CHAPTER 2

CATACLYSMIC VARIABLES AND DISK INSTABILITY

I could have been exploded in space:
Different orbits for my bones.
(Genesis 1974a)

2.1. DISK INSTABILITY

In this Chapter we will review the mechanisms which determine the instability in the accretion disks and the systems in which such instabilities occur when the accretor is a white dwarf. Such mechanisms are indeed needed in order to interpret, as we will see, the outbursts of Cataclismic Variables.

The outbursts undergone by these objects are in fact reasonably due to a sudden increase of the flow of matter from the disk (in practice, a collapse of a part of it) towards the compact star (see e.g. Warner 1995). In order to interpret the phenomenon, two theories were proposed: the first, called **mass transfer instability** (MTI), attributed to Bath (1973, 1975), assumes the occurrence of a periodic and sudden increase in the mass loss from the secondary, caused by turbulences in the envelope or by irradiation from the compact object. In this way the disc, in order to find a new equilibrium condition in which $\dot{M}$ is much larger, transfers mass onto the collapesd object at much faster rate, until the conditions holding before the beginning of the phenomenon are established again. What is not convincing in this model are the causes of a sudden and periodic increase of $\dot{M}$ in the Cataclysmic Variables and of its equally sudden return to the “pre-outburst” value, as neither turbulences in the envelope of the secondary star nor the irradiation from the accreting object are strong enough to justify them.

The second theory (**accretion disk instability**, or ADI), first formulated by Osaki (1974) and on which most of the astrophysicists agree, asserts that the instability is created directly inside the disc in the form of an unexpected increase of the gas viscosity. This increase takes place when the disk exceeds a certain critical mass. The instability, initially occurring only in a ring of the disk itself, expans quickly involving the rest of the disk, slowing down its orbital motion due to the consequent increase of the friction among the gas particles. The disk thus collapses onto the accreting star. Therefore, since the disk shows two possible states (outbursting and quiescent), we will have that, for every value of its surface density Σ, two different **stable** values for the temperature T must exist. Hoshi (1979) showed that, under certain conditions, the Σ-T relation is indeed S-shaped (Fig. 2.1b), and therefore that the previous condition is satisfied.

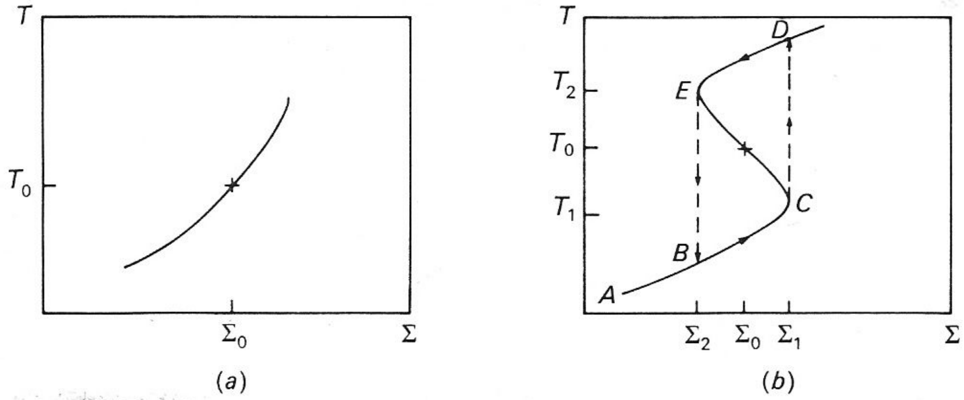

Fig. 2.1. Σ-T diagrams for an accretion disk (**a**) with a single stable configuration and (**b**) in which periodic instabilities occur (from: Frank et al. 1992).

Not all accretion systems, however, have an unstable disk. Its behavior strongly depends on the (supposedly constant) mass loss rate from the secondary star: if it is too high ($\geq 10^{-7}$ $M_\odot$ yr^{-1}), the disc it never enters periodic instability states, and its path in the (Σ-T) plane is increasing monotonically (Fig. 2.1a). Therefore, in order to study the disc instability, it is necessary to analyze the disk behavior in the (Σ-T) plane. Indeed, we have that, in order to produce disk instability, the solution of the equations that describe the disk behaviour must be in a part of its path in the (Σ-T) plane in which

$$\frac{\partial T}{\partial \Sigma} > 0, \tag{2.1}$$

that is, where the surface density increases with the temperature. In this way (Fig. 2.1a), if the disc is perturbed, it is found that, for instance, a density increase will lead to an increase of temperature and viscosity, so that the gas will dissipate energy more rapidly (because of internal friction); therefore, the disk will rapidly return to its state of equilibrium. This solution will thus be a stable one and the disc will not undergo rapid collapse phenomena; rather, it will carry matter in an ordered manner onto the compact star.

If instead the solution it is placed where

$$\frac{\partial T}{\partial \Sigma} < 0, \tag{2.2}$$

and therefore, for instance, in the central branch of an S-shaped curve (Fig. 2.1b), it turns out clearly that such a solution is not stable and that the disk cannot reach that position in any way. As a matter of facts, when the the disk description, in the (Σ-T) plane, is found in the lower branch of the S-shaped curve, any perturbation will move it towards the stable solution [Σ_0, T_0], making it to move along such branch. However, when the disk description reaches point C, the disk becomes unstable, temperature and viscosity increase suddenly and the system "jumps" to point D, in the upper branch of the diagram. Now, because of this sudden increase of the two physical quantities above, the gas starts to strongly irradiate, loses energy and collapses towards the central body; this forces the disk temperature and surface density to decrease and makes the disk configuration to move backwards along the upper branch of the S-shaped curve up to point E. From here, because of an instability similar to that described above (but with opposite effects), the disk desciption "falls back" onto point B, returning to the quiescence state and being ready to start a new cycle, which can thus be labeled as a "thermodynamic-gravitational hysteresis" of the accretion disc. All of the above is of course true in the assumption that the ambient variables (in particular, the mass loss rate of the companion star) remain constant during the entire cycle.

Under these conditions, Σ-T curves of this type can appear as a result of sudden changes in the vertical structure of the disk and connected to these physical quantities (for example, the transition from a radiative to a convective regime, or an increase in the opacity following a partial ionization of the medium); accurate enough models, however, are difficult to construct because the shape of the Σ-T curve depends on a very wide range of parameters. However, a more detailed discussion of this model and the problems related to it can be found in Warner (1995) and references therein.

Although the theoretical models still present several uncertainties and the processes that trigger the disk instability are simply supposed to and not known with certainty, we can still interpret the rapid luminosity changes that we see in objects (apparently) so different such as Cataclysmic Variables and Soft X-ray Transients with a single mechanism, namely the one just described.

In the next paragraphs we will briefly describe some classes of binary systems in which this instability regularly takes place in the accretion disk surrounding a white dwarf. Before that, however, we will illustrate the main features of these accreting compact objects.

2.2. WHITE DWARFS

According to the evolutionary theory, stars with an initial mass of less than 6 - 8 $M_\odot$ are not able, once the burning of He in their core is terminated, to trigger the process of fusion of heavier elements (see e.g. van den Heuvel 1983). The nucleus, therefore, degenerates and sustains itself through the degeneration pressure of electrons originated, in simplistic terms, by the impossibility of forcing these particles into a smaller space because of the uncertainty principle. The outer layers of the stellar building are then blown away by hydrodynamic instability phenomena in the star's envelope (Iben & Renzini 1983).

This creates a **white dwarf** (**WD**), mainly composed of carbon and oxygen and which may carry (**DA type WD**) or not (**non-DA type WD**) a residual quantity of hydrogen in its outer layers.

Objects of this kind have masses similar to solar, while their radii, their temperatures and their surface brightness are respectively of the order of 10^4 km, $\sim 10^{-3}\ L_{\odot}$ and $\sim 3 \cdot 10^4$ K, respectively; these dying stars, therefore, have the dimensions of a medium-sized planet while "weighting" as a star, and this means that their average density is about 10^6 times larger than that of the common matter. They are thus highly compact objects (their compactness factor is indeed of the order of 10^{24} g cm^{-1}, while for example that the Sun is $2 \cdot 10^{22}$ g cm^{-1}).

The source of luminosity of these objects is highly probably the residual thermal energy of particles of which they are made of (Cester 1984); however, if such a body is part of a binary system and receives mass from the companion, the gravitational energy released by matter accreting onto the object is added to the above source of emission: from one gram of falling matter falling, one can extract a quantity of energy obtainable using Eq. (1.12) and equal to

$$\frac{\Delta E_{\mathrm{acc}}}{m} = G\frac{M_{\mathrm{WD}}}{R_{\mathrm{WD}}} \sim 10^{17}\,\mathrm{erg\,g^{-1}}, \tag{2.3}$$

that is, only an order of magnitude less than the energy produced by the hydrogen thermonuclear fusion per gram of matter (one should remember that this is the most efficient nuclear fusion process), given by the equation

$$\frac{\Delta E_{\mathrm{nuc}}}{m} = 0.007c^2 = 6.3 \cdot 10^{18}\,\mathrm{erg\,g^{-1}}, \tag{2.4}$$

where c is the speed of light.

The energy of accretion onto a WD is mostly emitted in the form of radiation from the disk, which, as has been said, is generally present is such accretion systems, and the spectral region in which a large fraction of this energy is emitted is the ultraviolet ultraviolet range ($kT_* \approx 5$ - 10 eV), according to the Eq. (1.23).

Indeed, observationally one can see that binary systems hosting WDs generally emit most of their brightness in the ultraviolet; more energetic radiation is possibly originated by instability and collapse of part of the accretion disk toward the WD (Frank et al. 1992; Warner 1995), as typically occurring in Cataclysmic Variables (see below).

The energy emitted by the accreted material, however, is irradiated not only to the outside: the gas, when reaches the inner parts of the disk, may begin to burn in a controlled manner and, with the energy produced in this way, may give rise to pulsations of the outermost layers of the white dwarf (Tananbaum & Tucker 1974), which can generate an extended atmosphere around the object. It has been said in the previous chapter that, if the magnetic field of compact object is very strong, the gas will not be accreted in the form of a disk, but will fall on the magnetic poles of the degenerate star, giving rise to two accretion columns: usually this does not occur in systems hosting a WD, because its $\vec{B}$ field and its radius are such that the Alfvèn radius always remains below the stellar surface; there however is a class of close binaries with accreting WD in which this phenomenon is apparent enough to prevent the complete or partial formation of the disk (see next paragraph).

In conclusion, one can notice that the accretion that produces noticeable emission from WDs comes primarily from the inner Lagrangian point: indeed, only in the peculiar case of very intense winds ($10^{-4} \div 10^{-5}$ $M_\odot$ yr^{-1}), due to the low efficiency of the latter process and to the compactness factor of these bodies (which is large but certainly not comparable to that of objects such as neutron stars; see Sect. 3.1), the accretion luminosity reaches 10^{35} erg s^{-1}. This value is typical, although not among the highest possible ones, for X-ray binaries; in all other cases, it remains well below this value and is emitted in the form of less energetic radiation.

We now turn to rapidly describe the main class of binary systems in which periodic instabilities of the accretion disk around a WD occur: Cataclysmic Variables.

2.3. CATACLYSMIC VARIABLES

Cataclysmic Variables (CVs) are binary systems consisting of a WD accreting from a star of intermediate or late spectral type and which, more or less regularly, undergo through stages of eruptive activity. Depending on the outburst amplitude, they are classified into two main groups: **Novae** and **Dwarf Novae**. In the two following sections the general characteristics of these two classes will be described, beginning with that of Novae.

2.3.1. Novae

Novae are binary systems in which a WD accretes matter via internal Lagrangian point from a star which usually is quite evolved (most likely a red giant). This type of eruptive variables is characterized by outbursts during which the optical magnitude decreases by 11 - 12 units (but Novae with more pronounced luminosity jumps are not uncommon) and then returns, more or less slowly, to the typical value of the quiescent phase.

The optical light curve of these sources (Fig. 2.2), which has a roughly standard trend, shows a rapid increase to the maximum (reached within one or two days), preceded by a **pre-maximum** phase after which the increase in brightness gets slightly slower; once at the light maximum, the Nova remains there for a few days, and then it starts a decline which can be more or less rapid, depending on each case. When the light curve brightness reaches about 3.5 magnitudes below the maximum, the Nova passes through a

transition phase, during which its light can show quite strong fluctuations, or drop and then rapidly rise again; once this phase is ended, the decline continues until the object returns to the typical magnitude that the it had before the beginning of the phenomenon.

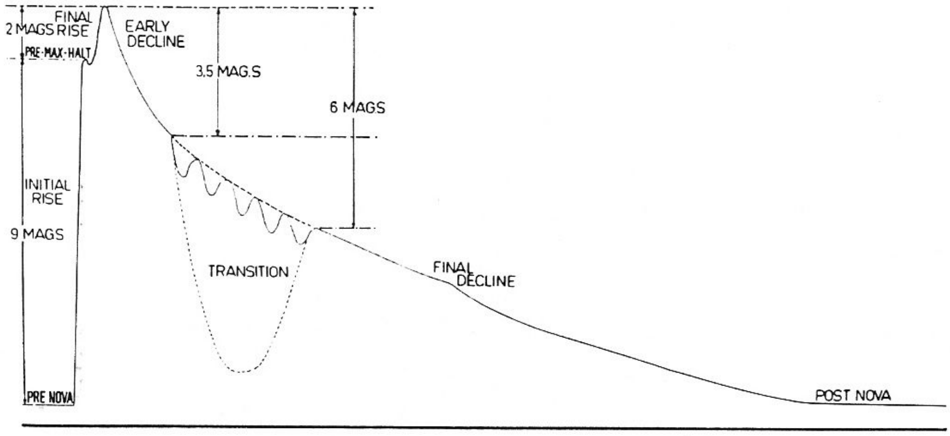

Fig. 2.2. Schematic light curve of a Nova (from: Warner 1995).

Novae are divided into two main classes: **Classical Novae** and **Recurrent Novae** (**RN**) depending if more eruptions for a given system are known or not; in turn, Classical Novae are grouped into **fast** (**NA**) and **slow** (**NB**), depending on the rate at which their brightness decays during outburst. The reference parameter for the rate of decline of a Nova is the time $\boldsymbol{t_3}$ it takes to decay by three magnitudes after having reached the brightness maximum; it is seen that, for NA Novae, the value of this parameter is around ten days, while for the NB Novae it can reach one hundred days (Petit 1987). In addition, the greater the increase in brightness, the faster is the decline (Rosino 1977). Of course, also the times spent by the object to go through the remaining parts of the light curve are proportional to t_3.

In general, RNe show luminosity variations which are much less marked (7 - 8 magnitudes) with respect to those of Classical Novae.

The spectroscopic analysis of the optical emission of Novae during light maximum shows Balmer, He, N and Fe emission lines, similar to those of dwarf novae in eruption (see Sect. 2.3.2) but with more complex structure. Later, during the transition phase, the spectrum becomes of **nebular type**, i.e. shows forbidden emission lines of N, O, Ne and Fe (Warner 1995) similar to those of emission nebulae. The presence of a P-Cyg effect in the emission lines is also found, which indicates the ejection of a gaseous envelope during the outburst. The amount of the ejected mass is correlated with the absolute magnitude of the maximum through the relation (Rosino 1977)

$$\mathrm{M}_{\mathrm{max}} = -17.2 - 2\,\mathrm{Log}\left(\frac{M_{\mathrm{gas}}}{M}\right); \tag{2.5}$$

from this, it appears clear that the mass of the object, and therefore its structure, does not undergo heavy changes during the eruption: given that, in general, $\mathrm{M}_{\mathrm{max}} \approx -7.5$, the ejected mass is around $1.5 \cdot 10^{-5}\ M_{\odot}$. The matter removed from the system then forms a shell (or more concentric shells, if the Nova is recurrent), similar in appearance to a planetary nebula, which eventually dissolves by expanding itself into the interstellar medium. These shells emit significantly at radio wavelengths even long after the end of the eruption; on the contrary, the X-ray emission of Classical Novae is negligible (Warner 1995).

The Nova eruption appears to be due to ADI; unlike the mechanism occurring in Dwarf Novae, however, in Classical Novae the disk material has density and temperature during the collapse which allow triggering thermonuclear burning processes. This explains the larger strength of Nova outbursts. Moreover, according to Petit (1987), if we consider Classical Novae as recurring over a period of 10^3 - 10^4 years, a generalization of the Kukarkin-Parenago relation (see Sect. 2.3.2) to include both Dwarf and Classical Novae is possible. This confirms that the Nova eruptions are more violent because more material is involved in the collapse; this would also explain why the outbursts of Classical Novae last longer than those of RNe.

These systems are mostly associated with a **bulge-disk** population, which is concentrated, in our Galaxy as well as in many other ones, in the area of the Galactic bulge. This indicates that these objects belong to an old stellar population; more specifically, they are of intermediate Population II (Warner 1995).

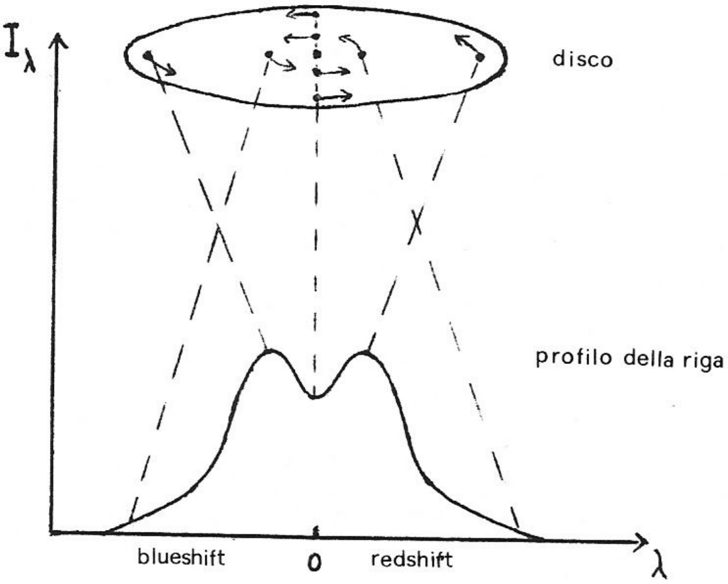

Fig. 2.3. Splitting of an emission line produced by the gas of the accretion disk and due to the orbital motion of the disk itself.

Once the system has returned back to quiescence, it is noted that the disk shows a smaller emissive power; concerning the optical spectrum, in addition to the Balmer He, N and Fe emission lines, one can also identify in its red part absorption lines and bands from the atmosphere of the secondary (this because the secondary stars in Novae are giants of late spectral type).

Furthermore, the Balmer emission lines are generally split, which indicates the presence of H at high temperature in rapid rotation around the compact object and therefore the existence of an accretion disk in these systems; the splitting of lines due to the Doppler effect is explained by the fact that, during the rotation of the disk around the WD, on side of it is approaching to the observer while the other moves away, as shown in Fig. 2.3.

The spectrophotometric analysis of Novae at minimum light allows determining the basic parameters of the system such as the orbital period, the masses of the components, the inclination of the orbit, and so on.

The light curve of quiescent Novae presents the *flickering* phenomenon, which is an irregular modulation caused by the impact on the accretion of the gas stream from the red giant. In case of eclipses, the orbital light curve minimum will occur, as one can expect, when the accretion disk, and in particular the hot spot, are obscured by the giant. To these variations one can add pulsation effects of the WD atmosphere, as mentioned in Sect. 2.2.

There are also binary systems that, despite the fact that they are not known to have undergone any historically recorded eruption, show many or even all of the characteristics of quiescent Novae: these objects are thus called **Nova-Like** (**NL**; see Warner 1995): likely, these are Novae in which outbursts have never been observed or are not produced because of the large mass transfer rate from the secondary (Warner 1995).

2.3.2. Dwarf Novae

Dwarf Novae (**DNe**) are binary systems in which a star of intermediate or late spectral type mid-late, but in this case on the Main Sequence, loses mass toward a WD via gravitational instability. These systems are therefore intrinsically faint at minimum light: according to Rosino (1977), their absolute visual magnitude during quiescence is between +6 and +9. They however undergo eruptions which are much more frequent and much weaker than those of Novae: indeed, DNe increase their brightness of 3 - 4 magnitudes or more with an almost periodic cadence of few tens of days and then return, within a few days, to the pre-outburst luminosity.

Their light curves thus show an alternation of maxima of short duration (a few days) and generally with an asymmetric shape with rapid rise and a slower decay, followed by longer-lasting (several weeks) quiescent phases: in this case one speaks of U Gem-type or SS Cyg-type stars (Fig. 2.4a); there is however a group of DNe, the so-called Z Cam-type stars (Fig. 2.4b), in which sometimes the descent towards the minimum stops and the object passes through a moderately long period (up to some hundreds of days) of nearly constant brightness, midway between that of the maximum and that of quiescence. Of some interest for this thesis there is a third subclass, formed by SU UMa-type DNe (Fig. 2.4c), in which short eruptions alternate with other, longer-lasting, ones (see Par. 2.4).

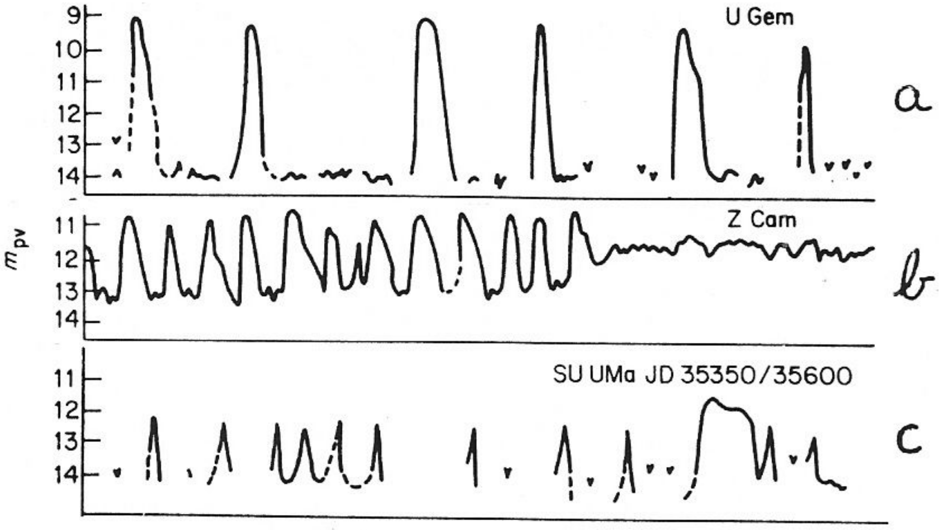

Fig. 2.4a-c. Light curves of DNe (**a**) SS Cyg, (**b**) Z Cam and (**c**) SU UMa (from: Petit 1987).

During the outburst maximum, the DN emission is dominated by the erupting disk, as in the case of Novae. From the analysis of the optical spectra (Fig. 2.5, top) one can see that they indeed show a blue continuum on which the Balmer emission lines are clearly detected, often within a broader absorption due to the high opacity of the disk at this stage; emission lines of He, N, C and Fe can also be seen.

Also in this case the outburst is reasonably caused by ADI: such a mechanism is indeed able to account for the observations and for the shape of the outburst light curve, whereas MTI is not (Warner 1995). The amplitude of the outbursts and the time separation between them are not constant: rather, they are variable, although not by much, around average values. This is moreover true not just for a given object, but also for the whole class. Indeed, there is (Warner 1995) a connection (the **Kukarkin-Parenago relation**) between the average amplitude of the eruption $A_{\rm ave}$ and the average time period $P_{\rm ave}$ between two eruptions, in the form

$$A_{\rm ave} = 1.90\,{\rm Log}\,P_{\rm ave} + 0.70, \tag{2.6}$$

in which $A_{\rm ave}$ is in magnitudes and $P_{\rm ave}$ in days. Thus, the outburst is stronger when the time spent in the quiescent state prior to it is longer. This can be interpreted, according to the ADI model, assuming that the longer the time spent in quiescence, the larger is the mass transferred from the secondary to the disk, and therefore the higher will be the outburst brightness according to Eq. (1.13).

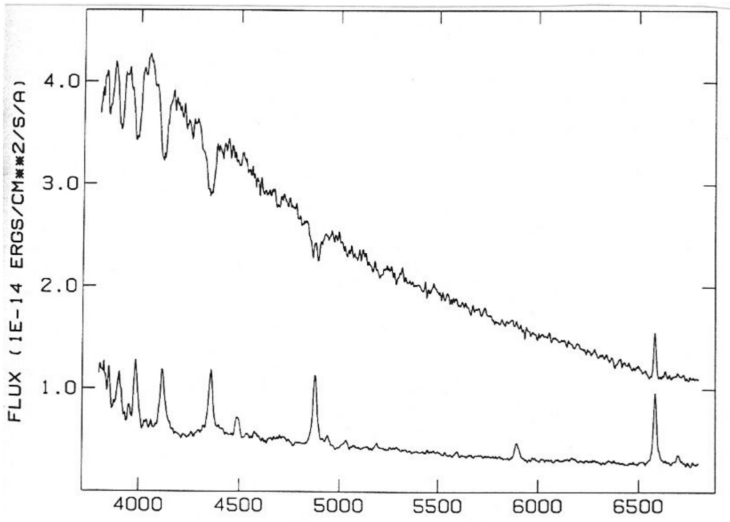

Fig. 2.5. Optical spectra of a DN in outburst (upper panel) and during quiescence (lower panel). From Shafter & Hessman (1988).

Once the outburst has faded away, the system returns to quiescence, and the cycle described in Sect. 2.1 can start again. In the quiescent phase, the disk has a smaller emitting power and the optical spectrum shows (Fig. 2.5, bottom), besides broad emission lines of the Balmer series (now no longer embedded within an absorption), He, N and Fe, the absorption lines of the secondary, in particular at longer wavelengths since the secondary stars in DNe are dwarfs of the last spectral types.

Again in this case, during quiescence the Balmer emission lines are generally split into two symmetric components: this confirms the existence of a disk around the WD.

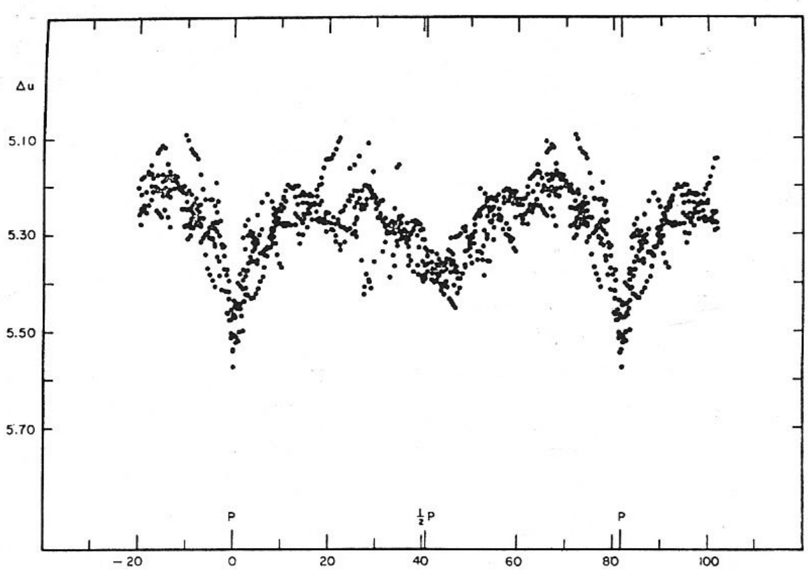

Fig. 2.6. Light curve of an eclipsing DN showing flickering (from: Rosino 1977).

The study of the periodic Doppler shift of absorption and emission lines at minimum light can then determine the orbital period and masses of the primary and the secondary components. The measurement of the orbital period, however, can also be accomplished photometrically through the analysis of the light curve of the system. It can indeed be noted that, due to UV illumination by the WD, the inner face of the secondary can become warmer than that the outer one. This produces a sinusoidal modulation in the optical bands at shorter wavelengths (i.e. *U*, *B* and *V*) and in the corresponding color indices. Often in these systems eclipses occur (Fig. 2.6), which help to accurately refine the orbital period. Since the source with larger emissivity is the WD, the main eclipses main will occur at the occultation of the latter by the secondary star. In some cases, however, the light curve of is difficult to interpret due to the presence of flickering in the light outside eclipses (see the example in Fig. 2.6), due to the continuous fall of matter onto the hot spot.

At red and infrared wavelengths, however, the above effect is weaker, and the modulation is dominated by the shape of the secondary. Indeed, given that it is distorted to a "rugby ball" shape due to the fact that it fills its Roche lobe, the observer sees an area of variable shape, since the major axis of the star always points to the compact object; this effect is called **ellipsoidal deformation** precisely because of the ellipsoidal shape of the secondary star. One can thus see a modulation not produced by a physical phenomenon but rather by a geometric one (Fig. 2.7a).

All this generates a **double-wave** or double-sinusoid light curve (Fig. 2.7b), that is, in which there are two maxima (corresponding to the positions in which we see the oblong side of the secondary) and two minima (which occur when the star shows itself as almost circular in shape).

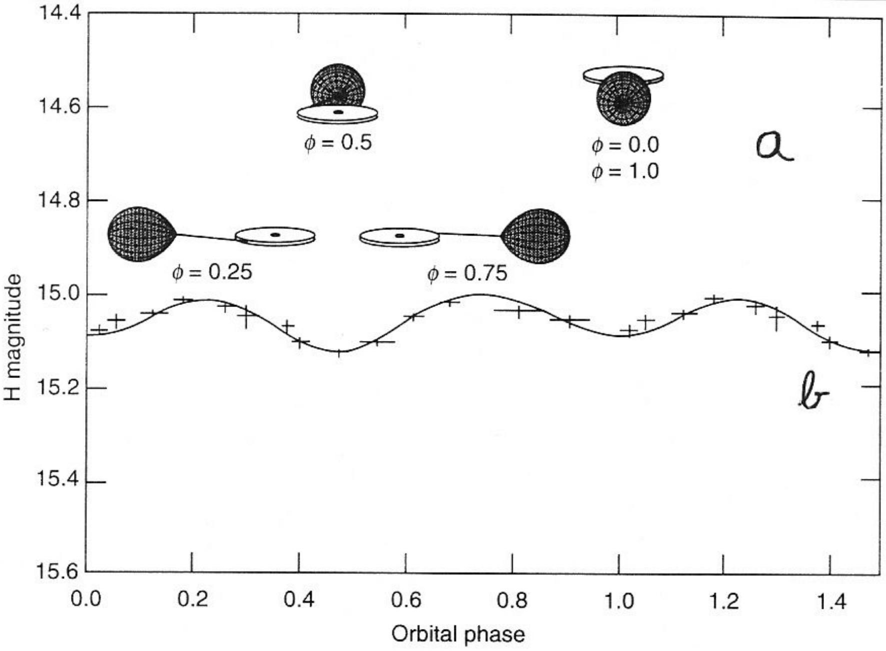

Fig. 2.7. (**a**) Ellipsoidal deformation and (**b**) double-waved infrared light curve of a quiescent DN (from: Charles & Seward 1995).

Theoretically, given the geometrical interpretation of the phenomenon, the two maxima should appear of equal intensity; the observations, however, seem to be at odds with this. The best explanation for this fact is the possible significant contribution from the hot spot emission. The two minima are different because the area of the star surrounding the inner Lagrangian point interior is cooler, and therefore has lower emissivity than the rest of the star surface.

Because of the very nature of this phenomenon, the characteristics of this type of light curve become more evident as the system is observed at longer optical wavelengths, that is, moving towards the infrared bands, and this because there the spectrum of the secondary dominates the quiescent emission of the system. Furthermore, the shape and amplitude of the light curve can be used to determine fundamental orbital parameters for the system, such as inclination i and mass ratio q (Bochkarev et al. 1979).

The investigation of the orbital periodicity of these systems has highlighted the fact that, in the vast majority of the cases, DNe have periods between 1 and 8 hours: these systems are therefore quite close, which further confirms the presence of a secondary medium to late spectral type still on the Main Sequence. The study of the distribution of the DN periods also stresses the absence of objects with period between 2 and 3 hours (the so-called **period gap**), due to the suspension of mass transfer from the secondary for magnetohydrodynamic reasons (Warner 1995 and references therein).

With respet to the X-ray emission from DNe, both in eruption and in quiescence, it can be said that in general is not remarkable: in the case in which, however, the WD possesses a strong $\vec{B}$ field, the gas lost from the secondary will not form an accretion but will rather fall on the magnetic poles of the degenerate star, giving rise to two accretion columns (Warner 1995): these systems are called ***polars*** or **AM Her type** DNe (Fig. 1.6). If, however, the $\vec{B}$ field intensity allows forming only the external parts of the disk, one deals with ***intermediate polar*** systems or **DQ Her type** DNe (Fig. 1.5). The matter falling following the field lines onto the magnetic poles thus determines two zones in which highly energetic radiation is produced and emitted preferentially in the direction of the magnetic axis; in this way, if an observer is aligned with that axis, s/he receives pulsed X-ray emission due to the motion of the star around its rotation axis, with a period equal to that of the WD spin (the formation of very intense magnetic fields also in these objects, from 10^4 up to 10^8 gauss, can be explained assuming a “freezing” of the $\vec{B}$

fiels in the stellar matter during the collapse of the star core). Radio emission, instead, is not an important issue in DNe (Warner 1995).

Let us now see in detail, in the last part of this chapter, one of the three subclasses of DNe, tha is, SU UMae, since these systems have several similarities with the objects dealt in this Thesis.

2.4. SU UMa-TYPE DNe AND SUPERHUMPS

SU UMa-type systems are composed of a WD and a dwarf star of M spectral type and, except for one case, have orbital periods shorter than 2 hours; thus, they lie below the period gap (Warner 1995). A peculiar characteristic of SU UMae is that they alternate outbursts typical of DN with **superoutbursts** which are five times longer (10 days versus ~2 days of 'normal' DN eruptions), about two magnitudes brighter and from 3 to 8 times less frequent, as well as of considerably different shape (Fig. 2.4c). According to Osaki (1989), this phenomenon is due to the fact that the disk loses little material onto the WD during short eruptions, and therefore these do not reduce either its mass or its size, which actually increase because of the continuous accretion of matter from the secondary. Thus, when the disk comes reaches a radius at which the Keplerian rotation period is 1/3 of the orbital period of the system (3:1 resonance), there are the conditions are met for the next eruption to trigger a tidal dissipation induced by secondary on the outer edge of the disc, and possibly an $\dot{M}$ increase from the secondary itself (Osaki 1985): this makes the outburst stronger and long lasting. In this way, the disc loses a large part of its mass onto the WD and the cycle described above (also called **supercycle**) can start again. In addition, during a superoutburst, the resonance and the dissipation induced by the secondary are such that, if the mass ratio q of the system is less than 0.25 - 0.33, the disk takes an elliptical shape and begins a slow precession motion (Whitehurst & King 1991). This condition is very likely always fulfilled in SU

UMae, given the short orbital period and hence the small mass of the secondary (Warner 1995).

During a superoutburst, one can note the presence of regular oscillations (called **superhumps**) with amplitude 0.2 - 0.3 mag in the *V* band and showing a period **of a few percent longer** than the orbital one: this latter feature is due to the disk precession. Such a modulation also has a characteristic "sawtooth" shape, with rapid rise and slower decay, and is found in all SU UMae during superoutburst. Superhumps are instead absent during the 'normal' outbursts.

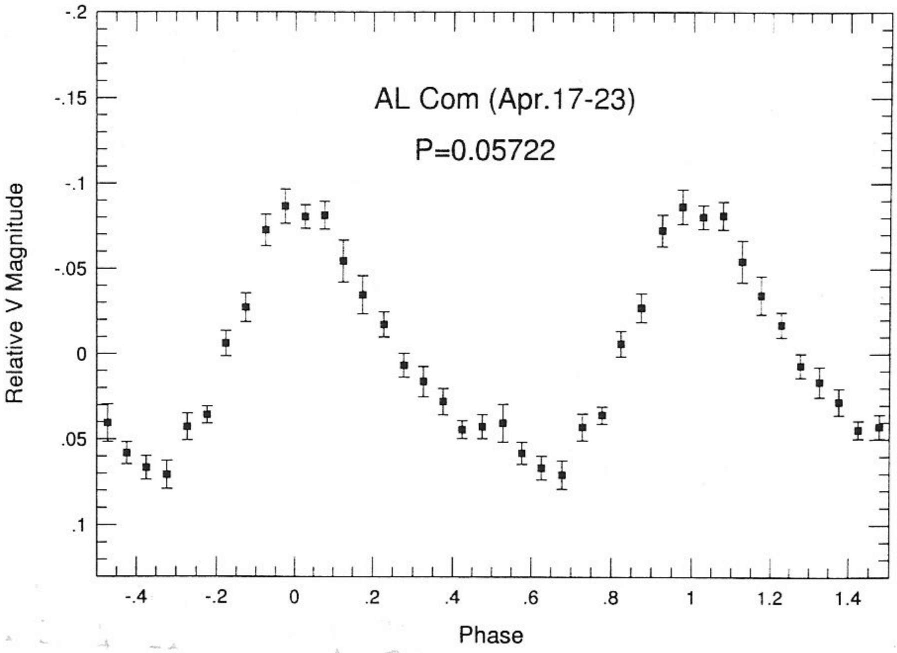

Fig. 2.8. Folded light curve of a superhump. One can notice the typical "sawtooth" shape (from: Kato et al. 1996).

The area of origin of this phenomenon is probably the outer region of the elliptical disk (O'Donoghue 1990); however, this is still the subject of an intense debate. The competing models to describe this phenomenon are basically two: the **tidal** one, in which the secondary produces a dissipative effect modulated in time, and the **potential** one, in which the modulation is due to the position of the hot spot on the edge of the disc during the orbital motion of the secondary. These models are described in more detail, with their advantages and problems, by Warner (1995); see also Chapter 4 and Appendix A of this thesis. It seems however clear (Billington et al. 1996) that the area of origin of the superhumps is ‘cold’, as the UV emission of the system reaches a minimum when the superhump optical light curve is at its maximum: this indicates that the area in which the phenomenon is originated has a low temperature and is optically thick.

Among SU Umae, there is a small subset of systems (called **ER UMae** stars) in which the supercycle is much shorter and superoutbursts are longer and less bright than those of ‘classical’ SU UMae. This seems to be due to the larger $\dot{M}$ from the secondary star in ER UMae: $\sim 5 \cdot 10^{-10}$ $M_{\odot}$ yr^{-1}, against $\sim 10^{-11}$ $M_{\odot}$ yr^{-1} of ‘classical’ SU UMae (Osaki 1995a,b).

The possibility to observe superhumps in these objects gives us the opportunity to estimate the mass of the primary even before acquiring spectroscopic measurements of radial velocities: indeed, according to Mineshige et al. (1992), if one assumes that the secondary is a star of late spectral type still in sequence, and since $P_{\mathrm{sh}} \approx P_{\mathrm{orb}}$ and that we should have $q < 0.33$ for superhumps to be developed in these systems, the following inequality should hold:

$$M_1 > 0.33 P_{\mathrm{sh}}(\mathrm{hr}) M ; \qquad (2.7)$$

In the cases in which the orbital period is also known, one can state that

$$M_1 \cong 0.0275 \frac{P_{\mathrm{orb}}{}^2}{P_{\mathrm{sh}} - P_{\mathrm{orb}}} \eta^{\frac{3}{2}} M , \qquad (2.8)$$

with the periods expressed in hours and in which η is a parameter (with value between 0.6 and 1) containing information about the radius of the accretion disk during quiescence.

Finally, one can also say that there exists an empiric relation between P_{sh} and P_{orb} (Robinson et al. 1987),

$$\frac{P_{\mathrm{sh}}}{P_{\mathrm{orb}}} = 0.0367(P_{\mathrm{orb}} - 2.00) + 1.043, \tag{2.9}$$

with the periods expressed in hours. Such a relation seems to be produced (Warner 1995) by the dependence from q of the disk precession frequency, the latter being responsible for the difference between the two periodicities above.

In conclusion, both in classical Novae (also in those in which the disk-instability mechanism causes large amplitude eruptions and therefore in which the optical magnitude jump is quite large) as well as in DNe the X-ray emission, either coming from the WD during the outbursts, or from hot spot or the inner parts of the disk when the system is in quiescence, does not seem to be likely to exceed the optical one by several orders of magnitude. However, if the secondary loses matter to an object which is much more compact than a WD, the X-ray production would certainly be larger. Observations made at high energies do show the presence of such objects in nature. The next chapter will describe these objects and the systems in which they are hosted, with particular attention to those that experience transient phenomena similar to those described here.

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