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THE PHYSICAL NATURE AND ORBITAL BEHAVIOR OF V523 CASSIOPEIAE[1]

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ABSTRACT

V523 Cassiopeiae is a dwarf contact binary with one of the shortest orbital periods among the nondegenerate systems. Its orbital history is marked by large period changes. The photometrically determined mass ratios have historically been inconsistent with those calculated from radial velocity curves. In 1998 we acquired high-precision and standardized Johnson-Cousins *UBV* light curves. Our simultaneous *BV* light curve/radial velocity curve solutions provided good fits to both the light curves and the radial velocity curves using standard gravity darkening coefficients with a mass ratio of ~0.5. Seven precision mean epochs of minimum light were determined from these observations. We combine these with all available published times of minimum light, along with 50 times of low light found from a search of the archival Harvard plate stacks in the interval 1901–1942 to give us 567 eclipse timings. Our period study covers nearly 160,000 orbits, or ~102 yr. We find a high-amplitude sinusoidal variation with a period of 101 ± 7 yr, overlaid on a strong continuous period increase. The quadratic term is common in contact binaries, but a sinusoidal one is not. This suggests a hierarchical three-star system. Assuming that this is the case and that the inclination from our orbital solution for the close pair is the same as the larger orbit, we obtain a mass for the third star of 0.41 $M_\odot$. This is similar to the masses of the stars that comprise the contact binary. If this scenario is correct, V523 Cas consists of a trio of late K and early M-type dwarfs having a total mass of ~1.6 $M_\odot$. We show that high-resolution imaging can confirm this suggestion.

Key words: binaries: close — binaries: eclipsing — stars: individual (V523 Cassiopeiae) — stars: variables: other

1. INTRODUCTION

V523 Cassiopeiae (WR16, CSV 5867, GSC 3257−167) has figured prominently in studies of very short period K-type nondegenerate eclipsing binaries over the past 30 years. At 336.5 minutes, its period is one of the shortest among late type, contact binaries. V523 Cas is also noted for variations in its light curve and for large period changes. It is a W-type W UMa binary (surface mean temperature of the smaller star is hotter; see Hendry & Mochacki 2000). The eclipses are relatively deep and are probably total.

Samec & Bookmyer (1987) and Samec et al. (1989) reviewed the early history of this system. Photometric solutions of V523 Cas in the contact mode have produced mass ratios of about $q_{\rm ph} = 0.6$ (Samec et al. 1989; $q = m_2/m_1$). This disagreed with the mass ratio, $q_{\rm sp} = 0.42$, derived directly from radial velocity curves (Milone et al. 1985). The author (R. G. S.) found that, even with the use of a simultaneous Roche lobe treatment, it is impossible to get a good fit to the light curve and the radial velocity curves. Maceroni (1986) performed a q-search and found that while q is not well determined, a value of $q = 0.5$ gave a fair fit to both the radial velocity and light curves. Niarchos & Duerbeck (1991) proposed that a circulation effect of sideward convection may affect the radial velocity curves in a systematic way, causing the discrepancy in $q_{\rm ph}$ and $q_{\rm sp}$. Pantazis & Niarchos (1998) empirically determined the gravity darkening coefficient for V523 Cas to be 0.53 ± 0.02, which is very different from the theoretical value of 0.32 (Lucy 1967) for convective atmospheres. Further modeling and the publication of new, high-precision radial velocity curves by Rucinski et al. (2003) have shown that this departure was not needed, as we show with the simultaneous solution presented in this paper.

For all these reasons, we felt the time was ripe for the determination of high-precision light curves for a light-curve and periodicity analysis of V523 Cas. We also determined to obtain a good U light curve in order to estimate the reddening and interstellar extinction. The short period of V523 Cas enables one to obtain a good light curve in only a few nights, a critical concern in such a variable system. Subsequent to our observations, Zhang & Zhang (2004) have published several light curves obtained over 1986–2000 documenting variable and possibly cyclic spot activity. Their period study, covering some 43,000 orbits, shows a strong quadratic period increase over the time interval, and they calculate a mass flow rate of $dm/dt = 9.2 \times 10^{-8}\ m_\odot\ {\rm yr}^{-1}$ toward the primary component. The mass ratio from their photometric solutions was ~0.5, very similar to that of Rucinski et al. (2003) and Lister et al. (2000). Lister et al. (2000; V and I light curves) and Zhang & Zhang (2004; B and V) calculated solutions by removing large

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TABLE 1

Coordinates and Identifications of the Variable, Comparison, and Check Stars

Star	α (2000)	δ (2000)	Identification
V523 Cas	00 40 06.246	50 14 15.503	GSC 3257 167
Comparison	00 40 58.418	50 13 06.2	GSC 3257 803
Check	00 40 15.0121	50 07 14.576	GSC 3257 1262

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

sections of the light curves to avoid the effect of asymmetries. They published 7 and 47 new times of minimum light in their papers, respectively.

2. OBSERVATIONS

D. R. F. observed V523 Cas on the nights of 1998 September 15–17 with the 0.79 m Lowell telescope on Anderson Mesa at Lowell Observatory in Flagstaff, Arizona. The Lowell "Blue Photometer" with standard Johnson *U*, *B*, and *V* filters was used. This photometer has a blue-enhanced S-13 cathode photomultiplier tube. On each night we observed standard stars to transform to standard magnitudes and colors. We obtained 571 observations of the variable in *U*, 570 in *B*, and 567 in *V*.

We have identified V523 Cas as GSC 3257 167. Table 1 lists GSC numbers and coordinates for V523 Cas and the comparison and check stars used. Figure 1 is a finder chart for the stars of Table 1. Standard magnitudes and colors for the comparison and check stars are found in Table 2. Standard magnitudes and colors for V523 Cas at four different phases are also included. Standard errors are given. The Tycho *V* magnitude and $B - V$ color index of V523 Cas are 10.77 and 1.054, well within the range of maximum and minimum that we established. From a $(B - V)$ versus $(U - B)$ plot we were able to deredden the comparison and check stars and estimate a spectral type for both. We did this for the primary component (the more massive, cooler star, or star 1) of the binary as well. These dereddened colors and spectral types are given in Table 3, together with the probable errors. The inferred temperature of

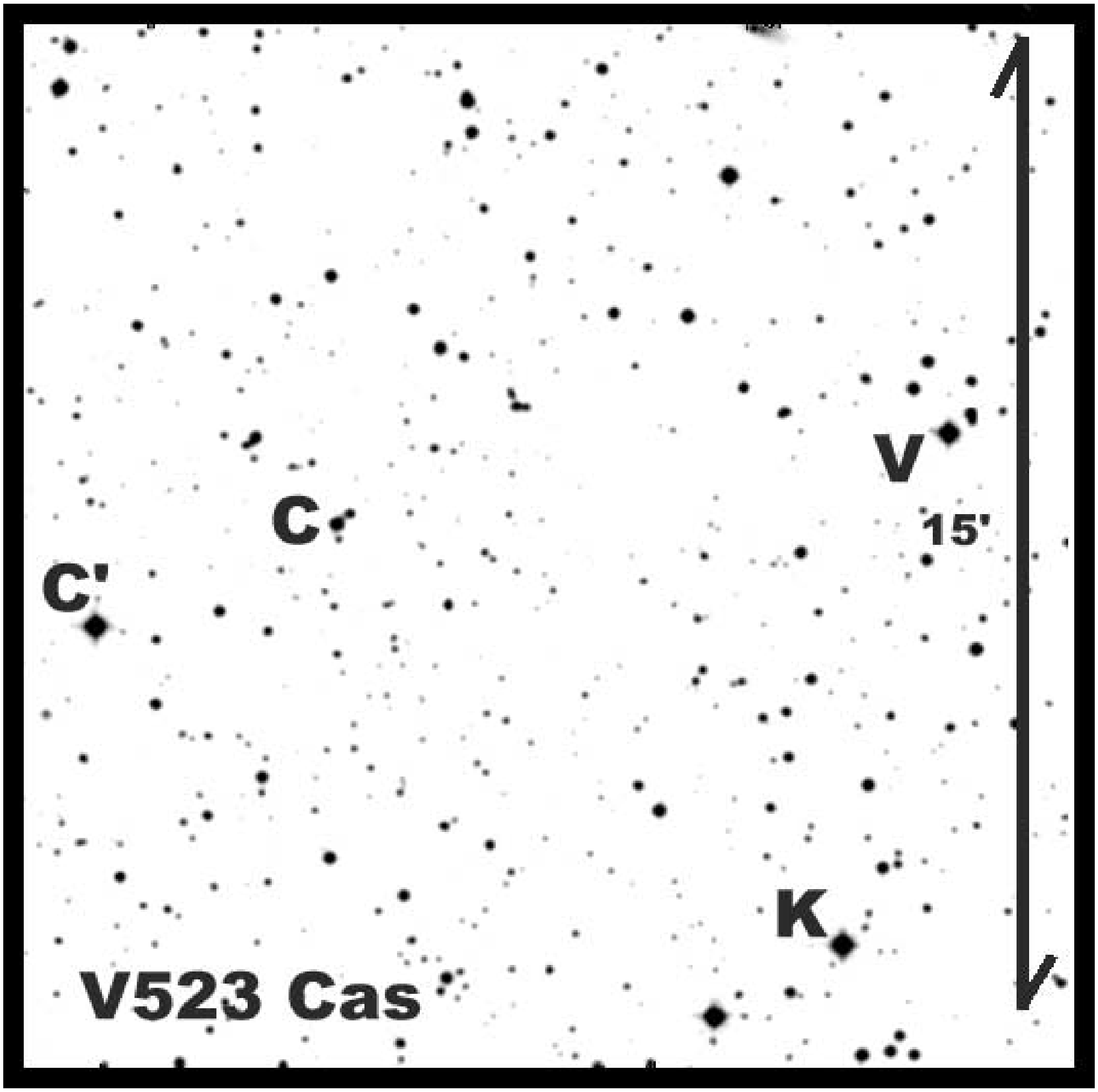

Fig. 1.—Finding chart for V523 Cas (V), comparison star (C), and check star (K). C′ marks a star previously used as a comparison (Samec & Bookmyer 1987).

TABLE 2

Standard Magnitudes and Colors of V523 Cas, Comparison, and Check Stars

Star	V	$B-V$	$U-B$	Phase
Comparison	12.402 ± 0.011	0.657 ± 0.011	0.131 ± 0.010	...
Check	9.732 ± 0.009	0.184 ± 0.009	0.177 ± 0.009	...
Variable	11.364 ± 0.033	1.086 ± 0.012	0.843 ± 0.011	0.00
	10.648 ± 0.019	1.029 ± 0.007	0.778 ± 0.009	0.25
	11.317 ± 0.019	1.074 ± 0.017	0.864 ± 0.012	0.50
	10.639 ± 0.009	1.027 ± 0.007	0.791 ± 0.008	0.75

TABLE 3

Dereddened Colors and Inferred Spectral Types

Object	$(B-V)_0$	$(U-B)_0$	Spectral Type
V523 Cas (Star 1)	0.97 ± 0.04	0.76 ± 0.03	K2–K3 V, $T_1 = 4762 \pm 102$ K
Comparison	0.46 ± 0.03	0.05 ± 0.03	F5–F5.5 V
Check	0.08 ± 0.03	0.09 ± 0.03	A2 V

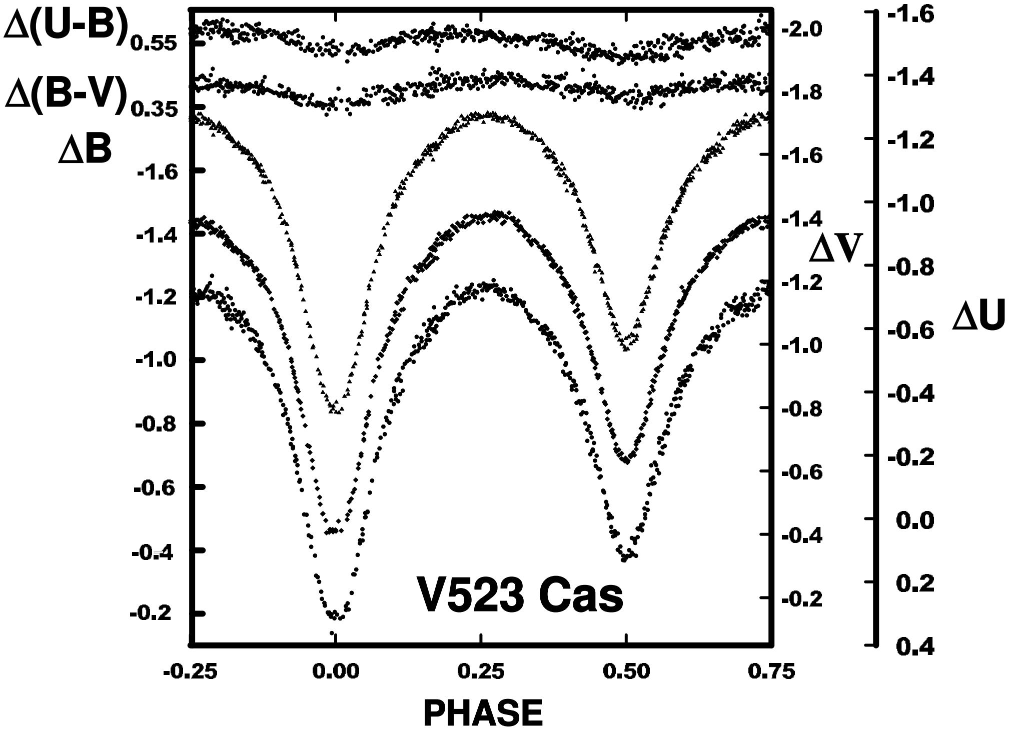

Fig. 2.—Standard UBV magnitude light curves and $U-B$ and $B-V$ color curves for V523 Cas.

TABLE 4

Some Epochs of Minimum Light for V523 Cas

HJD (2,400,000+)	Cycle	$(O-C)_1$	$(O-C)_2$
46708.77141[a]	0.0	−0.0059	−0.0001
51071.68813 ± 0.0032	18669.5	0.0366	−0.0019
51071.80465 ± 0.0023	18670	0.0363	−0.0023
51071.92218 ± 0.0023	18670.5	0.0369	−0.0017
51072.73946 ± 0.0014	18674	0.0363	−0.0023
51072.85657 ± 0.0025	18674.5	0.0366	−0.0016
51073.79282 ± 0.0037	18678.5	0.0381	−0.0005
51073.90809 ± 0.0010	18679	0.0365	−0.0021
51142.2632[b]	18971.5	0.0373	−0.0021
51162.2431[b]	19057	0.0367	−0.0029

Notes.—Others are current observations.

[a] Samec & Bookmyer (1987).

[b] E. Bisttler; BBSAG 119.

the primary component (hereafter called just "the primary") of the binary was 4762 ± 102 K.

The probable errors of single observations were 0.0124 mag in *U*, 0.0073 mag in *B*, and 0.0075 mag in *V*, so 1% or photometry was achieved. Figure 2 shows a phased plot of all of the standardized *UBV* observations. The flux varies continuously, indicating gravitational and rotational distortions, as expected in a contact binary. The primary eclipse is obviously more flat than the secondary. Later, we found that our light curve solution gives a duration of constant light during primary eclipse of about 28 minutes.

3. PERIOD STUDY

During the three nights of observation, three primary and four secondary eclipses were obtained. Seven mean epochs of minimum light were determined from these data using the bisection of chords technique. These times of minimum light are given in Table 4, along with standard errors. Also listed is the starting epoch of our light elements presented below and the two most recent published CCD timings from BBSAG (the Swiss Astronomical Society).

One of the authors (D. B. W.) obtained 50 timings of low light by examining archived photographic plates from the Harvard-Smithsonian Astrophysical Observatory (SAO). While it is not possible to measure times of minimum light from the plates, these times of *low light* (Samec et al. 2001) correspond well with eclipses. The timings cover the interval from 1901 to 1942 and greatly extend the baseline over which the period behavior of V523 Cas can be studied

In addition, 510 other epochs of minimum light were used in our periodicity analysis: F. Agerer, BAVM 60; Agerer et al. (2001); Gurol et al. (2003); E. Blättler, BBSAG 90, 93, 119; D. Böhme, MVS 8.24; Bradstreet (1981); T. Brelstaff, VSSC 59, 60, 61, 63, 66, 73; Haussler (1974); Hoffman (1981); G. Kirby, VSSC 72.25; M. Kohl, BBSAG 69, 70, 73, 74, 75, 77, 79, 81, 87, 89, 90, 91, 92, 96, 99, 108, 111, 114, 116; K. Locher, BBSAG 16–21, 24–27 (inclusive), 29, 30, 32, 33, 35, 36, 38, 101, 102, 103, 104, 105, 106, 107, 109, 112, 113, 115, 117, 118, 121–128 (inclusive); Lavrov & Zhukov (1976); Nelson (2001); H. Peter, BBSAG 78, 83, 86–89, 90–92, 93, 96, 98, 99, 100, 101, 102, 103, 105, 106, 107, 108, 110, 111, 112, 113, 114, 115, 116, 117; J. Hübscher et al., BAVM 1992;

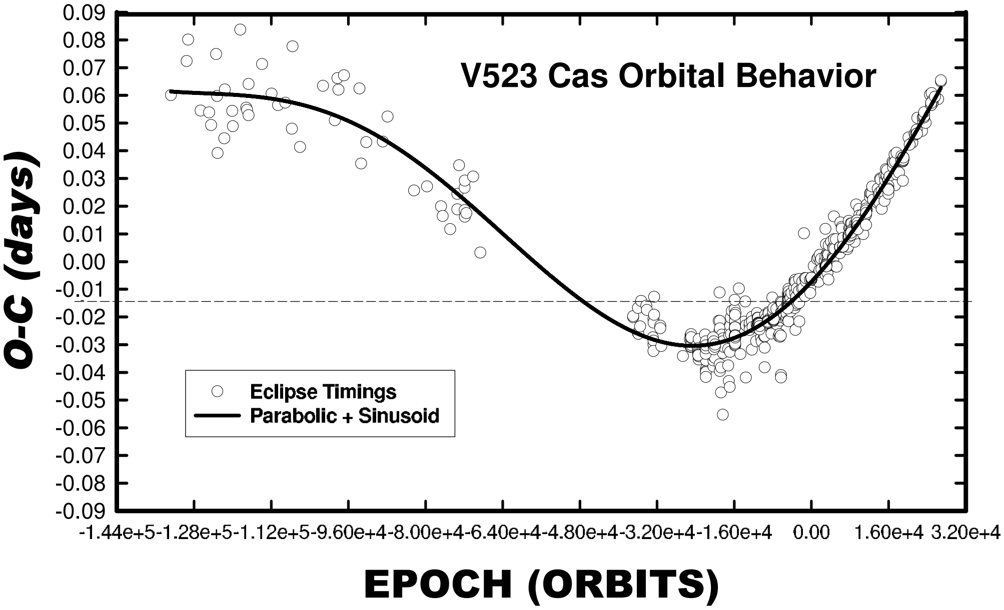

Fig. 3.—Period behavior for V523 Cas: sinusoidal and quadratic fit to linear residuals.

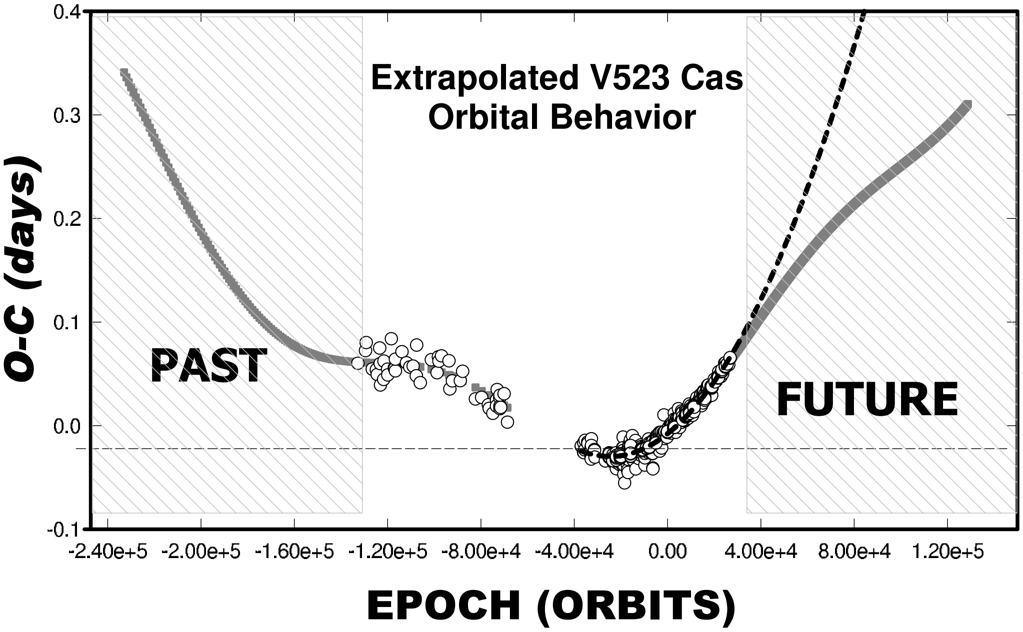

Fig. 4.—Ephemeris (eq. [2]) extrapolated into the future and past. A parabolic ephemeris is represented for the later eclipse timings. Our ephemeris shows recognizable departures from the parabola at about 40,000 epochs.

Pribulla et al. (2001, 2002); Samec & Bookmyer (1987); P. Wils, BBSAG 69, 73; G. V. Zhukov, TKZ 45.49; Lister et al. (2000); Zhang & Zhang (2004); and Diethelm (2003, 2004).

The latter span the interval from 1963 to 2004, yielding a 102 yr period history (with a 21 yr gap) spanning nearly 160,000 orbits. This is perhaps the longest period study ever undertaken for a W UMa binary. Results have been reported earlier (Samec et al. 2001). This updated report includes more than 150 additional times of minimum light. A least-squares linear fit to all available timings resulted in the following linear light elements:

$$\begin{aligned}\text{HJD Min. I} = {} & 2{,}446{,}708.7773 \pm 0.0024 \\ & + 0.233689935 \pm 0.000000078E. \qquad (1)\end{aligned}$$

The $O - C$ residuals for equation (1) are plotted in Figure 3. The $(O - C)_1$ residuals in Table 4 were calculated with these light elements.

Mathematically, the data strongly suggest a sinusoidal variation overlaying a continuous period increase. We fit the data to just such an equation. This equation gives a final ephemeris of

$$\begin{aligned}\text{HJD Min I} = {} & 2446708.8030 \pm 0.0024 \\ & + 0.233691049 \pm 0.000000078E + (1.02 \pm 0.10) \\ & \times 10^{-11}E^2 + (0.0364 \pm 0.0050)\sin[(3.87 \pm 0.25) \\ & \times 10^{-5}E - (1.042 \pm 0.094)]. \qquad (2)\end{aligned}$$

The fit is plotted with the data in Figure 3, and the $(O - C)_2$ residuals for equation (2) are given in Table 4. The correlation coefficient for this excellent fit is $R = 0.98$. The quadratic term, $1.02 \times 10^{-11} d/E^2$, may be due to mass accretion onto the primary component. Assuming conservative mass transfer, the components are currently separating. Such a continuous period increase or decrease is not unusual for short-period contact binaries. This could mean that V523 Cas is still undergoing thermal relaxation oscillations and has reached its highest fill-out (Qian 2003) and is on its way to back to a shallow contact mode and possibly a semidetached configuration. However, the sinusoidal behavior with an amplitude of 0.038 ± 0.005 days (light time 6.60 AU) is seen only in systems that have a third body present in the system. Assuming that this is the case, and that the inclination from our orbital solution for the close pair is the same as the larger orbit, from Kepler's third law and equation (2) we obtain a mass for the third star of 0.41 $m_\odot$. This is similar to the masses of the stars that comprise the

TABLE 5

Synthetic Curve Parameters for V523 Cas

Parameter	Simultaneous Solution
λ_B (nm)	440
λ_V (nm)	550
$\lambda_{\rm radial}$ (nm)	420
$V\gamma$ (km s^{-1})	−3.6 ± 0.6
Semimajor axis ($R_\odot$)	1.687 ± 0.012
$x_{1V,2V}$, $y_{1V,2V}$	0.799, 0.047
$x_{1V,2V}$, $y_{1V,2V}$	0.799, 0.047
g_1, g_2	0.32, 0.32
A_1, A_2	0.50
$x_{\rm bol,1}$, $x_{\rm bol,2}$	0.636
$y_{\rm bol,1}$, $y_{\rm bol,2}$	0.149
i	85°39 ± 0°11
T_1, T_2 (K)	4762 ± 102[a], 5104 ± 2[b]
Ω_1, Ω_2	2.8224 ± 0.0035
q (m_2/m_1)	0.520 ± 0.002
ϕ	0.5000 ± 0.0017
$L_1/(L_1 + L_2)_B$	0.550 ± 0.024
$L_1/(L_1 + L_2)_V$	0.527 ± 0.025
l_{3B}, l_{3V}	. . .
r_1, r_2 (pole)	0.4263 ± 0.0004, 0.3186 ± 0.0012
r_1, r_2 (side)	0.4560 ± 0.0005, 0.3352 ± 0.0014
r_1, r_2 (back)	0.4909 ± 0.0006, 0.3793 ± 0.0027
Fill-out	29% ± 2%
$\Sigma_{\rm res}{}^2$	0.054797

[a] Photometric uncertainty.

[b] Difference uncertainty in $(T_2 - T_1)$.

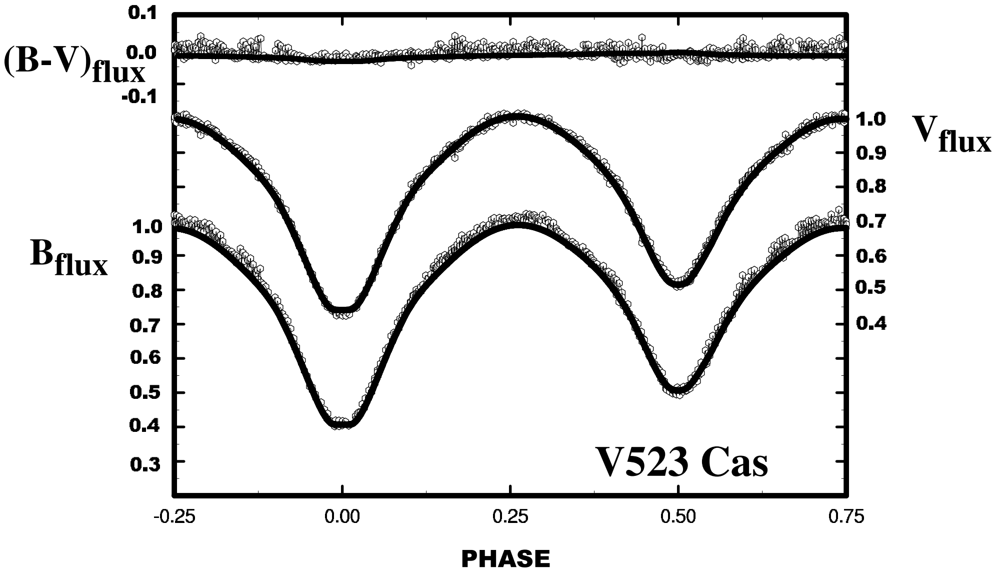

FIG. 5.—Synthetic light curve from computed model overlaid on normalized flux values for V523 Cas.

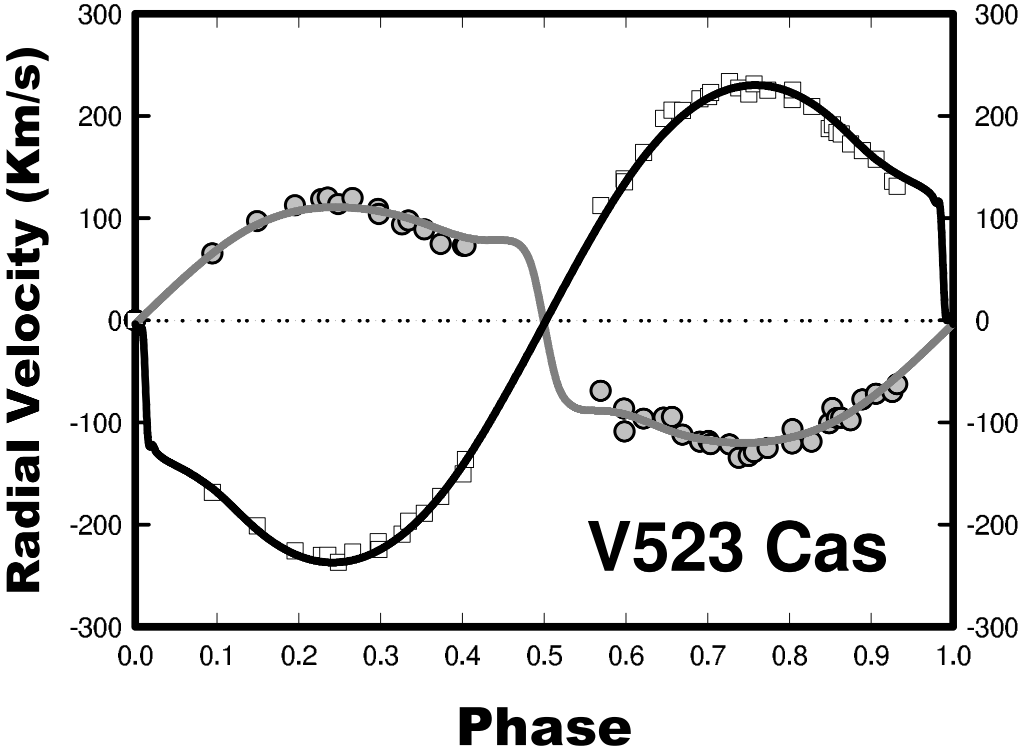

FIG. 6.—Synthetic radial velocity curve from the simultaneous solution overlaid on the observations of Rucinski et al. (2000).

TABLE 6

Starspot Parameters

Location	Primary
Colatitude	116° ± 2°
Longitude	7° ± 0°.7
Spot Radius	18° ± 1°
Temperature factor	1.165 ± 0.015
Spot area	2.5%

TABLE 7

Astrophysical Parameters

Parameter	Value
Mass:	
$m_{\odot 1}$	0.78 ± 0.02
$m_{\odot 2}$	0.40 ± 0.02
$m_{\odot 3}$[a]	0.41 ± 0.02
$R_{\odot 1}$	0.78 ± 0.02
$R_{\odot 2}$	0.58 ± 0.03
Magnitude:	
$M_{\mathrm{bol},1}$	6.18 ± 0.06
$M_{\mathrm{bol},2}$	6.49 ± 0.07
log g_1 (in cgs units)	4.55 ± 0.02
log g_2 (in cgs units)	4.51 ± 0.03
Distance (pc)	69 ± 2

[a] Determined from the $O - C$ diagram.

contact binary (0.78 and 0.40 $m_\odot$). The orbital period of the larger system is 101 ± 5 yr.

One might expect that the light of a third such star could be detectable in the light curves. However, these considerations reveal that the amount of light from the third star is only about 0.03. Such a small third light contribution can be easily masked in a light curve solution. While some of our model calculations produced this much light for a third star, most of the runs had nearly zero third light.

Future eclipse timings will also show if the sinusoidal behavior is continuing. Figure 4 represents our ephemeris (eq. [2]) extrapolated into the future and past. A parabolic ephemeris is represented to fit the recent eclipse timings, as suggested by many authors (e.g., Zhang & Zhang 2004). Our ephemeris show recognizable departures from the parabola at about 40,000 epochs. This will occur in the year 2013. Observers are requested to continue to patrol this interesting system.

4. LIGHT CURVE SOLUTIONS

Synthetic light curve solutions were calculated using the Wilson code (Wilson 1994, 1990; Wilson & Devinney 1971). To obtain absolute parameters, the B and V light curves were solved simultaneously with the radial velocity curves of Rucinski et al. (2003). The temperature of the primary, T_1, was held fixed at 4762 K, as set by the photometrically inferred spectral type. Linear and bolometric limb darkening coefficients ($x_1, x_2, x_{\mathrm{bol}}$, and y_{bol}) were determined from tables by Van Hamme (1993). We used standard values of bolometric albedos for convective atmospheres (Rucinski 1969, 1973).

Historically, the gravity darkening convective value of 0.32 (Lucy 1967) has led to poor fits to the light curves of V523 Cas. More recently, Pantazis & Niarchos (1998) have pursued an empirical method of determining gravity darkening exponents in contact binaries. They found that a value of 0.53 works well for this system. Indeed, our initial results using $g = 0.32$ were discouraging, but with 0.53, a good fit was realized. It appeared that we had confirmed the work of Pantazis & Niarchos. We also tried the higher but standard radiative value of $g = 1.00$, but this led to a detached model with nonphysical results. That appeared to be the end of the story. However, at the urging of the anonymous referee, we again attempted to use the standard convective g value. This time we performed a series of careful iterations slowly adjusting the g value from 0.53 to 0.32. To our surprise, an excellent model was obtained, with smaller residuals than the 0.53 case. The adjusted parameters included the orbital phase shift (*pshift*, ϕ, to adjust for phasing errors), inclination, mean surface temperature of the secondary component, surface potential, mass ratio, semimajor axis, third light, and the systemic velocity, $V\gamma$. Table 5 lists the results of our calculations. Figure 5 shows our synthetic light curves. Figure 6 is a plot of our synthetic radial velocity curve. Both plots have the observations overlaid. Note that the model fits the observations very well. The simultaneous light curve-radial velocity curve model gave a mass ratio of 0.517 ± 0.002.

In our final solution, the amount of light from the third source was essentially zero. Our final solution contains a hot spot, the parameters of which are listed in Table 6. Final astrophysical parameters for the system are listed in Table 7. We also note that the fill-out of 29% is high and is not consistent with that of usual short period shallow contact binaries. The representation of V523 is given in Figure 7.

Using the bolometric magnitude for the primary component from Table 7 and interpolating from a table from zero-age main sequence models of solar abundance by D.A. Vandenberg (Rucinski 1992), we obtain a bolometric correction of −0.61. From our solution we calculate $M_{\mathrm{bol}} = 6.18$ mag. Thus, we obtain an absolute V magnitude of 6.79. Using the apparent V magnitude at primary eclipse and

$$\frac{A_v}{E(B-V)} = 3.30 + 0.28(B-V)_0 + 0.04E(B-V)$$

gives a corrected magnitude [$E(B-V) = 0.105 \pm 0.020$] of $V_0 = 10.99$ and a distance modulus of 4.20, or a distance of 69 pc. This is very different from the Tycho (ESA 1997) distance of 9.1 ± 3.3 pc. The Tycho distance is almost certainly incorrect. An 11 mag star at the Tycho distance would have to be of type M, nearly an entire spectral type cooler than what it is known from both spectroscopy (Milone et al. 1985) and our photometry.

If there is a third member of this system, as we suggest here, then from Figure 3 it would appear that the companion should be near the greatest separation now. The size of the orbit and the distance of the system result in a maximum angular separation of about 0″.1. Again, using the same table (Rucinski 1992), we calculate that the expected V magnitude of the companion should be about 15. With adaptive optics on a large telescope with good seeing, it should be possible to resolve the companion, if it exists.

Thus, it appears that V523 Cas is a member of a hierarchical system of a K and two M type stars. The primary is an underluminous K0 dwarf in contact with an over luminous M2 dwarf orbited about by an M2 V companion at 6.6 AU.

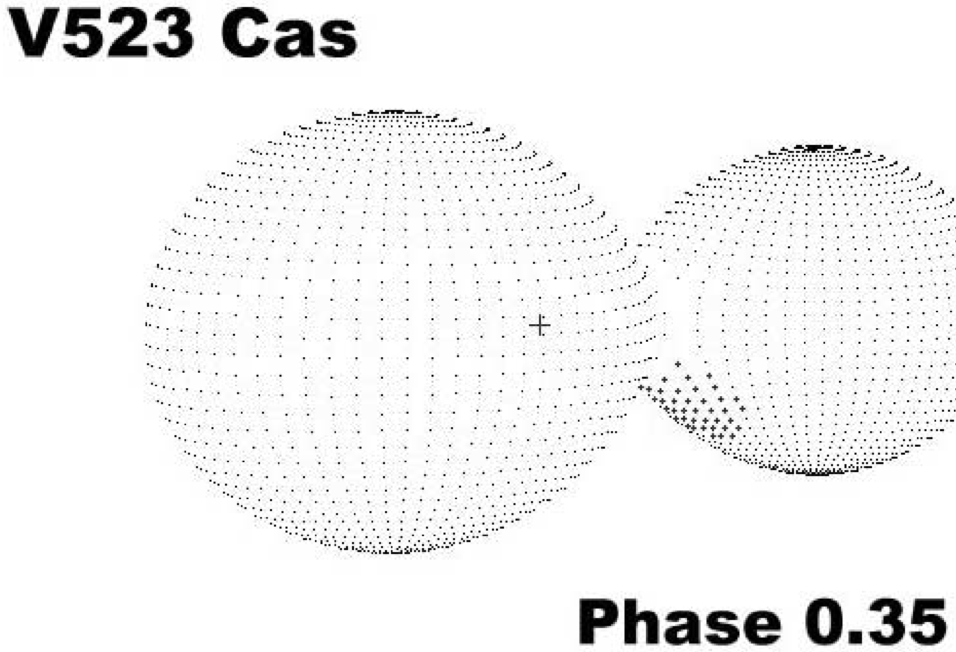

FIG. 7.—Geometrical representation of V523 Cas calculated from our simultaneous solution.

We wish to thank the many observers who spent thousands of hours observing V523 Cas to obtain the large number of timings that made this definitive period study possible. We also wish to thank the American Astronomical Society for their past and continuing support of the research of R. G. S. through their Small Research Grant Program. I would like to thank Walter Van Hamme for his assistance and Slavek Rucinski for sending his radial velocity data on V523 Cas. We wish to thank David Bradstreet for achieving our observations at the Catalog and Atlas of Eclipsing Binaries, http://ebola.eastern.edu.

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