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V677 CENTAURI: OVERCONTACT AND COMPLETELY ECLIPSING BUT A-TYPE OR W-TYPE?

PAMELA M. KILMARTIN
Mount John University Observatory and Department of Physics, University of Canterbury

DAVID H. BRADSTREET
Department of Computer Science, Mathematics, and Physics, Eastern College

AND

ROBERT H. KOCH
Department of Astronomy and Astrophysics, University of Pennsylvania
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ABSTRACT

The first photoelectric light curves of the contact binary V677 Cen show the system to be a completely eclipsing one. The mass and radius ratios between the component stars are far from unity and the analysis of the light curves is satisfactorily determinate. In distinction to most binaries of comparably short period, V677 Cen shows no temperature difference between the member stars, at least at the time of the present light curves. Main-sequence radius and mass values for the member stars are considered and rejected. An interpretation that recognizes the similarity of the system to FG Hya and describes it as a nearly limiting A type contact binary is also shown to have difficulties.

Subject headings: stars: eclipsing binaries — stars: individual (V677)

I. INTRODUCTION AND NEW OBSERVATIONS

Contact and overcontact binaries have seemed to exist uniquely in either of two mutually exclusive and exhaustive categories first enunciated by Binnendijk (1970). In A type systems the massive component is identical with the large (in radius) and hot star. In W type pairs the massive component is identical with the large (in radius) but cool star. The literature attempting interpretation of W type objects is voluminous.

V677 Cen (CoD −39°9135, CPD −39°6408, S4998 Cen) is a star whose history of variability is limited to Hoffmeister's (1956) discovery light curve, the characterization of the light curve as that of a W UMa-type binary, and a series of times of minimum light. Despite the remark in Wood *et al.* (1980), Hoffmeister's light curve is one of visual estimates; no photographic light curve has been published.

Because of the short period and the relatively long interval during which the star stays at minimum light, this binary was chosen as one of the first objects to be observed at the Mount John University Observatory on the joint program between the Universities of Canterbury and Pennsylvania.

All observations were made with an EMI 6094 multiplier photocell working in a pulse-counting mode and mounted on one of the 0.6 m Mount John reflectors. A filter set, following the prescription of Bessell (1976), was used except that a solid $CuSO_4$ element replaced the liquid cell for the U bandpass. For a given filter, three 10 s observations of V677 Cen were made between consecutive measures of the comparison star. The photometer is online with a Commodore microcomputer which controls filter changing and writes data onto a floppy disk and paper tape as well as onto a printer. For each filter more than 350 data were accumulated over seven nights. Standard stars were observed but these data have not yet been reduced.

On the first night a small number of stars was investigated as a possible comparison star and CoD −40°8886(= CPD −40°6667) was chosen. The check star is CoD −40°8888(= CPD −40°6668). The present comparison star is not necessarily recommended for further use. Compared to other nights, the differential light curve for V677 Cen is consistently bright on JD 2,446,218/9, and CoD −40°8886 is consistently faint with respect to the check star on that night. Only four check star measures were made on that night, and the displacement is not so unique for all four observations as to exculpate V677 Cen from intrinsic variability. This difficulty may, however, have an instrumental explanation. On the night of interest Moon was full and very near the variable's field. As a consequence, the observer was forced to use a focal plane diaphragm smaller than usual. The SRC/ESO films 327J and 327R show two stars very close to CoD −40°8886 and significantly fainter than the comparison star. It is possible that these two stars were within the usual diaphragm and were excluded only on the night of JD 2,446,218/9, thus giving rise to the unusually bright light curve interval. At present, there is no way of choosing among these alternatives.

Hoffmeister gives 32 epochs of minimum light from single visual estimates or from estimates amid visual series. By the method of Kwee and van Woerden (1956) the new timings in Table 1 have been determined from weighted means among the separate bandpasses. From the values of E and $(O-C)$ in Table 1, calculated with respect to Hoffmeister's ephemeris, it may be seen that the period of V677 Cen is definitely variable but unlikely to have varied greatly. No observations are known to have been made between the Sonneberg and the Mount John data sets. In addition, the minimum depths are very nearly equal. Thus, it is impossible to be absolutely sure of cycle count from Hoffmeister's time, and a new ephemeris was generated by a weighted least squares fit to the new times of minimum light:

$$\text{Mid-Time of Occultation} = \underset{(41)}{2{,}446{,}186.9256} + \underset{(214)}{0.3250296}E\ .$$

TABLE 1

TIMES OF MINIMUM LIGHT FOR V677 CENTAURI

JD(hel.) −2,446,000	E	(O−C)	Eclipse Type
186.9256(4)	36,194	−0.0374	Total
187.0875(4)	36,194.5	−0.0380	Annular
219.1033(11)	36,293	−0.0413	Total
271.9204(8)	36,455.5	−0.0476	Annular
272.8960(14)	36,458.5	−0.0472	Annular
274.8456(6)	36,464.5	−0.0480	Annular

The parenthesized numbers represent the probable errors of the last significant figures of the ephemeris terms. The light curves phased with this ephemeris are shown in Figure 1. The individual data points are not published here but may be requested as Unpublished Data File 198 (Breger 1986). Normal points including n observations each but excluding the data of JD 2,446,218/9 are listed in Table 2.

II. LIGHT CURVE ANALYSES

The light curves were analyzed at Pennsylvania with the codes of Wilson and Devinney (1971). Even though essentially no physical information exists regarding V677 Cen, the circumstance that the eclipses are complete offers an entry into the light curve study in the following way. Phases of second and third contact may be estimated from the light curves with fair precision and phases of first and fourth contacts for geometrically deep eclipsing contact binaries are well known from other systems. An initial radius ratio, r_2/r_1, may be calculated from these contact phases, Since the system is surely at least a contact one, an initial mass ratio can be known from the tables of Plavec and Kratchovil (1964) by equating the radius ratio to the ratio of their parameters, y_{12} and y_{11}. Both the radius and mass ratios are far from unity. The modified gravitational potential was assigned from the mass ratio in order to describe a contact system. A temperature was assigned by consulting the exhaustive inventory of contact systems by Mochnacki (1985) and noting that SW Lac, YY Eri, FG Hya, AB And, and W UMa all had periods within 3% of that of V677 Cen. The mean spectral type of these systems is G2 so T_1 could be assigned a value of 5850 K. On the other hand, Mochnacki's values of T_0 for these same stars give an average close to 5550 K. An average of 5700 K seemed the best choice. The inclination was initially set to 85°. All other light curve parameters were initialized at the values appropriate for stars with convective envelopes, and theoretical light curves and differential corrections to the system parameters were run with mode 3 of the code. The computational procedure was the familiar one: for a

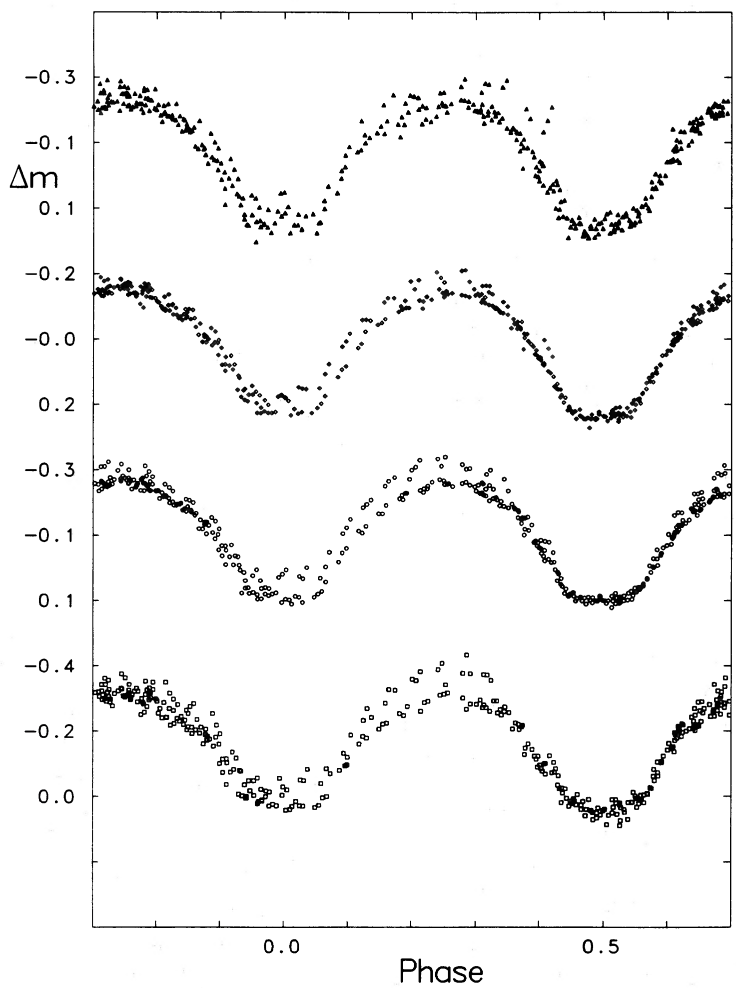

FIG. 1.—From bottom to top the red, yellow, blue, and ultraviolet observations of V677 Cen collected onto one cycle. The data of JD 2,446,218/9 are conspicuously bright through the maximum following phase 0.0.

TABLE 2

NORMAL POINTS FOR THE MEAN LIGHT CURVES OF V677 CENTAURI

Phase	$\Delta m(u)$	n	Phase	$\Delta m(b)$	n	Phase	$\Delta m(y)$	n	Phase	$\Delta m(r)$	n
0.0089	+0.175	1	0.0008	+0.180	3	0.0020	+0.100	3	0.0032	+0.027	3
0.0203	+0.156	3	0.0187	+0.225	4	0.0199	+0.099	4	0.0211	+0.027	4
0.0455	+0.117	1	0.0443	+0.226	1	0.0480	+0.090	1	0.0492	+0.035	1
0.0576	+0.140	3	0.0589	+0.194	3	0.0601	+0.065	3	0.0613	+0.011	3
0.0860	+0.031	2	0.0843	+0.116	1	0.0855	−0.018	1	0.0868	−0.080	1
0.0951	−0.026	1	0.0932	+0.088	2	0.0943	−0.052	2	0.0971	−0.096	2
0.1207	−0.091	3	0.1219	+0.006	3	0.1232	−0.116	3	0.1214	−0.173	2
0.1455	−0.130	1	0.1468	−0.044	1	0.1480	−0.166	1	0.1397	−0.193	2
0.1543	−0.140	2	0.1555	−0.056	2	0.1568	−0.179	2	0.1580	−0.224	2
0.1835	−0.153	4	0.1847	−0.099	4	0.1843	−0.215	3	0.1851	−0.252	2
0.1923	−0.207	2	0.1935	−0.096	2	0.1933	−0.244	3	0.1938	−0.276	1
0.2187	−0.187	6	0.2199	−0.118	6	0.2190	−0.241	5	0.2194	−0.281	3
0.2456	−0.216	3	0.2451	−0.148	2	0.2414	−0.267	3	0.2446	−0.311	1
0.2562	−0.209	3	0.2556	−0.139	4	0.2568	−0.256	4	0.2534	−0.316	2
0.2820	−0.223	3	0.2833	−0.132	3	0.2814	−0.261	2	0.2826	−0.286	2
0.3026	−0.202	6	0.3039	−0.135	6	0.3001	−0.244	5	0.3004	−0.288	3
0.3194	−0.190	8	0.3193	−0.121	7	0.3183	−0.232	9	0.3188	−0.277	5
0.3385	−0.172	5	0.3382	−0.086	6	0.3372	−0.201	5	0.3384	−0.266	5
0.3638	−0.124	7	0.3628	−0.047	5	0.3618	−0.176	6	0.3661	−0.218	3
0.3785	−0.090	5	0.3749	−0.022	6	0.3760	−0.138	6	0.3754	−0.194	3
0.3996	−0.016	10	0.3999	+0.056	11	0.4011	−0.061	11	0.4014	−0.098	9
0.4218	+0.044	7	0.4230	+0.129	7	0.4231	−0.001	6	0.4250	−0.068	4
0.4381	+0.115	9	0.4399	+0.189	8	0.4400	+0.061	9	0.4401	−0.007	10
0.4589	+0.148	8	0.4590	+0.230	9	0.4589	+0.089	8	0.4601	+0.018	8
0.4799	+0.168	8	0.4810	+0.246	9	0.4799	+0.099	8	0.4811	+0.049	8
0.5003	+0.146	8	0.4986	+0.236	5	0.4981	+0.098	7	0.4994	+0.053	7
0.5208	+0.149	11	0.5195	+0.231	12	0.5198	+0.099	11	0.5210	+0.039	11
0.5415	+0.134	8	0.5413	+0.216	9	0.5404	+0.084	9	0.5404	+0.025	8
0.5592	+0.103	9	0.5592	+0.172	8	0.5593	+0.055	9	0.5595	+0.008	10
0.5794	+0.035	9	0.5797	+0.105	10	0.5798	−0.017	9	0.5799	−0.060	8
0.6018	−0.035	8	0.6030	+0.027	8	0.6016	−0.079	8	0.6003	−0.134	8
0.6167	−0.085	8	0.6178	−0.008	8	0.6182	−0.126	9	0.6186	−0.194	10
0.6410	−0.141	12	0.6414	−0.060	11	0.6418	−0.178	10	0.6430	−0.221	10
0.6627	−0.189	7	0.6611	−0.089	7	0.6574	−0.194	6	0.6587	−0.257	6
0.6795	−0.196	11	0.6799	−0.113	12	0.7697	−0.225	14	0.6809	−0.277	14
0.7001	−0.211	5	0.7012	−0.136	5	0.7025	−0.245	5	0.7020	−0.295	4
0.7187	−0.222	12	0.7199	−0.146	12	0.7203	−0.256	11	0.7206	−0.309	12
0.7412	−0.234	7	0.7425	−0.156	8	0.7419	−0.274	8	0.7406	−0.322	6
0.7582	−0.228	11	0.7594	−0.149	11	0.7606	−0.260	11	0.7592	−0.316	12
0.7804	−0.226	12	0.7824	−0.143	11	0.7814	−0.256	10	0.7815	−0.295	11
0.8002	−0.209	7	0.8019	−0.112	7	0.7986	−0.238	8	0.7997	−0.288	8
0.8204	−0.186	8	0.8202	−0.092	7	0.8185	−0.209	7	0.8197	−0.249	7
0.8407	−0.155	7	0.8405	−0.069	8	0.8405	−0.187	9	0.8393	−0.236	7
0.8593	−0.126	6	0.8605	−0.047	6	0.8617	−0.157	6	0.8582	−0.215	7
0.8795	−0.066	8	0.8781	+0.001	7	0.8792	−0.125	7	0.8792	−0.182	8
0.9020	+0.004	7	0.9017	+0.051	8	0.9019	−0.061	7	0.9001	−0.126	5
0.9222	+0.040	4	0.9210	+0.110	3	0.9192	−0.033	4	0.9144	−0.082	5
0.9398	+0.119	7	0.9382	+0.165	7	0.9394	+0.048	7	0.9393	−0.023	8
0.9619	+0.156	6	0.9613	+0.205	7	0.9594	+0.082	5	0.9606	+0.012	5
0.9780	+0.145	4	0.9792	+0.219	4	0.9770	+0.074	6	0.9783	+0.009	6

given bandpass theoretical light curves were calculated by varying individual parameters or sets of them until a close approximation to the observed light curve was attained and then sets of parameters were subjected to least-squares differential correction. It was quickly found that the blue normal point closest to phase 0.0000 was conspicuously bright compared to the other normals within totality and this point was deleted thereafter. Since the light curves treated individually showed closely accordant parameters, the blue and yellow ones—those appearing to show the least observational noise—were then analyzed together for common geometrical and dynamical parameters. These were imposed on the red and ultraviolet data and the wavelength-dependent parameters for these curves were derived. After an acceptable geometry was found, the gravity parameter was studied singly because it seemed likely to make an improvement in the fit to totality without degrading the fit through the other phase intervals.

The accepted representation of the light curves is given in Table 3 and shown against the normal points in Figure 2. Near phases 0.0 and 0.5 small light gradients exist within the phase intervals of complete eclipse. Computer experiments were run in order to see if these small discrepancies could be removed by invoking a spotted photosphere for the large star. The location of any such spot must be on the exterior hemisphere of the star and must cover only a few percent of the stellar photosphere. However, the magnitudes of the discrepancies do not depend on wavelength and thus no consistent spot temperature could be found. The residual discrepancies therefore persist. In view of the fact that the present light curves of V677 Cen are the very first photoelectric ones, it seemed prudent not to resort to

TABLE 3

LIGHT CURVE PARAMETERS FOR V677 CENTAURI

Parameter	Value
$A_1 = A_2$	0.50 (assumed)
$g_1 = g_2$	0.45 (10)
L_3	0.00 (assumed)
T_1	5700 K (assumed)
T_2	5700(20) K
L_1, (u, b, y, r)	0.16(1), 0.16(1), 0.16(1), 0.16(1)
x_1 $(u, b, y, r) = x_2$	0.59(2), 0.60(2), 0.47(2), 0.37(2)
i	89°5(+5, −30)
q (star$_1$/star$_2$)	0.15(1)
$\Omega_1 = \Omega_2$	10.83(3)
Fillout factor	1.57
r_1 (pole, side, back)	0.231(2), 0.243(2), 0.297(5)
r_2 (pole, side, back)	0.522(2), 0.580(2), 0.605(2)
Volume$_1$	0.070
Volume$_2$	0.772
Mean density$_1$	1.38 g cm^{-3}
Mean density$_2$	0.84 g cm^{-3}

further manipulations of the light curve parameters in order to improve the fit.

In Table 3 the errors for the system parameters are given in parentheses and refer to the last tabulated digit. A few comments are appropriate. The light balance is seen not to be wavelength-dependent as must be required for a binary with no temperature difference between the component stars. The formal errors given for the limb darkening coefficients are obviously underestimates if only because of the residual discrepancies during the intervals of eclipse completeness. More to the point are the systematic differences between the empirical coefficients and theoretical ones derived, e.g., by Wade and Rucinski (1985). These discrepancies range from 0.24 to 0.15 monotonically from ultraviolet through red, respectively, with the empirical values being smaller. (The discrepancies are thus about 100% to 50% times the true errors of the coefficients.) For the yellow and blue bandpasses this situation is familiar, having been summarized by Twigg and Rafert (1980), but it is interesting to see that the ultraviolet and red bandpasses show

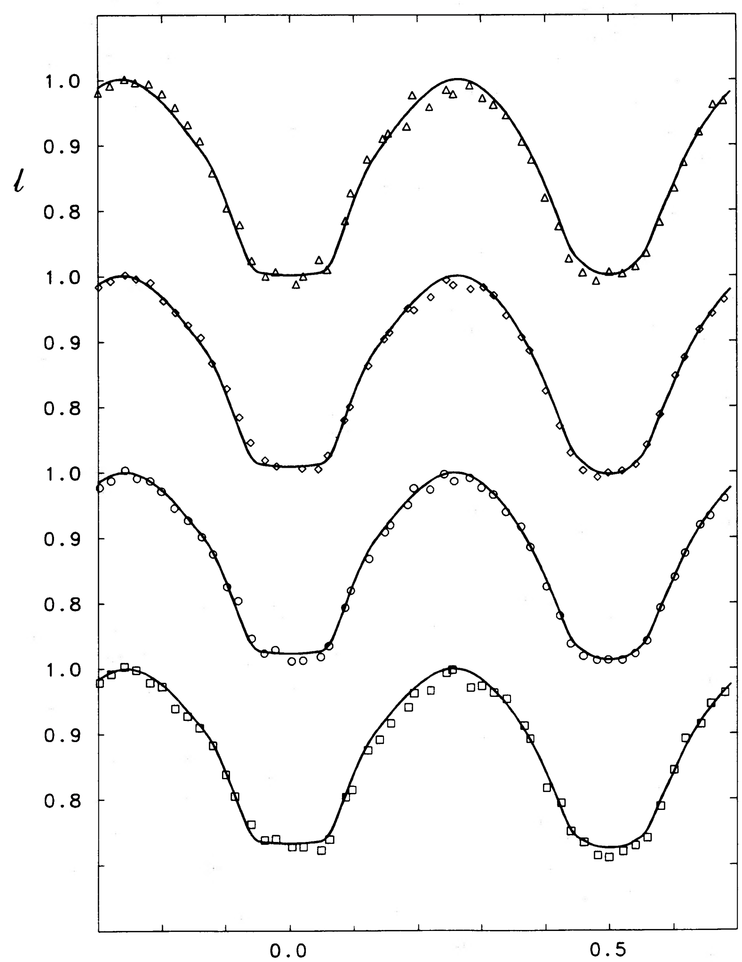

FIG. 2.—From bottom to top the red, yellow, blue, and ultraviolet normal points (in normalized intensity scale) for V677 Cen and the theoretical light curves derived from the parameters of Table 3. A unique size is shown for each symbol type but each normal really has the weight shown in Table 2.

the same result. A likely interpretation considers that contact binaries are poor test objects to verify theoretical coefficients either because the models are insufficiently parameterized or because the common envelope is not appropriately characterized by limb darkening. As was mentioned above, essentially all weight regarding the gravity-darkening coefficient comes from the interval of totality. The coefficient is, naturally, poorly determined but it is encouraging that the comprehensive empirical determinations of this coefficient by Kitamura and Nakamura (1986) show the tabulated value to be acceptable. Accord with their coefficient for UV Leo—a system somewhat similar to V677 Cen—is specifically encouraging. Although the null value of "third" light is listed as assumed, there is no evidence that any source of nonphotospheric light exists. The orbital inclination is, of course, constrained not to exceed 90° but is actually determined rather poorly. This arises in part because of the great difference in stellar radii: the small star does not sample a major fraction of the large star's photosphere during eclipse, and the differences in light loss over a few degrees change in inclination are very small.

III. SUMMARY

The appearance of the system at phase 0.18 is shown in Figure 3. The fillout of the system beyond the inner Lagrangian surface is readily apparent.

Even though essentially nothing beyond the content of this paper is known regarding the system, it is useful to speculate on the eventual interpretation of the binary. As one possibility, assume that $star_2$ has solar values of mass and radius. The companion would then have a mass of 0.15 $M_\odot$. Well-known stars which encompass this value of mass include CM Dra and YY Gem among close binaries and o^2 Eri and Kru 60A and 60B among visual binaries. The spectral types of these stars being known, it would be possible to assign a type of about M3 to $star_1$ of V677 Cen. The numerous stars for which radii have been determined by Lacy (1977) using the Barnes-Evans relationship include many early to middle M stars. From these radii it is possible to assign a radius of about 0.4 $R_\odot$ to an M3 star. This is very close to the value of the radius for the small star of V677 Cen if the large star has a radius of 1 $R_\odot$. Thus, the system would be one in which the small member has a radius appropriate for its main-sequence mass but is as hot as the bright star of the pair. It is possible that the lack of a temperature differential is driven by the large systemic fillout, but it would be a curious kind of stability which preserved the small stellar radius for a system in such intimate contact. This interpretation seems too flawed to be accepted even provisionally.

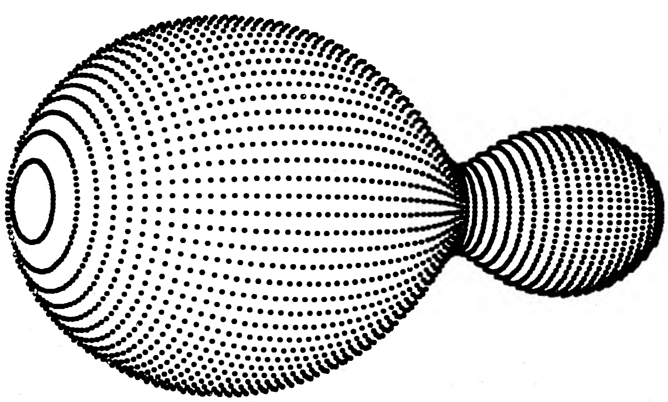

FIG. 3.—Three-dimensional view of V677 Cen projected onto the plane of the sky at orbital phase 0.18.

A second interpretation would be founded on the low mean density of the large star given in Table 3 and not on assumed values of mass and radius for the large star. By Mochnacki's (1981) reasoning, such a low density should derive from an evolved radius for the star. The mean density for $star_1$ is also too low for a main-sequence star and by a much larger factor than for the large star. The system possesses a considerable resemblance to FG Hya in all particulars except for the temperature difference between the component stars. A working interpretation then could describe V677 Cen as an A-type, greatly overcontact binary with zero temperature difference—an uncommon and limiting configuration with the energy exchange mechanism functioning at high efficiency. Such a conclusion would be accordant with the lack of success in invoking spots, which are more commonly associated with W-type pairs. This interpretation, however, fails to account for a gravity-darkening coefficient and the possible conspicuous intrinsic variability that are ordinarily associated with W-type systems. There is also a statistical argument to be made: infrequent observation of a contact binary is likely to reveal period changes for a W-type system but unlikely to do so for an A-type star. It is also possible that at the time of observation there was minimal differential spotting for the two stars. At present, therefore, it is unclear whether this system is an A- or a W-type contact system; possibly it falls in neither category.

Even if the similarity with only FG Hya be ignored, V677 Cen is not an unique object. Consider TZ Boo for which the mass ratio (0.13), period (0.297 days), and dubious type assignment are very similar to those for V677 Cen. In view of the great intrinsic variability of the Bootes star (Hoffmann 1980) and the anomalous light levels of JD 2,446,218/9, V677 Cen should be observed frequently in order to assess its intrinsic light and period variabilities. Its importance as a possible transitional object between A- and W-types can be determined only by continued study.

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DAVID H. BRADSTREET: Department of Computer Science, Mathematics, and Physics, Eastern College, St. Davids, PA 19087

PAMELA M. KILMARTIN: Mount John University Observatory, Lake Tekapo, New Zealand

ROBERT H. KOCH: Department of Astronomy and Astrophysics, University of Pennsylvania, Philadelphia, PA 19104-6394