

APPARENT ORBIT OF THE SPECTROSCOPIC BINARY β ARIETIS WITH THE MARK III STELLAR INTERFEROMETER

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ABSTRACT

The spectroscopic binary β Ari has been directly resolved with the Mark III Stellar Interferometer. Observations in 1988 were analyzed to determine the visual orbit of the system with the following results: eccentricity $e = 0.903 \pm 0.012$, semimajor axis $a'' = 0''.0361 \pm 0''.0003$, inclination $i = 44^\circ 7' \pm 1^\circ 3'$, longitude of periastron $w = 209^\circ 1' \pm 1^\circ 2'$, position angle of ascending node $\Omega = 79^\circ 1' \pm 0^\circ 8'$. The measured magnitude difference between two components, $\Delta m = 2.63 \pm 0.22$ at 800 nm, yields individual visual magnitudes of $m_{v1} = 2.70 \pm 0.02$ and $m_{v2} = 5.80 \pm 0.20$. Combined with data from spectroscopic observations, masses $M_1 = (2.34 \pm 0.10) M_\odot$, $M_2 = (1.34 \pm 0.07) M_\odot$, and geometrical parallax $\pi = 0''.053 \pm 0''.002$ are derived. These results demonstrate that both components of β Ari agree well with the empirical mass-luminosity relation.

Subject headings: interferometry — stars: binaries — stars: individual (beta Ari)

I. INTRODUCTION

The determination of the orbital elements of binary stars plays an important role in astrophysics. Particularly, the visual orbit of a spectroscopic binary yields very useful information for the study of stellar structure and evolution. Unfortunately, many spectroscopic binaries cannot be resolved by present observational techniques. The Mark III Stellar Interferometer, located on Mount Wilson, California, with an angular resolution of order $0''.006$ (at 800 nm) allows the determination of the orbits of close binary stars. The double-lined spectroscopic binary β Ari was first directly resolved by the Mark III stellar interferometer in 1988.

The star β Ari (H.D. 11636, HR 553; R.A. = $01^h 49^m 1^s$, Decl. = $+20^\circ 19'$ for equinox 1900.0) is a well-known spectroscopic binary. The system has total visual magnitude $m_v = 2.64$ and spectral type A5 V. Because of its unusually large orbital eccentricity, this star has attracted much attention. From spectroscopic observations, the first orbital solution to β Ari was obtained in 1907 (Ludendorff 1907), and further studies in 1938 (Petrie 1938) and 1970 (Gorza and Heard 1971) did not show significant changes of the orbital elements. During 1979–1984, Tomkin and Tran (1987) measured the radial velocities of the companion and determined a mass ratio of 0.57. In 1988 Hilditch (Hilditch *et al.* 1988) obtained spectrograms of the system very close to periastron passage. All of measurements above have given very similar results, and the final spectroscopic orbital elements used in this paper are given in Table 1.

The spectroscopic binary β Ari was observed 10 times by speckle interferometry during 1975–1981. However, the star was never resolved on any of the occasions it was included in the observing program (McAlister 1978; McAlister and Hartkopf 1988).

In this paper, we report the resolution of the spectroscopic binary β Ari with the Mark III Stellar Interferometer. Section II describes the observation of β Ari and the model fitting of the data to obtain the intensity ratio and the separations of the binary in R.A. and Decl. Section III provides the determination of the apparent orbit of β Ari and its error analysis. Section IV presents the physical parameters of β Ari after combination with the spectroscopically determined elements.

II. OBSERVATION AND ANALYSIS

The Mark III Stellar Interferometer (Shao *et al.* 1988) has two fixed “astrometric” baselines (AB): one is 12 m north-south, and the other is 12 m east-south. In addition, since 1988 July a variable baseline (VB) has been available (Mozurkewich *et al.* 1988). The variable baseline adds 12 piers, oriented north-south, at which to locate the siderostats. Up to 36 different baselines are available, with lengths ranging from 3 to 32 m. For maximum sensitivity, the fringe tracker uses a wide spectral channel. Simultaneously, precise fringe visibility measurements are made using two narrow bandpass filters, typically 25 nm wide at 800 nm, and at 500 or 550 nm. The effective apertures for amplitude measurements are typically 2.5 cm and 5.1 cm for the variable and fixed baselines, respectively.

The star β Ari was extensively observed by the Mark III Stellar Interferometer during 1988 September–November. A total of 446 scans over 44 nights on 14 baselines were obtained. Each scan consisted of typically 75 s of fringe tracking, followed by a 5 s measurement of dark count and sky background. From the recorded data, the square of the fringe visibility, V^2 , was estimated for each scan. The formal error for each 75 s scan, calculated from the statistics of V^2 using 0.5 s integrations, was typically less than 0.05.

In order to calibrate the systematic errors which are due to the atmosphere and the instrument, unresolved stars with an intrinsic visibility greater than 95% were periodically observed

¹ Work performed while at the Harvard-Smithsonian Center for Astrophysics.

TABLE 1
SPECTROSCOPIC ORBITAL ELEMENTS OF β ARI^a

P (days)	106.9954 ± 0.0005
T (JD)	2444274.276 ± 0.009
e_1	0.895 ± 0.003
e_2	0.879 ± 0.001
w_1	$24^\circ 5' \pm 2^\circ 0'$
w_2	$204^\circ 9' \pm 0^\circ 4'$
K_1 (km s ⁻¹)	38.1 ± 1.9
K_2 (km s ⁻¹)	66.6 ± 0.2
V_{01} (km s ⁻¹)	-3.8 ± 0.5
V_{02} (km s ⁻¹)	-2.9 ± 0.2
$(a \sin i)_1$ (10 ⁶ km)	25.01 ± 1.46
$(a \sin i)_2$ (10 ⁶ km)	46.69 ± 0.23
f_1 ($M_\odot$)	0.72 ± 0.03
f_2 ($M_\odot$)	0.50 ± 0.03

^a Tomkin 1987.

during the night. Approximate diameters for the calibration stars were determined using observations from the red and blue channels and the assumption of a wavelength-independent diameter. Each night was calibrated independently of the others in order to yield a calibration coefficient by which to normalize the measured visibilities. These normalized visibilities were used in the following analysis.

For single stars, the visibility function (Hanbury Brown 1974) is calculated as follows:

$$\Gamma(\theta) = 2J_1(\pi B\theta/w)/(\pi B\theta/w),$$

where $J_1(x)$ is a first-order Bessel function, w is the wavelength, B is the length of projected baseline, and θ is the angular diameter of the star.

For a double star, assuming an intensity ratio $R = I_1/I_2$, where I_1 and I_2 are the intensities of the two components, the visibility function $V^2(u, v)$ is given by

$$V^2(u, v) = \frac{\Gamma^2(a_2) + [R\Gamma(a_1)]^2 + 2R\Gamma(a_1)\Gamma(a_2) \cos \theta}{(1 + R)^2}$$

$$\theta = \frac{2\pi}{w} (US_r + VS_d).$$

In this expression, $a_1 = \pi B\theta_1/w$, $a_2 = \pi B\theta_2/w$, U and V are the components of projected baseline on the sky, S_r and S_d are the angular separations between the primary and the companion in right ascension and declination, respectively. As a function of time, the measured visibilities will change between values which are proportional to $I_1\Gamma(a_1) + I_2\Gamma(a_2)$ and $I_1\Gamma(a_1) - I_2\Gamma(a_2)$.

Using a nonlinear least-squares fitting algorithm and the equations above, the parameters R , S_r , and S_d are estimated from the normalized visibilities. Typical plots of the measured and best-fit fringe visibilities for different baselines as a function of time are shown in Figures 1(a)–1(d). It is obvious that the longer the baseline, the faster the periodic changes of fringe visibility. The formal errors of the model fitting for the visibility measurements are generally less than 5%.

For the orbit determination, observations from both the variable baselines (VB) and the two fixed baselines (AB) were used. In those cases where the number of scans per night was insufficient to accurately calculate the orbital parameters, the normalized visibilities from adjacent nights, at most three nights total, were combined for computation. Those observations which have less than 10 continuous data points are discarded. The observations epoch of each data set is referred to

TABLE 2
OBSERVATIONS OF β ARI WITH THE MARK III INTERFEROMETER (AT 800 nm)

JD 2,400,000.0 +	R	S_r (mas)	S_d (mas)	Baseline
47407.8875	0.109 ± 0.006	58.66 ± 0.34	-2.59 ± 0.24	AB(12 m)
47421.4948	0.083 ± 0.003	63.99 ± 0.46	-8.73 ± 0.63	AB(12 m)
47422.7833	0.078 ± 0.003	63.28 ± 1.60	-8.91 ± 0.46	VB(4 m)
47428.6633	0.101 ± 0.004	63.04 ± 0.29	-11.30 ± 0.28	AB(12 m)
47433.1462	0.082 ± 0.006	62.37 ± 1.00	-12.86 ± 0.36	VB(8 m)
47434.8574	0.067 ± 0.009	61.76 ± 1.25	-13.26 ± 0.41	VB(15 m)
47435.8800	0.064 ± 0.008	61.00 ± 1.42	-14.01 ± 0.49	VB(11 m)
47436.8541	0.060 ± 0.007	61.26 ± 1.20	-14.09 ± 0.42	VB(11 m)
47437.8771	0.069 ± 0.006	61.31 ± 0.57	-14.17 ± 0.20	VB(19 m)
47438.8312	0.076 ± 0.005	60.85 ± 0.40	-14.42 ± 0.16	VB(19 m)
47442.0377	0.098 ± 0.007	59.22 ± 0.39	-15.73 ± 0.26	AB(12 m)
47457.5316	0.083 ± 0.004	45.82 ± 0.32	-18.25 ± 0.08	VB(23 m)
47458.8309	0.103 ± 0.004	45.16 ± 0.16	-18.43 ± 0.05	VB(28 m)
47459.8405	0.117 ± 0.003	43.81 ± 0.10	-18.49 ± 0.03	VB(28 m)

the averaged moment of all observations in the set. The final results of the observations are listed in Table 2.

III. APPARENT ORBIT OF β ARI

In the Seventh Catalog of the Orbital Elements of Spectroscopic Binary Systems (Batten, Fletcher, and Mann 1978), the elements of the binary star β Ari are judged to be of "good" quality. As observations from the Mark III interferometer in 1988 could not include an entire revolution of the system, two orbital elements from spectroscopic results, i.e., the period P and the epoch T , are used below.

For the relative motion of a binary, the separations, S_r , S_d , in R.A. and Decl., are computed from the orbital elements by means of the following formulas (Heintz 1978):

$$S_r = BX + GY,$$

$$S_d = AX + FY,$$

$$X = \cos E - e,$$

$$Y = \sin E \sqrt{1 - e^2},$$

$$\mu(t - T) = E - e \sin E,$$

where e is eccentricity, E is eccentric anomaly, μ is the mean orbital motion, and X and Y are the elliptical rectangular coordinates in unit orbit. The Thiele-Innes constants B , G , A , F contain the semimajor axis a'' and the three orientation elements w , Ω , and i .

Applying the method of differential corrections to the initial elements estimated from spectroscopic observations, the visual orbit of β Ari is determined from following equations (Heintz 1978):

$$\delta S_r = X \delta B + Y \delta G + P_y \delta e - Q_y(\mu \delta T) + Q_y(t - T) \delta \mu,$$

$$\delta S_d = X \delta A + Y \delta F + P_x \delta e - Q_x(\mu \delta T) + Q_x(t - T) \delta \mu,$$

$$P_x = A \partial X / \partial e + F \partial Y / \partial e,$$

$$P_y = B \partial X / \partial e + G \partial Y / \partial e,$$

$$Q_x = A \partial X / \partial M + F \partial Y / \partial M,$$

$$Q_y = B \partial X / \partial M + G \partial Y / \partial M,$$

$$\partial X / \partial e = -1 - (\sin E)^2 / (1 - e \cos E),$$

$$\partial Y / \partial e = X \sin E / [(1 - e \cos E) \sqrt{1 - e^2}],$$

$$\partial X / \partial M = -(\sin E) / (1 - e \cos E),$$

$$\partial Y / \partial M = (\cos E) \sqrt{1 - e^2} / (1 - e \cos E).$$

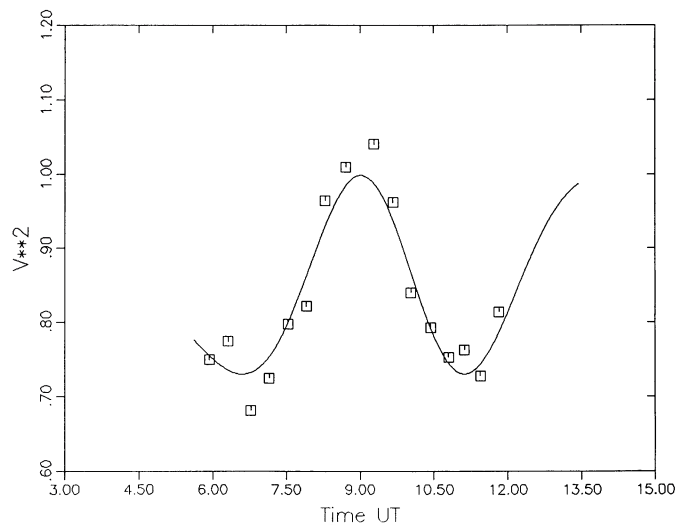


FIG. 1a

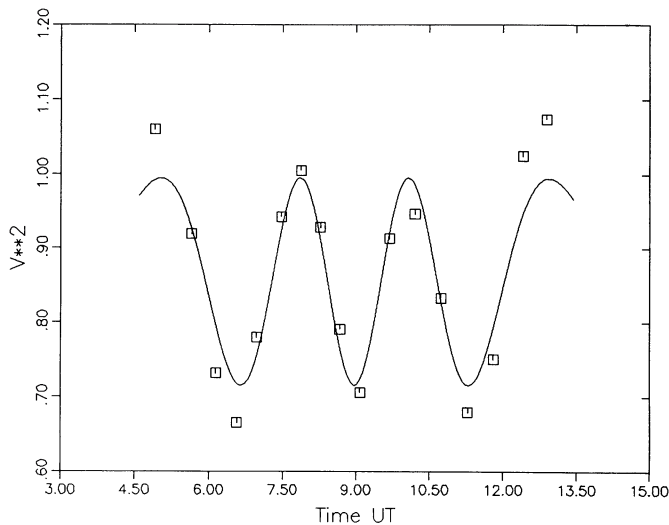


FIG. 1b

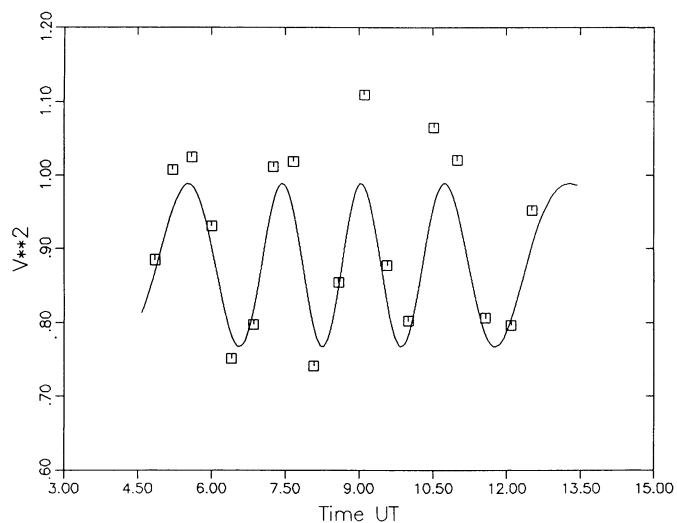


FIG. 1c

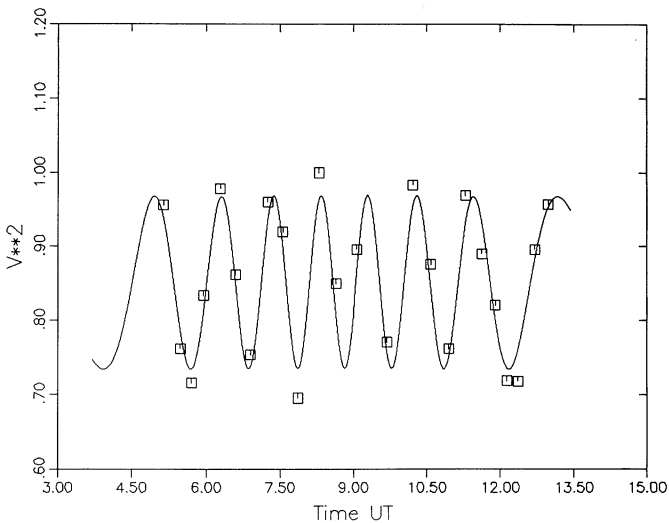


FIG. 1d

FIG. 1.—(a) Measured and best-fit fringe visibilities for β Ari on baseline number 4 (4 m), 1988 September 17. The best-fit curve corresponds to intensity ratio $R = 0.078$, and separations in R.A. and Decl. of 63.3 mas and -8.9 mas, respectively. The best-fit error of the normalized visibilities is 2.9%. (b) Measured and best-fit fringe visibilities for β Ari on baseline number 9 (8 m), 1988 September 28. The best-fit curve corresponds to intensity ratio $R = 0.082$, and separations in R.A. and Decl. of 62.4 mas and -12.9 mas, respectively. The best-fit error of the normalized visibilities is 3.7%. (c) Measured and best-fit fringe visibilities for β Ari on baseline number 12 (11 m), 1988 October 2. The best-fit curve corresponds to intensity ratio $R = 0.060$, and separations in R.A. and Decl. of 61.3 mas and -14.1 mas, respectively. The best-fit error of the normalized visibilities is 4.7%. (d) Measured and best-fit fringe visibilities for β Ari on baseline number 25 (19 m), 1988 October 3. The best-fit curve corresponds to intensity ratio $R = 0.069$, and separations in R.A. and Decl. of 61.3 mas and -14.2 mas, respectively. The best-fit error of the normalized visibilities is 2.7%.

From the two equations in S_r and S_d , two separate estimates of the eccentricity e are obtained: $e(S_r) = 0.905 \pm 0.013$, and $e(S_d) = 0.894 \pm 0.034$, which are consistent at the level of their formal errors. A weighted value, $e = 0.903 \pm 0.012$ is determined as the final result.

Since the orbital elements of β Ari, as determined spectroscopically a number of times from 1907 to 1988, are in excellent agreement, we will use these measurements of the period $P(d) = 106.9954$, epoch $T = \text{JD } 2444274.276$ and eccentricity $e = 0.895$. Thus, all of geometric elements of the star β Ari are obtained, and are listed in Table 3. The measured and calculated separations in R.A. and Decl., the residuals to the visual orbit, $O - C$, the corresponding total separation, ρ'' , and mean anomaly, E , are recorded in Table 4. The mean residual from

TABLE 3
GEOMETRIC ELEMENTS OF β ARI FROM
THE MARK III OPTICAL
INTERFEROMETER

$a''(\text{mas})$	36.1 ± 0.3
i	$44^\circ 7' \pm 1' 3$
w	$209^\circ 1' \pm 1.2$
Ω	$79^\circ 1' \pm 0^\circ 8$
B	-33.4 ± 0.1
G	13.0 ± 0.4
A	6.3 ± 0.1
F	25.3 ± 0.2

TABLE 4
ORBIT RESIDUALS FOR β ARI

Epoch JD 2,400,000+	$S_r(O)$ (mas)	$S_r(C)$ (mas)	$(O-C)_r$ (mas)	$S_d(O)$ (mas)	$S_d(C)$ (mas)	$(O-C)_d$ (mas)	ρ (mas)	E ($^\circ$)
47407.8875.....	58.66	58.48	0.18	-2.59	-2.67	0.08	58.54	137.86
47421.4948.....	63.99	63.50	0.49	-8.73	8.44	-0.29	64.05	163.66
47422.7833.....	63.28	63.62	-0.34	-8.91	-8.95	0.04	64.25	165.98
47428.6633.....	63.04	63.51	-0.47	-11.30	-11.17	-0.13	64.48	176.49
47433.1462.....	62.37	62.66	-0.29	-12.86	-12.73	-0.13	63.94	184.45
47434.8574.....	61.76	62.17	-0.41	-13.26	-13.30	0.04	63.58	187.50
47435.8800.....	61.00	61.84	-0.84	-14.01	-13.62	-0.39	63.32	189.32
47437.8771.....	61.31	61.08	0.23	-14.17	-14.24	0.07	62.72	192.90
47438.8312.....	60.85	60.67	0.18	-14.42	-14.52	0.10	62.39	194.62
47442.0377.....	59.22	59.09	0.13	-15.73	-15.43	-0.30	61.07	200.44
47457.5316.....	45.82	46.47	-0.65	-18.25	-18.33	0.08	49.95	230.76
47458.8309.....	45.16	45.00	0.16	-18.43	-18.43	0.00	48.62	233.58
47459.8405.....	43.81	43.80	0.01	-18.49	-18.48	-0.01	47.54	235.82

the newly determined orbit for the observations are $\langle \delta S_r \rangle = -0.12$ mas, $\langle \delta S_d \rangle = -0.06$ mas. The rms dispersions in R.A. and Decl. are $\sigma_r = \pm 0.40$ mas, $\sigma_d = \pm 0.17$ mas, respectively. In fact, the deviations to the visual orbit, either in R.A. or Decl., are all within the range of 1σ formal error of each measurement in Table 2. These observations spanned 52 days, for a change of $\sim 100^\circ$ in mean anomaly, and covered 49% of the revolution. All of the measured data are plotted along with the apparent orbit of β Ari in Figure 2, and the error bars in R.A. and Decl. for each measurement are indicated by the lengths of crosses.

IV. DISTANCE, MASSES, AND LUMINOSITIES

The newly determined elements i and a'' permit the direct determination of the individual masses and the distance to β Ari when combined with the spectroscopically determined mass ratio and the quantity $(a \sin i)$. The parallax derived from this method is $0''.0530 \pm 0''.0017$, corresponding to a distance of (18.87 ± 0.61) pc. This geometrical parallax of β Ari agrees very well with the trigonometric parallax of $0''.0590 \pm 0''.0072$ (van Altena, Lee, and Hoffleit 1990).

The linear semimajor axis for β Ari is $a = (0.68 \pm 0.02)$ a.u. Using the spectroscopically determined mass ratio, $M_2/M_1 = K_1/K_2 = 0.57 \pm 0.03$ along with the newly determined inclina-

tion $i = 44.7^\circ \pm 1.3^\circ$ and semimajor axis $a'' = 0''.0361 \pm 0''.0003$, the masses of the primary and companion are readily determined. The results are

$$M_1 = (2.34 \pm 0.10)M_\odot \text{ and } M_2 = (1.34 \pm 0.07)M_\odot.$$

With the Mark III Stellar Interferometer, not only separations of a binary system, but also the luminosity differences between the two components can be accurately determined. The mean intensity ratios of the two components of β Ari, calculated from the data in Table 2, are 0.089 ± 0.018 for VB, and 0.092 ± 0.013 for AB, respectively. Since the observations from the variable baseline used a smaller aperture (1 inch) than for the fixed baseline (2 inch), allowing more precise measurement of fringe visibilities, the intensity ratio of 0.089 ± 0.018 at a wavelength of 800 nm is adopted, which yields $\Delta m = 2.63 \pm 0.22$. With the aid of $(V-I)$ and $(V-R)$ for A5 V and G0 V stars from the tables of stellar colors (Johnson 1966), this leads to visual magnitudes $m_{v1} = 2.70 \pm 0.02$ and $m_{v2} = 5.80 \pm 0.20$ for primary and companion, respectively. The luminosity, L , of the primary is consistent with spectral classification A5 V, which was determined from the spectroscopic observations. But the spectrum of the companion, which has not been determined spectroscopically, is most likely of type late F5 III-V, or G0 V. For a system of A5 V and G0 V, bolometric corrections $BC = -0.12$ and -0.03 (Allen 1983) are obtained. Thus, absolute bolometric magnitudes $M_{1\text{bol}} = 1.2 \pm 0.1$, $M_{2\text{bol}} = 4.4 \pm 0.2$ are obtained, the latter assuming spectral type G0.

Thus, all of physical parameters of β Ari are determined, and are listed in the Table 5. The results are found to fit well into the empirical mass-luminosity relation, and both components of β Ari are plotted on the Hertzsprung-Russell diagram (Strand 1963) as shown in Figure 3.

TABLE 5

NEWLY DETERMINED PHYSICAL PARAMETERS OF β ARI (AT 800 nm)

Mass M_1	$(2.34 \pm 0.10) M_\odot$
Mass M_2	$(1.34 \pm 0.07) M_\odot$
Distance d	(18.87 ± 0.61) pc
Absolute bolometric magnitude $M_{1\text{bol}}$	1.2 ± 0.1
Absolute bolometric magnitude $M_{2\text{bol}}$	4.4 ± 0.2
$\log(M_1/M_\odot)$	0.37 ± 0.02
$\log(M_2/M_\odot)$	0.13 ± 0.02
$\log(L_1/L_\odot)$	1.36 ± 0.03
$\log(L_2/L_\odot)$	0.13 ± 0.08

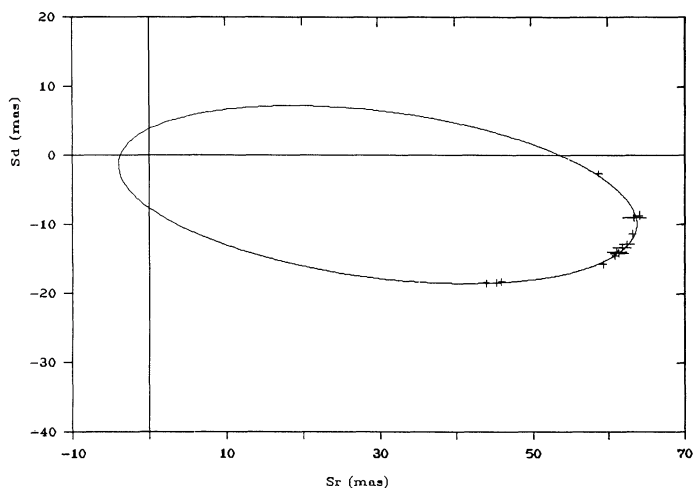


FIG. 2.—Measured data and apparent orbit of β Ari. The errors in R.A. and Decl. are indicated by the lengths of crosses.

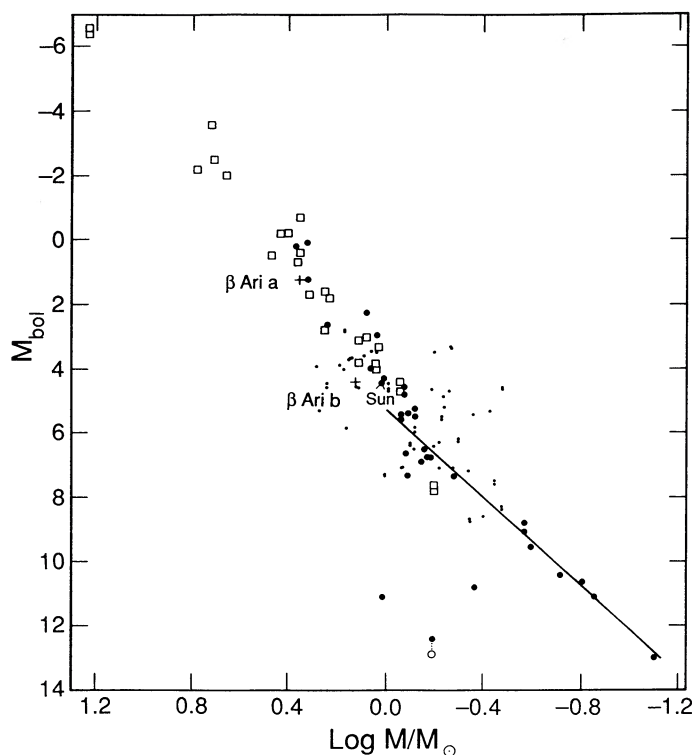


FIG. 3.—The empirical mass-luminosity relation adopted from Strand (1963). Visual binaries of high weight are indicated by large filled circles; those of low weight by small filled circles. Eclipsing binaries are indicated by unfilled squares. The solid line represents the adopted mass-luminosity relation for the late-type dwarf stars. The two components of β Ari shown as crosses on this figure. The errors in the luminosity and masses are indicated by the length of the crosses.

V. CONCLUSION

For the first time, the spectroscopic binary β Ari has been resolved directly, allowing for a direct determination of the visual orbit of the system. The large eccentricity of β Ari is

determined as well, and is consistent with the value determined from spectroscopic observations. The geometrical parallax from this work agrees well with the trigonometric measurements. The newly determined inclination and magnitude differences yield the mass-luminosity relations for both components of β Ari; these fit well into the empirical H-R diagram. Because of the limited range of eccentric anomaly in this observation season, and the small number of observations per night for the star, further observations of more than one revolution, particularly near periastron, are desired in order to independently determine all of the orbital elements for β Ari.

The ephemeris of the star β Ari from the newly determined orbit indicates that the maximum separation of β Ari is ~ 64 mas. However, the angular separation is more than 35 mas for ~ 83 days of each 107 day period, which is within the range of speckle interferometry. Thus, it should be possible to resolve this system by speckle interferometry if the magnitude difference $\Delta m = 2.6$ at 800 nm can be accommodated. This bright star system ($m_v = 2.64$) has an extraordinary eccentricity ($e = 0.9$), and the total separation between the two components will change from minimum 3.2 mas to maximum 64.6 mas during the period of 107 days. Thus it is a good object for study with modern optical interferometry.

At present the Mark III Stellar Interferometer has detected the 2.6 mag difference of β Ari. It is estimated that a 4 mag difference between two components of a binary is detectable with this instrument. It can be expected that more close binary stars can be resolved in the near future by this long baseline interferometer with high-angular resolution (6 mas at 800 nm), high measurement precision ($< 5\%$), and good detectability of magnitude differences (< 4 mag).

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REFERENCES

- Allen, C. W. 1983, *Astrophysical Quantities* (London: Athlone).
 Batten, A. H., Fletcher, J. M., and Mann, P. J. 1978, *Pub. Dom. Ap. Obs.*, **15**, 121.
 Gorza, W. L., and Heard J. F. 1971, *Pub. David Dunlap Obs.*, **3**, 99.
 Hanbury Brown, R. 1974, *The Intensity Interferometer* (London: Taylor and Francis), p. 122.
 Heintz, W. D. 1978, *Double Stars* (Hingham: Reidel), p. 48.
 Hilditch, R. W., Edwin, R. P., Milligan, H. M., and McFadzeam, A. D. 1988, *Observatory*, **109**, 228.
 Johnson, H. L. 1966, *Ann. Rev. Astr. Ap.*, **4**, 193.
 Ludendorff, H. 1907, *Ap. J.*, **25**, 320.
 McAlister, H. A. 1978, *Pub. A.S.P.*, **90**, 288.
 McAlister, H. A., and Hartkopf, W. I. 1988, *CHARA Contribution No. 2*.
 Mozurkewich, D., Simon, R., Hutter, D., Johnston, K., Colavita, M., Shao, M., and Pan, X. P. 1988, *Bull. A.A.S.*, **20**, 1006.
 Petrie, R. M. 1938, *Pub. Dom. Ap. Obs. Victoria*, **7**, 105.
 Shao, M., et al. 1988, *Astr. Ap.*, **193**, 357.
 Strand, K. Aa. 1963, *Basic Astronomical Data* (Chicago: University of Chicago), p. 285.
 Tomkin, J., and Tran, H. 1987, *A.J.*, **94**, 1664.
 van Altena, W., Lee, J., and Hoffleit, D. 1990, *Yale Parallax Catalogue* (New Haven: Yale University Observatory).

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