1995AJ....109..332M

THE ASTRONOMICAL JOURNAL VOLUME 109, NUMBER 1 JANUARY 1995

BINARY STAR ORBITS FROM SPECKLE INTERFEROMETRY. VII. THE MULTIPLE SYSTEM XI URSAE MAJORIS

BRIAN D. MASON,[1,3] HAROLD A. MCALISTER,[1,2,3,4] AND WILLIAM I. HARTKOPF[1,2,3,4]
Center for High Angular Resolution Astronomy, Georgia State University, Atlanta, Georgia 30303
Electronic mail: mason@chara.gsu.edu, hal@chara.gsu.edu, hartkopf@chara.gsu.edu

M. M. SHARA[2]
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218
Electronic mail: mshara@stsci.edu

Received 1994 July 29; revised 1994 September 7

ABSTRACT

Xi Ursae Majoris (HR 4374/5) consists of a visual binary having a period of nearly 60 yr, the primary component of which is a 669 day astrometric and spectroscopic subsystem, and the secondary is a 4 day spectroscopic binary. We report here improved elements for the long-period visual system (AB) and the short-period astrometric system (Aa). We also report the first direct detection of a fifth component to the multiple system (Bc) from speckle observations obtained in 1988 at the Canada–France–Hawaii Telescope.

1. INTRODUCTION

Observations of ξ Ursae Majoris (HR 4374/5) have played an historic role in the development of stellar astronomy. The visual components (ADS 8119 AB) were discovered by Sir William Herschel on May 2, 1780 (Herschel 1803; See 1895), and their relative positions were first accurately measured by F. G. W. Struve in 1826 (Struve 1827). The nature of the relative motion in this system helped inspire the conclusion that duplicity resulted from physical association rather than by chance alignment, and the orbit determined by Savary (1828), followed in 1829 by a solution from Herschel (1832), was the first orbit ever calculated for a double star. More than 1500 micrometer observations have been subsequently accumulated, and the orbit catalogue of Worley & Heintz (1983) lists the orbit of Heintz (1967) as the "definitive" orbit of this 59.84 yr system.

The visual primary (HR 4375) was found to have a variable radial velocity by Wright in 1900 (Campbell & Wright 1900), and this subsystem (designated Aa) was independently detected as a perturbation in visual micrometer observations by Nörlund (1905). Nörlund's period of 1.8 yr was soon confirmed by Wright (1908) in a follow-up to his earlier spectroscopic investigation. This astrometric perturbation in ξ UMa was one of the first such submotions ever detected. To complete the historical perspective of the multiple system comprising ξ UMa, the visual secondary (HR 4374) was found to be a 4 day single-lined spectroscopic system by Campbell (1918). No other wide or common proper motion companions have been detected or suggested.

Van den Bos (1928) published a detailed analysis of the visual and long-period spectroscopic systems, and his orbit for the 1.83 yr spectroscopic/astrometric orbit is the latest listed in the spectroscopic orbit catalogue of Batten *et al.* (1989), where it is rated as being of "average" quality. Heintz (1967) also studied the motions of the AB and Aa systems, revising van den Bos' period of 59.86 yr only very slightly to 59.84 yr, while adopting van den Bos' spectroscopically determined period of 1.832 yr for the Aa system. The most recent orbit of the short-period primary Ba associated with the visual secondary is that of Berman (1931), also considered as being of average quality. The spectral types of the visual components given by Bopp (1987) and adopted by Batten *et al.* (1989) are G0 V and G5 V.

In this paper, we report the detection of an additional close component of the system. This detection resulted from speckle observations obtained with the 3.6 m Canada–France–Hawaii Telescope (CFHT) under very good seeing conditions on Mauna Kea. We have also analyzed speckle observations from the 2.1 and 4 m telescopes at Kitt Peak published previously in our series of measurements papers, as well as previously unpublished measures from the 1.8 m Perkins Telescope on Anderson Mesa, Arizona, operated by the Lowell Observatory, and the 2.5 m Hooker Telescope on Mt. Wilson, California, operated by the Mt. Wilson Institute. The speckle measures of the AB visual system provide the means for improving the orbital elements of ADS 8119 AB, and the residuals in the speckle data from the improved orbit clearly show the submotion of the Aa system.

2. SPECKLE OBSERVATIONS OF ξ URSAE MAJORIS

ξ Ursae Majoris has been on the CHARA speckle program since 1976 for two principal reasons: first as a standard binary whose orbit is sufficiently well known to potentially calibrate speckle observations, and second, to attempt the

---

[1] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

[2] Visiting Astronomer, Canada–France–Hawaii Telescope, operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France, and the University of Hawaii.

[3] Visiting Astronomer, Mount Wilson Observatory, operated under a collaborative agreement between the Carnegie Institution of Washington and the Mount Wilson Institute.

[4] Guest Observer, Lowell Observatory.

0004-6256/95/109(1)/332/9/$0.90

TABLE 1. Speckle observations and residuals for ADS 8119.

Epoch	θ_{obs}	ρ_{obs}	θ_{calc}	ρ_{calc}	Δx	Δy	Code	Wt.
1976.3667	111°0	3″010	111°7	3″073	-0″054	0″047	2.1-m	10
1977.3278	110.3	3.043	109.7	3.048	0.029	0.016	2.1-m	10
1980.9041	101.9	2.760	102.0	2.831	-0.018	-0.069	Tok	5
1983.0673	98.2	2.656	96.5	2.593	0.090	-0.050	ISIT	10
1983.4277	95.8	2.585	95.4	2.545	0.021	-0.038	4-mR	20
1984.3558	89.9	2.334	92.6	2.409	-0.113	0.072	1.8-m	5
1984.3724	91.9	2.379	92.5	2.406	-0.028	0.026	4-mR	20
1985.0029	91.6	2.332	90.4	2.304	0.049	-0.028	4-mR	20
1985.1147	91.8	2.313	90.0	2.284	0.076	-0.028	1.8-m	5
1985.2515	90.5	2.303	89.5	2.261	0.039	-0.042	1.8-m	5
1985.9912	85.9	2.112	86.6	2.126	-0.024	0.016	1.8-m	5
1986.1539	85.0	2.089	85.9	2.095	-0.031	0.008	1.8-m	5
1986.2235	85.2	2.064	85.6	2.082	-0.012	0.018	1.8-m	5
1986.2372	84.6	2.070	85.5	2.079	-0.034	0.012	1.8-m	5
1987.1300	82.5	1.935	81.3	1.898	0.036	-0.043	1.8-m	5
1987.1956	81.5	1.903	80.9	1.884	0.017	-0.022	1.8-m	5
1987.1981	81.3	1.908	80.9	1.884	0.011	-0.027	1.8-m	5
1987.2092	81.3	1.902	80.8	1.881	0.012	-0.023	1.8-m	5
1987.2885	81.1	1.903	80.4	1.864	0.016	-0.042	1.8-m	5
1987.2913	81.1	1.902	80.4	1.864	0.016	-0.041	1.8-m	5
1987.2939	81.2	1.893	80.4	1.863	0.022	-0.034	1.8-m	5
1988.1624	73.8	1.655	75.1	1.672	-0.034	0.027	4-mR	20
1991.3268	37.1	1.000	38.0	0.985	-0.021	0.003	4-mR	20
1991.9000	24.4	0.922	25.8	0.906	-0.023	0.013	4-mI	20
1991.9052	24.0	0.927	25.6	0.906	-0.030	0.015	4-mI	20
1993.1969	352.8	0.893	353.5	0.871	-0.020	0.013	4-mI	20
1993.9260	337.7	0.956	336.5	0.943	-0.020	-0.013	2.5-m	5
1994.0930	336.9	0.943	333.1	0.967	-0.006	-0.068	2.5-m	5

detection of the astrometric component discussed by van den Bos (1928). The 28 speckle measurements of the wide AB system are recorded in Table 1 along with residuals from the newly determined orbit and other information to be described in the following section.

The first two speckle measures listed in Table 1 were taken with the 2.1 m telescope at KPNO (McAlister & Hendry 1982). The calibration for binary star speckle interferometry at that telescope was not as well established as that for the Kitt Peak 4 m telescope, and the photographic speckle camera then used incorporated a magnetically focused image tube with significant "S" distortion. Thus "wide" binaries such as the AB system of ξ UMa were not measured with high relative accuracy compared to our more recent CCD speckle results. The third measure in Table 1 is taken from Tokovinin (1982), while the fourth measure was taken with an ISIT camera (McAlister *et al.* 1987b) and is of reduced accuracy compared to subsequent speckle measures due to the spatial distortions inherent in ISIT's.

Of the remaining measures, 14 are from the 1.8 m Perkins telescope at Lowell Observatory (Al-Shukri 1991; Fu 1994), five (with the 4-mR code) were obtained at the KPNO 4 m telescope with an RCA ICCD camera (described below and reported in McAlister *et al.* 1987b; McAlister *et al.* 1993; Hartkopf *et al.* 1994), while the final three measures (with the 4-mI code) were obtained at the KPNO 4 m telescope with an ITT ICCD camera [described in Mason *et al.* (1993) and results reported in Hartkopf *et al.* (1994)]. All of these observations from the 4 m telescope are of similar high accuracy. The final two measures were obtained during the first two speckle observing runs with the 100 in. Hooker telescope at Mt. Wilson following its refurbishment. In the future, we hope to regularly use this great telescope to obtain speckle observations for the CHARA binary star program. A complete measurements paper of 100 in. speckle observations is in preparation.

The 1985 and 1988 4 m observations of ξ UMa were re-reduced and reanalyzed. These data were acquired by an RCA TC 1160 camera with a double-stage (chevron configuration) intensifier and a 256×256 SID 53601-X0 CCD chip, and stored as individual video fields within an RS-170 NTSC video signal (McAlister & Hartkopf 1982). The exposure time was 15 ms and data were recorded on a Gyyr-modified RCA time-lapse deck using VHS cartridges (and proprietary video format). These data required transfer to an 8 mm video format in order to be processed in our current reduction system. A modified version of the digitizing software was used which rejects frames contaminated by video noise effects. The raw frames were cropped to eliminate regions near the video guard bands which commonly show sync jitter and streaking, conservatively involving the top 80 video rows. The speckle images were centered in the video field, and this border cropping procedure removed relatively little significant information from the frames.

3. ξ URSAE MAJORIS SUBSYSTEMS

In this section we describe the orbital subsystems of ξ Ursae Majoris (HR 4374/4375): the wide AB pair (ADS 8119 = STF 1523 AB), the Aa astrometric/spectroscopic subsystem, and the newly discovered Bc system (CHARA 168 Bc).

3.1 The Orbit of ξ Ursae Majoris AB = ADS 8119

As a result of our continued study of this object, now approaching seventeen years, we have seen the wider component move through about one third of its orbit, and we are now in a position to apply the results from speckle interferometry to refine the orbit of Heintz (1967). The 1223 measured with complete ρ and θ information available from the Washington Double Star Catalog (WDS) and recent CHARA measurements (Hartkopf *et al.* 1994) allow a very accurate determination of the orbital period, encompassing nearly three complete orbital cycles. After the period was calculated with the "grid-search" method of Hartkopf *et al.* (1989) from the complete data set, the other orbital elements were calculated with a smaller sample of 70 measures from a restricted group of very reliable double star observers (Couteau, Heintz, Muller, van Biesbrock, and Worley) and the 28 speckle measures over the last orbital period. Of these visual points, two were eliminated as having unreasonably large residuals from the earlier orbit calculation. Visual observations covering the time base of the speckle data were given zero weight. The remaining visual points that were within an observing season were then converted into normal points averaged over a maximum four-month period. These are identified in Table 2 with *normal* listed as the observer. The points immediately under these with no listed weight are the measures used to make the normal point.

The data sample for the final orbit includes 28 speckle points, 13 normal points, and 13 other visual points not suitably placed in time to form normal points. These 26 visual points are listed in Table 2 along with residuals from the

TABLE 2. Visual observations and residuals for ADS 8119.

Epoch	θ_{obs}	ρ_{obs}	θ_{calc}	ρ_{calc}	Δx	Δy	Observer	Wt.
1937.2519	293°1	1″500	293°7	1″510	0″017	-0″003	normal	1.5
1937.1000	295.2	1.500					MLR	
1937.3900	291.2	1.500					MLR	
1939.2900	278.0	1.780	279.4	1.747	0.035	0.039	MLR	1.3
1946.4600	233.7	1.690	237.0	1.692	0.077	-0.056	MLR	1.1
1947.3000	231.7	1.740	231.3	1.661	0.039	0.069	MLR	1.2
1949.1801	219.0	1.460	218.1	1.614	-0.137	-0.075	VBS	2.2
1950.2635	208.5	1.562	210.2	1.606	-0.016	-0.060	normal	1.7
1950.1600	208.6	1.550					MLR	
1950.3300	208.4	1.570					VBS	
1951.1801	203.3	1.600	203.5	1.612	-0.010	-0.008	MLR	1.0
1952.4200	192.9	1.590	194.6	1.640	-0.038	-0.057	MLR	1.4
1953.1801	190.3	1.670	189.4	1.669	-0.004	0.029	MLR	0.9
1954.2600	181.1	1.750	182.3	1.723	0.028	-0.033	normal	0.9
1954.2200	180.8	1.760					MLR	
1954.3000	181.4	1.740					COU	
1955.2729	175.6	1.785	176.1	1.786	-0.001	-0.012	normal	2.0
1955.1500	175.8	1.740					WOR	
1955.3000	175.4	1.800					MLR	
1955.3500	175.6	1.810					MLR	
1956.1600	169.7	1.860	171.0	1.849	0.004	-0.041	WOR	1.0
1957.2825	164.8	1.946	165.1	1.939	0.006	-0.009	normal	1.6
1957.2600	165.2	1.940					WOR	
1957.2900	164.4	1.950					MLR	
1957.3000	164.8	1.950					COU	
1958.2645	159.2	2.052	160.3	2.023	0.014	-0.047	normal	1.7
1958.0800	161.8	2.030					WOR	
1958.3300	160.6	1.990					COU	
1959.3900	155.3	2.130					WOR	
1960.2720	152.0	2.164	151.9	2.205	-0.034	0.025	normal	1.3
1960.2000	151.2	2.190					WOR	
1960.3521	152.8	2.134					HEI	
1961.2210	147.9	2.334	148.3	2.293	0.026	-0.035	normal	1.7
1961.1500	148.1	2.360					WOR	
1961.2100	147.2	2.290					HEI	
1961.3199	148.3	2.350					COU	
1962.2729	144.7	2.270	144.7	2.390	-0.096	0.071	normal	1.2
1962.2400	144.7	2.200					HEI	
1962.3199	144.7	2.370					COU	
1963.2327	141.4	2.520	141.6	2.476	0.030	-0.035	normal	2.5
1963.1940	141.8	2.560					WOR	
1963.3101	140.7	2.440					HEI	
1964.3060	137.9	2.476	138.5	2.570	-0.084	0.047	normal	1.5
1964.1930	138.8	2.620					WOR	
1964.2200	138.3	2.390					HEI	
1964.4800	136.9	2.450					HEI	
1965.2500	134.5	2.490	135.8	2.648	-0.153	0.071	HEI	0.9
.3050	131.7	2.605	133.1	2.731	-0.133	0.049	normal	1.3
1966.2000	132.0	2.560					HEI	
1966.4100	131.3	2.650					HEI	
1969.7820	124.4	3.020	125.0	2.953	0.014	-0.071	WOR	2.0
1972.2500	119.3	2.975	119.8	3.052	-0.063	0.052	normal	2.4
1972.2300	119.2	2.890					HEI	
1972.2700	119.3	3.060					WOR	
1974.3580	114.5	3.080	115.6	3.088	-0.057	-0.018	WOR	2.0
1975.3101	113.4	2.820	113.8	3.087	-0.122	0.238	HEI	1.7
1976.2920	111.1	2.990	111.8	3.075	-0.064	0.066	WOR	2.0

newly determined orbit. Also listed in Table 2 are the observations comprising the normal points and codes for the individual observers, as well as the weight assigned to each individual measurement. Weights for visual observations were initially assigned following the precepts of Hartkopf *et al.* (1989), i.e.

$$w_i=0.5, \quad \text{telescope aperture}<18'',$$

$$w_i=1.0, \quad \text{telescope aperture}\geqslant 18'',$$

then modified as follows:

$$w_i'=\sqrt{n_i}w_i,$$

where n_i is the number of observations averaged into the published measure. Finally, normal points are assigned weights by the equation:

$$W_k=\sqrt{\sum_i (w_i')^2}=\sqrt{\sum_i n_i w_i^2}.$$

Visual measures contemporary with the speckle observations were omitted from this solution and are not listed in Table 2. The orbital solution is presented in Table 3 along with elements from the orbits of Heintz (1967) and van den Bos (1928). We note that the newly determined orbital period and semimajor axis agree more closely with the values found by van den Bos than with the more recent results of Heintz. This distinction is small, resulting in ~0.6% difference in a^3/P^2 between our results and Heintz'. On the other hand, van den Bos and Heintz are in close agreement in their determinations of the inclination and especially in their solutions for the eccentricity. It is a tribute to the work of van den Bos and Heintz that no significant change in the elements have resulted from the inclusion of speckle data.

Figure 1 shows the newly determined orbit with all 1223 measurements, while Fig. 2 shows this orbit with only the 26 visual/normal measures and 28 speckle measures. The rms of the residuals in x and y from the new orbit is ±0″016 with the rms speckle residual half that of the visual residual. The photographic and ISIT residuals are larger than other speckle residuals by about a factor of two. The standard deviations in x and y for the 46 points in the orbit of Heintz are the same, with no significant difference between the speckle and visual residuals. We will elaborate on this apparent similarity in the accuracies of the two techniques in discussing the Aa subsystem.

3.2 The Orbit of ξ Ursae Majoris Aa

At first glance, the difference in residuals from the two orbits of ξ UMa would seem to make the improvement negligible; however, hidden within these residuals of the AB orbit are submotions produced by the Aa pair. The high precision of the speckle observations offers the possibility of detecting submotions in wide visual binaries arising from closer unseen companions which are either too faint or too close to be directly detected. This has been shown in the case of HR 266 = ADS 784 in which CHARA data showed the first submotion detected by speckle interferometry (Cole

TABLE 3. Orbital elements for ADS 8119.

Reference	P(yr)	a(″)	i(°)	Ω(°)	T	e	ω(°)	a^3/P^2	Δ
Van den Bos (1928)	59.863	2.536	122.80	101.40	1935.027	0.413	127.18	0.0045513	+0.23%
Heintz (1967)	59.840	2.530	122.65	101.59	1935.170	0.414	127.53	0.0045225	−0.41%
CHARA (this paper)	59.878	2.536	122.13	101.85	1935.195	0.398	127.94	0.0045490	+0.18%

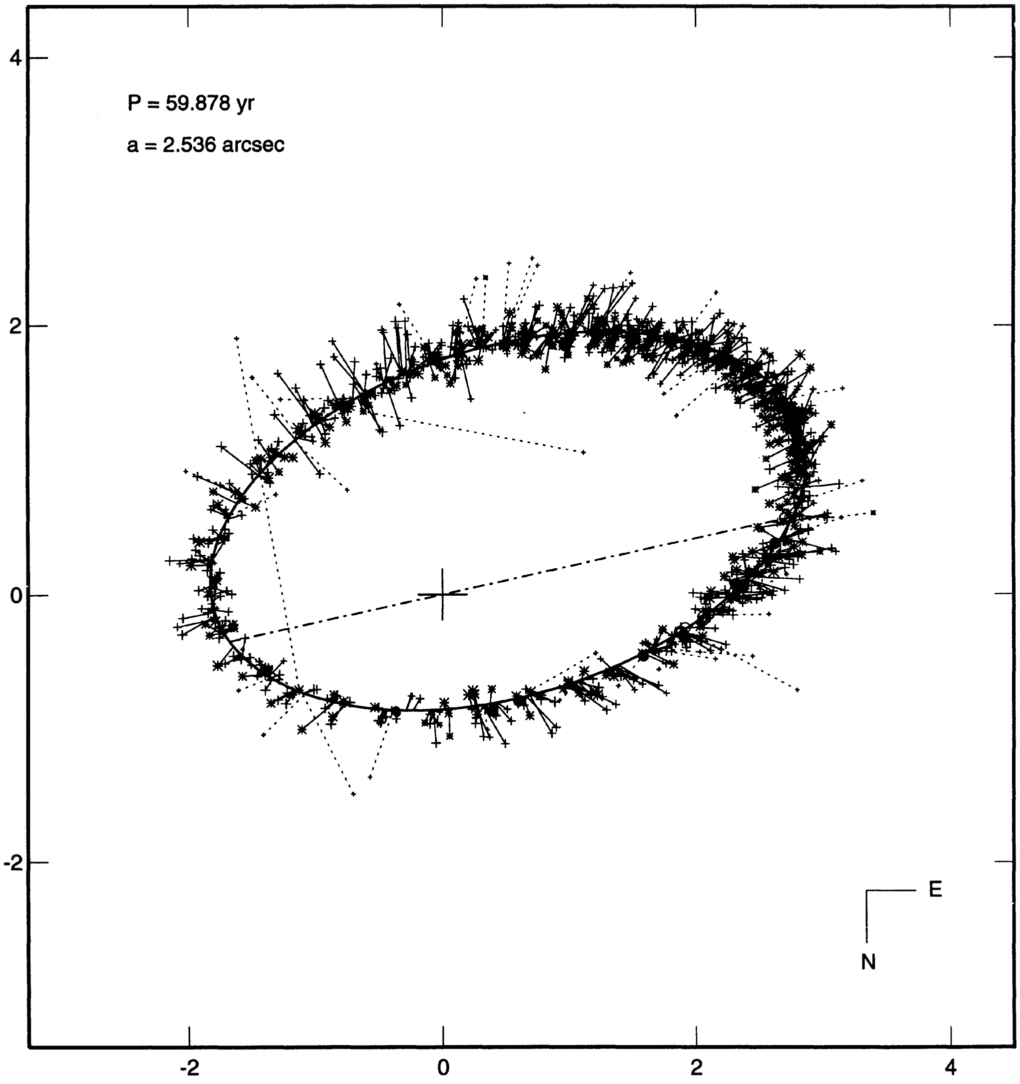

FIG. 1. The newly determined relative orbit for ADS 8119 with "small" visual observations (i.e., observations with apertures <18") are indicated by plus signs, "large" visual observations (apertures >18") by asterisks and filled circles indicating the CHARA speckle measurements. Each point is connected to the orbit by an O-C line. Those whose residuals were judged too large for the calculation were given zero weight and are connected by a dashed O-C line. The broken line is the line of nodes. All of these points were used in determining the period of the new orbit.

et al. 1992). The speckle residuals from the new AB orbit were therefore inspected for the presence of a submotion due to the Aa astrometric subsystem.

When calculating an orbit based on submotions from residuals, only data of the highest accuracy will reveal the submotion. Therefore, only data from Table 1 with weights of 20 were used. The x and y residuals from the AB orbit were transformed to polar coordinates (ρ, θ) in order to provide input data for the grid-search orbit program. This represents the motion of Aa in the reference frame of the Aa barycenter. These are presented in Table 4.

Taking these calculated positions along with P and e from the spectroscopic orbit of van den Bos (1928), a new orbital solution based only on the speckle residuals was calculated and is presented in Table 5 along with the elements from the orbit of Heintz (1967). The top panel of Fig. 3 shows the newly determined orbit with the eight speckle positions. One feature of this orbit is that the Aa angular separation is sufficiently wide to be detected by speckle interferometry from a 4 m telescope during a portion of the orbit. The bottom panel of Fig. 3 shows the "wobble" produced in the ξ UMa AB orbit by the Aa companion during the interval under consideration. The computed orbit shown here is not closed as the AB orbital period is not an integral number of Aa orbital periods. The top panel of Fig. 4 is a plot of the residuals in x for the AB orbit, converted to the proper phase for the Aa orbit. Also shown in this figure is the curve representing the expected position from the Aa orbit, as well as a dashed curve representing the expected residual from the orbit of Heintz (1967). A similar plot for the residuals in y is shown in the bottom panel of Fig. 4. In these two plots, the eight speckle points used in the calculation are shown as

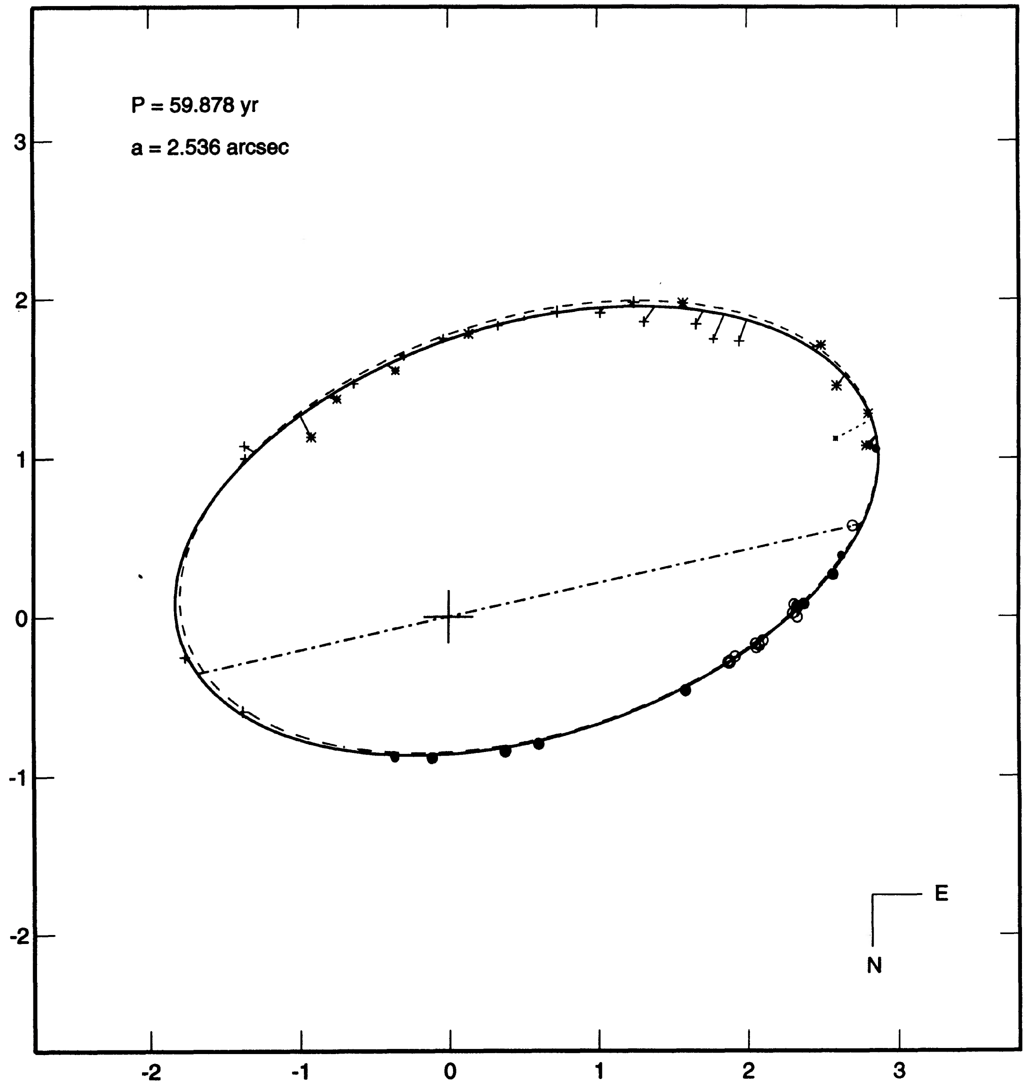

FIG. 2. The same orbit for ADS 8119, here with 26 visual and normal measures and 20 speckle measures (symbols the same as Fig. 1). These points, together with the period determined from all the data, were used in the calculation of the other orbital elements. The dashed curve is the orbit of Heintz (1967).

filled circles, the 2.5 m, 2.1 m, 1.8 m, ISIT, and other speckle observations as open circles, and the visual and normal observations as plus signs. While only eight speckle points were used in the calculation, all others from Tables 1 and 2 are also shown here to indicate the lower relative accuracy of the data excluded from the orbital solution. Four of the visual/normal points have residuals too large to plot on the figure for x, and one has a residual too large to plot on the figure for y. In examining these residuals, we see that what appeared to be similar levels of accuracy for the speckle and visual data in the AB orbit, are actually due to the tendency of the speckle data to closely follow the submotions. The major component of the speckle residual is due to the submotion, while a large fraction of the visual residual is due to observational error. The rms speckle residual in x and y from the new orbit is $\pm 0\overset{''}{.}002$, which is less than one sixth the rms visual residual. The photographic and ISIT residuals are significantly larger than other speckle residuals, but still less than the rms visual residual.

TABLE 4. Observed and calculated positions of ξ Ursae Majoris Aa.

Epoch	θ_{obs}	ρ_{obs}	θ_{calc}	ρ_{calc}	Δx	Δy	Code
1983.4277	119.5	0.044	134.8	0.041	-0.008	-0.009	4-mR
1984.3724	316.2	0.038	326.6	0.045	0.010	0.002	4-mR
1985.0029	150.7	0.057	140.0	0.052	0.009	0.006	4-mR
1988.1624	321.3	0.043	323.6	0.041	-0.001	0.003	4-mR
1991.3268	352.4	0.022	344.6	0.019	-0.003	-0.002	4-mR
1991.9000	331.0	0.026	320.9	0.030	0.000	-0.006	4-mI
1991.9052	334.1	0.033	320.6	0.029	-0.008	-0.004	4-mI
1993.1969	328.5	0.024	340.3	0.022	0.001	0.005	4-mI

TABLE 5. Orbital elements for ξ Ursae Majoris Aa.

Reference	P(yr)	a($''$)	i(°)	ω(°)	T	e	Ω(°)
Heintz (1967)	1.832	0.055	86.3	326.0	1935.410	0.56	326.0
CHARA (this paper)	1.832	0.057	94.9	143.0	1986.495	0.53	263.5

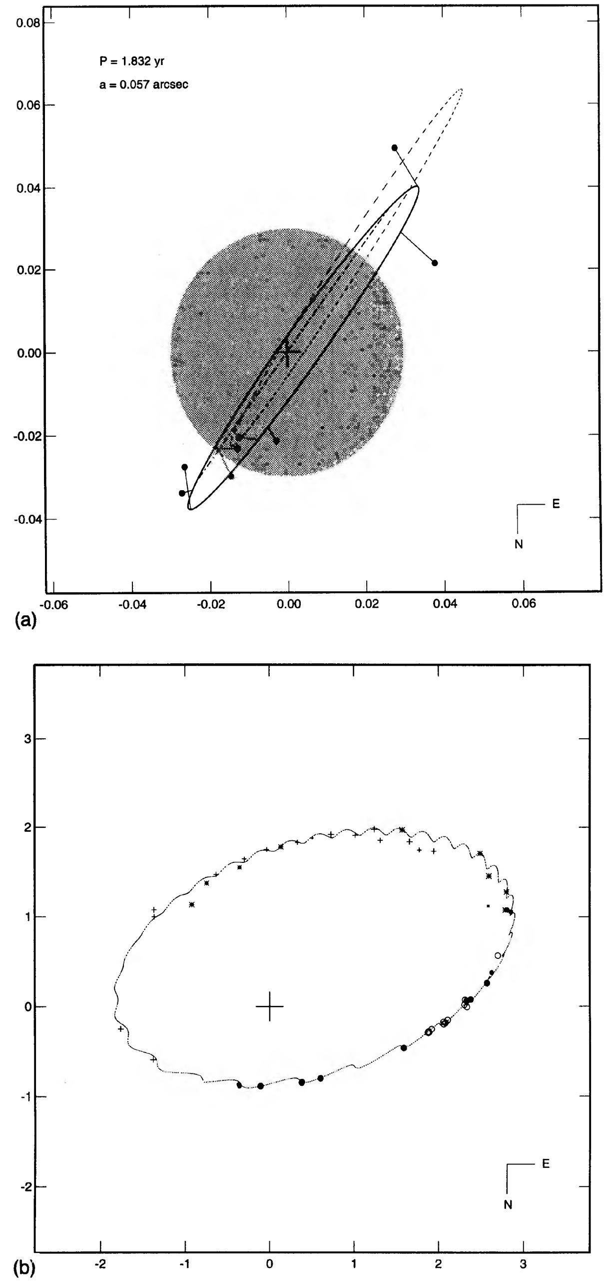

FIG. 3. The top panel shows the newly determined relative orbit for ξ Ursae Majoris Aa with filled circles indicating the CHARA speckle measurements, as deduced from residuals in the AB orbit. The dashed curve is the orbit of Heintz (1967). The shaded circular area about the origin indicates that region falling below the 0.″030 diffraction limit of a 4 m telescope. The bottom panel shows the observed orbit of ξ UMa AB to the same scale as Fig. 1 with the "wobble" produced by the Aa component. Labels are as in Fig. 1.

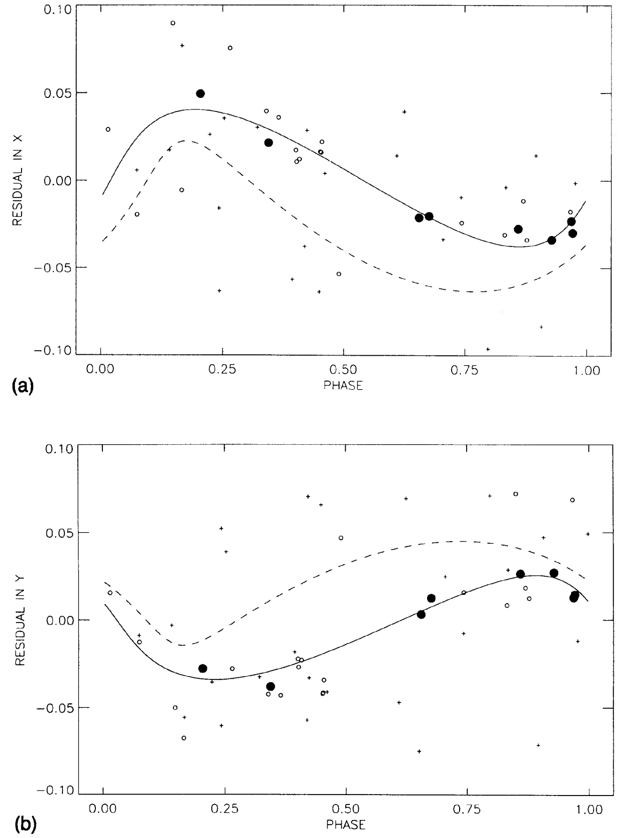

FIG. 4. The top panel shows a plot of residual in x vs phase of the Aa,b orbit, covering one complete orbit of ξ Ursae Majoris. Each point is the residual in x from the ADS 8119 orbit, converted to the proper location in the phase diagram. Filled circles represent CHARA CCD speckle measures used in the calculation; plus signs represent CHARA 2.1 m photographic, 2.5 m, 1.8 m, or ISIT speckle measures; and dots represent visual or normal measures. Note that the plus signs and dots almost form a scatter diagram indicating the need for highly accurate measures. The solid curve represents the expected residual from the Aa orbit. The dashed curve represents the expected residual from the Aa orbit of Heintz. Four of the visual or normal measures fall outside the range of this scale. The bottom panel is a similar plot of residual in y vs phase. One of the visual or normal measures falls outside the range of this scale.

It is possible to directly determine stellar masses from a combined visual/spectroscopic orbital solution if the system is double-lined or if the system is single-lined and has a reliable parallax. From the orbital solution presented here combined with the elements of van den Bos (1928), the average trigonometric parallax of 0.″127±0.″017 (Halliwell 1981), and the known spectral class (G0 V) of the Aa component from Bopp (1987), the mass of the Ab component is determined to be approximately 0.37 $\mathcal{M}_\odot$. This mass corresponds to spectral type M3 with $M_v \sim +11$. This is beyond our normal magnitude limit for direct detection and far beyond the Δm which can be observed; a result consistent with our failure to directly resolve Aa at four epochs when it was sufficiently separated to be resolved by the 4 m telescope (i.e., outside the shaded area in Fig. 3). At 2.2 μm wavelength, ΔK would be about 5 mag, but infrared speckle observation would require the Keck 10 m telescope to resolve the 0.″05 pair.

3.3 A New Companion to ξ Ursae Majoris B

An observation of ξ UMa obtained at the 3.6 m Canada–France–Hawaii Telescope on 1988 February 29 as part of a continuing survey of stars from the Yale *Bright Star Catalogue* Hoffleit 1982) showed a distinct and close companion to one component of the wide binary. Contrary to the conclusion stated above, it was first suspected that the Aa com-

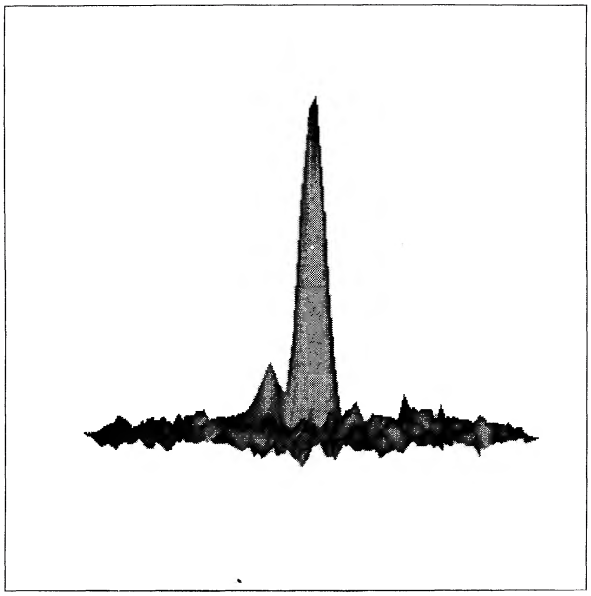

FIG. 5. The central region of the directed vector autocorrelation of the binary ξ Ursae Majoris is shown, following background subtraction. The truncated central peak corresponds to the zeroth order spatial correlations (i.e., speckles correlating with themselves), while the side peaks arise from the system duplicity.

ponent had indeed been directly detected, in spite of the large anticipated Δm. Further considerations, which are described here, indicate that this is a new addition to ξ UMa associated with the B component of the visual pair. The new component is therefore designated ξ UMa Bc (this new component was inappropriately identified as ξ UMa Bb in McAlister *et al.* 1993). It is most certainly not the 4 day spectroscopic companion.

Observing conditions on Mauna Kea for our 1988 observing run, while inferior to those of the first CFHT bright star survey of McAlister *et al.* (1987a), were still good with seeing noted as being about 1″. Figure 5 shows the "directed vector autocorrelation" (DVA) for ξ UMa passing (right to left) through the central and principal peaks. The background has been removed by the boxcar method described in Bagnuolo *et al.* (1992), and the central peak has been truncated to bring up the other peak. The signal-to-noise ratio of this detection, in terms of peak height above background divided by the rms background fluctuations, is 34:1.

As mentioned previously, this new component was originally believed to be associated with the Aa,b subsystem. There are several reasons for rejecting this supposition. The position angle of the newly observed companion, given along with the angular separation in Table 6, is more than 30° from the line of nodes of the highly inclined orbit for Aa. Furthermore, at the epoch of this observation, the orbit of Aa predicts the quantities $(\theta, \rho) = (323\overset{\circ}{.}6, 0\overset{\prime\prime}{.}041)$. Although the errors in the speckle observations leading to the Aa orbit are relatively large, it does not seem likely that the uncertainty in the Aa orbit would permit such a discordant detection of Aa. The hierarchical nature of multiple systems would also argue against the presence of another companion to A with an angular separation in the regime of separations expected for Aa. Instead, it is more likely that this component must therefore be associated with B.

TABLE 6. Speckle observation of ξ UMa Bc.

Epoch	$\theta_{\rm obs}$	$\rho_{\rm obs}$
1988.1624	104°3	0″056

The V magnitudes of ξ UMa A and B are 4.41 and 4.87 (Hoffleit 1982), giving a Δm of 0.46. However, the spectral types of Bopp (1987) for ξ UMa of G0 V and G5 V, yields a predicted Δm of 0.70. While this 0.24 mag discrepancy may be real, photometry of individual stars of a close bright pair is a difficult task. This discrepancy, then, should be considered as having large error bars. The mass function for the Bab pair from the orbit of Berman (1931) of 5.2×10^{-5} would exclude significant contributions of light from the very short period spectroscopic companion except in the case of an improbably small inclination (however, the inclination does appear to be very small, according to Strassmeier *et al.* 1989). If we take this one-quarter magnitude discrepancy as real, increasing the brightness of the Ba,b pair to account for this would require Δm of 1.5 or a Bc secondary of K2–3 V. This Δm is consistent with the speckle observation. Unfortunately, the width of this binary in the field of view of the CCD chip prevents determining a Δm more accurately using the technique described in McAlister *et al.* (1992). Using the trigonometric parallax of Halliwell (1981) and the error associated with it, estimates of the total mass of the system range from 1.5 to 3.4 $\mathscr{M}_\odot$. *HIPPARCOS* data, when published, should significantly constrain this mass range. While the lower extreme in this range can be ruled out considering the spectral types within the system, the mass range is not inconsistent with another previously undiscovered component.

This additional component was partially detected at Mt. Wilson at the epoch of the last measurement listed in Table 1. An elongation of the B-component peak in a direction consistent with the previous measure of this system in Table 6 was noted. A contour diagram of the elongated DVA peak containing information from all components is given in Fig. 6. Also shown in Fig. 6 is the comparison star HR 4380, observed five minutes after ξ UMa at almost the same zenith distance. The lack of any observed elongation rules out the possibility of atmospheric dispersion being the culprit in the contour diagram of ξ UMa. Because $\Delta m_{\rm Aa,b}\sim5$ mag any elongation could not be attributed to the 1.8 yr system Aa,b and the 4 day Ba,b system is far too close to contribute any elongation. Thus, we conclude that the observed elongation is due to the new Bab,c system. The ratio of major to minor axis for this observation is 1.23 ± 0.06 in direction $81°\pm10°$. While it was not possible to make a measurement of the object at this epoch, the sometimes superior seeing afforded at Mt. Wilson bodes well for detection of this difficult object in the future.

A mobile diagram in the style of Evans (1968) of ξ UMa (Fig. 7) shows the relationships of the components and some of their properties. It is significant that in only one observa-

1995AJ....109..332M

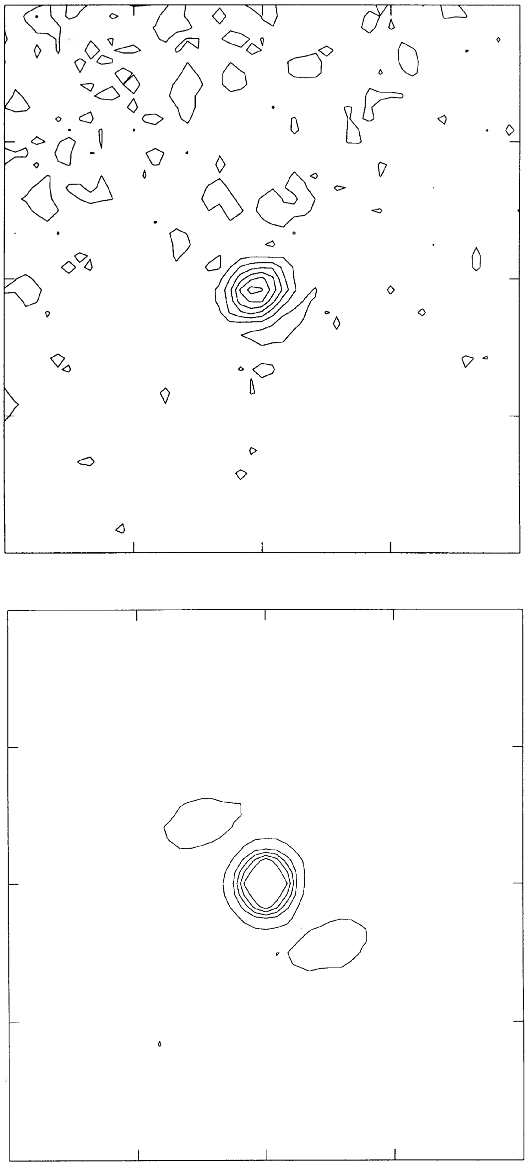

FIG. 6. On the top is shown the contour diagram of the DVA peak of the 1994 February 3 Mt. Wilson observation of ξ Ursae Majoris showing elongation in the suggested direction of the companion. On the bottom is shown the central peak of the star HR 4380. The angular width of the window is $0''.5$ for these observations.

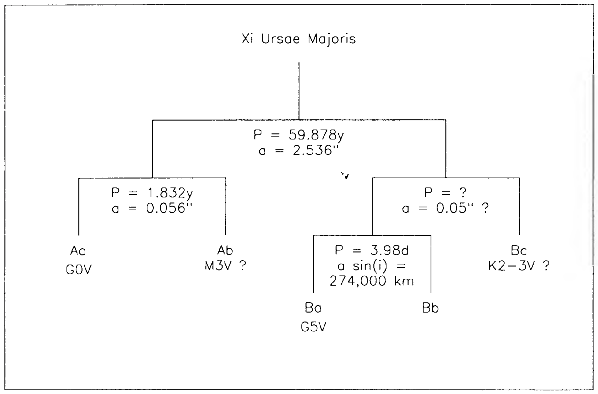

FIG. 7. Mobile diagram of ξ UMa and some of its properties.

tion of ξ UMa do we find an indication of this additional Bc component. However, careful inspection of the observations can allow some limitations to be placed on the orbit after establishing a definitive set of negative results. The observations from the Mt. Wilson 2.5 m, KPNO 2.1 m, and Lowell 1.8 m telescopes are not considered as definitive negative results, as they came from telescopes with a larger resolution limit than the 4 m. Furthermore, the nonlinearity of the ISIT camera makes those results less useful. The Tokovinin measure from Table 1 is also not considered in this set of definitive negative results as it was obtained under unknown observing conditions. This gives the same base set of eight observations that were used in the determination of the ξ UMa Aa orbit. Of those eight observations, the ones in 1983 and 1985 were noted as having very poor seeing, and are also rejected as definitive negative results. Thus, in addition to the one positive measurement from 1988, we have five negative results from Table 1: 1984.37, 1991.33, 1991.90, 1991.91, and 1993.20. While there is no listing in Table 1 for the observation, both A and B components were observed at Kitt Peak separately in March 1987, approximately one year before the CFHT observation. At these six negative result epochs, the new component was apparently either within the $0''.030$ diffraction limit of a 4 m telescope, or too faint to be detected.

We start with the assumption that the 1988.16 detection occurred at widest angular separation, and we count phase using this as a starting point. Orbital phases for the epochs of the five null detections were then calculated for orbital periods in the range 0.1 to 10.0 years (in 0.1 yr increments). The hierarchical nature of multiple systems precludes the presence of another companion to B with an orbital period similar to the AB or the Ba periods. If we exclude orbital periods where one or more null results fall within the phase range 0.9 to 0.1, we are left with two possible periods: ~2.2 and ~2.9 yr.

The tantalizing partial detection of this fifth component at Mt. Wilson, as described in the previous section, came 5.95 yr, or 2.05×2.9 yr, after the Mauna Kea detection. It is unclear why the object could be partially seen at one epoch (1994.0930) and not seen just two months earlier (1993.9260) under similar seeing conditions. Perhaps the apastron of the Bc component is close to $a''_{\rm min}$ so that the object spends most of its time in a position close to the Ba component rendering it unresolvable. Under this circumstance, the measurement obtained at the CFHT must be regarded as a fortuitous observation.

While being below the resolution limit is a possible reason for the lack of measurement, it is also possible that Bc would not be detected by us if the Δm grew to $\gtrsim 3.0$ mag or if either Ba or Bc were an intrinsic variable. Assuming that Bc was 1.5 mag fainter than Bab, the light from the entire ξ UMa system would only diminish by 0.1 mag if Bc were to disappear completely. If Δm grew to 3.0 mag, just reaching beyond the limit of detectability by speckle interferometry, the overall magnitude of the system would decline by only

0.03 mag. Photoelectric observations of ξ UMa described in Fitzgerald (1973) list the object as a possible variable with a range of 0.11 mag. The B component of ξ UMa was noted as being chromospherically active (Young & Koniges 1977) and the variability of ξ UMa is also reported in Strassmeier *et al.* (1989), who give a total range of variability of 0.050 mag. Strassmeier *et al.* also predict a photometric period of 810±20 days and a time of minimum light of 2 446 389 HJD±6. If we advance this time of minimum one period we reach the date 2 447 199 HJD (=1988.1023), just 22 days prior to our detection of Bc. It is at this minimum of ξ UMa B that it would be easiest to see this new Bc component. Also, it is interesting to point out that the period given by Strassmeier *et al.* of 810 days = 2.2 yr is one of the two possible values found in our search of allowed periods. While this discussion of variability is interesting, the 0.05 mag variation which is thought to arise from spot latitude variation on Ba (Strassmeier 1993) does not provide sufficient diminishment of Δm to bring Bc into detectability. Despite the intriguing photometric data, the evidence would seem to indicate that the lack of detection of the Bc component on the other dates of observation is due to the separation of the components being below the diffraction limit of the telescope employed. Apparently this component spends a majority of its time close to the primary, and persistent interferometric inspection is required to confirm this discovery as a companion to HR 4374.

The authors would like to acknowledge the comments and suggestions of our colleague Ingemar Furenlid who died on February 11, 1994. His critical eye towards this and other papers was greatly appreciated and will be sorely missed. The authors also acknowledge the contributions of Roger Griffin and Frank Fekel in securing references and for their many comments and criticisms throughout the writing of this paper. The authors also acknowledge the comments and suggestions of Klaus Strassmeier and Art Young. We also thank Hsieh-Hai-Fu and Ali Al-Shukri for their contributions to this paper. We also thank Dr. Robert Jastrow, Director of the Mount Wilson Institute and the support staff at Mt. Wilson Observatory, including Bob Cadman, Joe Russell, and Jim Frazier, for their hospitality. This research has made use of the SIMBAD database, compiled at CDS, Strasbourg, France. The binary star speckle program at Georgia State University has been supported by the National Science Foundation, most recently through NSF Grant AST 91-41927, by the GSU College of Arts and Sciences, and by the Chancellor's Initiative Fund from the Board of Regents of the University System of Georgia, administered through the GSU office of the Vice President for Research and Information Technology.

REFERENCES

Al-Shukri, A. 1991, Ph.D. thesis, Georgia State University

Bagnuolo, W. G. Jr., Mason, B. D., Barry, D. J., Hartkopf, W. I., & McAlister, H. A. 1992, AJ, 103, 1399

Batten, A. H., Fletcher, J. M., & MacCarthy, D. G. 1989, Pub. DAO, 17

Berman, L. 1931, Lick Obs Bull, 15, 109

Bopp, B. W. 1987, PASP, 99, 38

Campbell, W. W. 1918, PASP, 30, 351

Campbell, W. W., & Wright, W. H. 1900, ApJ, 12, 254

Cole, W. A., Fekel, F. C., Hartkopf, W. I., McAlister, H. A., & Tomkin, J. 1992, AJ, 103, 1357

Evans, D. C. 1968, MNRAS, 141, 109

Fitzgerald, M. P. 1973, A&AS, 9, 297

Fu, H.-H. 1994, Ph.D. thesis, Georgia State University

Halliwell, M. 1981, ApJS, 47, 243

Hartkopf, W. I., McAlister, H. A., Mason, B. D., Barry, D. J., Turner, N. H., & Fu, H.-H. 1994, AJ (in press)

Hartkopf, W. I., McAlister, H. A., & Franz, O. G. 1989, AJ, 98, 1014

Heintz, W. D. 1967, ANac, 289, 269

Herschel, F. W. 1803, Philos. Trans. RAS, 93, 339

Herschel, J. F. W. 1832, MRAS, 5, 209

Hoffleit, D. 1982, The Bright Star Catalogue (Yale University Observatory, New Haven)

Mason, B. D., McAlister, H. A., Hartkopf, W. I., & Bagnuolo, Jr., W. G. 1993, AJ, 105, 220

McAlister, H. A., & Hartkopf, W. I. 1982, PASP, 94, 832

McAlister, H. A., Hartkopf, W. I., Hutter, D. J., Shara, M. M., & Franz, O. G. 1987a, AJ, 93, 183

McAlister, H. A., Hartkopf, W. I., Hutter, D. J., & Franz, O. G. 1987b, AJ, 93, 688

McAlister, H. A., Hartkopf, W. I., & Mason, B. D. 1992, AJ, 104, 1961

McAlister, H. A., & Hendry, E. M. 1982, ApJS, 48, 273

McAlister, H. A., Mason, B. D., Hartkopf, W. I., & Shara, M. M. 1993, AJ, 106, 1639

Nörlund, N. E. 1905, ANac, 170, 117

Savary, F. 1828, Connaissance des temps pour l'an 1830

See, T. J. J. 1895, ANac, 139, 163

Strassmeier, K. G. 1993, private communication

Strassmeier, K. G., Hall, D. G., Boyd, L. J., & Genet, R. M. 1989, ApJS, 69, 141

Struve, F. G. W. 1827, Catalogus Novus Stellarum Duplicium et Multiplicium

Tokovinin, A. A. 1982, Soviet Astron. Lett., 8, 22

van den Bos, W. H. 1928, Mem Acad R Sc Let Denmark, 8th Series, 12, 295

Young, A., & Koniges, A. 1977, ApJ, 211, 836

Wright, W. H. 1908, Lick Obs. Bull., 5, 26

Worley, C. E., & Heintz, W. D. 1983, Pub. US Naval Obs., 24, Part VIII