2

DWARF NOVAE

I. CLASSIFICATION

I.A. HISTORICAL OVERVIEW

ABSTRACT: Dwarf novae are defined on grounds of their semi-regular brightness variations of some two to five magnitudes on time scales of typically 10 to 100 days. Historically several different classification schemes have been used.

see also: 145

nova-like stars: 95

Novae, or "new stars," have been known for some centuries. Stars given this name had never been seen before; then they suddenly appeared in the sky for some duration and disappeared again. Many of these old novae seen in historic times are now referred to as supernovae, describing a very powerful event which profoundly affects the mass and structure of the entire star; these are not dealt with in this book. The much less violent events of what we now call novae, recurrent novae, or symbiotic stars, and also nova-like stars are subjects of later chapters of this book. In this chapter, dwarf novae, which undergo comparatively less violent outbursts, are introduced. They became known only in the last century.

In December 1855, a star which behaved like a nova (later named U Geminorum), was detected by Hind (1856); it suddenly became visible and soon thereafter disappeared. However, in March 1856, and recurrently since then in semi-regular intervals of time, it brightened and disappeared abruptly again

(Pogson, 1906). By definition, it could not be a nova. Eventually more and more stars were detected which behaved similarly, so they were regarded as a new class of stars, and referred to as *dwarf novae*.

For a long time, the outburst light curve was the only observable feature of these stars, and so it was (and still is) the basis for their classification. That the temporal brightness changes were only approximately, and not strictly, periodic was confusing. A physical similarity between the two brightest of these stars, SS Cyg and U Gem was conjectured, but also doubted, since the time between successive brightness maxima and the shape of different maxima was confusingly different for each single star, and even more different from one star to another.

Müller and Hartwig (1918) gave a complete list of the then known variable stars. Stars which now are known as dwarf novae are described in this catalogue in terms of their similarity or dissimilarity to SS Cyg (for frequent, irregular maxima) or U Gem (for less frequent, but more regular, maxima). However, for a brief period, SS Cyg itself posed a problem and its relation to U Gem and other dwarf novae was questioned when it stopped exhibiting its normal outburst activity for a while during 1907 and 1908, and only exhibited irregular brightness fluctuations (see Figure 2-1c). Nevertheless, this anomalous event was soon forgotten, and SS Cyg returned to its place as a proto-type of dwarf novae.

The 1918 catalogue by Müller and Hartwig was followed by an updated version by Prager in 1934. In the introduction he gives a brief classification of types of variable stars. Under "physical variables," subtype "expanding stars," there appears a class "U Geminorum stars." The description reads: "The brightness changes of these stars are characterized by the appearance of short-lasting, moderately sharp maxima, clearly not unlike those of novae; their recurrence time ranges from 10 to 100 days for different stars and is not strictly aperiodic. The normal light is slightly variable." Furthermore he distinguishes four sub-classes of U Geminorum stars: SS Cygni stars ("variables with weak, almost constant normal light and quick brightening of large amplitude (up to 6 mag) in not entirely irregular time intervals"); flickering stars ("stars of low apparent brightness which suffer very short-lasting brightenings like SS Cygni stars. Amplitude 3 mag, duration of brightening about 30 minutes, ..." -nowadays these objects are not regarded to be dwarf novae); CN Orionis stars ("U Geminorum-like stars for which the constant minimum is very short or missing entirely so that an almost steady change of light by 2 to 3 mag originates"); and Z Camelopardalis stars ("similar to SS Cygni stars, but with shorter intervals up to the disappearance of a constant minimum and inclination for larger disturbances of the light curve; at times there are long standstills at a mean light level (declining shoulder) or degeneration of the light curve to a sequence of irregular low amplitude waves"). Neither of the terms dwarf nova or nova-like star are mentioned.

Parenago and Kukarkin (1934) and Kukarkin and Parenago (1934) refer to U Geminorum variables as a sub-type of nova-like variables. And Voronstsov-Velyaminov (1934) refers to stars like SS Cyg, RS Oph, and V Sge (which today would be classified as dwarf novae, recurrent novae, and nova-like stars, respectively) all as "nova-like" stars. Gerasimovič (1934) and Miczaika (1934) use the term SS Cygni stars for what Prager defined as U Geminorum stars.

For the next 30 to 40 years both terms became almost equivalents of the term dwarf novae, with a tendency for U Geminorum stars to be preferred.

In 1952 another attempt was made by Brun and Petit to establish definitions of sub-classes of U Geminorum variables. They distinguish seven sub-types, named after the best-known representatives: Z Camelopardalis stars (exhibiting standstills at a mean light level), CN Orionis stars (with very frequent relatively regular maxima), SU Ursae Majoris stars (exhibiting infrequent supermaxima of somewhat larger amplitude and much longer duration than the more frequent normal maxima), X Leonis stars (having frequent long and even more frequent short maxima), SS Cygni stars (with about the same number of long and short maxima alternating irregularly), U Geminorum stars* (high amplitude, quick rise, longer and shorter maxima, long minimum phase), and finally, UV Persei stars (with long minimum phases, large amplitudes, and either very long or very short maxima). This classification was subsequently used only by the authors, but otherwise it was not accepted in this form. For instance Kraft (1962b) defines the terms "U Geminorum star" and "dwarf nova" as equivalent names of the class of stars which consists of the two sub-classes of SS Cygni stars and Z Camelopardalis stars. The same definition was adopted by Mumford (1967b). Smak (1971) defines only one sub-class of Z Camelopardalis stars to the main class of U Geminorum stars.

Vogt (1974) and Warner (1975) independently detected that the dwarf nova VW Hyi exhibited periodic light variations, so-called "superhumps," during a supermaximum (see e.g., Figure 2-49); the remarkable feature of this superhump was that its strict periodicity

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*The term "U Geminorum star," in their scheme, thus denotes both the entire class as well as one particular sub-class.

was a few percent longer than the binary period of VW Hyi. Soon other stars were detected to show superhumps during supermaxima (and - almost - only then). They all belonged to the class of SU Ursae Majoris stars as defined by Brun and Petit (1952). Having become a favorite subject of astronomical research, the name *SU Ursae Majoris stars* was quickly established generally for this sub-class of dwarf novae. Ironically, with the introduction of a superhump as a defining characteristic of SU Ursae Majoris stars, its former proto-type, SU UMa, was excluded from the class which carried its name until, finally, in 1982 superhumps were detected during one of its superoutbursts (Wade and Oke, 1982), too.

During the outburst of WZ Sge in 1978 it turned out that this star, which so far had been classified as a recurrent nova, rather behaved like a (somewhat atypical) dwarf nova; mostly the very long outburst period of 33 years was disturbing. Thus another class, *WZ Sagittae stars*, containing just this one object, was introduced intermediate between recurrent novae and dwarf novae. Later it was discovered that during this same outburst WZ Sge displayed superhumps, which qualified it as an SU Ursae Majoris star. Currently all three classifications of WZ Sge are used. (In this book it will be referred to as a peculiar SU Ursae Majoris star.)

I.B. MODERN CLASSIFICATION

ABSTRACT: According to their outburst characteristics, three types of dwarf novae are distinguished: U Geminorum stars, Z Camelopardalis stars, and SU Ursae Majoris stars.

In the modern classification scheme which was discussed in the Introduction, dwarf novae are regarded to be a sub-class of cataclysmic variables. *The defining characteristic of dwarf*

novae is that they undergo outbursts, which are brightness increases of typically 3 to 5 magnitudes, in semi-periodic intervals of time. For most of them, the faint state, i.e., the *quiescent state* or *minimum*, is their normal state. Most of them can be found in outburst for only a relatively small fraction of the time. The time interval between outburst maxima, which is also somewhat misleadingly called the *outburst period*, usually is on the order of 10 to 100 days. Extreme cases do occur, like WZ Sge with an outburst period of about 33 years, or AH Her, the quiescent state of which can be as short as one day, or even not be reached at all before, after the decline from one maximum, rise to the next occurs. Possibly there is a continuous transition to nova-like stars. These latter in general do not exhibit any outburst activity, but can, on the contrary, sometimes drop in brightness by several magnitudes (see Chapter 3). For any given object, the outburst period is only a statistical average, which, however, usually is followed reasonably well within certain limits. The duration of an outburst[*] is of some 1 to 10 days, depending on the object. The rise to an outburst usually is fast, while the decline to minimum is slower. The shape of the outburst light curve, its period, and the quickness of rise and decline are characteristic features of every object, though an object can have more than one such typical shape. Also any particular outburst shape is not strictly repeated in all details, but only approximately.

Today, dwarf novae are divided into three sub-classes: the U Geminorum stars, the SU Ursae Majoris stars, and the Z Camelopardalis stars. The definition of *Z Camelopardalis stars* is that they occasionally, on decline from an outburst, stay at an intermediate brightness level, a so-called *standstill*, for weeks or years, exhibiting only minor brightness fluctuations before they return to minimum light (Figure

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[*] Superoutbursts are special types of outbursts and will not be distinguished from ordinary outbursts in this general section. For further details see Chapter 2.II.A.4.
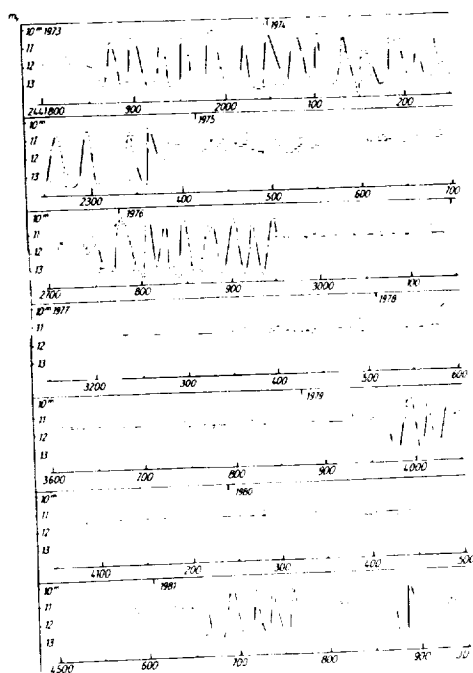
Figure 2-1a. Outburst light curve of the dwarf nova Z Cam (Gunther, Schweitzer, 1982; reproduced from Hoffmeister et al, 1984). Occasionally the star remains at some intermediate brightness for several months to several years.
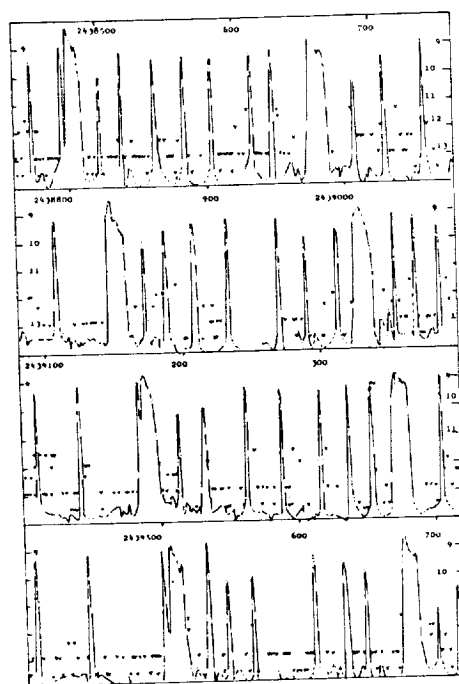
Figure 2-1b. Outburst light curve of the SU Ursae Majoris type dwarf nova VW Hyi (Bateson, 1977). Normally the system undergoes short outbursts; at rather regular intervals of time so-called superoutbursts occur which are brighter and last for much longer than normal outbursts.
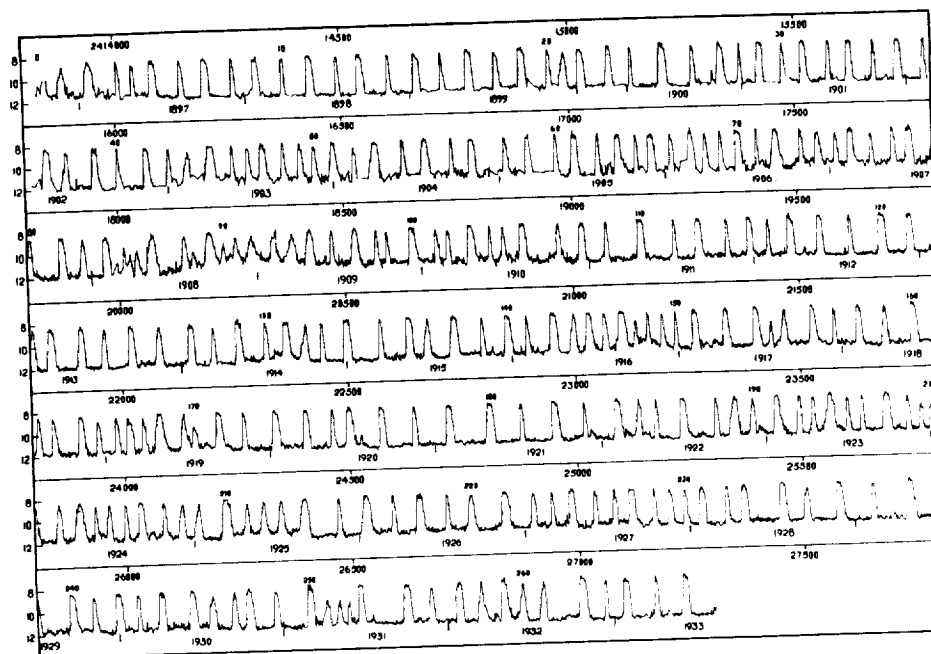

Figure 2-1c. Outburst light curve of the U Geminorum type dwarf nova SS Cyg in 1896 - 1933 (Campbell, 1934). Shorter and longer outbursts follow each other in an irregular sequence.

2-1a). *SU Ursae Majoris stars* exhibit two types of outbursts, so-called *normal outbursts* and the noticeably longer and brighter *superoutbursts* (Figure 2-1b). And the third sub-class is the *U Geminorum stars*, to which all those dwarf novae belong which are neither SU Ursae Majoris stars nor Z Camelopardalis stars (Figure 2-1c). The membership of a star in the class of SU Ursae Majoris stars or of Z Camelopardalis stars seems to be exclusive; the membership in the U Geminorum class is exclusive by definition. Since quite detailed observations are required in order to identify a star as belonging to the SU Ursae Majoris sub-class in particular, some as yet unrecognized SU Ursae Majoris stars may well be hidden in the U Geminorum stars.

Several lists of dwarf novae and their classification compiled under various aspects, have been published in the literature. One such list is contained in the *General Catalogue of Variable Stars* (Khopolov, 1985). The disadvantage of this list is that it contains variable stars of all kinds which makes it a tedious task to select the dwarf novae. Also by no means all stars which are classified therein as dwarf novae would be referred to as such by those who work in the field, and, vice versa, objects that are conventionally classified as dwarf novae are assigned some other type. *The AAVSO Variable Star Atlas* contains names, coordinates, classifications, and ranges of brightness variability of all those stars that are possibly observable with the telescopes of amateur astronomers. Again, since all kinds of variable stars are included, it is time-consuming to select just the dwarf novae. Since, however, practically all dwarf novae have been detected by amateurs, and thus are observable by them, this is likely to be the most reliable and complete source for dwarf novae. Lists of classifications and system parameters of cataclysmic variables (dwarf novae and other types) for which orbital periods are known, are given by Patterson (1984) and by Ritter (1984, 1987). The shortcoming of these catalogues is that, due to the adopted limitation, they are rather incomplete with respect to the full sample of known dwarf novae.

I.C.   SOME STATISTICS

ABSTRACT: Dwarf novae and nova-like stars are treated together here. Both the observed orbital periods and, to some extent, the ratios between the masses of the two stars seem to be related to the outburst behavior.

see also: 7

interpretation: 217, 219, 222

As was pointed out earlier, the first dwarf nova, U Gem, was detected in 1855, and the number of these systems increased only slowly thereafter. By the beginning of this century only one more dwarf nova, SS Cyg (detected in 1896), was known. Müller and Hartwig (1918) report that eight members of this class were known; by 1934 their number had doubled (Gerasimovič, 1934); and Petit (1958) states that, out of the 149 variable stars which by that time were classified as dwarf novae in the *General Catalogue of Variable Stars* and its supplements, only 56 were certain to be dwarf novae, a further 47 of them were probable dwarf novae, and the rest were doubtful. This same catalogue in the version of 1983 classifies 254 stars as dwarf novae; assuming that again some 30% are doubtful, this still means that currently some 200 dwarf novae are known.

In the Introduction (Chapter 1.V), statistical properties of dwarf novae and nova-like stars were discussed in the context of other cataclysmic variables, without, however, dealing with them in detail. As stated in the previous section, dwarf novae are divided into sub-classes, the U Geminorum stars, the SU Ursae Majoris stars, and the Z Camelopardalis stars. Similarly, as will be discussed in more detail in Chapter 3.I nova-like stars are also divided into sub-classes, namely the UX Ursae Majoris stars, the anti-dwarf novae, the DQ Herculis stars, the AM Herculis stars, and the AM Canum Venaticorum stars. Although
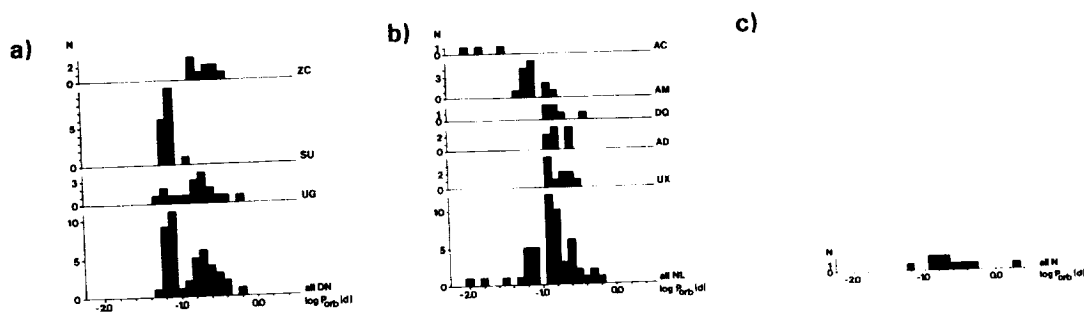
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Figure 2-2. Distribution of orbital periods among sub-classes of dwarf novae (a) and nova-like stars (b); for comparison the distribution of novae is given as well (c). No objects are found with periods between about two and three hours; only three peculiar systems have periods shorter than some 80 minutes; only very few objects have periods that are longer than some ten hours.
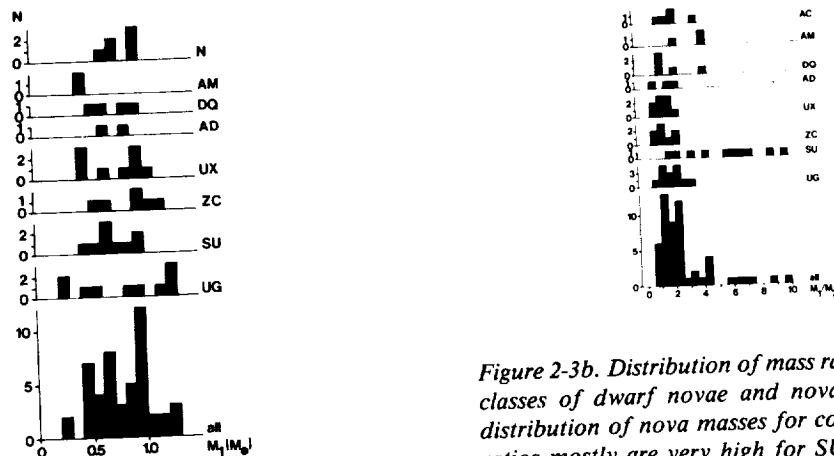

Figure 2-3a. Distribution of the masses of the white dwarfs among sub-classes of dwarf novae and nova-like stars; for comparison the distribution of novae is given as well. No very obvious relation to sub-classes seems to exist.

Figure 2-3b. Distribution of mass ratios among sub-classes of dwarf novae and nova-like stars with distribution of nova masses for comparison. Mass ratios mostly are very high for SU Ursae Majoris stars; they tend to be higher than normal for AM Herculis stars (i.e, for those nova-like stars which are believed to possess strongly magnetic white dwarf(s); otherwise typically the secondary star is half as massive as the white dwarf.

nova-like stars are not the issue of this chapter, they are still so similar to dwarf novae in almost all of their properties that it would seem all too artificial to formally separate them entirely. In particular, a statistical consideration of both groups together, the dwarf novae and the nova-like stars, can be rather illuminating. This is the course which will be pursued in this particular section; for the remainder of this chapter, however, only dwarf novae will be considered, and observations of nova-like stars will be the issue of Chapter 3.

Figure 1-2 gives all the known orbital periods of cataclysmic variables separated by object classes. In Figure 2-2 these same data are

presented in another way: the sub-classes of dwarf novae and nova-like stars are separated, and, for comparison, the orbital periods of novae are shown as well. Z Camelopardalis stars, and the UX Ursae Majoris stars, closely related in appearance, and anti-dwarf novae can all be found exclusively above the period gap; SU Ursae Majoris stars, on the other hand, with only one exception all have orbital periods below the gap, the one exception, TU Men, being very close to the upper edge of the gap; the AM Canum Venaticorum stars also fall below the period gap, below even the short period cut-off of all the other cataclysmic variables; all DQ Herculis stars can be found above the gap, except for EX Hya; the AM

Herculis stars tend to be found below it, although some objects lie above it; and finally, dwarf novae with no particular characteristics, the U Geminorum stars, can have any value of the orbital period.

White dwarf masses seem to be statistically identical for dwarf novae and nova-like stars as well as for their various sub-classes (Figure 2-3a). When, however, mass ratios are considered there is a tendency for SU Ursae Majoris stars and AM Herculis stars to have distinctly higher than average values, which might bear on the observable idiosyncrasies of these classes of objects (Figure 2-3b). Objects belonging to other classes tend to cluster around values of M_1/M_2 of 1 or 2, but much higher values are possible. For the entire sample, the white dwarf is the more massive of the components for the majority of systems; if mass ratios of less than one occur, they almost always are found to be close to one.

GENERAL INTERPRETATION: All cataclysmic variables are believed to be binary stars. Dwarf novae and nova-like stars are regarded to be essentially the same kind of objects. Due to a higher mass transfer rate from the secondary star into the Roche lobe of the white dwarf, nova-like stars normally can be found in the outburst state. The distribution of mass ratios and orbital periods is suspected to be due at least partly to evolutionary effects.

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *The physical difference between dwarf novae, nova-like stars, novae, and recurrent novae is not clear. (See 176, 229)**

- *Is binarity a necessary condition for an object to be a cataclysmic variable? (See 151, 179, 188, 190, 214)*

- *A vague relation between orbital periods and outbursts behavior has been observed. (See 177, 181)*

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*The raised points are dealt with theoretically in the indicated pages.

- *A minimum orbital period, a period gap, and some evidence for a maximum orbital period have been observed. (See 222)*

- *Most SU Ursae Majoris stars and AM Herculis stars seem to have higher mass ratios than other cataclysmic variables.*

- *Almost all known secondaries in cataclysmic variables seem to be cool main sequence stars. (See 219)*

II. PHOTOMETRIC OBSERVATIONS

II.A. OUTBURST BEHAVIOR

ABSTRACT: Outbursts of dwarf novae occur at semi-periodic intervals of time, typically every 10 to 100 days; amplitudes range from typically 2 to 5 mag. Within certain limits values are characteristic for each object.

related spectroscopic changes: 61, 81

nova-like stars: 102, 113, 125

interpretation: 171

The outburst behavior of dwarf novae is the one phenomenon which has been studied for the longest time about these objects. In fact, until the discovery of the binary nature of cataclysmic variables, essentially all research involved attempts to understand what physical processes could produce the semi-periodic, but not strictly periodic, recurrence times of the outbursts and the observed shapes of the light curves. As soon as some strictly periodic behavior was found as evidence for the binary motion, almost all research turned away from explaining the long-term variability. A limited interest in this field was reawakened with the detection of the peculiarities observed during superoutbursts in SU Ursae Majoris stars (see below), and again with the recent opportunity to perform observations in the UV and X-ray spectral ranges. Overall, a number of very valuable investigations have been undertaken, and these have revealed many interesting

features which are still far from being understood.

No strictly periodic pattern is obvious in the outburst behavior of dwarf novae (see Figures 2-1 a-c). There is some average time interval between successive outbursts; the individual scatter, however, can be considerable. Also the outburst amplitude for any individual object can only be given within ...de limits, the minimum as well as the maximum brightness levels being variable.

In spite of this apparently random behavior, attempts have been made since the beginning of this century to find some underlying systematics or periodicity in the behavior of both single objects and the entire class of dwarf novae. The highlights of these investigations shall be presented in the following section.

II.A.1. SS CYGNI — A WELL-STUDIED CASE

ABSTRACT: More than 600 outbursts of SS Cyg have been observed. Their investigation reveals a number of statistically characteristic features and repetitive properties.

see also 24

SS Cyg is by far the best-studied dwarf nova due to its large apparent brightness (m_v = 12.7 - 8.2 mag) and its outstanding position as a circumpolar star for many of the northern hemisphere observatories. Almost certainly not one single outburst has passed unobserved since the detection of SS Cyg in 1896, yielding well over 600 observed outbursts to date. In addition, the shapes of the outbursts as well as the brightness during minimum state have subsequently been recorded extremely well. Figure 2-1c displays the complete light curve between 1896 and 1933. Very extensive statistical studies have been carried out by Krytbosch (1928), Campbell (1934), Sterne and Campbell (1934), Martel (1961), Howarth (1978), and Bath and van Paradijs (1983). A summary of some of their results follows.

Inspection of Figure 2-1c reveals that the shapes of the outbursts are by no means always the same, but still some characteristic features are repeated. Campbell derived a classification scheme (Figure 2-4) based on the times needed for rise (light increase) from minimum level to maximum: class A is a very rapid rise, class B is somewhat slower, class C moderately slow, and class D extremely slow; further sub-division of each class was undertaken in order to account for different widths of maxima. Class A is by far the prevailing type with 64% of all 267 maxima investigated by Campbell, class B has 9%, class C 18%, and class D again 9%. Classes C and D together also are referred to as anomalous, a term that has since been used for other dwarf novae to describe all outbursts with slow rises, in spite of the fact that they have proved to be a rather normal feature of dwarf nova outbursts in general. There is an obvious distinction within classes A and B into long and short (wide or narrow) outbursts. This is seen even more clearly in the histogram of widths of 437 maxima of SS Cyg (Martel, 1961) in Figure 2-5; this can be approximated by two normal distributions centered at 7.5 and 15 days, respectively, with a gap at about 11 days. It appears that the width of class A outbursts lies close to the statistical averages of 7.5 and 15 days, whereas outbursts of class B, C, and D are more randomly distributed in duration. The rate of rise and decline (light decrease) in classes A and B is essentially the same for both long and short eruptions, the rise being about twice as fast as the decline. The main differences between both types are that during long eruptions the star remains at almost constant brightness for about a week, and statistically the maximum brightness of long eruptions is somewhat larger than that of short ones (8.4 mag vs. 8.6 mag). Almost all faint maxima which reach only a brightness of 8.8 mag or less have long rise times (Campbell's classes B, C, and D). There is a clear tendency for long and short outbursts to alternate and a less than random probability for sequences of long-long or short-short eruptions to occur.
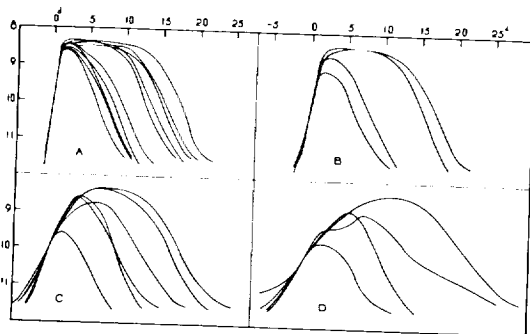
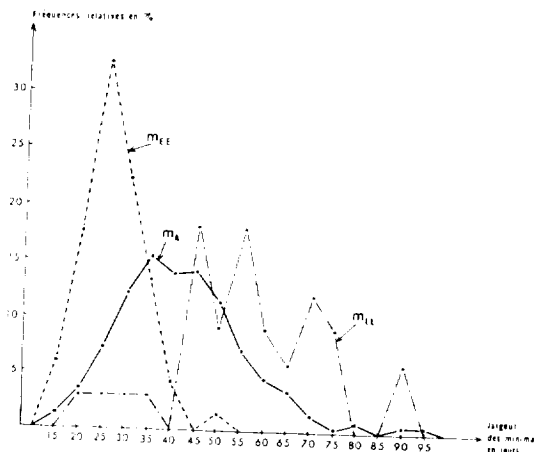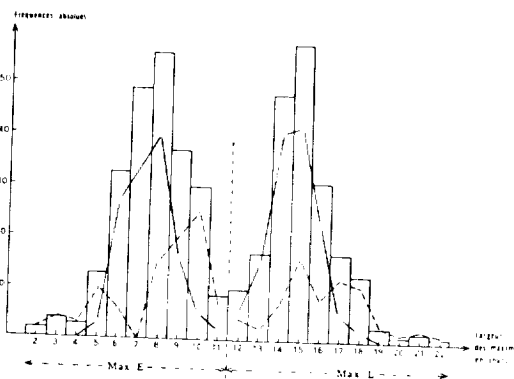Figure 2-4. Classification of outburst light curves of SS Cyg (Campbell, 1934).

Figure 2-5. Distribution of widths of maxima of SS Cyg. The histogram shows the total distribution, the solid line gives the frequency of type A outbursts, the dashed line that of types B, C, and D together (Martel, 1961; his figures 4 and 14 combined). In all cases a clear bi-modal distribution appears.

Figure 2-6. Duration of minima of SS Cygni in relation to the duration of both the preceding and the following outbursts (m_{EE} : between two short outbursts; m_{LL}: between two long outbursts; m_A: between either a long and a short, or a short and long outburst) (Martel, 1961). Minima between two short outbursts of SS Cyg tend to be short, minima between two long outbursts tend to be long.
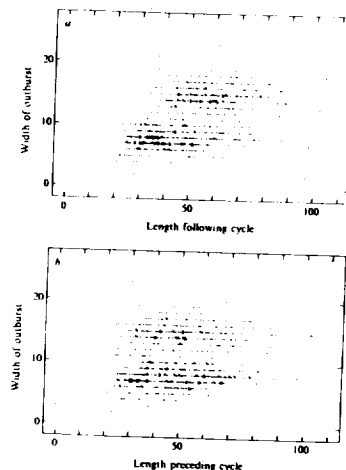

Figure 2-7. Width of maxima in SS Cyg versus the duration of the preceding and the following minimum time (Bath and van Paradijs, 1983). A vague correlation exists with the length of the following cycle, clearly not with the preceding cycle.

The maximum brightness of an outburst is un-correlated with the brightness of both the preceding and the following outburst.

Investigation of the length of minima between successive outbursts leads to the result displayed in Figure 2-6: the average duration of minima between long-short and short-long pairs is almost identical, peaked at some 35 days, while durations of only 10 days and up to 100 days are possible; minima between two successive short eruptions last for only some 25 days on the average, and hardly ever are longer than 50 days; and minima between successive long outbursts can last for almost any length of time between some 40 and some 95 days. Looking at all kinds of outbursts together, a loose correlation exists between the duration of an outburst and the duration of the following cycle, while there is no such relation with the preceding minimum period (Figure 2-7); class D outbursts, however, tend to be preceded by minima of considerably shorter duration than average (Bath and van Paradijs, 1983).

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One final statistical feature of outbursts of SS Cyg is that type A outbursts usually start from a quiescent brightness of 11.9 ± 0.12 mag, whereas all slower rises (classes B, C, D) start from brighter quiescent states of 11.64 ± 0.30 mag (Bath and van Paradijs, 1983).

II.A.2. OTHER DWARF NOVAE

ABSTRACT: Although samples are not as statistically significant as for SS Cyg, similar characteristic features seem to exist in other dwarf novae as well.

see also: 22

interpretation: 171

Equally extensive studies are not available for other dwarf novae, mostly because their lesser brightness makes it difficult for them to be observed by amateurs (who are the main source of information on dwarf nova outburst behavior). Besides SS Cyg, probably the best investigated dwarf novae concerning their outburst activity are U Gem (with comprehensive studies by van der Bilt (1908), Greep (1942) and Saw (1982a)) and VW Hyi, which has mostly been analyzed with respect to its superoutbursts, the discussion of which will be deferred to a latter section in this chapter.

Like the SS Cyg, the occurrence of two types of outburst, long (or wide) and usually more luminous ones, and short (or narrow) and often less luminous ones, is a very common, if not universal, feature of dwarf novae (some examples are given in Figure 2-8). We could not find one single conclusive case of a uni-modal distribution with the possible exception of WZ Sge for which, however, only a total of three outbursts were observed. But while most dwarf novae exhibit wide and narrow outbursts, and the SU Ursae Majoris stars exhibit normal as well as considerably wider (by a factor of five to ten) superoutbursts, TU Men (the only known SU Ursae Majoris star with an orbital period above the period gap between two and three hours) is the only known system which undergoes narrow, wide, and superoutbursts (Bateson, 1979, 1981; Warner, 1985a). Nor-

mally, within extreme ranges, all durations are possible, but some are still rare enough to leave the general distribution with two clear maxima. Szkody and Mattei (1984) claim that such bimodal distributions occur only in SU Ursae Majoris stars and very few others, while most stars in their sample show uni-modal distributions. It must be noted, however, that their data base is very short compared to that of most other investigations, and that statistics based on more data show clear evidence for a general bi-modal distribution of outbursts for the objects in their sample. A more convincing conclusion to be drawn from their investigation is that the overall outburst behavior of a dwarf nova may well undergo changes in the course of years. Histograms of the outburst activity of EM Cyg, probably a very radical example, illustrate the point (Figure 2-9): if the distributions of outburst widths for only a short interval of time are regarded (one and three years in this example), the resulting distributions may come out considerably different from each other, as well as from averages over long intervals of time. Furthermore, there are objects in which long and short maxima keep strictly alternating for many years. The most famous example of such outburst activity is U Gem, which was never seen to deviate from this regular alternation during the first 50 years of its surveillance (van der Bilt, 1908).

In general, provided both types of maxima occur about equally frequently, there is a tendency for them to alternate. When more short maxima than long ones occur, most of the long maxima are both followed and preceded by a short one, while a short one may well be followed by another short one; in other words, pairs of two short outbursts are not unlikely, while pairs of two long outbursts are extremely rare. When anomalous outbursts (i.e., outbursts with an unusually long rise time) occur in an object, these are likely to come in groups; i.e., they are the only kind of outburst to be observed for some duration, or at least then they occur considerably more frequently than any other type (Petit, 1961).
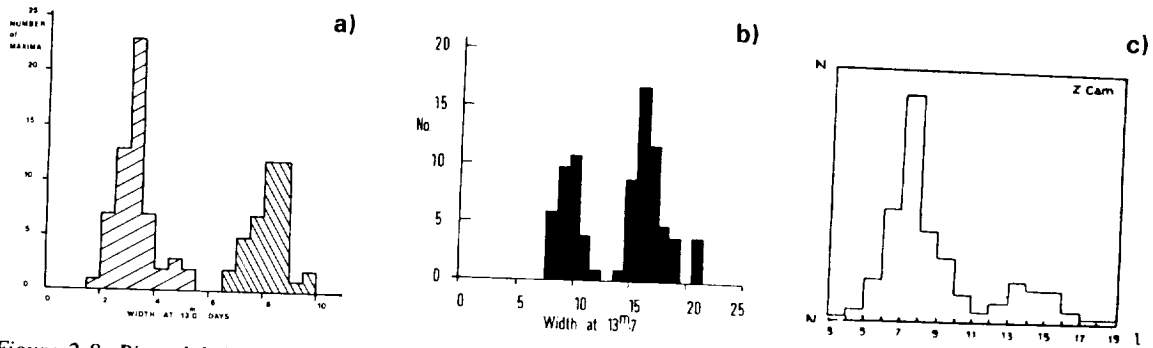
Figure 2-8. Bi-modal distributions of the lengths of dwarf nova outbursts: a:X Leo (Saw, 1982b), b:U Gem (Isles, 1976), c:Z Cam (Petit, 1961). Possibly all dwarf novae show distributions like this.
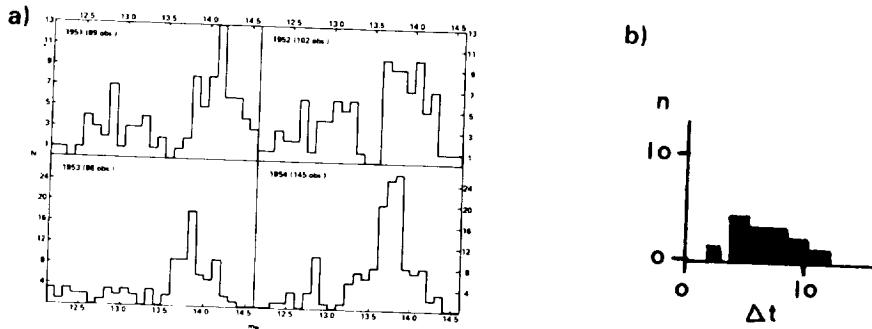

Figure 2-9. Distributions of durations of outbursts of EM Cyg for (a) the years 1951 through 1954 each (Brady and Herczec, 1977), and for (b) approximately 1974 - 1976 (JD 2442300 - 2443300) (Szkody and Mattei, 1984). The bi-modal distribution only becomes obvious when observations over a very long interval of time are considered.
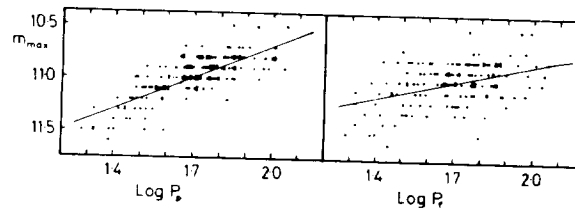
Figure 2-10. Maximum outburst magnitude versus the duration of the preceding (left) and the following (right) quiescent period in SS Aur (Howarth, 1977). In contrast to SS Cyg, in VW Hyi the maximum brightness of an outburst is dependent on both the durations of the preceding as well as the following minimum.
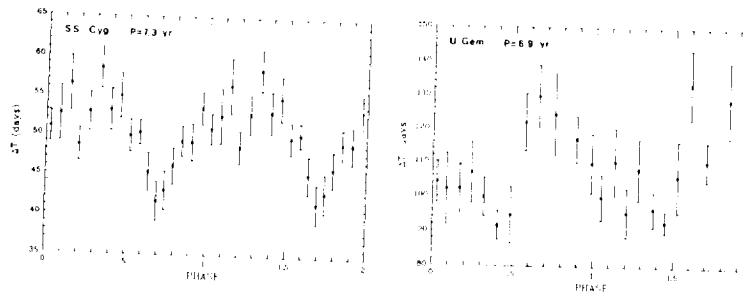
Figure 2-11. Semi-regular variations of the duration of quiescent intervals between two consecutive outbursts of SS Cyg and U Gem (Bianchini, 1988).

In this same investigation Petit found that the average ratio of the number of long per short maxima increases as the outburst period of a system increases: SU UMa and AY Lyr (with outburst periods of some 13.4 and 24 days, respectively) exhibit about one long outburst per 7 or 8 short ones; Z Cam (21 days), X Leo (20 days), and UZ Ser (31 days) have typically 1 long outburst per 2 or 3 short ones; in SS Cyg (50.7 days) and SS Aur (53.3 days) about 2 long outbursts can be observed per 3 short ones; and finally in U Gem (103.4 days) and UV Per (360 days) this ratio increases to approximately 5 long outbursts for every 4 short ones.

Several investigations have been carried out to look for a possible correlation between the length of quiescent (low brightness) intervals and the kind of outbursts a system undergoes. The emerging picture is clearly not consistent: In the case of SS Cyg, CN Ori, and CZ Ori the width of an outburst, and in the case of FQ Sco, BI Ori, and U Gem its maximum brightness (which normally is higher for long outbursts than for short ones) are correlated with the length of the following quiescent interval but not with the preceding one[*] (Bath and van Paradijs, 1983; Isles, 1976; Gicger, 1987); in the case of VW Hyi both the total width and the maximum brightness, in UZ Ser and TU Men the width, and in WW Cet the maximum brightness are correlated with the preceding minimum, but not with the duration of the following one[*] (Gicger, 1987; Smak, 1985; van der Woerd and van Paradijs, 1987); in the case of SS Aur the maximum brightness, and in the case of UY Pup the width correlate with both the preceding and the following quiescent state (Gicger, 1987; Howarth, 1977) (see Figures 2-7 and 2-10).

As to the length of quiescent periods between long and/or short outbursts, from investigating large amounts of data of many dwarf novae, Petit (1961) concluded that the durations of

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[*] Results for other correlations are not given.

minima, irrespective of kinds of outburst between which they occur, tend to be almost normally distributed about some mean value which is characteristic for each object. Minima occurring between two short outbursts have a tendency to be shorter than average. This is in agreement with results of detailed investigations of SS Cyg (Figure 2-6) and X Leo (Saw, 1982b). For several systems, there is some indication for them to be the fainter the longer the quiescent state lasts. Furthermore, in several objects, like in SS Cyg, U Gem, and RU Peg, there is evidence for cyclic secular changes in the duration of the quiescent period of dwarf novae (Campbell, 1934, Petit, 1961, Saw, 1983, Bianchini, 1988) (Figure 2-11).

II.A.3. NUMERICAL RELATIONS

ABSTRACT: Relations between the outburst amplitude, or the total energy released during outburst, and the recurrence time have been found, as well as relations between the orbital period and the outburst decay time, the absolute magnitude during outburst maximum, and the widths of long and short outbursts, respectively.

interpretation: 177, 181

All dwarf novae are highly individualistic objects; no two systems have been found which can be regarded as approximately identical, and certainly there is nothing like a "typical" dwarf nova. This applies to their outburst behavior, but it proves valid for other aspects of their nature just as well. Still, it clearly would be wrong to say that they are all totally different from each other.

For more than half a century attempts have been made to find some relations that all dwarf novae, if possible even all cataclysmic variables, would obey. The first such relation was found by Kukarkin and Parenago (1934) who suggested a relation

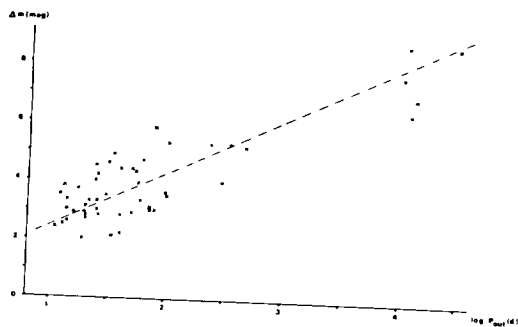$$A = 0.63 + 1.66 \log P \qquad (2.1)$$

Figure 2-12a. Kukarkin-Parenago relation between outburst amplitude Δm and recurrence time P_{out} of dwarf novae and recurrent novae (data from Petit, 1958). The original relation as given by Kukarkin and Parenago (1934) is indicated as a solid line; its physical significance is not clear.
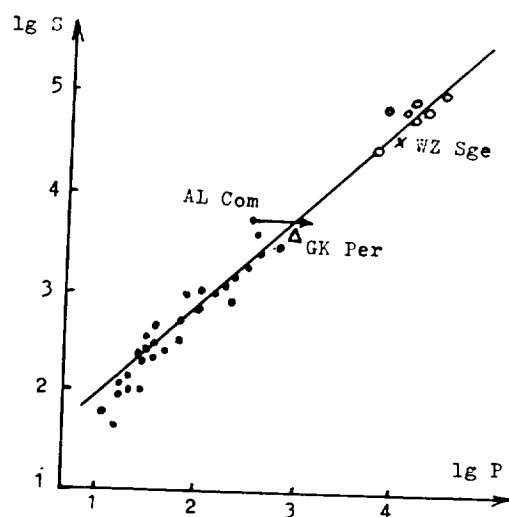

Figure 2-12b. Revised Kukarkin-Parenago relation between the energy spent during an outburst and the recurrence time (Antipova, 1987).
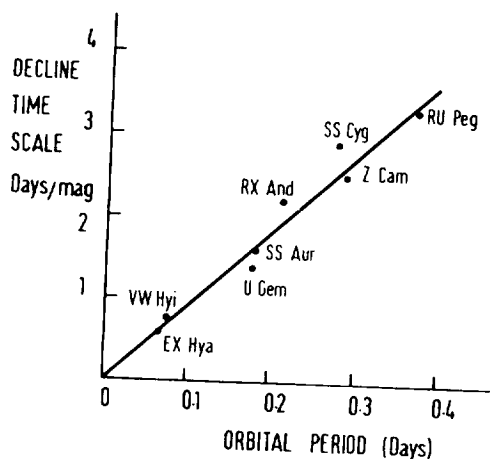

Figure 2-13. Bailey relation between the time for early decline from a dwarf nova outburst and the orbital period (Bailey, 1975).
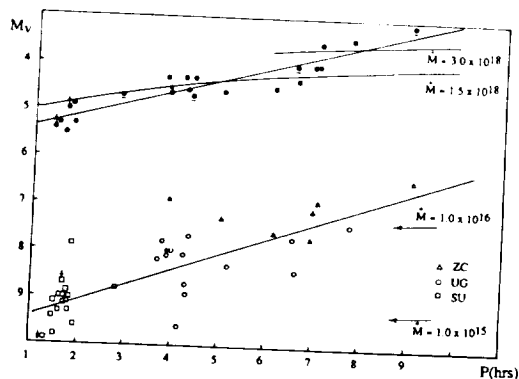
Figure 2-14. Relation between absolute brightness during outburst maximum and the orbital period (Warner, 1987).
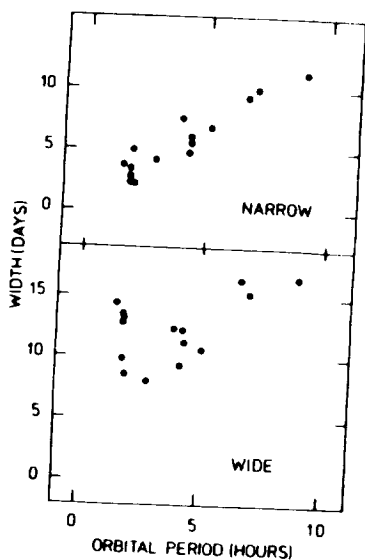

Figure 2-15. Relation between width of an outburst and orbital period (van Paradijs, 1983).

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between the outburst amplitude A of dwarf novae and recurrent novae (which fit into the same relation) and their recurrence time (outburst period) P (*Kukarkin-Parenago relation*). Since then this numerical relation has been somewhat modified by others (Petit, 1958; Khopolov and Efremov, 1976; Greep, 1942; Payne-Gaposchkin, 1957; van Paradijs, 1985), but the differences in effect are small (Figure 2-12a). Extrapolation to outburst amplitudes to novae would predict recurrence times of several thousand years, so the relation appears not unreasonable. It is not known, however, whether there is a common physical process underlying this relation or whether it is a mere product of chance: the scatter for dwarf novae is large enough for the relation to not be very meaningful for any single object; the inclusion of recurrent novae gives it a convincing appearance, but this often has been ascribed to pure chance because of the presumed very different outburst mechanisms for dwarf novae and recurrent novae*; and whether or not this relation holds for novae cannot be tested due to the very definition of novae.

A revised version of this relation recently has been suggested by Antipova (1987) who correlates the total outburst energy (instead of the amplitude) with the outburst period. Assuming that all quiescent dwarf novae have the same absolute brightness (which is a very questionable assumption - see Chapter 4.II.C.2), and after applying some (largely arbitrary) correction for the contribution of the secondary star, dwarf novae (normal outbursts as well as superoutbursts), recurrent novae, and even GK Per (which exhibits dwarf nova-like outbursts during its quiescent state as a nova - see Chapter 8), all seem to fall on a nearly straight line (Figure 2-12b). Due to the assumptions Antipova made, however, it is questionable whether this relation actually reflects a common underlying physical process, as it seems to suggest.

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*The outburst mechanism for recurrent novae is not known with certainty; it may or may not be the same as for novae; it clearly is not, however, the same as for dwarf novae, i.e., a collapse of the accretion disc.

Another relation, between the orbital period, P_{orb} and the rate of early decline of dwarf novae from their outburst, T (which always seems to occur in about the same way in each system, irrespective of the type of outburst), was first suggested by Bailey (1975) (*Bailey relation*, Figure 2-13):

$$T = 9.2\ P_{orb} \qquad (2.2)$$

Warner (1987) found a remarkably tight relation, namely that the absolute brightness of a dwarf nova during outburst increases approximately linearly as the orbital period of the system increases (Figure 2-14):

$$M_{V,max} = (5.64 \pm 0.13) \qquad (2.3)$$
$$- (0.259 \pm 0.024)\ P\ [hr]$$

From inspection of published data in the literature, van Paradijs (1983) found a relation between the orbital period of a dwarf nova system and the width of wide and narrow outbursts, respectively (Figure 2-15):

$$W_{wide}\ [d] = (1.2 \pm 0.5) \qquad (2.4a)$$
$$+ (28.6 \pm 2.9)\ P_{orb}\ [d]$$

$$W_{narrow}\ [d] = (9.89 \pm 1.2) \qquad (2.4b)$$
$$+ (15.3 \pm 9.7)\ P_{orb}\ [d]$$

And finally, Szkody and Mattei (1984) suggest that three relations exist between the duration of the entire outburst of a dwarf nova (including rise and decline), the rise time and the time needed for decline, on one hand, and the orbital period on the other. None of these, however, looks in any way convincing.

II.A.4. STANDSTILLS AND SUPEROUTBURSTS

ABSTRACT: Z Camelopardalis stars at times discontinue their normal outburst activity for a while and remain at an intermediate brightness level. - Besides normal (short) outbursts, SU Ursae Majoris stars also show superoutbursts; these occur at more predictable intervals of time than normal outbursts, they last 5 to 10 times longer, and are slightly brighter.

There are two special groups of dwarf novae, the Z Camelopardalis stars and the SU Ursae Majoris stars, both of which are classified on the basis of peculiarities in their outburst behavior.

The Z Camelopardalis stars behave like normal dwarf novae (U Geminorum stars) with short outburst periods most of the time, exhibiting all the normal features. Occasionally, however, at unpredictable times on decline from an otherwise seemingly normal outburst, they remain at a brightness level about midway to minimum brightness (Figure 2-16). This hold may last for a couple of days up to many months or years. Usually, after the end of such a *standstill,* the star returns to minimum brightness and resumes its normal outburst activity, which, however, may be ended by another standstill as soon as the next decline. However, at least one case is known (Mumford, 1962) in which a standstill of Z Cam ended in a rise to maximum. As can be seen in the example of Z Cam in Figure 2-16, before a period of standstill, the minimum brightness level reached between consecutive maxima may or may not increase continuously; and also a progressive decrease in the intervals between maxima before eruptions is observed occasionally. During standstills, brightness fluctuations of some tenths of a magnitude may occur which are reminiscent of the regular outburst behavior exhibited at other times.

The other special group of dwarf novae are the SU Ursae Majoris stars, for which the long outbursts (*superoutbursts*) are longer by about a factor of 5 to 10 than the short ones, and in all but one system (WZ Sge) occur much more seldom than the short (normal) ones. Extensive investigations of the outburst light curves of one of the best-known SU Ursae Majoris stars, VW Hyi, have been undertaken by Bateson (1977), Smak (1985), and van der Woerd and van Paradijs (1987). A part of the outburst light curve is presented in Figure 2-1b. All of these studies are based on the same compilation of data from almost 22 years of observations covering a total of 292 consecutive maxima, out of which 44 were supermaxima. The average time interval between normal (short) outbursts is 27.3 days; for superoutbursts it is 179 days; they last on the average for 1.4 and 12.6 days, respectively. The brightness at maximum is approximately 9.5 mag for normal and 8.5 mag for superoutbursts.

Normal outbursts of VW Hyi are like short outbursts of any other dwarf nova. Often a marked dip of up to 0.5 mag in a minimum brightness is seen immediately before the onset of an outburst, irrespective of whether it is a short or a long outburst, and often there is also an increase in brightness by about 0.5 mag as soon as the bottom of the decline has been reached.

Between three and eight normal outbursts can occur in VW Hyi between two consecutive superoutbursts (i.e., during a so-called 'supercycle'); the total length of the supercycle hardly is affected by this, but always has an average length of about 179 ±12 days. The last normal outburst before a superoutburst always occurs less than 167 days after the last superoutburst. As for normal outbursts, immediately after a superoutburst they are narrower and fainter than usual, and they then become increasingly more energetic later in the supercycle (Figure 2-17). The length of normal cycles decreases with increasing supercycle phase. Irrespective of the total number of short outbursts within a supercycle, the first outburst in each cycle always starts within 17 to 29 days after the last supermaximum, while in general the time elapsing between two consecutive normal outbursts can vary between 10.9 and 70.7 days, with an average of 36.0 days. The last two normal outbursts before a superoutburst tend to have about equal length, which is either short (both cycles together last for less than 45 days: type S superoutburst) or long (both together last for more than 60 days: type

L superoutburst); no values in the gap between 45 and 60 days seem to exist (Figure 2-18). After about half of a supercycle has elapsed, it can be distinguished whether the last two cycles are going to be long or short: the lengths of normal outburst cycles for type S superoutbursts decrease, while those in type L superoutbursts increase. When they are long (type L), the maximum visual brightness of the following superoutburst tends to be larger, the longer these last quiescent intervals last; no such relation seems to exist for S-type cycles. There also is no difference between the total length of type L and type S supercycles.

According to their shape, Bateson (1977) divided the optical light curves of supermaxima into eight classes, S1 to S8 (Figure 2-19). The rise always is indistinguishable from the rise to short outbursts. For somewhat less than half of the observed superoutbursts of VW Hyi, a more or less pronounced decline (dip) of up to two magnitudes occurs in the optical after the typical maximum brightness of short outbursts has been reached, after which the superoutburst starts as if triggered by a normal outburst (classes S6 to S8). A number of investigators (Pringle et al, 1987; Verbunt et al, 1987; van Amerongen et al, 1987; Polidan et al, 1987; Heise et al, 1987) carried out simultaneous observations of VW Hyi in many wavelengths and found that, although there was no trace in their data of a precursor in the optical, it was clearly seen in the UV and at X-rays. The time elapsed since the last superoutburst tends to be shorter than the average (151 ± 12 days vs. an average of 163 ± 12 days) if the last normal cycle was short, and it is followed sooner by a normal outburst than by other supermaxima. Furthermore, the larger the pre-supermaximum dip, the more normal outbursts follow before the next supermaximum occurs, and the maximum brightness is the larger and the maximum the broader, the deeper the dip is.

Vogt (1980) undertook an extensive study of the outburst properties of those SU Ursae Majoris stars known at that time. One very

striking feature of superoutbursts is their fairly strict periodicity which is kept within rather narrow limits, very unlike the short outbursts which, clustered about some mean value, occur at almost random intervals of time. The scatter of cycle lengths in SU Ursae Majoris stars amounts to roughly half the mean cycle length of normal outbursts, suggesting that superoutbursts may be triggered by normal outbursts. An even closer inspection of individual cycle lengths reveals that superoutbursts follow a very neatly defined linear ephemeris for typically 10 to 20 cycles, then they switch to another equally well defined ephemeris which is slightly different from the former one. For each star, a small number (typically two to three) of such superoutburst periods can be determined between which the star switches at random (Figure 2-20). The ratios between different cycle lengths of one star typically are on the order of 1.1 to 1.3. It remains to be seen whether similarly tight relations also hold for the more recently detected SU Ursae Majoris stars. An investigation of long outbursts of SS Cyg and U Gem did not yield any comparable results.

Vogt (1981) suggested a relation between the periods of normal outbursts and superoutbursts in SU Ursae Majoris stars. This relation looked quite convincing at the time he proposed it. Taking into account, however, the more recently detected SU Ursae Majoris stars and more modern values of outburst periods, there is no evidence for such relation any longer.

Based on the indication that probably all dwarf novae exhibit long as well as short outbursts, van Paradijs (1983) suggested that superoutbursts may be a general phenomenon in dwarf novae. Support for this comes from the observation that the duration of short outbursts seems to increase appreciably with the orbital period of the system, while the duration of long outbursts hardly does so (see above). The striking contrast between long and short outbursts in SU Ursae Majoris stars (all of which have very short orbital periods) appears to be a consequence of the increasing contrast
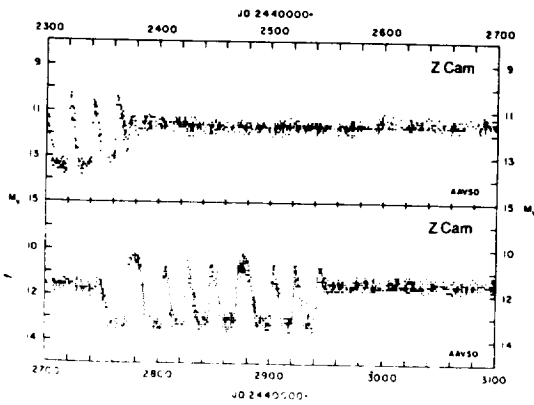
Figure 2-16. Outburst light curve of Z Cam (Lin et al, 1985 and see also Figure 2-1a). A standstill can be entered from either the bright state (the more frequent case) or from the quiescent state; in the particular example given the quiescent brightness level increased systematically before standstill was entered.
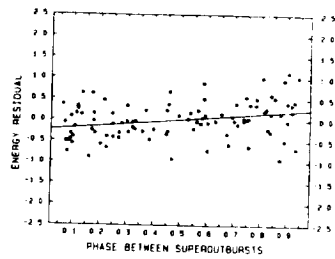

Figure 2-17. Residuals of the relation between outburst energy of VW Hyi and the duration of the preceding minimum versus supercycle (van der Woerd and van Paradijs, 1987). Before a superoutburst the short maxima become increasingly more energetic.
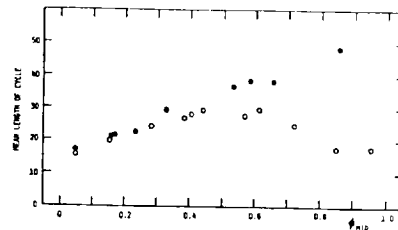
Figure 2-18. Mean length of normal cycles of VW Hyi as a function of the supercycle phase. Filled circles refer to L-type supercycles, open circles to S-type supercycles (see text for further explanation) (Smak, 1985).

a)

b)
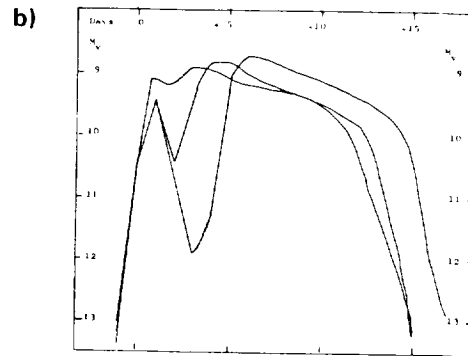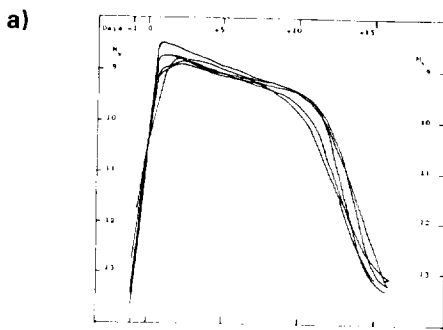
Figure 2-19. Classes of superoutburst light curves of VW Hyi with classes S1-S5 in 2-19a and S6-S8 in 2-19b (Bateson, 1977).
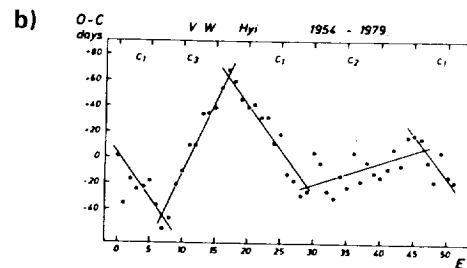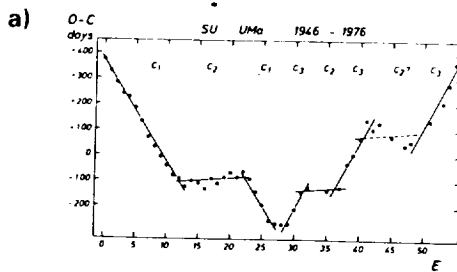
a)

b)

Figure 2-20. O-C residuals from a linear ephemeris versus supercycle number of superoutbursts of a) SU UMA and b) VW Hyi. The solid lines are fits to periods of constant cycle length (Vogt, 1980). Systems appear to switch between several possible intervals between successive superoutbursts; each period is followed for a certain time before the system switches to another one.

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between wide and narrow outbursts with decreasing orbital period; with increasing orbital period, wide and narrow outbursts become more and more similar.

The definition of the term *superoutburst* implies the occurrence of other features, in particular small-scale variations with a period slightly in excess of the orbital period, the so-called superhumps (see Chapter 2.II.C.2). The fact that superhumps are not observed during long outbursts of long-period (i.e., non-SU Ursae Majoris) systems, van Paradijs (1983) ascribes to an observational selection effect which makes it very difficult (but certainly not impossible) to observe such periodicities. Observational tests of this hypothesis clearly are called for.

II.A.5. TEMPORARY SUSPENSION OF ACTIVITY

ABSTRACT: Some dwarf novae are known to have suspended their normal outburst activity altogether for a while. They later resumed it without having undergone any observable changes.

nova-like stars: 102, 113, 125

interpretation: 177

Some cases are known in which dwarf novae interrupted their normal outburst activity altogether for some months or years and only fluctuated close to minimum brightness. Later they resumed their normal activity without any apparent trace that any irregularities had happened. The transition from very low-brightness anomalous outburst activity to what appears to be an almost total cessation of it, seems to largely be a question of taste.

The earliest recorded event of this sort happened to SS Cyg in 1907/8 (see Figure 2-1c). At that time this was so confusing that it was questioned whether SS Cyg could reasonably be regarded as a dwarf nova any longer. Inspection of the light curve over very long intervals of time reveals, however, that, strange as such

behavior may seem, SS Cyg is often seen to be on the verge of it.

Another similar example is SU UMa, which stopped virtually all relevant activity for over three years (AAVSO Circulars) before it returned to normal behavior. Mattei (1983, in discussion of Robinson, (1983)) hints at something similar having happened to HT Cas. Bateson (1985; see also Zhang et al, 1986) gives some evidence that the cycle length for super-outbursts in TU Men may have changed from values ranging between 123 and 162 days (for May 1963 to December 1981) to 164 to 517 days (in 1982 to 1984); it is not clear if this is merely a switch in cycle length as has been found for other dwarf novae (Vogt, 1980, see above) or if some major physical changes took place in the system.

II.A.6. COLOR VARIATIONS DURING OUTBURST CYCLE

ABSTRACT: The optical colors of dwarf novae all are quite similar during outburst, considerably bluer than during the quiescent state. During the outburst cycle, characteristic loops in the two-color diagram are performed.

interpretation: 173, 181, 193

Compilations of optical colors of cataclysmic variables can be found in Vogt (1983b), Bruch (1984), and Echevarria (1984). In Figure 2-21 the optical colors of dwarf novae during quiescence and during the outburst state are displayed in the two-color diagram. A few features become obvious: Dwarf novae are considerably bluer during outburst than during quiescence, and all dwarf novae have approximately the same optical colors during outbursts. SU Ursae Majoris stars statistically tend to be slightly bluer than other dwarf novae during quiescence in both (U-B) and (B-V), and they are bluer only in (B-V) during superoutbursts. In the two color diagram, all cataclysmic variables, in the faint as well as in the bright state, consistently appear above (i.e., are bluer than) the main sequence and often even above the black-body line.
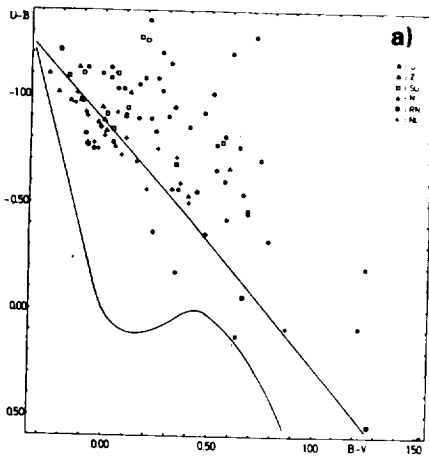
Figure 2-21a. Two-color diagram of cataclysmic variables during quiescence (corrections for interstellar reddening were applied wherever necessary); the solid lines represent the main sequence and black bodies, respectively (Bruch, 1984).
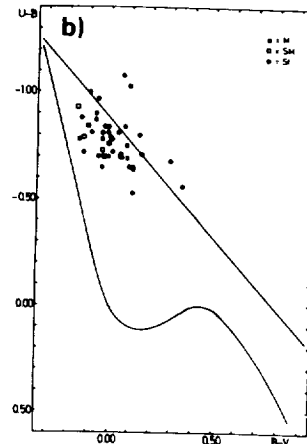
Figure 2-21b. Two-color diagram for dwarf novae during outburst. Presentation as in Figure 2-21a (Bruch, 1984). During outburst the optical colors of dwarf novae are remarkably similar.
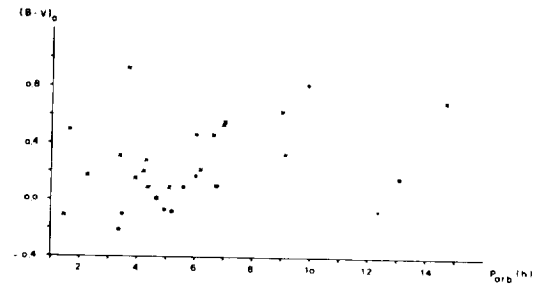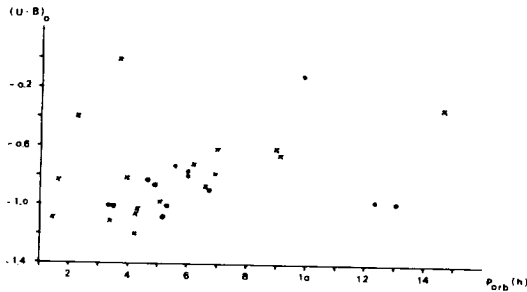

Figure 2-22. Relation between intrinsic optical colors of dwarf novae (x) and novae (o) during quiescence and nova-like stars (·) during the bright state versus the orbital period (values from Vogt, 1983b, Ritter, 1987). The longer the period the redder the systems appear.
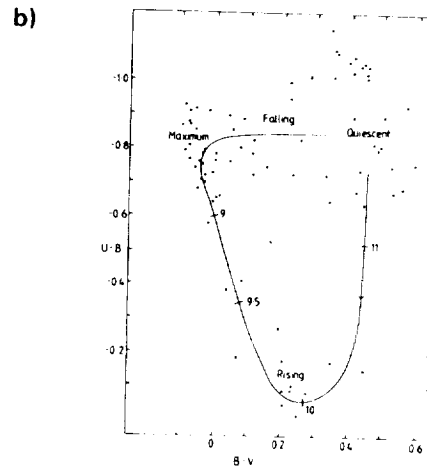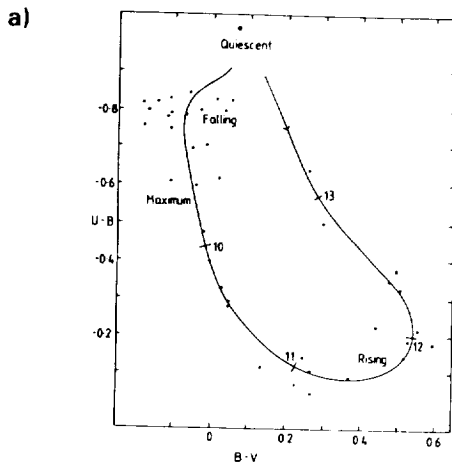

Figure 2-23. Loops of dwarf novae in the two-color diagram during the outburst cycle: VW Hyi (a) and SS Cyg (b) (Bailey, 1980). Color changes of dwarf novae during the outburst cycle seem to be rather characteristic for each object; the most pronounced changes occur during the rise phase.

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A gap in the two-color diagram with a width of almost 0.2 mag in which no cataclysmic variables could be found was discussed by Vogt (1981); this gap was thought to be highly significant at that time, although it has since completely disappeared as more data have become available.

For cataclysmic variables with orbital periods in excess of some 3 hours, there may be a tendency for the colors to be loosely correlated with the orbital period of the system (Figure 2-22), although some otherwise not obviously peculiar systems do not follow this relation, and in the set of intrinsic colors as determined by Bruch (1984) this tendency is even less pronounced. It is remarkable that, again, cataclysmic variables of all different kinds follow the same relation. Systems with orbital periods shorter than 2 hours have about the same colors as other cataclysmic variables, but do not follow the above relation.

Only very few investigations of color changes in dwarf novae during the full outburst cycle have been carried out. It is obvious, however, that all dwarf novae perform a loop in the two-color diagram during such a cycle. Complete loops have been published for VW Hyi and SS Cyg (Figure 2-23). The data presented cover eight normal outbursts of VW Hyi and seven normal outbursts of SS Cyg. Single data points available for other objects (Z Cam, V436 Cen, WW Cet, U Gem, AH Her) follow the same trends. In all cases very large color changes take place during the fast rise to maximum. Color changes during the decline to quiescence are not very dramatic and take place slowly.

Single observations of VW Hyi during rise to supermaximum follow the same trends as observed for rises to normal outbursts. During rises to anomalous outbursts in SS Cyg, however, color variations are restricted almost entirely to changes in (B-V). Whether the same behavior can be observed during anomalous outbursts of other objects is as yet unknown.

GENERAL INTERPRETATION: The outbursts of dwarf novae are understood to be due to enhanced mass transfer through the accretion disc, a picture which can be reconciled with the observed color changes. The two possible scenarios which are currently discussed are: either temporarily enhanced mass transfer from the secondary star into the accretion disc, or a spontaneous release of material which was stored in the outer disc areas during quiescence. Standstills are believed to be semi-permanent outbursts, i.e., large mass transfers through the accretion disc which last for long times.

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *Some dwarf novae not only undergo normal outbursts, but in addition also undergo superoutbursts or standstills. (See 184)*

- *Outburst durations (in all systems?) exhibit a bi-modal distribution.*

- *Long and short outbursts tend to alternate.*

- *It is not quite clear whether superoutbursts are merely a particular case of long outbursts, or whether they have a different physical cause. (See 184)*

- *TU Men, the SU Ursae Majoris star with the longest orbital period, is the only known system to undergo narrow and wide outbursts, as well as superoutbursts.*

- *There is some regularity, but no strictly repeated pattern, in the shapes of outbursts. (See 174)*

- *Outbursts occur semi-periodically rather than periodically. (See 174, 179)*

- *Superoutbursts follow a much stricter periodicity than other outbursts. (See 184)*

- *There are several superoutburst periods for each SU Ursae Majoris object, each of which is maintained for a while, until an abrupt change to a slightly different period occurs.*

- *Some objects occasionally stop all relevant outburst activity for a while. (See 177)*

- *Relations have been proposed between outburst amplitude and outburst period, between decay time and orbital period, and between absolute brightness during outburst maximum and orbital period. (See 177, 181)*

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- *During the course of an outburst, color changes follow a certain characteristic pattern, which seems to be different for normal and for anomalous outbursts. (See 173, 181, 193)*

- *Dramatic color changes only seem to occur during the rise phase. (See 173, 181, 193)*

- *All dwarf novae have about the same optical colors during outburst, but not during quiescence. (See 193)*

- *For systems with orbital periods in excess of three hours, the optical colors in quiescence are related to the orbital period. (See 193)*

II.B. ORBITAL CHANGES DURING THE QUIESCENT STATE

ABSTRACT: At a time resolution on the order of minutes, strictly periodic photometric changes due to orbital motion become visible in the light curves of dwarf novae. These are characteristic for each system.

related spectroscopic changes: 73

nova-like stars: 96, 103, 114, 117, 123, 125, 140

interpretation: 151, 153

As the time resolution of photometric observations is enhanced from days or hours to minutes or seconds, many more structures in the light curves of dwarf novae become apparent. At first, features seen during the quiescent state of dwarf novae shall be described.

Three different features imposed on a generally flat light curve can be distinguished in the light curves of dwarf novae: a temporary increase in brightness by some tenths of a magnitude for about half of the orbital cycle, which is referred to as a *hump*; an *eclipse* lasting for a couple of minutes, the depth of which in some objects can reach some two magnitudes; and rapid, irregular brightness changes of some 0.5 mag, the so-called *flickering*, superimposed on the orbital light curve. In addition, brightness variations on time-scales of minutes or seconds with amplitudes of

typically some 0.02 mag are seen in some objects. However, these usually are not apparent in the raw light curves (these will be discussed in Chapter 2.II.D.2). Eclipses and humps are variable from one object to another as well as to some extent in the same object, so that in general an orbital light curve never is strictly repeated. If these features occur, however, they appear with a very strict periodicity which in almost all objects (exceptions are, e.g., CN Ori and TT Ari, see Chapters 2.II.B.3 and 3.III.A.2) is identical with the periodicity in the radial velocity curve; neither outbursts of dwarf novae nor changes in the brightness state of nova-like stars change this phase relation.

II.B.1. ORBITAL LIGHT VARIATIONS IN THE OPTICAL

ABSTRACT: The appearance of the light curve is characteristic for each dwarf nova, but a wide range of appearances is possible for the whole class: some objects exhibit no periodic features at all, others show humps (occasionally, or in each cycle), intermediate humps, eclipses, or double eclipses, or even several of these features, and they all repeat with a strict periodicity. For most of the time the optical colors remain constant, conspicuous changes occur during eclipses.

see also: 46, 75

nova-like stars: 96, 103, 114, 117, 119, 122

interpretation: 151, 153, 166

Many of the known dwarf novae exhibit neither a hump nor an eclipse. An example is given in Figure 2-24. These objects still show appreciable brightness variability due to flickering activity, but no features can be detected which repeat strictly periodically.

Many others, however, possess more elaborate light curves. An example of an object exhibiting a very clear hump in the light curve is VW Hyi (Figure 2-25). The relative and absolute amplitudes of humps are variable from cycle to cycle, with a tendency for them to be brighter when the entire system is brighter (in
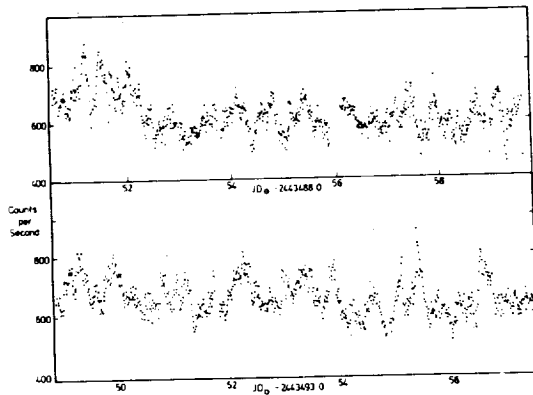
Figure 2-24. Optical light curve of V436 Cen (Bailey, 1979b). The light curves of some dwarf novae are entirely governed by irregular variations and show no periodically repeating patterns.
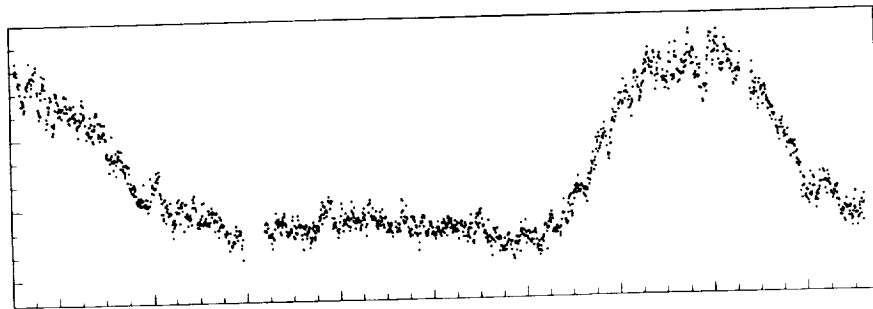

Figure 2-25. Optical light curve of VW Hyi (Warner, 1975). In other dwarf novae the hump repeats with a strict periodicity which turns out to be the orbital period.
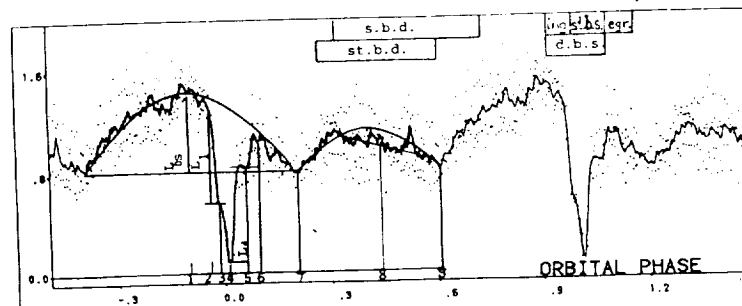

Figure 2-26. Optical light curve of OY Car (Schoembs and Hartmann, 1983). In some systems, in addition to the orbital hump, a so-called intermediate hump occurs which lasts approximately from the end of one main hump until the beginning of the next. OY Car possesses a so-called double eclipse (see text and Figures 2-29, 2-30, and 2-31).

many systems the brightness during quiescence varies by some tenths of a magnitude or more). If a hump is present, it normally lasts for about half of the orbital period, with beginning and end always occurring at approximately, though not precisely, the same orbital phases.

In addition to the main hump, other objects like BV Cen or OY Car (Figure 2-26) at times or always (depending on the system) exhibit an additional *intermediate hump* lasting

from approximately the end of one main hump until the beginning of the next. The intermediate hump normally is considerably less pronounced in brightness than the main hump, and it is more variable in shape and brightness. As can be seen from the little scatter at the respective points in Figure 2-26 (which is the average light curve of 14 orbits), the beginnings and the ends of the main and intermediate humps are remarkably well defined.
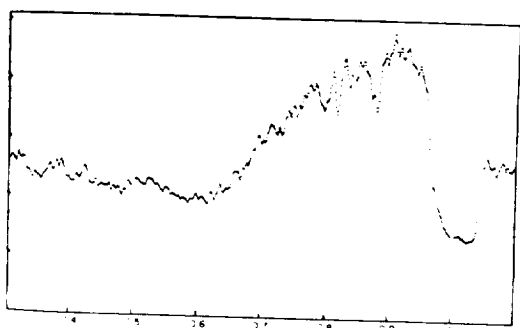
Figure 2-27. Optical light curve of U Gem (Warner and Nather, 1971). In several dwarf novae an eclipse occurs at the declining part of the orbital hump. It is mostly eclipsing systems which also exhibit an orbital hump.
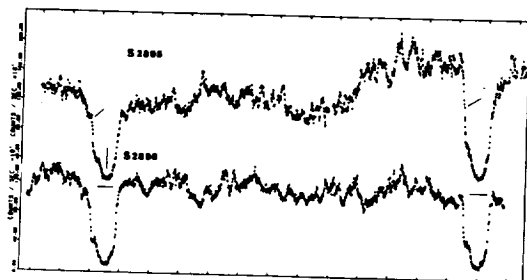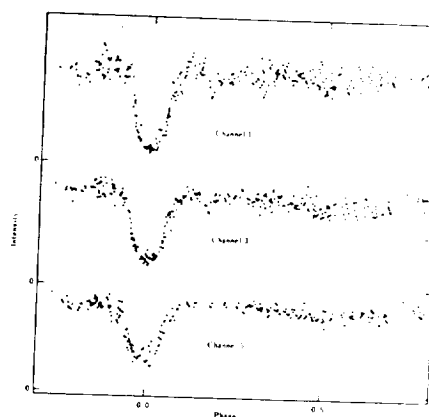

Figure 2-28. Orbital light curve of AC Cnc at 3330-3700 Å (Channel 1), 4300-4670 Å (Channel 3), and 5265-6005 Å (Channel 5), from Yamasaki et al (1983). There are some dwarf novae which have an eclipse but no hump at all.

Figure 2-29. Orbital light curves of V2051 Oph (Warner and Cropper, 1983). In still other systems the orbital hump is present at times but absent at others.
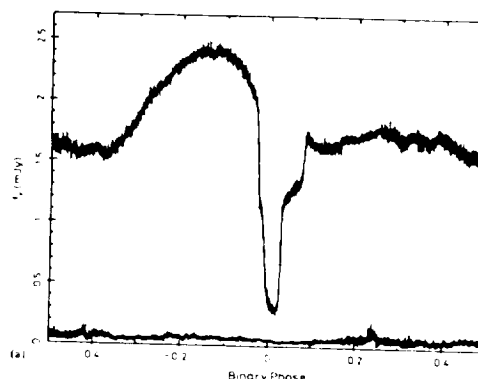

Figure 2-30. Optical light curve of Z Cha (Wood et al, 1986). In five known dwarf novae two eclipses occur, one during the other; this phenomenon is called a double eclipse.

In many objects, a fast considerable drop in brightness, the *eclipse*, occurs shortly after hump maximum (Figure 2-27). Its total duration usually is on the order of 0.1 of the orbital period. The exact shape of the eclipse also is subject to some variability if different minima of one object are compared. The general shape of the eclipse is approximately the same for all eclipsing objects with the exception of systems which show a so-called double eclipse (see below). No case of a dwarf nova is known in which the eclipse occurs at or before hump maximum (though in some nova-like stars this happens occasionally, see Chapters 3.II.C and 3.III.B), nor is there any case in which it occurs entirely outside the hump. Some objects

are known, however, which do not have a hump but which do show an eclipse (Figure 2-28), or which, although they are eclipsing, show a hump at some times, though usually they don't (Figure 2-29).

Five dwarf novae (Z Cha, OY Car, V2051 Oph, HT Cas, IP Peg) are known to exhibit a very special kind of eclipse, the so-called *double eclipse* as shown in Figure 2-30: the ingress into eclipse, as it occurs in many other dwarf novae, holds for a short while at a brightness level somewhat below the normal brightness outside the hump, before ingress into even another eclipse occurs. The depth of these double eclipses can reach up to 2.5 mag. The egress also occurs in two steps, with the hold

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between both parts of the rising branch being considerably longer than on the declining branch. Since these double eclipses potentially reveal a lot of information about the physical properties of the different components of the systems, they have been subject to extensive investigations (e.g., Warner, 1974a; Bailey, 1979; Patterson et al, 1981b; Warner and Cropper, 1983; Berriman, 1984; Cook and Warner, 1984; Cook, 1985a; Schoembs et al, 1986; Wood, 1986; Wood et al, 1986; Zhang et al, 1986). Inspection of examples of many different eclipses of every one of these objects (e.g., Figure 2-31) demonstrates how variable the eclipse shapes can be even from one orbital cycle to the next. It is clear from these observations that two light sources are eclipsed, and that the first sharp drop is the eclipse of the primary (or white dwarf, supposing the applicability of the Roche model), followed by the eclipse of the hot spot after a brief hold; after a more or less flat-bottomed minimum there is the egress of the white dwarf, followed after a longer hold, by the egress of the hot spot. This latter phase in the light curve, the egress of the hot spot, is particularly variable from one cycle to the next. Also the ingress phases of the hot spot are variable, but much less so than the egress, and there seems to be no correlation between the durations of one and the other. The primary eclipse in all objects proved to be a highly stable feature.

The eclipse light curve of Z Cha has been investigated in detail by Warner (1974a), Bailey (1979a), and Cook and Warner (1984). In all these sets of observations the primary eclipse appears to be highly stable in its occurrence in orbital phases, with ingress and egress lasting for about 40 sec each. The eclipse of the hot spot, in contrast, is subject to appreciable variability. Warner noted holds before ingress and egress of 20 sec and 340 sec, respectively, whereas Bailey reported that the standstill before ingress lasts for 80 sec, and the standstill before egress often is not apparent at all. In Cook and Warner's data the standstill before egress of the hot spot lasts for some 300 sec.

Furthermore, not only the orbital phases of the onset of ingress and egress of the hot spot are variable; the times for which both last are variable as well: times for the ingress have been observed to last between 84 and 207 sec, for egress between 42 and 203 sec (Cook and Warner, their Table 3). The brightness of the primary was constant within 20% for all the measurements by Bailey; the hot spot varies by nearly a factor of two in brightness; variations can be very strong at times, or approximately stable for a couple of orbital cycles. The flux level at the bottom of the eclipse is low and possibly variable, but essentially unaffected by minor brightness fluctuations of the system outside eclipse (see also Patterson et al, 1981b; Warner and Cropper, 1983).

If all these findings are regarded together, it is obvious that a dwarf nova consists of at least three sources of luminosity: one (the primary star) which is geometrically relatively sharply confined and has approximately constant brightness, a second (the hot spot, which in the Roche model is supposed to be located at the outer edge of the accretion disc) which is highly variable in geometrical position and dimensions as well as in brightness, and is much more extended than the primary and not spherically symmetric; and a third source (the secondary star) which is eclipsing the others and which is supposed to be responsible for at least part of the brightness remaining during eclipse minimum; another brightness contribution may originate from uneclipsed parts of the accretion disc.

At phases outside a hump or an eclipse, the optical colors of dwarf novae in quiescence are essentially featureless, subject to only irregular fluctuations of at most 0.05 mag. When a hump appears in the light curve, (U-B) becomes slightly redder during hump maximum and slightly bluer during hump minimum, and the total amplitude of the change is on the order of 0.1 mag (Figure 2-32). (B-V) usually is not variable at all with hump phase; if so, it is somewhat bluer at hump maximum and
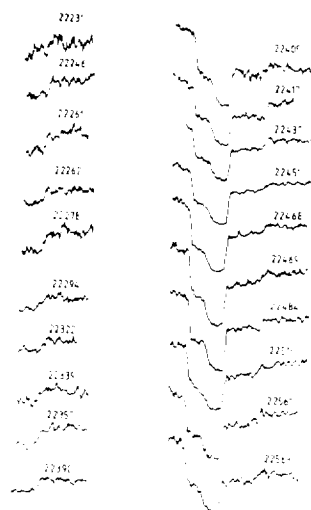
Figure 2-31. Double eclipses of OY Car (Cook, 1985a). The exact shape and duration of the double eclipse is variable from one orbital cycle to the next; the first ingress and egress are rather stable features.
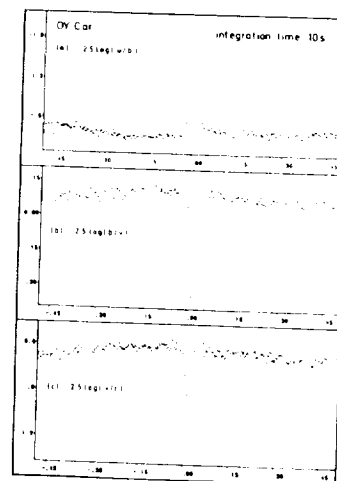

Figure 2-33. Orbital light and color curves of OY Car (Schoembs et al, 1986). During eclipse the system becomes bluer in (U-B) and redder in (B-V).
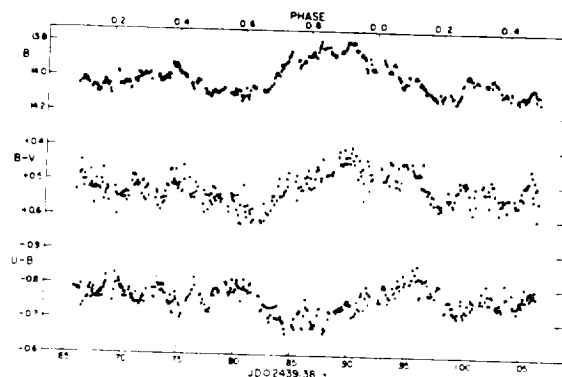

Figure 2-32. Orbital light and color curves of Z Cam (Kraft et al, 1969). Outside the hump the optical colors do not change; during times when the hump is visible the system becomes slightly redder in (U-B) and bluer in (B-V); in many systems (B-B) is hardly variable at all.

somewhat redder at hump minimum (e.g., Kraft et al, 1969). Truly conspicuous changes in the colors only occur during eclipse: (U-B) becomes considerably bluer, (B-V) equally considerably redder than during normal light (Figure 2-33). The same trend as in (B-V) (reddening during eclipse) can be seen in (B-R) and (B-I) light curves of OY Car (Schoembs et al, 1986). Observations of V2051 Oph by Cook and Brunt (1983), in addition to the blue peak during the very eclipse, show a short reddening in (U-B) at ingress and egress of the eclipse.

In general not much is known in detail about the color behavior of quiescent dwarf novae. Since the results which are available in the literature all show the same tendency, these probably are common to all dwarf novae.

II.B.2. ULTRAVIOLET AND INFRARED PHOTOMETRY

ABSTRACT: Hardly any information about photometric variability in the UV on orbital time scales is available. The contribution of the hump decreases with decreasing wavelengths. - At IR wavelengths in some dwarf novae, in addition to the

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primary minimum a secondary minimum appears half an orbital period later; only in two (peculiar) dwarf novae is this minimum seen in the optical.

related spectroscopic changes: 74, 78, 80

nova-like stars: 99, 108, 115, 118, 121, 123, 135, 139, 142

interpretation: 151, 193

Due to the lack of powerful UV photometers, hardly anything is known about light variations of cataclysmic variables at UV wavelengths on time scales shorter than some dozens of minutes (i.e., shorter than the time resolution obtainable for cataclysmic variables with the IUE satellite). Phase resolved photometry of dwarf novae in the UV has been carried out by Wu and Panek (1982) with the ANS satellite (Figure 2-34). They observed U Gem and VW Hyi during their quiescent states with a time resolution of some 10 min. In VW Hyi there is a slight indication for the hump to be present at UV wavelengths, although with decreasing amplitude at shorter wavelengths. In U Gem, a system which shows a very pronounced hump at optical wavelengths, a comparable effect is not seen, neither in Wu and Panek's data, nor in the IUE. Clearly better time resolution and observations of more objects are desirable.

The situation is considerably better concerning the infrared wavelength range. Some dwarf novae have been observed at high time resolution during their quiescent states; no such observations during the outburst states have been published. Figure 2-35 shows a typical example of an IR light curve of a quiescent dwarf nova.

The depth of the primary eclipse and amplitude of the hump increase with increasing wavelength. OY Car so far is the only case where a sufficiently high time resolution has been achieved in the infrared to resolve fine structures of the primary eclipse (Figure 2-36 — compare with Figure 2-31). It appears that, although the general shape is changed appreciably at 12500 Å (J-band), the character of a double eclipse still is there.

In many systems at about phase 0.5 (with respect to the center of the primary eclipse), a secondary eclipse becomes visible which is not seen in the optical (the only two exceptions are the peculiar dwarf novae WZ Sge and BD Pav, see Chapter 2.II.B.4). The general character of all the light curves in the infrared changes from one cycle to the next, but the shape of the secondary eclipse is particularly severely affected by this.

The variety of infrared light curves among dwarf novae is huge, as far as one can tell from the still very limited number of available observations. In some objects, like EM Cyg (Jameson et al, 1981), the light curves in the IR still closely resemble the appearance in the V-band, with only the addition of the secondary eclipse (if the systems are eclipsing at all). U Gem and TW Vir, on the other hand, exhibit sinusoidally-shaped light curves in the IR, which are totally different in appearance from the optical light curves (Figure 2-37a, see also Mateo et al, 1985). In Figure 2-37b, observations are shown which were taken shortly before an outburst, and at the end of decline from the same outburst; both minima have been affected by the outburst, the secondary minimum to a much larger degree than the primary minimum.

II.B.3.   CONTINUOUS LONG-TERM MONITORING

ABSTRACT: In some dwarf novae the quiescent brightness between consecutive outbursts undergoes systematic changes. Two dwarf novae were observed in a high speed photometric mode more or less continuously for many days during quiescent state each. The light curves show semi-periodic, in one case clearly transient, events.

interpretation: 174

SS Cyg and U Gem probably are those two dwarf novae which have been monitored best in their optical appearance over very long intervals of time (Mattei et al, 1985; 1987). In particular, a very good coverage of the quiescent light is available. Inspection of this reveals that
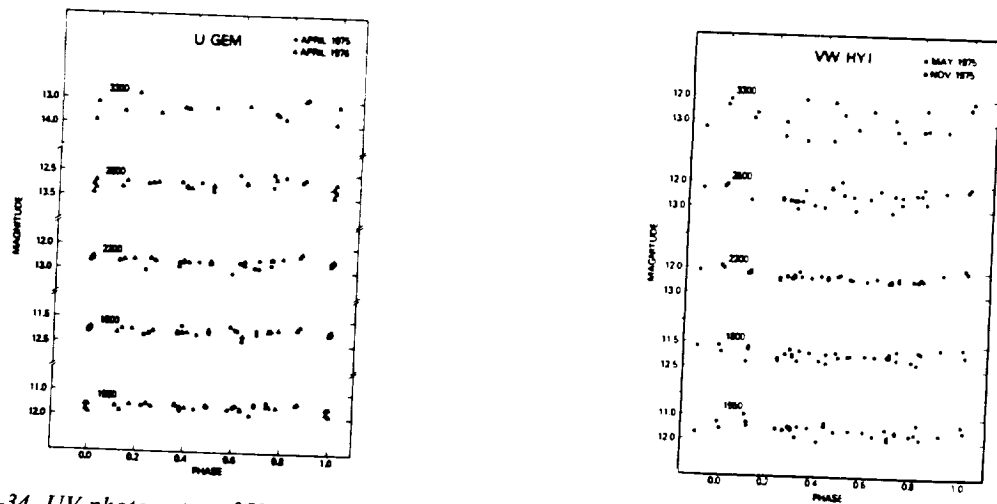
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Figure 2-34. UV photometry of U Gem (a) and VW Hyi (b) (Wu and Panek, 1982). Possibly the orbital hump is seen in VW Hyi.
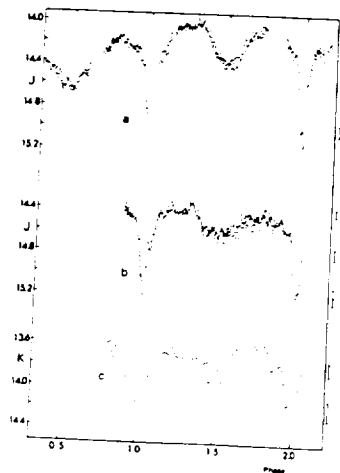

Figure 2-35. IR photometry of OY Car (Sherrington et al, 1982). The shape of the light curve varies appreciably with wavelength. A secondary eclipse is seen in the infrared.
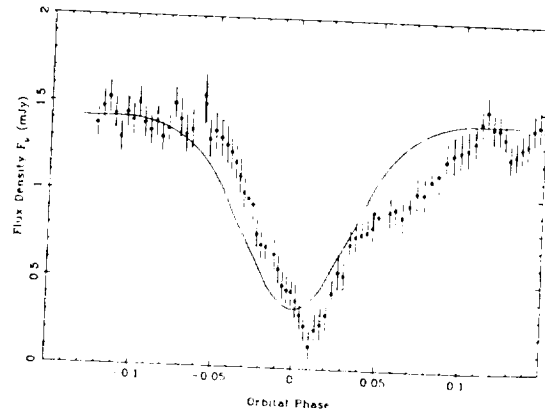

Figure 2-36. IR light curve of OY Car (Berriman, 1987). The double eclipse is still visible at IR wavelengths. (The solid line corresponds to a model discussed in Berriman's text.)
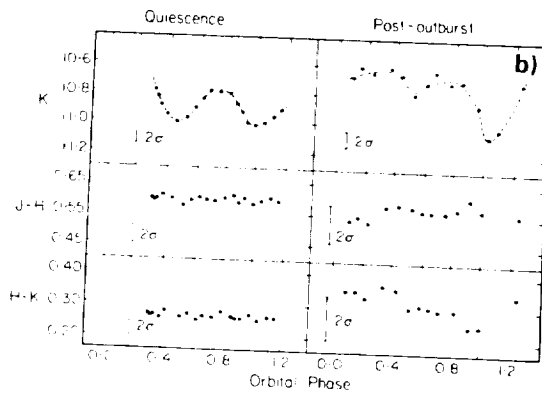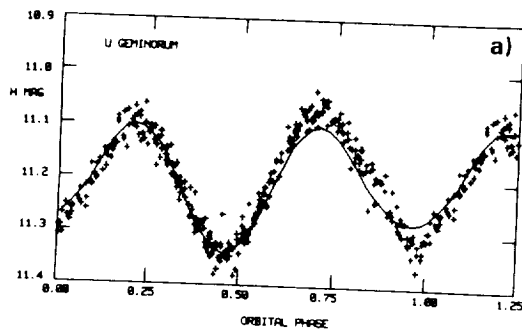

Figure 2-37. IR light curve of U Gem. a) During quiescence the light curve is approximately sinusoidally shaped (Oke and Wade, 1982, and optical light curve in Figure 2-27). b) It is highly distorted just after the end of an outburst (Berriman et al, 1983).

in U Gem the minimum flux level stays constant within fairly narrow limits between consecutive outbursts, and clearly no systematic trend of any kind can be detected. SS Cyg, on the other hand, while normally it has stable quiescent levels like U Gem (Figure 2-38a), exhibits at other times a systematic increase in flux level over several consecutive quiescent phases (Figure 2-38b); and at even other epochs, a very considerable decrease in the flux level can be observed between two consecutive outbursts (Figure 2-38c).

Semi-continuous monitoring of one star in a photometric high-speed mode over a time-interval of many days has been carried out in only one case: CN Ori was observed during quiescence from the end of decline from an outburst until the end of the next outburst (Figure 2-39), with only some short gaps in the light curve during quiesceuce. The hump amplitudes vary in a beat-like manner between the eruptions, with an additional superimposed general trend of increasing maximum light of successive humps; at the same time the minimum brightness of the inter-hump regions stays practically constant. A display of the entire minimum light curve on a larger time scale (Figure 2-40) reveals a large variability of the hump structure from one orbital cycle to the next, while the overall shape is approximately maintained. The times of minimum light between the humps are variable in duration, and the structure of the light curve is never exactly repeated from one cycle to the next.

The dwarf nova OY Car also has been monitored for a long time during quiescence, but this was done from only one observing site, so the gaps between runs of uninterrupted monitoring are longer than in the case of CN Ori (Figure 2-41). In this object additional minor "flares" of some 0.1 m lasting for 0.2 or less of the orbital period are superimposed on the otherwise very smooth and regular light curve (some of them are marked with "0" in Figure 2-41). A further investigation of the temporal repetition of these flares revealed that

they repeated with a good periodicity, different from the orbital period, for about 6 days, and then they dissolved into irregularity. On one occasion a flare coincided with a double eclipse and became partly eclipsed itself.

II.B.4. WZ SGE AND BD PAV — TWO VERY UNUSUAL DWARF NOVAE

ABSTRACT: While WZ Sge displays two kinds of orbital light curves during its quiescent state, only one resembles that of a cataclysmic variable. Color variations are atypical for a dwarf nova. WZ Sge and the similar dwarf nova BD Pav have extremely long outburst periods.

comparison with "normal" dwarf novae: see above

One object is quite unique among the dwarf novae in almost all its characteristics, so occasionally it will have to be discussed separately. This object is WZ Sge. Originally it was classified as a recurrent nova because of its outburst period of about 33 years, because of its outburst light curve, and because of its large outburst amplitude of about 8 mag, which make its light curve look rather like that of an ordinary nova than like that of a dwarf nova (Figure 2-42). However, during the last outburst, in 1978, it was detected that WZ Sge exhibited superhumps which, by definition, qualify it as a SU Ursae Majoris star. Still, its optical light curve during the quiescent state was much different from that of a "normal" dwarf nova (Figure 2-43). At times the light curve closely resembled that of a W Ursae Majoris star (Krzeminski and Smak, 1971), i.e., it showed a sinusoidal light variation with two symmetric minima of comparable depth; at other times the behavior became more erratic, resembling the light curve of a cataclysmic variable with an eclipse placed on the declining branch of a hump. The appearance of the light curve changed back and forth, transitions from one to another occurring as quickly as within one orbital cycle. Shapes, and in particular, depths of minima were only approximately repeated. No extended photometry of
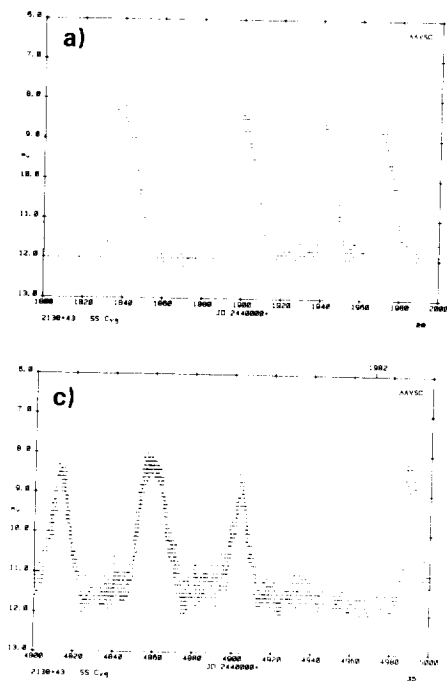
Figure 2-38. Outburst light curves of SS Cyg (Mattei et al, 1985). The quiescent light level between outbursts can be flat (a), it can rise systematically until the next outburst starts (b), or it can decline systematically (c).
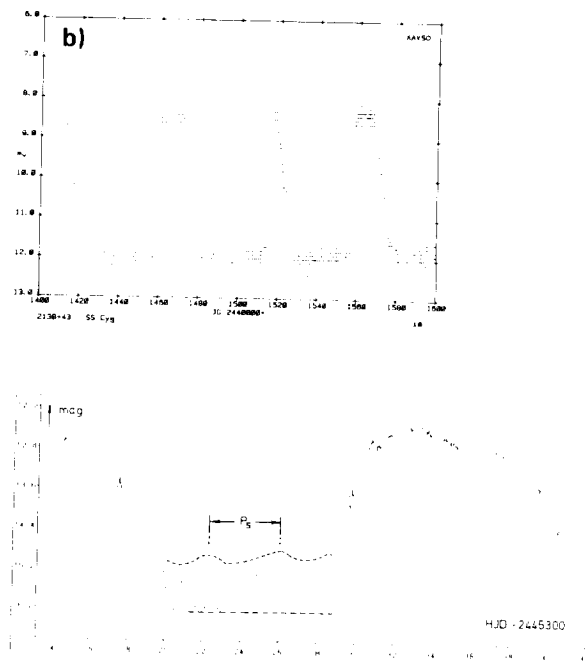

Figure 2-39. Light curve of CN Ori between two successive outbursts (Mantel et al, 1988). The minimum light level at interhump phases stays practically constant, while the hump amplitude undergoes cyclic variations.
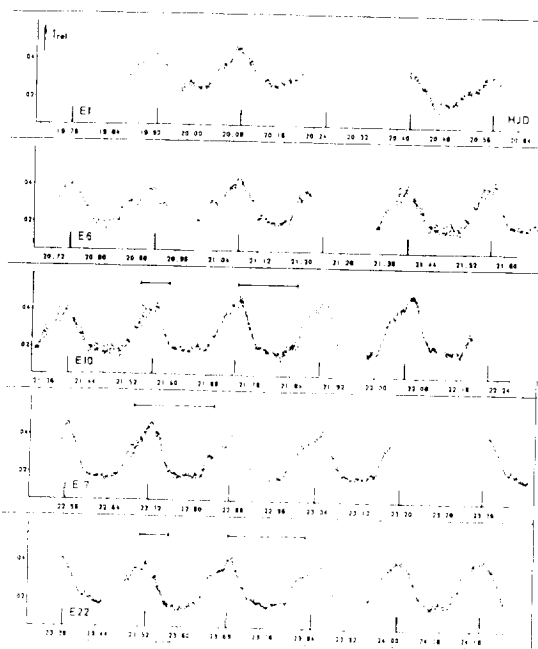

Figure 2-40. Same data as in Figure 2-39, at higher resolution (Mantel et al, 1988). The hump structure appears to be highly variable from one orbital cycle to the next.
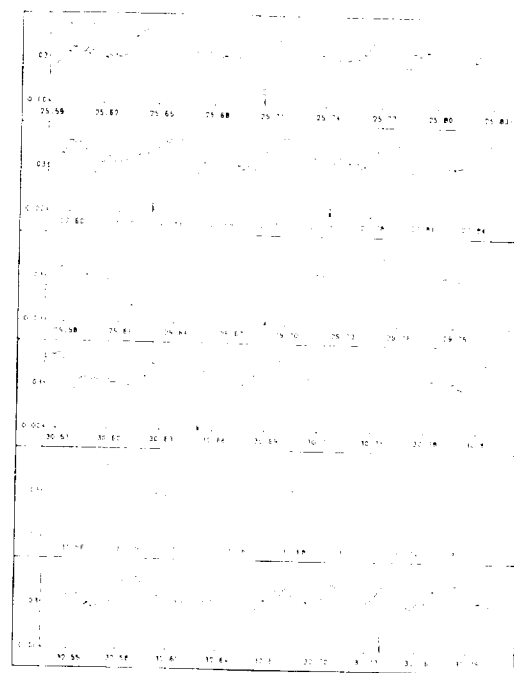

Figure 2-41. Optical light curve of OY Car in quiescence (Schoembs et al, 1986). For a while flares repeat with a good periodicity and then resolve.
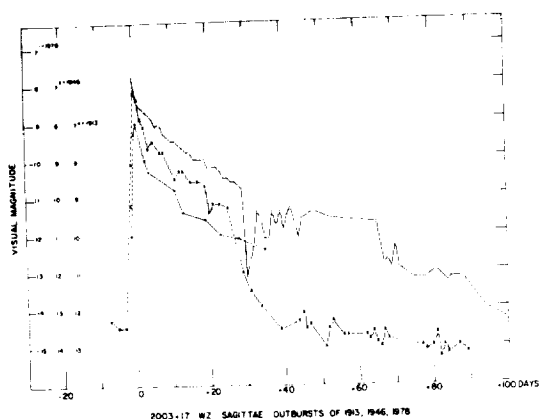
43

Figure 2-42. Outburst light curves of WZ Sge (Patterson et al, 1981b). The light curve resembles more that of a nova than that of a dwarf nova.

a)

b)

Figure 2-43. Orbital light curves of WZ Sge (a: Krzeminski and Smak, 1971; b: Warner and Nather, 1972). The character of the light curves is entirely different; changes can occur as quickly as within one orbital cycle.
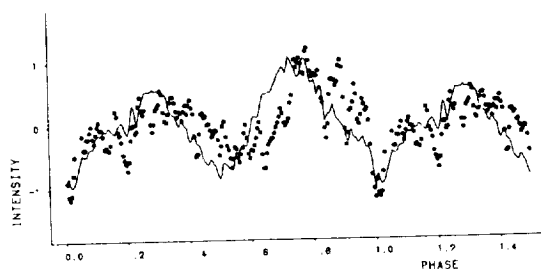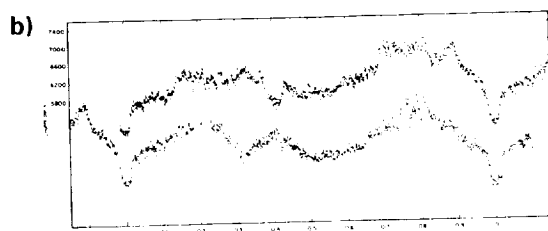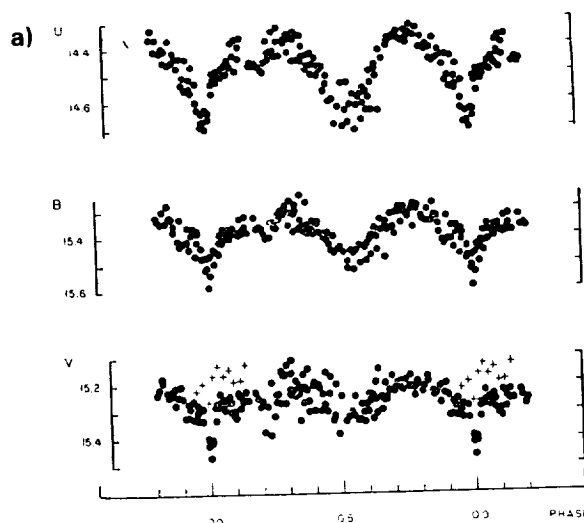

Figure 2-44. Orbital light curve of BD Pav, asterisks are observations in U light, the solid line corresponds to V (Barwig and Schoembs, 1983). In many ways BD Pav is similar to WZ Sge.

WZ Sge after the 1978 outburst has been published.

One feature all the light curves of WZ Sge have in common is a "dip," a sort of additional eclipse-like feature at about phase 0.25. Its depth, exact phase (the minimum occurring between phase 0.2 and 0.4), width (ranging from 0.06 to 0.1 of the orbital period), and shape are very variable from one cycle to another. The depth, however, was never observed to drop below that of the primary minimum.

The primary minimum recurs with a stable period of 0.056688 days, irrespective of the shape of the light curve; its depth amounts to some 0.3 m in V but is variable, as are its shape and width (between some 200 and 300 sec). It usually, but not always, is flat-bottomed. When

the light curve is of cataclysmic variable-type, the ingress and egress of primary eclipse are fairly steep and well defined. In the case of the W Ursae Majoris-type light curve, a secondary eclipse is clearly visible. Its exact shape and depth, however, are highly variable, and, in particular, it occurs somewhere between phase 0.50 and 0.59 with respect to the primary eclipse (Krzeminski and Smak, 1971) and not, as expected for an eclipse of a stellar object, always at the same phase; or it even can disappear completely. In the cataclysmic variable-type light curve, an eclipse-like feature occurs around phases 0.4 to 0.5, but neither its shape nor its position is repeated even approximately.

There is a very strong color dependence of the light curves; in particular, the secondary
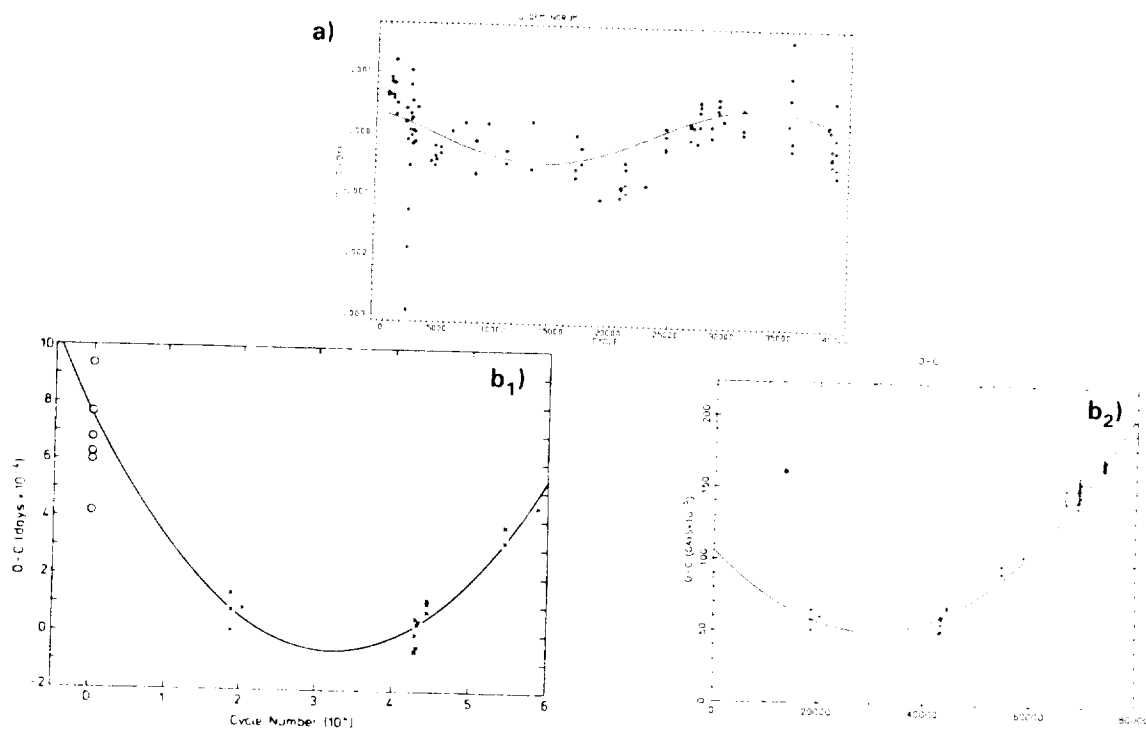
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Figure 2-45. Secular variations of the orbital period were observed in several dwarf novae. In U Gem (a) the variation appears to be cyclic (Eason et al, 1983); in Z Cha (b1 and b2) it appears to be steadily increasing (Wood et al, 1986).

eclipse can at times completely disappear in V while it is well visible at shorter wavelengths (U and B). In both sorts of light curves, the W Ursae Majoris-type and the cataclysmic variable-type, color variations in WZ Sge are opposite to what normally is observed in dwarf novae (see Chapter 2.II.B.1 and Figure 2-33): during primary eclipse the system becomes slightly bluer in (B-V) or does not change at all, but in (U-B) it becomes strongly redder; during secondary minimum the system becomes redder in both colors.

BD Pav is a system reminiscent of WZ Sge. Originally it also was classified as a nova (outbursts were observed in 1934 and 1985 — Duerbeck, 1987), but new observations rather let it appear as a dwarf nova with very long outburst periods (Barwig and Schoembs, 1983). The quiescent light curve looks similar to the cataclysmic variable-type light curve of WZ Sge (Figure 2-44). Strong flickering is present at all orbital phases, possibly slightly diminished during a periodically recurring narrow eclipse. The brightness variations in the U and V filters

coincide during eclipse but are out of phase by up to 0.1 of the orbital period 180° away from eclipse. Colors are remarkably red for a cataclysmic variable of as short a period as BD Pav has.

II.B.5. SECULAR VARIATIONS OF THE ORBITAL PERIOD

ABSTRACT: Secular changes of the orbital period have been measured in several dwarf novae. In some objects, changes seem to be semi-periodic with time-scales on the order of 10 years.

nova-like stars: 98, 111, 115

interpretation: 186

As discussed above, the detailed shape of the orbital light curve of a dwarf nova usually is somewhat variable. The period with which humps or eclipses occur, however, is very stable, and phase relations seen during minimum are not disturbed by the eruptions. Nevertheless, in a couple of systems, very slow systematic period changes seem to occur.

The two best studied cases are U Gem in which the orbital period appears to cyclically decrease and increase (Figure 2-45a), and Z Cha in which the observations suggest that the period increases on a time-scale of $P/\dot{P} = 2.46$ 10^7 years (Wood et al, 1986, and Figure 2-45b). Similar general trends might be contained in the data from other systems (e.g., Beuermann and Pakull, 1984). Clearly more observations are needed in order to determine whether these changes are significant, whether this behaviour is universal in dwarf novae or even in cataclysmic variables in general, and whether these all rather are cyclic variations as seen in U Gem.

A different sort of period changes was observed in CN Ori. From data taken during the decline from one outburst and the rise to the following one, which occurred after only a very short stay of the star at quiescent brightness, Schoembs (1982) determined two photometric periods of some 234.9 and 229.6 min, respectively, from the times at which hump maxima occurred, and when the entire run was analyzed together; on the other hand when decline, minimum, and rise were analyzed separately, hump periods of 233.6, 234.8, and 235.7 min, respectively, were obtained (Mantel et al, 1988). Observations taken one year later confirm none of these periods (for the data base, see Figure 2-39): derivation of a period from hump maxima yielded a period of some 236.0 min.

For dynamical reasons it can be excluded that these photometric periods reflect actual changes of the orbital period of the system. Instead, it seems that hump maxima do not repeat at exactly the same orbital phase in all objects. This result probably needs to be taken into account when evaluating the reliability of orbital changes in cataclysmic variables.

GENERAL INTERPRETATION: Orbital changes in cataclysmic variables are ascribed to periodically varying aspects under which the binary system is seen. Systems which are seen almost pole-on display hardly any photometric changes; while the larger the

angle of inclination becomes, i.e., the more the system is seen edge-on, the more pronounced become light contributions from the hot spot, which are visible as a hump in the light curve. At very high inclinations the hot spot, and at even higher inclinations also the central object, are eclipsed by the secondary star, thus causing a single or a double eclipse, respectively. Due to the varying shape, temperature, and position of the hot spot, its eclipse as well as its spectral distribution are variable, while the eclipse of the central white dwarf/boundary layer is a stable feature. At IR wavelengths, light contributions from the secondary star become prominent; under certain conditions this star can be eclipsed by the disc around orbital phase 0.5, or the IR variation, if sinusoidal, can be due to rotational variations of the non-spherical secondary star.

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *In several objects there occurs an intermediate hump.*

- *CN Ori, at various times exhibits different photometric periods; it is not clear which, if any, is the orbital period.*

- *The hump amplitude in CN Ori during quiescence was observed to undergo quasi-periodic variations, while the brightness of the inter-hump regions did not change.*

- *The orbital period of some dwarf novae seems to be variable. (See 186)*

- *WZ Sge and BD Pav, in several respects, are very unusual dwarf novae.*

II.C. ORBITAL CHANGES DURING THE OUTBURST STATE

ABSTRACT: Remarkably little is known about orbital variations during the course of an outburst.

Given the importance of outbursts in the life of a dwarf nova and the many observations of them that have been carried out, remarkably little is known about the orbital light curves during the outbursts. Due to its intrinsic unpredictability, it is difficult to observe the very start of a rise. Still, such observations are of particular importance for investigations of the outburst behavior since they can put constraints
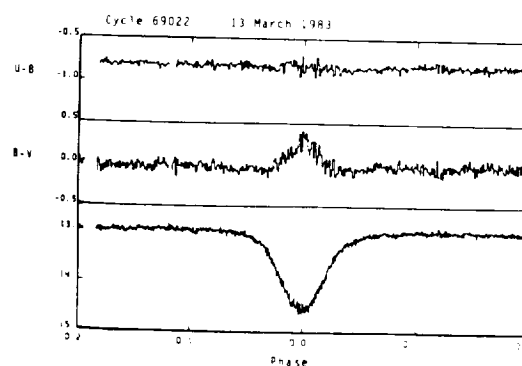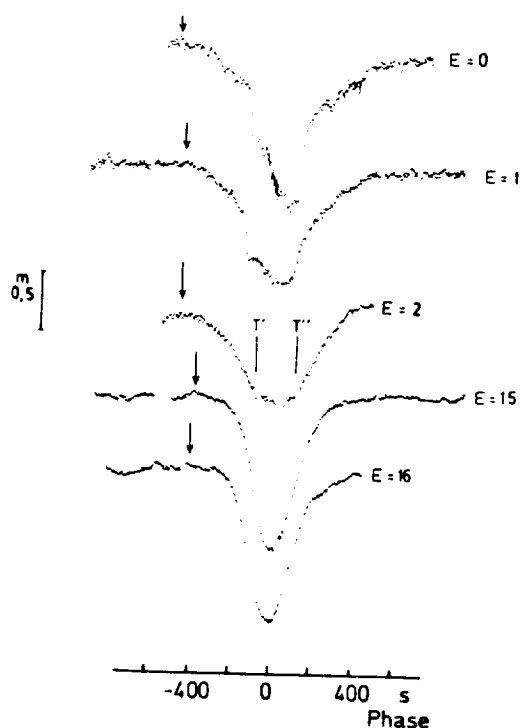
Figure 2-47. Orbital color changes in Z Cha during a normal outburst (Cook, 1985b). Changes are comparable to what is seen during quiescence.

Figure 2-46. Development of the eclipse shape in OY Car during rise to an outburst, epochs (E) are counted from onset of rise (Vogt, 1983a). Gradually the double eclipse evolves into a single one.

on possible theoretical models (Chapter 4.III). In spite of considerable effort, so far it has not been possible to fully monitor the transition from quiescent state to outburst in any dwarf nova. Nevertheless, some very valuable information is available, about the rise phase as well as about the further development of a dwarf nova outburst.

II.C.1. NORMAL OUTBURSTS

ABSTRACT: Observations seem to indicate that an outburst starts without any previous notice. Hump light curves can be traced all through the outburst, and the hump amplitude is more variable than during quiescence, though mostly of about the same intensity. Single eclipses largely disappear, and double eclipses become single during light maximum.

related spectral changes: 65, 81

nova-like stars: 96, 103, 113, 114, 117, 119, 122, 125, 140

interpretation: 151, 153, 194

All available observations of different dwarf novae indicate that the onset of an outburst occurs rather suddenly without a conspicuous precursor. Figure 2-39 shows an observation of

CN Ori in which this critical phase was almost covered (similar observations are reported in Schoembs, 1982). In the quiescent light curves immediately preceding the rise, no indication like, for instance, increased hump intensity, can be detected for the outburst to come. In CN Ori the hump intensity remains constant during rise until an optical brightness of about 13.5 m is reached. Then the hump shape becomes rather irregular for the greater part of the outburst with occasional, brief flare-like, appreciable brightness increases. The hump only gains back its quiescent shape at the optical brightness of, again, some 13.5 m on decline (Mantel et al, 1988).

Several observations of the rise to an outburst of VW Hyi are available (Vogt, 1974; Warner, 1975; Haefner et al, 1979). Normally the hump amplitude remains constant within a factor of two during rise; it becomes almost invisible for some two days around maximum light (when the disc is very bright), probably due mostly to contrast in intensity, and recovers at decline, resuming the old orbital phase relation. Rather dramatic changes of the hump in-

tensity from one cycle to the next, reminiscent of the observations of CN Ori reported above, were seen during one outburst of VW Hyi (Warner and Brickhill, 1978). On one occasion the hump amplitude was seen to be enhanced by a factor of up to 8.7 on the rising branch, at a phase in the outburst cycle when normally it is not appreciably changed with respect to its quiescent brightness. On one other occasion, for a few days during minimum light immediately after outburst, the hump shape and amplitude, were seen to be more intense and less stable than later during the quiescent state.

At times VW Hyi, like some other dwarf novae, in addition to the normal hump, exhibits a highly variable intermediate hump about half a period out of phase with the normal hump (Figure 2-25). This *intermediate hump* usually is much less intense than the orbital hump. It disappears during rise and only occasionally is visible during outburst maximum. In one of the observed outbursts it grew quickly in intensity as outburst maximum was approached, and exceeded the intensity of the main hump by a factor of three; during the next night it was very faint (Haefner et al, 1979). No relation could be detected between the amplitude of the hump, or that of the intermediate hump during the course of the outburst and any other characteristics of the outburst. Similar observations of other dwarf novae mostly indicate that the intensity of the hump remains mostly unaffected by an outburst.

The double eclipsing dwarf nova OY Car was observed photometrically by Vogt (1983a) during the rise to an outburst (Figure 2-46). At early rise the double eclipse is fully present, like it is in quiescence; as the rise proceeds the eclipse becomes single and flat-bottomed, while the depth and the phases of ingress and egress remain unaffected. At maximum light the ingress occurs later and the egress earlier than during quiescence, the eclipse becomes very deep, partial, and symmetric. Similar conclusions can be drawn from less complete observations of Z Cha (Vogt, 1982a).

On the declining branch the development of the eclipse shape is approximately reverse from what is seen during rise: during maximum light it is deep and partial; at a somewhat later stage it first becomes flat-bottomed, but still is single; slowly then, during the course of a couple of days, the double eclipse in its original shape is restored step by step (Figure 2-52). Other eclipsing dwarf novae were observed to show very similar behavior. Although the shape of the eclipse and times of ingress and egress change during the outburst, the post-outburst light curves follow the same phase relations as before outbursts. In addition, in some objects the eclipse appears wider right after an outburst than just before rise, but times of mid-eclipse don't change (Krzeminski, 1965; Cook, 1985b).

Cook (1985b) carried out color measurements of Z Cha during a normal outburst and found that, like during the quiescent state, the system becomes significantly redder in (B-V) during the eclipse, whereas, unlike in quiescence where the more pronounced reddening is in (U-B), during outburst maximum there is no change in this color (Figure 2-47).

II.C.2. STANDSTILLS AND SUPEROUTBURSTS

ABSTRACT: Orbital light curves during standstills cannot be distinguished from those at comparable brightness levels during normal outbursts. During superoutbursts very characteristic superhumps can be observed. Their recurrence period is slightly larger than the orbital period and survives in the form of the late superhump for some time after the end of the superoutburst. Only once were superhumps seen during an ordinary outburst of an SU Ursae Majoris star.

related spectral changes: 48

interpretation: 178, 184

No peculiarities have been observed during times of standstill in Z Camelopardalis stars. The light curves do not look any different from those of comparable brightness stages during normal declines from outburst.
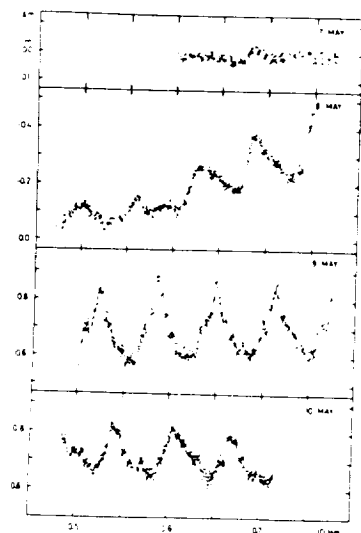
Figure 2-48. Formation and development of superhumps in V436 Cen (Semeniuk, 1980). It starts to develop at late rise just before outburst maximum; at maximum (May 9) the amplitude is largest, during the slow decline on the plateau it gradually decreases.
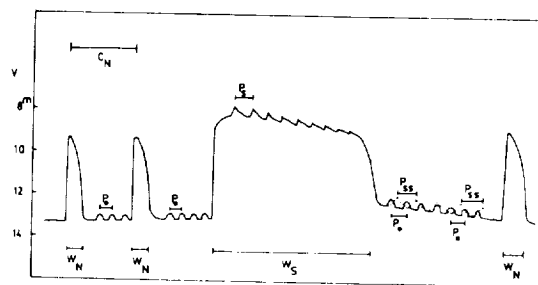

Figure 2-49. Main features of a superoutburst (Vogt, 1983c). At about superoutburst maximum the superhumps originate and very quickly reach their maximum amplitude; superhumps recur with a period P_s that is slightly longer than the orbital period P_o; during the course of the outburst, on the plateau of the superoutburst, the superhump amplitude gradually disappears while the superhump period decreases slightly; after the fast decline from superoutburst the remains of the superhump and the orbital hump interfere with each other to form the late superhump with a period P_{ss}.

Superoutbursts of SU Ursae Majoris stars, however, do present several peculiarities, all of which were seen in all observed superoutbursts. In fact, normal outbursts of SU Ursae Majoris stars in general cannot be distinguished from outbursts of other dwarf novae, nor do they exhibit any of the typical SU Ursae Majoris features (as discussed below). Also there is no intermediate type of outburst. One single exception to this is known of one short outburst of VW Hyi exhibiting superhumps (Marino and Walker, 1979). This outburst occurred shortly before the expected time for a superoutburst; the next outburst was the then somewhat delayed superoutburst.

Originally the class of SU Ursae Majoris stars was defined by their occasionally exhibiting superoutbursts, i.e., outbursts of exceptionally long duration which also are slightly brighter than normal outbursts (Brun and Petit, 1952 and also Chapter 2.1). Observing the same superoutburst of the SU Ursae Majoris star VW Hyi with high time resolution in December 1972, Vogt (1974) and Warner (1975) independently detected the presence of strong

hump-like features during light maximum, whereas most dwarf novae show only weak, if any, humps during the bright state, as does VW Hyi during normal (short) eruptions. More striking than their presence was the fact that these superhumps repeated with a period that was some 3% longer than the orbital period as determined from the quiescent hump. Since then the presence of superhumps in addition to, or almost rather than, long outbursts has become the defining characteristic of SU Ursae Majoris stars. The most recent edition of Ritter's catalogue (1987) lists 18 SU Ursae Majoris stars, and their number probably will keep increasing, as it did during the last decade, since the search for superhumps and investigation of the SU Ursae Majoris stars has become fashionable, and, correspondingly, a lot of detailed information about their properties has become available.

Superhumps have been observed during all superoutbursts in all stars which ever have been observed to exhibit them. The rise to a superoutburst cannot be distinguished from the rise to a normal outburst. Superhumps

normally do not develop until some time after maximum brightness of a normal outburst has been reached. Their appearance usually is accompanied by a further brightness increase by some tenths of a magnitude. Figure 2-48 gives an example of the light curve of V 436 Cen during a superoutburst. In VW Hyi, there often occurs a drop in brightness before the final rise to a superoutburst (Figure 2-1b); the superhump normally does not develop until rise to the very supermaximum (Marino and Walker, 1979).

During the first one or two days after its appearance, the superhump develops to reach an intensity of some 30% to 40% of the total system intensity, then the amplitude decreases as the superhump proceeds. Unlike the minimum hump, its shape is well-defined and repeats with some flickering superimposed. The shape usually is slightly asymmetric with the rise to maximum light being faster than the decline. A decline from superhump maximum usually is immediately followed by the next rise without a longer interhump phase of constant brightness. Warner (1985a) points out that there is some indication for the superhump amplitude to be modulated by the orbital hump, indicating that the latter still might be present at the appropriate phase also during superoutbursts.

The main features of a superoutburst are given schematically in Figure 2-49: the superhump develops around maximum brightness, and quickly reaches its maximum amplitude and period. Both decrease gradually during the course of the outburst, and the superhump becomes almost undetectable at the end of the *plateau*, i.e., before the steep decline to quiescence. Already at about the middle of the plateau, the original superhump structure resolves into many distinct features of comparable strength, all of which still repeat with the superhump period (Figure 2-50), while the original superhump disappears. After, in a steep drop of intensity, the star has returned to almost minimum brightness the so-called *beat phenomenon* occurs: one of the features,

the *late superhump*, which is about 180° out of phase with the original superhump, for some time modulates the amplitude of the orbital hump with the beat period of the orbital motion and the superhump period (Figure 2-50).

Superimposed on the general shape of the superoutburst and the decay of the superhump amplitude, Schoembs (1986) found in OY Car a semi-periodic brightness variation with a periodicity of some 3 days persisting well into the quiescent level (Figure 2-51).

Superhumps occur in all SU Ursae Majoris stars irrespective of the angle of inclination of the system with respect to the observer on Earth. It is observed with comparable strength for instance in OY Car (which exhibits a double eclipse in quiescence, indicating an inclination on the order of 90°), in VW Hyi (which shows only a hump) and in WX Hyi (which has neither a hump nor an eclipse at minimum light, thus probably having a very low inclination angle of some 30° or 40°). In all cases the superhump period is a few percent longer than the orbital period (extremes are between 0.8% for WZ Sge and 12.7% for TY Psc; the average is some 3% or 4%). During the course of a superoutburst in most objects the superhump period decreases slightly, though never reaching the length of the orbital period; however, in V436 Cen and OY Car there is indication for an increase of the superhump period with time. For any object the superhump period and its rate of temporal change are constant within the error limits for all outbursts (e.g., van Amerongen et al, 1987b).

In OY Car, Z Cha, and WZ Sge pronounced "dips" (of some 5% to 10% of the intensity) in the light curve have been observed (Figure 2-52, marked with "D") which are too strong to be attributed to flickering; they also cannot be eclipse features since their orbital as well as their superhump phases are variable. Closer inspection reveals that in all three objects the dips cluster about times when the orbital and superhump phases coincide (Schoembs, 1986).
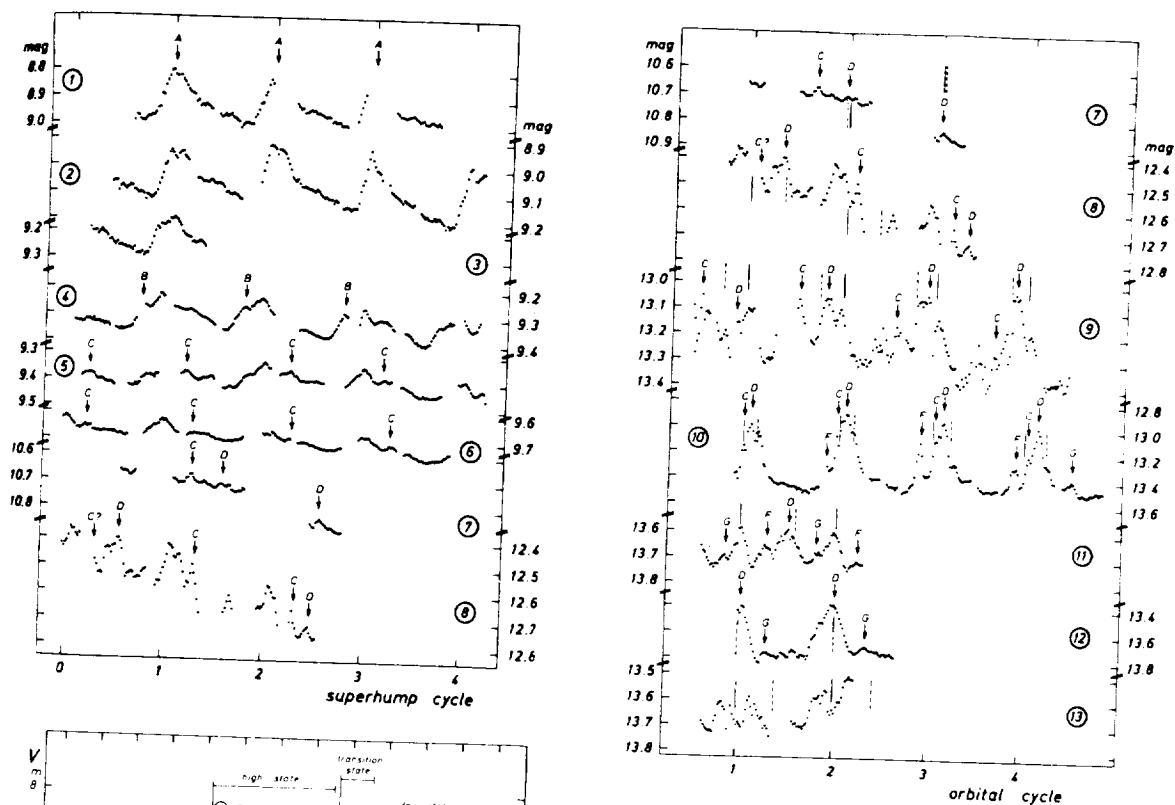
Figure 2-50. Development of superhumps during the course of a superoutburst (Schoembs and Vogt, 1980). The superhump gradually resolves into several components, one of which survives the drop to minimum light level and, together with the orbital hump, forms the late superhump.
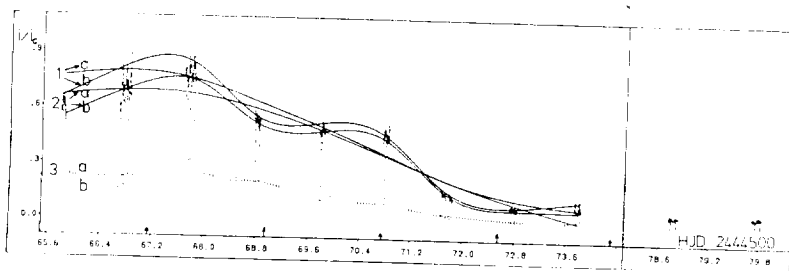

Figure 2-51. Semi-periodic brightness variations of OY Car on decline from a superoutburst (Schoembs, 1986).

Two SU Ursae Majoris stars, OY Car and Z Cha, show double eclipses during the quiescent state. Those eclipses can be used as a probe for the origin and location of the superhumps, which in turn seem closely related to the phenomenon of superoutbursts. The eclipses of OY Car have been observed by Krzeminski and

Vogt (1985) and Schoembs (1986) for the early and later parts of two different superoutbursts, respectively. During the first half of the superoutburst (including times when the superhump had not yet developed), Vogt found the depth of the eclipse (in magnitudes) to increase with time, with a superimposed periodic

51

variation with superhump period. The width of the eclipse, on the other hand, decreases with also a superimposed variation of superhump period, but 180° out of phase with respect to the changes in depth of the eclipse. The amplitude of the variation increases with increasing wavelength.

As to the second half of the outburst, from inspection of Figure 2-52a and the sketches given at the right side of each panel, it can be seen that the ingress is flattened when the superhump phase zero (labeled "C") occurs close to the eclipse (runs 4 and 5), and egress is flattened when it occurs far away from this (runs 2, 3, and 6). The situation becomes more complicated for later stages of the outburst when the minimum shape of eclipse is slowly restored. At the plateau of the outburst the eclipse is round-bottomed and approximately symmetric, without any indication for a second eclipse within this eclipse, like it is detectable at minimum. Also no variation of the slight asymmetry with the beat period can be detected, as was found during earlier stages of the different outburst which was observed by Vogt (see above). Immediately after the fast drop in brightness at the end of the superoutburst plateau, the eclipse bottom becomes flatter and shows irregular features with indication of a second eclipse; gradually the total width of the eclipse becomes narrower, regaining its normal quiescent appearance. This process of restoring the quiescent light curve is not a well-defined one, but when quiescent features evolve, they well may experience setbacks, become more like what they were during outburst, and later develop anew (Figure 2-52b).

Warner (1985a) observed Z Cha during different superoutbursts and finds that, not taking into account the superhump, the shape of the light curve and in particular the shape of the eclipse are well repeated from one outburst to another. Eclipse depths correlate with the superhump phase, being deepest when the superhump occurs at about orbital phase 0.5 (i.e., 180° away from eclipse), somewhat unlike

what has been observed in the case of OY Car where there is no clear relation between depth of eclipse and superhump phase, though a modulation is present. Furthermore, in Z Cha the eclipse occurs at a later time than predicted ($\Delta\varphi$ some 0.005) whenever it coincides with the superhump.

The color variations of superhumps have been investigated by Vogt (1974), Schoembs and Vogt (1980), and van Amerongen et al (1987a) in the case of VW Hyi. Very extensive five-color measurements by the latter authors reveal several remarkable features: the shape of the superhump is qualitatively the same in all five (Walraven) colors they observed, but with decreasing amplitude toward shorter wavelengths; all amplitudes decrease as the superoutburst proceeds and the superhump becomes progressively redder. And while one period fits times of the superhump maxima in all colors, there is a phase shift between the times of superhump maximum in that it occurs increasingly later towards shorter wavelength (Figure 2-53); the total phase shift amounts to about 0.06 of the orbital period between the V and the W filters. Qualitatively similar results were obtained by the other groups. TU Men is reported to become bluer in (B-R) and (B-I) at times of rise to superhump maximum (Stolz and Schoembs, 1984).

WZ Sge already has been introduced as a slightly extravagant system (see Chapter 2.II.B.4). In 1978 it underwent an outburst which in its overall shape resembled a nova outburst (outburst light curve, see Figure 2-42) rather than that of a dwarf nova. Its photometric appearance on orbital time scales strongly resembles superoutburst light curves of SU Ursae Majoris stars, in particular in exhibiting a very strong periodic hump feature (Figure 2-54). The periodicity of this feature turns out to be some 0.8% longer than the quiescent orbital period, which by definition qualifies WZ Sge to be a member of the SU Ursae Majoris class of dwarf novae. The eclipse feature seen during quiescence could not be detected during outburst.
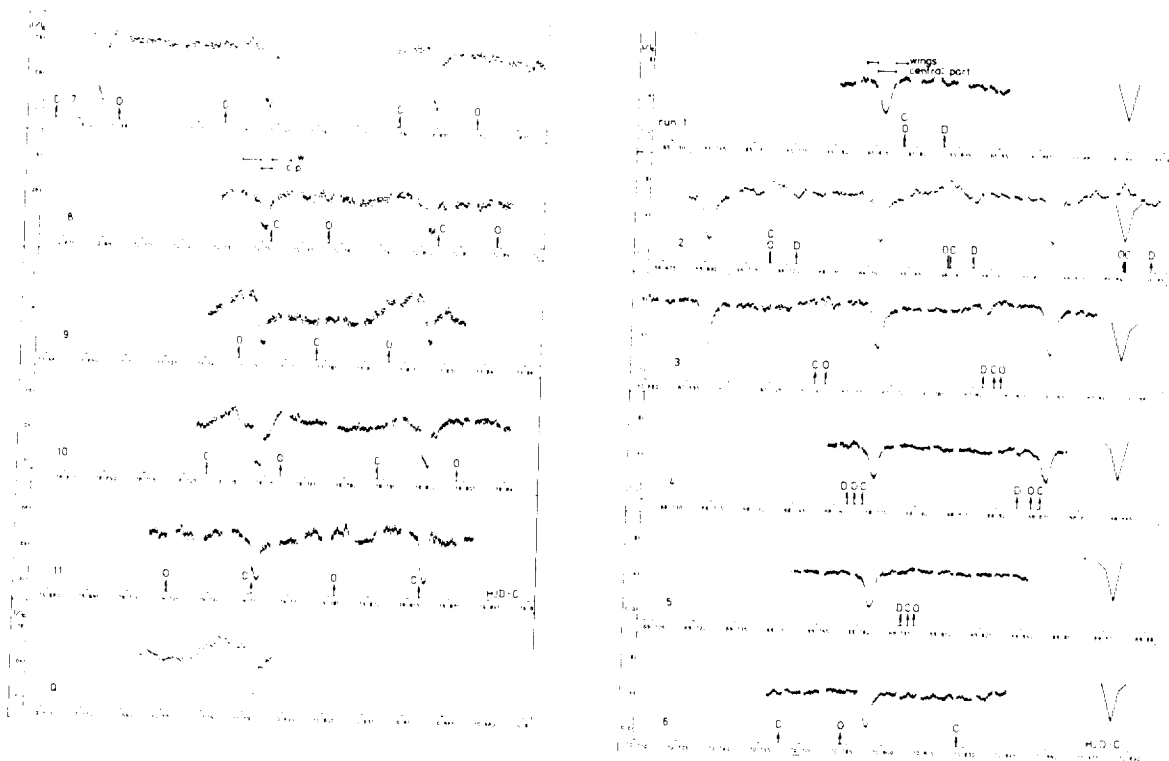
Figure 2-52. In OY Car the eclipse shape during superoutburst is seen to vary with the superhump phase (Schoembs, 1986). Also shown is the gradual restoration of the double eclipse at the end of the superoutburst.
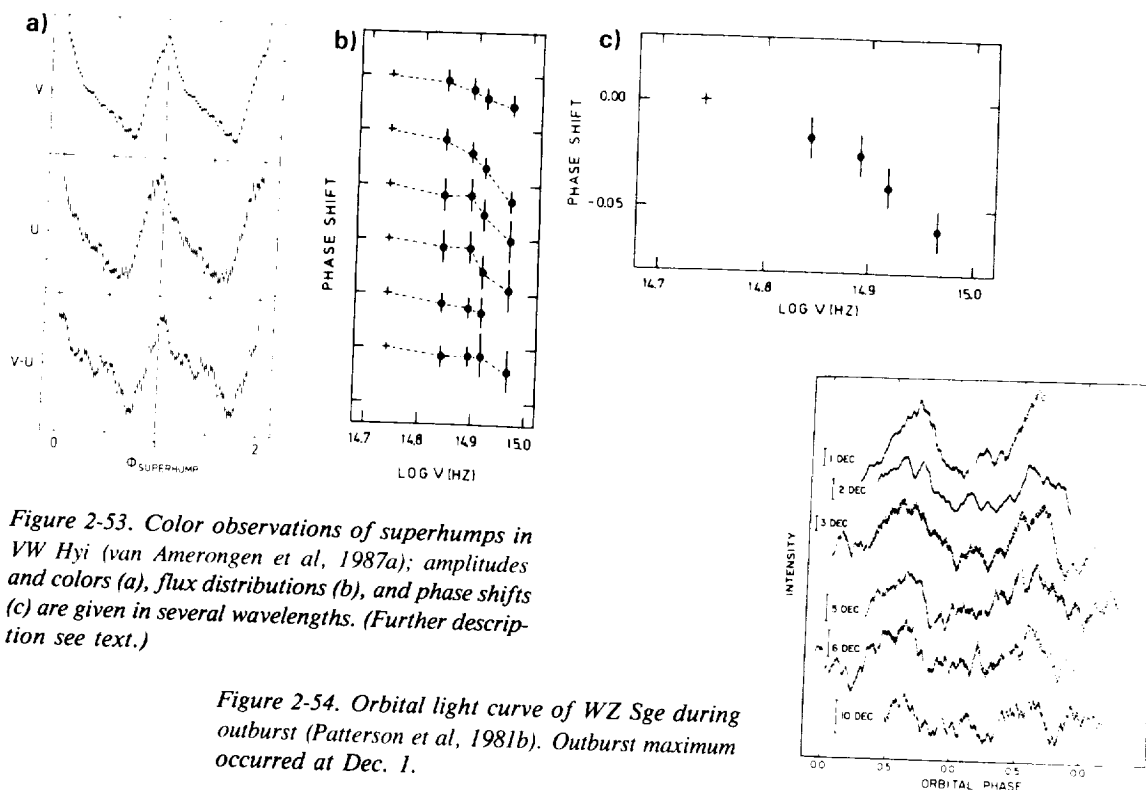
Figure 2-53. Color observations of superhumps in VW Hyi (van Amerongen et al, 1987a); amplitudes and colors (a), flux distributions (b), and phase shifts (c) are given in several wavelengths. (Further description see text.)

Figure 2-54. Orbital light curve of WZ Sge during outburst (Patterson et al, 1981b). Outburst maximum occurred at Dec. 1.
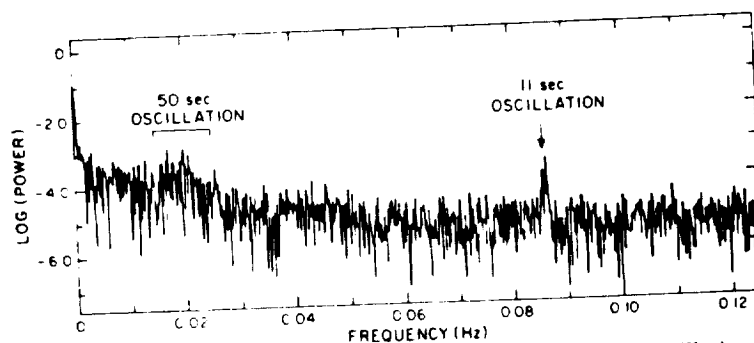
Figure 2-55. Power spectrum of RU Peg (Patterson, 1981) showing coherent oscillations at 11 s, quasi-periodic oscillations at 50 sec, and flickering at even lower frequencies.

GENERAL INTERPRETATION: Most photometric variations on orbital time scales during outburst or standstill are ascribed to aspect variations due to orbital revolution. Double eclipses become single because the brightness distribution in the disc changes considerably. Outbursts are believed to be due to an instability either in the disc or in the secondary star; standstills are understood to be prolonged outbursts. The mechanism of superoutburst and superhumps is not well understood.

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *Why do outbursts occur? (See 171)*

- *Why do standstills occur? (See 178)*

- *What are superoutbursts and superhumps? (See 184)*

- *The amplitude of superhumps seems to be rather independent of the angle of inclination. (See 184)*

II.D. SHORT-TERM VARIATIONS

ABSTRACT: On time-scales of minutes and seconds, further more or less periodic types of variability are seen in dwarf novae.

In dwarf novae there occur three different types of short-term variations: the *flickering*, a random light variation which is present to some degree at all stages of activity with amplitudes of some tenths of a magnitude and time-scales of seconds or minutes; the *coherent oscillations* (which are also referred to as *dwarf nova oscillations, dwarf nova pulsations,* or, possibly somewhat misleadingly, as *white dwarf*

pulsations) with periods of a few tens of seconds and amplitudes on the order of 0.002 mag, occurring in dwarf nova outbursts, in nova-like stars during their bright state, and in WZ Sge during quiescence; and finally, also seen during dwarf nova outbursts, there is an intermediate class of variations, the so-called *quasi-periodic oscillations* with periods on the order of one minute and somewhat larger amplitudes than the coherent oscillations, in which periods change stochastically. Figure 2-55 is a power spectrum of the dwarf nova RU Peg showing all three types of variability.

II.D.1. FLICKERING

ABSTRACT: Flickering is a random, aperiodic brightness variability on time-scales between some 20 sec and many minutes. Amplitudes can reach up to 0.5 mag and generally are highly variable. Flickering is present to some degree in all dwarf novae (as well as nova-like stars and old novae), and in all brightness stages. During eclipse minimum it is either strongly reduced or disappears altogether. The amplitude is largest in U and slightly decreases toward longer wavelengths.

nova-like stars: 98, 103, 106, 114, 117, 119, 122, 128, 140

interpretation: 151, 181

As can be seen in many of the previous figures in this section, the light curves of dwarf novae — and other cataclysmic variables as well — besides exhibiting humps, eclipses and light variations due to outbursts, are by no means smooth. Superimposed on the orbital light
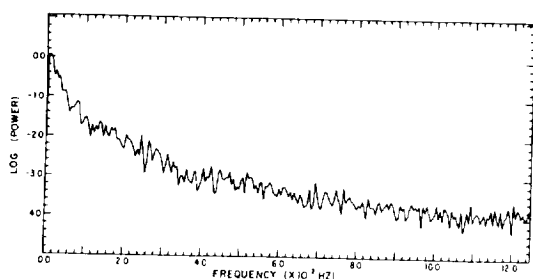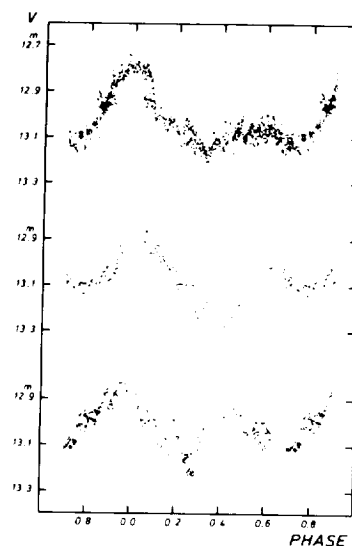
Figure 2-56. Power spectrum of RX And showing only flickering (Robinson, 1973b).

Figure 2-57. Optical light curve of BV Cen (Vogt and Breysacher, 1980b). Variable flickering activity can give the light curves rather different appearances.

variations, brightness changes occur at random with amplitudes of typically some 0.1 to 0.5 mag on time scales of some 10 minutes. This phenomenon is called *flickering* (for a collection of flickering amplitudes see Moffet and Barnes, 1974). Power spectra clearly indicate that flickering time-scales can well be as short as 20 sec, and with a continuous distribution of frequency, there is practically no limit to longer time scales.

To some degree flickering is present in all dwarf novae and nova-like stars in all stages of activity, as well as in novae during the quiescent state. No periodicities or general patterns of amplitude changes can be found in the flickering of these stars.[*] A typical power spectrum of the flickering is shown in Figure 2-56: the power is large at low frequencies and falls off toward higher frequencies; no peaks indicating prevailing periods are present. In general, however, even during comparable brightness levels in a given object, very different degrees of flickering activity have been observed in many systems (e.g., Figure 2-57). Usually there is a tendency for the flickering amplitude to be largest at times of hump max-

imum and to be strongly reduced during eclipse. Detailed observations of eclipses of the dwarf novae HT Cas, V2051 Oph, and the nova-like system RW Tri (which is very similar to dwarf novae) indicate that the main source of the flickering is the hot inner disc close to the white dwarf, rather than the hot spot, as often has been claimed (Patterson, 1981; Warner and Cropper, 1983; Horne and Stiening, 1985). In general, flickering is present during outburst, but then it can be stronger as well as weaker than during quiescence, varying from object to object and also during the course of an outburst (e.g., Robinson, 1973a, b).

No significant differences have been found between the pattern of flickering in different colors, only normally the amplitude is larger at shorter wavelengths. There is no information about flickering activity in the UV.

A systematic investigation of flickering in dwarf novae was carried out by Elsworth and James (1986) on YZ Cnc. They find that the frequency distribution is not that expected from a point-like source but rather that from some kind of extended optically thick source. The geometrical extent of this source appears to increase as the system's brightness increases.

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[*]This is due mainly to terminology: there are periodic variations hidden in this seemingly random behavior which are referred to as *oscillations*, as will be discussed later.

II.D.2. OSCILLATIONS

Application of fast-fourier-transformation techniques to cataclysmic variables revealed that hidden in the random flickering there are periodic light variations with periods of some dozens of seconds. These were called *oscillations*.

II.D.2.a. COHERENT OSCILLATIONS

ABSTRACT: During outburst of dwarf novae, strictly monochromatic oscillations with time scales of typically 10 to 30 sec, amplitudes of $5\ 10^{-3}$ to $5\ 10^{-4}$ mag, and coherence times of several minutes can sometimes be seen. They were only found during certain observing runs in some dwarf novae. Periods always lie in a certain characteristic range for any given object. During the course of an outburst, characteristic shifts in frequency can be seen; at any moment only one frequency contains considerable power.

see also: 59, 61, 63

nova-like stars: 98, 106, 112, 116, 117, 119, 122, 129, 141

interpretation: 185, 213

The so-called *coherent oscillations* (or *dwarf nova oscillations, dwarf nova pulsations,* or *white dwarf pulsations*) are observed mostly in dwarf novae during outburst, though they were seen to occur in some nova-like stars in their bright state as well. These are purely monochromatic oscillations with periods of typically between 10 and 30 sec, coherence times of typically 10^3 cycles, and amplitudes of 0.0005 to 0.005 mag. Because of these characteristics they usually are invisible in the raw observational data, and only very special representation of data makes them appear. In the power spectra these oscillations appear as single sharp peaks with power up to 100 times as much as the neighboring frequencies, and no power in excess of noise in any of the harmonics (Figure 2-58). When a signal appears to be wider than the numerical resolution it can always be resolved, at closer inspection, into several independent spikes; they never seem to form a continuum. As ever smaller segments of one observing run are analyzed, the power

can be seen to slowly migrate from one frequency to another with usually only one frequency being strongly excited at any one time, and no continuum of frequencies being present (e.g., Figure 2-61 and Warner and Bickhill, 1974). It is not obvious that, as has been claimed by several authors, more than one frequency can be present at a time with appreciable power; this multi-frequency appearance well might be an artifact of too coarse a time resolution. It never has been observed that excited frequencies which apparently coexisted were more than a fraction of a second separated from each other.

Coherent oscillations cannot always be seen in all dwarf novae. Despite considerable searching they have so far never been detected during the quiescent state of any dwarf nova. They have been observed in all types of dwarf novae during normal outbursts and superoutbursts; however, they have never been seen during the standstill phase of any Z Camelopardalis star. Reported detections of coherent oscillations in dwarf novae have been summarized by Warner (1986b). The period of the oscillation is variable in all stars, but for different outbursts they always cluster around some characteristic value. During the course of an outburst the oscillation period is subject to very characteristic changes in the log period — log intensity plane of the spectrum, called the "banana diagram" by Patterson (1981, and also Figures 2-59 – 2-62): at some stage of the rising branch the oscillations appear with an identifiable period, the period shifts towards shorter periods as the system brightens, when it approaches maximum visual brightness the oscillations fade or even become undetectable, and at the declining branch they reappear first with quickly increasing, then with slowly decreasing amplitude. As the system fades the period shifts to ever longer periods; this happens not quite monotonically but with no evidence for sudden changes, almost displaying a mirror image of the light curve (Figure 2-60). Any period typically is strong for some 20 min and stable for about one hour. The rate at which the period changes
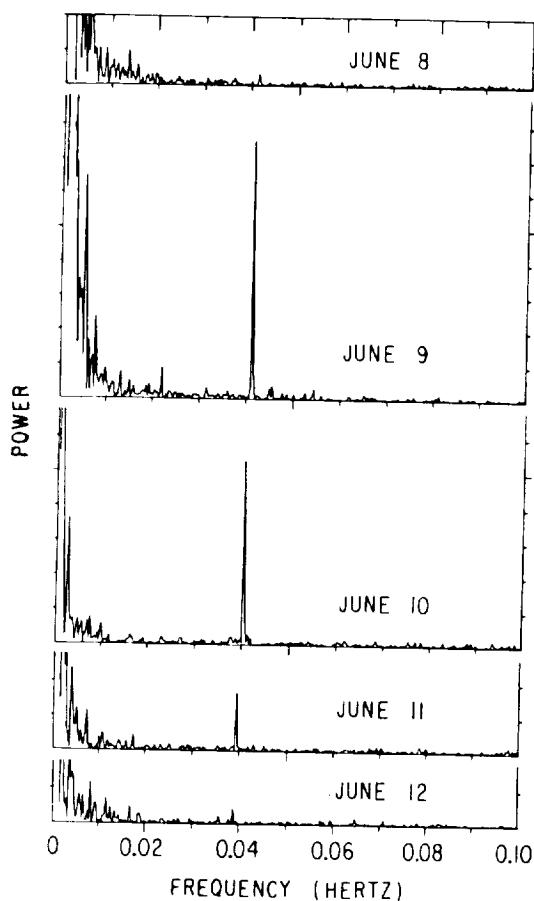
Figure 2-58. Power spectra of AH Her (Stiening et al, 1979) showing strictly monochromatic coherent oscillations and their development during the course of an outburst.

Figure 2-60. Similarly the intensity of the oscillation varies with the general brightness level (Patterson 1981). The full curves represent variations of the oscillation periods, the broken lines give the brightness variations for comparison.
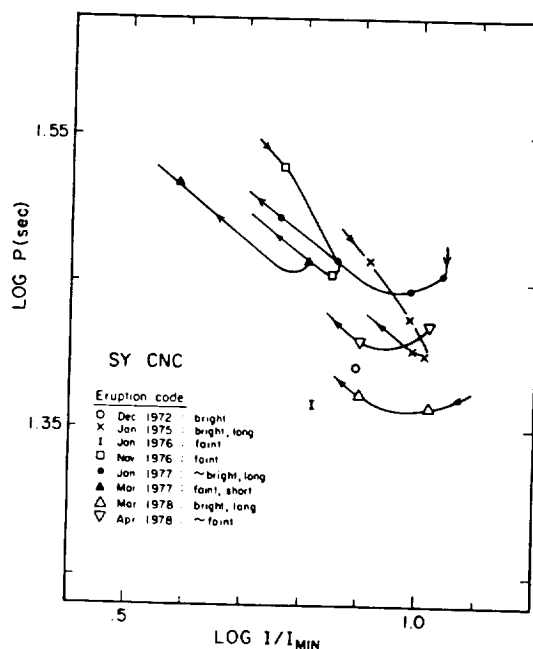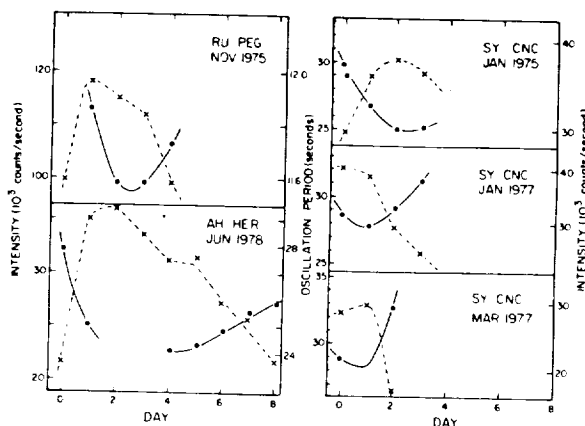

Figure 2-59. The "banana diagram:" the periods of coherent oscillations undergo characteristic frequency changes as the system's brightness changes during the course of an outburst (Patterson, 1981).

as the system brightness changes is roughly constant for different outbursts in each object on the declining branch, while it is fairly variable on the rising branch. The actual values of the period at a given system brightness vary from one outburst to another in every object (Figure 2-59).

Oscillations have not been detected in outbursts of all dwarf novae, and in no object can

they be seen in all outbursts. The result of a systematic search for oscillations by Nevo and Sadeh (1978) might be representative: they detected oscillation in 11 out of 90 runs, and in 4 out of 11 objects. It is not clear if there are outbursts in which oscillations are really not present, or, since they are a somewhat transient phenomenon, if they have only remained unobserved.
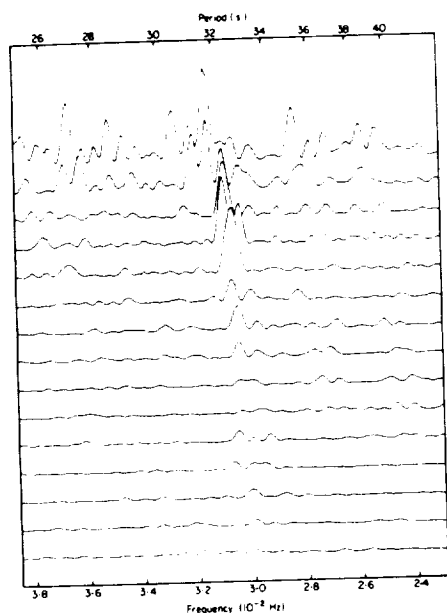
Figure 2-61. Development of oscillations in CN Ori during rise; time increases toward the top (Warner and Brickhill, 1978). It is not quite clear whether the oscillations are really polychromatic or monochromatic but then survive only for a short while.
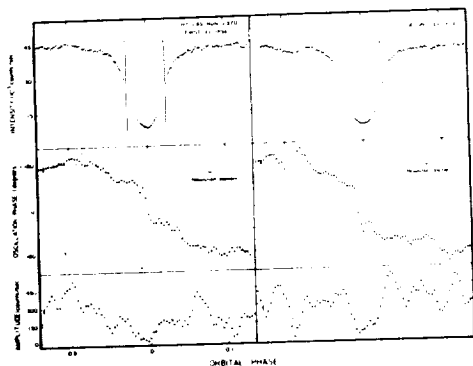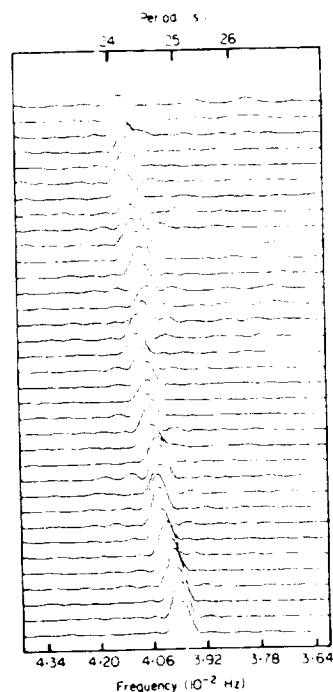

Figure 2-62. Period shifts of the coherent oscillations in CN Ori during the course of an outburst (Warner and Brickhill, 1978). A cyclical variation is superimposed on a general period drift.

Figure 2-63. During eclipse in HT Cas the oscillations undergo a phase shift of −360° and amplitudes are strongly reduced just before mid-eclipse (Patterson, 1981).
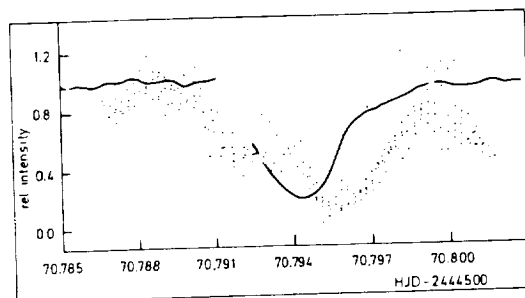

Figure 2-64. In OY Car the oscillations are almost totally eclipsed, but only after photometric mid-eclipse (Schoembs, 1986). Dots represent the relative oscillation amplitude, the full line is the light curve, both in relative units.

In several systems (Warner and Brickhill, 1978; Patterson, 1981; Schoembs, 1986), coherent oscillations have been observed during photometric eclipses. In HT Cas (Patterson, 1981) the oscillations undergo a steady phase shift of −360° during eclipse. The amplitudes of the oscillations were observed to be strongly reduced shortly before mid-eclipse, and the eclipse of the oscillation preceded that

of the optical light by 0.01 of the orbital period (Figure 2-63). The oscillations in OY Car (Schoembs, 1986) are practically completely eclipsed; this eclipse, however, followed that of the visual light by a short time (Figure 2-64). In OY Car no phase variations of the oscillations during the eclipses were found.

The colors of the oscillations were investigated by Hildebrand et al (1981) in AH
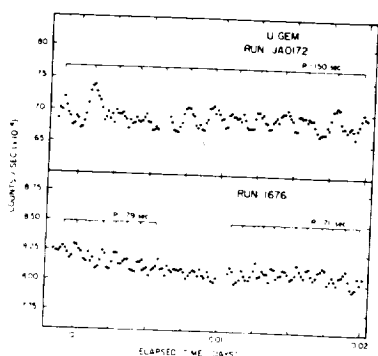
Figure 2-65. Quasi-periodic oscillations in U Gem (Robinson and Nather, 1979); sometimes they are easily visible already in the raw data.

Her and by Middleditch and Córdova (1982) in SY Cnc. AH Her was measured in two colors and the authors found the flux ratios to be in agreement with a black body temperature of 28000 K < T < 73000 K. SY Cnc was measured in three colors and it was found that no kind of black body nor a power law could be fitted to the data. No change of the colors was evident during three nights of observations.

II.D.2.b. QUASI-PERIODIC OSCILLATIONS

ABSTRACT: Besides, or instead of, flickering and coherent oscillations, polychromatic oscillations of some 0.001 mag amplitude are displayed in some dwarf novae during outburst. Usually they consist of a wide range of periodicities which are considerably longer than those of the coherent oscillations. Very different values of periods are possible in one object during different outbursts.

see also: 51, 61, 63

nova-like stars: 98, 106, 112, 116, 117, 119, 122, 129, 141

interpretation: 185, 213

There is still a second kind of short-term variability present in some dwarf novae: the so-called *quasi-periodic oscillations* (Figure 2-55). They are characterized by a broad hump in the power spectrum indicating a (quasi-) continuum of frequencies with amplitudes of up to 0.01 mag. Because of these relatively large amplitudes, quasi-periodic oscillations are often already visible in the raw data without any help

of data analysis (Figure 2-65). Often, however, the autocorrelation function lets the periodicity appear more clearly. The periods of the quasi-periodic oscillations normally are several times as long as those of the sharply defined coherent oscillations, so usually no confusion is possible. But, there are exceptions to this, as will be seen.

Quasi-periodic oscillations have been detected in many dwarf novae, and, like coherent oscillations, they are seen only during outburst; they also can be found in some nova-like systems (Ritter, 1987, see also Chapter 3). Periods typically range from some 20 sec to several hundred sec, and, like the coherent oscillations, they are confined to a fairly narrow period range which is just a few seconds wide. During different outbursts of one object, however, fairly different period values seem possible. In addition, sometimes several such ranges of frequencies occur simultaneously, each with somewhat different characteristics: usually one is a quasi-periodic oscillation in the conventional sense, while another more resembles coherent oscillations. Like the coherent oscillations, quasi-periodic oscillations do not seem to occur in all outbursts of a dwarf nova, and in many dwarf novae they have never been detected at all. When seen during different outbursts of a system, they can have significantly different periods (e.g., Robinson and Nather (1979) found a period of 150 sec in one outburst of U Gem, while during another outburst, Patterson (1981) found quasi-periodic oscillations with a period of only 24 sec). Quasi-periodic oscillations may or may not appear simultaneously with coherent oscillations: in objects like RU Peg and SS Cyg they do; in other objects, either only coherent oscillations or only quasi-periodic oscillations, or in some cases none at all, were detected. It is not clear whether quasi-periodic oscillations can occur on the rising branch of an outburst.

As the name suggests, the quasi-periodic oscillations are not strictly periodic. For a short interval of time, a mean period can be defined, which however is not usually kept strictly. The decay times of these mean periods are on the

order of just a few cycles, and within that short a time, new periods emerge (Figure 2-65) which usually are not strongly different from the former. The change of periods occurs at random and does not follow any monotonic trend as in the case of coherent oscillations. At times the amplitudes are strong, while at other times they die out completely for some minutes, and during such times, phase and/or period changes are very likely to occur. There are entire nights without any detectable quasi-periodic oscillations, while during both the preceding and the following night they might be strong (Robinson and Nather, 1975).

In U Gem quasi-periodic oscillations have been observed to be present throughout the eclipse, whereas flickering in this object largely is eclipsed (Robinson and Nather, 1975).

II.D.2.c. X-RAY PULSATIONS

ABSTRACT: In U Gem, SS Cyg, and VW Hyi, pulsations were detected at soft X-rays during outbursts. In SS Cyg the periods were on the same order as optical coherent oscillations, but with much shorter coherence times; in VW Hyi they were of a considerably different length than optical oscillations; in U Gem they have been observed simultaneously with optical quasi-periodic oscillations.

In all three dwarf novae which so far could be observed extensively in the soft X-rays (SS Cyg, U Gem, and VW Hyi), oscillations, or pulsations as they are called in the x-ray regime, were observed during decline from outburst (Figure 2-66).

SS Cyg was observed twice, once during maximum of a long outburst and once on the declining branch of a short one. Both times the pulsation period was in the same range as the optical coherent oscillations: 8.8 sec and 10.7 sec, respectively. U Gem was observed at three outbursts, during one of which pulsations with a period of some 25 sec were detected — and observed simultaneously in the optical (Córdova, 1979). In another outburst there was marginal evidence for 21 sec pulsations, and the third outburst did not show any pulsations at all. In the optical, no coherent oscillations were found in U Gem so far, but only quasi-coherent oscillations with periods of some 75 sec and 150 sec, respectively.

VW Hyi was monitored with EXOSAT during several normal outbursts and superoutbursts during the years 1983 through 1985 (van der Woerd et al, 1987). Only during two superoutbursts could pulsations be detected in soft X-rays (> 5Å). In November 1983, there appeared coherent oscillations with a period of 14.06 ± 0.02 sec. During another superoutburst in October 1984, rather unstable pulsations were seen, which were variable in frequency between 14.2 and 14.4 sec and also variable in amplitude; in addition these seem to have had a somewhat harder spectrum than those seen the year before. No simultaneous optical observations are available, but oscillations in VW Hyi which are at times seen in the optical (see below) normally are variable with periods of some 30 sec.

The X-ray pulsations are remarkably incoherent and rather resemble the optical quasi-periodic oscillations than the coherent oscillations, although in the case of SS Cyg they have the same periodicity as the optical coherent oscillations. In SS Cyg they showed coherence times of about 20 cycles and 2 cycles, respectively, for the two sets of observations, as opposed to typically some 1000 cycles in the optical. Like the optical coherent oscillations, however, they also perform slow shifts in frequency in X-rays as time goes by (Córdova et al, 1984).

The pulsed fraction of the soft X-ray radiation varies between zero and 100%, with typical values of 30% and 17%, respectively, in the two observations of SS Cyg, and some 15% in U Gem (Córdova et al, 1980) — as opposed to
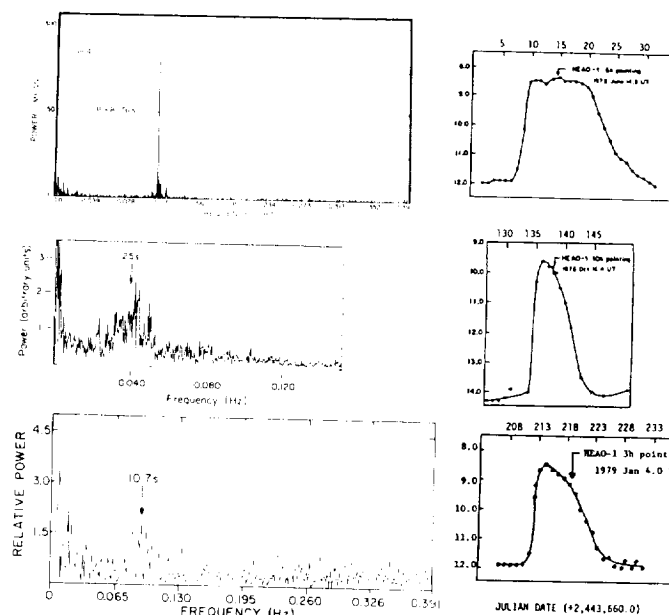
Figure 2-66. X-ray pulsations in SS Cyg and U Gem (Córdova and Mason, 1980); they have approximately the same periods as the optical coherent oscillations.
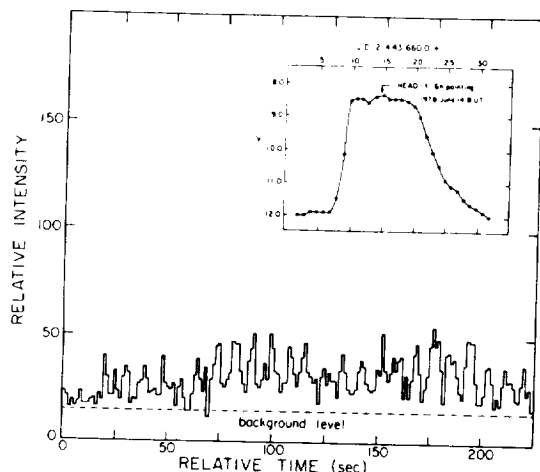

Figure 2-67. X-ray pulsations in SS Cyg (Córdova et al, 1980). Because they involve a considerable fraction of the X-ray flux, the pulsations are readily seen in the raw data.

some 2% in the optical. The range of variability was seen to be much narrower (about 15 to 20%) in the case of VW Hyi. Because of this great strength, the pulsations are already easily seen in the raw X-ray light curves (Figure 2-67). Frequent and sudden amplitude and phase changes were seen in all cases.

II.D.2.d. VW HYI — A VERY CONFUSING CASE

ABSTRACT: Many different kinds of oscillations have been observed in VW Hyi, which cannot be classified as any of the conventional types.

For oscillations in dwarf novae, the *normal* case seems to be that coherent oscillations have periods on the order of typically 10 to 30 sec, while quasi-periodic oscillations rather have periods on the order of 50 to 100 sec. However, it has been mentioned already that in U Gem quasi-periodic oscillations with periods as short as some 24 sec have been detected in X-rays, casting some doubt on the physical significance of the strict distinction between coherent and quasi-periodic oscillations. The case of VW Hyi makes this even more questionable.

In various independent observations, the oscillations in VW Hyi (all with periods on the order of 30 sec) appear to be changing periods in a much more erratic way than do oscillations in other dwarf novae, in which the multiple peaks probably reflect quick changes (or insufficient time resolution), rather than several frequencies being present simultaneously (Figure
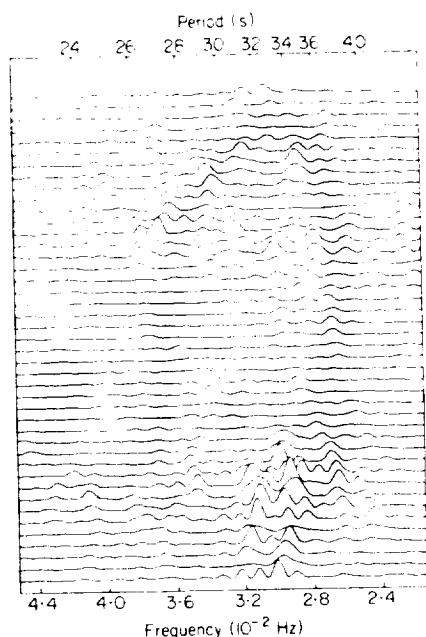
61

Figure 2-68. Quasi-periodic oscillations in VW Hyi (Warner and Brickhill, 1978). Unlike in other dwarf novae, in VW Hyi periods rather change at random.

Figure 2-69. Observation of two sets of quasi-periodic oscillations in VW Hyi, no coherent oscillations are visible (Robinson and Warner, 1984).

2-68). The first time any oscillations were observed in VW Hyi, in December 1972 (Warner and Brickhill, 1974), there was no doubt that the oscillations were coherent: drifting slowly (though not altogether monotonically, a feature which is not common in other dwarf novae) from 28 sec toward longer periods. During a normal outburst of VW Hyi in November 1974, oscillations were seen to be modulated in amplitude with a period of 413 ± 1 sec. In observations of a superoutburst in December 1974, Haefner et al (1977) found a coherent oscillation with 192.3 sec at very early rise which could only be observed again two nights later (with a period of 193.7 sec). During the following night close to maximum light, there appeared a strictly coherent oscillation of 266.0 sec which never appeared again. At the end of another superoutburst in 1975, one could see a couple of clearly distinct sinusoidal periods between 85 and 90 sec for seven consecutive nights, which appeared at random with
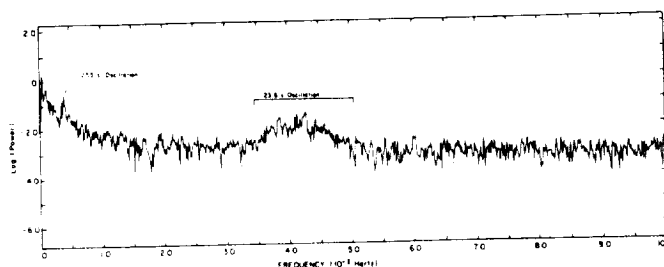
no obvious trend of development, and it seems that several of these were present simultaneously. Their coherence times, however, seem to have been on the order of several hours (Schoembs, 1977; Haefner et al, 1977). So, from their lengths and erratic changes, these variations should be classified as quasi-periodic oscillations; according to their stability and their being distinct from each other, they qualify as coherent oscillations. For these oscillations, there are indications that their amplitudes are larger at times of orbital hump maximum than at other times, as in the case of flickering. This did not appear to be the case in any oscillations in any other dwarf nova. In addition, in two of the above mentioned observations, there also appeared coherent oscillations with periods of 28.8 and 35.7 sec, respectively, in close agreement with observations during another outburst of VW Hyi by Warner and Brickhill (1974). Finally, somewhat more erratic processes, possibly quasi-periodic oscillations, were observed to develop at late decline, with a general tendency to drift from a mean value of some 130 sec to some 150 sec as the decline proceeds.

In 1978 Robinson and Warner (1984) observed two simultaneous sets of quasi-periodic oscillations, but no coherent oscillations, during a normal outburst of VW Hyi. In the power spectrum (Figure 2-69), an oscillation near 23.6 sec is clearly visible, having all the characteristics of a quasi-periodic oscillation except for the unusually short period. An
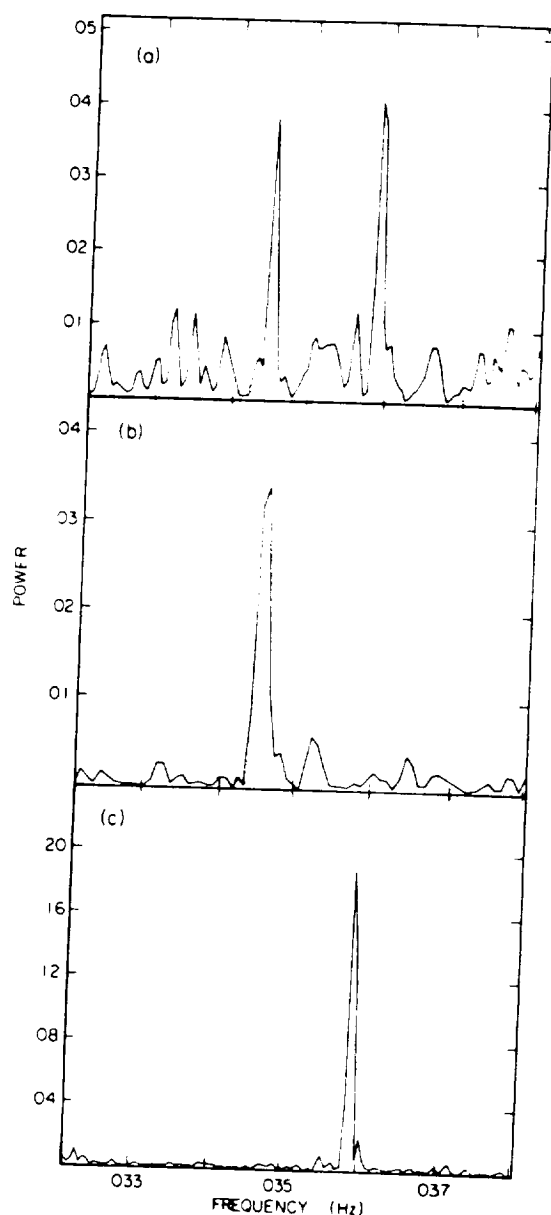
Figure 2-70. Power spectra of WZ Sge during quiescence (Robinson et al, 1978). The 28.87 sec period was seen to be almost always present for several years, other periods were seen occasionally.

Figure 2-71. Secular variations in the 29 sec period in WZ Sge in 1976 through 1978 (Patterson, 1980).

II.D.2.e. WZ SGE — AS USUAL, AN UNUSUAL CASE

ABSTRACT: In WZ Sge coherent oscillations have been observed in quiescent state; they proved to be very stable over a couple of years.

related spectroscopic observations: 91

nova-like stars: 98, 106, 112, 116, 117, 119, 122, 129, 141

interpretation: 185

In photometric observations of WZ Sge, Robinson et al (1978) detected coherent oscillations during the quiescent (!) state with a period of either 27.87 ± 0.02 sec or 28.98 ± 0.04 sec. Either or both of those periods were present every time they observed the system, and no other periods containing significant power could be detected (Figure 2-70). Either the amplitudes were about 0.0043 and 0.0034 mag, respectively, or the periods were undetectable altogether. No shift in the periods could be detected during any observing run.

Patterson (1980) added new observations to these until the time of outburst in December, 1978, and carried out a more extensive investigation of the periods. He found that the period of 28.87 sec was very stable and was always present during the years 1976 through 1978, though with irregularly varying amplitude. Besides this, there were four other

oscillation at 253 sec appears to be almost monochromatic, thus being rather similar to coherent oscillations. Inspection of the light curve, however, reveals that this latter period is subject to frequent erratic changes and at times dies out altogether, a behavior very characteristic of quasi-periodic oscillations.
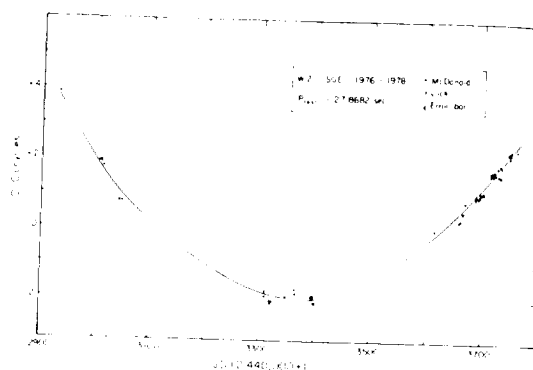
peaks at lower frequencies, usually with much less power. The period of 28.97 sec seems to be real, the others can be explained as orbital sidebands of the principal frequency, though their relatively high power makes this hard to believe. Investigation of the principal period revealed it to be like a highly stable clock, though with a continuously increasing period between 1976 and 1978 (Figure 2-71).

The amplitudes of all the observed periods were variable, but no systematic variations, in particular none in connection with the orbital period, could be detected. There also was no indication for the oscillations to be in any way influenced by the eclipse. No similar investigations have been carried out so far, after the 1978 outburst.

GENERAL INTERPRETATION: Flickering is ascribed mainly to slight variations of the mass stream hitting the disc at the hot spot, thus causing slight temperature variations. However, other observations rather would suggest that its origin is in the vicinity of the white dwarf. — There is practically no understanding of what physical process causes the oscillations, and whether coherent and quasi-coherent oscillations have different causes, or whether they rather are different aspects of the same phenomenon. The short periods place their origin in, or in the vicinity of, the white dwarf.

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *In dwarf novae and nova-like stars, short-period oscillations are occasionally observed. (See 185)*

- *They cannot be observed at all times. (See 185)*

- *When they occur, this is always only during the high brightness state. (See 185)*

- *The frequencies undergo characteristic changes which are related to the general brightness level of the system ("banana diagram").*

- *Oscillations in the optical and at X-rays seem to be correlated with each other.*

- *The systems VW Hyi and WZ Sge behave in very atypical ways.*

II.E. POLARIMETRIC OBSERVATIONS OF DWARF NOVAE

ABSTRACT: Only very few dwarf novae have been detected polarimetrically. The fraction of polarized radiation typically is some tenths of a percent or less. Variations in the fraction of polarized light were seen in VW Hyi during decline from a superoutburst.

nova-like stars: 98, 106, 113, 131

As a consequence of the small apparent magnitude of dwarf novae, polarimetric data of dwarf novae are extremely scarce. SS Cyg has been observed by Kraft (1956), U Gem by Krzeminski (1965), and Z Cam by Belakov and Shulov (1974), all with negative results.

Schoembs and Vogt (1980) carried out polarimetric observations of VW Hyi during maximum and decline from superoutburst. They found a significant but small linear polarization between 0.02% and 0.1%, which increases as the source becomes fainter during decline. During outburst the radiation is clearly less polarized than during quiescence. No clear evidence for periodic variability on time scales between 120 sec and twice the orbital period could be detected.

Szkody et al (1982a) carried out a systematic search for polarized radiation in dwarf novae and nova-like stars. They observed four dwarf novae, out of which three, SS Cyg, AH Her, and RX And, did show polarization on also the 0.3% level; but no polarization could be detected in U Gem. There is no significant change evidently related to the outburst cycle. RX And was observed well enough for investigations on orbital time scales (Figure 2-72); a variability is clearly present, but whether or not this is related to the orbital period cannot be decided with certainty.

The wavelength dependence of the polarization could be investigated in three nova-like systems (AE Agr, V426 Oph, CI Cyg (Szkody et al, 1982a)) and in the dwarf nova SS Cyg. In all of them it was found to be decidedly different from the wavelength dependence of the interstellar polarization, suggesting an origin in the systems themselves.
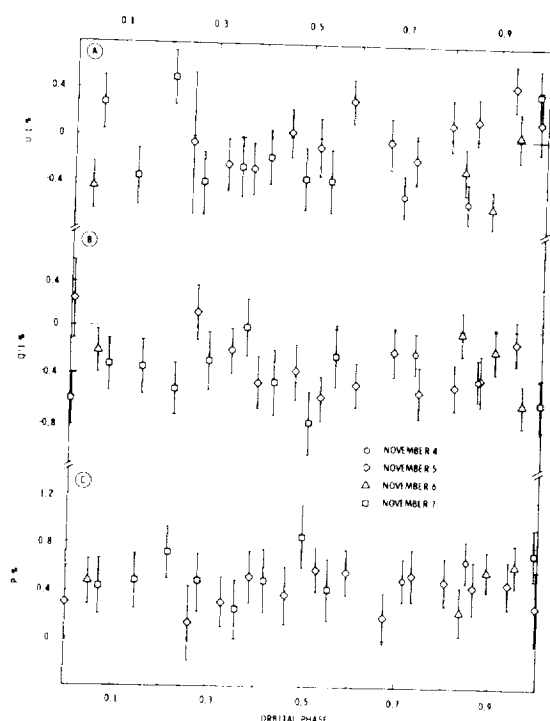
Figure 2-72. Polarimetric observations of RX And (Szkody et al, 1982a).

GENERAL INTERPRETATION: The polarized fraction of the light is believed to be due to scattering in a non-spherical corona above the disc. As this corona changes its shape during the course of an outburst, also the fraction and position angle of the polarized light change.

GENERAL CONSTRAINTS TO MODELS:

* It is still not clear whether the above scenario is theoretically feasible.

III. SPECTROSCOPIC OBSERVATIONS

III.A. GENERAL FLUX DISTRIBUTION

Appreciable flux is emitted by dwarf novae at all wavelengths from the X-rays to the longest IR wavelengths, and in some cases even in the radio. The general flux distribution of dwarf novae and its characteristic changes during the outburst cycle shall be presented in what follows. We shall first deal with the UV through IR emission, which can be observed over the

entire range. The X-rays are separated from this by a gap between 912 Å and some 300 Å due to interstellar absorption. The flux and its changes in X-rays will then be considered. Finally some brief remarks will be made about attempts to detect dwarf novae at radio wavelengths.

III.A.1. ULTRAVIOLET, OPTICAL, AND INFRARED EMISSION

ABSTRACT: The strongest flux is usually emitted in the UV, falling monotonically towards longer wavelengths. During outburst, the spectrum is steeper than during quiescence with even more flux at high energies. The flux distribution is very different from that of single stars. It roughly can be fitted by a power law distribution over, typically, wavelength ranges of 1000 to 2000 Å; an even approximate fit with just one black body clearly is not possible. In some objects the flux rises again in the IR and only falls off longward of a maximum around 15000 to 20000 Å. — Rise to an outburst either occurs simultaneously at all wavelengths, or it starts at long wavelengths and then is seen at progressively shorter wavelengths. The decline is simultaneous at all wavelengths. In any one object, no differences seem to exist between the continuous flux distributions at the same optical brightness between different outbursts; this does not hold for the line radiation.

photometric changes during outburst cycle: 21, 47

nova-like stars: 99, 107, 116, 119, 122, 124, 134, 141

interpretation: 151, 192

In general terms, the continuum flux is falling monotonically from the Lyman edge to the infrared. During outburst, in addition to a general increase in flux, the distribution steepens markedly toward the blue, indicating that much higher temperatures prevail then. Though in general this appearance is shared by all dwarf novae, in detail the distributions are fairly different for different objects and for different outburst states. Figure 2-73 gives examples of observed flux distributions of dwarf novae in various outburst states. In Figure 2-73, an attempt has also been made to ascribe some
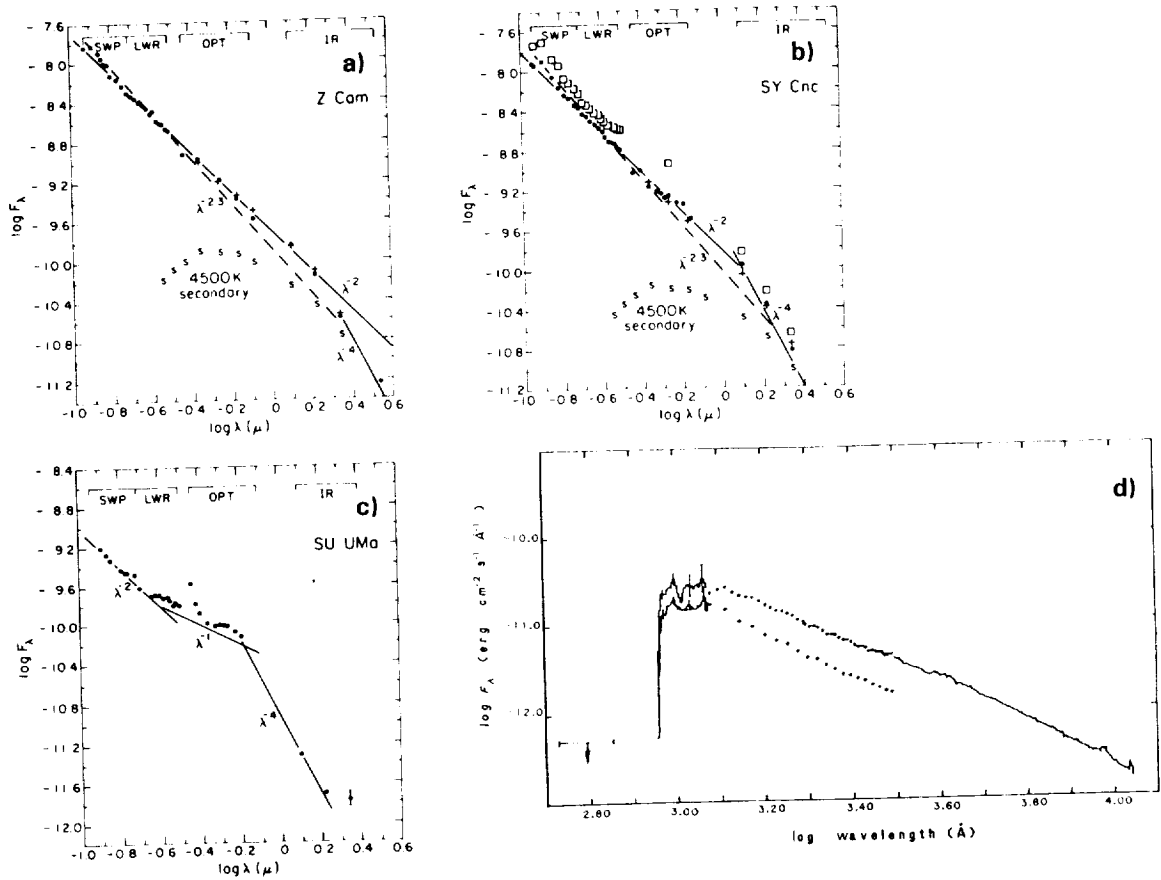
65

Figure 2-73. Typical flux distributions of dwarf novae: (a) Z Cam at standstill, (b) SY Cnc at maximum and decline, and (c) SU UMa at minimum (Szkody, 1981 — dots and squares represent the observed continuum flux at various brightness stages, the solid lines are fitted power laws, the symbol "S" indicates the flux distribution of the secondary component), and (d) SS Cyg (upper) and U Gem (lower) at outburst (Polidan and Holberg, 1984).
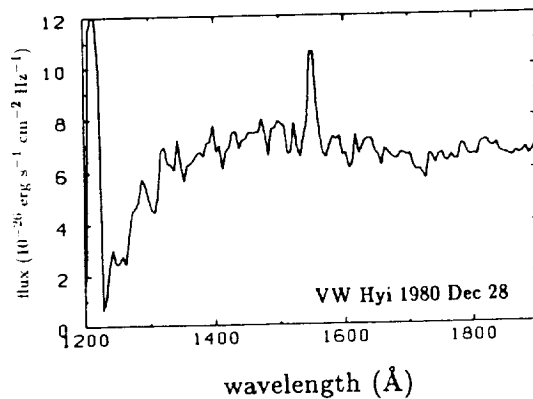

Figure 2-74. UV flux distribution of VW Hyi during quiescence (Verbunt, 1987). In some dwarf novae (and nova-like stars in the low state) the UV flux is seen to steeply decline at short wavelengths.

power law fits to the flux distributions. Typically slopes of α_λ (with $F_\lambda \sim \lambda^{\alpha_\lambda}$) between 0.0 and -4.0 apply locally to the spectra of dwarf novae (as well as to nova-like stars), but usually at least two such fits are needed in order to represent reasonably accurately the entire range from the Lyman limit to the IR; and clearly no black body fit is in any way satisfactory.
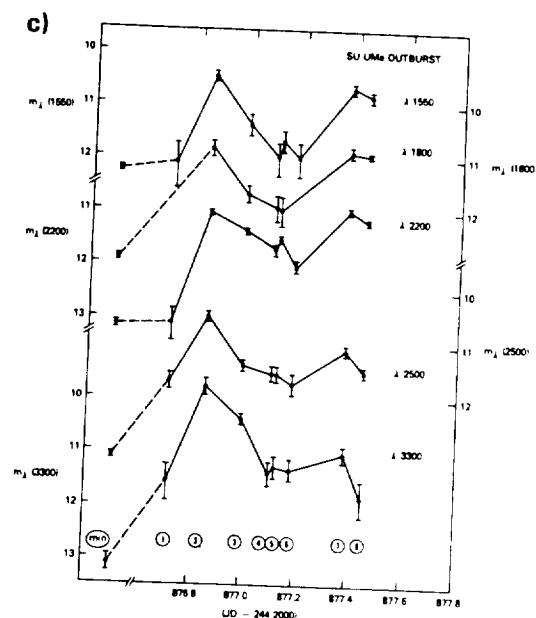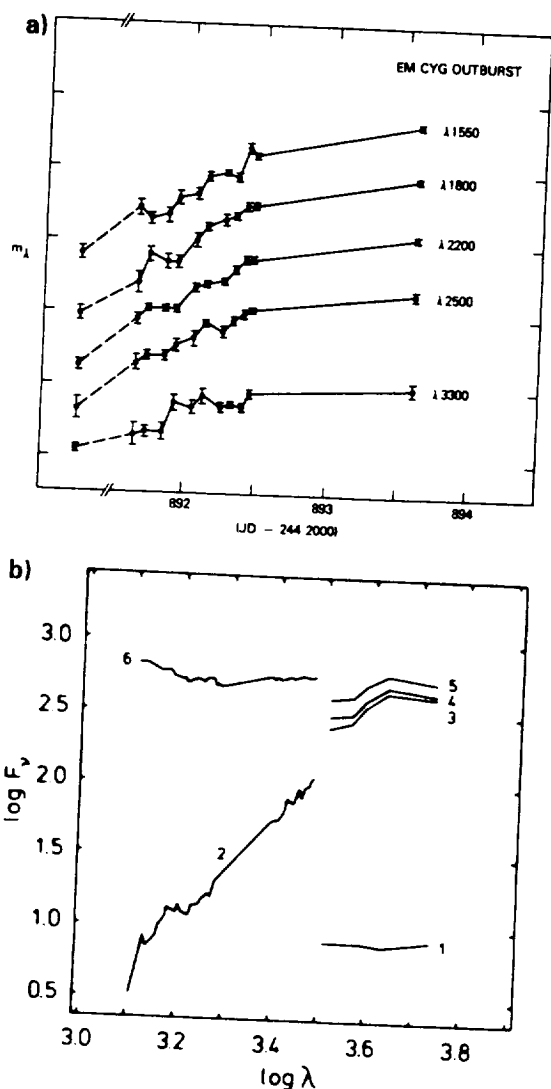
a)

EM CYG OUTBURST

mλ

λ1550

λ1800

λ2200

λ2500

λ3300

892   893   894

JD − 244 2000

b)

$\log F_\lambda$

3.0

2.5

2.0

1.5

1.0

0.5

6

5
4
3

2

1

3.0   3.2   3.4   3.6   3.8

$\log \lambda$

c)

SU UMa OUTBURST

m_λ (1550)

m_λ (2200)

m_λ (3300)

λ1550

λ1800

λ2200

λ2500

λ3300

m_λ (1800)

m_λ (2500)

876.8   877.0   877.2   877.4   877.6   877.8

JD − 244 2000

Figure 2-75. Flux distributions during rise to outburst: (a) in EM Cyg the flux rises simultaneously at all wavelengths (Wu and Panek, 1983); (b) in VW Hyi the rise is progressively delayed toward shorter wavelengths (van Amerongen et al, 1987a - the numbers indicate the order in which the observations were taken); (c) in SU UMa the flux first rises simultaneously at all wavelengths, then drops, the more the shorter the wavelength, and only after this rises to outburst (Wu and Panek, 1983).

In several objects during quiescence the flux increases in the IR between roughly 6000 and 12000 Å, due to the contribution of the cool companion (Figure 2-73). Contrary to what at times has been claimed in the literature, from inspection of published flux distributions (e.g., Oke and Wade, 1982; Sherrington and Jameson, 1983) there is no evidence for an additional red component to be present preferably in just those dwarf nova systems with long orbital periods; for any period a red component may or may not be visible*. At the short

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*Still it holds that in the optical lines of the secondary component are visible only in long period systems (see Chapter 2.III.B.1.a).

wavelength end of the spectrum, in four dwarf novae (WZ Sge, EK TrA, Z Cha, and VW Hyi; see Verbunt, 1987) during quiescence the flux is seen to decrease considerably shortward of some 1400 Å (Figure 2-74). In the Roche model this can be ascribed to either the wings of the Lyα line of the white dwarf (when the disc is cool enough to not contribute much flux at these wavelengths), or to a generally cool disc. During outburst, both the short wavelength turn-over as well as the infrared excess disappear when the contrast to the generally increased flux level becomes too small.

At rise to an outburst in most objects the flux distribution changes entirely. In several cases

this phase in outburst cycle has been observed simultaneously in the optical and in the UV. Three principally different modes of behavior were observed. In CN Ori, EM Cyg and SS Cyg (Pringle et al, 1986; Wu and Panek, 1983; Verbunt, 1987) the flux rose simultaneously in the optical and in the IR with a steady steepening of the spectral slope (Figure 2-75a). In VW Hyi, WX Hyi, SU UMa, RX And, SS Cyg (for which both types of rise were seen to occur) and possibly also in SS Aur (Hassall et al, 1983; Wu and Panek, 1983; Pringle and Verbunt, 1984; Polidan and Holberg, 1984; Schwarzenberg-Czerny et al, 1985; Verbunt, 1987), the rise to an outburst in the optical precedes that in the UV by typically several hours to half a day (Figure 2-75b); furthermore in VW Hyi there is indication for this delay to continue into X-rays (see below). Two such events were observed in VW Hyi, but at comparable optical brightness the slopes of the UV continuum were different (Verbunt et al, 1987). Van Amerongen et al (1987c) performed mulit-wavelength photometric measurements of VW Hyi in the optical during two rises to outburst and found that the delay in rise toward shorter wavelengths also holds for just the optical range (Figure 2-75b). From photometric observations of RX And at infrared wavelengths, Szkody (1976) finds some evidence that this delay might extend into the infrared as well; attempts to carry out similar observations of other dwarf novae so far did not lead to any conclusive results (Szkody, 1985a; 1985b). A third kind of change during rise in the UV has been observed in SU UMa during rise to a normal outburst (Wu and Panek, 1983) and in VW Hyi during rise to a superoutburst (Polidan and Holberg, 1986): in both cases the UV first rose up to the level of a normal outburst, delayed with respect to the optical, and then the flux dropped to some intermediate level (the drop was considerably deeper at shorter wavelengths than at longer ones), after which another rise led to the outburst or superoutburst, respectively (Figure 2-75c). In the case of SU UMa the corresponding optical changes are not quite clear. In VW Hyi, where occasionally such precursors to

superoutbursts are observed in the optical (see Chapter 2.II.A.4, Figure 2-19), no drop in optical brightness was observed in this particular outburst; it clearly was seen, however, at soft X-rays (van der Woerd et al, 1986).

During outburst maximum the flux in all dwarf novae is markedly bluer than during all other times. Decline from outburst always proceeds simultaneously at all wavelengths. As the typical example of Figure 2-76a shows, the spectral index stays roughly constant throughout outburst longward of some 15000 Å, and just the flux level as a whole changes. In the optical and UV, after an initial decline at constant flux distribution, the flux level decreases ever more rapidly with decreasing wavelength. Only at the very last phase of decline is the quiescent flux distribution restored (Figure 2-76b). During quiescence, between outbursts, the flux of VW Hyi and WX Hyi in the UV has been seen to keep falling until onset of the following outburst (Figure 2-77), while no such trend could be detected in U Gem (Hassall et al, 1985; Verbunt et al, 1987); appropriate observations of other dwarf novae in the UV are not available. VW Hyi also was monitored in the optical for this purpose. After the end of an outburst — as defined from the general outburst light curve — the system brightness kept declining slightly for another couple of days; but after this, besides erratic variations, the flux level stayed constant (van Amerongen et al, 1987c). Similarly, extensive monitoring of CN Ori during quiescence demonstrated that the brightness of the inter-hump times from the very end of one outburst until the onset of the next stayed constant (Figure 2-40).

The UV-optical flux distribution of all dwarf novae, nova-like stars, and quiescent novae can be described to a very first approximation by a power law fit during all stages of activity; when looked at in more detail, however, there are clearly differences in the continuum flux
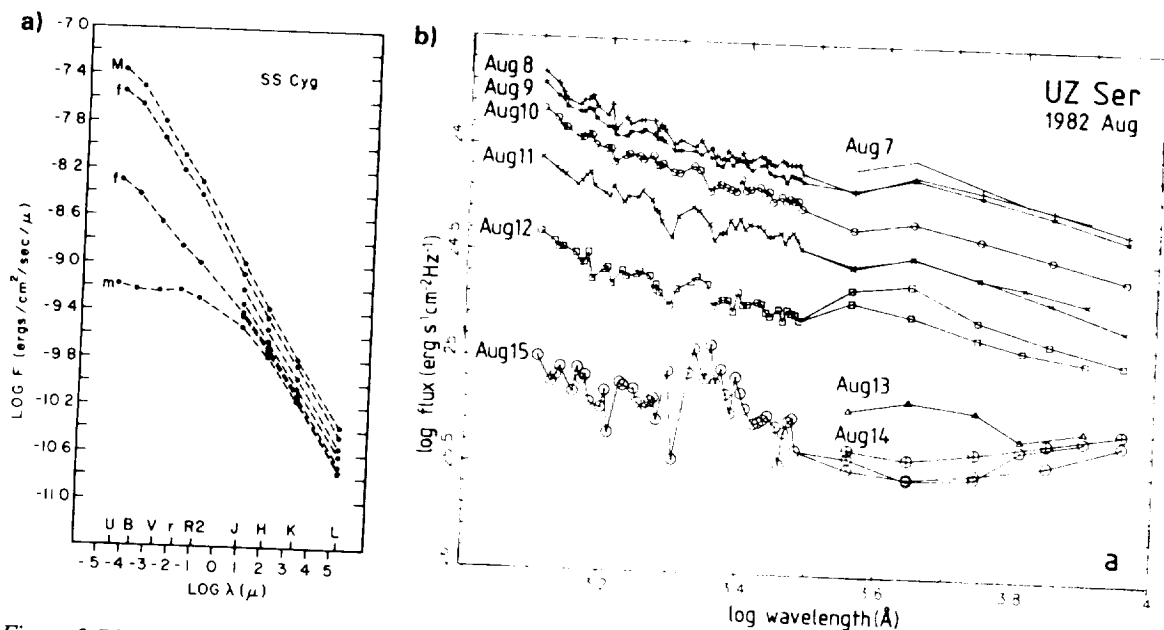
Figure 2-76. Flux changes during decline. (a) SS Cyg no color changes occur at long wavelengths, while they are appreciable at short ones (Szkody, 1977); (b) in UZ Ser the flux declines simultaneously at all optical and UV wavelengths except for very late stages (Verbunt et al, 1984).
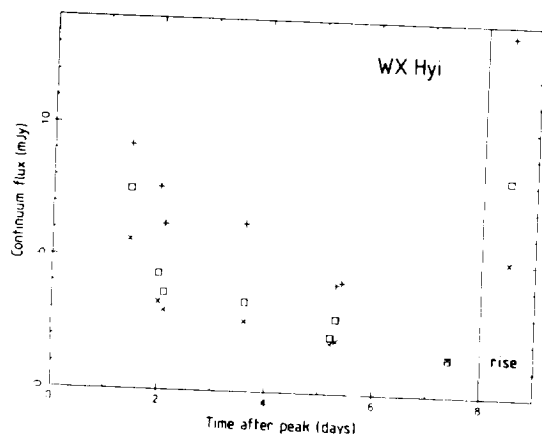

Figure 2-77. In this observation WX Hyi the UV flux keeps declining after an outburst until the following rise (Hassall et al, 1985).

distributions. Verbunt (1987) carried out an extensive survey, in particular of UV observations, at all stages of outburst activity with — besides others — the aim of deciding whether or not relations can be found between the continuous flux distribution and some other properties of cataclysmic variables. He could not find any correlation with the orbital period, with the angle of inclination, or with the

average length of the outburst cycle. He did find, however, that, no matter when during an outburst of a dwarf nova a spectrum was taken, the continuous UV flux distribution is the same at the same optical brightness level; the only exceptions, of course, are spectra taken during the rise.

III.A.2. X-RAY EMISSION

ABSTRACT: During quiescence dwarf novae emit mostly hard X-rays; during outburst, soft X-rays. A relation seems to exist between the amount of hard X-rays emitted and the equivalent width of Hβ. The X-ray flux is highly variable on all time-scales.

nova-like stars: 108, 119, 122, 134

interpretation: 212, 153, 193

The X-ray radiation of stars only became accessible to astronomers when technical developments permitted observations to be
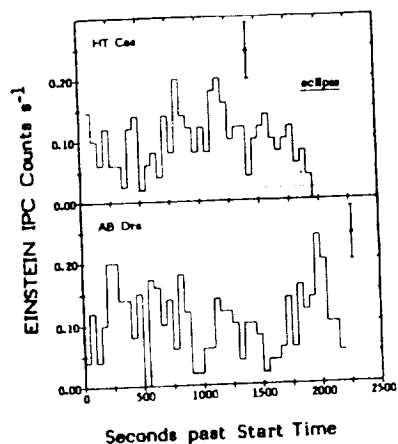
Figure 2-78. In quiescent dwarf novae the flux level at hard X-rays is highly irregularly variable (Córdova and Mason, 1984).
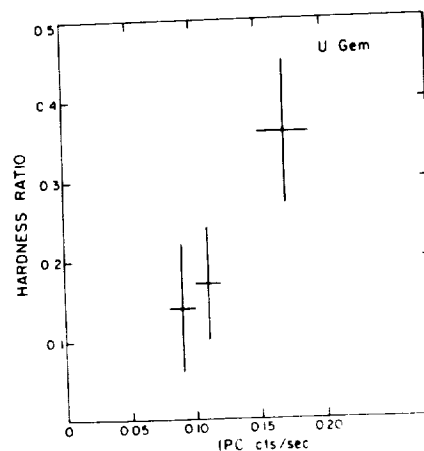

Figure 2-79. In U Gem the X-ray spectrum during quiescence becomes harder as the source becomes more intense (Fabbiano et al, 1981).
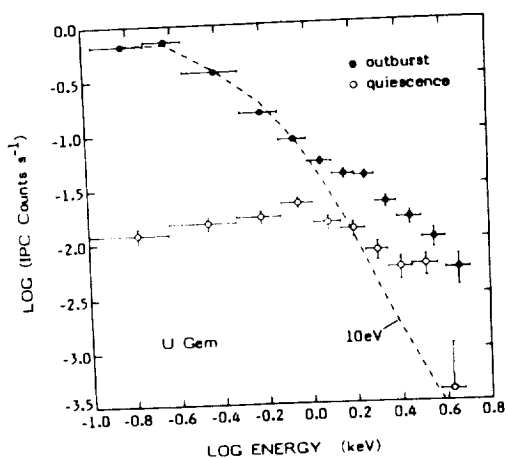

Figure 2-80. X-ray flux in U Gem in outburst and quiescence (Córdova and Mason, 1984). There are hardly any changes at hard X-rays while the soft X-ray flux strongly increases.
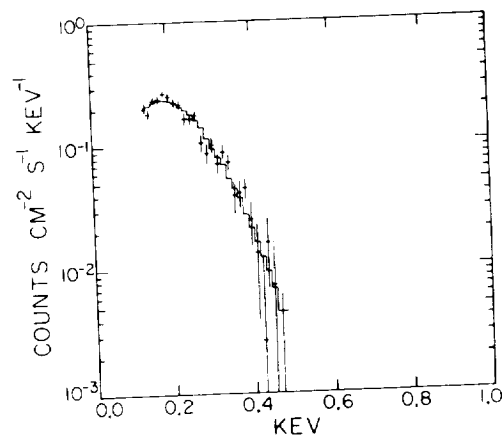

Figure 2-81. Soft X-ray flux distribution of SS Cyg in outburst (crosses); the flux can well be fitted with a 30 keV black body (solid line) (Córdova et al, 1980).
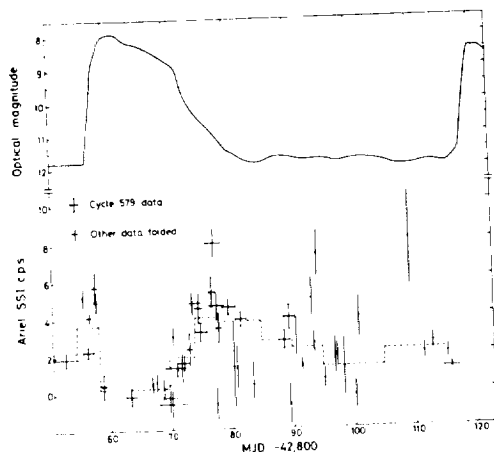

Figure 2-82. Optical and X-ray light curve of SS Cyg during the outburst cycle (Ricketts et al, 1979). For discussion see text.
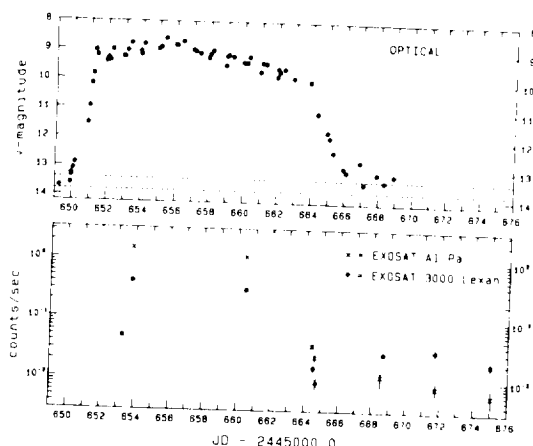
70

Figure 2-83. Superoutburst light curve of VW Hyi in the optical and X-rays (van der Woerd et al, 1986). For discussion see text.
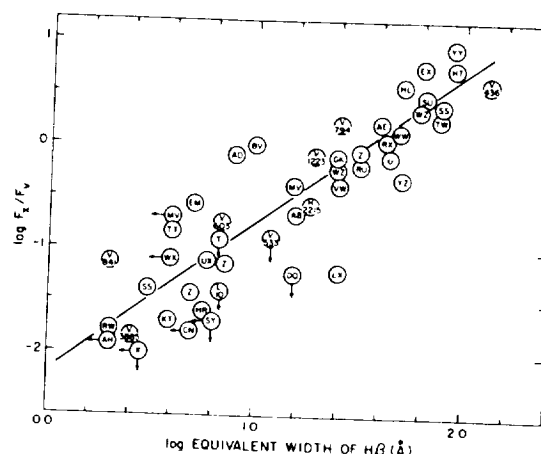

Figure 2-84. Relation between the Hβ equivalent width and the ratio between optical and X-ray flux (Patterson and Raymond, 1985a).

made from space. The first dwarf nova detected in X-rays was SS Cyg, which was seen during an optical outburst in soft X-rays (0.15 - 0.28 keV) in a rocket experiment (Rappaport et al, 1974). Further detections of, again, SS Cyg, and eventually also other cataclysmic variables in different outburst states and in different energy bands, soon followed by the HEAO 1, Apollo-Soyuz, Ariel V, Einstein, and EXOSAT satellites. In spite of considerable effort, before Einstein, SS Cyg and U Gem were the only dwarf novae which were positively detected in X-rays, although some nova-like stars had been seen as well. Altogether, Einstein was pointed at 66 cataclysmic variables, out of which 45 (of all sub-classes) could be detected in X-rays at a level of about 10^{29} $(d/100pc)^2$ erg/s (Córdova and Mason, 1983; Patterson and Raymond, 1985a).

During the quiescent state, cataclysmic variables can only be detected in hard X-rays (~0.1 - 4.5 kev). The flux distribution in this range follows approximately a thermal bremsstrahlung spectrum of $kT_{brems} \approx 10keV$ (Córdova and Mason, 1983; Patterson and

Raymond, 1985a). In some systems, like SS Cyg or some nova-like stars, two flux components can be fitted to the observations (see SS Cyg, below). The flux level is highly irregularly variable on time-scales of minutes, hours, and days by a factor of two or more (Figure 2-78).

Investigation of the variations in SS Cyg during quiescence revealed that hard (2-20 keV) and soft (0.04 - 2 keV) X-rays vary together in similar ways, with a maximum correlation for a time lag of $+60 \pm 15$ sec between the hard and soft signals (King et al, 1985). The fast intensity changes are accompanied by changes in the flux distribution. The hardness ratio (color) as a function of count rate has been investigated for U Gem and SS Cyg during quiescent state: in both cases, though "hardness" refers to slightly different energy regimes, since the data were acquired with different satellites, the spectrum becomes harder as the source becomes more intense (Figure 2-79).

For dwarf novae during outburst, the ratio of X-ray flux to optical flux, F_x (0.1-4 keV)/F_v (5000-6000 Å), is found to be on the order of

1 to < 0.06%(Córdova and Mason, 1984); only the brightest dwarf novae were detected marginally in soft X-rays. During outburst there is hardly any increase, or in some objects there is even a decrease in the hard X-ray flux (van der Woerd et al, 1986: Córdova and Mason, 1984) (Figure 2-80); while in those systems which have so far been detected in soft X-rays, the soft X-ray flux (0.18 - 0.5 keV) rises by a factor of 100 or more, even though most of the radiation is hidden in the EUV range (Córdova and Mason, 1984). The soft X-ray spectra can be fitted with either black bodies of $kT \approx$ 25 eV - 30 eV or, alternatively, with bremsstrahlung spectra of 30 or 40 eV (Figure 2-81). Rather extensive studies of X-ray changes during the outburst cycle are available only for U Gem, SS Cyg, and VW Hyi, but considering the detection limits of X-ray satellites, there is no contradiction to the assumption that all dwarf novae follow more or less the same pattern of behavior.

The dwarf nova studied most extensively during the outburst cycle at X-rays is VW Hyi (van der Woerd et al, 1986); less extensive coverage is available for SS Cyg (Ricketts et al, 1979; Watson et al, 1985) and U Gem (Mason et al, 1978; Swank, 1979). The behavior is slightly different in all three systems; but in each system it seems to be rather accurately repeated from cycle to cycle.

In SS Cyg, both during early rise and also during late decline of the optical outburst, the hard X-ray flux increases appreciably; during the outburst, however, it drops to practically zero intensity, and then recovers slowly during the optical decline (Figure 2-82). A similar hard X-ray flare during rise was seen in U Gem (Mason et al, 1978; Swank, 1979), but never in VW Hyi. On the other hand, as in SS Cyg, the hard X-ray flux in VW Hyi disappears altogether during outburst maximum, recovers to somewhat above normal during optical decline, and is highly, erratically, variable during the optical quiescent level (van der Woerd et al, 1986).

Three normal outbursts and two superoutbursts of VW Hyi were observed with EXOSAT. In one of the superoutbursts (November 1983) the rise in X-rays was delayed with respect to the optical by about 2.5 days — i.e., the delay is even much larger than the typical delay of some 12 hours between the optical and the UV in VW Hyi (Figure 2-83); while in the case of all other outbursts which were observed in X-rays, the delay was shorter than 12 hours (van der Woerd et al, 1986). As to decline, no matter what kind of optical outburst occurs, the soft X-ray flux seems to start declining immediately after the flux maximum in X-rays has been reached; at superoutburst the rate during first decline is smaller than normal (Figure 2-83). After the optical decline has ended, the soft X-ray flux keeps falling down to well below the quiescent level, then rises gradually to slightly above the normal level and goes on falling at a small rate until onset of the next outburst. Only when the minimum soft X-ray flux is reached after the end of the outburst does the generally soft spectrum seen during outburst change into the hard quiescent spectrum.

No significant difference in X-ray characteristics seems to exist between members of sub-classes of dwarf novae and nova-like objects, respectively, but Córdova and Mason (1983) found some indication that in general the X-ray flux might be higher in dwarf novae than in nova-like stars. Furthermore, Patterson and Raymond (1985b) found that eclipsing systems emit significantly less X-ray flux than others. From inspecting the relation between hard X-rays and optical flux from cataclysmic variables, they found that those objects for which both fluxes are of comparable strength exhibit optical spectra with strong hydrogen emission lines, while the lines become less pronounced, the stronger the visual flux is compared to the X-rays. Relating the ratio of the X-ray flux to the visual flux with the equivalent width of $H\beta$, an amazingly tight relation emerges (Figure 2-84) which contains only observational data.

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III.A.3. RADIO EMISSION

nova-like stars: 119, 134

Searches for radio emission from dwarf novae have been conducted with the 100 m telescope in Effelsberg as well as with the VLA (Córdova et al, 1983; Benz et al, 1985). Córdova et al checked six dwarf novae and nova-like stars and could detect none. Benz et al detected SU UMa during an optical outburst at 4.75 GHz; during quiescence SU UMa was too weak to be observable; it also could not be detected at 4.9 GHz by later observers (Chanmugam, 1987). In addition, the dwarf novae TZ Per and UZ Boo both were detected at 2.5 GHz (Turner, 1985).

GENERAL INTERPRETATION: The UV flux and most of the optical flux of dwarf novae and nova-like stars is believed to originate in the accretion disc. The IR flux seen during quiescence, and possibly some of the optical flux, come from the secondary star and, if strong, cause a rise of the flux at IR wavelengths. The rise to an outburst either occurs simultaneously at all wavelengths when the rise is slow, or, when it is fast, starts progressively later with decreasing wavelengths as ever more central (hotter) parts of the disc become involved. During decline, all of the disc cools simultaneously. In a small or cool disc, contributions from the boundary layer between the disc and the white dwarf might be seen in the UV. X-ray radiation is ascribed to the boundary layer which is optically thin during quiescence (thus emitting hard X-rays) and optically thick during outburst (emitting soft X-rays because the radiation is thermalized before escape).

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *The UV through optical flux distribution of dwarf novae is clearly not that of a normal star. (See 192, 194.)*

- *Very characteristic flux changes at all wavelengths occur during the outburst cycle. (See 192, 194.)*

- *There exists some relation between short-term changes in the optical and the X-ray flux. (See 212.)*

- *There is no obvious relation between the spectral index and any of the system parameters.*

III.B. LINE RADIATION

III.B.1. SPECTRA DURING QUIESCENCE

III.B.1.a. GROSS APPEARANCE

ABSTRACT: Most dwarf novae exhibit strong emission line spectra in the optical and UV during quiescence, although some have only very weak emissions in the optical and/or weak absorptions at UV wavelengths. Many exhibit double-peaked profiles in the Balmer emission lines. In several objects, the absorption spectrum of a cool main sequence star is visible.

photometric appearance: 35

nova-like stars: 99, 107, 117, 119, 122, 124, 134, 141

interpretation: 192, 200

In the quiescent state, the optical spectra of dwarf novae usually are characterized by more or less strong emission lines of the Balmer series of hydrogen and He I, and occasionally of He II and/or Ca II; and sometimes even lines of Fe II, C III-N III, etc., can be seen (exceptions will be discussed below). Corresponding to the emission line strength, the Balmer jump is normally seen in emission during quiescence. The Balmer decrement generally is very flat, with Hβ or even Hγ often stronger than Hα. In many objects the Balmer lines appear to have two peaks, shortward and longward of the rest wavelength. All dwarf novae which show an eclipse also show such double-peaked emission lines, but many others do as well. Most of these dwarf novae exhibit a strong hump in their light curve, but there is, for example, V436 Cen which has neither a hump nor an eclipse but clearly shows double-peaked emission lines (Gilliland, 1982a). A representative collection of quiescent optical spectra of dwarf novae is given in Figure 2-85.
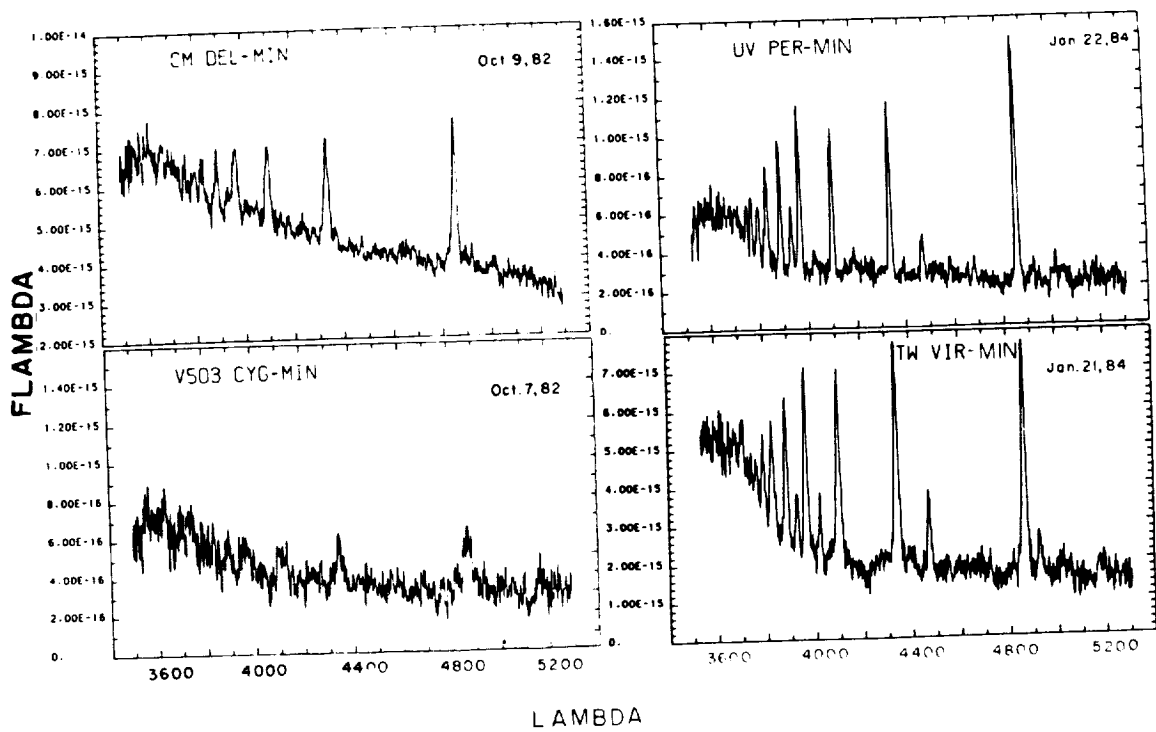
Figure 2-85. Typical quiescent spectra of dwarf novae in the optical (Szkody, 1985a). Almost all the spectra show the Balmer lines and the Balmer jump strongly in emission.
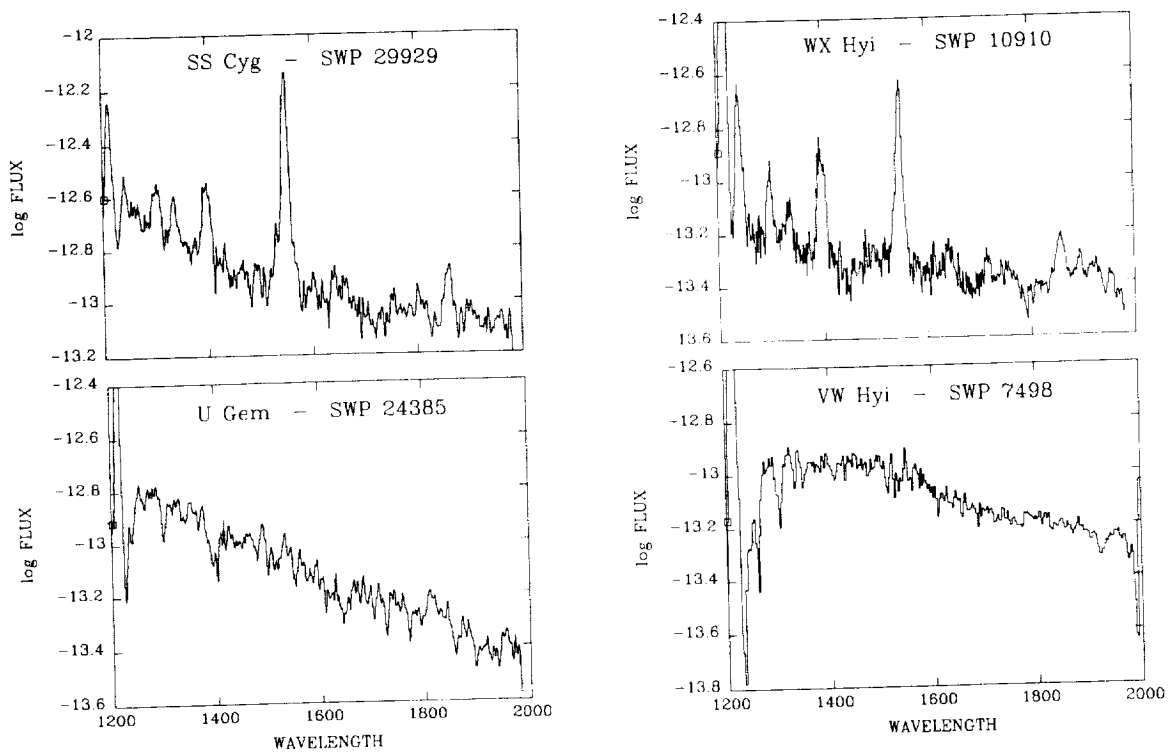

Figure 2-86. Typical quiescent spectra of dwarf novae in the UV. Flux is in erg cm^{-2} sec^{-1} $Å^{-1}$.

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Williams (1983) published equivalent widths and line widths of all measurable lines for a sample of 153 spectra of novae, dwarf novae, recurrent novae, and nova-like stars. Comparing values for various types of cataclysmic variables, it turns out that the equivalent widths of the Balmer lines are statistically significantly larger for dwarf novae and nova-like stars than for novae. On the average, they are also larger for dwarf novae than for nova-like stars, but the difference is small enough to not be a distinguishing characteristic. No significant difference appears to exist between the equivalent widths and line widths of the various sub-classes of dwarf novae and nova-like stars. While the ratios of the equivalent widths of $H\beta/H\gamma$ are approximately the same for all dwarf novae and nova-like stars, $H\beta$ often is of comparable strength to, or even stronger than $H\alpha$ in dwarf novae, whereas $H\alpha$ is generally the stronger line in nova-like stars. The Ratio of $H\alpha/HeII$ (4686 Å) is on the order of one for novae, and is very much larger than this for dwarf novae and nova-like stars. The line wings in all cataclysmic variables can extend to as much as 2000 km/s away from the line center. In novae, the full line widths at half intensity are statistically smaller than in dwarf novae and nova-like objects, being some 500 to 600 km/sec and some 700 to 800 km/sec, respectively. In all cases, however, the scatter between different objects of the same class is very large (see also chapter 6.III.A, Table 6.6, and Figures 6.14a, b, c, d).

In addition to the emission line spectrum, a cool absorption spectrum, normally of spectral type G5V or later, is visible in some objects. Provided the systems are bright enough at minimum light level, this cool spectrum normally is seen in the optical in objects with orbital periods in excess of some 6 hours, but at close inspection, and in the infrared, it also is seen at much shorter periods.

Quiescent dwarf novae usually also exhibit a strong emission line spectrum of all the resonance lines in the UV which can be seen by IUE, frequently with the exception of N V 1240 Å; moreover, He II 1640 Å is usually also seen. As in the optical, normally the line width is on the order of several hundred km/sec Doppler velocity. Only few objects, like U Gem, Z Cha, CN Ori, and TY Psc, instead show a weak absorption spectrum consisting of also mainly the resonance lines. A sample of representative UV spectra of dwarf novae during the minimum state is given in Figure 2-86. There is no apparent relation between the appearance of the UV spectrum (emission or absorption lines) and the optical spectrum, nor is there any relation to any sub-classes of dwarf novae. Also, independent of what the UV spectrum at shorter wavelengths looks like, strong emission in the Mg II doublet (2800 Å) is present in many objects.

In general, the quiescent spectrum of each dwarf nova is very characteristic for each system and is repeated in fair detail after each outburst.

III.B.1.b. THE HOT SPECTRUM

ABSTRACT: No conclusive information about orbital spectral changes in the UV is available. In the optical, usually all lines undergo profile changes on orbital time scales; in particular many of these lines are weakened during photometric eclipse. In some objects the changes seem to be unrelated to orbital changes.

related photometric changes: 35

nova-like stars: 99, 107, 117, 119, 122, 124, 134, 141

interpretation: 192, 200

No general changes in the appearance of the quiescence spectra of any dwarf nova could be found in the UV during all the time IUE has been working. The only long-term changes that have been detected so far are slight decreases in the UV line fluxes from VW Hyi and WX Hyi (sufficiently accurate data are not available for other systems) between successive outbursts (Hassall et al, 1985; Verbunt et al, 1986).
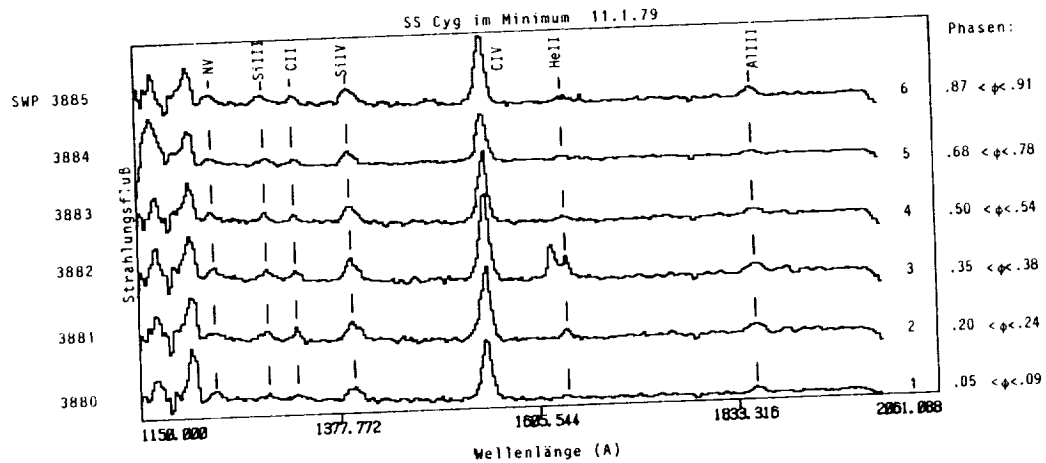
Figure 2-87. Changes of the UV flux on orbital time-scales in SS Cyg during quiescence. It is not clear whether the changes are related to the orbital revolution or not (la Dous, 1982).
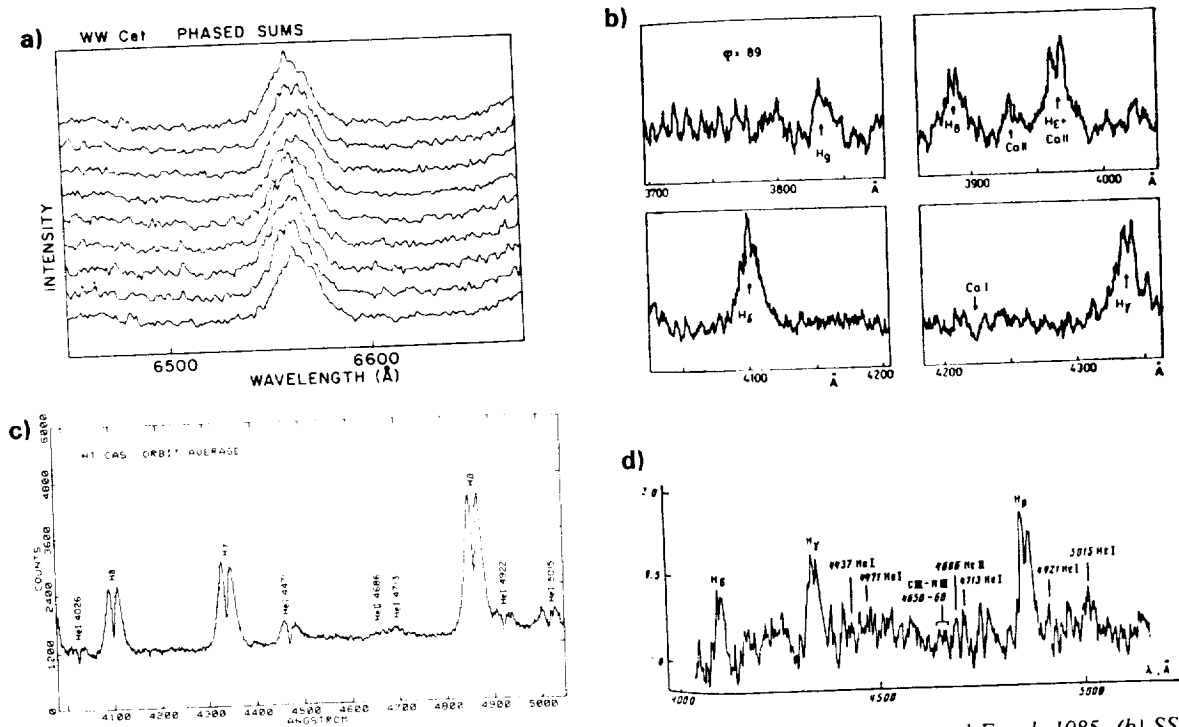

Figure 2-88. Optical emission line profiles in dwarf novae: (a) WW Cet: Thorstensen and Freed, 1985, (b) SS Cyg: Giovannelli et al, 1983, (c) HT Cas: Young et al, 1981b, (d) RZ Sge: Voikhanskaya and Nazarenko, 1984, (e) Z Cha, Marsh et al, 1987. (See text for discussion.)

Most dwarf novae are too faint in quiescence for any orbital phase-resolved spectroscopy in the UV to be possible, not even in the low resolution mode of IUE, since exposure times are still typically on the order of the orbital period. Two exceptions are SS Cyg and U Gem. In both cases some marginal variability of the line profiles and strengths is visible, but it is not clearly related to orbital variations (Figure 2-87). No radial velocity measurements are possible with IUE in the low dispersion mode, nor is the wavelength resolution good enough for line profiles to be investigated in detail.
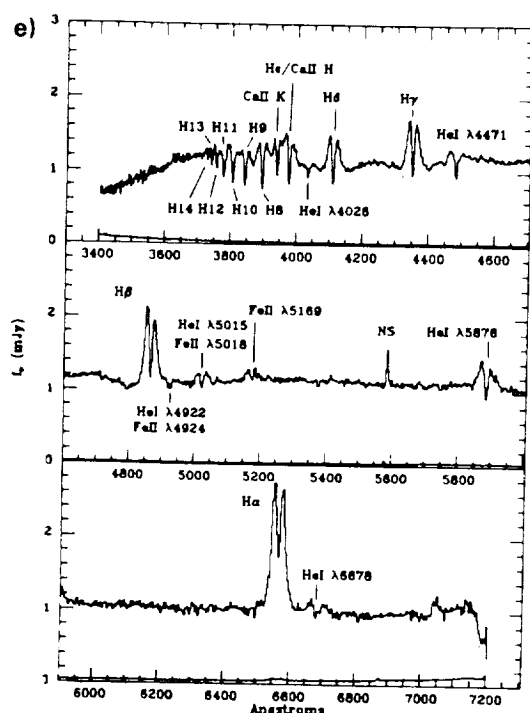
Figure 2-88e.

Figure 2-89. Orbital line profile variations in U Gem (Stover, 1981a). Phase zero is at mid-eclipse.

As mentioned already, the optical emission lines (Balmer lines and He II) often exhibit a double-peaked structure when observed at sufficiently high spectral resolution. Many objects* also have single-peaked lines when observed at high resolution (Figure 2-88a), but still the structure of the profiles is extremely complicated and by no means smooth. In other cases (Figure 2-88b), some of the Balmer lines are clearly double peaked; others are not, or are so only at certain orbital phases. There is a general tendency for the higher members of the Balmer series to have more complex profiles than the lower ones. When a clear double-peaked structure is present, the relative depth of the central dip in most objects increases with increasing quantum number (Figure 2-88c); in some, like RZ Sge or V436 Cen it decreases

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*That most objects are discussed extensively in the literature have doubl-peaked profiles must be regarded as a selection effect, namely which objects astronomers choose to observe. Objects with a double-peaked structure tend to have high inclination angles which allow for a relatively easy determination of the system parameters; consequently they are observed with high priority.
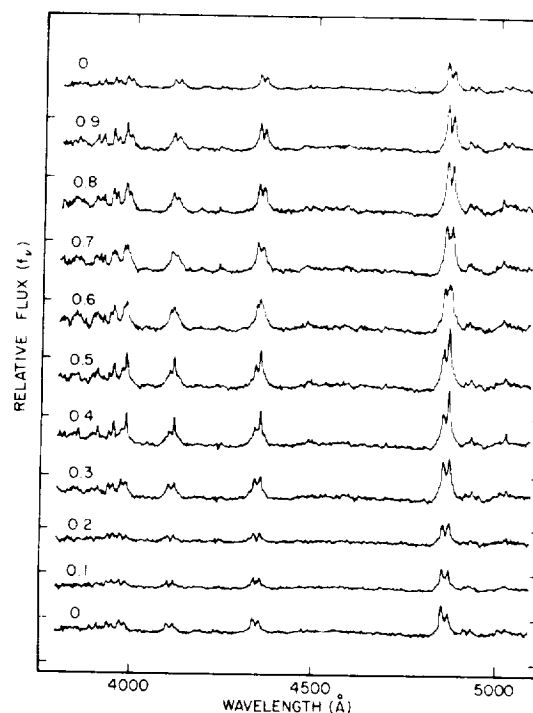
(Figure 2-88d). In many objects, the separation between the two emission peaks of the hydrogen lines, measured in Doppler velocities, increases with increasing quantum number (e.g., Schoembs and Hartmann, 1983). In OY Car and Z Cha the absorption is seen to clearly drop below the continuum level in the higher Balmer lines, from $H\gamma$ on (Figure 2-88e). In Z Cha the emission peaks even completely disappear for $H\epsilon$ and higher members of the series, so that this object emits a combination of an emission and an absorption spectrum in quiescence in the optical. In Z Cha, OY Car, and possibly also in HL CMa during the quiescent state, the strong hydrogen emission lines from $H\beta$ on are placed in very wide, shallow absorption features (Figure 2-88e).

All the lines usually are subject to profile changes with the orbital cycle. Whether, or to what extent, these variations are a stable pattern over long time-scales, and whether the source of the emissions undergoes changes are unknown; all investigations so far only covered, at best, just a few orbital cycles which were not
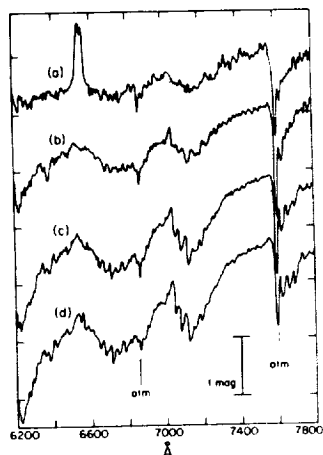
Figure 2-90b. IR spectrum of U Gem (distribution a; distributions b - d are of M dwarfs for comparison) (Wade, 1979). In this system the secondary spectrum is clearly visible at IR wavelengths.
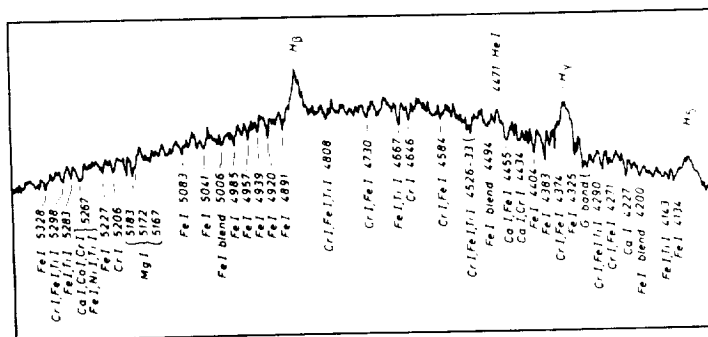

Figure 2-90a. Optical spectrum of BV Cen during quiescence (Vogt, 1980b). The absorption spectrum of the cool companion is well visible at optical wavelengths.

separated by longer time intervals. However, the strength and nature of these changes seems to become more pronounced with increasing inclination angle; i.e., changes become stronger when a hump or even an eclipse is present. In eclipsing dwarf novae there normally are no dramatic orbital changes in the appearance of the line profiles outside eclipse, but emission line fluxes are appreciably reduced only at times when a strong orbital hump is seen. During eclipse, however, the continuum flux as well as the lines are strongly reduced; the line profiles undergo dramatic changes showing clearly how first the blue and then the red wings of the lines are being eclipsed (Figure 2-89). During all these kinds of changes the width of the line wings is hardly affected. Photometrically, EM Cyg is an extremely variable, quickly, erratically changing object, showing rapid flickering and a shallow eclipse which is highly variable in both shape and depth (Stover et al, 1981). The behavior of the emission lines seems to follow this general characteristic, line profiles and strengths are extremely variable on time-scales at least as short as the orbital period (some 7 hours), being single-peaked, double peaked, or even more complex; but no correlation with the orbital phase can be detected. A similarly chaotic behavior is reported for the also

photometrically very active star BV Cen (Vogt and Breysacher, 1980b).

III.B.1.c. THE LATE ABSORPTION SPECTRUM

ABSTRACT: At IR wavelengths and in systems with long orbital periods at wavelengths longward of some 6000 Å, the absorption spectrum of a cool main sequence star becomes visible.

related photometric observations: 39

nova-like stars: 102, 109, 115, 122, 139

interpretation: 153, 194

In many of the dwarf novae with long orbital periods, the absorption spectrum of a cool star has been detected, in addition to the emission spectrum, in the optical and, more often, in the IR (Figure 2-90a). The spectral type usually is G5 or later, approximately that of a cool main sequence star (Figure 2-90b). The visibility of the secondary spectrum varies inversely with the continuum flux: it is easily visible during quiescence when the continuous flux of the hot component is low, and it essentially disappears during outburst. No variation could be detected in these secondary spectra except for that due to orbital changes. The orbital changes usually only consist of changes in the radial velocity. In RU Peg does the luminosity class of the secondary change from spectral type III at upper conjunction (red star behind) to spectral type V at right angles to this (Kraft, 1962b),
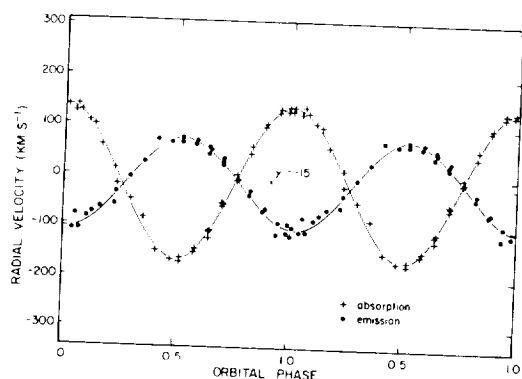
78

Figure 2-91. *Radial velocity changes of SS Cyg during quiescence (Stover et al, 1980). The velocities of the Balmer emissions and the cool absorptions are out of phase by not quite 180°.*

suggesting that the side of the secondary star facing the white dwarf is less dense due to reduced gravity around L_1.

III.B.1.d. RADIAL VELOCITY CHANGES

ABSTRACT: *The radial velocity curves of both emission and (cool) absorption lines have the same periods as the hump/eclipse light curves. Emission and absorption spectra are out of phase by about 180°.*

related photometric changes: 35

nova-like stars: 101, 107, 115, 119, 122, 134, 142

interpretation: 151, 156

The emission lines and, to the extent measureable, the absorption lines undergo periodic changes in their radial velocities.* In almost all dwarf novae, the spectroscopic periods are identical with the photometric periods**, determined from eclipse features or humps, within the limits of accuracy. Emission and absorption lines are out of phase by almost

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*There are considerable difficulties connected with measuring radial velocities in cataclysmic variables, which will be discussed in chapter 4.II.C.1. There is no very basic difference, however, between radial velocities derived from either of the emission peaks, the central absorption, or the line wings, even though it is not clear exactly what physical property is being measured.
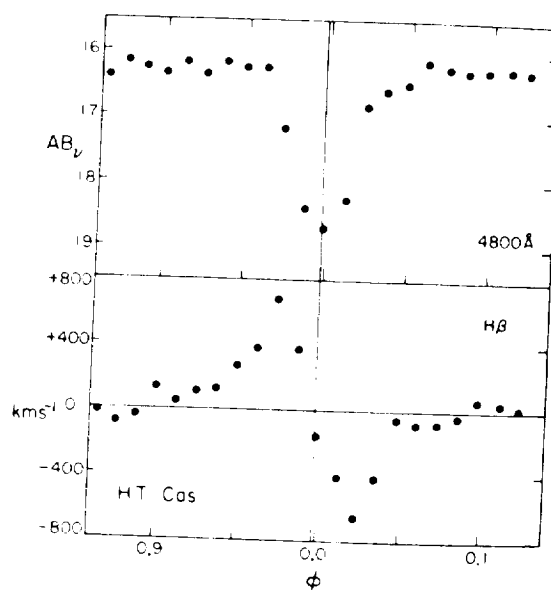

Figure 2-92. *Radial velocity changes in HT Cas through eclipse (Young et al, 1981b).*

(not quite!) 180° (Figure 2-91): there is a phase lag of typically 5° to 10° of the emission with respect to the absorption in all objects that have been investigated in sufficient detail so far; the exact angle varies from one object to another but seems to be stable for any given system (e.g., Kraft et al, 1969). The K-amplitude is typically on the order of 50 to 200 km/sec. The phase of maximum emission-line velocity is on the rising branch of the hump, so eclipses have phases of 0.2 to 0.3 with respect to this.

As mentioned earlier, very dramatic changes in the emission line profiles occur during eclipse (Figure 2-89). The radial velocity changes of $H\beta$ through eclipse of HT Cas are shown in Figure 2-92: within only five minutes the line velocity changes from +700 km/sec to -700 km/sec, centered at phase 0.998. Young et al, (1981b) call this the *Z-wave* for its resemblance to this symbol.

**In CN Ori several different photometric periods have been measured at different times, of which it is not clear which is the orbital period. No reliable spectroscopic period is available as yet (Mantel et al, 1988).
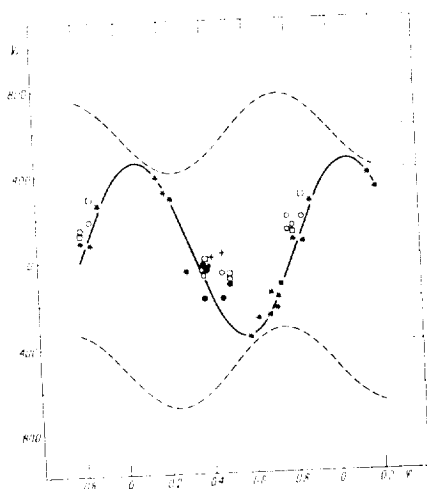
Figure 2-93. Radial velocity changes of the S-wave in U Gem (Smak, 1976). The various symbols represent radial velocity measurements in different lines; the solid line is the solution for He I 4471 Å; the dotted line represents radial velocity measurements for the red and blue wings of Hγ, respectively.

III.B.1.e. THE S-WAVE

ABSTRACT: The particular orbital changes connected with profiles of double-peaked emission lines often are referred to as "S-wave."

nova-like stars: 102, 110, 122, 124, 135, 142

Inspecting Figure 2-89, one realizes that the relative strength of the red and blue peaks of the hydrogen lines varies systematically over the orbital cycle, irrespective of whether or not the system is being eclipsed. Similar effects are seen in other lines (He I, Ca II), and in other objects. There are still other objects, however, like OY Car, Z Cha, and others, in which no such effects could be found despite an intensive search. This effect of changing profiles is usually referred to as S-wave. This often is understood to be an additional third emission component which wanders independently between the two wings of the line. Smak (1976) determined its radial velocity from the hydrogen lines of U Gem, but also from He I 4471 Å and Ca II K, both of which seem to originate entirely in the source of the S-wave emission in U Gem (Figure 2-93). It should be

noted that the velocity amplitude of the S-wave is more than twice that of the wings, and that there is a phase shift of about 100° in U Gem, slightly different for different lines, between the S-wave and the main emission of the hydrogen lines. A phase shift of about -80° is seen in HT Cas (Young et al, 1981b); and the radial velocity curve of the main component and the S-wave in T Leo are almost anti-correlated (Shafter and Szkody, 1984). There is no way to explain the almost random behavior of the profiles in EM Cyg with some kind of S-wave.

III.B.1.f. UV FLARES

nova-like stars: 117

Walker and Chincarini (1968) and Walker (1981) report the appearance of "UV-flares" in the spectra of SS Cyg during quiescence. These are temporarily (on the order of some tens of minutes) increased fluxes in mostly the Balmer lines, but He I and Ca II can also be affected at times, and to a small degree the continuum flux. Similar flares have been detected in the nova-like stars RW Tri and AE Aqr (sometimes also classified as dwarf novae), however, with a much lower frequency than in SS Cyg (Walker, 1981).

GENERAL INTERPRETATION: The generally observable emission line spectra in quiescent dwarf novae are ascribed to optically thin disc areas; absorption spectra in the UV, as seen in a few systems, may indicate that the inner accretion disc is basically optically thick. The cool absorption spectrum in the (optical and) infrared is ascribed to the secondary star. — Periodic changes in radial velocities and line profiles are ascribed to orbital changes, and periodic random profile changes to inhomogeneities in the brightness distribution of the accretion disc. The double-peaked line profiles in high-inclination systems are believed to be due to disc rotation. In those cases where the dip between both peaks reaches below the continuum level, the white dwarf absorptions are believed to influence the line flux significantly. The phase shift between the radial velocities determined from emission and absorption is an effect of binarity, as the emission lines originate in the disc and the absorption spectrum in the secondary star.

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OBSERVATIONAL CONSTRAINTS TO
MODELS

- The high-inclination systems in particular exhibit double-peaked emission line profiles. (See 202.)

- In many systems, the emission line profiles undergo characteristic changes during the orbital cycle.

- In many systems, an "S-wave" is seen to move between the two peaks of the emission lines in phase with the orbital cycle.

- A relation is observed to exist between the line width and the equivalent width of the hydrogen lines and the sub-types of cataclysmic variables.

- In some objects, the Balmer emission lines are placed in broad absorption shells. (See 151, 194.)

III.B.2. SPECTRA DURING THE OUTBURST STATE

III.B.2.a. GROSS APPEARANCE

During outburst, there appears an absorption spectrum of the resonance lines and of He II 1640 Å in the UV and of mostly the Balmer lines in the optical (Figure 2-94, 2-95), where He II, and C III-N III may be present as well. At maximum and during decline, the optical lines sometimes have emission cores. The UV resonance lines often display strong asymmetric blue-shifted line profiles or P Cygni profiles. The late absorption spectrum, which might have been seen in quiescence, disappears due to the increased hot continuum flux during outburst. In both the appearance and the variability of their spectra, there is no difference between the sub-classes of dwarf novae (which were defined on grounds of photometric behavior).

III.B.2.b. THE RISE PHASE

ABSTRACT: During rise the emission lines gradually sink into broad absorption shells. The cool absorption spectrum can hardly be detected any longer.

Until the very onset of an outburst, no changes of the line profiles in excess of normal variations could be observed in SS Cyg during the quiescent state (Clarke et al, 1984, and Figure 2-96). During the very early rise in SS Cyg, the flux in the Balmer emission lines remained constant, an observation confirmed by Walker and Chincarini (1968) for a different outburst of SS Cyg. As the continuum level increased, however, the equivalent widths decreased slightly, and for a while the spectrum appeared almost featureless. When the steep rise to maximum began, the emission line flux decreased rapidly and became undetectable; at the same time strong Balmer absorption lines appeared. Also, at late rise to an outburst in SS Cyg as well as in many other systems, the Balmer jump as well as the Balmer absorption lines can, for a short while, become much stronger than during the remainder of the outburst. Also during the rise in SS Cyg (Walker and Chincarini, 1968), the Ca II K line, which is clearly in emission during quiescence, was seen to go into absorption and to split into two peak components which are separated from each other by about 800 km/sec Doppler velocity, in contrast to some 300 km/sec separation of the tiny emission peaks in quiescence. The He I emission lines largely followed the early hydrogen emissions in their development during the rise and were undetectable during most of the bright state. The He II emission line at 4686 Å and the C III - N III blend at 4650 Å (which are only marginally visible, if at all, in quiescent dwarf novae) basically followed the development of the continuum flux during outbursts: they became strongly visible at late rise, faded during decline, and disappeared again at some late stage of decline. No extensive coverage is available for any other dwarf nova; but the information that is available does not contradict the assumption that this kind of
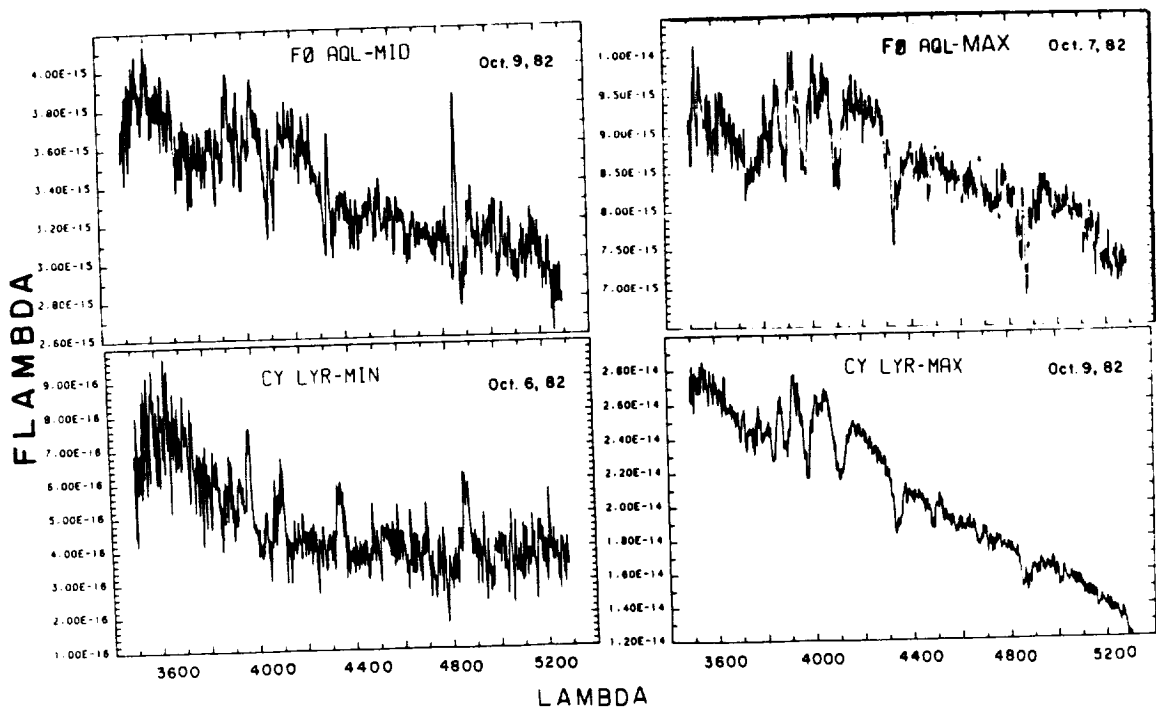
81

Figure 2-94. Typical spectra of dwarf novae during outburst: FO Aql at maximum and decline; CY Lyr at maximum and quiescence (Szkody, 1985a). During outburst the spectra are dominated by strong Balmer absorption lines.
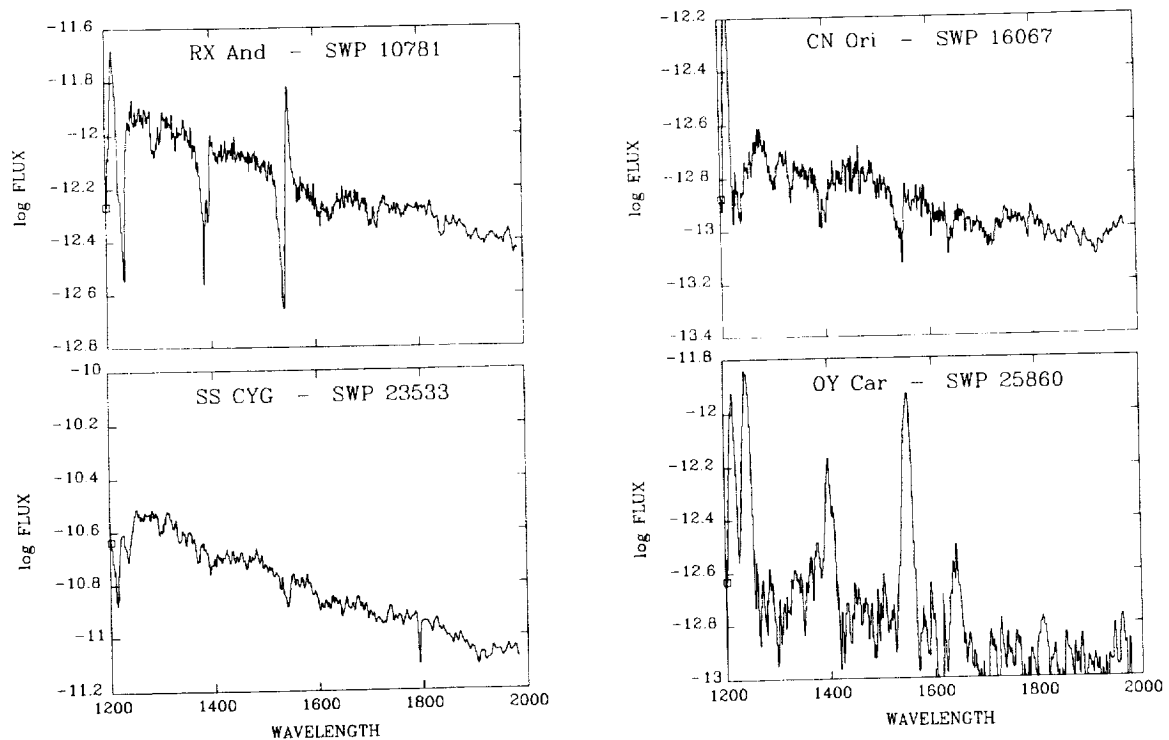

Figure 2-95. Typical UV spectra of dwarf novae during outburst. Flux is in erg $cm^{-2} sec^{-1} \mathring{A}^{-1}$. The spectra are dominated by absorption lines, possibly P Cygni profiles; only double-eclipsing systems show pure emission spectra.
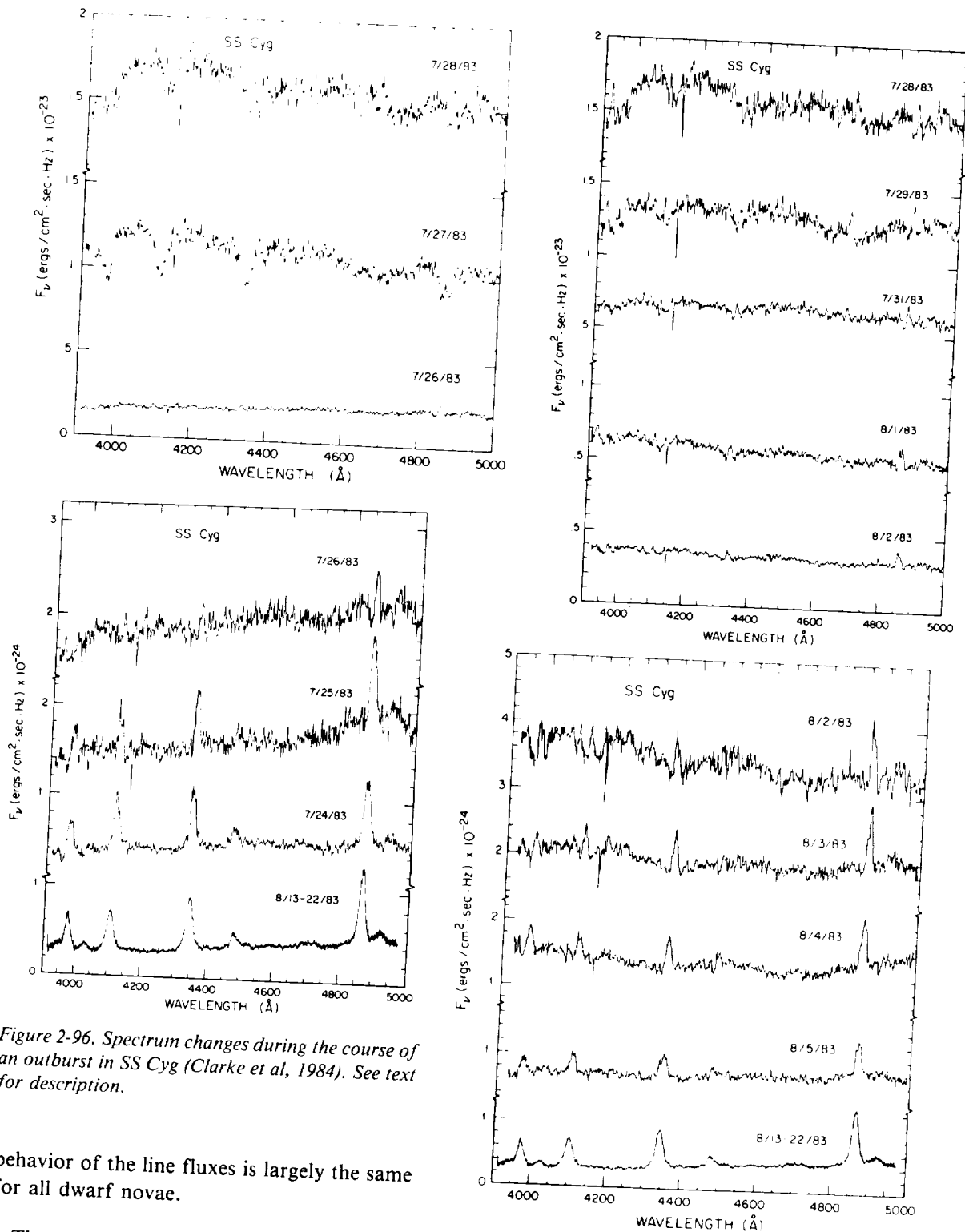
Figure 2-96. Spectrum changes during the course of an outburst in SS Cyg (Clarke et al, 1984). See text for description.

behavior of the line fluxes is largely the same for all dwarf novae.

The absorption line spectrum of the cool component soon disappeared almost completely in the rising continuum flux and could only be reliably detected again just before the

minimum brightness had been reached at the end of the decline. Hessman et al (1984), however, did succeed in observing the secondary spectrum in SS Cyg during outburst.

III.B.2.c. OUTBURST MAXIMUM AND DECLINE

ABSTRACT: At or shortly after maximum light emission cores begin to grow in the absorption lines; during the course of decline gradually the quiescent spectrum is restored.

related photometric observations: 46

interpretation: 192, 194, 200

The usual appearance of the line spectra of dwarf novae in the optical during outburst is that of hydrogen absorption lines the wings of which extend several thousand km/sec Doppler width away from the line center. Relatively narrow emission components of different strength can be present at times, superimposed on these absorptions. Besides these lines, there are usually emissions of the He II and C III-N III, and probably a few other lines. Thus either a pure absorption spectrum (the less common case), or a mixed absorption and emission spectrum can develop (Figure 2-97). The Balmer jump is generally very weak, on the order of 0.1 mag at maximum; it decreases during the course of decline and eventually goes into emission around the time when the quiescent state is reached again. No P Cygni profiles or asymmetric line profiles, which are common in the UV, have been detected in the optical. In one case, in Z Cha during a superoutburst (there are no observations of a normal outburst), there are no broad absorption lines of hydrogen, but rather the Balmer lines of Hα through Hγ appear as pure, double-peaked emission lines (the peak-to-peak separation is clearly less than during quiescence), while the higher series members appear as pure single-peaked absorption lines (Figure 2-98), so the spectrum looks very similar to the quiescence spectrum (Figure 2-88e). Also during superoutburst, OY Car and Z Cha exhibit pure emission spectra in the UV (see below) — both stars show double eclipses during the quiescent state and thus have an inclination angle close to 90°. No basic difference (at any rate, no more dif-ference than is normal between different outbursts) seems to exist between the spectra of outbursts and superoutbursts and of standstills in dwarf novae.

The development of the lines during decline in dwarf novae can be seen from the typical example of SS Cyg in Figure 2-99 (see also Figure 2-96): as the continuum flux fades, the, in the beginning small, Balmer emission cores grow inside the absorption lines while the absorption gradually fades. At all phases the emission is the weaker the higher the quantum number of the Balmer lines. At the brighter stages of the outburst, the hydrogen lines are considerably narrower than those seen during quiescence; they become progressively broader as the decline proceeds. Comparison between the two sets of decline spectra of SS Cyg demonstrates that, though the gross behavior is repeated, the line profiles, as well as the sort of lines visible besides the hydrogen lines, vary from outburst to outburst. Hessman (1986) investigated the profiles of the absorption components of the Hβ and Hγ lines during decline in the SS Cyg, and found that they are practically constant throughout decline.

Schoembs and Vogt (1980) observed VW Hyi spectroscopically during decline from a superoutburst. First there was a pure absorption spectrum near maximum brightness. Around the end of this outburst a faint emission spectrum exhibiting lines of H, He I, and Fe II was observed, which, however, was replaced by an essentially continuous spectrum during the following two nights. The spectra during these two nights stayed featureless, while photometrically large changes of up to 0.5 mag were observed, due to a coincidence of the orbital hump and the superhump. At the very end of decline of VW Hyi from a normal outburst, Schwarzenberg-Czerny et al (1985) observed very dramatic changes in Hα and Hβ on time scales of hours, which, however, were not related to the orbital phase (Figure 2-100).
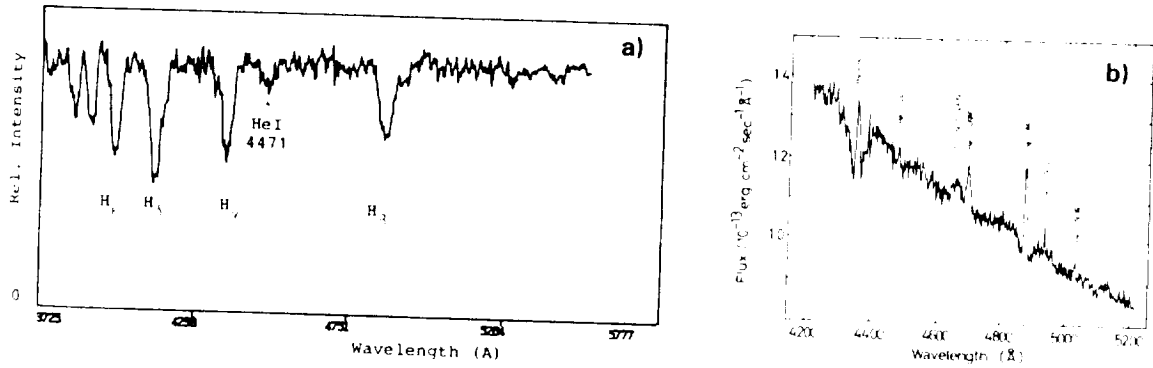
Figure 2-97. Outburst spectra of dwarf novae: a) TU Men (Stolz and Schoembs, 1984) shows pure absorption profiles; b) the more normal case is that emissions are placed in the cores of the absorptions, as e.g., in HL CMa (Wargau et al, 1983a).
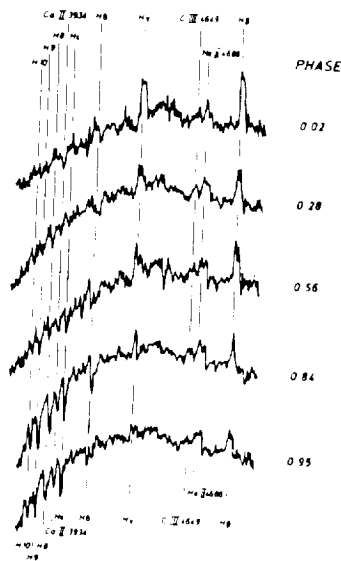

Figure 2-98. Optical spectrum of Z Cha during superoutburst (Vogt, 1982a). The spectrum is hardly any different from the quiescent spectrum (See Figure 2-88e).
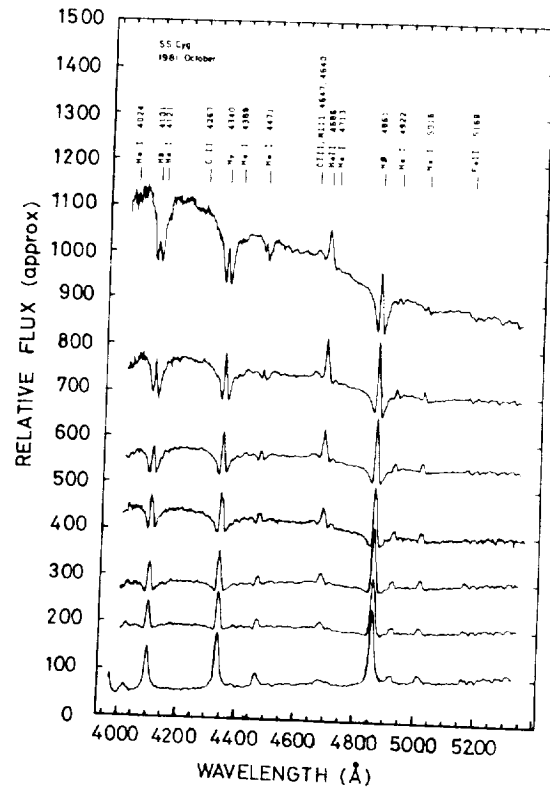

Figure 2-99. Development of optical lines in SS Cyg during decline from outburst (Hessman et al, 1984). Emission cores gradually grow in the centers of the absorption lines.
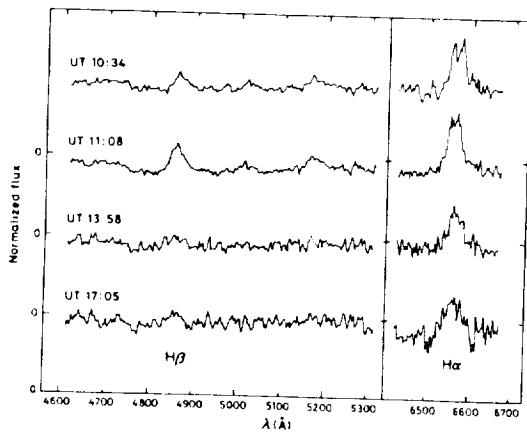
Figure 2-100. Line profile changes in VW Hyi at late decline (Schwarzenberg-Czerny et al, 1985).

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For a few objects, phase resolved spectra during outburst or superoutburst have been taken. In TU Men (Stolz and Schoembs, 1984), which shows a pure absorption spectrum without emission cores of the Balmer lines during the plateau of superoutburst, variability of the line profiles during the orbital cycle can be seen. However, only for the absorption of He I 4471 Å might there be a correlation with the orbital phase, in that the absorption is enhanced near the upper conjunction of the secondary (near phase 0.5). In HL CMa (Wargau et al, 1983), the emission cores of the hydrogen lines are very variable on time scales of a fraction of an orbital period, but no relation with the orbital phase can be detected. In Z Cha, on the plateau of the superoutburst during eclipse, the emission lines of H are significantly stronger and the absorption lines significantly weaker than outside eclipse, unlike in quiescence where there were no strong variations of the line profiles with orbital phase; and during the remainder of the orbital cycle line fluxes decrease or increase, respectively (Vogt, 1982a, and Figure 2-98). In SS Cyg, on the other hand, during an outburst in October 1981 the narrow Balmer emission components showed a clear S-wave that normally only is seen in quiescent spectra of dwarf novae. In EK TrA it was possible to separate the contribution of the superhump from the radiation emitted by the rest of the system (Hassall, 1985): this revealed an almost featureless continuous spectrum which contains significant flux only shortward of some 4200 Å in the optical.

III.B.2.d. RADIAL VELOCITIES DURING OUTBURST

ABSTRACT: Radial velocities during outburst are roughly the same as during quiescence, K- and γ-velocities can be different. In TU Men and Z Cha, the γ-velocity seems to be a function of both the orbital and the superhump phase.

see also: 91

nova-like stars: 101, 107, 115, 119, 122, 134, 142

Radial velocity measurements of outburst spectra and of quiescence spectra yield roughly the same orbital elements, within the limits of error. The most extensive study in this respect was carried out on SS Cyg (Hessman et al, 1984; Hessman, 1986). Radial velocity changes of the wings of the Balmer absorption lines in outburst yield the same K-velocity (K_{out} = 97 ± 6 km/sec, K_{min} = 96 ± 3 km/sec), and also the same shape of the curve, as the wings of the Balmer emission lines seen during quiescence. The wings of the emission cores in outburst, however, have a K-velocity (107 ± 3 km/sec) some 10 km/sec larger than the quiescent emission lines. The only remarkable difference is that the γ-velocity, which was found to be 0 ± 4 km/sec at outburst for the absorption components, was -23 ± 2 km/sec at quiescence. Also the phase shift between Balmer emissions and the absorption spectrum of the secondary star was 190° ± 2° in quiescence, while during outburst it was seen to be 174° ± 4° for the hydrogen absorption wings. The wings of the emission cores, however, were shifted by 199° ± 2° with respect to the late component. The γ-velocities agree within the indicated limits. At different nights during decline from the outburst no substantial changes in the radial velocities could be found.

Again in the well-studied system SS Cyg, the radial velocities of the He II line at 4688 Å are different when measured from the base of the line at continuum level or from the peak (Figure 2-101): The K-velocity and the γ-velocity are 118 ± 6 and −60 ± 4 km/sec, respectively, for the line base, and 52 ± 7 and −47 ± 5 km/sec for the peak, i.e., considerably different for both components of the Balmer lines and, as will be seen immediately, also from the secondary spectrum. The phase shift with respect to the latter is +216° ± 3° and 217° ± 9°, respectively, for line base and peak — again different from anything else that has been measured.
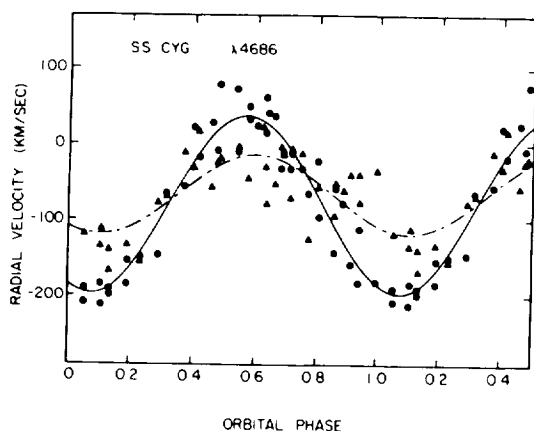
Figure 2-101. Radial velocities of the He II 4686 Å line as measured from the line base (circles) and from the peak (triangles) (Hessman, 1986). See text for discussion.
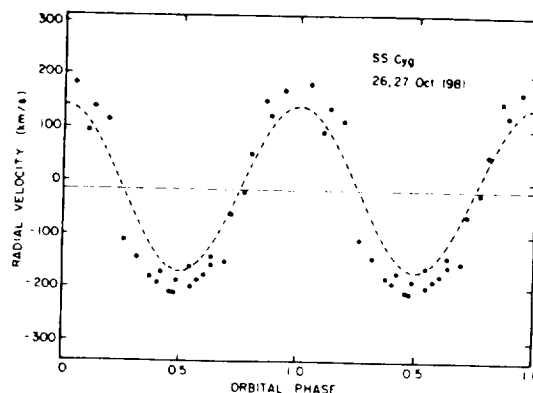

Figure 2-102a. Radial velocity curve of the secondary absorption spectrum in SS Cyg during outburst (dots); the curve as determined during quiescence is indicated as a dashed line (Hessman et al, 1984).

While detailed interpretations of these results certainly will involve a good deal of modeling, it is clear from the above results that many different light sources contribute to the integrated flux of the system, and to various degrees of importance at different brightness levels. It also is clear that neither the K-velocity nor the γ-velocity should reasonably be ascribed exclusively to dynamic properties of the system (systemic motion, orbital motion), but that changes in temperature and luminosity distribution are involved as well, and that this effect can be quite different for different lines, as they obviously originate in different parts of the system (several aspects of this will be discussed in Chapters 4.II and 4.IV).

In SS Cyg the absorption spectrum of the late component has been measured during outburst, and radial velocity curves could be derived (Hessman et al, 1984). On all nights of the decline, the phase shift with respect to the late absorption spectrum seen in quiescence was zero within the error limits, but the K-velocity showed a systematic development (Figure 2-102): it was considerably larger than during quiescence at the peak of the outburst, and the difference gradually decreased to zero as the
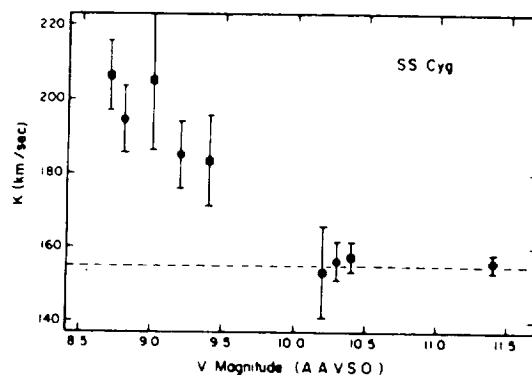

Figure 2-102b. The K-amplitude of the secondary absorption spectrum gradually decreases as the optical flux declines (Hessman et al, 1984). See text for discussion.

system faded. The γ-velocity was somewhat lower at outburst maximum than during quiescence (−21 ± 2 km/sec vs. −15 ± 2 km/sec), and was more than twice the quiescent value (−35 ± 4 km/sec) at late decline.

In Z Cha and TU Men, both observed spectroscopically at the plateau of a superoutburst, the γ-velocity of the hydrogen absorption lines, (not those of the hydrogen emission lines in Z Cha!) were seen to vary from night to night (Vogt, 1982a; Stolz and Schoembs, 1984). The values measured in TU Men are compatible

III.B.2.e. DEVELOPMENT OF LINES IN THE ULTRAVIOLET

ABSTRACT: In slow gradual changes from quiescent to outburst spectrum and back, the UV follows the same general pattern as the optical. Unlike the continuous flux distribution, the appearance of the line spectrum of one object varies slightly from one outburst to another. While most systems exhibit absorption spectra during the outburst, possibly with P Cygni emission components in C IV, double eclipsing systems show pure emission spectra.

interpretation: 194, 206

In some dwarf novae the rise phase has been observed in the UV. WX Hyi has a spectrum exhibiting strong emission lines in quiescence. At early rise the line fluxes increase slightly as the continuum level rises (Figure 2-103). At some time during rise the whole character changes considerably, since at late rise the spectrum resembles very much that of seen at maximum light (Hassall et al, 1983): strong P Cygni profiles are visible in the C IV and Si IV lines. Two nights later, at the peak of the supermaximum (normal outburst and superoutburst exhibit similar spectra), the emission component of C IV had strongly decreased, that of Si IV had disappeared altogether, and the absorption components of both lines had increased strongly in strength, while the terminal velocities had remained approximately the same. Early rise has also been observed in VW Hyi (Verbunt et al, 1986). In quiescence the only lines seen are C IV in emission and Si III in absorption. At early rise Si III becomes stronger, while C IV turns into absorption, and He II appears as a very strong absorption line. A late rise spectrum of AH Her (Verbunt et al, 1984), as in the case of WX Hyi, looks like a maximum spectrum with the lines absorbing just a little less flux than at maximum.

Aside from rise, the outburst spectra of dwarf novae in the UV are all characterized by very strong absorption lines of the resonance lines visible in the UV range, and in the EUV by the Lyman series (Polidan and Holberg, 1984, and Figure 2-73b). Normally C IV has a strong asymmetric absorption profile with the blue wings extending some 4000 to 6000 km/sec Doppler velocity (depending on the object and the particular outburst observed) away from the line center; and often this line even has a P Cygni profile, but the emission component typically only extends some 2000 km/sec redward. In some spectra, Si IV and N V also show marginal P Cygni emission components in addition to asymmetric absorptions (Figure 2-95). Whenever P Cygni profiles are observed in some outbursting dwarf novae, the strength of the absorption component in absolute terms is considerably larger than that of the emission component except for the rise. There are objects like VW Hyi, however, in which all lines are usually symmetric, and only very rarely does C IV show an indication of an asymmetric profile. Only a high resolution spectrum of VW Hyi during a superoutburst revealed that the line centers of the six strong symmetric resonance lines, the doublets of N V, Si IV and C IV, all are shifted shortward by 400 ± 100 km/sec with respect to the rest wavelengths (Verbunt et al, 1984).

The development of the UV lines during late rise and during decline of an outburst is shown in Figure 2-104. Different, but in principle the same, behavior is seen in detail in all other dwarf novae. During the course of decline the lines gradually fade as the continuum fades, without dramatically changing their appearance. The characteristic minimum spectrum only appears at the very end of decline in a smooth transition. It has been found ever again that, although the continuous flux distribution of different outbursts and also of standstills (these spectra are not basically different from those observed during normal outbursts) show the same wavelength dependence at the same optical brightness in the continuum, the line profiles do by no means follow this pattern: at the same brightness level in different outbursts absorption as well as emission line
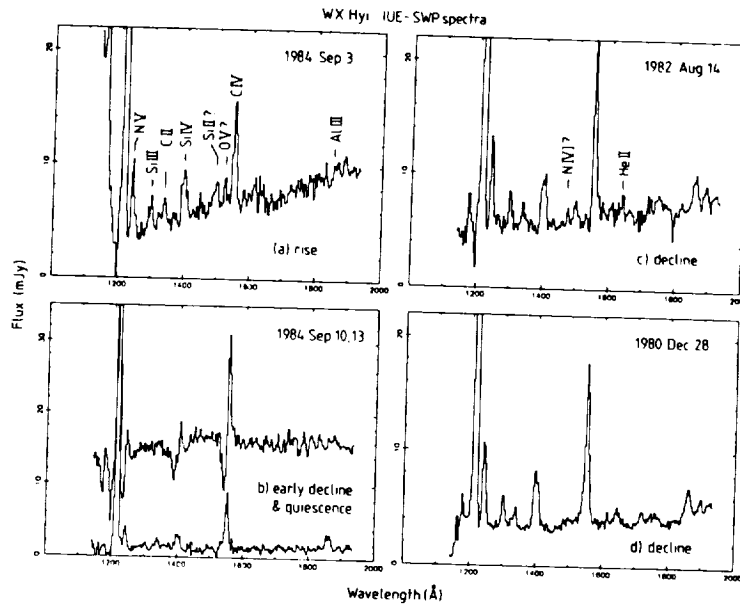
Figure 2-103. Development of the UV spectrum of VW Hyi during the course of an outburst (Hassall et al, 1985).
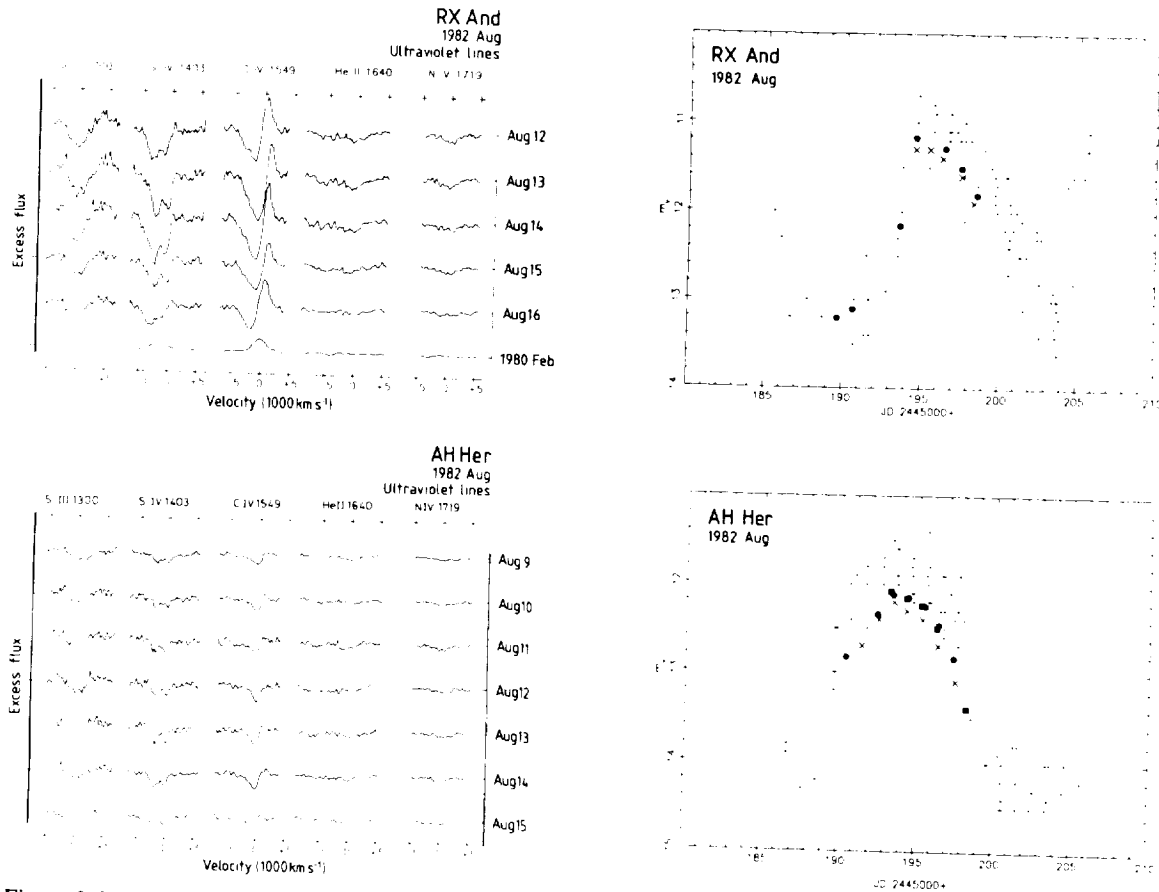

Figure 2-104. Development of UV lines in RX And and AH Her during the course of an outburst; the outburst light curves are given for comparison (Verbunt et al, 1984). Small dots are optical observations by the AAVSO, large dots are SAAO observations in the Johnson V filter, and crosses are IUE-FES observations.
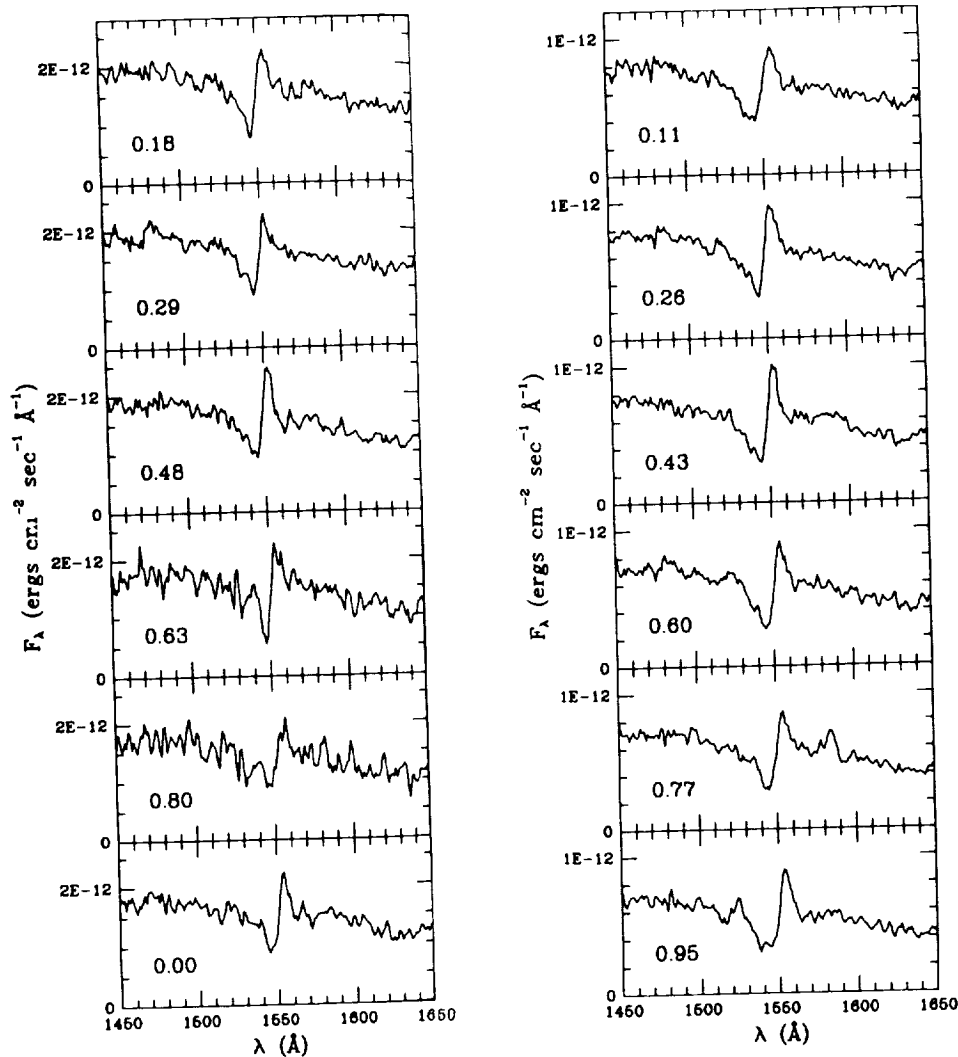
Figure 2-105. Phase-resolved C IV line profiles in Z Cam during outburst (Szkody and Mateo, 1986). The two series were taken two days apart. It appears that although profile changes occur on orbital time-scales, the variations are not directly related to the orbital revolution.
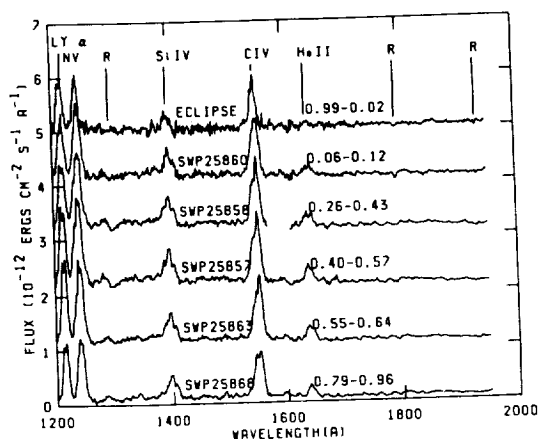

Figure 2-106. Phase-resolved UV spectra of OY Car during a superoutburst (Naylor et al, 1987). For discussion see text.

profiles can look entirely different. Thus for any system the physical state of the continuum source at outburst obviously is characteristic, and the same conditions and their temporal development are found in every outburst. The observed absorption lines thus do not seem to originate together with most of the continuum, reflecting that their source is not as well determined in its physical state. Finally, the emission lines probably originate from an extended region, the exact shape and/or physical state of which is not reproduced in detail from one outburst to another.

Phase-resolved UV spectra of Z Cam on decline from outburst were acquired by Szkody and Mateo (1986). In the C IV profile (Figure 2-105), considerable changes are seen on time-scales on the order of one hour, but no obvious relation to the orbital phase can be detected. The equivalent widths of the resonance lines, however, seem to suggest some vague phase dependence of the absorption components on the maximum absorption coinciding with the optical hump maximum. Appreciable variations of the C IV P Cygni profile with the orbital phase was observed in YZ Cnc (Drew and Verbunt, 1988).

During a superoutburst of the high-inclination (double eclipsing) system OY Car, Naylor et al (1987) got phase-resolved UV spectra of this object (Figure 2-106); in particular they got spectra during the eclipse phase. Unlike most dwarf novae, OY Car exhibits a pure emission line spectrum during (super-)outburst, with the resonance lines of C IV, Si IV, N V, Lyα, and He II being visible. Compared to a "normal" minimum spectrum of a dwarf nova (OY Car itself is too faint at quiescence to be observed with IUE) the lines are unusually broad. The strength of N V 1240 Å is comparable to that of C IV 1550 Å, which is very unusual for a dwarf nova. The C IV line is strongly asymmetric, with a steep strong blue and a somewhat fainter red component. At some phases, there appear two separate emission peaks which are separated by some 10 Å

(the separation of the doublet components is 2.5 Å). All the line profiles are variable during the orbital cycle, but no clear phase relation is evident. Except for Lyα, which is not eclipsed, all other lines are considerably eclipsed at the same time no eclipse is visible at soft X-rays.

III.B.2.f. THE SPECTRAL BEHAVIOR OF WZ SGE

ABSTRACT: Appreciable changes in the appearance of the line spectrum occurred as a consequence of the outburst in 1978, and lasted until very long after the end of the outburst.

related photometric observations: 42, 63

Except for the last outburst in 1978, spectra of WZ Sge have been published for only a few occasions before and after the outburst: Krzeminski and Kraft (1964) describe the spectrum as it appeared several years before the outburst; Voikhanskaya (1983a) obtained spectra both half a year before and two and a half years after the outburst; Gilliland et al (1986) observed WZ Sge six months after the outburst when it had not yet quite returned to its quiescent state. In fact, ten years after the outburst it still keeps declining in brightness at a very small rate (Hassall, private communication). Finally, Brunt (1982) observed the star half a year before and half a year after the outburst.

The emerging picture concerning the spectral appearance of WZ Sge is confusing. All authors agree that WZ Sge exhibits a blue continuum with superimposed double-peaked hydrogen emission lines which are placed in wide absorption troughs (Figure 2-107); but this is about as far as the agreement reaches. The strength of the emission lines is clearly highly variable when spectra taken before and after the outburst are compared. There was no emission in Hα half a year before outburst, while half a year afterward it was very strong. The depth of the minimum between the two line peaks clearly reached far below continuum level for Hβ on towards higher series members half a year after outburst; but at least in Hβ, the minimum was clearly much less deep before as
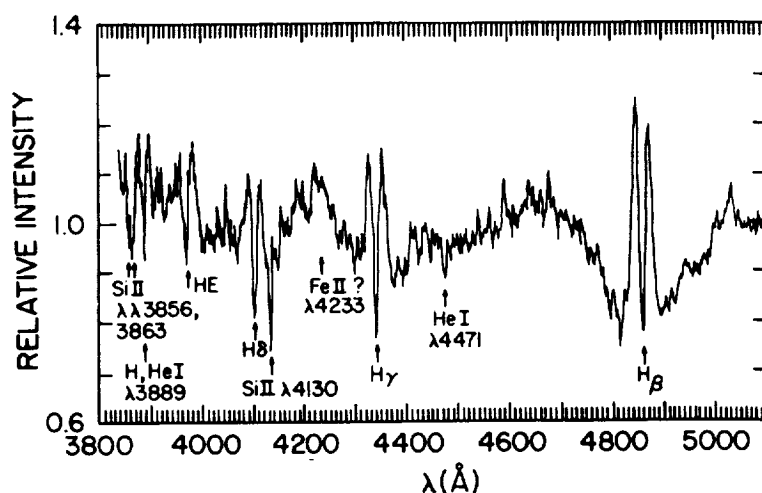
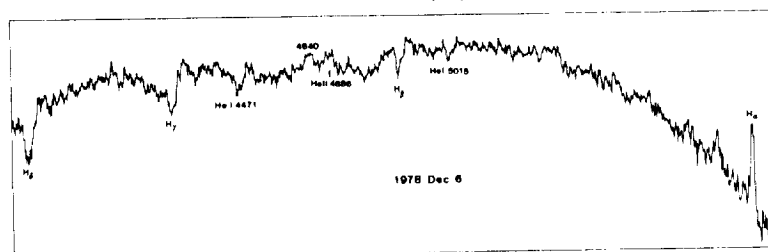*Figure 2-107. Near-quiescence optical spectrum of WZ Sge (Gilliland et al, 1986). See text for discussion.*

Figure 2-108. Optical spectrum of WZ Sge shortly after outburst maximum (Ortolani et al, 1980).
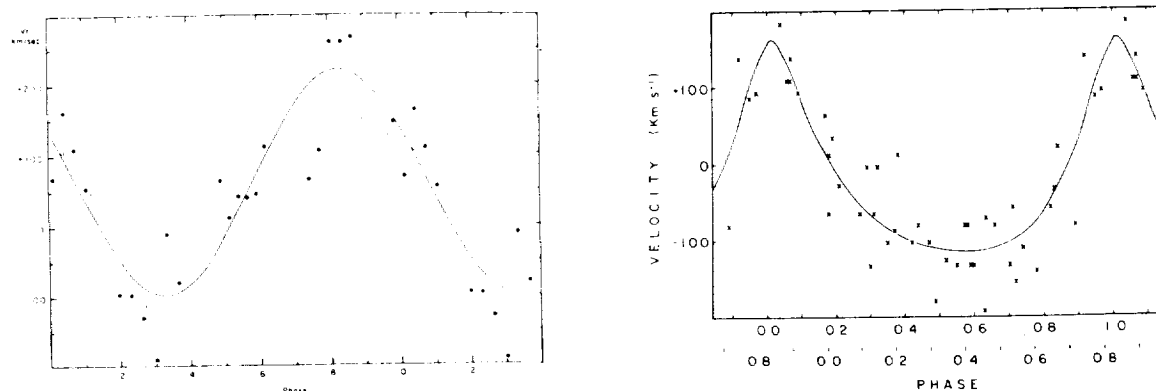

Figure 2-109. Radial velocity curves of WZ Sge on decline from outburst: a:Walker and Bell, 1980: b:z Gilliland and and Kemper, 1980. See text for discussion.

well as long after outburst. A strong S-wave is reported to have been present at times long before outburst, while at other times it was seen to be weak; after outburst it has not been seen to be of any major importance. The separation of the peaks of the Balmer lines decreased from some 1450 km/sec before outburst to some 1370 km/sec afterwards. The radial velocity before the outburst was rather smooth and well in phase with the orbital motion, while after outburst radial velocity variations of both the emission and the absorption components were

rather erratic in shape and amplitude, implying that phase shifts were occurring with respect to the pre-outburst radial velocity curve. Furthermore, a considerably different γ-velocity was determined from the spectra for each of the considered epochs, different even for different lines (Hα, Hβ) and different parts of the same line (emissions, absorptions). It is not clear how the observations can be accommodated within the framework of the Roche model, which also applies to the rather dwarf nova-unlike photometric changes in WZ Sge.
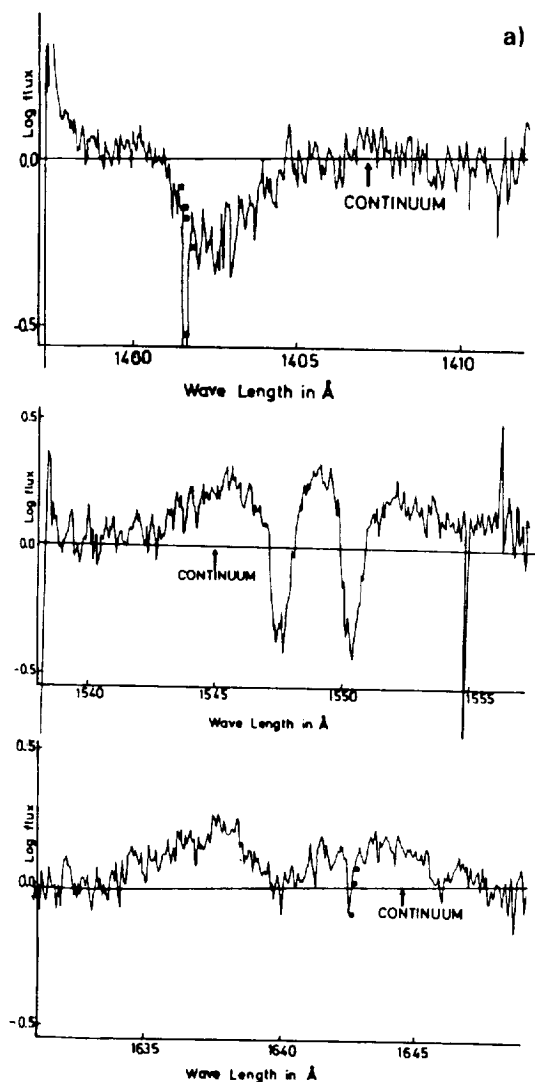
Figure 2-110. UV spectra of WZ Sge during outburst: a: Friedjung, 1981; b: Fabian et al, 1980. See text for discussion.

The first spectrograms of the outbursts were taken by Brosch et al (1980) at the very maximum of the outburst on December 1, 1978. They report Hα and Hβ to have been in emission together with He II 4686 Å and C III - N III 4640 Å, while the higher Balmer lines were in absorption. At maximum light, on December 1.7, Hα could hardly be detected above the continuum, while 24 hours later it was strongly in emission with a clear double-peak structure and a peak separation of about 10 Å, one third of the separation seen at quiescence. The structure of Hβ was similar.
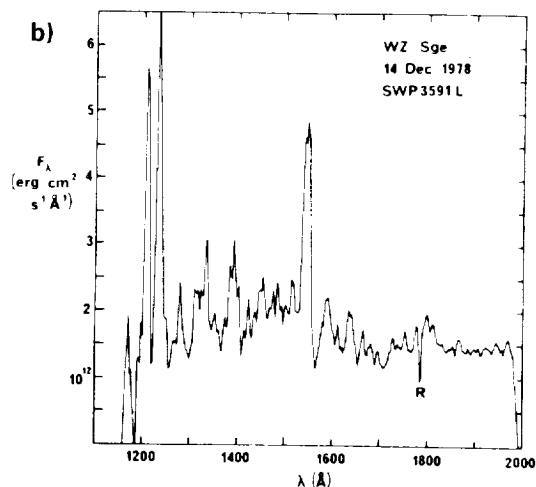
For most of the outburst only Hα (along with He II, C III - N III) was seen in emission, while the other Balmer lines and He I were in absorption (Figure 2-108). The peak separation of Hα was still seen to be 10 Å on December 8. When the next spectrum was taken, on December 20, the double-peaked emission had disappeared, only to return on December 22, but then with a peak separation of some 30 Å, the value observed during quiescent state. One night before this (and only then), Hβ, which for most of the outburst was seen in absorption, showed clear inverse P Cygni profiles, the emission component of which varied with the orbital phase (Gilliland and Kemper, 1980).

On some occasions during the outburst, radial velocity measurements were undertaken. For December 9 and 10 a sine curve gives an acceptable fit to the data points when they are plotted on the pre-outburst phasing (Figure 2-109a); the shape of the curve for December 14 has changed considerably (Figure 2.109b), so these data points were fit assuming an eccentric orbit with e = 0.4(+ .05,-2). Observations taken by Walker and Bell (1980) on December 21 agree in shape and phasing with the December 14 data. Gilliland and Kemper note that there was no change in the shape of the radial velocity curve between December 14 and 23, although the γ-velocity did change considerably from night to night, which also is consistent with the measurements by Walker and Bell (a phenomenon also observed in TU Men and Z Cha during superoutburst).

Four days after outburst maximum high resolution IUE observations of WZ Sge were acquired. They show wide absorption profiles of C II and Si IV, much narrower deep absorptions which are superimposed on broad emissions of C IV and N V, and a possibly double-peaked profile of He II (Figure 2-110a). On December 14 the UV spectrum is characterized by emission lines of C IV, N V, Si IV and He II, and by absorption lines of the lower ionization lines, on a steep blue continuum; not unlike, but also not quite like, a dwarf nova in outburst (Figure 2-110b). The spectrum is highly variable on time-scales of a few tens of minutes, in the continuum as well as in the line flux. C IV shows a pronounced variable double-peak structure which is reminiscent of the optical S-wave phenomenon as seen in many dwarf novae. On December 24 the continuous spectrum has somewhat flattened, the line strengths have decreased, and the spectrum as a whole is only a little variable.

GENERAL INTERPRETATION: During outburst all the disc is assumed to be opaque, thus only absorption spectra can be seen. Blue-shifted absorption profiles are believed to be caused by a high-velocity wind which is blown off the system during outburst. The general pattern of profile changes is understood to be due to opacity changes in the accretion disc: the disc is (partly) optically thin during quiescence and turns optically thick during outburst; changes take place gradually. Variations in K- and γ-velocities with respect to quiescent values, and variations in the phase relations between the disc spectrum and the secondary spectrum are suspected to be caused by brightness changes in the disc. Profile changes are likely to be brightness inhomogeneities in the disc.

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *In most dwarf novae, in the optical as well as in the UV, emission spectra are seen during quiescence, and absorption spectra are seen during outburst. (See 151, 192.)*

- *Profile changes during the course of an outburst follow a very characteristic pattern.*

- *The Balmer decrement is very small during outburst. (See 194.)*

- *The faint cool absorption spectrum seen in several systems in the optical during quiescence disappears during outburst. (See 151, 194.)*

- *There is a good relation between the continuous flux distribution and the optical brightness changes during the course of an outburst: this does not hold for the line spectra.*

- *Line wings and line cores follow different radial velocities.*

- *There is a different phase shift between the primary and secondary spectra during quiescences as compared to outburst. (See 156.)*

- *K- and γ-velocities can have different values during outburst then during quiescence.*

- *Double-eclipsing systems display pure emission spectra in the UV during outburst. (See 206.)*

- *Spectrum changes in WZ Sge are very atypical for a dwarf nova.*