The Spreading Layer and Dwarf Nova Oscillations

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Abstract. We describe recent theoretical work on the final stage of accretion when material passes from an accretion disk onto a white dwarf surface. Our calculations focus on understanding the latitudinal spreading and differentially rotating profile of this material, so we call it the “spreading layer” (SL) model. The SL typically extends to an angle of $\theta_{SL} \approx 0.01 - 0.1$ radians, with respect to the equator. At low accretion rates ($\dot{M} \lesssim 10^{18} \, \text{g s}^{-1}$) the amount of spreading is small, so that the dissipated energy is radiated back into the accretion disk. When $\dot{M}$ is high, such as in dwarf novae, symbiotic binaries, and supersoft sources, the material spreads to higher latitudes to be more easily observed. The SL may contain shallow surface modes, and we propose that such waves could produce dwarf nova oscillations (DNOs). This hypothesis naturally explains many key properties of DNOs, including their frequency range, sinusoidal nature, sensitivity to $\dot{M}$, and why they are only seen during outburst.

1. Introduction

If a white dwarf (WD) is weakly magnetized, accreted material reaches its surface at the equator and then must lose angular momentum and kinetic energy before settling onto the star. When the WD spin is much less than breakup, nearly half of the accretion luminosity is released in this process, making this region as luminous as the accretion disk and crucial to understanding the luminosity from cataclysmic variables (CVs). This transition from accretion disk to WD is typically treated in a boundary layer (BL) model. One-dimensional BL studies follow the radial flow of material and assume a vertical scale height (e.g. Popham & Narayan 1995), while other BL models study both radial and latitudinal directions simultaneously using numerical techniques (e.g. Kley 1989a, 1989b). Inogamov & Sunyaev (1999; hereafter IS99) approached this problem from a new angle to study accreting neutron stars (NSs). Their method follows the latitudinal flow of matter and provides information about the spreading area of hot, freshly accreted material which is not captured in BL models. We apply these same methods to the case of WDs (Piro & Bildsten 2004a; hereafter PB04a) and call this model the spreading layer (SL), to differentiate it from BL studies.

The SL is found to be a thin hot band of extent $\theta_{SL} \approx 0.01 - 0.1$ radians, with an effective temperature of $\sim (2 - 5) \times 10^5 \, \text{K}$ for $\dot{M} = 10^{17} - 10^{19} \, \text{g s}^{-1}$,
implying that it contributes to accreting WD spectra in the extreme ultraviolet (EUV) and soft X-rays. At low $\dot{M} \lesssim 10^{18}$ g s$^{-1}$ the spreading is small, so that its radiation is absorbed by the accretion disk or its winds. Nevertheless, the SL may be important for calculating the underlying continuum scattered by these winds.

The material in the SL is much hotter in temperature and lower in density than the underlying WD. This contrast allows waves in the SL to travel freely, unencumbered by the material below. We propose that dwarf nova oscillations (DNOs) are shallow surface waves in a layer of recently accreted material confined to the WD equator (Piro & Bildsten 2004b; hereafter PB04b). This model explains the main properties of DNOs, including their sinusoidal nature, dependence on $\dot{M}$, large pulsed amplitude in the EUV, and why they are only seen during outburst.

2. The Spreading Layer Calculation

The SL is treated as a one-zone, plane-parallel layer with $\theta$ (the angle from the equator) as the independent coordinate. The surface gravitational acceleration is significantly decreased by centrifugal effects due to the nearly Keplerian speed of the layer, so we use an “effective” gravitational constant

$$g_{\text{eff}} = \frac{GM}{R^2} - \frac{v_\theta^2}{R} - \frac{v_\phi^2}{R} \approx \frac{GM}{R^2} \frac{v_\phi^2}{R}$$

where $v_\theta$ and $v_\phi$ are the latitudinal and azimuthal velocities, respectively. Hydrostatic balance integrates to $P = g_{\text{eff}} y$, where $y$ is the column depth (cgs units of g cm$^{-2}$). The flux in the layer is assumed constant since most of the viscous dissipation occurs at the layer’s base. Radiative diffusion integrates to

$$F = \frac{a c T^4}{3 \kappa y}$$

where $a$ is the radiation constant and $\kappa = 0.34$ cm$^2$ g$^{-1}$ is the Thomson scattering opacity for a solar composition.

We insert this one-zone model into a set of differential equations describing the steady-state conservation of mass, momentum, and energy, as done by IS99 for NSs. The total viscous stress, $\tau$, is from the turbulence created as high entropy fluid quickly rotates against the lower entropy WD material below, so parametrizing $\tau$ in terms of a unitless constant, $\alpha_{\text{SL}}$,

$$\tau = \alpha_{\text{SL}} \rho v^2$$

where $v^2 = v_\theta^2 + v_\phi^2$. We treat $\alpha_{\text{SL}}$ as a free parameter and study its effect on the spreading properties for the values $\alpha_{\text{SL}} = 10^{-4} - 10^{-2}$. This range is chosen for the physically realistic solutions that result (see PB04a for further discussion).

Integration requires setting boundary conditions for $\theta, T, v_\theta$, and $v_\phi$. Shakura & Sunyaev (1973; for gas pressure dominating radiation pressure and a Kramer’s opacity) show the disk subtends an angle at the WD surface

$$\theta_{\text{disk}} = 1.8 \times 10^{-2} \alpha_{\text{disk}, 2}^{-1/10} M_{17}^{-3/20} M_1^{-3/8} R_{9}^{1/8}$$
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where \( \alpha_{\text{disk}} \) is the viscosity parameter for the accretion disk, \( \alpha_{\text{disk,2}} \equiv \alpha_{\text{disk}}/10^{-2} \), \( \dot{M}_{17} \equiv \dot{M}/(10^{17} \text{ g s}^{-1}) \), \( M_1 \equiv M/M_\odot \), \( R_9 \equiv R/(10^9 \text{ cm}) \), and we set the factor \( [1 - (r/R)^{-1/2}] \approx 1 \). The material which comes in from the disk must start at an angle \( \sim \theta_{\text{disk}} \), so we use an initial angle of \( \approx 10^{-3} \). The initial \( v_\phi \) is set to 0.

\( v_K = (GM/R)^{1/2} \) is the Keplerian velocity, and the initial \( T \) is set using the disk’s midplane temperature (Shakura & Sunyaev 1973). Finally, the initial \( v_\theta \) is set by the natural tendency for the differential equations to asymptote to the limit where initially the viscous dissipation is radiated away locally (PB04a).

This is different than what IS99 find for NSs, where more advection takes place, due to \( \dot{M} \) closer to the Eddington limit.

In Figure 1 we plot the velocities, \( T \), \( T_{\text{eff}} \) and the pressure scale height, \( h = P/(\rho g_{\text{eff}}) \), of the SL for \( \alpha_{\text{SL}} = 10^{-3} \) and a range of \( \dot{M} \). At the high accretion rates (\( \dot{M} \sim > 10^{19} \text{ g s}^{-1} \)) more advection takes place, resulting in solutions which look similar to what IS99 found for NSs. Most notably, the \( T \) profiles show large peaks at high latitudes due to energy being advected away from the equator and deposited higher up on the star. The panel plotting \( T_{\text{eff}} \) has an additional dashed line at \( 3 \times 10^4 K \), a fiducial temperature of the underlying accreting WD (Townsley & Bildsten 2003) to show the contrast between it and the SL.

Using the results from Figure 1, we plot the dependence of \( \theta_{\text{SL}} \) on \( \dot{M} \) in Figure 2. This shows that high \( \dot{M} \) are needed for any hope of appreciable spreading to take place, so that typically the SL will be absorbed and re-radiated by the accretion disk and its winds. Nevertheless, even when the accretion disk covers the main portion of the SL, the profiles of \( T_{\text{eff}} \) shown in Figure 1 are important for understanding the WD spectra.

3. Comparisons to Dwarf Novae in Outburst

The high \( \dot{M} \) needed for appreciable spreading suggests that a good candidate to show a SL are dwarf novae in outburst. Evidence for spreading can be explored by following \( T_{\text{eff}} \) versus \( \dot{M} \) in the EUV. Since we find that the radiating area increases with \( \dot{M} \), the SL model predicts a shallower change in \( T_{\text{eff}} \) with \( \dot{M} \) than if the radiating area was fixed. PB04a use this relation in an attempt test for evidence of spreading during an outburst of SS Cyg (Wheatley, Mauche & Mattei 2003), but are not able to make any definite conclusions with the current data. Further detailed observations following CVs in outburst are needed to test the SL model in better detail.

The ease of investigating the SL depends on the angle of the observed system. Face-on systems show a continuum most likely from the SL region, but with strong absorption lines from the disk winds (Mauche 2004). Assuming the fractional emitting area is approximately equal to \( \theta_{\text{SL}} \), modeling of this spectra finds \( \theta_{\text{SL}} \approx 5.6^{+6.0}_{-4.5} \times 10^{-3} \) (for SS Cyg; Mauche 2004), which, though not highly constraining, is consistent with our calculations. Edge-on systems show evidence of a SL emission that is scattered into the line of sight by line emission in the disk winds (OY Car; Mauche & Raymond 2000), but is otherwise obscured by the accretion disk. It is therefore difficult to make direct comparisons with the SL model.
Figure 1. The velocities, temperature, effective temperature and pressure scale height of the SL for a WD with $M = 0.6 \, M_\odot$ and $R = 9 \times 10^8 \, \text{cm}$, with $\alpha_{\text{SL}} = 10^{-3}$ and $\alpha_{\text{disk}} = 0.1$. From left to right the $\dot{M}$ are $10^{17}$, $10^{18}$, $10^{19}$ and $3 \times 10^{19} \, \text{g s}^{-1}$. The dashed lines shows $T_{\text{eff}} = 3 \times 10^4 \, \text{K}$, a fiducial temperature for the underlying accreting WD (Townsley & Bildsten 2003).

4. Dwarf Nova Oscillations

DNOs are oscillations observed during dwarf nova outbursts that have periods of $P \approx 3 - 40 \, \text{s}$, scale monotonically with EUV luminosity, and thus $\dot{M}$ (Mauche 1996), and are fairly coherent ($Q \sim 10^4 - 10^6$). Their large pulsed fraction in
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Figure 2. The spreading angle, $\theta_{SL}$, versus $\dot{M}$ for a WD with $M = 0.6 M_\odot$ and $R = 9 \times 10^9$ cm and three values of $\alpha_{SL}$. The spreading angle is defined as the angle at which $v_\phi = 0.1 v_K$. This shows that high $\dot{M}$ are needed for the SL to extend beyond the angle made by a Shakura-Sunyaev disk, equation (4) (dashed line).

the EUV implies that they originate close to the WD surface and have a similar covering fraction as the SL (Córdova et al. 1980; Mauche & Robinson 2001; Mauche 2004). We propose that DNOs are produced by nonradial oscillations in the SL (PB04b). In the following sections we present a simple model to describe these oscillations and make comparisons with observations.

4.1. Nonradial Oscillations in the SL

Patterson (1981) showed that (at the time) all known DNOs on WDs with measured masses have $P \gtrsim P_K = 2\pi(R^3/GM)^{1/2}$. This relation is an important constraint for any explanation of DNOs, so we first show why a SL mode should mimic such a period. The large entropy contrast between the surface layer and the underlying material confines nonradial oscillations to high altitudes with little or no pulsational energy extending deeper into the WD. When the horizontal wavelength is much greater than the layer depth, these shallow surface waves have a frequency

$$\omega^2 = g_{\text{eff}} h k^2,$$

where $k$ is the transverse wavenumber. The SL can be thought of as a waveguide with latitudinal width $2\theta_{SL}R$ and azimuthal length $2\pi R$, but since $\theta_{SL} \ll 1$ the latitudinal contribution dominates, so $k \sim 1/(\theta_{SL}R)$. Setting $g_{\text{eff}} = \lambda GM/R^2$,
where $\lambda \lesssim 1$ is a dimensionless parameter that depends on the spin of the layer, we rearrange the terms in equation (5) to find

$$\omega = \left(\frac{GM}{R^3}\right)^{1/2} \left(\frac{\lambda h}{\theta_{\text{SL}}^2 R}\right)^{1/2},$$

(6)

so that the mode’s frequency is the Keplerian frequency times a factor less than unity (as long as $\lambda h \lesssim \theta_{\text{SL}}^2 R$), and therefore consistent with Patterson (1981).

To find how these modes scale with $\dot{M}$ and $M$ we consider a simple model to estimate $h$. Approximately half of the accretion luminosity is released at the WD surface, so that the flux of this layer is given by $4\pi\theta_{\text{SL}}^2 R^2 F = GM\dot{M}/(2R)$. This flux is related to $T$ by radiative diffusion, equation (2). The column depth is set by continuity to be $y = \dot{M} t_{\text{SL}}/(4\pi\theta_{\text{SL}} R^2)$, where $t_{\text{SL}} = h^2/\nu$ is the timescale for viscous dissipation in the SL. The viscosity between the fresh material and the underlying WD is given by $\nu \approx \tau h/(\rho v\phi) \approx \alpha_{\text{SL}} v\phi h \approx \alpha_{\text{SL}} v_K h$. Using an ideal gas equation of state, the above set of equations can be solved for $h$. We set $\theta_{\text{SL}} \sim \theta_{\text{disk}}$ using equation (4), since the disk may be setting the spreading angle as suggested by Figure 2. Equation (5) then gives a period

$$P_{m=0} = 30 \text{ s} \alpha_{\text{disk},\text{2}}^{-2/15} \alpha_{\text{SL},\text{3}}^{-1/6} \lambda_1^{1/6} M_{17}^{-2/15} M_1^{-1/3} R_{9}^{19/12},$$

(7)

where $\lambda_1 \equiv \lambda/10^{-1}$. Since this lowest order mode does not propagate in the azimuthal direction, we denote it with azimuthal wavenumber $m = 0$. Equation (7) provides both a scaling with $\dot{M}$ and a period suggestive of DNOs.

The SL can contain additional modes, most notably those that propagate in the azimuthal direction. These modes have an observed frequency of $\omega_{\text{obs}} = |\omega - m\omega_{\text{SL}}|$, where $\omega_{\text{SL}}$ is the spin of the SL and $m$ is the azimuthal wavenumber. Even though the layer is spinning quickly, Coriolis effects will not alter $k$, since $\theta_{\text{SL}} \lesssim \omega/(2\omega_{\text{SL}})$ (Bildsten, Ushomirsky & Cutler 1996). Setting $P_{\text{SL}} = 2\pi/\omega_{\text{SL}}$, where $P_{\text{SL}} \gtrsim P_K$, the next lowest order modes have

$$\frac{1}{P_{m=\pm 1}} = \left|\frac{1}{P_{m=0}} \mp \frac{1}{P_{\text{SL}}}\right|,$$

(8)

for their periods.

### 4.2. DNOs in the CV Population

We compare the most recent compilations of DNO periods (Table 1 of Warner 2004) and WD masses (Ritter & Kolb 2003) of CVs in Figure 3. We plot systems that have shown both high and low DNO periods as two separate points (these CVs are SS Cyg, CN Ori, and VW Hyi). The heavy, dashed line denotes the surface Keplerian period, $P_K$, for a given WD mass (using the mass-radius relation of Truran & Livio 1986). This demonstrates that DNOs exist both above and below $P_K$, so we consider SL nonradial oscillations with $m = 0$ and $m = -1$. For each mode we plot periods for $\dot{M} = 10^{16} - 10^{18} \text{ g s}^{-1}$, the range expected during a DN outburst. To calculate the $m = -1$ mode we must assume a period for the SL’s spin, $P_{\text{SL}}$, so we plot mode periods for both $P_{\text{SL}} = P_K$ and $P_{\text{SL}} = 2P_K$. This shows that our model is insensitive to the SL spin rate.
Figure 3. The DNO periods versus measured WD masses. The vertical bars show the range of periods observed from each CV, while the horizontal bars are mass measurement errors. CVs that have shows two distinct DNO periods are plotted as two separate points. The thick dashed line is the Keplerian period, $P_K$. The $m = 0$ mode (wide, heavy shaded region) is plotted for $\dot{M} = 10^{16} - 10^{18} \text{ g s}^{-1}$ (from top to bottom), using equation (7). The $m = -1$ mode is also plotted for $\dot{M} = 10^{16} - 10^{18} \text{ g s}^{-1}$ (from top to bottom), for both $P_{\text{SL}} = P_K$ (light shaded) and $P_{\text{SL}} = 2P_K$ (medium shaded), using equation (8).

Besides predicting multiple classes of DNOs with different period ranges, we also predict that each of these groups should have a different dependence on $\dot{M}$. This can be seen from the size of each shaded band, which is much wider for the $m = 0$ mode than the $m = -1$ mode. The DNOs with $P \lesssim P_K$ show less variation with $\dot{M}$, qualitatively consistent with the $m = -1$ mode of our model. To further investigate the $\dot{M}$ dependence we plot our predicted DNO periods versus $\dot{M}$ for a $M = 1.0 M_\odot$ WD in Figure 4. This illustrates the shallower dependence for the $m = -1$ mode. The separation and relative slopes of the
$m = -1$ and $m = 0$ modes are suggestive of the frequency doubling during the October 1996 outburst of SS Cyg (Mauche & Robinson 2001).

In Figure 4 we also plot the $m = 1$ retrograde mode for $P_{\text{SL}} = (1 - 1.5) \times P_K$. Due to the difference taken in equation (8), this mode has a complicated dependence on $\dot{M}$, no longer being a power law nor monotonic. It has a higher period than typical DNOs, and may be relevant for the long period DNOS (lpDNOs; Warner, Woudt & Pretorius 2003). To identify these as modes requires checking for this predicted scalings between $P$ and $\dot{M}$. Such a test may negate a mode explanation for lpDNOs since Warner et al. (2003) claim to find no such correlation and thus favor a spin related mechanism. On the other hand, on separate occasions there have been $32 - 36$ s (Robinson & Nather 1979) and $83 - 110$ s (Mauche 2002b) oscillations seen from SS Cyg, in the domain expected for these modes. This wide spread of periods may be explained by the $m = 1$ mode’s steeper dependence on $\dot{M}$. The $32 - 36$ s oscillations showed less coherence than typical DNOs, which could be due to these retrograde oscillations beating against the accretion disk. Oscillations from VW Hyi at $\sim 90$ s (Haefner, Schoembs & Vogt 1977) may be of similar origin.
An important property of WDs that would affect the modes is a magnetic field. A strong field inhibits shearing between the SL and WD and modifies the frequency of shallow surface waves. It is therefore interesting that no intermediate polars (IPs) have shown DNOs or lpDNOs. Even LS Peg and V795 Her, neither of which are IPs, but both show polarization modulations (Rodríguez-Gil et al. 2001, 2002) indicative of a reasonably strong magnetic field, are without DNOs or lpDNOs.

5. Discussion and Conclusions

The SL model provides a new area of investigation in the study of accreting objects. The initial calculations by IS99 and in this paper describe the main features of spreading that will lead to further studies of how accreted material settles onto stars. This may include studying how differential rotation affects the underlying stellar surface. Spectral modeling of the SL, along comparisons with observations, will help in identifying if and when spreading is present. In this review we focus on comparisons with dwarf novae, but symbiotic binaries (Sokoloski 2004) and supersoft sources are also promising for studying the SL.

We propose that DNOs in outbursting CVs are nonradial oscillations in the SL. A number of DNO properties are then simply understood: (1) the highly sinusoidal nature of the oscillations is consistent with nonradial oscillations, (2) the periods can change on the timescale of accretion because there is little mass in the layer \(\lesssim 10^{21} \text{ g; PB04}\), (3) the periods vary inversely with \(\dot{M}\) because they have the temperature scaling of shallow surface waves, (4) the covering fraction is naturally small for the SL, (5) the DNOs are only seen during DN outbursts when an optically thick layer of material builds up at the equator, and (6) the largest pulsed amplitude is in the EUV, consistent with the SL temperature.

There are difficulties that must be answered about this idea for explaining DNOs. From the SL model we borrowed the concept of hot material in hydrostatic balance covering a small fractional area of the WD, but we ignored important details of these calculations, and instead only presented a very simple model for the modes. The data do not require such additional complications, so we refrain from including them for now. In a more sophisticated model it would probably still be true that \(k \propto 1/(\theta_{\text{SL}} R)\), but an eigenvalue calculation would determine the constant of proportionality.

Further studies should work toward understanding the excitation mechanism for the modes, which would explain the high coherence typical of DNOs. Material deposited at the WD equator spreads quickly, \(~ 10 - 100 \text{ s (PB04a)}\), so that following an outburst, when \(\dot{M}\) has fallen, the accreted material will spread over the star and not be seen as a separate hot component. This also means that the material is moving through the oscillating region on timescales of order the mode period. This short timescale is problematic if the modes are to remain coherent, which puts limits any proposed excitation mechanism.

Our explanation of DNOs raises interesting questions about the relationship between oscillations originating from accreting compact objects. Mauche (2002b) showed that there is a correlation in the high to low oscillation frequency ratio of WDs, NSs, and black holes (BH). Using this picture, DNOs are associated with the kilohertz QPOs of low mass X-ray binaries. Suggestively, the
Fourier frequency resolved spectroscopy of NSs (Gilfanov, Revnivtsev & Molkov 2003) imply that both the normal branch oscillations and the kilohertz QPOs originate in the NS BL. Using a NS mass and radius our model provides frequencies in the range expected for kHz QPOs, but it does not explain their $P$-$L$ relation (the “parallel tracks”; van der Klis 2000). Interestingly, DNOs may also show the parallel tracks phenomenon, as seen in three observations of SS Cyg (Mauche 2002a), once again supporting the correlation. On the other hand, continuing the analogy to WD and BH oscillations is problematic because in the case of BHs there is no surface for nonradial oscillations.

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