

THE DOUBLE-LINED ECCENTRIC SPECTROSCOPIC BINARY BETA ARI

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ABSTRACT

Low-noise, near-infrared, Reticon spectra reveal β Ari as a double-lined spectroscopic binary. The secondary velocities provide a well-defined velocity curve with $K = 66.6 \text{ km s}^{-1}$ and $e = 0.88$. This eccentricity represents a slight reduction of the eccentricity determinations from earlier analyses of the primary velocity curve. Comparison of the secondary ω and Petrie's 1935 vintage primary ω shows no significant evidence of periastron advance. The nondetection is consistent with the expected small change of periastron whose predicted $\sim 100\,000$ yr period of advance means that it has yet to rise above the threshold of observational detectability. Gorza and Heard's suggestion of an apsidal regress is not confirmed. The difference between the A5 V primary's minimum mass $M_1 \sin^3 i = 0.87 M_\odot$ and its estimated actual mass indicates an orbital inclination $i \approx 50^\circ$, ruling out the possibility of eclipses. The spectroscopic results, parallax ($\pi = 0''.074$), and estimated orbital inclination require a maximum separation in the apparent orbit of $0''.084$. Thus, although β Ari has not been resolved by speckle interferometry, this day cannot be far off.

I. INTRODUCTION

Vogel (1903) announced the spectroscopic binary nature of β Ari, and Ludendorff (1907) made the first determination of its orbit. He established that the period is almost exactly 107 days and that the orbit is extremely eccentric ($e = 0.88$). Table I gives β Ari's vital statistics.

Further spectroscopic studies by Petrie (1938) and Gorza and Heard (1971) confirmed Ludendorff's findings. These later investigations yielded slightly larger orbital eccentricities—Petrie found $e = 0.892$, while Gorza and Heard determined $e = 0.896$ —so that in the *Seventh Catalogue of the Orbital Elements of Spectroscopic Binary Systems* (Batten, Fletcher, and Mann 1978), which adopts Gorza and Heard's orbital elements, β Ari appears with an eccentricity of 0.90. With the exception of an entry for a short-period visual binary, this makes β Ari and one other star (σ Psc), which also has a catalog eccentricity of 0.90, the two most eccentric spectroscopic binaries in the catalog. However, Griffin's (1984) recent discovery of a new high-eccentricity spectroscopic binary (HD 210647, $e = 0.904 \pm 0.004$) plus the restoration of β Ari's eccentricity to the neighborhood of 0.88 reported in the present paper, mean that β Ari is no longer a serious contender for the distinction of "most eccentric known spectroscopic binary."

Gorza and Heard suggested that the difference between their determination of the longitude of periastron ($\omega = 20.0$) and Petrie's ($\omega = 24.2$) may be real. Batten *et al.* (1978) remarked that "if so, it represents an apsidal regress, perhaps to be ascribed to some form of periastron effect in this very eccentric orbit."

The system's nearness ($\pi = 0''.074$) and its 107 day period have attracted the attention of the speckle interferometrists (McAlister 1978; Hartkopf and McAlister 1984), but β Ari has not given up its secrets to their scrutiny, thanks to the large magnitude difference between its components and their modest separation.

In this paper, we report the detection of the secondary spectrum on low-noise, near-infrared, Reticon spectra at $8800 \text{ \AA}$. The secondary spectrum shows the sharp lines and neutral atomic species characteristic of a late F or G spectral type, indicating that the secondary must be a late F or G type

main-sequence star. Analysis of the secondary velocity curve provides the secondary semiamplitude and revised values of the other orbital elements. Comparison of the secondary ω and Petrie's (1938) determination of the primary ω shows no sign of an apsidal regress; within the limits of their observational errors, the primary and secondary ω are consistent with each other.

We use the spectroscopically determined e , ω , $a \sin i$ ($= (a_1 + a_2) \sin i$), an estimate of i , and the parallax to estimate the shapes and sizes of the true and apparent orbits. We find that maximum separation in the apparent orbit is $\sim 0''.08$, in which case β Ari must be on the verge of resolution by speckle interferometry.

II. OBSERVATIONS

The observations were made with the McDonald Observatory 2.7 m telescope, coudé spectrograph, and a Reticon, self-scanned, silicon photodiode-array detector (Vogt, Tull, and Kelton 1978). The secondary lines of interest were the $8806 \text{ \AA}$ Mg I line and some weaker neighboring Fe I lines. The observations covered $100 \text{ \AA}$ at a resolution of $0.2 \text{ \AA}$ and had signal-to-noise ratios of between 200 and 500.

Figure 1 shows the weak, but nonetheless unmistakable, lines of the secondary spectrum in two β Ari observations—one away from periastron and one near periastron. The latter observation reveals the large radial-velocity shift characteristic of periastron passage in an eccentric orbit.

Beta Ari's secondary velocity curve has an extended, almost flat, maximum, and a brief, very sharp minimum—see

TABLE I. Basic data for β Ari.

V	2.64
B - V	0.13
π	$0''.074$
M _v	1.99
Sp. T. (Primary)	A5 V
Period	107 ^d 0

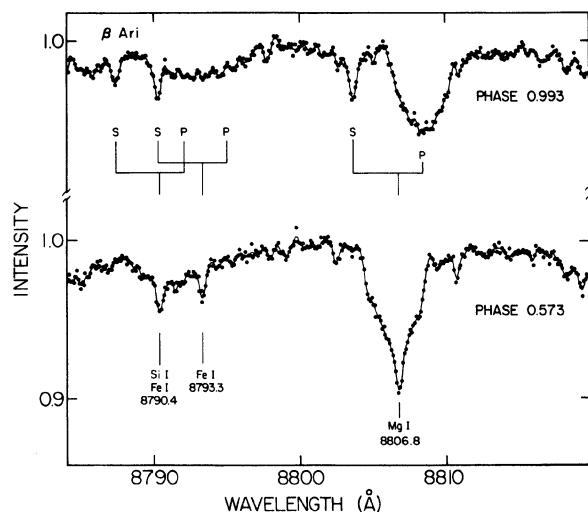


FIG. 1. Two β Ari observations plotted on an expanded intensity scale. Three pairs of primary and secondary lines are identified. In the lower observation, the separation between the primary and secondary spectra is small, so the secondary 8806 Å Mg I line lies at the bottom of its broader, stronger, primary counterpart. In the upper observation, which was made near periastron, the separation is sufficiently large that the sharp, secondary, Mg I line has climbed out of its primary counterpart and enjoys the open spaces of the continuum. The primary's large rotational broadening merges the 8790 and 8793 Å primary lines into a single, barely perceptible, shallow feature. The slightly curved appearance of the spectrum is due to its location at the high point between the 8750 and 8862 Å Paschen lines.

Fig. 2(a). The brevity of the secondary's minimum velocity combined with the nearness of β Ari's period (106^d.99) to an integer number of days means that, over any interval of a few years, the minimum always takes place at the same time of day.* This synchronism, and the circumstance that during the time (1979–1984) of these observations the minimum was soon after sunrise as seen from the longitude of McDonald Observatory, called for daytime observations in order to cover the secondary velocity curve's full range. Thanks to β Ari's brightness ($V = 2.64$), the observations' near-infrared wavelength, and the Reticon's sky-subtraction capability, we were able to make these daytime observations.

Each observation was followed by an observation of a Fe–Ne comparison spectrum for later use in the radial-velocity measurement procedure, and a small number of observations were accompanied by an observation of α Ari (K2 IIIab), the adopted radial-velocity standard. Summer-time observations were also accompanied by an observation of a hot star, such as Rigel, in order to map the menacing summertime telluric lines. Table II gives the dates of the observations.

III. RADIAL-VELOCITY MEASUREMENTS

Four secondary lines—8790.4 Å Fe I and Si I, 8793.3 Å Fe I, 8806.7 Å Mg I, and 8824.2 Å Fe I—were used to measure the secondary velocities.

The 8806 Å Mg I line has a stronger, much broader counterpart in the primary—see Fig. 1. In nearly all the observations, the secondary Mg I line was either close to the flat-

*This minimum, which occurs at the nodal passage closest to periastron passage, precedes periastron passage by 5.6 hr.

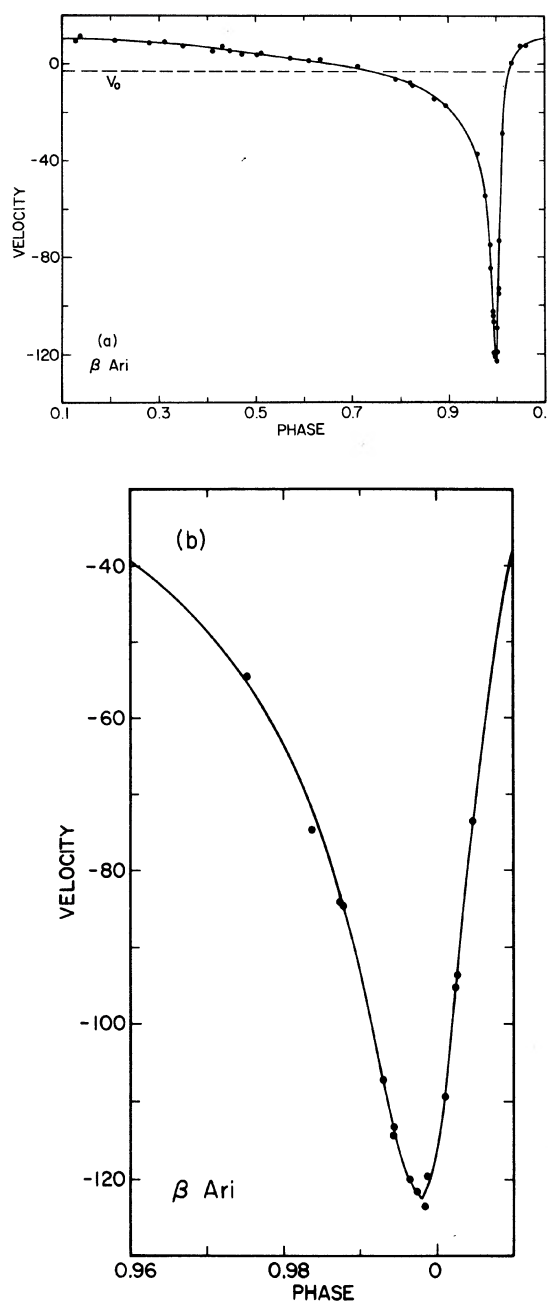


FIG. 2. (a) Full secondary velocity curve. (b) Periastron-passage part of the velocity curve.

bottomed center of its primary counterpart, where it did not suffer significant distortion, or completely outside the primary line; in the small number of observations in which it was distorted by a location on the steep sides of the primary line, it was not used in the velocity measurements. This complication did not affect the three other lines which are not present in the primary to any appreciable extent. All four lines were screened for interference by telluric lines.

The radial velocities were measured by the procedure described in Tomkin (1983). The adopted velocity of α Ari, the radial-velocity standard star, was -14.3 km s^{-1} (Wilson 1953). Table II gives the secondary velocities.

TABLE II. Radial velocities of the secondary of β Ari.

HJD (-2440000)	Phase	Velocity	O - C
3892.6010	0.4328	7.3	1.4
3907.6000	0.5730	2.2	-0.3
3922.5490	0.7127	-1.6	0.6
3939.5560	0.8716	-14.5	-0.8
3945.5650	0.9278	-25.4	-0.9
4144.8770	0.7906	-6.5	-0.1
4147.9000	0.8189	-8.3	0.1
4173.7800	0.0607	7.4	-0.7
4180.8450	0.1268	9.7	-0.9
4181.7880	0.1356	10.6	-0.0
4189.8850	0.2113	9.5	-0.4
4211.7430	0.4156	5.3	-1.0
4217.6270	0.4705	3.9	-1.2
4271.6240	0.9752	-54.5	0.8
4272.5350	0.9837	-74.7	-2.5
4273.5400	0.9931	-107.4	-0.2
4274.3950	0.0011	-109.6	-1.0
4274.5450	0.0025	-95.2	0.6
4275.5460	0.0119	-28.9	0.8
4277.5460	0.0306	0.3	0.5
4381.1050	0.9984	-123.4	-1.3
4381.1480	0.9988	-119.8	1.5
4448.9310	0.6324	1.7	0.9
4476.9830	0.8945	-17.0	0.0
4483.9590	0.9597	-36.6	2.7
4487.9870	0.9974	-121.8	0.6
4535.8970	0.4452	5.8	0.1
4576.6450	0.8260	-9.3	-0.3
4595.5540	0.0027	-93.8	-0.1
4600.5350	0.0493	7.3	0.9
4660.5530	0.6102	0.9	-0.5
4804.9240	0.9595	-37.8	1.3
4807.9520	0.9878	-84.6	0.2
4808.8730	0.9964	-120.2	0.5
4808.9750	0.9974	-121.7	0.7
4839.0090	0.2781	8.5	-0.4
4862.8750	0.5012	3.7	-0.7
4949.7780	0.3134	9.0	0.7
4953.7320	0.3503	7.8	0.2
5663.8760	0.9875	-84.2	-0.7
5664.6100	0.9943	-114.5	-1.7
5665.7140	0.0047	-73.8	1.1
5719.6640	0.5089	4.3	0.1
5771.5910	0.9942	-113.4	-1.3
Standard deviation			0.97

We also used the Reticon spectra to measure primary velocities. Initially, we tried the 8806 Å Mg I line. Although the line profile is distorted by the presence of the secondary line, in near-periastron observations with wavelength separations large enough to completely disentangle the primary and secondary lines it promised a means of measuring primary velocities in a few observations. Unfortunately, because of the line's width— $v \sin i$ is 79 km s⁻¹—the cross correlation with the standard star (Vega, A0 V) was broad and fuzzy. Artificially broadening the Vega spectrum so that the width of its Mg I line matched that of the β Ari primary line did not significantly improve the situation. We therefore abandoned the 8806 Å primary Mg I line as a possible velocity indicator.

The 8862 Å Paschen line is the only other primary line of any strength included in the 95 Å span of the Reticon spectra. The line's extreme width (~ 100 Å) means it is blended

with its secondary counterpart at all phases, but the secondary's inferred late F spectral type means that the secondary line must be weak and may be negligible. The line was used to measure primary velocities for all the observations, but, as will be discussed in Sec. IV, the orbital solution showed them to be discouragingly crude.

IV. ANALYSIS OF RADIAL VELOCITIES

The first step was to analyze the secondary velocities, allowing variation of all the orbital elements, including the period, and compare the results with those of the earlier studies (Petrie 1938; Gorza and Heard 1971) of the primary. Table III makes this comparison. While the overall consistency of the primary and secondary solutions is satisfactory, inspection shows that Petrie's results match the secondary results better than Gorza and Heard's do. In particu-

TABLE III. β Ari orbital elements.

	Primary			Secondary	
	Petrie (1938)	Gorza & Heard (1971)	Petrie - new solution	All elements	Fixed P
P (days)	106.9973 ± 0.0012	106.9973 (fixed)	106.9950 ± 0.0131	106.9940 ± 0.0009	106.9954
V_0 (km s $^{-1}$)	-3.68 ± 0.17	-4.0 ± 0.4	-3.8 ± 0.5	-2.9 ± 0.2	-2.9 ± 0.2
K (km s $^{-1}$)	37.63 ± 0.57	37.1 ± 0.9	38.1 ± 1.9	66.6 ± 0.2	66.6 ± 0.2
e	0.892 ± 0.002	0.896 ± 0.003	0.895 ± 0.007	0.8793 ± 0.0009	0.8793 ± 0.0009
ω ($^\circ$)	24.17 ± 0.72	20.0 ± 1.3	24.5 ± 2.0	204.9 ± 0.4	204.9 ± 0.4
T (-2400000)	28010.944 ± 0.030	40208.398 ± 0.033	28010.987 ± 0.104	44274.276 ± 0.009	44274.276 ± 0.009
a Sin i (10 ^{6} km)	25.027	24.3 ± 0.7	25.01 ± 1.46	46.69 ± 0.23	46.69 ± 0.23
m Sin ^{3} i (m $_\odot$)	-----	-----	$0.87^a \pm 0.03$	0.50 ± 0.03	0.50 ± 0.03

^a Calculated with the secondary-based e.

lar, the $180^\circ.7 \pm 0.7$ difference between the primary and secondary longitudes of periastron (ω) for Petrie's solution is consistent with the 180° difference expected in principle, while the $184^\circ.9 \pm 1.3$ difference for Gorza and Heard's solution is not. (Although this ignores the possibility of periastron advance, we will see that the potential periastron advance is not expected to be large enough to materially affect the Petrie versus Gorza and Heard ω question.) In view of the less satisfactory agreement between Gorza and Heard's orbital elements and the secondary orbital elements, we decided not to make use of the Gorza and Heard velocities.

To refine the period, we solved Petrie's (1938) and our primary velocities together. The 50 yr time base of these observations—Petrie's date from 1933 to 1938 and ours from 1979 to 1984—allows crisp definition of the period. A preliminary step was to make an orbital solution of Petrie's velocities—all 134 of them—with the same differential-corrections program used to analyze the secondary velocities. Table III gives the orbital elements from this reanalysis of Petrie's velocities, which used Petrie's weights for the individual velocities. Note the marginal changes of some elements of the new solution compared with Petrie's; the period decreases from $106^\circ 9973$ to $106^\circ 9950$, and the semiamplitude (K) increases from 37.6 to 38.1 km s $^{-1}$, for example. These slight differences may be attributed to the practice of Petrie's time of grouping observations of similar phase into a single representative observation, or "normal place," in order to make the solution amenable to manual calculation.

Unfortunately, our primary velocities, i.e., the Paschen-line-based Reticon velocities, proved to be of low accuracy. A solution of these velocities on their own yielded a K 6 km s $^{-1}$ smaller than Petrie's and had typical residuals of 6 km s $^{-1}$, and in a combined solution with Petrie's velocities their residuals were as large as 18 km s $^{-1}$. The low contrast of the Paschen line, the fact that the Reticon spectra covered only part of its profile, or the possibility of significant distortion by the secondary Paschen line (one of these factors, or a combination of them) probably account for the poor quality

of the Paschen-line primary velocities, which were discarded.

In the absence of reliable modern primary velocities, we obtained a refined period of $106^\circ 99532 \pm 0.00068$ from the epochs of periastron passage (T) of the secondary velocities and Petrie's primary velocities. We confirmed this period with a second $106^\circ 99539 \pm 0.00043$ estimate of the refined period derived from analysis of Petrie's velocities combined with modern pseudoprimary velocities obtained by transforming the secondary velocities. The transformation consisted of multiplying the distances of the secondary velocities from the systemic-velocity axis by the ratio K_1/K_2 and then reflecting them about this axis. The good consistency of the primary and secondary solutions suggested that, for the limited purpose of refining the period, this was an acceptable expedient.

A refined period of $106^\circ 9954 \pm 0.0005$ was adopted as representative of these two estimates. It is not so close to a whole number of days as Petrie's $106^\circ 9973$ period, so the synchronization of β Ari's periastron passage with a particular time of day is loosened.

The results of a second solution of the secondary velocities with the period fixed at $106^\circ 9954$ are given in Table III. They are identical to the results of the secondary solution, in which all elements were allowed to vary.

Figure 2 shows the secondary velocities and the calculated secondary velocity curve. This calculated velocity curve and the phases and O — C for the secondary velocities in Table II are based on the orbital elements of the $106^\circ 9954$ fixed-period solution.

V. ESTIMATED ORBITAL PROPERTIES

The mass ratio, $\mathcal{M}_2/\mathcal{M}_1 = K_1/K_2 = 0.57$, is the principal feature of β Ari's orbit that follows from the secondary velocity curve and the already known primary velocity curve. This, plus an estimate of the primary's mass based on its A5 V spectral type, allows a reliable estimate of the secon-

dary's mass. The determination of both primary and secondary velocity curves also measures the linear size of the orbit, apart from a factor $\sin i$, which we can pin down by comparison of the observed minimum masses and estimated actual masses of the components. We will use this new information to discuss β Ari's periastron advance and estimate the sizes of the true and apparent orbits.

Comparison of the primary's properties—A5 V spectral type and $M_v = 1.99$ —with the properties of detached main-sequence binaries with reliable masses (Popper 1980, Table II) indicates a primary mass of $\sim 1.9 M_\odot$. This and the mass ratio lead to an estimated secondary mass of $1.1 M_\odot$. Thus the secondary must be a late F or G0 main-sequence star, an inference that accords with its sharp lines and the presence of the secondary Mg I and Fe I lines on the 8800 Å Reticon observations.

The primary's observed minimum mass, $M \sin^3 i = 0.87 \pm 0.03 M_\odot$ (Table III), and the estimated actual mass demand $i = 50^\circ \pm 2^\circ$. The 2° error is based on a $\pm 0.2 M_\odot$ uncertainty in the $1.9 M_\odot$ estimated primary mass; its surprising smallness is a happy effect of the cube root. The estimated inclination combined with the $a \sin i$ * fixes the linear size of the secondary orbit with respect to the primary at $a = (96 \pm 4) \times 10^6 \text{ km} = 138 \pm 5 R_\odot$. The corresponding apastron and periastron separations of 259 and $17 R_\odot$ show that, in spite of its large eccentricity, β Ari is comfortably detached even at periastron—hardly a surprising conclusion, seeing as how the orbit would not have the high eccentricity it does if it was not detached at all phases.

The inferred masses of β Ari's components and size of its orbit combined with the formula for the rate of apsidal advance (Batten 1973) lead to an estimate of $\sim 100\,000$ yr for the period of periastron advance. This includes both relativistic and nonrelativistic effects; the rotational distortion of the primary ($v \sin i = 79 \text{ km s}^{-1}$) contributes the major term. The difference between the observed secondary and primary ω , which would, in principle, be 180° in the absence of any periastron advance, is $180.4 \pm 2^\circ$ (see Table III), so the 50 yr spanned by our secondary observations and Petrie's (1938) primary observations show no sign of periastron advance. The nondetection is consistent with the calculated $\sim 100\,000$ yr periastron-advance period, which corresponds to a 0.2 change of ω in 50 yr—a number that is well below the 2° threshold of observational uncertainty. Petrie's (1938) remark that “notwithstanding the very eccentric nature of the orbit, the elements are fixed, or vary so slowly that many more decades must elapse before such variation can be detected” is still valid.

The estimated linear size of the orbit, $a = 96 \times 10^6 \text{ km}$, transforms to an angular size $a = 0.047$ of the true orbit with the aid of β Ari's 0.074 parallax. Maximum separation in the true orbit, which is at phase 0.5, is $a(1+e) = 0.088$. The equation $\rho^2 = r^2\{1 - \sin^2(\nu + \omega) \sin^2 i\}$ (Heintz 1978),

where ρ and r are the separations in the apparent and true orbits, respectively, and ν is the true anomaly, leads to a corresponding separation of 0.083 at the same phase in the apparent orbit. Maximum separation in the apparent orbit, which is at a phase of ~ 0.46 , is 0.084 . The very leisurely orbital motion near apastron means that in both the true and apparent orbits β Ari must be at, or near, maximum separation for a considerable phase of its orbit.

This estimated maximum separation in the apparent orbit is nearly three times greater than the 0.030 optimum resolution limit of the unresolved β Ari speckle-interferometric observations (McAlister 1978; Hartkopf and McAlister 1984) so the nonresolution of β Ari must be a question not only of separation but also of magnitude difference between the components.

This magnitude difference may be estimated from the strength of the secondary lines. Their measured strength on the 8800 Å Reticon spectra, combined with the assumption that their intrinsic strength must be approximately the same as in a single star of the same spectral type (G0 V), provides an estimated magnitude difference of 2.5 at 8800 Å. With the aid of the $(V-I)$ for A5 V and G0 V stars from Johnson (1966), this corresponds to $\Delta V = 3.09$. A second approach to ΔV via the mass ratio, a $L \propto M^{4.0}$ mass-luminosity relation (Smith 1983), and bolometric corrections for A5 V and G0 V stars from Johnson (1966) leads to the somewhat smaller result, $\Delta V = 2.56$. We adopt $\Delta V = 2.8$ as a representative value of these two estimates of the V magnitude difference between the primary and secondary. This difference exceeds the limit of between 2.0 and 2.5 mag beyond which the secondary can go undetected, regardless of the angular separation (McAlister, private communication).

Evidently, it is the magnitude difference between the components, more than their small separation, that puts β Ari beyond the grasp of the speckle observers. However, such is β Ari's brightness that even though the secondary is fainter than the primary, its apparent magnitude is still $V \approx 5.5$, which gives reason to hope that it will not be able to elude direct detection for much longer.

VI. CONCLUSIONS

We have measured the secondary velocity curve of β Ari for the first time. This has provided a precise value of the secondary K , more precise values for all the other spectroscopic orbital elements, and has shown that the apparent orbit must be on the verge of resolution by speckle interferometry. Measurement of the apparent orbit will reveal the inclination, which is the only unknown standing in the way of direct determination of the masses and orbital dimensions of this interesting, very eccentric binary. Measurement of a new primary velocity curve, especially to improve the determination of K_1 , would also be worthwhile.

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* $a \sin i = (a_1 + a_2) \sin i = (1 + K_1/K_2) a_2 \sin i$ with K_1/K_2 and $a_2 \sin i$ from Table III in order to maximize use of the more accurate secondary-based orbital elements.

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