PROPERTIES OF SYMBIOTIC STARS FROM STUDIES IN THE OPTICAL REGION

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1. Definition of Symbiotic Stars.

The traditional definition of Symbiotic Stars (SS) is that of objects which display a combination spectrum (e.g.Merrill,1950) that is emission lines requiring high-excitation conditions, superposed to the continuum and absorption features of a low-temperature star, most commonly an M-type giant. About one hundred of SS are known and listed today. It is anyway apparent that the classification criteria are rather rough, and since the excitation varies from the simple Me to SS with coronal emission, it is not well defined where a clear division should be made. As a result, the available lists include a very heterogeneous set of objects, probably different phases in stellar evolution. Moreover it has been remarked that SS show a rather confusing variety in their spectroscopic and photometric behaviour. Different intensities of both absorption and emission lines are reported from star to star. These facts indicate a high degree of individuality among SS, which is partly cause and/or effect of the adopted definitions.

In order to clarify this point, we recall the conditions proposed by Boyarchuk (1969): (a) absorption features of a late spectral type (TiO bands, metallic lines of low-excitation like CaI,CaII,FeII,etc.) must be seen; (b) emission lines of HeII,|OIII|, or highly ionised atoms must also be present (width for not more than 100 km/s); in addition he took into consideration that (c) the brightness can vary with amplitude up to 3 mag and period several years.

Some of these conditions appear not appropriate to Allen (1978), who has adopted the following different criteria: (a) the object must appear stellar; (b) emission from ions of IP $\geq$55 eV (e.g.HeII) must be present, at some time, while evidence for a spectrum G or later must also exist (from optical or IR data); (c) when clear evidence of a late spectral type is lacking, IP must at some time exceed 100 eV (e.g.|FeVII|).Variability is not considered necessary. These criteria allow to include, besides the SS according to the definition of Boyarchuk, also the recurrent novae (T CrB, RS Oph) and the "very slow novae" (RR Tel, V1016 Cyg) or type II SS (Paczynsky and Rudak,1980). It is suggested that the differences among these types are only in the timescale between outbursts, correlated with the range of variability, and that such nova-like outbursts

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may be a feature of all the objects which fulfill his criteria.
It has been also proposed to widen the definition of SS, as to include the so called "yellow SS", whose spectrum indicate a yellow-red dwarf-subdwarf star, instead of a red giant-supergiant (U Gem and Z Cam stars, also explosive variables). One can also consider similar to SS the VV Cep stars, showing the presence of an M supergiant and an OB star, on or above the main sequence (population I stars): they appear more luminous objects than classical SS, with which the evolutionary relation is not clear.

2. Photometric and spectroscopic evolution.

Typical SS present characteristic light variations, of more or less irregular shape and usually rather small amplitude ($\leqq$ 1 mag) on timescales of months or years, which are described as a complex of small simultaneous flares. Occasionally at larger time intervals they also undergo larger variations or outbursts (3-5 mag), where the increase in brightness is steeper than the decline. The explosive character of these variations allows to define SS as "nova-like stars" (Of course T CrB and RS Oph have true recurrent nova outbursts).It is to be said that different stars show different light curves (regular, irregular, Mira-type), and in addition that the variability characteristics may change for the same stars from time to time (quasi-periodic trends from 200 to 900^d ; periods with small variations; different levels of minimum; etc.). During the brightness variations the stars are much redder at minimum with increasing (B-V) color, while the UV excess also increases. In the two-color diagram the data for SS are rather far from the main sequence trend, which is explained with more than one radiation source.
Typical spectroscopic variations are well correlated with the light curve, although they have not always been followed throughout full cycles, nor in all stars. We have in general, but mostly following the well studied properties of Z And, which is a prototype of the classical SS (e.g. Swings and Struve,1941) :
i- Near minimum brightness, emission lines of low (e.g.permitted and forbidden FeII) and high excitation (e.g.HeII,|OIII|, in some cases up to |FeVII|) are present with large intensity. Together with the nebular spectrum, also an M-type giant (or supergiant) absorption spectrum is prominent with strong TiO bands.
ii- When the star brightens, the TiO bands become less conspicuous. Nebular and high-excitation permitted emissions progressively weaken, while the intensity of other emission lines may present fluctuations. An early-type shell spectrum develops, its continuum dominating the photographic region and covering the M spectrum.
iii- Around maximum light, the high-excitation and nebular emission spectrum disappears: only H,HeI,CaII,|OIII| remain. The emission/absorption ratio decreases toward the higher members of the Balmer series (emission from H_α to H_ε, then in absorption); the Balmer continuum is weakly present in absorption. The early-type shell spectrum is now well developed, with metallic lines (emission + absorption) of TiII,MgII,FeII,|FeII|,etc. In most cases also emissions of H and HeI have violet-displaced absorption components. At this time the spectrum is thus similar to that of the P Cyg-type stars.

It is often reported that the late-type absorption features completely disappear. Actually the most important TiO bands in the red-near IR are still visible during outburst, even when P Cyg features are revealed (Mammano et al.,1974).

iv- During the light decline we have the opposite trend. Shell characteristics of P Cyg components and metallic lines disappear, while a blue continuum becomes more evident. Higher Balmer members and their continuum come back to emission. Permitted and forbidden emissions develop again, the degree of ionization progressively increasing as luminosity declines (e.g.H,HeI,|OIII|,|NeIII|,|NeV|,|FeVII|). The ratio nebular/ auroral lines increases. At the same time the late-type features like TiO bands are gradually enhanced over the continuum.

The general spectral behaviour suggests that some kind of matter ejection in a nova-like manner is taking place, and that this matter forms an envelope. It originates the shell features, and later on in the expansion leads to the appearance of observed emission lines from permitted and forbidden transitions. This is somewhat similar to a nova outburst, with obvious differences in the ejection velocity and mass, but in which a similar mechanism may be operating. At maximum, faint |FeII| and absence of other forbidden lines give indication of a rather dense envelope, or at small distance from the exciting source. Not high dilution effects tell us that the P Cyg shell should have $r \sim 5R_*$, that is of the order of 10^6 km. This is a much smaller dimension than expected from the expansion velocity, since we do not have a single expanding layer, as it occurs in the normal P Cyg-type stars where continuous ejection is observed.

3. The three-component model for SS.

The energy distribution of SS and color variations show that the continuum is steeper and Balmer jump increases when the star becomes fainter. Boyarchuk (1968) has thus supposed three sources of energy in SS, finding a satisfactory agreement between observed and theoretical distribution.

(1) An M-type giant (in general say G-M) which plays an important role in the visual-red spectrum, like a normal star of its class. The typical deep absorption features are reduced, but well seen in the red-near IR region where there are no other significant energy contributions. Bands of TiO,VO, and other luminosity criteria whenever possible, allow a classification as class III. We do not find S-type stars, but at least in UV Aur a C-type object is clearly present. Typical parameters are $T \sim 4000°$, $R \sim 10^2 R_o$, $M_V \sim -0.5$, masses probably of the order of 3-7 M_o.

(2) A hot and small component from which the strong blue continuum must come. It has typical values of $T \sim 10^5°$, $R \sim 0.5\ R_o$, M_V=0-2, mass possibly of the order of 1-2 M_o. If one supposes that the late-type components of SS are normal giants, as favoured by the spectroscopic data, it follows that their hot components are located below the main sequence. In this region also central stars of PN, hot components of U Gem stars, novae, are also located, suggesting physical and evolutionary connections.

(3) Both stars are surrounded by a nebulosity, with $T_e \sim 17000°$, $n_e \gtrsim 10^6$-10^7 cm^{-3}, $R \sim 10^4 R_o$, mass of the order of $10^{-3} M_o$. Forbidden and permitted (at least in part) lines, usually found also in PN, are emitted from this

region and excited by the hot nucleus.
Forbidden lines of intermediate IP, e.g. OII 7325,SIII,ArIII, commonly among the strongest features in gaseous nebulae and nova ejecta, are absent or very weak in most SS, although lines of lower and higher IP (like |FeII| and HeII or sometimes |FeVII|)are usual in SS of comparable ionization stage. This absence is not due to an effect of density (which can be estimated from |SII|,|OII| doublets) but of ionization. The absence of these ionization stages is explained with a smaller dimension of the nebula, where ArIII and SIII are further ionized. SIII requires 35 eV, very close to the IP of OII, and OIII is indeed represented by strong lines.
Some permitted emissions are usually associated with the nucleus: CIII, NIII (showing the P Cyg effect), weak OIII, and (probably to some extent) H,HeI. This nuclear spectrum would indicate a temperature of $T_{\star}$=5 10^4 - 10^5°, in agreement with the excitation stage in the nebula. Although the 4640 feature is typical of WR stars, it is not implied that the nucleus were an object of this type, where the emission is much broader. It is also possible that the "nuclear" emissions are produced in the innermost regions of the nebular shell.
On the other hand the low IP emissions of FeII,|FeII|, are observed simultaneously with |OIII| or even |FeVII|, a behaviour not recorded in the nebular spectrum of PN or novae. This presence of different IPs leads to suppose that they are not emitted in the nebula, but are possibly located in the extended atmosphere of the M giant or in a part of the envelope very close to it. In the dense atmosphere of the cool star single ionized atoms and TiO can be shielded, and further ionization or dissociation is prevented.
With the three-component model of SS one can determine the relative contribution of radiation from each source at any wavelength and time. It appears that the cool component does not undergo remarkable brightness variations, neither does the nebula, as confirmed by the spectral characteristics not changed since before the outburst. On the contrary the variations of the hot component are larger, so they determine the stellar variability on the whole. The temperature of the hot component should increase simultaneously with its magnitude; which is in agreement with the observed spectral and color changes of SS. From the computations in this model, the visual magnitude and temperature of the hot component result to vary in such a way that L_{bol} does not significantly change. In conclusion the outburst is most likely explained with the presence of a transient optically thick envelope surrounding the hot star.The individuality of SS is possibly due to a range in densities and velocities during this ejection phase. The observations of TiO bands together with the P Cyg-type spectrum support the interpretation that the shell is expanding around the hot star; since it is responsible for the high excitation, we understand why no HeII and faint HeI are observed during the P Cyg phase. We may think that also mass ejection takes place from the late-type object, especially if in the LPV stage, and it contributes significantly to the formation of the nebula. Also the ejection around the hot source can be itself a result of mass outflow from the cool companion. The nebular spectrum is similar before and after the outburst, suggesting that the distance of the nebula from the exciting component is large in

comparison with the radius of P Cyg-type shell. The weak nebular spectrum at maximum light can be understood in terms of partial volume of ejection, not completely shielding the exciting radiation, or of little amount of ejected mass (dilution before recombination).

4. Evidence for the binary nature.

It has been now assumed that SS are interacting binary systems, consisting of a red giant which provides the low-temperature spectrum and the required gas, and a hot star being the source of high-excitation lines which are difficult to be explained with the observed color temperature. Both are surrounded by a nebula of relatively small dimension and high density. All the basic observational data can be explained in this double-star hypothesis, which is the oldest and appears till now the simplest one. Of course it is not needed it is valid for all the objects classified SS, since they do not form an homogeneous class. Evidence for this interpretation is found as follows :

(a) The behaviour of the different components is well correlated with the spectral and photometric variations. The location of spectral features, indicating different physical conditions, is explained in the easiest way.

(b) Radial velocity curves with long periods (of several 10^2 days, mostly in agreement with light variations) are observed as in spectroscopic binaries. Lines of the red giant show an opposite trend to that found for high-excitation emissions associated with the hot source. The periodic changes are not accompanied by changes in the M spectrum. Among these cases we have e.g. AG Peg (820^d),BF Cyg (750^d),RW Hya(370^d),Z And (725^d), AX Per(880^d),CI Cyg(885^d),possibly R Aqr(9740^d). AG Peg (Hutchings et al., 1975) is rather strange having an $1M_o$ hot star with mass transfer toward the cool primary (not filling its Roche lobe), contrary to what expected. Although it is not clear, it might represent material lost after outburst. AG Peg was characterized by a protracted outburst, lasting much more than in other classical SS. If one include the recurrent novae among SS, T CrB is another known binary system with $P=228^d$, where the M giant looses mass onto the $2.6M_o$ companion, accreting through a disc.
Besides the objects with established periodicity, there is another group in which at least variations of radial velocity are recorded, and which deserve careful investigation. The orbital periods cannot anyway be easily detected when large orbits are present.Of course one must be careful in considering which lines may reflect an orbital motion, for instance most emission lines should arise from the surrounding region, and gas motion would add variable components to the data.

(c) A particular example is given by AR Pav, the first eclipsing variable among SS (see Thackeray,1959). During the orbital period of 605^d (probably indicated also by velocity variations) we observe that low-excitation lines like FeII,|FeII|, and TiO bands are better seen during the eclipse, while HeII disappears, H and HeI are weakened, and nebular emissions persist with small attenuation. We interpret these results with the occultation of a hot nucleus (primary star) exciting a dense nebula with stratification like in PN, by a cool giant filling its lobe.
While asimmetric lines led to the suspicion that also in Z And we may have a partial occultation, we have now a second case in CI Cyg with repea

ted eclipses observed in 1975 by Belyakina (1979) and during summer 1980 by many others. The period is P=885^{d}, and is accompanied by correlated spectroscopic variations.

(d) A rapid flickering (0.04 mag in 5^{m}) in blue light, together with larger and slower flares (0.1 mag in 15-20^{m}), has been reported for CH Cyg (Slovak and Africano,1978). This type of photometric activity, typical of the binary dwarf-novae, is a strong evidence for a binary system in which mass transfer between components is taking place. It is supported by the strong blue continuum detected at all phases over a typical M6III spectrum. The authors suppose a widely separated binary where the cool component (a SR giant?) is blowing a stellar wind, then interacting with the hot component. One must however note that CH Cyg (with low-excitation spectrum) is not a typical member of the SS group, where such flickering activity is not usually present (Walker,1977).

(e) The binary nature for SS appears to be confirmed by observations in the ultraviolet and infrared regions. Evidence is respectively reported for continuum of and lines excited by the very hot component, and continuum,features,in some cases typical variability of the cool giant.

(f) We may finally note how the proposed association of late giant and hot underluminous stars is displayed by other objects. Ordinary and dwarf novae where anyway the cool primary is a dwrf star, are binary systems. Because of the similarity between SS and some PN in spectral properties, it is to recall that also binary nuclei for PN are increasingly detected.

5. Spectroscopic properties and anomalies.

In describing the spectra of SS, and trying to deduce physical information from them, it is necessary to take into account that effects of stratification af layers and asymmetry are clearly present. Thus in some important lines, contributions from more than one region are probably involved, and derived parameters cannot be reliable ones. Otherwise different parts of the system, with particular velocity,temperature and density conditions, can be responsible for different lines. This seems to explain the difference in profile and velocity observed for the |OIII| lines at 4363 and 5007-4959 Å: the first one is usually narrow and variable, the other are broader and less affected by velocity variations. They respectively indicate geometrical and kinematical properties of the inner zone where 4363 is emitted, and of the lower density extended region from which $N_{1,2}$ mostly come.For the same reasons displacements of different lines in radial velocity curves are recorded. There can also be contributions from a gaseous stream between components, affecting the regularity of an orbital motion: phase shifts are indeed observed from forbidden and permitted lines in the two line systems.

Attention must be paid to the interesting behaviour of some lines (see e.g. Swings,1970). In the HeI spectrum, a peculiarity is known for the enhanced singlet/triplet line ratio, which is moreover sometimes variable indicating time variations in the physical conditions. Singlet and triplet emissions also differ in showing different velocity curves. The OI 8446 triplet is usually strong in emission in SS, contrary to what observed in PN or novae: it is commonly explained with the mechanism of Ly_{β} fluorescence, which is favoured in the case of expansion of the emitting gas. Two strongly correlated (same region, same atom) features at

6830-7090 Å have been recently discussed. They have no certain identification, are rather broad (20-30 Å), often variable; certainly they arise in a different region from that of forbidden lines. They are associated with only SS of high-excitation stage (IP$\geq$ 100 eV) where λ 6830 can be one of the strongest emissions. Allen (1980a) suggests they may be velocity broadened since formed in a rotating cloud like disc in dwarf-novae and X-ray binaries, which could be generated around the hot component by mass transfer from the cool giant. Also the feature at 6830 Å is not absorbed by TiO bands.

6. Single-star interpretations .

Owing to some difficluties among which the absence of radial velocity variations in many SS, single-star models have been also proposed. One of the alternative pictures described SS as single cool stars with very extended and dense coronae. High excitation should be in it produced from shock waves, or magnetic activity from the surface, but this remains the main difficulty. Usual absence of coronal lines, and the blue continuum detected at quiescence in several stars, are not understood in this type of model.

Otherwise it is proposed that the SS may represent a transition between the red giant and blue degenerate phases, thus obtaining two sources of radiation in the evolution of a single object. They would consist of a very hot, small, condensed core (remnant) surrounded by an extended atmosphere, possibly consisting of different layers or partial envelopes. This latter would be the M-type atmosphere now dissipating into space, and in whose outer parts the cool absorption spectrum can be formed, shielded in dense clumps, whereas the hot emissions would originate in the inner part. At the same time the nucleus is contracting and remains separated from the extended atmosphere.

A more recent version of this type has been proposed by Kwok to explain the origin of planetaries from objects like V1016 Cyg and HM Sge (e.g. Kwok et al.,1978; Kwok and Purton,1979). Widths and intensity evolution are predicted for different emission lines, and these tests for the model should be checked by appropriate observations. The transformation of the red giant through continuous mass loss should indeed lead to systems of lines typical of low-density from the red-giant slow remnant wind, of permitted lines due to the high density from the high-velocity new stellar wind of the exposed nucleus, and of forbidden lines of moderately high density from the shell which is being formed at the interface of the two winds by their interaction. In this evolution the first system should weaken with time. Some reported observational data may agree with this picture. We anyway think that it is still hard to explain in this way the origin of the cool continuum, its periodic variations, and the molecular features within which the emission spectrum is not obviously absorbed as foreseen in this case. It rather seems to indicate that an M star is present in the system.

7. The "very slow novae" and BQ| | stars.

A sequence of morphological properties, connecting typical SS (no ArIII and SIII, no IR excess, no radio emission) to compact PN like NGC 7027 (strong ArIII and SIII, IR excess, radio emission) can be found through objects like V1016 Cyg (strong radio emission, large IR excess, similar

ArIII and SIII doublets),HM Sge,V1329 Cyg. They form a small group of stars which underwent a single large (~5 mag) outburst, and then remain at maximum or fade in a very long time, from which the name of "very slow novae" (see e.g.Allen,1980b; Mammano and Ciatti,1975). Before the outburst they presented colors and spectrum with low-excitation emission typical for LPV. The emission spectrum, already present during the rise in brigthness contrary to that found in ordinary novae, has successively increased its ionization stage toward very high levels (up to |FeVI,VII| and λ 6830),and is very rich in forbidden lines (Ciatti et al.,1979, and references therein). Symbiotic characteristics are found in the visible-near IR continuum and features of a very cool source. In particular at least in V1016 Cyg there are Mira-type pulsations which appear to confirm its binary nature, although the single-star model has been also applied to this star.

These objects are correlated with the slow novae RR Tel,RT Ser, although in these cases the spectrum at maximum indicated a true nova outburst (see again Ciatti et al.,1979). In RR Tel the LPV pulsating before maximum is still detected with the same periodicity (Feast, quoted by Allen, 1980b) as it may be the case for V1016 Cyg. A number of similarities between these two objects have been remarked.

They are also suggested to represent early stages in the formation of PN, at least some kinds of them, since the large envelope already results in a very similar spectrum, and there is evidence for further expansion. In V1016 Cyg the nebula expands with 35 km/s, while material is ejected by the central star at 105 km/s.

Such "very slow novae" match the properties of the so called type II SS, or "symbiotics with dust" in which strongly correlated radio emission and IR excess from dust shell are recorded. Their cool components are mostly of very late spectral type, and present variations typical of Mira stars. One can explain all these differences with the classical SS, by considering that emission and dust are strongly favoured by low-density, and this means more extended envelopes, in whose outer parts this condition can be reached. Mira stars which have considerable mass loss by stellar wind well account for the formation of extended nebulae (later spectral type - stronger mass loss - more extended nebulae - lower density - forbidden lines and dust).The Mira characteristics are here enhanced so that the question has been put on whether the dust is cause or effect in symbiotic systems containing a Mira (Feast et al.,1977).

The photometric properties of this class make possible that other SS of high excitation and unknown variability had underwent, on longer time scale, a similar large outburst. May be there is a graduality in light and spectral variations, similar to that among novae of different classes, which would suggest a similar mechanism. It has been proposed that the same accretion of matter lost by the giant may trigger in the hot component H-shell flashes with increasing UV flux into the nebula, which mimics the unveiling of degenerate core in the single-star model. Interval and duration of flashes would depend on the accretion rate, thus providing a possible explanation for several cases of variability. A similar model applies to the novae, and RR Tel might represent a transition case in a sequence dwarf novae-classical novae-SS.

Also the soft X-ray emission, absent in other SS of any spectral excita

tion, is found only for the "very slow novae". The intensity declines after the optical outburst, so that it can be related to the occurrence of thermonuclear surface burning.
These particular symbiotic objects are connected with the subclass of BQ|| stars which are also characterized by IR excess and sometimes by radio emission (Ciatti et al.,1974). Most of them are of lower spectral excitation than classical SS indicating that their hot components could be of lower temperature. There are no evidences of optical outbursts, while the spectrum shows typical lines of relatively high density (10^6-10^7 cm^{-3}) in the nebula, and support their binary nature with the presence of bands of late-type stars. They possibly represent a similar evolutionary phase in a different mass interval than the other SS.

8. Comparison of SS with other classes.

The spectroscopic properties of SS at different times have been compared with those of other classes of objects, like Wolf-Rayet (much denser and smaller envelopes), Of stars (lower excitation and small, dense shells), P Cyg-type stars, and Novae (larger ejection velocity and mass, transient nebulosity, binary nature). As already discussed, most remarkable is the similarity of the nebular spectrum of SS like Z And with that of PN of high excitation: forbidden lines are well represented, stratification effects are found, a great range in excitation conditions (e.g.NGC 7027) occurs, spectral variability is observed in both classes. For these reasons some SS were first classified as PN and the same is still possible true for other objects, where at least the cool spectrum is relatively less conspicuous. The main differences are in the intensity of λ 4363, weakness of |OII| 3727, in the Fe spectrum, in the presence of usually strong OI 8446, and absence of intermediate excitation lines (|ArIII|, |SIII|) in typical SS. From all these properties we infer that their nebulae have higher density (of the order of 10^{6-7} against 10^{3-4} cm^{-3}). A much closer similarity is found with compact planetaries like IC 4997 which is sometimes considered intermediate object between nebulae and stars.
Evolutionary connections among SS and PN are thus envisaged, with SS possible progenitors having smaller and more compact ejected envelopes, but the picture is not yet clear. It appears anyway that expansion velocities are comparable, as well as the location in the HR diagram and their kinematical and galactic distribution. Also in the binary star hypothesis for SS, we again recall the increasing number of binariety in well studied nuclei of PN too.
On the other hand Sahade (1965,1975) has most considered the relations of SS with other types of eruptive variables: U Gem and Z Cam, classical Novae, ultra-short-period binaries. In this discussion, the symbiotic phenomenon requires a binary system, with the presence of a hot subdwarf component together with a red giant (or supergiant) which is filling its Roche lobe. These conditions still hold for the other groups of variable stars undergoing outbursts related to mass accretion, except that the cool component is not a giant. In particular objects like T CrB are interpreted as transition cases between Novae and SS. Different orbital and variability periods imply however different evolutions. A discriminating parameter could be the evolutionary phase of the subdwarf compo

nent, larger outbursts corresponding to older and hotter stars.
In order to define the evolutionary status and perspectives for SS, we need more accurate data and analysis. Unfortunately we do not have many mass determinations for their components, and the evolutionary traks in the region they cover in the HR diagram are not well known. We may add some information on their distribution inside the Galaxy (Boyarchuk,1974) although the relatively small number may be not appropriate for statistics. There is no particular distinction with the properties of PN, in galactic latitude and longitude, and thus they have been assigned to the old disk population. One can also obtain that the total number of SS would not significantly exceed 10^3, that is they are rather rare objects in the Galaxy. We can also see that the abundances are not well determined for these stars. Boyarchuk reported that 8 SS do not differ in chemical composition from the solar atmosphere, but different results have been presented elsewhere. One has to be careful in studying line intensities which likely come from a range of different layers in the system: better calibrated high-dispersion spectra are needed for this purpose.
Without going into details, we may finally quote the works on the origin and evolution of SS presented by Tutukov and Yungel'son (1976), Paczynsky and Rudak (1980), all in the frame of binary model with mass exchange, as well as that of Bath (1977) where the properties of the outbursts and their similarity to those of novae are explained.

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