Eruptive Binaries

JÓZEF SMAK (Warsaw)

I. Introduction

Two periods can be distinguished in the past history of our subject. The first period, which begun about 100 years ago, was dominated by intensive studies of novae and U Gem type stars at their outbursts and led to a fairly detailed, photometric and — particularly — spectroscopic description of these phenomena. The faintness of all these objects at minimum was a seriously hampering circumstance for observing them spectroscopically outside of their outbursts and it was only about 30 years ago that two pioneering surveys — of novae by HUMASON (1938) and of U Gem type stars by ELVEY and BABCOCK (1943) — begun to unravel their true nature.

The second period was opened in mid 1950-ies with the discoveries of the binary nature of AE Aqr (JOY 1954), DQ Her (WALKER 1954), and SS Cyg (JOY 1956), the first binary-models of UX UMa (WALKER and HERBIG 1954) and AE Aqr (CRAWFORD and KRAFT 1956), and a prophetic hypothesis by STRUVE (1955) that all novae and nova-like objects might be binaries. This hypothesis seems now to be fully verified by the results of extensive spectroscopic surveys by KRAFT (1962, 1963, 1964). His results, together with those of the parallel photometric investigations by KRZEMIŃSKI, MUMFORD, WALKER, as well as the results of many others, provided us with a wealth of information concerning the general properties of the eruptive binaries and gave a stimulus for several theoretical investigations.

The ultimate goal of our studies of eruptive binaries is to solve the following three major problems:

(a) the evolutionary origin of these objects and of the observed variety of their types;

(b) the mechanism, or mechanisms of their outbursts and other types of the nova-like variability; and

(c) the role of eruptive binaries in the evolution of the Galaxy.

At the present moment we are still rather far from giving definite answers to any of these questions. There are good reasons to believe, however, that we are just entering into the third period which will bring us much closer to the solution of the enigma of eruptive binaries.

It is impossible to give, in a short review, a full summary of all the observational and theoretical results obtained in this field, nor to give a complete list of references to individual papers. The reader is refered here to the more extensive reviews and books published during the last 15 years (ARKHIPOVA 1970, GORBATZKY 1970, GORBATZKY and MININ 1963, GREENSTEIN 1960, JOY 1960, KRAFT 1963, 1966, McLAUGHLIN 1960, MUMFORD 1967a, MUSTEL 1970, and PAYNE-GAPOSCHKIN 1957). The aim of this review will be to discuss selected topics which — in the author's opinion — seem to be the most important and intriguing. One important group of problems will, however, be omitted completely, namely the vast area of the spectroscopic and dynamical problems of the expanding envelopes of novae.

II. Classification

The commonly adopted classification of eruptive binaries is based entirely on their behaviour at outbursts or other large scale variations. Accordingly we have:

(a) novae (N), with a subtype of recurrent novae (RN),

(b) U Gem type stars (U), with a subtype of Z Cam variables, and

(c) nova-like objects (NL).

The amplitudes of outbursts of novae are between 9 and 13 mags. Those of recurrent novae are between 7 and 9 mags, with their outbursts repeating on a time-scale of 10—100 years. The U Gem type outbursts have amplitudes between 3 and 6 mags and repeat on a time-scale of 10—200 days; those of Z Cam stars are more frequent and of smaller amplitudes and, in

https://doi.org/10.1017/S0252921100033042 Published online by Cambridge University Press

addition, protracted „hesitations" at an intermediate brightness are often observed. Finally, the nova-like objects, while being spectroscopically and photometrically similar to other groups, show only irregular variations with amplitudes up to about 3 mags; it is possible that at least some of them are actually old novae, whose outbursts went unrecorded in some distant past. The total energy emitted during an outburst in the optical region amounts to about 10^{45} ergs for novae and about 10^{44} ergs for recurrent novae, but only $10^{38}-10^{39}$ ergs for the U Gem type variables.

The amount of mass ejected during an outburst is strongly correlated with total luminosity. It amounts to about $10^{-3}\,\mathfrak{M}_\odot$ and $5 \times 10^{-6}\,\mathfrak{M}_\odot$ for novae and recurrent novae, respectively, the latter estimate being based, however, on a single case of RS Oph only. In the case of the U Gem type stars there is actually no convincing evidence concerning the mass loss at outbursts and the often quoted value of about $10^{-9}\,\mathfrak{M}_\odot$, as based on arguments of similarity with novae (GORDELADSE 1938), can hardly be considered as meaningful. Similarly, there is no evidence concerning the mass loss from eruptive binaries between outbursts including the nova-like objects. These differences in the occurence of the ejection of matter are at least partly responsible for the observed differences in the spectroscopic behaviour of novae and U Gem type stars at their outbursts.

The common property of all objects considered is their binary nature and there are good reasons to believe that a certain combination of characteristics of a binary system is a necessary condition for an object to be an eruptive binary. The most relevant questions in this context are: which of the basic characteristics of a binary are indeed of primary importance for the phenomena considered and which of them are responsible for the observed variety of types?

In a partial answer to the first question we could try to define an eruptive binary as a close binary system with the primary component being a highly evolved object of low luminosity and the secondary component being a late type star filling its Roche lobe; the ejection of matter by the secondary and the formation of a disk surrounding the primary become a natural consequence of such a combination and form the logical second part of our definition. One should add, however, that such a definition is not precise enough to draw a distinct demarcation line between the nova-like systems and certain „related" objects, such as symbiotic binaries or, probably, some of the X-ray sources. This implies that the definition of an eruptive binary must also include an answer to our second question. In this respect, however, the situation is very unsatisfactory: the eruptive binaries, when observed outside of their major outbursts, show a large number of similarities, but the differences between the different types are not obvious. Some of them will be discussed below and we shall see that if any such differences seem to be present, they are barely significant when compared with a large spread of properties whithin each type considered.

III. A Model for Eruptive Binaries

Investigations of individual objects have led to fairly detailed models for many of them and while there are still certain objects and certain features which remain unclear, it is possible now to discuss all eruptive binaries in the framework of a single, universal model. This will be done here starting from some general, qualitative theoretical considerations. Let us consider an eruptive binary (Fig. 1), in which the secondary component loses mass through the internal Lagrangian point. Many dynamical details of the process of mass-exchange are reasonably well understood within a purely mechanical approach (cf., e. g., KRUSZEWSKI 1966, 1967). The matter ejected by the secondary is streaming toward the primary carrying a large amount of the angular momentum. This leads to the formation of a gaseous disk rotating around the primary component. The density of matter in the disk is sufficiently high for a collision to take place between the stream coming from the secondary and the outer part of the disk. As a result a hot spot is formed in the region where the collision takes place. The geometry of the stream particle trajectories (e. g. KRUSZEWSKI 1964, KRZEMIŃSKI and SMAK 1971) is such that in the most typical cases the spot must be located at the phase angle roughly

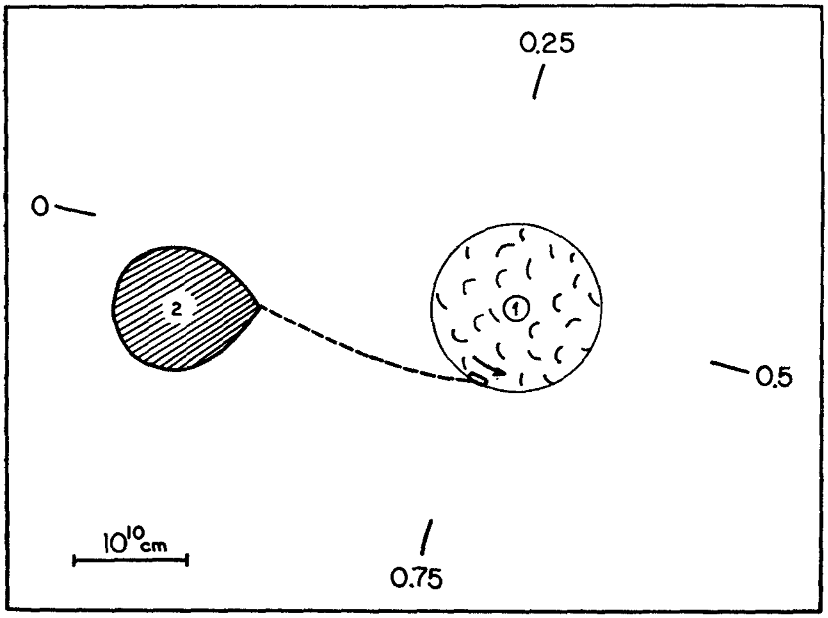

Fig. 1: A model for WZ Sge (KRZEMIŃSKI and SMAK 1971). The phases are on the observed system, the spot being eclipsed at phase zero.

between 0.8 P and 0.0 P, except for very small disks, when its phase angle can be smaller than 0.8 P, or for large disks and large direct velocities of ejection, when it can be larger than 0.0 P.

The total amount of radiation and its spectral properties are, in the case of the spot, as well as of the disk, rather complicated functions of the physical conditions. A common feature of nearly all systems is that the disk and the spot are optically thick in the optical range.

The integrated properties of a system depend, of course, on the relative contribution from the two stellar components, from the disk and from the spot. Since the primary component is usually quite faint, the observed spectrum is dominated either by the secondary and the disk plus the spot or — when the secondary is faint — by the gaseous components alone. Without a detailed model for the disk and for the spot no meaningful general predictions can be made concerning the spectroscopic characteristics. From a purely photometric point of view, however, the situation is simpler. Depending on the relative contribution from the spot we can expect two photometric types to be present among systems with orbital inclinations being not too small, particularly among the eclipsing ones:

Type I will occur when the luminosity of the spot is comparable with that of the disk. Then, due to the obscuration by the disk, a broad maximum (usually referred to as the shoulder) should be observed, lasting for about one-half of the period and centered at the phase when the spot is seen face-on. Even with an intermediate inclination of the orbit the shoulder may be a sufficiently pronounced feature of the light curve to indicate, in spite of the absence of eclipses, that we are dealing with a Type I system. The location of the spot has two important observational consequences. First, the maximum of the shoulder will usually precede the moment of conjunction. Second, if the orbital inclination is favourable for an eclipse to occur, it will consist primarily of the occultation of the spot by the secondary component with secondary effects due to the occultation of the disk. Simple geometrical considerations (SMAK 1971a) lead to the following conclusions concerning an eclipse of the spot:

(a) it should occur after the conjunction,

(b) its ingress should be longer than its egress, and

(c) if the radius-vector of the spot r_s is variable, the width of eclipse should be larger for larger values of r_s.

Properties (a) and (b) together with the existence of a pronounced shoulder are thus the basic classification criteria for Type I systems.

Type II will occur when the luminosity of the spot is low, as compared with the luminosity of the disk. Then the shoulder will be less pronounced and the eclipse, if present, will be caused primarily by the occultation of the disk. The occultation of the spot will be a secondary effect; its central phase will be shifted, as compared with the main eclipse, toward larger phases producing an asymmetry of the overall curve, with the egress being longer and less smooth than the ingress. This property, together with the existence of only a small shoulder, may be considered as useful criteria for Type II systems. When no eclipse is present, then no distinct features will be present in the light curve and in such cases proper classification will be impossible.

The best example of a Type I system is U Gem. Fig. 2 shows its light curve together with a tentative reconstruction of these portions of it which are affected by the effects of eclipse. Table I lists all the objects which can be tentatively identified as Type I systems using the criteria specified above. It includes also two marginal cases: WZ Sge, which shows the U Gem type light curve only occasionally, and EX Hya, on account of its close similarity to WZ Sge.

The best examples of Type II systems are listed in Table 2. The reader is refered to the original papers for the observational and interpretational details. Here it is worth to make

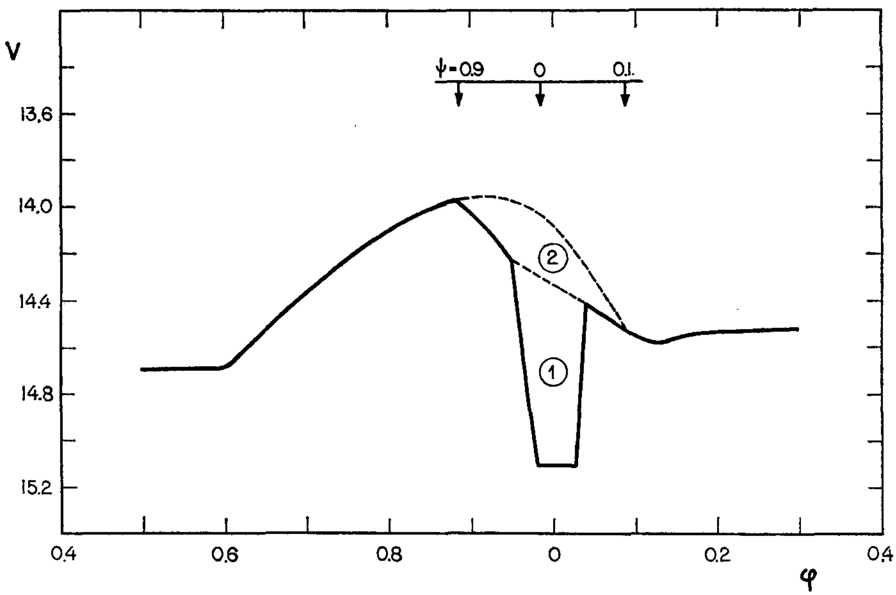

Fig. 2: Schematic light curve of U Gem on JD 2438030/31 (after KRZEMIŃSKI 1965). Broken lines are the reconstructed parts of the curve, corrected for the effects of the eclipse of the spot (area marked „1") and of the partial occultation of the disk (area marked „2"). Phases ψ marked above the curve are counted from the moment of conjunction and show that the eclipse of the spot occurs after $\psi = 0$ (cf. SMAK 1971a).

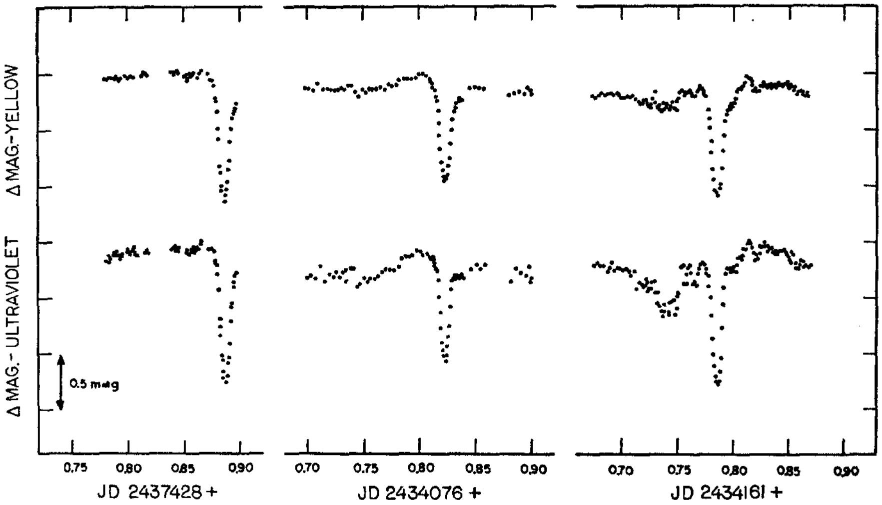

Fig. 3: Light curves of UX UMa (JOHNSON, PERKINS and HILTNER 1954, and KRZEMIŃSKI and WALKER 1963). Zero-points of the magnitude scales are arbitrary.

two general comments. First, that the shapes of the eclipse curves of Type II systems, which were difficult or impossible to interpret on the basis of a conventional model involving two spherical stars (WALKER 1956, 1958, 1963a), can be understood in terms of the eclipse of a disk (KRAFT 1959, GORBATZKY 1965b, IVANOV 1969); further studies along this line may provide important data on the structure of disks. The second comment concerns the relatively unstable shapes of the light curves during and outside of minima. As an example, Fig. 3 shows a variety of curves of UX UMa, starting from a nearly shoulder-less behaviour on J. D. 2437428, through a typical case of J. D. 2434076, to a strange behaviour on J. D. 2434161, when a deep depression — instead of a shoulder — occured prior to the eclipse. The variable shapes of the eclipse curves will be discussed in Section VII.

Let us now compare the content of Tables 1 and 2. In spite of the uncertainties involved it is possible to make two conclusions:

(a) the periods of Type I systems seem, on the average, to be shorter than those of Type II objects; we note, in particular, that all four ultra-short period systems, with $P < 0.1$ day, are either certain, or at least marginal members of Type I;

(b) the U Gem type stars are dominating members of Type I and seem to be completely absent in Type II; in terms of our definition of the two types this means that the spots in the U Gem type systems are generally brighter, as compared with the disks, than in novae or nova-like objects.

IV. *Period Variations*

Many eruptive binaries are known to show variations of their orbital periods. But while only a few years ago it seemed that in most cases we were dealing with increasing periods [cf. MUMFORD (1969) and SMAK (1969a) for U Gem, WALKER and CHINCARINI (1968) for SS Cyg, and NATHER and WARNER (1969) for DQ Her], the situation appears now to be more complicated. The O—C diagram for U Gem (MUMFORD 1970, SMAK 1972) indicates that the period was indeed increasing between 1962 and about 1966, but is now either constant or slightly decreasing. A more complicated behaviour is also indicated for SS Cyg

Table 1: Eruptive Binaries of Type I [1]

	Type	P	References [2]
WZ Sge (?)	RN	0ᵈ0567	KRZEMIŃSKI and SMAK (1971)
EX Hya (?)	U	0.0682	MUMFORD (1967b)
VV Pup	NL	0.0697	HERBIG (1960), WALKER (1965), GORBATZKY (1967, 1971), SMAK (1971b)
Z Cha	U	0.0745	MUMFORD (1971a, 1971b)
RR Pic	N	0.1451	VAN HOUTEN (1966), MUMFORD (1971a)
U Gem	U	0.1769	KRZEMIŃSKI (1965), PACZYŃSKI (1956c), GORBATZKY (1967, 1971), SMAK (1971a), WARNER and NATHER (1971)
CN Ori	U	~ 0.25	MUMFORD (1967, 1971b)
Z Cam	U	0.2898	KRAFT, KRZEMIŃSKI, and MUMFORD (1969), SMAK (1970)

[1]) Marginal or uncertain cases are marked with (?) following the object's name.
[2]) Only the most recent or the most relevant papers concerning the observational data and their interpretation are listed.

Table 2: Eruptive Binaries of Type II [1]

	Type	P	References [2]
VZ Scl [3]) (?)	NL	0ᵈ1446	KRZEMIŃSKI (1966, 1971)
DQ Her	N	0.1936	WALKER (1956, 1961), KRAFT (1959), GORBATZKY (1965b), NATHER and WARNER (1969)
UX UMa	NL	0.1967	WALKER and HERBIG (1954), KRZEMIŃSKI and WALKER (1963)
T Aur (?)	N	0.2044	WALKER (1963b)
RW Tri	NL	0.2319	WALKER (1963a), IVANOV (1969)
EM Cyg (?)	NL	0.2909	MUMFORD and KRZEMINSKI (1969)

[1]) Marginal or uncertain cases are marked with (?) following the object's name.
[2]) Only the most recent or the most relevant papers concerning the observational data or their interpretation are listed.
[3]) = Ton S 120.

by the most recent observations by WALKER and REAGAN (1971). Finally, the two nova-like variables — UX UMa and RW Tri, which have been followed for more than three decades, show alternating variations of their periods (KRZEMIŃSKI and WALKER, 1963, MANDEL 1965). It appears that such alternating variations may be typical for all eruptive binaries, except for cases where the period variations are too small to be detected.

Quite generally, an O—C diagram can be approximated locally by a conventional formula

$$\text{Zero Phase} = T_0 + P\,E + A\,E^2, \tag{1}$$

the value of A and the period variations being related by

$$\frac{d \ln P}{dt} = \frac{2A}{P^2} \tag{2}$$

(note that since A is expressed in days, P and t in Eq. 2 are also expressed in days). The observed values of $|A|$ are generally between 10^{-11} and 10^{-10} day (cf. references given above), what corresponds roughly to $|d \ln P/dt| = 10^{-9}\ \text{day}^{-1}$.

The period variations in close binary systems can be caused by several factors (cf. KRUSZEWSKI 1966) and, generally, at least three mechanisms should be considered:

(a) The mass exchange between the components. Depending on the mass-ratio, the period may either increase or decrease (cf. the first term in Eq. 3 — below). The rate of period variations can be affected by the possibly variable rate of the mass transfer, but its sign should be constant.

(b) The mass loss from the system. Except for the nova outbursts, there is no observational indication that this mechanism can be important and therefore it will be neglected below. Besides, we may note that this mechanism is also uncapable to produce alternating variations of the period.

(c) The variations of the orbital momentum due to the exchange with the rotational momenta of the stars and of the disk. The amount of momentum that can be stored in the disk is — per unit mass — much larger than in the case of either component and therefore in a crude approximation we can consider only the exchange between the orbital momentum and the rotational momentum of the disk. Two counteracting processes are to be considered: (i) the transfer of mass and momentum from the secondary component to the disk (cf. PACZYŃSKI 1967), and (ii) the transfer of momentum from the disk — via the tidal interaction — to the system.

When the combined action of the mechanisms (a) and (c) is considered we can obtain the following expression for the period variations (SMAK 1972):

$$\frac{d \ln P}{dt} = \frac{3}{\mathfrak{M}_2} \left[\left(1 - \frac{\mathfrak{M}_2}{\mathfrak{M}_1}\right) \left(- \frac{d \mathfrak{M}_2}{dt} \right) - \frac{d (F \mathfrak{M}_d)}{dt} \right], \tag{3}$$

where

$$F = \left[\frac{2 \pi G}{P} (\mathfrak{M}_1 + \mathfrak{M}_2) \right]^{1/3} V_d^{-1}; \tag{4}$$

here $\mathfrak{M}_d$ is the mass of the disk, V_d — the mean rotational velocity of the disk, and all the parameters are expressed in the c. g. s. units. We may add that F is the rotational momentum of the disk per unit mass, expressed in units of $J/\mathfrak{M}_2$, where J is the orbital momentum of the system.

The first term in Eq. 3 can be either positive or negative, depending on the mass-ratio. The sign of the second term depends on the variations of F and $\mathfrak{M}_d$. This term and the variations of its sign can account for the alternating variations of the period provided it dominates over the first term. It appears therefore that the observed variations of periods of eruptive binaries indicate the importance of an exchange between the rotational momentum of the disk and the orbital momentum.

If this interpretation is correct, then we are led to conclude that the amount of mass and momentum stored in the disk must be quite large to be responsible for the observed phenomena. A closer, quantitative analysis based on Eq. 5 permits to give an estimate of the masses involved (SMAK 1972). If the variations in $F \mathfrak{M}_d$ can be as large as 100 percent, then we obtain a very conservative estimate

$$\mathfrak{M}_d > 10^{-6} \mathfrak{M}_2. \tag{5a}$$

Such large variations would, however, affect seriously the observed properties of the disks and there is no observational evidence to support such an assumption. If we assume that they are much smaller and amount only to 1 percent, then we get a much stronger estimate for the mass of the disk:

$$\mathfrak{M}_d > 10^{-4} \mathfrak{M}_2. \tag{5b}$$

Our interpretation results therefore in a very important information concerning the disk. However, if this approach is correct, we cannot possibly use the period variations for estimating the rate of mass transfer.

V. *Properties of the Components*

Direct observational evidence concerning the components is seriously limited by the faintness of these objects and by various contaminating effects due to the presence of the circumstellar material. Even in the case of masses, in spite of the wealth of radial velocity data, the situation is not very satisfactory. Two main limitations are: (a) the velocity curves of the primary components, as based on measurements of the emission lines belonging to the disks, are affected by the contribution from the spot and usually show spurious amplitudes, phase shifts, and eccentricities (cf. SMAK 1970); (b) there is no even a single case of a double-line spectroscopic binary, being simultaneously an eclipsing object. Nevertheless, the estimates and determinations made so far permit to say generally that the components of eruptive binaries have masses of the order of 1 $\mathfrak{M}_\odot$, but show a large spread in this respect. Furthermore, it seems relevant to mention the existence of the following, apparently strange cases:

(a) masses in DQ Her appear to be very small [0.12 and 0.20 $\mathfrak{M}_\odot$, respectively; KRAFT (1964)];

(b) the mass of the secondary component of WZ Sge is extremely small, definitely below 0.1 $\mathfrak{M}_\odot$ (KRZEMIŃSKI and KRAFT 1964, KRZEMIŃSKI and SMAK 1971);

(c) masses in T CrB are very large [larger than 1.9 and 2.6 $\mathfrak{M}_\odot$, respectively; KRAFT (1964), PACZYŃSKI (1965b)];

(d) the mass of the primary component of U Gem seems also to exceed the conventional white dwarf limit, if we use the spectroscopic data of KRAFT (1962) and the recent model of this system (SMAK 1971a).

The mean absolute magnitudes are about $M_V = +4.2$ for novae and $M_V = +7.5$ for the U Gem type stars (SCHMIDT-KALER 1962, KRAFT 1964, KRAFT and LUYTEN 1965) with a considerable scatter of individual values, particularly for the former. Most of this scatter is due to the large differences in absolute magnitudes of the secondary components. For example, the secondary of T CrB has about $M_V = +0.2$ (KRAFT 1958), while the secondary of WZ Sge is likely to be as faint as $M_V = +17$ (KRZEMIŃSKI and SMAK 1971). KRAFT (1964) noted that the luminosities of the secondaries are determined primarily by their dimensions and, as a result, there exists a correlation between M_V and the orbital period. This explains why the objects with longer periods are double line-line binaries, while those with shorter periods show usually only the emission lines and no measurable contribution from the secondary component. It has also been noted (KRAFT 1964) that the observed luminosities of the secondary components of novae seem too low, as compared with those computed from their dimensions and spectral types. A similar discrepancy for the U Gem type stars has been only partly resolved by the arguments presented by KRAFT and LUYTEN (1965); the case of SS Cyg, with the spectral type of its secondary being dG5 and its parallax leading to $M_V = +9.5 \pm 0.8$, remains still enigmatic.

Only two novae show spectra containing features belonging probably to their primaries. These are: WZ Sge (GREENSTEIN 1957) and DI Lac (KRAFT 1963, 1964), and in both cases the broad and shallow absorption lines of hydrogen may indicate that the primaries are white dwarfs. In the case of WZ Sge such an identification fits consistently into the model of the system (KRZEMIŃSKI and SMAK 1971). In the case of DI Lac KRAFT (1963) noted that the shapes of its absorption lines may indicate rapid rotation. An indirect evidence concerning the white dwarf nature of the primary component is available also for DQ Her in the case of which the 71-second light variation is attributed to the pulsation of the white dwarf (WALKER 1958, 1961, KRAFT 1959, NATHER and WARNER 1969).

Spectra of the secondaries are of the late types. Those of novae are from G to M with the luminosity classes as high as III, e. g. gM3 for T CrB (SANFORD 1949, KRAFT 1958), or G5IIIp for V1017 Sgr (KRAFT 1964). The U Gem group is more homogeneous: G—K, and V—IV, respectively (KRAFT 1962, 1963). However, as mentioned above, our sample is strongly biased against fainter objects. We may also note here an interesting case of RR Tel. Prior to its outburst in 1949 the star showed regular light variations with P = 387 days, the amplitude being of about 3 mags. (PAYNE-GAPOSCHKIN 1955). Pulsations of a Mira type secondary are likely explanation (HENIZE and McLAUGHLIN 1951) but no direct spectroscopic evidence is yet available.

Let us turn now the problems of interpretation. Much work has been done over the last decade on the evolution of the close binary systems (cf. PACZYŃSKI 1971). It was shown that the Case B evolution can produce systems containing white dwarfs (cf. REFSDAL and WEIGERT 1971). In all these studies, however, only a single process of mass exchange has been considered, with no mass loss from the system, what leads to relatively long periods and requires the secondary to be essentially unevolved. To produce the relatively short periods of eruptive binaries it would be necessary to consider much more complicated situations, including the evolution of the secondary, the occurence of the contact configuration at certain stages, and the mass loss from the system. With respect to the final properties of the primary, white dwarf component, it appears that no major modifications are to be expected. since these properties are determined primarily by the parameters of the helium core of the evolving star (REFSDAL and WEIGERT 1971). On the other hand, some important differences can be introduced by considering the rapid rotation of these components. Indeed, due to the transfer of mass and momentum from the disk to the primary component, rapid rotation is likely to occur; this may permit some of the primaries to exceed the conventional white dwarf limit for masses (OSTRIKER and BODENHEIMER 1968).

With respect to the secondary components a broad range of possibilities may be expected. If the mass of the secondary was initially not much smaller than that of the primary and if a major mass loss from the system has occured, including the entire envelope of the primary and the outer layers of the secondary, then we are likely to see now the initially deep layers of the secondary. Two questions are to be asked in this case: (a) are they sufficiently nuclear-processed to show any abundance anomalies? and (b) if so, is it possible in the case of low mass secondaries to have a large overabundance of the He^3 isotope produced in the first two reactions of the p—p cycle (cf. PARKER, BAHCALL, and FOWLER 1964)? Another possibility is that the process of mass exchange and mass loss ended with an accumulation by the secondary of the material ejected by the primary. In this case we should ask: was this matter sufficiently nuclear-processed in the initially deep layers of the primary to show any abundance effects? The significance of all these questions comes from the fact that the material observed now in the disks, the material of the present outer layers of the primary component, and the material ejected during an outburst are supplied from the outer layers of the secondary. Its chemical composition is then of importance for any mechanism of outbursts. In this context it is worth to note that the ejected envelopes of novae seem to show a significant overabundance of C, N, O and a slight overabundance of helium (cf. MUSTEL and BOYARCHUK 1959, POTTASCH 1959, BARTASH and BOYARCHUK 1965, MUSTEL and BARANOVA 1965).

VI. *Properties of the Circumstellar Matter*

Spectra of the majority of eruptive binaries between their outbursts are dominated by the radiation coming from the disks and hot spots. The emission lines are present in nearly all of them. Statistically, the emission lines in novae are of higher excitation and ionization: in addition to the Balmer lines we observe usually the He I and He II lines; the emission lines in the U Gem type stars appear, however, to be relatively stronger (cf. KRAFT 1962, 1963, 1964). In addition to these differences we should also note a large spread in these characteristics, particularly among novae. For example, one of the strongest emission spectra belongs to DQ Her — a nova; lines of He II are present in SY Cnc (HERBIG 1950), which is a U Gem type object, while only the Balmer lines are visible in the spectra of certain novae, like WZ Sge or DI Lac.

Emission lines originating in disks are often double, usually when the orbital inclination is close to 90°. The separation of the components corresponds roughly to the rotational velocity of the outer parts of the disk (SMAK 1969b). In the so-called Keplerian approximation we have the often used formula

$$V_d^2 = \frac{G\mathfrak{M}_1}{r_d}, \tag{6}$$

where V_d and r_d are the rotational velocity and radius of the outer parts of the disk; note that observations give only $V_d \sin i$.

As compared with the emission lines originating in the disk, the emission components coming from the spots are usually weaker [e. g. in U Gem, KRAFT (1962, 1963)], or even completely absent [e. g. in VV Pup, where no phase dependence is observed (HERBIG 1960)]. Radial velocity data together with other, model-type considerations imply (KRZEMIŃSKI and SMAK, 1971, SMAK 1971a) that the radius-vector of the spot is slightly smaller than the outermost radius of the disk, i. e. that the spot is formed somewhat inside the disk.

Of particular importance is the observed Balmer decrement, which is not as steep as in gaseous nebulae; in certain objects the spot components show a much flatter decrement than that of the lines from the disk (e. g. U Gem and WZ Sge). This implies that the observed radiation comes from regions of high optical thickness (cf. GORBATZKY 1965a, KUNKEL 1970). If the lines and the continuum are formed roughly in the same regions, then it is also possible to understand — in terms of high optical thickness — why the lines, when compared to the continuum radiation, are not very strong. In particular, it appears that the observed colours are affected by the emission lines only slightly; for example, in the case of a very strong spectrum of DQ Her, the emission lines contribute to the B-band of the UBV system only about 12 percent of the total radiation.

The observed colours of eruptive binaries are composite. It is possible, however, to extract from them and from their variations with phase at least some information concerning the photometric properties of the circumstellar matter. Two methods can be used for this purpose. The first one, applicable to all systems showing pronounced shoulders (Type I of Section III), permits to determine the colours of the hot spot and the combined colours of the remaining parts of the system (cf. SMAK 1969a). The second method, less precise as to the identification of the sources considered, and applicable to all eclipsing systems, permits to obtain the colours of the eclipsed body and of the remaining parts of the system seen at the eclipse; the eclipsed body will usually be either the spot or the relatively brightest parts of the disk including the contribution from the spot. These two methods (refered to as method „s" and method „e", respectively) have been applied to 9 systems and the results are shown in Table 3 and Fig. 4.

The most characteristic feature of Fig. 4 is that the colours of the spots or eclipsed bodies are very close to those of type Ia supergiants and this may not be a simple coincidence. Indeed, with these sources being optically thick, the contribution from the emission lines being insignificant, our result may mean that the densities involved may be comparable to those in the atmospheres of supergiants and that we actually observe radiation coming from the outer layers of the spot, or of the disk, respectively. Adopting this interpretation we can estimate the effective temperatures using the calibration for supergiants (JOHNSON 1966). We obtain a range from about 18,000 °K (for Z Cha and EX Hya) down to about only 7,000 °K (for VV Pup). This seems to be surprisingly low! It can be shown, however, that it is not inconsistent with other evidence. Let us consider first these cases where the colours of the eclipsed body are representative for those of the disk. The dimensions of disks are in the range $10^{10}-10^{11}$ cm. Assuming that the thickness of the disk is about $1/3$ of its diameter, taking for the average temperature $T_e = 12{,}000$ °K, and using the bolometric correction of about -1.1, we obtain that the absolute visual magnitudes of disks should be between $+3$ and $+8$; this is not inconsistent with the observed absolute magnitudes. For a second test let us consider the case of U Gem. The colours of its spot imply the effective temperature of about 10,000 °K. The colours at the outburst imply $T_e \approx 12{,}000$ °K (see Section VII) while the visual brightness at the outburst is about 100 times higher than of the spot. From these data it results that the dimensions of the spot should be about 8 times smaller than those of the bright body seen at maximum; this again is not inconsistent with other estimates (cf. SMAK 1971 a, WARNER and NATHER 1971).

Table 3: Colours in Eruptive Binaries [1])

	Object [2])	Hot spot or eclipsed body		Remaining parts		References
		B—V	U—B	B—V	U—B	
1	Z Cam s	+ 0.05	− 0.40	+ 0.55	− 0.80	Obs. on JD 2439138 (KRAFT, KRZEMIŃSKI, and MUMFORD 1969)
2	Z Cha e	− 0.15	− 1.10	+ 0.80	− 0.30	MUMFORD (1971a)
3	EM Cyg e	0.00	− 0.15	+ 0.40	− 0.70	Cycles E = 1004 and 1591 (MUMFORD and KRZEMIŃSKI 1969)
4	U Gem s	0.00	− 0.55	+ 0.30	− 1.00	KRZEMIŃSKI (1965), PACZYŃSKI (1965c), and MUMFORD (1967)
4	U Gem e	+ 0.05	− 0.65	+ 0.20	− 1.10	KRZEMIŃSKI (1965), PACZYŃSKI (1965c), and MUMFORD (1967)
5	DQ Her e	+ 0.15	− 0.75	[3])	[3])	WALKER (1956)
6	EX Hya e	− 0.05	− 1.10	− 0.05	− 1.10	MUMFORD (1967b); no colour vars. at eclipse
7	VV Pup s	+ 0.40	+ 0.50	+ 0.05	− 0.95	Obs. on JD 2438469 and 474 (WALKER 1965)
8	RW Tri e	+ 0.15	− 0.55	+ 0.40	− 1.20	Mean colours (WALKER 1963a)
9	UX UMa e	+ 0.05	− 0.80	+ 0.20	− 0.80	JOHNSON, PERKINS, and HILTNER (1954)

[1]) The colour index values have been rounded up to 0.05 mag.
[2]) Symbols „s“ and „e“ refer to the hot spot and the eclipsed body, respectively.
[3]) Colours affected by the envelope ejected during the outburst.

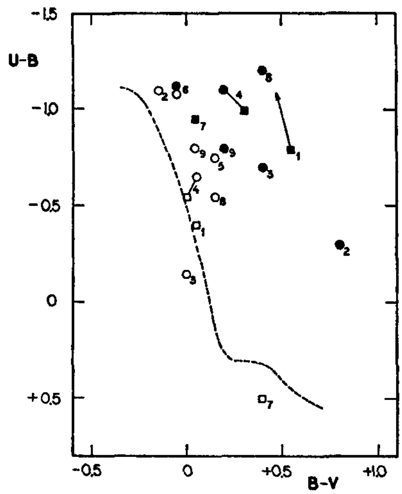

Fig. 4: Colours of the eruptive binaries. Open squares are the colours of spots; open circles — of eclipsed bodies; filled symbols correspond to the remaining parts of a given system. Numbers are those of Table 3. An arrow at Z Cam shows a correction for the secondary component if its contribution amounts to 1/3 of the total radiation. A broken line is the two-colour relation for the Ia supergiants (JOHNSON 1966); see Fig. 5 for the temperature scale.

Turning to the colours of the „remaining parts" of the system (filled symbols in Fig. 4) we note that no single interpretation should be attempted here because of their composite nature. There are cases where these colours are strongly affected by the secondary component (e. g. in Z Cam and, probably, in Z Cha). There are cases where the amount of light seen at eclipse forms only a very small part of the total light und may come from the outermost parts of the disk which may be different from the main body. There are cases, however, where a more definite identification is possible and where we encounter an apparent dilemma. In U Gem and VV Pup the colours of the „remaining parts" are those seen outside of the shoulder and correspond probably mostly to the disk. Any conventional calibration (like black body) applied to these colours leads to the temperatures higher than 12,000 °K, i. e. higher than those of the spots. The disks are by one order of magnitude larger than the spots. Altogether we should expect then that the disks should be brighter than the spots by roughly two orders of magnitude, but this is not the case, the two sources being of comparable brightness! Putting the arguments around we can say that the surface brightness of the disks indicates effective temperatures definitely below 10,000 °K in the case of U Gem and 7,000 °K in the case of VV Pup, what seems difficult to reconcile with the colours of these objects as well as with the existence of the emission lines. In the case of U Gem our point can be strengthened further by noting that during the outburst, when the dimensions of the bright body are comparable with those of the disk, its temperature being about 12,000 °K, the object is brighter about 100 times; this implies again that the disk is strongly underluminous, as compared, say, with a black body at $T_e = 12{,}000$ °K.

Our discussion clearly demonstrates that the structure of disks and hot spots and the nature of processes responsible for their radiation must be rather complicated. And while first attempts to construct their models have already been made (cf. GORBATZKY 1968, PRENDERGAST and BURBIDGE 1968), much is to be done in this important area.

Among the many observational data concerning the dynamical and spectroscopic properties of the expanding envelopes of novae, we shall mention only one piece of evidence based on the shapes of such envelopes. It is well established that the envelopes of novae are not spherically symmetrical. Instead there are several cases known of a definite axial symmetry, the best examples being DQ Her and V603 Aql (cf. MUSTEL and BOYARCHUK 1970, and other references listed in their paper). The general pattern was in both these cases similar: the envelope consisted of a ring, or system of rings, and two blobs ejected along the symmetry axis. In the case of DQ Her we have an independent evidence from polarimetric studies (DIBAY and SHAKHOVSKOY 1966) concerning the orientation of the orbit and it appears that the axis of symmetry of the envelope is perpendicular to the orbital plane. There are three possible ways of explaining this axial symmetry:

(a) the motion of the envelope is governed by the magnetic field (MUSTEL 1956, 1970);

(b) the primary component is rapidly rotating and the outburst originates in its outer layers;

(c) the outburst originates in the disk, or — if the outburst originates in the spherically symmetric primary — the mass of the disk is sufficiently large to modify the geometry of the expanding envelope; in both cases the mass of the disk should be comparable with the mass of the ejected envelope, i. e. of the order of $10^{-3}\,\mathfrak{M}_{\odot}$.

In the case of the U Gem type stars, earlier evidence from photometric and spectroscopic studies of their outbursts (e. g. ZUCKERMANN 1961, BARTAYA 1966, CHALONGE, DIVAN, and MIRZOYAN 1968) can be supplemented with two results for SS Cyg and U Gem. WALKER and CHINCARINI (1968) found that the outburst of SS Cyg is associated with the hot component (although his does not necessarily mean the star itself), that no measurable expansion of the envelope occurs, and that the emission lines of the disk, while being obliterated by the extra radiation, do not change their intensity; these findings refer to the initial phases of the outburst. An analysis of the photometric behaviour of U Gem (SMAK 1971a) leads to the conclusion that during an outburst the luminosity increases due to an extra source of light in the central parts of the disk, the dimensions of the disk increase by about 50 percent, while the brightness of the hot spot remains nearly constant; following the outburst we observe a contraction of the disk.

Spectra of the U Gem type stars at maximum are either continuous, or show absorption lines of hydrogen. The spectral energy distributions and the intensities of these lines roughly correspond to the spectral type A; this is similar to the early spectral development of novae. The colours (Fig. 5) are very similar to those of the Ia supergiants and imply that the temperatures at maximum are close to 12,000 °K, but continue to increase somewhat after maximum; apparently the dimensions of the extra source of light responsible for the outburst reach their maximum before maximum light.

All these results consistently suggest that the brighthening of a U Gem type variable is either due to the increased luminosity of the central parts of the disk or due to the appearance of an additional, bright, gaseous envelope around the primary component.

In the case of the nova-like objects we observe only irregular variations on a time-scale of days, months, and years and while no good spectroscopic coverage of such events is available, at least some conclusions can be obtained from the photometric behaviour. In Table 4 we have a summary of data for three eclipsing nova-like objects (this table is based partly on an unpublished discussion by the author). In all three cases the light variations are accompanied by the colour variations and by significant changes in the shape of the eclipse curve. There is a systematic trend in B—V, the colour being redder when the object is fainter. But perhaps more important, and certainly easier to interpret, is the change in the shape of eclipse: the eclipse becomes wider and shallower when the system is brighter. The natural explanation is that when the object is brighter, the disk is not only brighter, but also bigger; then the eclipse lasts longer but, since larger fraction of the disk can remain uneclipsed, its photometric depth must be smaller. It can be added that the variations in the dimensions of

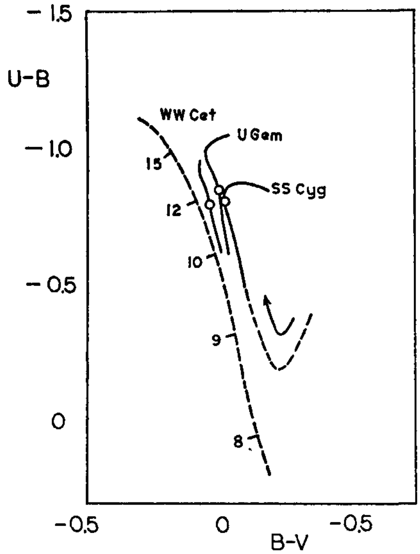

Fig. 5: Colour variations of three U Gem type stars during their outbursts [WW Cet: PACZYŃSKI (1963), SS Cyg: GRANT and ABT (1959), ZUCKERMANN (1961), U Gem: KRZEMIŃSKI (1965)]. An arrow shows the direction of variations and open circles mark the colours at maximum. A broken line is the two-colour relation for the Ia supergiants with temperatures marked in 10^3 °K (JOHNSON 1966).

the disk are likely to be accompanied by significant variations in its surface brightness. Finally, in addition to the three systems of Table 4, we can mention the case of large, irregular variations of VV Pup, which can also be tentatively explained as being due to the variable behaviour of the disk (SMAK 1971b).

VIII. *Variability: Theories and Hypotheses*

On the basis of the evidence presented above one can conclude that from a purely observational point of view the outbursts and other types of a large-scale nova-like variability are phenomena occuring either in the disks or in the envelopes — expanding or non-expanding — around the primary components. What kinds of physical mechanisms and what types of instabilities can lead to these phenomena? Many theories and hypotheses have been advanced to answer this question but so far none of them can claim to be fully successful. Space does not permit to review all of them in a detailed manner. Instead, we shall consider three general possibilities making only appropriate references to the relevant theories or speculations. The three possibilities refer to the three different regions where an instability producing, or at least triggering an outburst can occur; these are: the outer layers of the primary component, the outer layers of the secondary component, and the disk.

1. The primary component

Two groups of theories are to be considered. In the first advanced by SCHATZMAN (1965, and earlier references given there), it is suggested that nonradial pulsations are set up in the primary component by the tidal action of the secondary due to the resonance between the orbital motion and high gravitational modes. The outburst is due to an instability in the hydrogen-burning shell with a detonation being produced by the highly temperature sensitive

Table 4: Variations in Nova-Like Systems

	EM Cyg		RW Tri		UX UMa	
	bright	faint	bright	faint	bright	faint
Colours[1]) outside of eclipse:						
B—V	+ 0.1	+ 0.6	+ 0.2	+ 0.2	+ 0.0_5	+ 0.1_5
U—B	− 0.9	− 0.5_5	− 0.6	− 0.7_5	− 0.8	− 0.8
Colours[1]) at eclipse: B—V	+ 0.1	+ 0.7	+ 0.3	+ 0.5_5	+ 0.1_5	+ 0.2_5
U—B	− 0.9	− 0.7	− 1.0	− 1.3	− 0.8	− 0.8
Shape of eclipse:	shallower, wider, more symmetric	deeper, narrower, often asymmetric	shallower, wider	deeper, narrower	shallower	deeper
Observed range of variations:	2 mags		1 mag.		0.25 mag.	
Photometric data:	MUMFORD and KRZEMIŃSKI (1969)		WALKER (1963a)		JOHNSON, PERKINS, and HILTNER (1954)	

[1]) The colour index values have been rounded up to 0.05 mag.

reaction $He^3 + He^3$. One of the most unclear points of this hypothesis is how the tidal action resonance mechanism could operate equally efficiently in a large range of orbital periods from below 0.1 to over 200 days. Besides, this theory is essentially unconnected with the process of mass exchange between the components and leaves aside one of the basic, intrinsic properties of eruptive binaries, namely that their secondaries fill-up their Roche lobes and lose mass to the primaries.

The second group makes a fuller use of the binary characteristics and connects the outburst with an instability of the hydrogen burning in the envelope of the white dwarf, as it grows in mass due to the mass exchange. This mechanism was suggested by KRAFT (1962, 1963), following an argument advanced by MESTEL (1952) in his accretion theory of supernovae, and was explored in the detailed model calculations by GIANNONE and WEIGERT (1967), ROSE (1968), SECCO (1968), and STARRFIELD (1971a, 1971b). According to the most extensive results of STARRFIELD, the termal runaway in a non-degenerate shell source (SCHWARZSCHILD and HÄRM 1965) cannot lead to an outburst because the outer layers can expand fast enough to cool the runaway. If, however, the hydrogen burning shell is degenerate, then the resulting flash can produce an outburst with the energy and mass loss typical for novae, provided the white dwarf has the luminosity and effective temperature low enough so that a sufficiently massive hydrogen-rich layer can be accumulated prior to the instability. STARRFIELD (1971b) finds also that the outbursts should be more violent in the case of more massive stars. A general picture emerging from all these results is fairly consistent with the energy outputs, ejection of the envelopes, observed time scales, and the recurrence of novae. It is entirely unclear, however, whether the outbursts of the U Gem type stars could originate due to a similar mechanism and if so, what could be responsible for their much higher frequency and less violent character. Indeed, we have no observational evidence whatsoever that the primaries in the two types are different, nor that the rates of mass transfer are different.

2. The secondary component

Following KRZEMIŃSKI's (1965) earlier interpretation of U Gem, leading to the conclusion that the secondary was responsible for the outbursts, several authors devoted their attention to the possible instability of the late-type dwarfs against the outflow of mass (PACZYŃSKI 1965a, BATH 1969, PACZYŃSKI, ZIÓŁKOWSKI, and ŻYTKOW 1969, and OSAKI 1970). Their results can be summarized as follows. Certain types of instability are likely to occur in the outer convection layers of the late-type stars filling their Roche lobes and losing mass. The time scales, including the recurrence, can be of the correct order for the U Gem type stars. However, the outbursts cannot be made sufficiently violent [an apparent success of BATH (1969) in this respect is presumably due to an error pointed out by OSAKI (1970, p. 623)].

While there are now good reasons to disregard the secondary component as being entirely responsible for the outbursts, it appears that its possible instabilities deserve further attention even if they can only produce significant variations in the rate of mass transfer, what could act as a trigger in other possible mechanisms. It is indeed remarkable that these instabilities are the only ones, studied so far, that could reproduce the time scales of the U Gem events, while some of the OSAKI's models could reproduce the Z Cam behaviour.

3. The disk

Until very recently the disks were not given any attention in this respect. However, if the evidence concerning their masses (cf. Sections IV and VII) is to be taken seriously, then we should consider them as a likely candidate. Let us consider the energy stores of a typical disk. We shall assume that the mass can be of the order of 10^{29} g, while the mean radius of the disk is about 10^{10} cm. If the Keplerian approximation is correct, then the total amount of the mechanical energy (potential plus kinetic, rotational) appears to be about

$$|E_m| = 10^{45} \text{ ergs.} \tag{7}$$

To estimate the total amount of thermal energy, we can take $T = 10^4\,°K$ as a lower limit, and $T = 10^6\,°K$ as an upper one. The latter results from a model of the disk by PRENDERGAST and BURBIDGE (1968) and is still not drastically inconsistent with the lack of detectable X-ray radiation from typical eruptive binaries. With these values we get for the thermal energy

$$E_t = 10^{41} - 10^{43} \text{ ergs.} \tag{8}$$

Although no definite mechanism can be proposed at present for a sudden liberation of the available energy, it is clear that the amounts available are just sufficient to explain the energy output of a nova outburst and well in excess of what is needed for the U Gem outburst.

There are several observational arguments in favour of such a hypothesis. As mentioned in Section II, the differences between the different types of eruptive binaries (e. g. between novae and U Gem objects), which would parallel their different outburst behaviour, are not very obvious. However, the evidence presented in Sections III, V, and VI shows that whenever such differences are noticeable they are connected mostly, if not only, with the properties of the circumstellar material rather than with either component. Nearly all evidence concerning the variability (Section VII) shows that the observed phenomena are always connected with disks or — at least — with the circumstellar material in general. Although this is not a decisive argument, it should be remembered that there is no single observational evidence — direct or indirect — which would point strongly to the primary component, as to the seat of the observed phenomena.

IX. *Related Objects*

Many other objects and many observed processes are related, in one way or another, to the eruptive binaries. The most obvious are: symbiotic binaries, certain types of close binary systems at relatively early evolutionary stages, certain types of X-ray sources, and various unique, peculiar objects.

1. Symbiotic binaries

The photometric and spectroscopic data (cf. SAHADE 1965, BOYARCHUK 1969, and references given there) permit to describe them roughly as nova-like objects with giant or supergiant secondaries and very long orbital periods. The most important difference lies in the presence of a variety of high-excitation emission lines, including the forbidden ones, typical for the planetary nebulae. These come obviously from a large, low density nebulosity surrounding presumably both components.

2. W UMa type binaries

These have been suggested (KRAFT 1962, 1963) to be the progenitors of the U Gem type binaries. It is clear that a verification of this hypothesis must come from evolutionary models including the mass loss and mass exchange between the components.

3. Close binaries with disks

The existence of disks and other forms of circumstellar matter in close binary systems representing certain, relatively early phase of evolution, has been known for decades (cf. BATTEN 1970, and references given there). The most recent results, particularly due to HALL (1969, 1971, HALL and TAYLOR 1971), indicate that disks contribute in certain systems a significant portion of the total light and are probably responsible for practically all peculiarities in the light curves and spectra and their irregular variations. As compared with the eruptive binaries, these effects are apparently of a much smaller magnitude, but this is at least partly due to the large intrinsic brightness of the primary components. Having the primary components replaced with white dwarfs, we could presumably observe nova-like systems in many such cases. And this appears to provide a partial argument in support of the disk-instability hypothesis for eruptive binaries (Section VIII). For in this case, with the primary component being an obviously normal main sequence star, it is difficult to make it responsible for the instabilities occuring in the disk.

4. X-ray sources

There is a class of X-ray sources which are photometrically and spectroscopically similar to eruptive binaries and most likely to be binaries themselves (cf. PRENDERGAST and BURBIDGE 1968, HILTNER and MOOK 1970, and references given there). If a binary model advanced for eruptive binaries is applicable to this group of objects, then the major difference lies in their extremely high energy output in the X-ray region. Indeed, if the conventional eruptive binaries were equally strong X-ray radiators, nearly all of those mentioned by name in this article would have been detected in the X-ray surveys. A discussion of various possible mechanisms involved in the large X-ray emission is beyond the scope of this review. If, however, a close similarity exists between these objects and the eruptive binaries, then it may be relevant to ask: is not this large energy output in the X-ray region a safety valve which prevents the X-ray sources from undergoing major outbursts? And if so, is not the property of the circumstellar material rather than the nature of either component, that is really important in this respect?

5. Other peculiar objects

Let us mention only two objects which are rather unique (partly due to the observational selection), completely different, but — again — similar in certain respects to the eruptive binaries. One of them is V Sge (HERBIG et al. 1965), whose light variations are of the nova-like type, but its secondary is not a late type star, while the combined spectrum resembles a WR-type object. Another object to be mentioned is BD $+ 16^{\circ}516$, discovered recently to be an eclipsing binary consisting of a K0V star and a white dwarf (NELSON and YOUNG 1970). There is no evidence, however, of the existence of a disk or of the mass exchange. The object may be either prior to or after its eruptive binary stage.

The author wishes to acknowledge the indebtedness to his colleagues in Warsaw for many discussions concerning the subject. Thanks go also to Dr. W. KRZEMIŃSKI for his unpublished data for VZ Scl and to Mrs. E. KIERZKOWSKA for preparing the drawings under great time pressure.

References:

ARKHIPOVA, V. P., **1970**, in A. A. Boyarchuk and R. E. Gershberg (eds.), Eruptivnye Zvezdy, Nauka, Moscow, Ch. 1, p. 11.
BARTASH, T. M., and BOYARCHUK, A. A., **1965**, Izv. Krymsk. Astrofiz. Obs., **33**, 173.
BARTAYA, R. A., **1966**, Astrofizika, **2**, 467.
BATH, G. T., **1969**, Ap. J., **158**, 571.
BATTEN, A. H., **1970**, Publ. Astron. Soc. Pacific, **82**, 574.
BOYARCHUK, A. A., **1969**, in L. Detre (ed.), Non-Periodic Phenomena in Variable Stars, Academic Press, p. 395.
CHALONGE, D., DIVAN, L., and MIRZOYAN, L. V., **1968**, Astrofizika, **4**, 603.
CRAWFORD, J. A., and KRAFT, R. P., **1956**, Ap. J., **123**, 44.
DIBAY, E. A., and SHAKHOVSKOY, N. M., **1966**, Astron. Zh., **43**, 1319.
ELVEY, C. T., and BABCOCK, H. W., **1943**, Ap. J., **97**, 412.
GIANNONE, P., and WEIGERT, A., **1967**, Z. Astrophys., **67**, 41.
GORBATSKY, V. G., **1965a**, Astrofizika, **1**, 129.
GORBATSKY, V. G., **1965b**, Trudy Astron. Obs. Leningrad, **22**, 16.
GORBATSKY, V. G., **1967**, Astrofizika, **3**, 245.
GORBATSKY, V. G., **1968**, Astrofizika, **4**, 505.
GORBATSKY, V. G., **1970**, in A. A. Boyarchuk and R. E. Gershberg (eds.), Eruptivnye Zvezdy, Nauka, Moscow, Ch. 2, p. 63.
GORBATSKY, V. G., **1971**, Astrofizika, **7**, 57.
GORBATSKY, V. G., and MININ, I. N., **1963**, Nestatsionarnye Zvezdy, Gos.Izd.Fiz.-Mat.Lit., Moscow.
GORDELATSE, Sh. G., **1938**, Bull. Abast. Obs., **3**, 91.
GRANT, G., and ABT, H. A., **1959**, Ap. J., **129**, 323.
GREENSTEIN, J. L., **1957**, Ap. J., **126**, 23.
GREENSTEIN, J. L., **1960**, in J. L. Greenstein (ed.), Stellar Atmospheres, Univ. of Chicago Press, Chicago, Ch. 19, p. 676.
HALL, D. S., **1969**, Bull. A.A.S., **1**, 345.
HALL, D. S., **1971**, This Colloquium.
HALL, D. S., and TAYLOR, M. C., **1971**, Bull. A.A.S., **3**, 12.
HENIZE, K. G., and MCLAUGHLIN, D. B., **1951**, Ap. J., **114**, 163.
HERBIG, G. H., **1950**, Publ. Astron. Soc. Pacific, **62**, 211.

HERBIG, G. H., 1960, Ap. J., 132, 76.
HERBIG, G. H., PRESTON, G. W., SMAK, J., and PACZYŃSKI, B., 1965, Ap. J., 141, 617.
HILTNER, W. A., and MOOK, D. E., 1970, Ann. Rev. Astron. Astrophys., 8, 139.
HUMASON, M. L., 1938, Ap. J., 88, 237.
IVANOV, L. N., 1969, Trudy Astron. Obs. Leningrad, 26, 33.
JOHNSON, H. L., 1966, Ann. Rev. Astron. Astrophys., 4, 193.
JOHNSON, H. L., PERKINS, B., and HILTNER, W. A., 1954, Ap. J. Suppl., 1, 91.
JOY, A. H., 1954, Ap. J., 120, 377.
JOY, 1956, Ap. J., 124, 317.
JOY, 1960, in J. L. GREENSTEIN (ed.), Stellar Atmospheres, Univ. of Chicago Press, Chicago, Ch. 18, p. 653.
KRAFT, R. P., 1958, Ap. J., 127, 625.
KRAFT, R. P., 1959, Ap. J., 130, 110.
KRAFT, R. P., 1962, Ap. J., 135, 408.
KRAFT, R. P., 1963, Adv. Astron. Astrophys., 2, 43.
KRAFT, R. P., 1964, Ap. J., 139, 457.
KRAFT, R. P., 1966, Trans. I.A.U., XIIB, 519.
KRAFT, R. P., KRZEMIŃSKI, W., and MUMFORD, G. S., 1969, Ap. J., 158, 589.
KRAFT, R. P., and LUYTEN, W. J., 1965, Ap. J., 142, 1041.
KRUSZEWSKI, A., 1964, Acta Astr., 14, 231.
KRUSZEWSKI, A., 1966, Adv. Astron. Astrophys., 4, 233.
KRUSZEWSKI, A., 1967, Acta Astr., 17, 297.
KRZEMIŃSKI, W., 1965, Ap. J., 142, 1051.
KRZEMIŃSKI, W., 1966, Inf. Bull. Var. Stars, No. 160.
KRZEMIŃSKI, W., 1971, Private communication.
KRZEMIŃSKI, W., and KRAFT, R. P., 1964, Ap. J. 140, 921.
KRZEMIŃSKI, W., and SMAK, J., 1971, Acta Astr., 21, 133.
KRZEMIŃSKI, W., and WALKER, M. F., 1963, Ap. J., 138, 146.
KUNKEL, W. E., 1970, Ap. J., 161, 503.
MANDEL, O. E., 1965, Perem. Zvezdy, 15, 474.
McLAUGHLIN, D. B., 1960, in J. L. Greenstein (ed.), Stellar Atmospheres, Univ. of Chicago Press, Chicago, Ch. 17, p. 585.
MESTEL, E., 1952, Mon. Not. R.A.S., 112, 583 and 598.
MUMFORD, G. S., 1967a, Publ. Astron. Soc. Pacific, 79, 283.
MUMFORD, G. S., 1967b, Ap. J. Suppl., 15, 1.
MUMFORD, G. S., 1969, in M. Hack (ed.), Mass Loss from Stars, D. Reidel Publ. Co., Dordrecht, p. 204.
MUMFORD, G. S., 1970, Ap. J., 162, 363.
MUMFORD, G. S., 1971a, Ap. J., 615, 369.
MUMFORD, G. S., 1971b, Private communication.
MUMFORD, G. S., and KRZEMIŃSKI, W., 1969, Ap. J. Suppl., 18, 429.
MUSTEL, E. R., 1956, Astron. Zh., 33, 182.
MUSTEL, E. R., 1970, in A. A. Boyarchuk and R. E. Gershberg (eds.), Eruptivnye Zvezdy, Nauka, Moscow, Ch. 1, p. 28.
MUSTEL, E. R., and BARANOVA, L. I., 1965, Astron. Zh., 42, 42.
MUSTEL, E. R., and BOYARCHUK, A. A., 1959, Izv. Krymsk. Astrofiz. Obs., 21, 3.
MUSTEL, E. R., and BOYARCHUK, A. A., 1970, Astrophys. Space Sci., 6, 183.
MUSTEL, E. R., 1970, Astrophys. Space Sci., 6, 183.
NATHER, R. E., and WARNER, B., 1969, Mon. Not. R.A.S., 143, 145.
NELSON, B., and YOUNG, A., 1970, Publ. Astron. Soc. Pacific, 82, 699.
OSAKI, Y., 1970, Ap. J., 162, 621.
OSTRIKER, J. P., and BODENHEIMER, P., 1968, Ap. J., 151, 1089.
PACZYŃSKI, B., 1963, Publ. Astron. Soc. Pacific, 75, 278.
PACZYŃSKI, B., 1965a, Acta Astr., 15, 89.
PACZYŃSKI, B., 1965b, Acta Astr., 15, 197.
PACZYŃSKI, B., 1965c, Acta Astr., 15, 305.
PACZYŃSKI, B., 1967, Acta Astr., 17, 287.
PACZYŃSKI, B., 1971, Ann. Rev. Astron. Astrophys., 9, in press.
PACZYŃSKI, B., ZIOLKOWSKI, J., and ŻYTKOW, A., 1969, in M. Hack (ed.), Mass Loss from Stars, D. Reidel Publ. Co., Dordrecht, p. 237.
PARKER, P. D., BAHCALL, J. H., and FOWLER, W. A., 1964, Ap. J., 139, 602.
PAYNE-GAPOSCHKIN, C., 1955, Astron. J., 60, 175.
PAYNE-GAPOSCHKIN, C., 1957, The Galactic Novae, North Holland Publ. Co., Amsterdam.
POTTASH, S., 1959, Ann. Astrophys., 22, 412.
PRENDERGAST, K. H., adn BURBIDGE, G. R., 1968, Ap. J. Letters, 151, L 83.
PRENDERGAST, K. H., and BURBIDGE, G. R., 1968, Ap. J. Letters, 151, L 83.
REFSDAL, S., and WEIGERT, A., 1971, Astron. Astrophys., in press.
ROSE, W. K., 1968, Ap. J., 152, 245.
SAHADE, J., 1965, Kl. Veröff. Bamberg, IV, Nr. 40, p. 140.
SANFORD, R. F., 1949, Ap. J., 109, 81.
SCHATZMAN, E., 1965, in L. H. Aller and D. B. McLaughlin (eds.), Stellar Structure, Univ. of Chicago Press, Chicago, Ch. 6, p. 327.
SCHMIDT-KALER, Th., 1962, Kl. Veröff. Bamberg, Nr. 34, p. 109.
SCHWARZSCHILD, M., and HÄRM, R., 1965, Ap. J., 142, 855.
SECCO, L., 1968, Pubbl. Osserv. Astron. Padova, No. 145.
SMAK, J., 1969a, in L. Detre (ed.), Non-Periodic Phenomena in Variable Stars, Academic Press, Budapest, p. 345.
SMAK, J., 1969b, Acta Astr., 19, 155.
SMAK, J., 1970, Acta Astr., 20, 311.

SMAK, J., 1971a, Acta Aster., 21, 15.
SMAK, J., 1971b, Acta Astr., 21, in press.
SMAK, J., 1972, Acta Astr., 22, in press.
STARRFIELD, S., 1971a, Mon. Not. R.A.S., 152, 307
STARRFIELD, S., 1971b, Mon. Not. R.A.S., in press.
STRUVE, O., 1955, Sky and Telescope, 14, 275.
VAN HOUTEN, C. J., 1966, Bull. Astron. Inst. Neth., 18, 439.
WALKER, M. F., 1954, Publ. Astron. Soc. Pacific, 66, 230.
WALKER, M. F., 1956, Ap. J., 123, 68.
WALKER, M. F., 1958, Ap. J., 127, 319.
WALKER, M. F., 1961, Ap. J., 134, 171.
WALKER, M. F., 1963a, Ap. J., 137, 485.
WALKER, M. F., 1963b, Ap. J., 138, 313.
WALKER, M. F., 1965, Mitt. Budapest, No. 57.
WALKER, M. F., and CHINCHARINI, G., 1968, Ap. J., 154, 157.
WALKER, M. F., and HERBIG, G. H., 1954, Ap. J., 120, 337.
WALKER, M. F., and REAGAN, G. H., 1971, Inf. Bull. Var. Stars, No. 544.
WARNER, B., and NATHER, R. E., 1971, Mon. Not. R.A.S., 152, 219.
ZUCKERMANN, M.-C., 1961, Ann. Astrophys., 24, 431.

Discussion to the paper of SMAK

MAMMANO: I don't believe on the importance of the disk, at least for normal close binaries, where disappearance of the ring lines does not produce variations in the light curve. No evidence of a disk has been achieved for symbiotics, where we can speak only of a nebula, so far.

SMAK: I agree that in the case of symbiotic stars there is no evidence for disks, but rather for extended and tenuous envelopes. In the case of the Algol type binaries there is certainly a large diversity of situations. There are cases, like RW Tau, where the disk is a transient phenomenon and — even when present — does not contribute much to the total luminosity. What I have had in mind, however, were those systems studied recently by Dr. HALL, like RY Per, where disks are fairly bright and showing instabilities capable of producing variable shapes of the eclipse curve.

SCHUMANN: A question to the light curve you drew on the blackbord: Is the deep minimum caused by the occultation of the hot spot? Why should the flicker restart after the superposed shallower minimum?

SMAK: No, the deep part is due to an occultation of the primary and the disk. The other part, due to an occultation of the spot is shifted to the right producing a still-stand, and it is this part during which no flickering is present.

MUMFORD: Simultaneous photoelectric and spectroscopic observations of Cygnus X-2 by Dr. MUMFORD and Dr. LYNDS, respectively, over a period of 6 hours some two years ago showed virtually no brightness or radial velocity variations. This work has not been published.

WARNER: My observations during outbursts show that the flickering stays constant in intensity units, showing that the bright spot does not change its properties during outbursts. I also have observed Cyg XR-2 for several hours on one night and found no flickering or flaring activity.

SAHADE: I wonder whether Dr. KELLOGG could tell us whether the Uhuru satellite has run into any of the objects that have been discussed by Dr. SMAK.

WARNER: In the absence of Dr. KELLOGG I can speak to this. My calculations show that the bright spots will radiate maximum energy in the 0.1 keV region. Uhuru is not capable of observing such soft X-Ray sources.

SAHADE: The figures that you gave for T_e refer to the U Gem stars. How is it in the case of UX UMa or DQ Her?

SMAK: It is difficult to say, because the colours refer to a combination of three sources (the primary, the disk and the spot). The combined colours of this eclipsed body are, however, similar to those of the spot in U Gem.

SAHADE: Have you made any estimate of the mean speed of the gaseous stream?

SMAK: Such estimates have been made by several people and one gets values of the order of 500 km/sec for the relative velocity of collision with the disk. This should produce the X-ray radiation, but below 1 keV.