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PHOTOSPHERIC SPOTS AND A CHROMOSPHERIC PLAGE ON V523 CASSIOPEIAE

NICHOLAS M. ELIAS II
Astrometry Department, US Naval Observatory, Navy Prototype Optical Interferometer, P.O. Box 1149, Flagstaff, AZ 86002-1149; nme@nofs.navy.mil

AND

ROBERT H. KOCH
Flower and Cook Observatory, University of Pennsylvania, DRL E1, 209 South 33d Street, Philadelphia, PA 19104-6394; rhkoch@sas.upenn.edu

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ABSTRACT

The cool, overcontact, close binary, V523 Cassiopeiae was observed with the 1 m reflector at the US Naval Observatory, Flagstaff Station. The photometry was very good, with a precision on the order of a few millimagnitudes, but not numerous enough for complete light-curve analyses (e.g., differential corrections). A conventional published synthesis has been found acceptable as a fiducial model, and most of the observational weight has been used to develop a spot model for the stars and to support the validity of theoretical limb-darkening coefficients. Both photospheres and chromospheres contribute to the model. This result indicates that multifilter measures of this and similarly cool binaries are necessary for fuller descriptions of stellar activity cycles. A number of newly determined times of minimum light solidify the published rate of period variability.

Key words: binaries: close — binaries: eclipsing — stars: individual (V523 Cassiopeiae) — stars: late-type — stars: spots

1. INTRODUCTION

V523 Cassiopeiae is a cool, overcontact, close binary of the W type (Binnendijk 1977), i.e., the cool member is brighter and more massive than the hot member. Its original interest lay in its extremely short period, but subsequently it was invoked as an example of the angular momentum loss (AML) hypothesis of Guinan & Bradstreet (1988, hereafter GB). Both of these topics, as well as an extensive history and comprehensive light curve syntheses invoking photospheric spots, have been treated by Samec, Van Hamme, & Bookmyer (1989, hereafter SVB).

2. OBSERVATIONS

Observations for this paper were performed with the 1 m Ritchey-Chrétien aplanatic telescope at the US Naval Observatory station in Flagstaff, Arizona, on 1997 November 18, 20, 21, and 22 (UTC). The attached instrument was an updated version of the Tektronix 1K × 1K CCD camera described in Gunn et al. (1987). The camera's field of view was $\approx 11' \times 11'$. The exposure times depended on the atmospheric transparency and filter. The longest integration times, between 60 and 180 s, were required for the U filter, while the I_C filter required integration times between 5 and 15 s.

Filters were chosen such that the telescope-filter-instrument ensemble reasonably reproduced magnitudes in the standard Johnson BV and Cousins $R_C I_C$ systems. At the time of these observations, the U filter was shifted slightly toward redder wavelengths compared with the standard Johnson U filter. The color corrections of the system-to-standard transformations are listed in the second column of Table 1, but they were not applied to the data since they were not required for our modeling. No differential zenith angle corrections were calculated because of the small field size. System magnitudes were calculated automatically using the real-time photometry program at the telescope. Eighteen comparison stars were identified and used in the final photometric reductions for the CCD-frame system magnitudes. The mean pseudo–spectral type for the comparison stars in the CCD frames was approximately G5, reasonably close to the K4 spectral type of V523 Cas. A finding chart for the program and comparison stars is displayed in Figure 1.

Average system differential magnitudes ("delmags") for comparison stars 2 through 18 versus comparison star 1 were calculated nightly for each filter. Differences between the nightly averages were of order 0.01–0.03 mag. Because these numbers are small and nothing in the literature indicates that these stars are variable, the differences are attributed to instrumental systematics such as flat-fielding errors and telescope tracking errors. Individual measures were corrected on a nightly basis using the differences between the averages of nights 2, 3, and 4 versus night 1. After these corrections were applied, weighted least-squares solutions (reduced χ^2) were calculated for each filter to determine the global system delmags of the comparison stars and the CCD-frame system magnitudes using the equation

$$\Delta m_{ij}^{\mathrm{obs}} = \Delta m_i + m_j^{\mathrm{frame}} , \tag{1}$$

where $\Delta m_{ij}^{\mathrm{obs}}$ is the observed system delmag (nightly corrections already applied) of comparison star i (2–18) versus comparison star 1 on CCD frame j; Δm_i is the global system delmag of comparison star i (2–18) versus comparison star 1; and m_j^{frame} is the system magnitude of CCD frame j. The Δm_i are listed in Table 2. The errors of the nightly averages were used for the initial estimates of the individual measurement errors. With these estimates, the reduced χ^2 for each fit was between 1.1 and 2. As an attempt to include unmodeled systematics into the fit errors, the initial measurement error estimates were increased (by scaling) such that the reduced χ^2 became identically 1.

The program-star minus CCD-frame system delmags versus orbital phase for each filter are shown nested together in Figure 2. These data are listed in Table 3 and are available from N. M. E. by request. The error bars are smaller than the symbols, typically between 0.0015 and 0.005 mag. Calculation of the orbital phases is described in

TABLE 1

COLOR CORRECTION TERMS FOR THE SYSTEM-TO-STANDARD EQUATIONS

Filter	Color Corrections (mag)	K4 Program Star – G5 "Frame" Star (Color Correction Differences) (mag)
U	$+0.156(U-B)$	+0.125
B	$-0.010(B-V)$	−0.003
V	$+0.020(V-I_C)$	+0.014
R_C......	$+0.035(R_C-I_C)$	+0.009
I_C	$+0.042(V-I_C)$	+0.028

§ 3. Model curves are also included in this plot (see § 4). Because the amount of time necessary to cycle through the filters is long with respect to the short period of the binary, color indexes versus phase were calculated only for the model curves.

3. TIMINGS OF MINIMUM LIGHT AND KEPLERIAN PERIOD

The data density at the minima was low in each bandpass. Timings of minimum light were obtained by bisecting chords at equal light levels across the minima; more elaborate procedures were not justified. Within the errors, there was no dependence of minimum timing on bandpass, so timings from individual bandpasses were averaged. The averages and their 1 σ errors appear in Table 4. The timing residuals were calculated from the ephemeris of Lavrov & Zhukov (1976, hereafter LZ). The secondary minimum did not significantly deviate from $0.5P$.

All of the photoelectric timing residuals were fitted to quadratic and cubic polynomials. By any conventional criterion, the quadratic fitting was preferred and resulted in

$$O-C = -0.0002(3) - 0.00000017(4)E + 2.93(9) \times 10^{-11}E^2, \tag{2}$$

where $O-C$ is in days, E is the orbital cycle number since the epoch defined by LZ, and the numbers in parentheses are the 1 σ errors of the last digit in the polynomial coefficients. The data and the fit are displayed in Figure 3. The numerous visual timings do not conflict with this representation of the residuals, but they add no weight to its determination. The very early minima, which occur near $E = -9250$ and $E = -7775$, are formally better fitted by a larger quadratic term, but the difference is not statistically significant. Since they are not photoelectric measures, they are not used here. No new light ephemeris was calculated for this paper. Instead, the phases from the ephemeris of LZ were shifted in order to center the minima at $0.0P$ and $0.5P$.

When GB conceived of Keplerian period diminution to support their concept of AML over a Galactic kinematic timescale, knowledge of V523 Cas's period variability was primitive. SVB have already called attention to the unten-

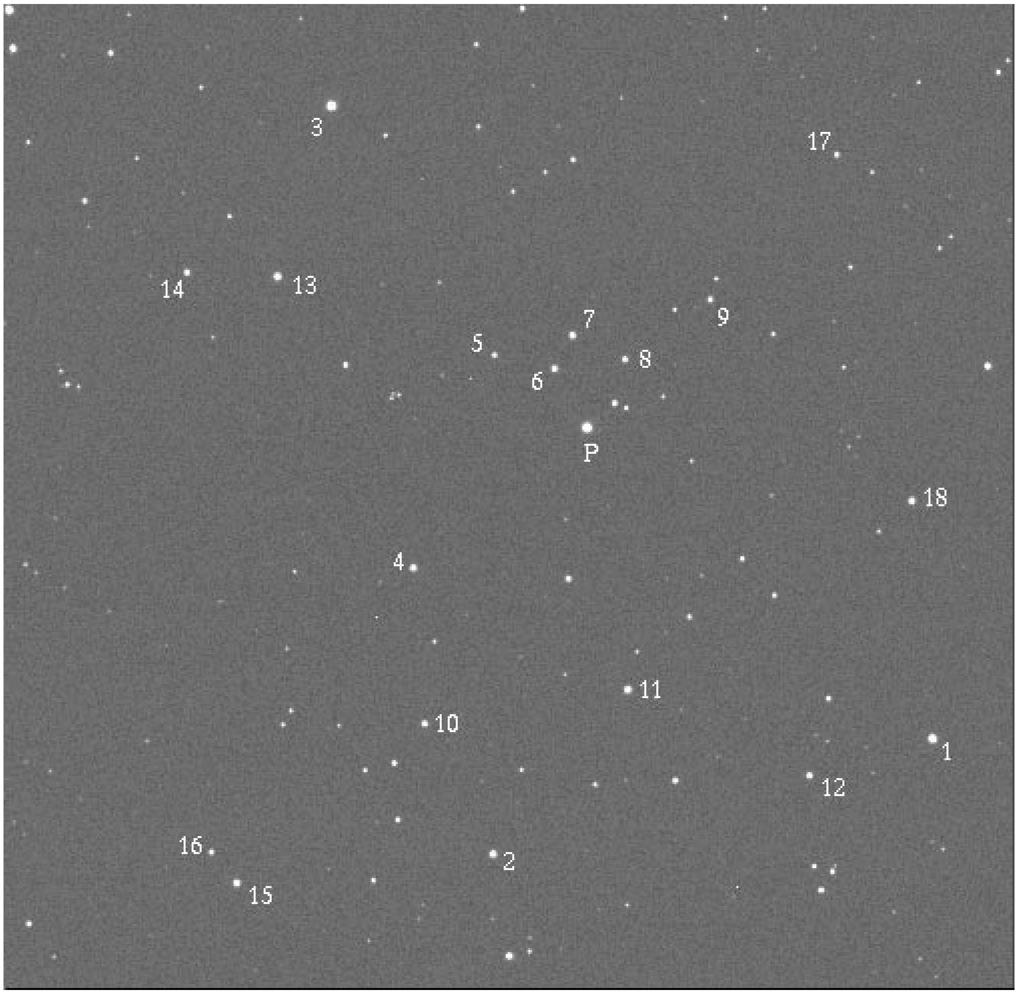

FIG. 1.—CCD image of V523 Cas and comparison stars, V filter, 15 s exposure, 1997 November 20 (UTC)

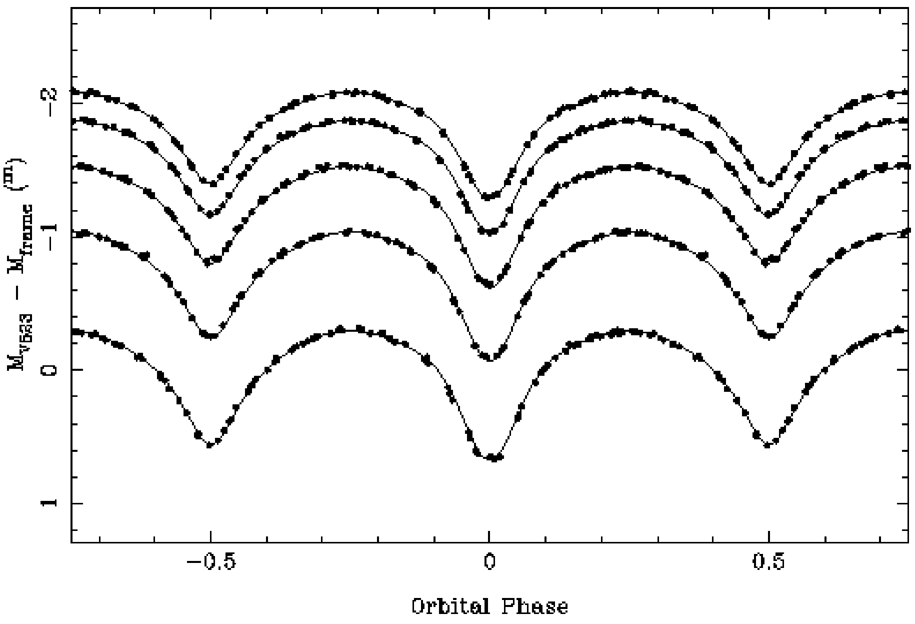

FIG. 2.—V523 Cas $UBVR_CI_C$ light curves (*bottom to top*) and models vs. orbital phase

ability of the original AML invocation. The timings reported here confirm the SVB critique with high weight.

If the period variability was due to a light-time effect in a triple system, the third star could not be very bright since the eclipses are photometrically and geometrically deep. This possibility is not likely for three additional reasons:

1. Early photographic minimum timings of Häussler (1974) show that the period was decreasing before the earliest photoelectric timings. Therefore, the major axis of the supposed large orbit would have to be very nearly in the line of sight, which is statistically improbable.
2. The dimension of that orbit would have to be very large, more than 7.3 AU at this time, but the gravitational binding of the triple system could not be very strong with stars of such low mass (the two K-type stars and perhaps a white dwarf).
3. The spectrum of a third star has never been seen and the color indexes of V523 Cas appear normal for its assigned spectral type.

It is possible that the period variability seen thus far is only one segment of alternating lengthening and shortening. This type of variability might well have an explanation seated in the thermal relaxation oscillation (TRO) theory of Lucy (1976), which states that departures from local thermodynamic equilibrium cause structural changes in a star. The evidence thus far permits only a secular lengthening of the period, so only more timings will distinguish between the triple-system and TRO possibilities.

4. LIGHT-CURVE STUDIES

The light curves have insufficient observational weight to

TABLE 2

COMPARISON STAR Δm_i FOR $UBVR_CI_C$ FILTERS

ID	*U*	*B*	*V*	R_C	I_C
2	+0.9638 (0.0015)	+0.9063 (0.0010)	+0.8310 (0.0008)	+0.7835 (0.0015)	+0.7470 (0.0016)
3	+0.1016 (0.0014)	−0.3914 (0.0009)	−0.7304 (0.0009)	−0.9027 (0.0013)	−1.0082 (0.0015)
4	+1.0157 (0.0014)	+0.9902 (0.0011)	+1.0545 (0.0080)	+1.0879 (0.0019)	+1.1302 (0.0025)
5	+2.5507 (0.0035)	+2.4465 (0.0021)	+2.2818 (0.0021)	+2.1884 (0.0034)	+2.0927 (0.0052)
6	+2.8164 (0.0037)	+1.8264 (0.0015)	+1.1830 (0.0011)	+0.8509 (0.0016)	+0.5938 (0.0022)
7	+1.9521 (0.0023)	+1.4823 (0.0013)	+1.0297 (0.0009)	+0.7703 (0.0015)	+0.5411 (0.0022)
8	+1.9188 (0.0023)	+1.8891 (0.0017)	+1.9633 (0.0015)	+1.8394 (0.0027)	+1.824 (0.0038)
9	+1.7562 (0.0022)	+1.7706 (0.0016)	+1.7211 (0.0015)	+1.6817 (0.0023)	+1.6444 (0.0026)
10......	+1.5989 (0.0022)	+1.5740 (0.0014)	+1.5511 (0.0013)	+1.5315 (0.0024)	+1.5150 (0.0026)
11......	+0.8059 (0.0016)	+0.6945 (0.0009)	+0.6083 (0.0008)	+0.5394 (0.0013)	+0.4914 (0.0016)
12......	+1.6077 (0.0020)	+1.5923 (0.0014)	+1.4983 (0.0009)	+1.4292 (0.0014)	+1.3676 (0.0029)
13......	+2.1388 (0.0029)	+1.1861 (0.0012)	+0.5292 (0.0009)	+0.2085 (0.0013)	−0.0533 (0.0016)
14......	+2.1385 (0.0027)	+1.8555 (0.0016)	+1.5651 (0.0010)	+1.4029 (0.0023)	+1.2729 (0.0022)
15......	+2.3603 (0.0034)	+1.5033 (0.0013)	+0.8542 (0.0010)	+0.5338 (0.0014)	+0.2585 (0.0017)
16......	+2.2570 (0.0031)	+2.2063 (0.0021)	+2.0800 (0.0014)	+2.0116 (0.0022)	+1.9559 (0.0035)
17......	+2.8825 (0.0045)	+2.5741 (0.0027)	+2.2685 (0.0017)	+2.0958 (0.0024)	+1.9417 (0.0034)
18......	+2.3464 (0.0034)	+1.5955 (0.0016)	+0.9911 (0.0009)	+0.6669 (0.0013)	+0.3690 (0.0014)

NOTE.—Comparison Star Δm_i vs. comparison star 1. Numbers in parentheses are 1 σ errors.

TABLE 3

V523 Cassiopeiae Delmags

HJD	Filter	Delmag	Delmag error
2,450,770.57964......	*U*	0.6521	0.0039
2,450,770.60732......	*U*	−0.1401	0.0038
2,450,770.61759......	*U*	−0.2293	0.0038
2,450,770.62582......	*U*	−0.2667	0.0038
2,450,770.63569......	*U*	−0.2854	0.0038

Note.—Table 3 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

TABLE 4

New Timings of Minimum Light Averaged over Bandpass

$\mathrm{HJD}_{\mathrm{min}}$ (2,450,770+)	*E*	$O-C$ (days)
0.6912 ± 0.0006......	40,867.5	+0.0411
0.8094 ± 0.0002......	40,868	+0.0424
2.6782 ± 0.0001......	40,876	+0.0417
2.7956 ± 0.0004......	40,876.5	+0.0423
3.7307 ± 0.0005......	40,880.5	+0.0426
4.6647 ± 0.0003......	40,884.5	+0.0418
4.7814 ± 0.0009......	40,885	+0.0417

attempt the usual light-curve syntheses and differential correction procedures. SVB's model 2, freed of spots, was accepted as the fiducial one. This decision implies that we are using only the photometric mass ratio (q_{phot}), as opposed to the mass ratio obtained from the weak–absorption-line radial-velocity data (q_{spec}) of Milone, Hrivnak, & Fisher (1985, hereafter MHF). The effect of ignoring q_{spec} is, at most, a second-order one. We also looked at the Bradstreet (1993) representation of the SVB data. In general, Bradstreet's and SVB's results are very similar.

The value of the new light curves is in the extended wavelength coverage compared with previous work. Therein lies an opportunity to build upon any current model and upon the recognition of Ca II emission by MHF. Our initializing procedure may be described as follows: The SVB/Bradstreet model was accepted for the unspotted photospheres of the *BV* light curves and was supplemented by the Van Hamme (1993) theoretical limb-darkening coefficients, *X*. Conventional gravity (0.32) and albedo (0.5) parameters appropriate for unspotted, convective photospheres were also used. The results were convincing confirmations in *B* and *V* of the assumed dynamical and geometric parameters of the model and also of the improved theoretical limb darkening.

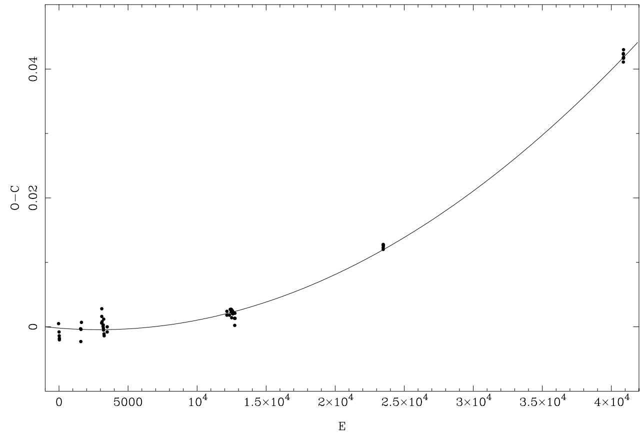

Fig. 3.—Timings of minimum light vs. orbital cycle for V523 Cas. The $O-C$ values are in units of days, and the LZ ephemeris was used to calculate *E*. The last group of points on the right are timings from the new photometry in this paper.

Theoretical limb-darkening coefficients appropriate for the $UR_{\mathrm{C}}I_{\mathrm{C}}$ light curves were added to this model and compared with the observations. The models are completely satisfactory for the $R_{\mathrm{C}}I_{\mathrm{C}}$ data, but in the *U* band, the models are too faint in the primary eclipse and much too bright in the secondary eclipse. While the problem in the primary eclipse can be resolved by diminishing the limb darkening of the hot star below its very large theoretical value, the option of significantly increasing the limb darkening of the cool star is not realistic unless new evidence is obtained favoring this possibility.

It is not difficult to envision the resolution of this discrepancy. Although the two light-curve maxima are essentially at the same level for each filter, the system can still be abundantly spotted. To overcome the differences between the *U* light curve and the model, it is only necessary to include a spot (with a *U*-band excess) on the remote hemisphere of the cool star and another spot (no excess) on the remote hemisphere of the hot star. A spot with a *U*-band excess is consistent with the Ca II emission seen by MHF. The only reason for caution is that their spectra and our light curves are separated by years and the activity of the system may have changed the plage distribution over time. In any case, the behavior of the $U-B$ index shows that excess *U* flux is visible at the primary eclipse. There is no previous evidence for a spot on the hot star, so some intrinsic activity appears to have occurred for this component.

This limited prescription has an element of naive inconsistency about it, viz., the unlikelihood that spots would fail to manifest themselves in all bandpasses. After all, it is well known that the ratio of sunspot umbral intensity to photospheric intensity diminishes with decreasing wavelength (Allen 1973). For the hot star, the contrast favors spot detection in *U*, but the spot should also be visible in *B* and *V*. For R_{C} and I_{C}, the contrast becomes even smaller. This difficulty can also be overcome by diminishing the large limb darkenings for the hot star and increasing the spot contrast. The light curves can then be fitted as satisfactorily as desired. The special location of the spot works to diminish the limb-darkening effect. Of course, the contrast dependence itself can be relaxed, so it can be even easier to model spots at the proper location for all the light curves.

A similar argument can also be made for a photospheric spot and chromospheric region on the cool star. We assume that the phenomenon is a solar-like plage. As for Sun, the photospheric spot should lie beneath the chromospheric plage, detectable in all bandpasses. If this is accepted, the modeling device described in the preceding paragraph can be exploited to develop the spot parameters for all wavelengths.

For all the spot modeling, software developed by Bradstreet (1993) was used; the model light curves appear in Figure 2 along with the data. An abbreviated final model is summarized in Table 5, suppressing parameters listed in SVB and Bradstreet. The temperature factors and limb darkenings show the values required for both spots to be

TABLE 5

PHOTOSPHERE AND SPOT PARAMETERS FOR V523 CASSIOPEIAE

	COOL STAR					HOT STAR				
PARAMETER	U	B	V	R_C	I_C	U	B	V	R_C	I_C
L	0.52	0.54	0.56	0.57	0.58	0.48	0.46	0.44	0.43	0.42
X	0.99	0.96	0.82	0.69	0.54	0.96	0.95	0.80	0.67	0.53
x	0.99	0.80	0.65	0.60	0.50	0.96	0.80	0.55	0.55	0.45
T	1.07	0.92	0.94	0.95	0.96	0.90	0.92	0.94	0.95	0.96

NOTE.—L is the fractional luminosity, X is the theoretical limb darkening, x is the model limb darkening, and T is the temperature factor. Each star has a single spot at colatitude 90° and longitude 180° (see Bradstreet 1993 for definitions). The spot radii for the cool and hot stars are 20° and 10°, respectively. Note the plage emission evident from the U-filter T of the cool star.

visible in all bandpasses. This demand makes it necessary to change slightly the limb darkenings for both stars in order to sustain good models for both eclipses. Even though two significant figures are tabulated for the limb-darkening coefficients, their determinacy is really lower than indicated because the finite observational weight has been diluted by the degeneracy between the spot and limb-darkening characterizations. All that can be said is that the model limb-darkening values are not grossly inappropriate for the system. Also, there has been no attempt to refine greatly the positions and radii of the spots.

Something must be said about the temperature factors since they are wavelength dependent, contrary to normal usage. First, the values in Table 5 have actually been derived assuming blackbody functions, preserving the umbra-to-photosphere contrast seen on the Sun. Second, their ranges with wavelength are not very great, translating into only ≈ 250 K for the spot on the hot star. The values might well be averaged for each spot. Last, the temperature factors act as surrogates for the skewness between the blackbody functions of the spots and photospheres (since we do not use model atmospheres, the spot temperatures are, in reality, brightness temperatures).

5. AN ACTIVITY CYCLE?

The spot on the cool star is larger and brighter than the one described by SVB 13 years ago. It is also not displaced from the stellar equator as before and is almost 90° away from the 1986 location. SVB found no spot on the hot star.

Clearly, the spot behavior of V523 Cas is variable. For instance, observations in 1975 (Zhukov 1988) and 1979 (Bradstreet 1981) indicate almost unspotted conditions. Observations in 1980 and 1981 by Zhukov (1988) have never been analyzed, but his 1988 light curve (Zhukov 1989) resembles that of SVB in 1986. Those data, in turn, lead to a different spot characterization than our 1997 light curve. Finally, the radial velocities from 1982 and 1983 imply a spot with an active chromospheric region (and an underlying photospheric spot) on the cool star but with a different size and location from those found here. When all these measures have been compared and new ones added, an activity cycle length could possibly be determined.

6. DISCUSSION AND CONCLUSION

The arguments in favor of the existence of spots for these symmetric light curves are straightforward. The required evidence is the U light curve, which is not commonly available for cool contact systems for well-known reasons. Modern detectors have eliminated this historical limitation. Assiduous care with CCD image reduction will surely permit routine detection of even low-contrast spots. This would justify a model atmosphere synthesis rather than the blackbody one used here. No matter which synthesis model is used, the driving motivation for a spot is the impossibility of increasing the limb darkening for the secondary eclipse beyond $x = 1.0$ in the absence of a spot.

The value of the U light curve is actually twofold. Had it not existed, it would have been possible to model the remaining light curves by changing the gravitational potential from its historical value. Such a change is not impossible, although it requires a cause now unknown and can perhaps be folded into the TRO theory. However, the $U-B$ change at the bottom of primary minimum showed convincingly that the most economical hypothesis would not demand a dynamical foundation but only a modification of the accepted spot-mapping process.

This paper makes conspicuous analogies with solar phenomena. For instance, the U-band excess is believed to arise by essentially the same mechanism as the K2 R and V and H2 R and V reversals seen in the solar spectrum. For V523 Cas, the emissions are so strong that they create a net emission within the bandpass, overwhelming the feeble continuum attenuated by the many strong metal-line absorptions. In addition, we suggest that a photospheric spot underlies the chromospheric active region just as for the Sun. There is no justification other than convenience that these overlapping regions be of the same diameter. It is also true that the surface brightness of the spots found here are more like solar penumbrae than solar umbrae.

With much greater data density at critical phases, can the chromosphere height be recovered from broadband U light curves of this kind? Observational noise works against this possibility, especially when the Ca emission is diluted by all the other radiation passed by the filter. A somewhat weaker testimony to the same interpretation is the lack of any need for an Hα emission region to model the R_C light curve. If the chromospheric height were several times the 1500 km extent known for the Sun, the situation would be more favorable, but a larger telescope aperture and narrower filters are the obvious needs for a meaningful attempt of this kind. Still less accessible is the detailed plage structure seen in spectroheliograms. None of these problems should discourage theorists from attempting to create more realistic spatial and thermal structure for model spots.

V523 Cas should be observed more industriously than previously. With a period less than 6 hours and a high declination, coverage of more than a single orbital cycle per night is easily possible. Three collaborating stations could ensure essentially continuous coverage and fully describe the spot behavior over an observing season.

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