A Boundary Layer Origin for Dwarf Nova Oscillations

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Received ______________________; accepted ______________________

ABSTRACT

Dwarf nova oscillations (DNOs) have been observed in a number of cataclysmic variables. I propose that these oscillations could be produced by a non-axisymmetric bulge at the transition between the optically thick disk and the optically thin boundary layer region. This would naturally explain the observed oscillation periods and the dependence of the oscillation amplitude on photon energy. The transition radius moves inward and outward with changing mass accretion rate, which explains the correlation between period and flux, and the timescale for period variations. The underlying cause of the non-axisymmetry which produces the oscillations is not known, so it is not possible to predict the oscillation amplitude from first principles.

1. Introduction

Dwarf nova oscillations (DNOs) in the light from cataclysmic variables (CVs) have been observed for over 25 years, but the origin of these oscillations remains mysterious. DNOs are periodic variations in the observed flux, which are observed both in the optical/UV and in the EUV/soft X-ray bands (see Warner 1995 for an excellent review). They have periods comparable to the Keplerian rotation period at the surface of a white dwarf, and amplitudes which are large in the X-ray and EUV but small in the optical. Thus it is generally thought that they originate from either the accreting white dwarf or the hot inner regions of the disk. The oscillation periods vary on a timescale of hours, systematically decreasing as the observed flux from the system increases and vice versa.

In one major class of models, the oscillation is produced by a bright spot on the surface of a rotating white dwarf. The changes in oscillation period occur too rapidly to be due to the whole white dwarf being spun up or down. Instead one must assume that the rotation of a thin surface layer containing the bright spot is decoupled from the rotation of the rest of the white dwarf (Paczyński 1978). The mass of this layer is assumed to be such that it spins up on the correct timescale. Warner (1995) proposes a variant of Paczyński's model where DNOs arise if the white dwarf magnetic field is strong enough to channel the accretion flow onto spots, as in the DQ Her stars, but weak enough to allow the surface layers to spin at a different rate than the interior. The DNO periods decrease during outburst due to accretion spinup of the surface layer, and then increase again due to viscous interaction between the surface layer and the interior.

This "decoupled spot" model clearly relies on several untested assumptions; in addition, it disagrees with some of the observed characteristics of DNOs. For instance, it is difficult to understand why pulsations from hot spots would not be present during quiescence. The model also disagrees with the observed period variations of DNOs. It predicts that $\dot{P}$ is proportional to the net torque on the surface layer, the difference between the accretion spinup and the viscous spindown. Since the accretion torque should be proportional to $\dot{M}$, one would expect that the surface layer would spin down when $\dot{M}$ is low, and spin up whenever $\dot{M}$ is high enough to make the accretion torque exceed the viscous torque. But DNO periods reach their minimum values and start to increase again at the time of outburst maximum, when $\dot{M}$ and the spinup torque should be largest. Put more succinctly, the decoupled spot model would predict a correlation between $\dot{P}$ and $\dot{M}$, while DNOs show a correlation between P and $\dot{M}$.

Finally, the model requires that the surface layers of white dwarfs in DNO-producing systems must be rotating at near-Keplerian speeds. Observed rotational velocities of the surface layers of white dwarfs in quiescent dwarf novae, as given by the best-fit spectral models, are a few hundred km/s (e.g. U Gem (Sion *et al.*1994), VW Hyi (Sion *et al.*1995)). This implies that their rotation periods are on the order of a few hundred seconds, much longer than the DNO periods. The timescale to spin up the envelope to the observed near-breakup rotation periods is $P/|\dot{P}| \simeq 3 \times 10^6$ s, much longer than the rise time of an dwarf nova outburst.

Another major class of DNO models involves rotating features in the inner disk or the boundary layer between the disk and the white dwarf. The observed characteristics of DNOs tend to support an inner disk or boundary layer origin in several ways. First, the periods of the optical DNOs are quite close to the Keplerian rotation periods at the surface of white dwarfs, which are in the range $P_K(R_*) \simeq 7 - 18$ s for white dwarf masses of $1.0 - 0.6\mathrm{M}_\odot$, respectively. This suggests that the oscillations originate from the the inner part of the disk, which should be rotating at Keplerian velocity, or the boundary layer between the disk and the star. Second, the oscillation has the largest amplitude in the extreme ultraviolet (EUV) and soft X-ray bands. This also suggests an origin in the inner disk or the boundary layer, where the gas is hot enough to produce EUV and soft X-ray radiation. The white dwarfs in CVs are probably heated by accretion, but the effective temperature of the white dwarf surface is generally a few $\times 10^4$ K, rather than a few $\times 10^5$ K as needed to produce soft X-rays. Third, the tight relationship between the oscillation period and the observed count rate implies a similar relation between the period and the mass accretion rate. This also seems to favor a disk origin for the oscillations, since all the disk properties depend directly on $\dot{M}$, whereas the white dwarf properties do not.

Disk models also face some serious difficulties. Features in the disk are rapidly sheared apart by differential rotation. If the radial extent of the bulge corresponds to different rotation periods, it may produce a broader range of periods than is observed. A bulge in the disk should drift inward, so its rotation period should always decrease, whereas the oscillation periods have been observed to both increase and decrease. Finally, a bulge in the inner disk will be eclipsed by the white dwarf in high-inclination systems, producing non-sinusoidal light curves, as argued by Knigge *et al.*(1998).

In this paper I propose that DNOs are produced by a nonaxisymmetric bulge at the transition radius where the optically thick inner disk and the optically thin boundary layer meet. §2 begins by discussing the nature of the optically thick–to–thin transition which is inferred from X-ray observations of CVs and seen in models of CV boundary layers. Next, the scenario for producing DNOs at the transition radius, and how such a scenario can overcome the difficulties listed above, is described in more detail. Finally, the predictions of this scenario are compared to the observed characteristics of DNOs. §3 discusses the implications of the model and useful observational tests of the model predictions.

2. A Boundary Layer Origin for DNOs

2.1. Optically Thin Boundary Layers in CVs

The soft X-ray and EUV radiation observed from CVs is thought to originate from the boundary layer between the inner accretion disk and the accreting white dwarf. Hard X-rays tend to be produced by systems with low mass accretion rates, like dwarf novae in quiescence. When dwarf nova outbursts occur, the accretion rate increases rapidly, and the system brightens in both optical and soft X-ray light, but hard X-ray production is suppressed (e.g., Jones & Watson 1992). This has long been thought to be due to the change in the vertical optical depth of the boundary layer region. At low accretion rates, the boundary layer is optically thin and cools inefficiently, so it reaches very high temperatures and radiates hard X-rays. When the accretion rate increases in an outburst, the boundary layer becomes optically thick and cools more efficiently, radiating EUV and soft X-rays. This scenario was worked out by Pringle (1977), Pringle & Savonije (1979), Tylenda (1981), and Patterson & Raymond (1985).

Narayan & Popham (1993, hereafter NP) did boundary layer calculations which supported and quantified this scenario for X-ray production in CVs. Models with low accretion rates of $10^{-9.5}$ and $10^{-10.5}$ $M_\odot$ yr^{-1} develop an optically thin zone in the boundary layer region. The radial width and temperature of this zone increases as the accretion rate decreases. In the optically thin zone, free-free radiation cannot radiate away all the energy that is dissipated, and some of this energy heats the accreting gas and is advected inward with the gas. The gas reaches temperatures $T \sim 10^8$ K and radiates hard X-rays.

The transition between the optically thick inner disk and the optically thin boundary layer region is quite abrupt, as shown in Figure 1. The gas temperature jumps by about 3 orders of magnitude, reaching temperatures in excess of 10^8 K and producing hard X-ray emission. The gas density drops by a similar factor, from $10^{-5} - 10^{-6}$ g cm^{-3} in the inner disk to $10^{-8} - 10^{-9}$ g cm^{-3} in the optically thin region. When it reaches the surface of the white dwarf, the heated gas piles up, becomes optically thick again, and radiates EUV and soft X-rays.

In models with high accretion rates ($10^{-7.5}$ and $10^{-8.5}$ $M_\odot$ yr^{-1}), the boundary layer is optically thick (in fact, the $10^{-8.5}$ $M_\odot$ yr^{-1} solution contains a small optically thin region). The optically thick boundary layers have effective temperatures of a few $\times 10^5$ K, producing soft X-rays.

2.2. A Boundary Layer Scenario for DNOs

Here I propose that DNOs are produced by a nonaxisymmetric bulge in the disk, located at the transition radius between the optically thick inner disk and the optically thin boundary layer. The bulge rotates at the local Keplerian velocity, and thus the oscillation period is just the Keplerian period at the transition radius. Variations in the DNO period are produced by changes in $\dot{M}$. As $\dot{M}$ increases during a dwarf nova outburst, the optical depth of the disk increases and the transition radius moves inward, so the oscillation period gets shorter. Similarly, as $\dot{M}$ declines, the period gets longer.

The size of the bulge must be sufficient to produce the observed modulation in soft X-ray and EUV flux. Córdova *et al.*(1980) found that a emitting region with $kT \sim 30$ eV and an emitting area $A \sim 2 \times 10^{15}$ cm^2 could produce the observed soft X-ray modulation in SS Cygni. Mauche *et al.*(1995) also found $kT \sim 20 - 30$ eV based on the EUV spectrum of SS Cygni in outburst.

Optical DNOs are produced mostly by reprocessing of the EUV and soft X-ray light from the bulge. There is also a contribution to the optical oscillations from light emitted directly by the bulge, but this is small, since a bulge with the temperature and emitting area inferred from the X-ray observations would produce a very small optical flux. The optical DNOs must originate from a region with a size comparable to that of the disk; in eclipsing systems the eclipse of the DNOs has a similar width to that of the disk (Schoembs 1986; Knigge *et al.*1998).

When $\dot{M}$ is high, the boundary layer region becomes optically thick (NP), and a large drop in hard X-ray production is predicted and observed (e.g., Jones & Watson 1992). Thus it would appear that the DNOs should also vanish during outburst, but in SS Cyg they are present when the hard X-ray flux has dropped to low values (Jones & Watson 1992). However, in the models there is a fairly wide range of $\dot{M}$ in which an optically thin zone exists in the boundary layer, but is not hot enough to produce large fluxes of hard X-rays.

If the bulge sits at the transition radius between the optically thick disk and the optically thin boundary layer, several problems usually associated with disk models are alleviated. As the infalling gas crosses the transition radius, its density and opacity drop very abruptly. In effect, there is a "wall" at the transition radius, which is illuminated by the boundary layer radiation. This sharp transition means that only a single period will be produced, rather than a range of periods corresponding to a range of radii. Also, the period of the oscillation can decrease or increase as the transition radius moves in or out in response to changes in the accretion rate.

Direct light from a rotating bulge in the inner disk will be eclipsed as the bulge passes behind the white dwarf if the bulge is located at $R < R_{WD}/\cos i$, where i is the inclination. Thus, one prediction of this scenario is that high-inclination systems should show non-sinusoidal X-ray light curves containing eclipses. Since the optical DNOs come from reprocessing by the whole surface of the disk, eclipses of a small portion of the inner disk by the white dwarf should be less prominent in the optical light curves.

A common problem for models involving features in the disk is that these are sheared apart rapidly by differential rotation. A bulge in the disk with radial extent ΔR experiences a rotational velocity difference $\Delta v \sim (dv_K/dR)\Delta R \sim (1/2)\Omega_K \Delta R$. Thus, if one were to place a lump of denser gas within the disk, it would not survive for long. However, a bulge at the inner edge of the optically thick disk would presumably be created by a nonaxisymmetric instability in the disk. Rather than being "dropped" into the disk, the bulge would have to arise spontaneously in the presence of differential rotation. Thus, the length of time over which the bulge will survive in the presence of differential rotation depends more on the instability mechanism than on the timescale for differential rotation.

A major unknown in this theory is the origin of the bulge or nonaxisymmetry at the transition radius. The obvious candidate is an $m = 1$ nonaxisymmetric instability. Axisymmetric vertical or radial instabilities could also produce oscillations in the flux, but cannot account for the eclipse-related phase shifts observed in some systems. The sharp density cutoff at the transition radius can serve as a reflecting boundary, the presence of which may be essential to the growth of an instability (Goldreich & Narayan 1985). Nonaxisymmetric $m = 1$ instabilities have been seen in some disk simulations (e.g., Blaes & Hawley 1988; Różyczka & Spruit 1993), albeit with somewhat different physics. Until the instability mechanism which produces the proposed bulge at the transition radius can be identified and studied in more detail, it will be impossible to predict the oscillation amplitude or pulse shape from first principles.

2.3. Comparison With Observations

Periods: The periods of DNOs are observed to fall in the range 2.8–39 s. These periods are $\sim 1 - 2$ times the Keplerian rotation periods at the stellar surface for white dwarfs in the mass range $\sim 0.5 - 1.3 \mathrm{M}_{\odot}$. In the model, DNOs should have periods given by $P_K(R_{tr})$, and we should have $R_* < R_{tr} <$ few R_*. For example, for the two models shown by NP, $R_{tr} \simeq 1.16 R_*$ and $R_{tr} \simeq 1.44 R_*$ for $\dot{M} = 10^{-9.5}$ and $10^{-10.5}$ $M_\odot$ yr^{-1}, respectively. These transition radii will produce DNO periods of 1.25 and 1.73 times $P_K(R_*)$.

Most systems show DNO periods in the 20–30 second range. This is expected since most white dwarfs have masses in the low end of the range given above (Webbink 1990; Bergeron, Saffer, & Liebert 1992), corresponding to longer rotation periods. For example, $P_K(R_*) \simeq 18$ s for a $0.6 M_\odot$ white dwarf, using the mass-radius relation of Nauenberg (1972).

Timescale for Period Changes: Period changes result from changes in $\dot{M}$, which cause the transition radius to move in or out. This will happen on the viscous timescale $t_{visc} = R^2/\nu \simeq \alpha^{-1}\Omega_K^{-1}(H/R)^{-2}$. Using $P = 2\pi/\Omega_K$, $\alpha = 0.1$, and $H/R \sim 0.01$ for the optically thick inner disk from the models of NP, we find $t_{visc} \simeq 10^5 P/2\pi$. This matches the observed timescales for period change $t_{spinup} = P/|\dot{P}|$, since observed values of $|\dot{P}|$ are in the range $10^{-4} - 10^{-6}$.

Variation of Period with Flux: Observations of high-energy DNOs in SS Cygni have shown $d\log P/d\log F \simeq (-0.1) - (-0.15)$ (Jones & Watson 1992; Mauche 1996). In the optical, the relation varies from star to star, but is generally somewhat steeper, with $d\log P/d\log F \simeq -0.25$ (Warner & Robinson 1972; Nevo & Sadeh 1976; Patterson 1981; Warner, O'Donoghue, & Allen 1985; Warner, O'Donoghue, & Wargau 1989). Since the DNOs occur in the hot inner disk, the high-energy DNOs should provide a better comparison to the model. In the models presented by NP, we have $P(R_{tr}) \simeq 7.9$ s at $\dot{M} = 10^{-9.5}$ $M_\odot$ yr^{-1} and $P(R_{tr}) \simeq 10.5$ s at $\dot{M} = 10^{-10.5}$ $M_\odot$ yr^{-1} (Fig. 1), giving $d\log P/d\log \dot{M} \sim -0.14$, which matches the measured values for high-energy DNOs in SS Cygni quite well.

Range of Periods for Individual Stars: The DNO period of an individual star generally varies by a factor of $\lesssim$1.5. In the NP models, the rotation period at the transition radius R_{tr} increased by a factor of ~ 1.4 as $\dot{M}$ decreased from $10^{-9.5}$ to $10^{-10.5}$ $M_\odot$ yr^{-1} (Fig. 1). In both SS Cygni (van Teeseling 1997) and VW Hydri (van der Woerd *et al.*1987), soft X-ray DNOs have been observed with substantially shorter periods than the optical DNOs from the same system. These would require correspondingly larger variations in $\dot{M}$.

Amplitude: Until the mechanism which produces the bulge at the boundary layer/inner disk transition is better understood, one cannot predict the oscillation amplitudes from first principles. By modeling the optical oscillations which would be produced by reprocessing of the high-energy radiation from a bulge of a given size and shape located at a given position in the disk, it should be possible to use the observed oscillation amplitudes (and pulse profiles, as discussed below) to constrain these parameters.

Appearance and Disappearance with Changing $\dot{M}$: We expect the oscillations to be seen when the boundary layer has an optically thin region. The absence or disappearance of the oscillations at the peak of outburst, as observed in several systems (e.g. VW Hyi, Warner & Brickhill 1978; AH Her, Hildebrand *et al.*1980), may be due to the disappearance of the optically thin region at high $\dot{M}$. The oscillations are also not detected during quiescence. Observations of DNOs in systems fading toward quiescence indicate that this may be due to a decrease in the coherence of the oscillations (Hildebrand, Spillar, & Stiening 1981; Cordóva *et al.*1984).

Pulse Shape: The model predicts non-sinusoidal oscillations in the X-rays and EUV for systems viewed at high inclination. In SS Cyg, the oscillations are quite accurately sinusoidal (Córdova *et al.*1980; Jones & Watson 1992; Mauche 1996; van Teeseling 1997); however, the inclination of this system is only 33°, so no eclipses would be expected unless $R_{tr} \lesssim 1.2 R_{WD}$. The other two systems in which X-ray oscillations have been observed, VW Hyi and U Gem, are both viewed at larger inclinations (60° and 70°, respectively) and thus should show eclipses when $R_{tr} \lesssim 2R_{WD}$ and $R_{tr} \lesssim 2.9R_{WD}$, respectively. In both cases, the existing X-ray power spectra are too noisy to tell whether the oscillations are sinusoidal or not (van der Woerd *et al.*1987; Córdova *et al.*1984).

The pulse shape of the optical/UV oscillations is determined by the reprocessing from the disk, and potentially from the white dwarf and companion star as well. The pulse shape will depend on a number of parameters, and will be explored further in a later paper.

Eclipse-Related Phase Shifts: Both UX UMa and HT Cas show a phase shift in the oscillations during eclipse by the secondary, such that one cycle is lost over the course of the eclipse (Nather & Robinson 1974; Patterson 1981; Knigge *et al.*1998). According to calculations by Petterson (1980), this implies that the bright part of the oscillation occurs when the part of the disk closest to the observer is illuminated. But the reprocessed flux from a concave disk surface should be brightest when the back side of the disk is illuminated. Therefore Petterson (1980) and Knigge *et al.*(1998) argued that most of the oscillating light in the optical/UV DNOs from UX UMa must be seen directly, while reprocessed flux makes up a smaller share. However, the gradual and incomplete eclipses of the oscillating light show that this light comes from a large portion of the disk.

The calculations by Petterson (1980) assumed that the disk has an inner edge at $R_{in} = 3.5R_{WD}$, thus eliminating reprocessing by the inner part of the disk, as well as "eclipses" of the inner disk by the white dwarf. When these calculations are redone with the disk extending all the way in to the star, the eclipse by the white dwarf reduces the amount of reprocessed light from the back side of the disk below that from the front side without requiring any direct light from the oscillating source. These results will be reported in a future paper.

3. Discussion

If the model presented here is correct, it would have important implications for our understanding of accretion in CVs and LMXBs. Most simply, it would allow us to observe the rotation periods in the inner disk directly. This would place constraints on the white dwarf mass in CVs; for instance, the 2.8-s oscillations in SS Cygni would constrain the white dwarf mass in this system to be $\gtrsim 1.25 M_{\odot}$ (van Teeseling 1997).

Observations of DNOs could also be combined with models of the boundary layer region to study the mass accretion rate and viscosity parameter in CV disks. Changes in the oscillation period could be used to estimate the changes in $\dot{M}$ at the inner edge of the disk during dwarf nova outbursts. These variations in $\dot{M}$ could then be compared to the changes in the observed fluxes and colors in the X-ray, UV, and optical bands. Popham & Narayan (1995) showed that the optical depth of the boundary layer region in CVs also depends on the white dwarf mass and rotation rate and the viscosity parameter α. In a system where the other quantities are constrained by previous observations, it would be possible to place constraints on α.

Clearly, the ideas presented in this paper represent only the beginnings of a theory for quasi-coherent oscillations in accretion disks. Before the potential applications of the model can be explored, several major pieces of the theory still need to be developed. The most important of these is understanding the mechanism, presumably some sort of nonaxisymmetric instability, which can produce a rotating bulge at the transition radius between the optically thin boundary layer and the optically thick disk. This will be a challenging task, as a 2-D or 3-D time-dependent calculation will be required, and the spatial resolution will have to be quite high in order to resolve the abrupt transition from the optically thick disk to the optically thin boundary layer.

Another topic which needs to be explored is the possibility of constraining the size and location of the rotating bulge by calculating the reprocessing of light from such a bulge. A reprocessing calculation of this type can produce light curves for various wavelengths, allowing comparisons with observed amplitudes, pulse profiles, and eclipse-related phase shifts.

Additional observational data on DNOs will be invaluable in understanding the origin of the oscillations. Most fundamentally, it is important to verify that optical/UV and EUV/soft X-ray DNOs represent the same phenomenon, and that DNOs are not present in hard X-rays. Observations at UV and higher energies are particularly valuable, since they probe the inner regions of the disk more directly. UV spectra can constrain the temperature of the oscillating source (Knigge *et al.*1998; Marsh & Horne 1998), and EUV/soft X-ray observations are even more valuable for this. The location of the oscillations could be constrained, and the model proposed in this paper tested, by determining whether EUV/soft X-ray DNOs are eclipsed in systems viewed at high inclinations.

We thank Henk Spruit for his helpful comments.

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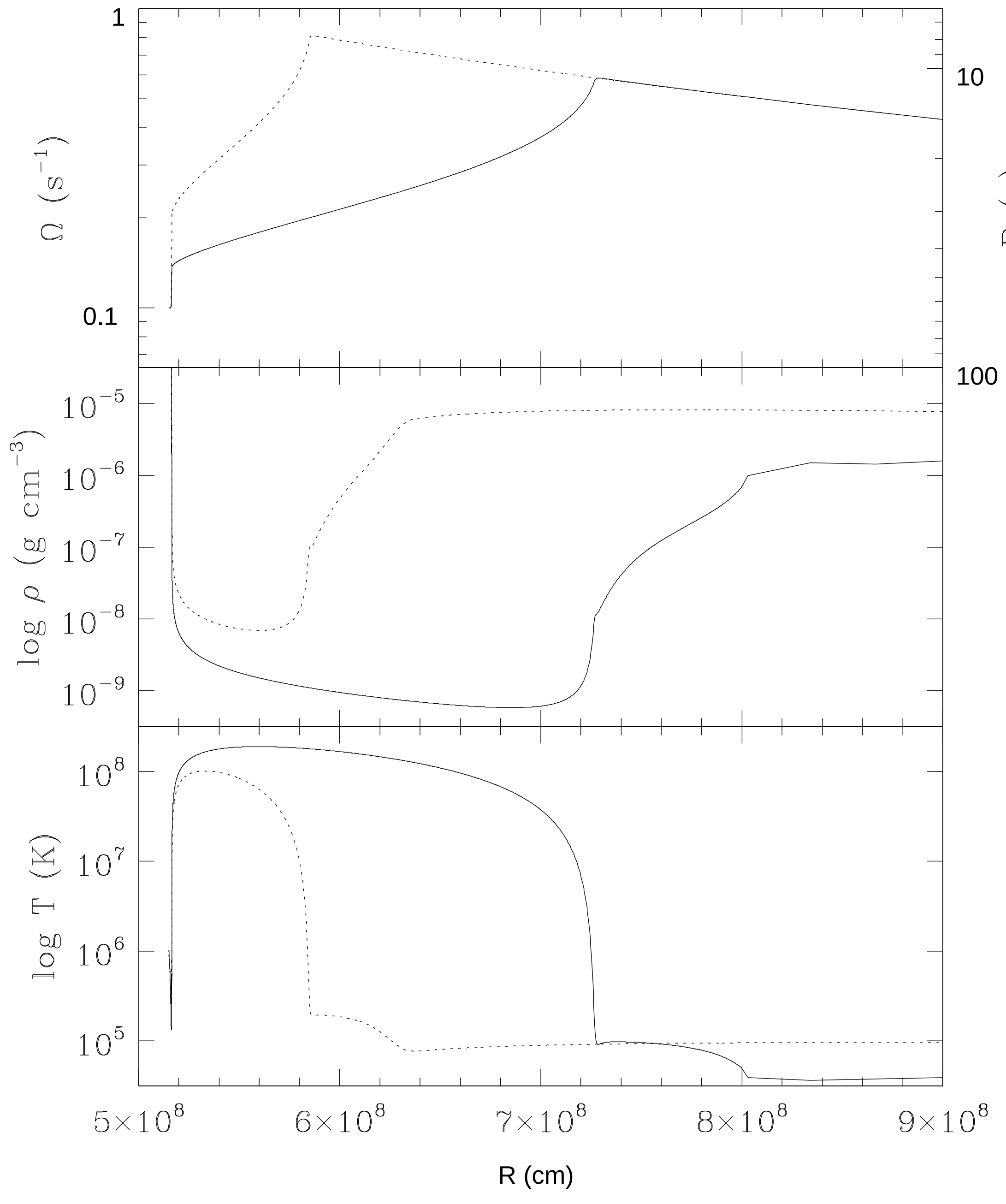
Fig. 1.— The variation in the transition radius, where the optically thick disk meets the optically thin boundary layer, with mass accretion rate. Boundary layer solutions from NP are shown for two mass accretion rates: $\dot{M} = 10^{-9.5}$ $M_\odot$ yr^{-1} (dashed) and $10^{-10.5}$ $M_\odot$ yr^{-1} (solid). Note that as the accretion rate increases, the transition radius moves inward from $\sim 7.2 \times 10^8$ cm to $\sim 5.8 \times 10^8$ cm, with a corresponding change in the rotation period at the transition radius. The optically thin boundary layer zone has very low density and high temperature.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