A Photometric Study of the Eclipsing Binary NSV 1000

Thomas J. Richards
Pretty Hill Observatory, Kangaroo Ground, Victoria, Australia; tompretttyhill@gmail.com

Colin S. Bembrick
Mount Tarana Observatory, Bathurst, NSW, Australia

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Abstract NSV 1000 is an unstudied eclipsing binary in Hydrus. Our photometric research in the period 2014-2016 shows it is a W UMa system with a period of 0.336 579 6(3) d, consistent with the catalogued period. Model fitting to our B, V, and Ic light curves shows the two stars are barely in contact. The parameters derived from the fit satisfy the broadly defined characteristics of a W-type W UMa system.

1. Introduction

NSV 1000 (HV 11909, GSC 9151 0041, ASAS 025619-7431.1, 3UC 031-005816) is a V = 12.75 variable in Hydrus (J2000 02^h 56^m 18.81^s, –74° 31' 03.9"). The GCVS simply lists it as type E (eclipsing) and magnitude 13.5–14.0 (Samus *et al.* 2016). The AAVSO VSX (Watson *et al.* 2014, hereafter VSX) lists it as an EW-type eclipsing binary with a period P = 0.336582 d. Its discovery was reported by Boyce (1943) from a study of photographic plates in the region between the two Magellanic Clouds. That report contains no period or minima timings, simply describing the variable as "Eclipsing or cluster." Except for that one reference, the literature seems to have ignored the star. The ASAS-3 survey (Pojmański 2002) records photometric data for it, folded into a noisy but distinctively EW light curve (Ast. Obs. U. Warsaw 2016) from which S. Otero derived a period and zero epoch which is recorded in the VSX. His elements are E_0 = HJD 2451869.122 (20 November 2000), P = 0.336 582 d, with no uncertainty estimates. The APASS catalogue (Henden *et al.* 2016) gives a color index of 0.727, corresponding to G5-G8 on the Main Sequence.

2. Methods

Richards (AAVSO obscode RIX) carried out 14 nights of time-series observations at Pretty Hill Observatory, Kangaroo Ground, Victoria, Australia (37° 40' 54.0" S, 145° 12' 12.71" E, 163m AMSL), as recorded in Table 1. Instrumentation is an RCOS 41-cm Ritchey-Chrétien reflector equipped with an Apogee U9 camera with a Kodak KAF6303e CCD sensor using Custom Scientific Johnson B, V, and Cousins I_c filters.

All data were calibrated in MUNIWIN (Motl 2007) using bias frames, dark frames and flat-field frames. Photometry was executed in MUNIWIN using comparison and check stars as in Table 2. The APASS catalogue (Henden *et al.* 2016) was used to obtain magnitudes of the Table 2 stars in Johnson B, V, and Sloan *g, r, i* bandpasses, from which I_c magnitudes were derived using the conversions in Munari *et al.* (2014). The comparison star was chosen for having a B–V color index very close to NSV 1000 (0.727 from APASS), eliminating secondary extinction differences; also, being 0.8 magnitude brighter, its contribution to observational errors is reduced.

Table 1. Observations of NSV 1000.

Date (y-m-d)	*Duration (h:m)*	*Filters*
2014-11-11	7:18	B V I_c
2014-11-18	3:49	B V I_c
2014-12-12	2:50	B V I_c
2014-12-13	5:18	B V I_c
2014-12-17	2:22	B V I_c
2014-12-20	3:52	B V I_c
2015-11-22	1:28	B V I_c
2015-11-23	1:23	B V I_c
2015-11-24	6:39	B V I_c
2015-11-26	5:06	B V I_c
2015-12-12	4:54	B V I_c
2016-10-27	1:51	unfiltered
2016-10-28	1:47	V
2016-11-19	6:09	V

3. Results

3.1. Minima and period

Eight of the Table 1 observation sets contained measurable minima—11 minima in all. These times of minima were estimated in PERANSO (Vanmunster 2015) using a fifth-order polynomial fit on un-transformed V data (see Table 3). These are re-measurements since the minima recorded in (Richards *et al.* 2016). Errors are those reported by the fitting algorithm.

Table 2. Comparison (C) and check(K) stars for NSV 1000.

Star	*GSC Ident.*	*R.A. (J2000) h m s*	*Dec. (J2000) ° ' "*	*B*	*B_{err}*	*V*	*V_{err}*	*I_c*	*$I_{c\,err}$*
C	9151 0903	02 55 40.23	-74 29 27.3	13.047	0.011	12.298	0.032	11.543	0.035
K	9151 0875	02 55 08.23	-74 24 52.8	13.752	0.012	13.09	0.0	12.365	0.022

Table 3. NSV 1000, minima estimates. Minima types are primary (P) and secondary (S).

HJD Min.	*Error*	*Type*
2456973.047	0.002	P
2456973.2154	0.0017	S
2457005.022	0.002	P
2457012.090	0.002	P
2457351.026	0.002	P
2457351.1947	0.0017	S
2457353.046	0.002	P
2457369.034	0.002	S
2457690.1305	0.0011	S
2457712.0079	0.0015	S
2457712.1742	0.0015	P

The computer clock was synchronised to a nearby SNTP atomic time service with a variance of < 0.3 sec.

The light elements derived by linear regression from these minima are:

$$En = \text{HJD } 2\,456\,973.0472(4) + 0.336\,579\,6(3)n \text{ d} \qquad (1)$$

(Parenthesised numbers are the standard errors in the regression fit, expressed relative to the last digit.)

As a check, we executed a period search in PERANSO using its ANOVA method. This gave $P = 0.336579(5)$ d, which differs from the regression period in equation (1) by 0.1 sigma.

3.2. Light curve

Observations were made of the Southern Landolt field LSE 259 (Landolt 2007) using the same telescope/filter/camera system as for the NSV 1000 observations. From them transformation coefficients were derived to correct raw photometry to the standard system. These had uncertainties, calculated using the standard method of error propagation, of 0.08 magnitude or less. These coefficients were then used to correct the raw instrumental photometric data of NSV 1000.

The 2014 observations were of sufficient quality and coverage to construct complete phased light curves in B, V, and I_c. Later observations were aimed at eclipse phases only. In particular 2015 observations (undertaken in B, V, and I_c in case later observations could be added to give sufficient phase coverage for modelling work) were taken under poor sky conditions with cloud interruptions—too poor in the end for light curve work; further observations were not possible. The 2014 light curves together with the derived color index curves are shown dotted in Figure 2, along with a model fit (solid line, discussed below).

3.3. Light curve analysis

Our B, V, and I_c data were imported into BINARYMAKER3 (hereafter BM3) for light curve analysis (Bradstreet 2005). Input parameters were set as follows. These assume the two stars are in contact. Star 1 is the cooler star.

Effective wavelengths: *B* 4400 Å, *V* 5500 Å, I_c 8070 Å.

Star temperatures: T_1 = 5390 K. This was chosen as the temperature of a main-sequence star with (B–V) = 0.72 (Cox 2000:388). *T*2 is an adjustable parameter.

Gravity brightening: $G_1 = G_2 = 0.32$, the value for convective stars, which have $T_{eff} < 7200$ K (Lucy 1967).

Limb darkening: $X_1 = X_2 = 0.719$, derived from the Van Hamme (1993) tables.

Reflection coefficient: $R_1 = R_2$ = \0.5, the value for convective stars (Ruciński 1969).

The adjustable parameters are:

T_2, which is adjusted with respect to T_1 to obtain the correct relative depths of the two eclipses.

Inclination *i* of the orbital axis to the observer, which adjusts the absolute depths of the two eclipses.

Fillouts f_1 and f_2, which affect eclipse shapes (equal for stars in contact). There are varying definitions of *f*; we use that of Bradstreet (2005) in which for contact and over-contact binaries (i.e., with surfaces in contact and between the inner and outer Roche surfaces) $0 \leq f \leq 1$ represents the fractional distance of the surfaces from the inner to the outer Roche surfaces.

Mass ratio $q = m_2/m_1$, where star 1 is the more massive, which affects the relative sizes of the two stars.

These four parameters are not entirely independent of each other, requiring concomitant adjustments of all four to obtain the best match of a computed light curve to an observed one. Of these, T_2 and i are easy to adjust to approximate fits to the light curve. We chose T_2 = 5555 K and $i = 72.5°$ as offering the best initial fits to relative and absolute eclipse depths. Note for W-type W UMa eclipsing binaries the smaller star is hotter and is (partially) occulted in the primary eclipse, so by convention it is star 2. Then we adjusted the two equal fillouts to a value that gave approximate matches to the eclipse shapes, viz. f = 0.01. To arrive at the fourth adjustable parameter, q, we then conducted a "q-search" (see e.g. Liakos and Niarchos 2012) of values of q from 0.1 to 0.9 on our V phased data in BM3 to obtain the sum-of-squares residuals for the observed minus calculated (O–C) light curves. Changes to i and T_2 invariably made residuals worse—so our initial choices were left as is. These residuals are plotted against q in Figure 1.

The q-search residuals minimised at q = 0.3.Successively finer-grain searches were then executed in a matrix of values of q near 0.3 and f near 0.01 to find the minimum residual in that region. The best was $q = 0.268$, $f = 0.025$. That same region was then searched in the same way with the *B* and I_c phased data. Small adjustments of all four adjustable parameters were then executed separately in all three bandpasses, resulting in the following best (minimum residuals) values. Table 4 lists the resulting output parameters calculated in BM3 from the assumed parameters and final adjustments of the four adjustable parameters, also listed.

Its last line records the sum-of-squares of residuals in each bandpass.

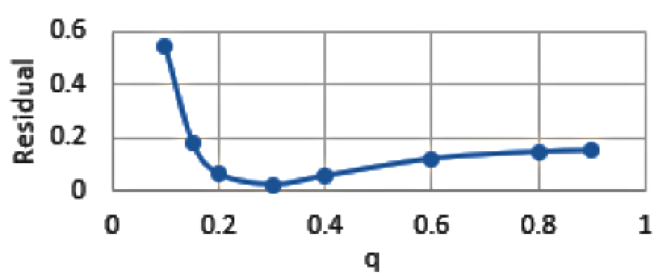

Figure 1. Sum-of-squares residuals plotted against q for V-bandpass data.

Table 4. Parameters for NSV 1000. The length unit for the radii, surface area, and volume parameters is orbital major axis = 1.

Parameter	*Bandpass*					
	B		*V*		I_c	
	Star1	*Star2*	*Star1*	*Star2*	*Star1*	*Star2*
			Assumed			
Effective Temperature Teff	5390		5390		5390	
Gravity brightening G			0.32			
Limb darkening coeff. X	0.901		0.719		0.468	
Reflection coefficient R			0.5			
			Adjusted			
Mass ratio m2/m1	0.301		0.269		0.254	
Fillout f	0.024		0.025		0.030	
Inclination i (°)	72.5		72.5		72.5	
Effective Temperature Teff (K)		5555		5555		5485
			Output			
Omega	7.022		7.538		7.816	
Omega inner	7.037		7.554		7.835	
Omega outer	6.413		6.926		7.205	
Radii: r(back)	0.516	0.307	0.527	0.298	0.532	0.294
r(side)	0.491	0.273	0.502	0.265	0.508	0.261
r(pole)	0.457	0.262	0.465	0.254	0.470	0.250
r(point)	0.620	0.380	0.631	0.369	0.637	0.363
Mean r	0.488	0.281	0.491	0.272	0.503	0.268
Surface area	3.029	1.007	3.153	0.947	3.225	0.920
Volume	0.486	0.093	0.516	0.085	0.533	0.081
Relative luminosity	0.715	0.285	0.742	0.258	0.767	0.233
Sum-of-squares residuals	*0.0501*		*0.0206*		*0.0129*	

The adjusted parameters agree well except the *B* mass ratio is a little higher, as is the I_c fillout. In Figure 2 the resulting model light curves (line) are shown fitted to the observed light curves (dots) in each bandpass. The *B* light curve shows the presence of a slight O'Connell effect, (see e.g. Hilditch 2001:264) Since it is not present in the other light curves, we have not attempted to model it, e.g. by color-sensitive hot or cool spots – which anyway are not likely to be the explanation of the effect.

Figure 3 is a diagram of the system, also showing the inner and outer Roche surfaces, and the centers of mass of each component and the system. Star 1 in the above list is the larger star, on the right in the top diagram of that figure. In accordance with the low fillout, the two stars are joined by a very narrow neck.

The diagram is from the V model – the B and I_c diagrams are indistinguishable from it.

4. Conclusion

From the eleven minima estimates in our data we derived by linear regression the following light elements.

$$E_n = \text{HJD } 2\,456\,973.0472(4) + 0.336\,579\,6(3)n \text{ d} \quad (1)$$

Is there evidence of period change? From the VSX light elements, the (*O–C*) of the zero epoch E_0 (VSX cycle 15164)

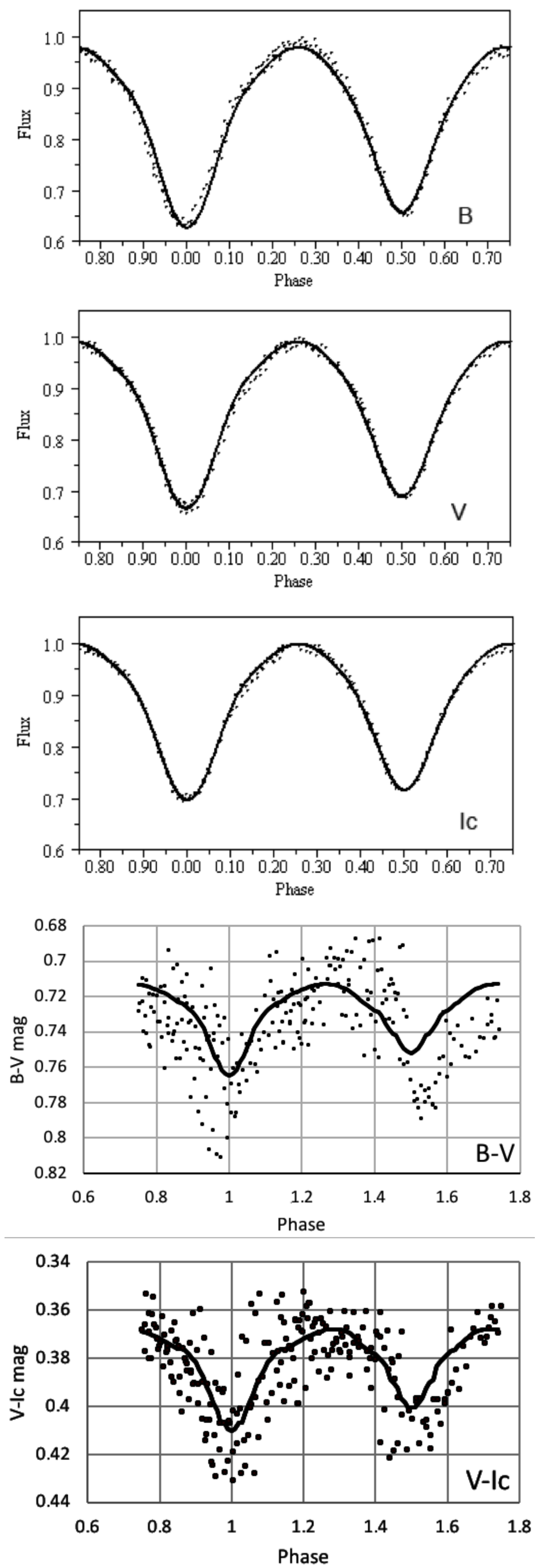

Figure 2. The computed model light curves (line) fitted to the observed phased light curve data points (dots). Top to bottom: B, V, and I_c bandpasses, B–V and V–I_c color indices.

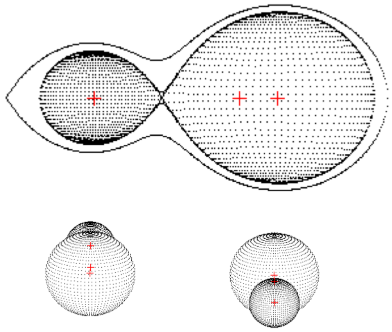

Figure 3. The NSV 1000 system, showing the centers of mass of each star as crosses, and (top) the inner and outer Roche surfaces. Top, phase 0.25 at i = 90.0°. Bottom, phases 0.0 and 0.5 at i = 72.5°.

in Equation 1 is –0.004(2) d. This is ten times the 1-sigma uncertainty on E_0 in Equation 1. The precision error of the VSX E_0 and P is not stated. However a 1-sigma error in the VSX P of 3×10^{-7} d, which is very likely too small since that period is only given to six decimal places, would give an (*O–C*) error for E_0 in Equation 1 of 0.005 d, sufficient to reconcile calculation with observation. Consequently, within conservatively small error limits, no period change is detected.

The light curve shape (Figure 2) is typical of an EW (W UMa) eclipsing binary. This places the spectral type of the stars as G5 or G8, and temperature ~5390 K (Cox 2000:388). EWs in that temperature range are classified as W-type (Binnendijk 1970). These are characterized by the larger and more massive star being cooler and fainter, unequal eclipse depths of up to 0.1 magnitude, the frequent presence of the O'Connell effect (unequal maxima), mass ratio q = 0.4 to 0.6, slightly over-contact, and both components on or close to the main sequence.

The characteristics of W-type W UMa binaries are satisfied by NSV 1000. Star 1 in the above list is indeed larger, more massive, and cooler. It does have a higher luminosity due to its size, but the unit surface brightness b is less as it must be since it is cooler ($b_1 / b_2 = 0.858$).

When star 1 is placed on the H-R diagram in the position of the (*B–V*) color index above, it can be seen to be intermediate between spectral classes G5 and G8, very closely similar to the Sun, and with mass 0.85 $M_\odot$ (Cox 2000:389). In that case star 2 at 5555K is G5 and (from q) 0.23 $M_\odot$. (Being less luminous it must be displaced downwards in the H-R diagram and hence to the left of the Main Sequence, as is common with the secondaries of W-types.) Then, from Newton's modification of Kepler's third law, we derive the orbital radius $a = 9.72 \times 10^{-3}$ AU.

Our light curves (Figure 2) show the uneclipsed V magnitude of the system is m = 12.75. Star 1 contributes 0.74 of the luminosity of the entire system, so $m_1 = 13.07$ in V. The absolute V magnitude of a main sequence star intermediate in G5-G8 spectral class is +5.3, so the distance modulus is 7.77 and distance 358 pc, not allowing for interstellar extinction.

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