A WAVE MODEL FOR DWARF NOVAE

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ABSTRACT

The rapid coherent oscillation during a dwarf nova outburst is attributed to an accretion-driven wave going around the white dwarf component of the binary system. The increase and decrease in the period of this oscillation is due to the change in the velocity of the wave as it is first being driven and then damped. Qualitatively, a large number of observations can be explained with such a model. The beginnings of a mathematical representation of this model are developed.

INTRODUCTION

The dwarf nova is a close binary system consisting of a white dwarf and a red star that overflows its Roche lobe (see Figure 1). Material

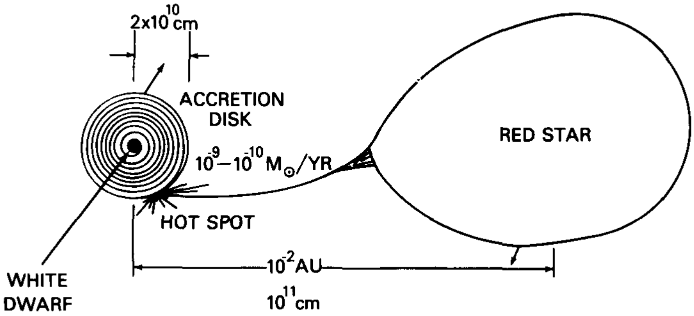

Fig. 1. Dwarf Nova binary consisting of a red star overflowing its Roche lobe and a white dwarf with an accretion disk.

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from the red star forms an accretion disk around the white dwarf. During the eruption of a dwarf nova, the luminosity of the white dwarf and/or its disk increases by 3-5 magnitudes for 4-8 days. These eruptions occur every 20-80 days with the higher amplitude dwarf novae having the longer mean eruption periods (Kukarkin and Parenago 1934). There appears to be little or no ejection of material during these eruptions. (See Warner 1976, for a thorough review of dwarf novae observations.) High speed photometry of the dwarf novae during eruption reveals a low-amplitude coherent oscillation in the visual light (Warner and Robinson 1972). Recent observations (Cordova et al. 1980) of these objects in the X-ray region indicate a similarly rapid oscillation. Long-term observations (Patterson et al. 1977; Hildebrand et al. 1980) in the visual show that the period of this oscillation decreases until approximately the middle of the outburst and then increases. The oscillation is never found during quiescence, thus strongly implying a connection between it and the dwarf nova eruption.

As the name implies, it is tempting to consider the dwarf nova as a small scale version of a common nova. The brightness of a common nova outburst increases by 9-12 magnitudes and takes from months to years to return to quiescence. It is universally accepted to be the result of a thermonuclear runaway in the accreted, degenerate, hydrogen-rich layers of the white dwarf (see Starrfield in these proceedings for a review of common novae). However, the amount of hydrogen-rich material needed for it to reach ignition temperatures and densities forces the energy of the outburst to be at least 4 orders of magnitude above that of a dwarf nova. There does not appear to be any way to scale down a thermonuclear runaway to produce a dwarf nova (Sparks and Starrfield 1975)

Having eliminated thermonuclear reactions as a possible source of energy for the dwarf nova, it appears that the gravitational potential energy of the accreting material is the most likely source. Bath (1973) proposed that the outburst is due to quasi-periodic instabilities in the red component, causing mass transfer to the accretion disk, while Osaki (1974) suggested that it is due to intermittent mass transfer from the disk to the white dwarf without specifying a mechanism. We agree with Osaki and the purpose of this paper is to propose such a mechanism.

THE ACCRETION-DRIVEN WAVE MODEL

The upper diagram of Figure 2 is a schematic pole-on view of the white dwarf's surface, showing the disk material in Keplerian orbits. The disk material works its way down due to loss of angular momentum, and strikes the white dwarf's surface tangentially with speeds of the order of 1000 km s^{-1}. The impact of the accreting material will make the equatorial surface layers of the white dwarf turbulent (middle diagram in Figure 2) (Kippenhahn and Thomas 1978), and, we suspect, in time will create surface waves. This process is analogous to the creation of wind-driven surface waves on the ocean, which also start out with a random, choppy pattern (Kinsman 1965, p.5). (The analogy is

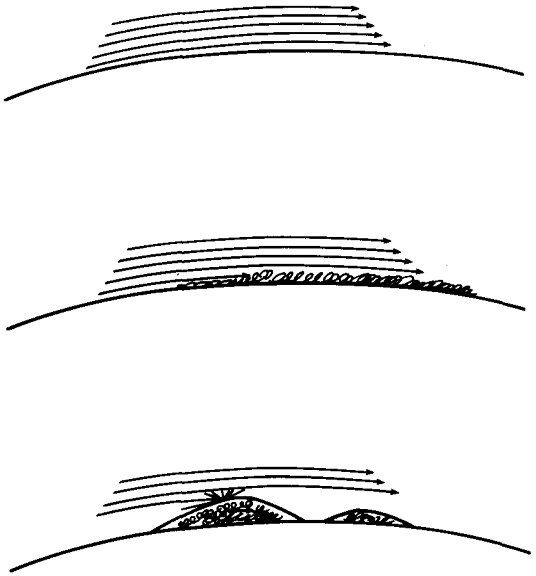

Fig. 2. A schematic pole-on view of the white dwarf's surface showing the growth of the accretion-driven wave.

only partially correct since the surface waves on the white dwarf accrete their driving matter while ocean waves do not.) While the waves grow, their crests will extend further and further into the disk. Disk material, including energy and momentum, will thereby be accreted by the white dwarf, and the waves will continue to grow. The waves with the highest amplitudes (lower diagram in Figure 2) will accrete a disproportionately large amount of the disk material and eventually dominate over the rest. In the simplest case which we will assume, we would have a single wave being driven around the white dwarf by accretion (upper diagram in Figure 3) which gives rise to the observed rapid oscillation. A fraction of the transfered rotational energy will be converted into radiation which we propose is responsible for the observed outburst. With increasing amplitude the dissipative forces acting on the wave will also grow. When they become equal to the driving force the amplitude of the wave ceases to grow.

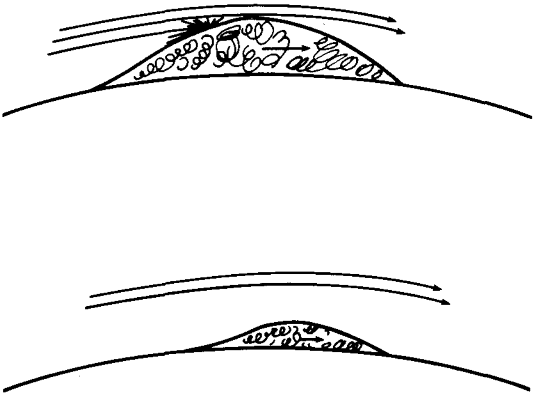

Fig. 3. A schematic pole-on view of the white dwarf's surface showing the decay of the wave.

At this point there exists two possibilities for future development. 1) If matter continues to be accreted (due to dissipative forces in the disk) at a rate such that the driving force remains equal to the dissipative forces in the wave, an equilibrium state is established. Since this accretion rate, which is equal to the mean accretion rate from the red star, is now less than during the earlier growth phase, the transfered energy is less and so is the outburst. 2) If the amplitude of the wave decreases faster than the lower edge of the disk moves inward, then the driving force vanishes because the disk material no longer strikes the wave. The amplitude of the wave will now decay at a rate depending only on its dissipative forces and leave a vacuum between the disk and the white dwarf (lower diagram in Figure 3). The outburst is repeated whenever, by dissipation of angular momentum, disk material has once again come into contact with the white dwarf. In summary, we attribute the light curve of the dwarf nova outburst to the conversion of orbital kinetic energy into radiation and the rapid oscillation to the accretion-driven wave going around the white dwarf.

COMPARISON WITH OBSERVATIONS

Although our model is still very schematic, it explains naturally a large number of observations, at least qualitatively. 1) According to our model the higher the amplitude of the wave (which implies a stronger outburst), the longer will be the time to the next outburst. This agrees with the observed mean period-amplitude relationship of Kukarkin and Parenago (1934). 2) The case of the driving force equaling the dissipative forces in the wave corresponds to the standstill phase in the Z Cam stars. 3) The case of the driving force vanishing after the wave reaches a maximum implies that afterwards the luminosity comes entirely from the decaying wave. This explains the rather sudden cutoff of the light curve. The sudden cutoff has been a serious problem for the thermonuclear runaway model. 4) The source of the light of the outburst will be concentrated at the white dwarf, which eclipse observations (Smak 1971; Warner 1974) confirm. 5) If we associate the observed rapid oscillation of the dwarf nova with the wave being driven around the white dwarf, then the increase and decrease in frequency can be qualitatively explained by the driving and damping phases. 6) In our model the brightness of the hot spot is independent of the outburst. Observations (Smak 1971; Warner and Nather 1971) indicate that the brightness of the hot spot remains constant or changes only slightly during outburst. Bath's red star overflow model for dwarf novae does not predict this, which has been a major criticism raised against it.

MATHEMATICAL REPRESENTATION

Next we must express our model mathematically. As a first approximation we propose to represent the accretion-driven wave by the wave equation,

$$\frac{\partial^2\eta}{\partial t^2} = \frac{v^2}{R^2}\frac{\partial^2\eta}{\partial\theta^2} - D\frac{\partial\eta}{\partial\theta} + F, \qquad (1)$$

where θ is the azimuthal angle, t is the time, R is the undisturbed radius of the white dwarf, η is the height above R, v is the wave velocity, $D\,\partial\eta/\partial\theta$ is the dissipation term, and F is the driving term. In general D and F are functions of η and $\dot{\eta}$, and vary slowly with time. In this initial investigation we are assuming, for the boundary conditions, that η is periodic and initially sinusoidal, i.e.,

$$\eta(\theta,t) = \eta(\theta+2\pi,t)$$

and

$$\eta(\theta,0) = \eta_o \cos\theta.$$

Using these boundary conditions, the solution of the homogeneous part of Equation (1) is identical to that of the classical damped oscillator which applies when the driving force vanishes. We are now investigating the inhomogeneous solution of Equation (1).

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DISCUSSION

STARRFIELD: How high a wave do you expect to get out of this model?

SPARKS: In the solution of this equation, the height is equal to the velocity squared over the gravitational acceleration, g. For a typical white dwarf, g is like 10^8 cm/s^2 and the velocity is like 10^8 cm/s so you do get heights like 10^8 cm.