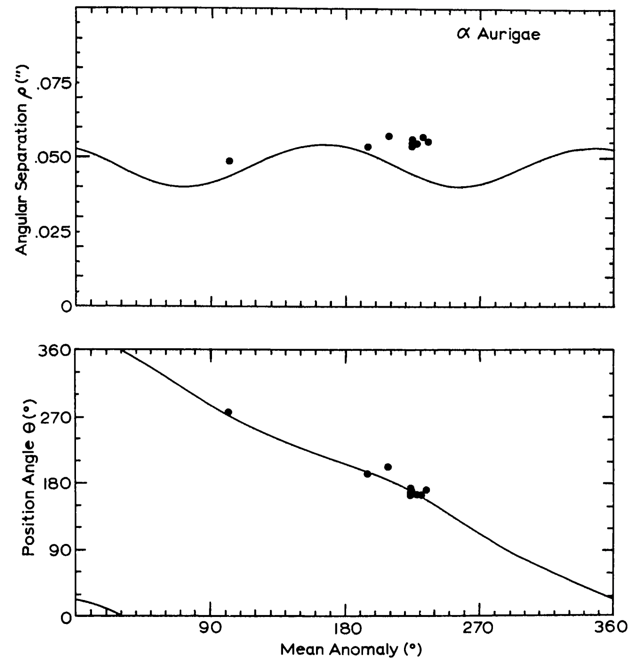

FIG. 3.—Observational results for α Aur (Capella) from table 1 are compared with a theoretical orbit calculated by the authors using orbital elements obtained by Struve and Kilby (1953) and Merrill (1922).

6. *Beta Coronae Borealis* was resolved by speckle interferometry with the 5-m telescope, and visually by Couteau (1973) using the 50- and 75-cm refractors at Nice. The results of these two measurements are in agreement. The system β CrB is a single-line spectroscopic binary for which dynamical elements were given by Neubauer (1944). Based on the colors reported by Couteau, we have assumed comparable spectral types for the two components in order to obtain a mass ratio using the mass-luminosity relation of Baize and Ramani (1946). According to our preliminary orbit (table 2) the star is presently near maximum separation and will remain observable by conventional visual techniques for some time.

Beta CrB is an F0p star which shows both magnetic and photometric variability over an $18\overset{d}{.}5$ period. Preston (1967) has noted a 10.5-year periodicity in the amplitude of the magnetic field variation and suggested that this may be an effect associated with the spectroscopic companion which was described by Neubauer (1944) and is discussed here. The early F spectrum and our observed $\Delta m = 1.5$ suggest an F0 subgiant primary star and an F0 V secondary.

7. *Iota Serpentis* has been studied as a visual binary by van den Bos (1967). His orbit II, with a period of 22.14 years, predicts positions close to those which we measured (table 1, fig. 2).

8. *Delta Scorpii* was previously reported to be a single-lined spectroscopic binary having a period of about 20 days (van Hoof, Bertiau, and Deurinck 1963). The new component reported here was previously unknown and appears to have a much longer period. It is not possible to derive orbital elements from the present observational data.

9. *Sigma Herculis* is not a spectroscopic binary, and the companion we resolved was previously unknown. Two of the three observations yielded fringes in the Fourier transform, and the fringe spacings were quite different. This is difficult to reconcile with the 50-year period estimated from Kepler's law.

10. *c Herculis* is a close visual binary studied by Eggen (1945). The position found agrees well with both of the possible orbits he proposed, with a slightly better fit to the second.

11. *Chi Draconis* is a known spectroscopic (Crawford 1928) and astrometric (Alden 1936) binary. Our three observations cover approximately one period. Dynamical elements were given by Crawford (1928) using lines from a single spectrum. The second spectrum was later studied by Spite (1967), who deduced a mass ratio of 1.31. This is in reasonable agreement with the value 1.29 obtained by combining Crawford's elements with our data (table 2). However, we found orientation elements Ω and i quite different from the values given by Alden (1936).

12. *Beta Cephei.*—The third companion to β Cep ($\rho = 0''.250$) was discussed in Paper I and was previously unknown. We observed no significant rotation over an interval of almost one and one half years. Kepler's law suggests a period of at least 100 years. Attempts by Couteau (1973) to observe the companion visually were unsuccessful. This observation supports the rather large magnitude difference indicated in table 1. Some variable, anisotropic features in the Fourier transform of β Cep may indicate the presence of other companions or of circumstellar matter.

We have calculated seven new stellar masses from previously determined orbital elements and our speckle interferometry observations. The masses and luminosities for β Per, γ Per, β CrB, and χ Dra are listed in table 3. When these values are plotted in the mass-

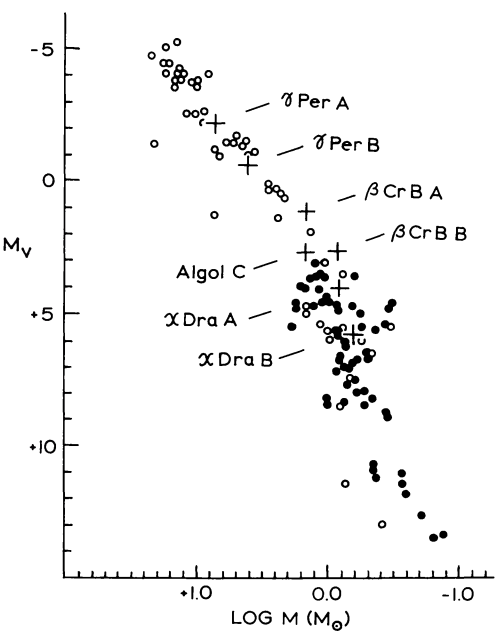

FIG. 4.—Mass-luminosity data for seven stars from table 3 plotted on the empirical mass-luminosity diagram adapted from Harris *et al.* (1963). *Open circles*, spectroscopic binaries; *filled circles*, visual binaries.

TABLE 3

MASS-LUMINOSITY DATA FOR SEVEN STARS*

Object	Combined Apparent Visual Magnitude, Σm_v	Parallax† (″)	Observed Magnitude Difference, Δm_v	Deduced Photometric Data: Absolute Visual Magnitude, M_v	Deduced Photometric Data: Deduced Spectral Type	Deduced Photometric Data: Bolometric Correction,‡ B.C.	Results: Corrected Absolute Visual Magnitude (M_v−B.C.)	Results: Derived§ Stellar Mass ($M_\odot$)
γ Per A	*2.9*	*0.011*	~1.5	−1.6	G8 II	0.5	−2.1	7.3
γ Per B				−0.1	A3 III	0.4	−0.5	4.2
β Per AB‖	*2.2*	*0.039*	~2.5	0.3‖	...	...	...	2.3‖
β Per C				2.8	A7$_m$	0.1	2.7	1.5
β CrB A	*3.66*	*0.031*	1.5	1.3	F0 IV	0.2	1.1	1.5
β CrB B				2.8	F0 V	0.1	2.7	0.86
χ Dra A	*3.58*	*0.120*	~2	4.1	F7 V	~0	4.1	0.84
χ Dra B				6.1	G9 V	0.2	5.9	0.66

* Numbers in italics are adopted values referenced in the text.

† Hoffleit 1964.

‡ Allen 1964.

§ Derived masses are based on the adopted and calculated orbital elements listed in table 2.

‖ Combined properties of the unresolved A and B components.

luminosity diagram of Harris, Strand, and Worley (1963), the new data follow the general behavior of the empirical mass-luminosity relation (fig. 4).

Finally we note that β Per, τ Per, and especially β Cep exhibit anisotropic Fourier transform features at the limit of the 200-inch telescope theoretical resolution. The features do not appear to be caused by instrumental aberrations or atmospheric dispersion and may be evidence of additional stellar companions or circumstellar material. However, we note that none of these stars show evidence for a significant infrared excess.

We wish to thank the director of the Hale Observatories and the director of the Kitt Peak National Observatory for extending us the privileges of guest investigatorship. We are grateful to M. Simon and A. A. Hoag for their cooperation and encouragement, P. Couteau for cooperative astrometric observations and the computation of physical and orbital parameters for β CrB, M. Schneider for additional variable star observations, and D. M. Peterson for several stimulating discussions. This work was funded in part by the National Science Foundation.

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