VIII. CATACLYSMIC VARIABLES AND POLARS

THE NATURE OF THE DIFFERENCE BETWEEN NOVAE, DWARF NOVAE, AND NOVALIKES

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I. INTRODUCTION

Novae (N) and Dwarf Novae (DN) are considered to belong to the class of the Cataclysmic Variables (CVs). The Novalike stars and recently discovered Polars (the AM Herculis-type stars) seem to have the same nature as CVs and probably are members of this class. It is usually assumed that CVs are close binary systems, each system contains a degenerate dwarf and a nondegenerate second component, their period being usually less than 16^h (e.g. see: Robinson 1976). A second star is believed to overfill its Roche lobe and its matter flows onto the degenerated component. Then around the degenerated dwarf there arises an accretion disk. This disk and the hot spot where the interaction between the disk and outflowing stream occurs are the main sources of the blue and ultraviolet continuum and strong H and He emission lines.

The principal difference between CVs is connected with their outburst activity. The Novae and Recurrent Novae outbursts have an amplitude of $7\text{-}14^m$. The mean energy of a single outburst is $\lesssim 10^{45}$ ergs and the recurrence time between two successive outbursts is larger than 10 years. The outbursts are thought to arise from unstable thermonuclear burning of hydrogen accreted and accumulated on the surface of degenerated dwarf (Starfield et al., 1974). The outbursts of the DN have much smaller amplitudes $2\text{-}6^m$, a total energy output on the order of $10^{38}\text{-}10^{39}$ ergs and a recurrence time between roughly 10 days and 3 years. The DN are of U Gem and Z Cam type, but we assume that they are of similar nature and do not consider why they are different. Recently Szkody (1974, 1976 and 1977) has shown that during the outbursts the main sources of the DN radiation are the accretion disk and degenerated dwarf but between outbursts the main sources are the hot spot on the disk and the nondegenerated star.

Now there seems to be no generally recognized explanation of the DN phenomenon. Two groups of theories are well known. In the theories of the first group (Bath et al., 1974; Gorbatsky 1975) an instability of the envelope of the nondegenerated star was assumed to be the cause of the outbursts. This instability leads to a sharp increase in the luminosity of this star and/or an increase in the rate of outflow. This

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increased outflow is thought to lead to the increase in the accretion rate and, therefore, to expansion and brightening of the disk. However, remaining unsolved questions connected with these theories are: why is the hot spot on the periphery of disk brighter than the whole disk in the state of low luminosity? Why is the disk brighter than the spot in the state of high luminosity? And what causes the empirical relation between the total energy of the outburst E, the low state luminisoty L_{min}, and the recurrence time to the next outburst $\Delta t \sim E/L_{min}$? In the theories of the second group, by analogy with Novae, the outbursts are supposed to be connected with unstable thermonuclear burning of hydrogen accreted onto the surface of a degenerate dwarf (Starrfield et al., 1972). But in this case other important questions arise: what causes the difference between Novae and Dwarf Novae? And why is the intermediate class absent?

II. THE LOCAL THERMONUCLEAR BURNING OF THE HYDROGEN ONTO THE SURFACE OF A MAGNETIZED DEGENERATE DWARF

Let us assume that the outbursts of DN result from the unstable thermonuclear burning of hydrogen onto the surface of degenerate dwarf. Let us also assume that the dwarf has a strong magnetic field 10^6-10^8gs. The conditions on the dwarf's surface are not homogeneous because the accretion heats a small part of the surface to a high temperatures and a strong magnetic field leads to heterogeneities in the heat conductivity. In the presence of a magnetic field the conditions of the accumulation and nuclear burning of the accreted hydrogen are different in different points of the surface (Mitrofanov, 1978).

The area of the local region (LR) exposed to the accretion may be estimated by assuming that the plasma from the second component or disk flows along the lines of the dipole magnetic field $S \simeq 10^{14} \div 10^{15} cm^2$. The hydrogen may spread over the whole surface of the dwarf due to mutual diffusion of the plasma and the magnetic field or due to instabilities. The diffusion time is $t_{dif} \simeq 4\pi\beta l^2/C^2 \sim 10^8(T/10^6)^{1.5}(\ell/10^6 cm)s$, where T is the temperature of the LR, ℓ is its characteristic size and β is the plasma conductivity. Local accumulation and ignition takes place if the inner edge of the hydrogen layer approaches the surface density n_{cr} for unstable burning in the LR faster than the hydrogen plasma spreads over the whole surface, i.e. if the time of accumulation $t_{acc} = S \cdot n_{cr}/\dot{M} = 10^7(S/10^{14}cm^2)(n_{cr}/10^9 g\ cm^{-2})(10^{16} g\ s^{-1}/\dot{M})s$ is smaller than t_{dif}.

1) The LR may have a high temperature $\lesssim 10^7$. The critical density n_{cr} decreases with the increase of temperature. Therefore, the layer of hydrogen which is stable above the main cold part of the surface may appear unstable in the LR.

2) The LRs are situated near the magnetic poles of a degenerate dwarf. One can suppose that in such regions the heat conductivity is strongly decreased (e.g. due to suppression of the convection) and the conditions necessary for the unstable burning to occur appear much softer.

The mass of the burning hydrogen may be estimated as

$M = S \cdot n_{cr} \simeq 10^{23} - 10^{24}$g for $n_{cr} \simeq 10^{9}$g cm^{-2}. Assuming that W, the mean energy per gram released in the outburst dwarf novae is similar to W for novae, one can estimate W to be 10^{16} ergs g^{-1} which leads to a DN outburst energy E of $10^{39} - 10^{40}$ ergs. This magnitude agrees well with the observations.

If the difference between the LR and other parts of the dwarf's surface is not very large and the magnitudes of n_{cr} for these two regions are approximately the same, the hydrogen layer may become unstable on the whole surface. This may be the case of the dwarf's magnetic field or the accretion rate are sufficiently small $B \lesssim 10^{6}$gs or $\dot{M} \lesssim 10^{14}$g $\cdot$ s^{-1}. These stars should have their outbursts as Novae with a recurrence time $\gtrsim$10 yrs. In this way it becomes clear why there are few CVs with an outburst energy between 10^{40} ergs and 10^{43} ergs and with a recurrence time between 3 and 10 years.

The accumulation of the hydrogen mass occurs because accretion is more rapid than the destruction of hydrogen due to stable nuclear burning at the bottom of the layer. The burning becomes unstable if the rate of energy generation is larger than the rate of the cooling. It was shown (Paszynski and Zytkow, 1978) that the burning of a spherical shell is stable if $\dot{M} \gtrsim 10^{19}$ g s^{-1} because hydrogen burning occurs at a temperature where the rate of nuclear reactions is great enough to ensure equilibrium between the burning and the accretion. This result seems to be qualitatively appropriate also to local case and one can estimate the critical accretion rate to be $\dot{M}_{cr} \sim 10^{19} \cdot (S/S)$g $\cdot$ s^{-1} $\sim 10^{16}$ g $\cdot$ s^{-1}. This magnitude decreases as the dw of the magnetic field increases. Thus, the hydrogen burning is stable and outbursts are absent if the magnetic field and the accretion rate are sufficiently large. This regime is likely to take place in the case of AM Her-type stars ($B \gtrsim 2 \cdot 10^{8}$gs and $M \gtrsim 10^{16}$g $\cdot$ s^{-1}). These stars all have the properties of CVs with the exception of the most significant one - the outbursts themselves. They are the true Novalikes in contrast to the false ones which seem to be Novae with unrecorded outbursts.

III. THE POSSIBLE MECHANISM OF THE DWARF NOVAE OUTBURSTS

It is obvious that the local burning of hydrogen should differ significantly from the spherical case. It seems very difficult to investigate this difference quantitatively because of the influence of the magnetic field, the heterogeneity of the temperature and the possibility of flows into the layer. In the remainder of this paper a rough, qualitative approach will be used.

The optical depth of the layer before the onset of unstable burning, $\tau_o = \sigma_e n/m_p$, is very large (σ_e is the effective absorption cross-section). During the unstable burning, the layer usually begins to expand (Starrfield et al., 1972, 1974). In the spherical case its optical depth does not change. In the local case the matter from the LR expands almost isotropically and for $r \gg S^{1/2}$(r is the radius of the expanding hemisphere) its optical depth $\tau \simeq \tau_o \cdot (3S/2\pi r^2)$ becomes much smaller. From the equation of heat transport one can estimate the radiative cooling time $t_{cool} \simeq Cr^2/\kappa_r$, where $C = N_e k_B$ is the specific heat of the plasma and κ_r is the coefficient of radiative heat conductivity. This estimation has another form $t_{cool} \simeq \tau^2 k_B/\sigma_e \sigma T \simeq 4 \cdot 10^{-16}\tau^2(10^6/T)$s ($\sigma$ is the Stephan-Boltzman's constant). When the cooling time appears comparable with the time of expansion r/V_{exp}, the internal pressure and the rate of the thermonuclear burning decrease, and the expansion stops. From the condition $t_{cool} \sim t_{exp}$ one can estimate r_{max} and t_{exp}. If $V_{exp} \simeq 10^7$cm/s they appear to be $r_{max} \sim 10^8$cm and $t_{exp} \sim 10$ s.

During the phase of the plasma expansion the frozen magnetic field becomes deformed. When the internal pressure decreases the field begins to restore its geometry. Therefore, expanded plasma has to fall down just onto the LR. Suitable conditions for the unstable thermonuclear burning are restored and the cycle is repeated.

This qualitative mechanism seems to explain the regular variation of the soft X-rays from SS Cyg at outburst with a mean period of 8.9 s and an amplitude of ~50% (Cordova et al. 1978). This mechanism also may explain the regular pulsation of the DNs optical luminosity during outburst (Robinson, 1973 a,b,c,). An additional fact in favor of this explanation is the relationship observed for Z Cam between the mean period of the pulsations and the energy of the outburst. It seems difficult to imagine another pulsation mechanism explaining this fact.

During the outburst the released energy is transported from the LR to the accretion disk. One possible transport mechanism is the generation of shock waves above the region of pulsing plasma. These waves may propagate through the disk and heat it. So, during the outburst the disk becomes the main source of the optical light of DN while the burning region is the main source of X-rays.

IV. CONCLUDING REMARKS

The distinction between DN and N may be a result of the local burning of hydrogen on the surface of a degenerate dwarf (Mitrofanov, 1978). The main cause of this localization seems to be the strong magnetic field $10^6 - 10^8$gs on the dwarf's surface. This supposition seems to agree with the observations of X-rays from some DN such as SS Cyg (Rappaport et al., 1974; Heise et al., 1978 and Cordova et al., 1978), U Gem (Mason et al., 1978, Swank et al., 1978) and EX Hya (Watson et al., 1978). If the field strength or the accretion rates are sufficiently small (e.g. $B \lesssim 10^6$gs or $\dot{M} \lesssim 10^{14}g \cdot s^{-1}$) the localization has to disappear and the usual Novae outburst should be observed. Conversely, a very strong magnetic field together with a high accretion rate ($B \gtrsim 2 \cdot 10^8$gs and $\dot{M} \gtrsim 10^{16}g \cdot s^{-1}$) is likely to lead to the steady burning with no outbursts. It seems to be the case of the true Nova-likes specifically the stars of AM Her-type.

The mechanism of local outburst with pulsation may explain the strong regular variations of SS Cyg X-rays and weak similar variations of the optical light from Z Cam, CY Cnc, AH Her, CN Ori, KT Per and SS Cyg. The essential decrease in X-ray flux at the late stage of the SS Cyg outburst (Ricketts et al., 1979) is possible due to the flow of matter from the burning region to the accretion disk instead of the normal accretion flow.

The above mentioned empirical relation, $\Delta t \sim E/L_{min}$, may be explained from the theoretical relation, $t_{acc} = M/\dot{M}$, by substituting instead of M and $\dot{M}$ the observable magnitudes E and L_{min} (E is a total energy of a burst and L_{min} is the low state luminosity produced by the flux from the hot spot on the disk). In this case we obtain $t_{acc} \sim E/L_{min}$. Using this relation two independent sequences of outbursts were discovered for some DNs. For example, Vogt (1974) and Bateson (1974) have found two types of outbursts for **VW Hyi (Table 1).** It is natural to relate them with two different magnetic poles with slightly different conditions. In this case the estimations of the accretion rate $\dot{M}$ for the both sequences of the outbursts should be equal and indeed, it is easy to verify that the difference is less than 5%. This is a good confirmation of the proposed explanation of the nature of the Dwarf Novae.

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TABLE 1. THE OUTBURSTS OF VW HYA

	First type of outbursts	Second type of outbursts
Mean duration of outbursts, δt	4^d	11^d
Mean recurrence time, Δt	$28\overset{d}{.}7$	179^d
Mean amplitude Δm	$3\overset{m}{.}9$	$4\overset{m}{.}6$
Mean accretion[1] rate, $\dot{M}$	$5.00\ L_{min}/W$	$5.05\ L_{min}/W$

1) formulae for the estimation of the accretion rate

$$M = \frac{L_{min}}{W} \cdot \left(\frac{L_i}{L_{min}} \cdot \frac{\delta t_i}{\Delta t_i}\right), \quad i = 1, 2.$$

DISCUSSION FOLLOWING MITROFANOV

van Paradijs: Your model ascribes the difference between N and NL variables to a difference in the mean accretion rate of at least a factor of 100. You would then expect a systematic difference of about that factor in the steady luminosity of these systems (in between eruptions). How does this compare to the observations?

Mitrofanov: The difference between N and NL results not only from the difference in the accretion rate but also from the difference of the magnetic fields. Therefore there may be no difference in total luminosity. Even if the difference exists the energy is emitted in different spectral bands (e.g. ultraviolet and X-ray).

Nariai: What are the mass accreted and the rate of accretion?

Mitrofanov: The mass which is associated with the DN outburst is about 10^{22}- 10^{23}g; the rate of accretion seems to be about $10^{14}$to 10^{16} g/s.

Nariai: I wonder if the binary can maintain the rigid structure from the onset of accretion to flash. Otherwise the magnetic field will be winding the white dwarf and the localized accretion will not be possible.

Mitrofanov: The dipole approximation for the dwarf's magnetic field seems to be sufficiently good. This field is frozen into the core of the white dwarf. The diffusion time for accreted plasma is much smaller than the free-fall time. So, one can say that the accreted plasma is canalized by the magnetic field.

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