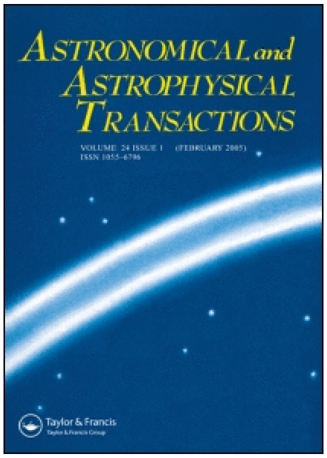

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T. S. Polushina [a]; I. B. Pustylnik [b]
[a] Ural State Univ., Ekaterinburg, Russia
[b] W. Struve Astroph. Obs., Tõravere, Tartu, Estonia

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THE PARAMETERS OF CIRCUMBINARY GAS IN THE INTERACTING BINARY SYSTEM SZ CAMELOPARDALIS

T. S. POLUSHINA[1] and I. B. PUSTYLNIK[2]

[1] *Ural State Univ. 198904, Leninski Prospect 51, Ekaterinburg, Russia*
[2] *W. Struve Astroph. Obs., Tõravere, EE2444, Tartu, Estonia*

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UBVR light curves of the interacting early-type binary system SZ Camelopardalis have been analyzed and compared with model light curves which take into account the influence of anisotropic stellar wind from one of the components. It is indicated that the best fit can be achieved assuming mass transfer from the secondary component with the mass loss rate of $1 \div 5 \times 10^{-7} M_{\odot}$/yr.

KEY WORDS Close binaries, mass loss and mass transfer

The variable star SZ Camelopardalis (HD25638) is the northern component of a visual binary $\sum 485 = ADS2984(18'')$, being an eclipsing variable with both components of the early type. This system is the brightest object in the open cluster NGC1502 viewed as projected upon its central part.

There is no universal agreement concerning the determination of the spectral class of this star (Table 1), even more controversy is connected with its luminosity class, the estimates ranging from V to II. Some investigators find evidence for a rapid rotation and the presence of interstellar absorption lines, the latter, however, not always being confirmed.

Amazingly good regular light curve based upon more than 12000 photographic observations was obtained by Wesselink (1941) between 1930–1937. This curve has been repeatedly used in many subsequent investigations for the purpose of determining photometric orbital elements. SZ Cam has been classified as a detached binary belonging to one of the exceptional cases where the limb darkening coefficient for a hot star has been reliably established (Kopal and Shapley, 1956). Nevertheless, its value disagrees with theoretical models (Heintze and Grygar, 1970).

The first photoelectric UBV light curves of SZ Cam based upon the observations in 1970–1971 have been published by Kitamura and Yamasaki (1972). Budding (1973, 1974, 1977) was the first to analyze them applying various methods. He had problems equally with the evaluation of the coefficient of limb darkening and the determination of orbital elements (r_1, r_2, i). In addition, he discovered the

Table 1 **Estimates of the spectral class of SZ Cam**

Sp	*Author*
09.5	Gutnick P. and Prager R. (1930)
B0nk	Plaskett J. S. and Pearce J. A. (1933)
B1	Zug R. S. (1933)
B0	Stebbins I. and Huffer C. M. (1940)
(09–09.5)+B0	Wesselink A. J. (1941)
B0nk	Neubauer F. J. (1943)
B1	Sanford R. F. (1949)
B0	Wallenquist A. (1954)
B0	Beals C. J. and Oke J. B. (1954)
B0 II–III	Munch G. (1957)
B0 II–III	Hoppmann J. (1958)
B0n	Dombrowsky B. and Gagen–Torn B. (1964)
09 V	Murphy R. E. (1969)
B0 V	Murphy R. E.
09 V	Murphy R. E.
09.5+[B2]	Budding E. (1975)
BI III	Harris G. (1976)
B0 III	Martin P. G. and Cambell B. (1976)
09.5V + B0	Chochol D. (1980)
B0 III	Abt H. A. (1981)

local absorbing material around SZ Cam having the density $2M_{\odot}/pc^{-3}$ based on the K Ca II absorption lines and the colour excess. These estimates deviate both from the values typical of the whole cluster and the ambient stellar field (Budding, 1975). The record of all available photometry is given in Table 2 and illustrated in Figures 1–6. A comprehensive photometric and spectroscopic study has been undertaken by Chochol (1980). Analyzing the light curves during the observational seasons of 1930–1937, 1971–1972 and 1972–1975, he discovered that the radius of the secondary component increased by about one fourth and the star subsequently filled in the respective Roche lobe. However the accompanying increase of brightness by 0.13 has not been recorded. At the same time, Chochol claims that there is a complicated system of gas streams around SZ Cam diminishing its brightness and largely distorting the derived elements of orbit and physical parameters. Similarly Mardirosian *et al.* (1980) analyzing the light curve obtained in 1971–1972 found that the secondary component fills in its Roche lobe. In this way a considerable luminosity excess for the secondary component (which is six times brighter than a MS star of the same mass) finds an explanation.

Thus in SZ Cam the first stage of mass transfer has already occurred, the roles of the components are reversed and the secondary component fills in its critical Roche lobe losing material. Both the observed light curves and period variation diagram (Figures 1–7) urge one to examine to what extent this process is stable. A continuous mass loss by the secondary component was observed between 1971 and 1985. If all the material has been transferred to the primary one, $\Delta P = 5.924 \times 10^{-8}/P$ yields the mass transfer rate $\dot{M} = 3 \times 10^{-5} M_{\odot}/\mathrm{yr}$.

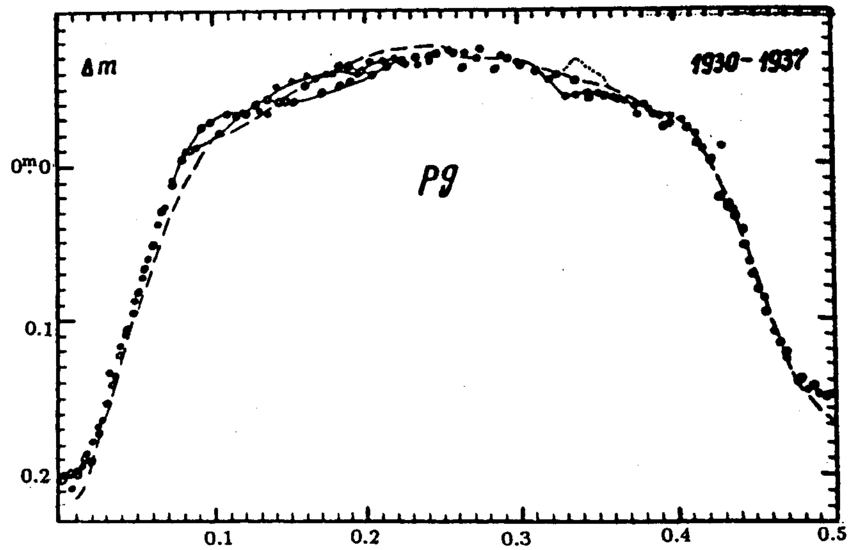

Figure 1 The photographic light curve of an early-type interacting binary SZ Cam obtained by Wesselink (1941). Filled circles denote the observations in the phase range $(0 \div 0.5)P$, empty circles in the phase range $(0.5 \div 1.0)P$. Dots denote averaged light curves, obtained during the winter season of 1971–1972 by Kitamura and Yamasaki. The same notation is adopted in Figs. 2–6.

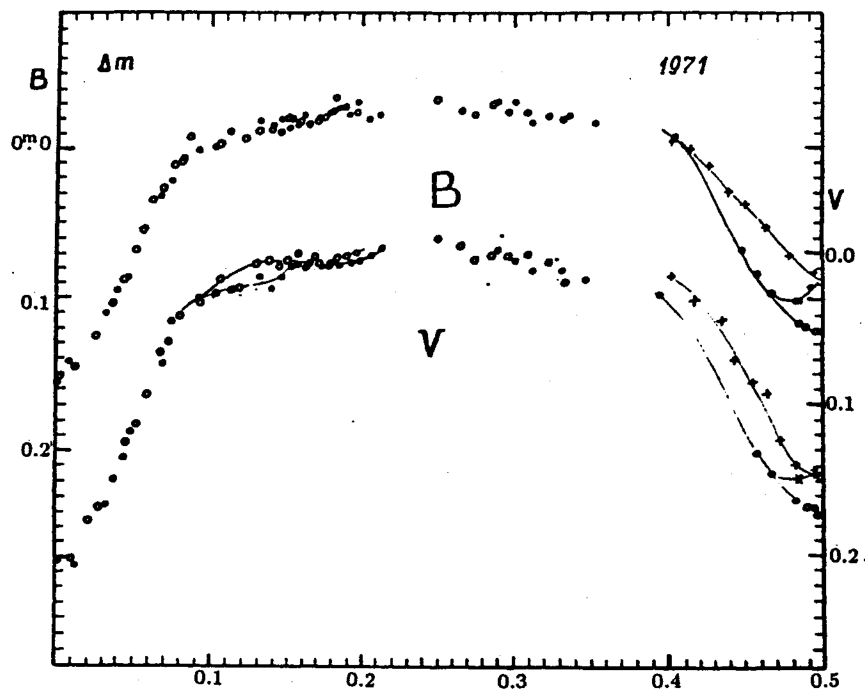

Figure 2 The B, V light curves of SZ Cam obtained by Polushina (1977).

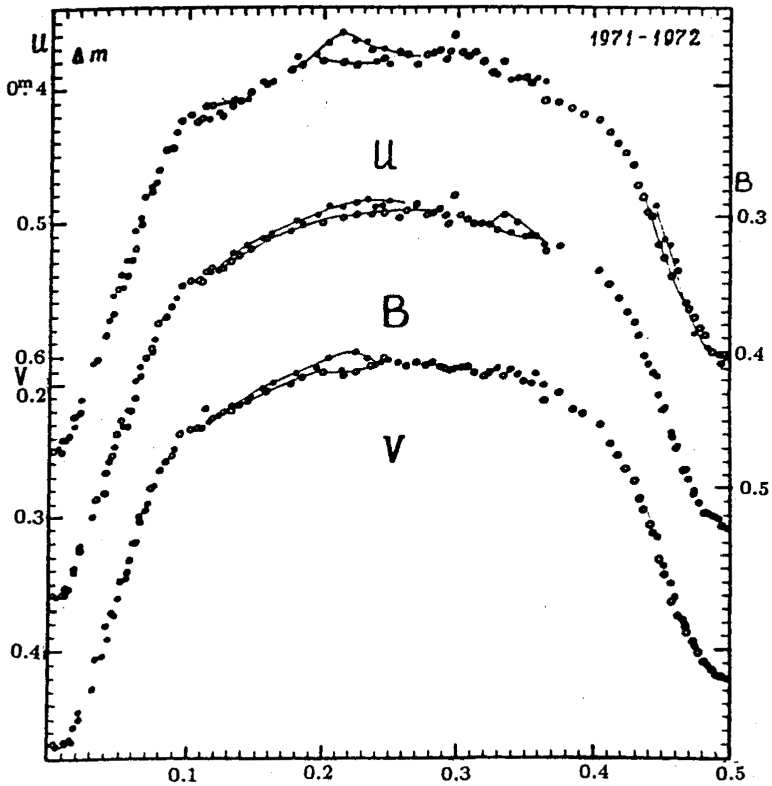

Figure 3 The UBV light curves of SZ Cam by Kitamura and Yamasaki (1972).

The main goal of the present investigation is to determine the mass loss rate from the secondary component using available photometric data. To this end all available observational data have been used (Table 2, Figures 1–6). Inspection of the light curves reveals that i) practically for all of them there are portions influenced by additional absorption or emission of non-photospheric origin, ii) there is a tendency of developing of certain depressions on a large time-scale (since 1930 up to 1988). The most stable light curve has been recorded between 1930 and 1937. On the contrary, the most noisy light curves have been observed in 1984–1985, iii) the depressions are of a markedly selective nature. Three types of them can be identified: a) continuous absorption appreciable already in the V range and strengthening towards the R colour. This powerful symmetric absorption at the maximum adjacent to the nearest secondary minimum and in the minimum II manifested itself during 1972–1974, considerably increased in 1984–1985, lost its symmetry and reappeared in B and U colours, b) some light curve distortions apparently are due to an additional emission maximum in U, V ranges involving strong hydrogen lines, c) additional distortions whose source is difficult to trace, d) peculiar light curves were recorded in August-October 1971. During this period

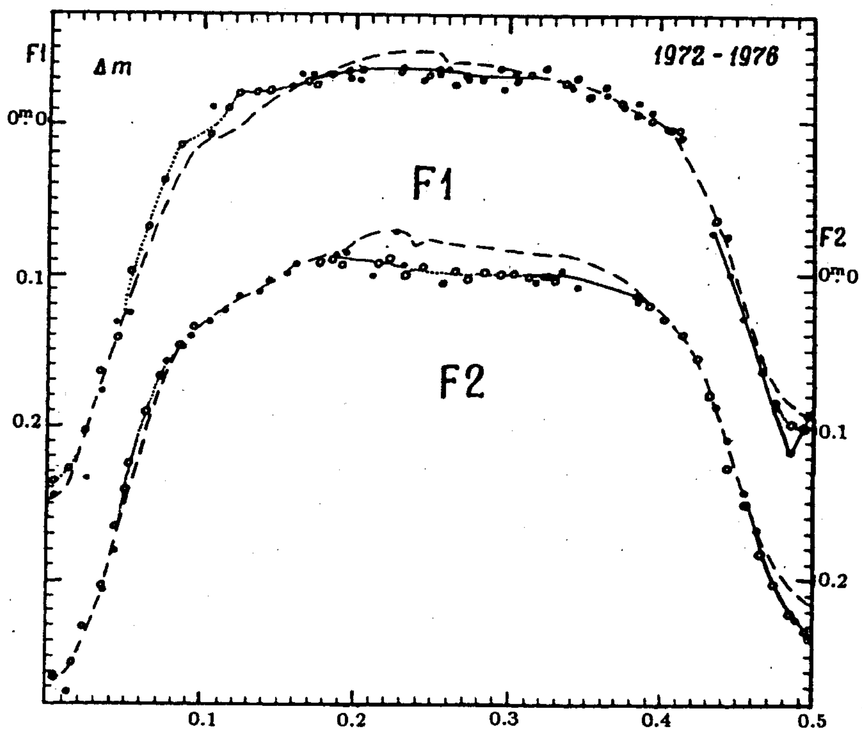

Figure 4 The photoelectric light curves of SZ Cam in F1, F2 filters (close to B, V colours of Johnson system, respectively) obtained by Chochol (1980).

the amplitude of the light changes has diminished by 0.079, 0.112, 0.073 in UBV colours, respectively, whereas the maximum brightness remained constant.

In some light curves an enhancement in brightness (most pronounced in U colour and by a factor of 2–3 smaller in B and V) is evident on the ascending branch of the primary minimum (at phase 0.22), notably for the light curves obtained by Kitamura and Yamasaki (1972). This effect is also present in observations made between 1930–1937. During other observational periods it may be partially obscured by other effects. This enhancement may be ascribed to the hot spot connected with the mass transfer from the secondary component. On the other hand, appreciable depression developed in the light curves was revealed for 1972–1974. It has increased in subsequent ten years reaching its maximum in R colour and is accompanied by a pronounced asymmetry. In view of the above mentioned peculiarities, intercomparison between the light curves is complicated since brightness measurements are normalized to maximum light. The light curves normalized to the same maximum brightness level show a tendency to increasing depth of the secondary minimum since 1972.

It is instructive to compare the behavior of the light curve with the period variations. No period changes have been recorded between 1930 and 1937. Un-

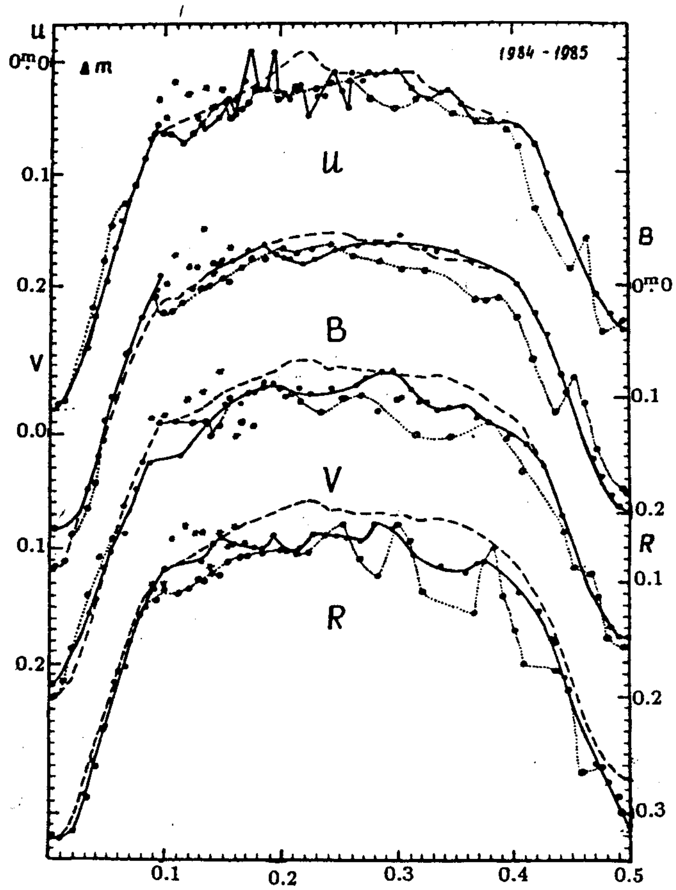

Figure 5 The UBVR light curves of SZ Cam obtained by Gorda and Polushina (1987).

fortunately, the relevant observational series was resumed only in 1971. By that time an abrupt period change has occurred. Between 1971–1984, a secular increase of the period $\Delta P/P = 5.942 \times 10^{-8}$ was recorded. An abrupt period decrease by $0.0940d$ (with respect to a secular increase) happened between 1985 and 1988, whence $\Delta P/P = 7.5 \times 10^{-5}$. The observed secondary minimum in 1988 was shallower by $0^m.031$, $0^m.029$, $0^m.050$ in R, V, B colours, respectively. Thus, one cannot help feeling that the decrease of the amplitude and the change of the period are interrelated events.

Most probably, brightness variations at maximum are due to the variation of the contribution from the envelope into the total light. Complicated temporal colour variations apparently are caused by the influence of strong emission lines. One may recall as well the results of multi-colour photometry of the related objects Serpentides by Young and Snyder (1982) who found the evidence for a simultaneous presence of several different temperature regimes in circumbinary gas of the latter.

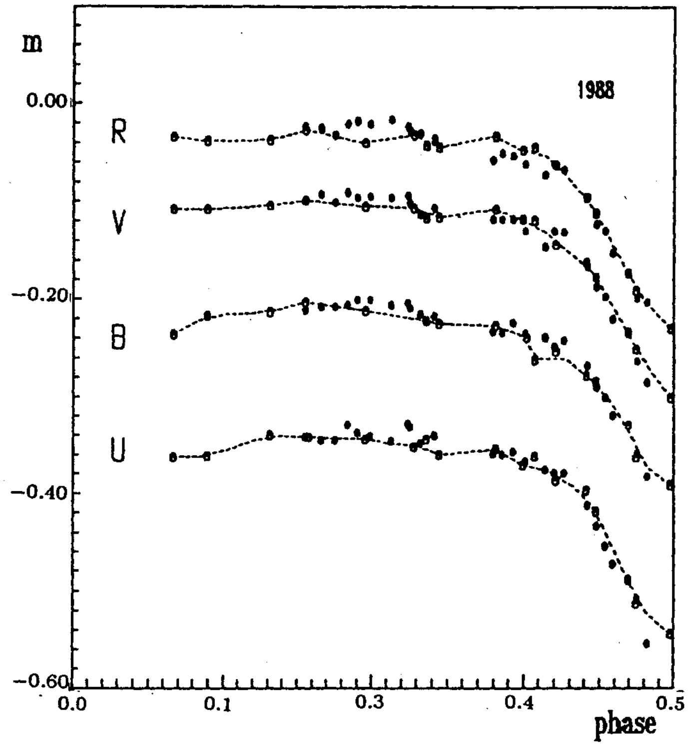

Figure 6 The secondary minimum and maximum brightness measurements in UBVR of SZ Cam obtained by Polushina (1992).

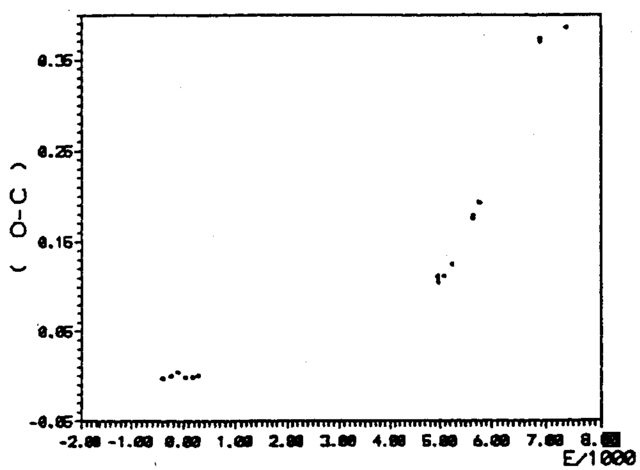

Figure 7 The $O - C$ diagram of SZ Cam between 1930 and 1988.

Table 2 Bibliography of photometric investigations

Technique	*Time sequence*	*Author*
photogr.	1930–1937	Wesselink (1941)
photoel. UBV	1971–1972	Kitamura and Yamasaki (1972)
photoel. UBV	1971	Polushina (1977)
photoel. F1,F2	1972–1976	Chochol (1980)
photoel. UBVR	1984–1985	Gorda and Polushina (1987)
photoel. UBVR	1988	Polushina (1992)

A new technique enabling one to take into account the influence of the anisotropy of the stellar wind upon the light curves of eclipsing binaries has been introduced by one of the authors (Pustylnik, 1994). The anisotropy of the stellar wind is due to the periodic variations of gravitational attraction causing the displacement of the sonic point. Since the matter density exponentially increases with depth in the chromosphere, even a small displacement of the sonic point can lead to a significant change of the mass flux $J = \rho_s v_s r_s^2$ with an angle between the line joining the centers of the components and the direction considered.

Table 3 Variations of maximum brightness of SZ Cam, an average at two elongations (variable minus comparison star in stellar magnitudes)

No	*Time sequence*	*U*	*B*	*V*	*R*	*Author*
1	1930–1937	–	−0.07	–	–	Wesselink
2	1971	−0.055	−0.03	−0.003	–	Polushina
3	1971–1972	−0.115	+0.05	−0.012	–	Kitamura
4	1972–1974	–	−0.035	−0.008 (F2)	–	Chochol
5	1984–1985	−0.010	−0.038	−0.035	−0.045	Polushina
6	1988	−0.060	−0.042	−0.005	+0.025	Polushina

The effect of the anisotropy of the stellar wind on the light curves of eclipsing variables has been evaluated under the following assumptions: i) both components are black-body emitters surrounded by a common non-spherical scattering envelope formed by a radially expanding stellar wind from one of the components, ii) only the opacity caused by scattering on free electrons has been taken into account, iii) both components are treated as point sources when calculating the optical depth along the line of sight. In addition to mutual eclipses with a conventional limb darkening effect being taken into account, the ellipticity effect along with the contribution from the "third light", i.e. the luminosity of the envelope has been considered.

Linear dimensions of the envelope are of the order of the accretion radius $R_{\rm accr}$ around the mass-gaining component (the values of $R_{\rm accr}$ as a function of v_s/v_e and q have been tabulated by Pustylnik, 1994), v_s/v_e being the ratio of the sonic to escape velocity and q is the mass ratio.

In the framework of our model, the influence of the stellar wind on the light curve is a combined result of the following factors: a) an additional screening effect of the radiation of both components which increases the depth of both minima, notably during the eclipse of the mass-gaining component, b) distortion of the light curve during minimum and increased widths of minima, c) diminishing of the eclipse amplitude due to the contribution from the brightness of the envelope. The albedo of the scattering determines which of the effects a) or c) is more important.

Thus, the effect of anisotropic stellar wind results in deeper and broader minima distorting both the ascending and descending branches of the minima, the shape of light curve changes in time. At a quantitative level, the influence of the stellar wind in the framework of our model is determined basically by three parameters: a) the gas optical depth (for instance, at elongation), b) the accretion radius R_{accr}, c) the third light, e.g., the luminosity of the envelope L_{env}. In principle, one should take into account minor effects such as the velocity field and the degree of anisotropy, the latter being dependent on the ratio of the sonic to escape velocity of the gas. Usually the light curves are rather insensitive to these subtle effects which are very important when dealing with spectral lines.

The choice of SZ Cam as the potential source of information on $\dot{M}$ based on its anomalous light curves was justified on the following grounds: a) both components are early type stars, close to B0 where numerous previous investigators find evidence on the presence of a substantial stellar wind, b) significant variations of both the shape and the depths of minima have been recorded, c) by all evidence, the radii of the components are smaller than the accretion radii, d) in an earlier paper (Pustylnik and Einasto, 1986) a satisfactory agreement between the observed and the model light curves has been found (though in the framework of a cruder equilibrium model).

Since the orbital elements and physical parameters of the binary have been repeatedly determined and are known with a satisfactory accuracy, we adopted the initial elements from the Catalogue of Close Binary Systems compiled by Svetchnikov (1986) and estimated maximum optical depth along the line of sight at the moment of superior conjunction of the mass-gaining component. From the optical depth $\tau(\pi)$ one can proceed to the mass loss rate $\dot{M}$ using the following relation (a detailed derivation can be found in Pustylnik, 1994):

$$\dot{M} = 10\pi\mu v_s \tau_2(\phi = \pi) f(a, i, r_2, R_a)^{-1}, \tag{1}$$

where

$$f(a, i, r_2, R_a) = \arctan\sqrt{\frac{R_a^2 - a^2\cos^2 i}{a\cos i}} + \arctan\frac{a\sin i - r_2}{a\cos i},$$

and $R_a = \sqrt{a^2 - 2a\delta(1 - \delta/a)}$, $\delta = \sqrt{R_{accr}^2 - H^2}$, H being the scale length for the isothermal drop-off of the gas flow near the first Lagrangian point.

Here on the left-hand side $\dot{M}$ is the mass loss in units of 10^{18} g/s, μ on the right-hand side is the molecular weight, v_s the velocity of the gas at the sonic point of the chromosphere of the mass losing component, R_{accr} the accretion radius and r_2 the radius of the mass-gaining component.

For mass loss rates exceeding a certain minimum value (depending on the absolute parameters of a binary and in typical cases being in the range of $\dot{M}$ =

$10^{-9} \div 10^{-7} M_\odot/\mathrm{yr}$) increase of $\dot{M}$ results in an abrupt change of the ratio of the minimum depths thereby setting an upper limit on the permissible values of $\dot{M}$. Thus, comparison of the model light curves with the observed ones enables one at least to assess an upper limit of $\dot{M}$, whereas in those cases where there are long observational series and the time-scale of $\dot{M}$ variations considerably exceeds the orbital period, one can determine more exactly the mass loss rate.

For a given set of orbital elements and physical parameters of a binary, our computer code has analyzed alternatively the case of mass loss either from a primary or a secondary component.

Inspection of the observed light curves of SZ Cam reveals that the depth of the primary minimum experiences slight temporal variations of an order of 0.01–0.03 in the intensity scale, for the secondary minimum they are somewhat greater. The attempts to solve the light curves assuming the mass loss from the primary component have not produced satisfactory results. If one assumes that the secondary loses its mass, a much better agreement between the model and the observed curves can be achieved (Figures 8, 9). The value of $\tau_2(\phi = \pi)$ determined from the light curves is of order $\tau_2 = 0.1$ and the respective mass loss rate is $\dot{M} \simeq 1 \div 5 \times 10^{-7} M_\odot/\mathrm{yr}$.

This is an estimate average over many years. The uncertainty in the final value of $\dot{M}$ is due to a limited accuracy of τ_2 as well as μ and v_s. If, for instance, we would assume the mass loss of $\dot{M} = 5 \times 10^{-6} M_\odot/\mathrm{yr}$ from the primary component, the resulting optical depth of gas along the line of sight at phase 0.5 would be so high that the secondary minimum would be deeper than the primary one. At the same time, the difference in the depths of minima depends on the luminosity of the envelope. Judging by the difference in the depths of minima, the luminosity of the envelope is no higher than 0.02–0.05 of the total luminosity of both components in the visible range. However, apparently L_{env} increases sporadically, during the observational season of 1971 (light curves secured in Giss AO) the depths of both minima were less than for all the remaining curves by about 0.07–0.08 in relative intensity units. The analysis of these light curves with the elements of orbit taken from Svetchnikov's catalogue produces satisfactory results only if one assumes $L_{\mathrm{env}} = 0.25 - 0.30$ and $\dot{M}$ approximately by a factor 3.5 higher than the above estimates but under the assumption of the mass loss from the primary component. Nonetheless, in this case the shape and the depth of the secondary minimum do not comply well with the observed curves.

As our computations demonstrate, the most advantageous for the verification of the validity of the adopted model would be the case when mass loss is connected with the star of a higher mass and smaller radius, a situation typical of the so-called "reversed Algols". In such a case both the shape and the depth of a secondary minimum will be rather sensitive to the density gradient of the envelope surrounding the primary component, the more the higher is the value of an inclination angle i. Unfortunately, in SZ Cam one deals with an opposite case where, by all the evidence, the mass loss is connected with a star of a greater radius whereas the inclination angle is relatively small ($i = 72°$).

The uncertainty in determining $\dot{M}$ is apparently due mostly to the value of the sonic velocity which is poorly known (the above estimate of $\dot{M}$ was based on the

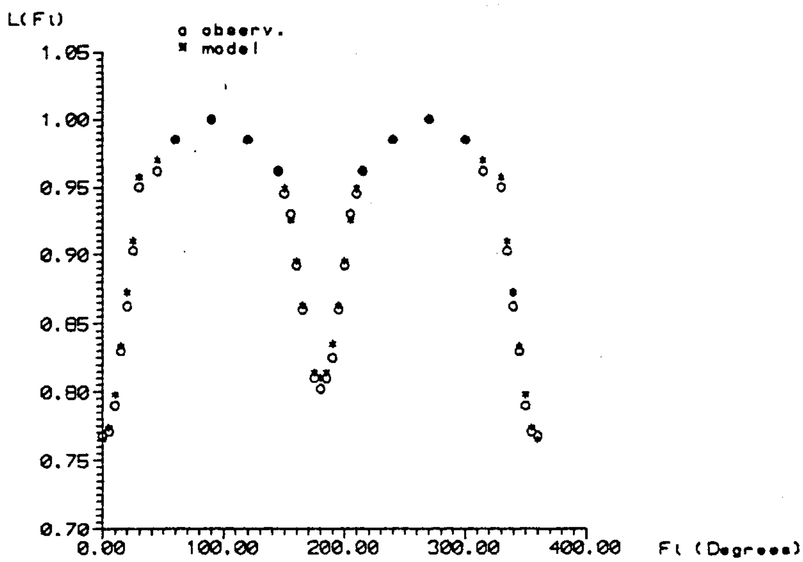

Figure 8 Comparison between the best fit model light curve (orbital elements and physical parameters indicated in Table 4) and the observed B curve of Gorda and Polushina (1987).

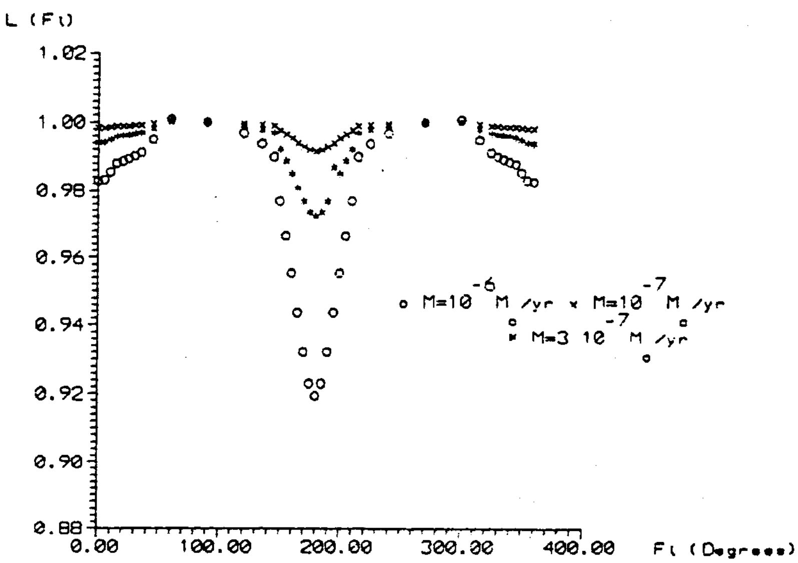

Figure 9 Light changes due to the influence of anisotropic stellar wind only (for orbital elements and physical parameters given in Table 4) and $\dot{M} = 10^{-7} M_{\odot}/yr$, $\dot{M} = 3 \times 10^{-7} M_{\odot}/yr$ and $\dot{M} = 10^{-6} M_{\odot}/yr$.

temperature of the chromosphere of $T \simeq 10^5 K$). In principle, independent estimates of $\dot{M}$ can be found using the measurements of the radio flux from H II regions. The most probable values of the parameters of a model for SZ Cam are summarized in Table 4 below.

Table 4 Elements of the orbit for SZ Cam and parameters of the circumstellar gas

$r_1 = 9.48 R_\odot$	$r_2 = 5.64 R_\odot$	$T_1 = 2.8 \times 10^4$ K	$T_2 = 2.65 \times 10^4$ K
$e_{11} = 0.14$	$e_{12} = 0.02$	$e_{21} = 0.16$	$e_{22} = 0.02$
$i = 71.7°$	$u_1 = 0.5$	$u_2 = 0.95$	
$\tau_2(\phi = \pi) = 0.1$	$\dot{M} = 1 \div 5 \times 10^{-7} M_\odot/\mathrm{yr}$	$L_{\mathrm{env}} = 0.02 - 0.05$	$R_{\mathrm{accr}} = 13.4 R_\odot$

Orbital elements i, r_1 and r_2 have been taken from Svetchnikov's catalogue, the effective temperatures $T_{1\mathrm{eff}}$ and $T_{2\mathrm{eff}}$ are fixed in accordance with the spectral classes of the components from the same Catalogue. The ellipticity factors correspond to a three-axial ellipsoid with the semi-axes being the best approximation of the inner Roche lobe, $e_{j1} = \sqrt{(a_j^2 - b_j^2)/b_j^2}$, $e_{j2} = \sqrt{(c_j^2 - b_j^2)/b_j^2}$ where j enumerates the components, b is the smallest of the semiaxes and a is the largest one. Parameters $i, r_1, r_2, T_{1\mathrm{eff}}$ and $T_{2\mathrm{eff}}$ are kept constant, the remaining have been found from the best fit of the model and the observed light curves.

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