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Research Note

Photometric orbital modulation in V 1080 Tauri

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Abstract. We present a photometric study of the variable star V 1080 Tauri. All photometric data, spanning in total about 9 years, can be folded with the period of 8.8451741 days, yielding a single-wave course with the full amplitude of 0.14 mag. The Hipparcos data show that the secular trend in the brightness variations is not larger than 0.04 mag and that the modulation persists for the whole covered interval. We modeled the light curve by ellipsoidal variations because the spectroscopic analysis of Martín (1993) proved V 1080 Tau to be a close binary. We argue that the true orbital period is 17.69348 days, giving a double-wave light curve which can be attributed to the proximity effects in the semi-detached Algol binary. The absence of eclipses and the relatively large amplitude suggest the inclination angle within $55^\circ - 69^\circ$. The deviations from the ellipsoidal modulation, mainly near the phases 0.25 and 0.5, are interpreted in terms of interaction in the binary.

Key words: stars: activity – stars: binaries: close – stars: binaries: general – stars: circumstellar matter – stars: individual: V 1080 Tau

1. Introduction

V 1080 Tauri (BD+24°676) is an emission-line star in the Taurus – Auriga region (Stephenson 1986). This object was originally classified as a pre-main sequence star with a substantial reddening (Walter et al. 1990).

Walter at al. (1990) classified V 1080 Tau as an A3 star according to the spectrum of the blue region which displays absorption lines of the Balmer series. Martín (1993) summarized the respective spectral classifications of V 1080 Tau and found that its spectral type becomes progressively later as one proceeds from the blue to the red spectral region. This suggests the composite spectrum of a hot and a cool star. Spectral lines of the cool component, corresponding to the type G to early K, are indeed present in the Hα region and their intensities suggest that this star is evolved off the main sequence (Martín 1993). Variations of the radial velocity of the cool star by at least 160 km s^{-1} were attributed to the orbital motion in the binary. The low Li abundance rules out the pre-main sequence nature of V 1080 Tau.

Bouvier et al. (1993ab, hereafter B93a and B93b, respectively) discovered the brightness variations on the time scale of 8.8 days with the full amplitude of about 0.3 mag(V). Since the color indices were bluer at minimum brightness, B93a rejected the rotational modulation of a spotted T Tau-type star. Instead, they rose a possibility of the orbital modulation in the binary.

In our paper we present a photometric analysis of the brightness variations in several sets of data, determine the orbital period and show that the modulation can be attributed to the ellipsoidal variations in an Algol-type binary.

2. Observations and the data collection

In order to achieve the coverage of the light curve as long as possible, we have made use of three sources of the photometric data, summarized in Table 1.

B93b published a table of their $UBVRI$ photometry, collected during the $COYOTES$ multi-site campaign for monitoring of T Tau stars. Their measurements were obtained with the photoelectric photometers and are given in the absolute magnitude scale. Usually one to four observations were secured within a single night, which allowed us to conclude that their scatter was not larger than 0.02 mag for a given night.

A set of CCD data was obtained at Brno Observatory within January–April 1998. V 1080 Tau was observed using Newton 400/1750 mm, equipped with the CCD camera SBIG ST-7. The variable, the comparison star (GSC 1834-299) and the check star (GSC 1834-412) were placed in the same image. Usually a series of 5–10 closely spaced images was secured each night and an average brightness was determined. The brightness of V 1080 Tau was given with respect to the comparison star. The typical standard deviation of this average was about 0.017 mag(R). The comparison and the check star were stable within $\sigma = 0.023$ mag(R) through the whole season.

We also included a set of 69 observations obtained with the photometer onboard the Hipparcos satellite in the $H_{\rm P}$ passband (Perryman et al. 1997). The $H_{\rm P}$ filter has its maximum roughly

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Table 1. Sources of the photometric data used for the analysis

Source	Bands	Coverage	Years	No. of obs.
Bouvier et al. (1993b)	R (Set A1)	88 days	1991	55
Bouvier et al. (1993b)	V (Set A2)	88 days	1991	55
Bouvier et al. (1993b)	B (Set A3)	88 days	1991	52
Bouvier et al. (1993b)	U (Set A4)	88 days	1991	42
Brno Obs., CCD ST-7	R (Set B)	93 days	1998	23
Hipparcos	$H_{\rm P}$ (Set C)	915 days	1989–1992	69

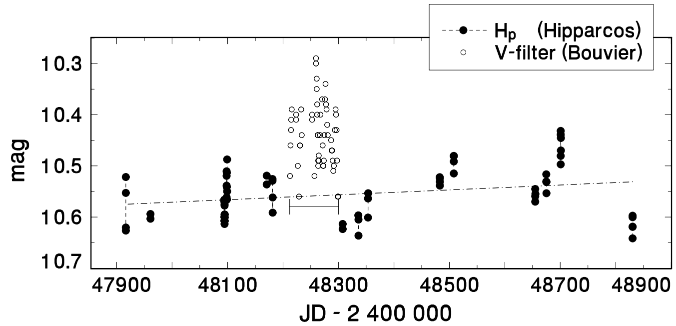

Fig. 1. The photometric data of V 1080 Tau plotted in real time. The dot-dashed line sets the upper limit of the long-term trend for the Hipparcos data (set C). The data of B93b (set A2) are shifted due to the different filters used. See Sects. 2 and 3.1 for details.

between the V and B filter. These $H_{\rm P}$ data were used just for determination of the period.

3. Analysis of the data

3.1. Period search

The Hipparcos data (set C) represent the longest coverage, and although they are seriously sampled, they offer the best impression of the long-term stability of the mean level of brightness (Fig. 1). It can be seen that the brightness changes are dominated by the short-term variations, occurring on the time scale of several days. The linear fit of the Hipparcos data spanning 915 days, displayed in Fig. 1, sets the upper limit of 0.04 mag to a possible secular trend. However, it is quite probable that the slope of the fitting line is purely due to the sampling. The standard deviation of this fit 0.05 mag is quite large and we will show that it is caused by the orbital modulation. The V-band data of B93b (set A2) which are plotted in Fig. 1, too, appear to be shifted by more than 0.1 mag. This shift can easily be explained by the different wavelengths of the filters used. The $H_{\rm P}$ passband used in Hipparcos has its maximum roughly between the V and B filter. V 1080 Tau is heavily reddened ($B-V \approx 1.2$; $E_{\rm B-V} = 1.1$; Walter et al. 1990) and this reddening causes that V 1080 Tau appears systematically brighter in V and fainter in B in comparison with the $H_{\rm P}$ passband.

In the first step separate period searches were carried out for the data sets A1, B, C using the PDM (Phase Dispersion Minimization) program, based on the method of Stellingwerf (1978) and written by Dr. J. Horn at the Ondřejov Observatory. This program enables not only an automatic search for the best period within a given interval, but also an interactive examination of the resultant data foldings for the respective period lengths. The PDM method evaluates the significance of the period by the parameter Θ which lies in the range 0–1. The lower Θ, the better defined period. The period near 8.8 days was found in all three sets. The best Θ value always laid below 0.4, suggesting a well defined period. The Hipparcos data can therefore be interpreted as the constant long-term level of brightness with variations due purely to the modulation with P near 8.8 days, persisting for the whole interval.

We found that the amplitude of the modulation slightly decreases from the R to V and B passbands. Fortunately, the difference of the amplitude in the R and $H_{\rm P}$ passbands is small enough to allow us to refine the period length using the combined set of data. We proceeded in the following way. Under the reasonable assumption that the secular trend is absent or very small, it is possible to shift the respective data sets to their common zero point. This shifting is quite justified for sets A1 and C. We also carried out this procedure for set B, because we have magnitudes just in the relative system for the Brno data. All three sets were solved for their common zero point using the code SPEL (author J. Horn). This program solves the parameters of the folded curve. It takes the systematic shifts of the subsets of the input data file into account and evaluates them. The mean brightness of set A1 was used as the basic level and the remaining two sets were allowed to converge to it.

First, the folded data of set B were allowed to converge to set A1 in SPEL. The systematic shift, determined this way, proved to be only marginally sensitive to the exact value of the period length. The refined period was determined again from the new set, combined of A1 and the corrected B. In the next step the Hipparcos data were included to the set A1+B and converged in SPEL again to evaluate their shift. In the last step the sets A1, B and C were solved simultaneously in PDM; the final period length of 8.8451741 days was determined this way. The significance parameter $\Theta = 0.48$ still suggests a plausibly defined period. The final values of the shifts of set B and set C with respect to set A1 were determined to be $+13.11 \pm 0.01$ mag(R) and -0.96 ± 0.01 mag($H_{\rm P}$), respectively. This simultaneous solution for the sets A1, B and C allowed to resolve between several closely spaced aliases which were present in the solution just for A1+B. The resultant folding is displayed in Fig. 2a. The course is approximately sinusoidal with the full amplitude about 0.14 mag. We can readily see that the agreement of the respective data sets, shifted to the same mean level of brightness, is very good. It confirms that the shifting procedure is justified.

3.2. Character of the orbital modulation

The binary nature of V 1080 Tau was convincingly proven from spectroscopy by Martín (1993). This system comprises the main-sequence hot star and evolved cool star. The smooth modulation of brightness (Fig. 2), allows us to infer that the light

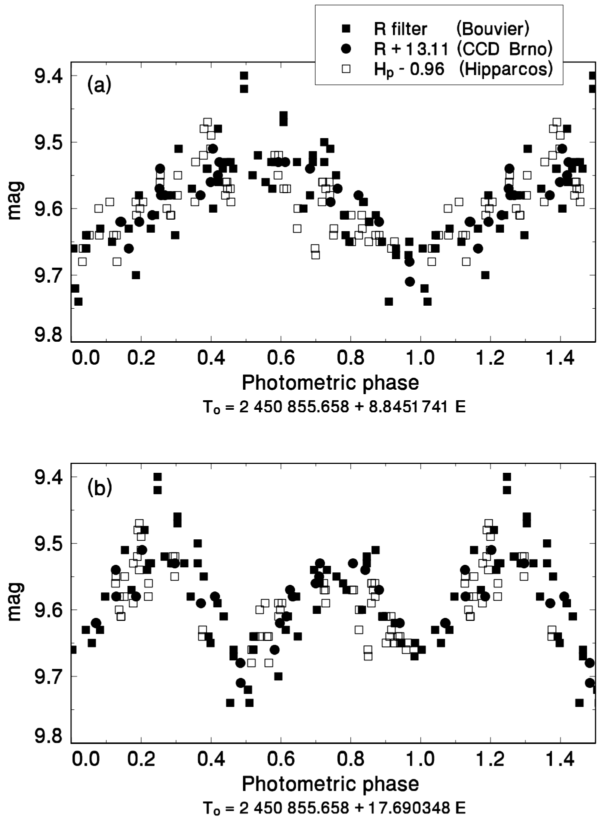

Fig. 2a and b. The respective data sets shifted to the same mean brightness, folded with the period lengths yielding the single-wave **a** and double-wave **b** light curve. The symbols and the shifts are the same for both figures. See Sect. 3.1 for details.

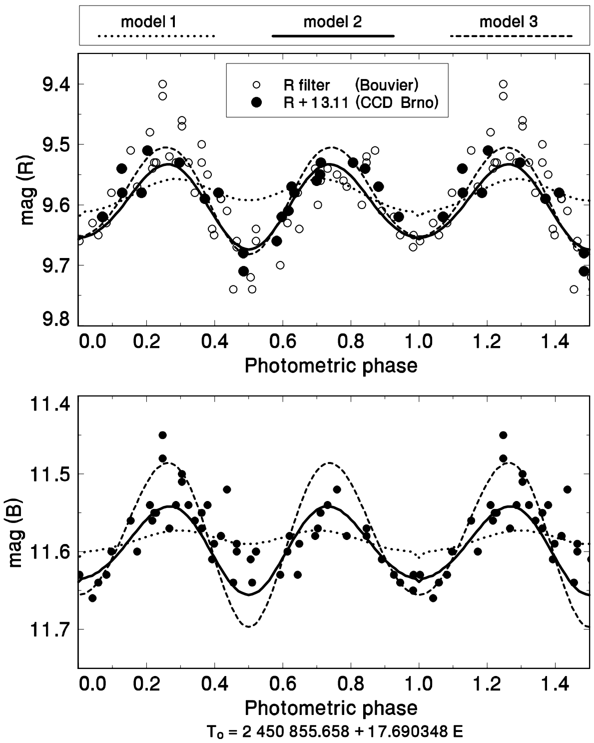

Fig. 3a and b. Observations of V 1080 Tau in the R **a** and B filter **b** with the superposed ellipsoidal variations in semi-detached binary. The parameters of the respective synthetic light curves are listed in Table 2. See Sect. 3.2 for details.

variations may be caused by the proximity effects in the close binary. Only the reflection effect and ellipticity can play a role since no eclipses are apparent in Fig. 2.

The folded light curve of V 1080 Tau displays a scatter which cannot be entirely attributed to the observational inaccuracies. For example the maxima of the light curve observed by B93ab display unequal height for the respective cycles. As a result, it gives rise to enhanced scatter at some orbital phases of the folded data although this scatter is intrinsic. We will also show that there are some differences between set A1 and set B which are separated by a long gap. Due to the low amplitude of the variations these cycle-to-cycle changes smear the course of the modulation caused by the geometrical effects. Nevertheless, it is still instructive at least to constrain the role of the proximity effects in V 1080 Tau. The light curve can be still analyzed under some reasonable assumptions. The spectroscopic parameters (A3V primary and the evolved secondary of the type G to early K) put the basic constraints. The secondary, less luminous than the primary, is evolved off the main sequence while the primary is still a main-sequence star. This situation is typical for Algols which underwent mass transfer between the components. It can offer a natural explanation for the overluminosity of the secondary in V 1080 Tau. It also yields an additional constraint on the mass ratio $q = M_{\rm cool}/M_{\rm hot} = M_2/M_1 < 1$ because almost all Algols are observed in the phase after the mass ratio reversal. In order to further lower the number of parameters to be searched for, the fractional radius of the secondary r_2 can be set equal to the radius of its Roche lobe, as typical for Algols.

We generated a set of synthetic orbital light curves for the above-mentioned parameters using the code *Binary Maker 2.0* (Bradstreet 1993). This program, which uses Roche geometry, enables one to calculate theoretical light curves and their comparison with the observations. It is reasonable to suppose that the modulation in V 1080 Tau is due to the large tidally distorted secondary because the main-sequence primary lies deep inside its lobe; its departure from a sphere is therefore very small. We therefore modeled the R-band data (set A1 and set B) first because the contribution of the cool secondary is larger here. We attempted to match the single-wave modulation ($P = 8.8$ days) with the synthetic light curve first. It became quite clear that no match, fulfilling the constraints given above, is possible. The single-wave modulation implies that only the reflection effect is prominent, it means that the luminosity of the primary is much higher than that of the secondary. This would be in contradiction with the spectroscopic evidence for the lines of the secondary in the red region, confirming that the luminosities of both components cannot be largely divergent here.

Further we examined the possibility that the modulation is double-wave with the real orbital period $P = 17.690348$ days (Fig. 2b) and obtained much better agreement (Fig. 3). The system parameters are summarized in Table 2. The three models

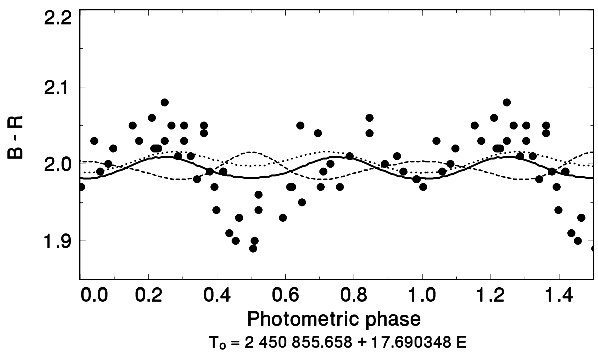

Fig. 4. Variations of the color index $B - R$ through the orbital cycle. Phases were calculated using Eq. (1). Meaning of the smooth curves is the same as in Fig. 3. See Sect. 3.2 for details.

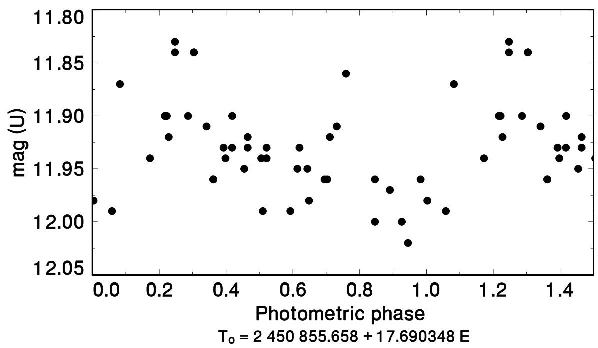

Fig. 5. Orbital modulation of V 1080 Tau in the U band (set A4). The phases were calculated using Eq. (1). Notice the large scatter and the very different course in comparison with the R and B bands (Fig. 3).

brake the interval of the possible temperatures of both components and also *the remaining parameters in model 1 and model 3 were chosen so that they act to minimize the amplitude of the modulation in the former and maximize it in the latter case*. The values of q brake the typical range seen in Algols. The radii of the stars in Table 2 are fractional, i.e. the distance a between the centers of the two stars is defined to be unity and the radii of the components of the binary are expressed as fractions of a. The fractional radii of the primary correspond to the main sequence or a slightly evolved star. We only matched i of each set because it just scales the amplitude of the modulation in a simple way. The limb-darkening coefficients were taken from the table of Al-Naimiy (1978). Set A1 and set B are resolved by the different symbols in Fig. 3a. The set A1 suffers from a larger scatter than set B, mainly at phases 0.25 and 0.5. This effect may be due to the intrinsic activity in the binary (see below). The light curves with the geometrical parameters and temperatures from Table 2 were also generated for the B-band (set A3) and are plotted in Fig. 3b. The course of the modulation is plausibly reproduced for model 2 (Table 2), despite an increased scatter of the observations at phase 0.25. The standard deviations of the residuals for the respective models in the R-filter are 0.06, 0.04 and 0.04 mag(R) while for the B band we obtain 0.04, 0.03 and 0.05 mag(B).

The relation of the brightness variations in the red spectral region, in which the cool secondary is prominent, and in the blue region, where the hot primary dominates, can be emphasized by the color index $B - R$ (Fig. 4). The $B - R$ curve, folded according to Eq. (1), displays a double-wave course with the minimum at phase 0.5 deeper than that at phase 0.0. The synthetic color indices, corresponding to models 1, 2, 3, are superposed. It can readily be seen that while model 1 and 2 give the same sense of the color variations as the observed data (apart from the phases 0.4–0.6, see below), model 3 is ruled out because it yields an opposite sense. In conjunction with the residuals of the respective models, mentioned above, *model 2 best represents the observations of V 1080 Tau*.

We note that the U-band data (set A4) display a very large scatter and the course of the modulation largely differs from the R and B bands. Notice mainly that while we obtain a clearly double-wave modulation for the R and B filters, the maximum at phase 0.75 is just barely visible in U. An intrinsic activity may at least partly account for these effects (see below).

Table 2. Parameters used for generation of the respective synthetic light curves of V 1080 Tau. T_1 and T_2 refer to the effective temperature of the primary and the secondary while r_1 and r_2 denote the fractional radii of the components. The mass ratio and the inclination angle are abbreviated as q and i, respectively. See Sect. 3.2 for details.

	Model 1	Model 2	Model 3
T_1	10000 K	9000 K	8000 K
T_2	4500 K	5000 K	5900 K
r_1	0.15	0.10	0.05
r_2(side)	0.242	0.272	0.295
q	0.2	0.3	0.4
i	68°	69°	55°

Because the double-wave light curve (Fig. 2b and 3) does not enable to resolve unambiguously the superior and the inferior conjunction of the primary, an additional constraint is needed. Three measurements of the radial velocities (RVs) of the cool secondary (88, 94 and -64 km s^{-1}) are available (Martín 1993). They set the lower limit of 160 km s^{-1} to the full amplitude of the RV variations. As we will show below the real amplitude is not expected to be much larger than this and we can therefore state that the systemic velocity of V 1080 Tau is not very different from 0 km s^{-1}. It means that the velocities 88 and 94 km s^{-1} must occur in the part of the orbital cycle when the secondary is receding from the observer. Calculation of the orbital phases for these RVs enabled to adjust the proper moment of the superior conjunction of the primary (Eq. (1)). This ephemeris is used in Figs. 2b – 4.

$$T_0 = 2\,450\,855.658 + 17.690348\,E \qquad (1)$$

4. Discussion

We have shown that the brightness variations in V 1080 Tau are periodic and are present in all data, spanning about 9 years and covering the region longward from the U band. The proximity effects (mainly the ellipsoidal variations) can plausibly reproduce the main features of the double-wave light curve of V 1080 Tau with the orbital period of 17.69 days while no match of the 8.8 day single-wave curve is possible. We therefore argue that 17.69 days is the true orbital period. The proximity effects in the binary can explain especially the smooth course of the modulation, the decrease of the amplitude from the red to the blue spectral region and bluer color at minimum brightness. The brightness variations can be interpreted in terms of modulation in a typical Algol-type binary with $q = 0.3$, comprising the evolved cool star ($T_2 = 5000$ K, consistent with filling its lobe) and the detached main-sequence or slightly evolved primary ($T_1 = 9000$ K).

The double-wave light curve of V 1080 Tau shows that the reflection effect is very small and that the observed variations are caused almost exclusively by the ellipticity of the large cool secondary. Model 2 in Table 2 implies that the fractional luminosities of the primary and the secondary are comparable in the R band while the secondary contributes just about 33% in the B filter. This is consistent with the early spectral type in the blue region of the low-resolution spectrum, such as that of Walter et al. (1990), and, on the other hand, with the presence of the lines of the secondary near Hα (Martín 1993). We can conclude that these parameters are in accordance with the spectroscopic classification of the components by Walter et al. (1990) and Martín (1993).

The validity of the above-mentioned parameters can be also checked using the total luminosity of the binary. The distance to V 1080 Tau, measured by Hipparcos, is 400 pc. Assuming the mass of the primary $M_1 = 2.2\ M_\odot$ (Harmanec 1988), appropriate for T_1 in model 2, the absolute radii of the components can be calculated from the fractional radii. The combined magnitude for the reddening $E_{\rm B-V} = 1.1$ (Walter et al. 1990) and $d = 400$ pc is then approx. 11 mag(V). This is slightly fainter than the mean observed brightness 10.45 mag(V) (Fig. 1). This difference can be explained in several ways. The reddening was determined by Walter et al. (1990) under the assumption that V 1080 Tau is a single A star. Taking the secondary star into account therefore could diminish $E_{\rm B-V}$ and hence increase the total brightness. Also the mass of the primary may be higher because its radius for model 2 corresponds to a star evolved off the main sequence. Increase of M_1 would lead to increase of the absolute radii of both stars and hence to their larger luminosities. We can therefore conclude that the agreement is plausible and probably the best that can be obtained with the data at hand.

Assuming an early A primary, we obtain the expected full amplitude of RV variations of the secondary about 170 km s^{-1}, in agreement with the lower limit of 160 km s^{-1} determined from Martín's (1993) data.

There are several lines of evidence of activity in V 1080 Tau. Martín (1993) found Hα in strong double-peaked emission with variable strength and profile. The U-band data appear to be affected by the activity, too, the modulation in U is largely divergent from those in the B and R bands, especially near the phase 0.5. Slight distortions, not explicable by the pure proximity effects, can also be resolved in the light curve in the R band, although they are much smaller than in the U-filter. Comparison of set A1 and set B suggests that the latter, which displays smaller scatter, was obtained at epoch of weaker activity. The course of the light curve in the R filter slightly deviates from the course of the synthetic curve mainly at phases 0.25 and 0.5. The dip in the color index $B - R$, centered on the phase 0.5, shows that V 1080 Tau is bluer here than can be explained purely by the proximity effects. In the framework of the proximity effects, the bluer color at minima is caused by smaller contribution of the cool distorted secondary. The "blue excess" at phase 0.5 means that the contribution of the secondary is even smaller here. We offer an interpretation of this effect in terms of the mass stream. The effects of such streams are well-known from the distortions of the light curves of the eclipsing Algols (e.g. Olson & Bell (1989), Olson & Etzel (1994)). The gas leaving the L_1 point is cooler than the photosphere of the secondary. The stream projects on the disk of this star within phases 0.4–0.7. Stream with sufficiently large optical depth will therefore block part of the light from the secondary and will give rise to a decrease of brightness and bluer color index near phase 0.5. On the other hand, the side of the stream irradiated by the primary will be exposed to the observer near phase 0.0 and can give rise to excess light seen in some data of B93a.

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