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The influence of new opacity data on the vertical structure of accretion disks

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Abstract. Using the most recent opacity tables and the corresponding equation of state (EOS) data, we compute the vertical structure of accretion disks in cataclysmic variables, and give the new numerical results. We also present the resulting viscosity-surface density relation. We conclude that the improvement of opacity and EOS hardly influences the disk structure compared to the uncertainties connected with parameterization of viscosity and mixing length.

Key words: accretion, accretion disk – instability – stars: individual – novae, cataclysmic variables

1. Introduction

New astrophysical opacities which became available recently allowed to eliminate discrepancies between theoretical models for stellar structure and pulsations and the observations. The most significant change was the increase of opacity for population I stars at temperatures of a few hundred thousand degrees. Low temperature opacities had also been improved taking into account molecular line absorption, grain absorption and scattering in more detail. The vertical structure of accretion disks is affected by uncertainties in opacity values in the same way as the structure of stars. The structure of cool disks depends sensitively on opacity values. This has further consequence on the relation between viscosity and surface density, which determines the limit cycle behavior of dwarf nova accretion disks. Computations of the disk structure based on new opacity data and the corresponding EOS data are needed to clarify the situation. The aim of this paper is to examine the influence of new opacity data on the vertical structure of accretion disks in dwarf novae system.

Our investigation is based on two sets of opacity tables, on the updated OPAL opacities of Iglesias & Rogers (1996) for temperatures down to 5600 K and the low-temperature opacities of Alexander & Ferguson (1994, hereafter AF). Together with the new opacities we used the values from the OPAL Equation of State Tables of Rogers et al. (1996).

In Sect. 2 we describe the implementation of opacities and equation of state values in our computer code. We show the numerical results for the accretion disk structure and changes due to improved opacities in Sect. 3. We also discuss uncertainties arising from the viscosity parameterization. In Sect. 4 the results are summarized.

2. Opacity tables and EOS in the numerical code for accretion disk structure

Our vertical structure computations are performed following the physics described in the investigations by Meyer & Meyer-Hofmeister (1983) and Meyer-Hofmeister (1987) of geometrically thin accretion disks. The viscosity is parameterized for our present work with constant α. Contributions to viscosity in the atmosphere are also included and are important in cool disk regions. The changes of the numerical code only concerns opacities and EOS.

The combination of the updated OPAL opacities (Iglesias & Rogers 1996) and low-temperature opacities (Alexander & Ferguson 1994) was already implemented by Weiss (private communication) for stellar evolution computations and we could use these tables. We adopted a solar chemical composition: $X = 0.70, Y = 0.28, Z = 0.02$, the mixture of metals according to Grevesse and Noels (1993). The molecular weight of the unionized gas is $\mu_0 = 1.307$. Details for this table are given in Salaris et al. (1997). We refer to these opacities in our work as OPAL-AF table. For the equation of state we used the updated OPAL EOS

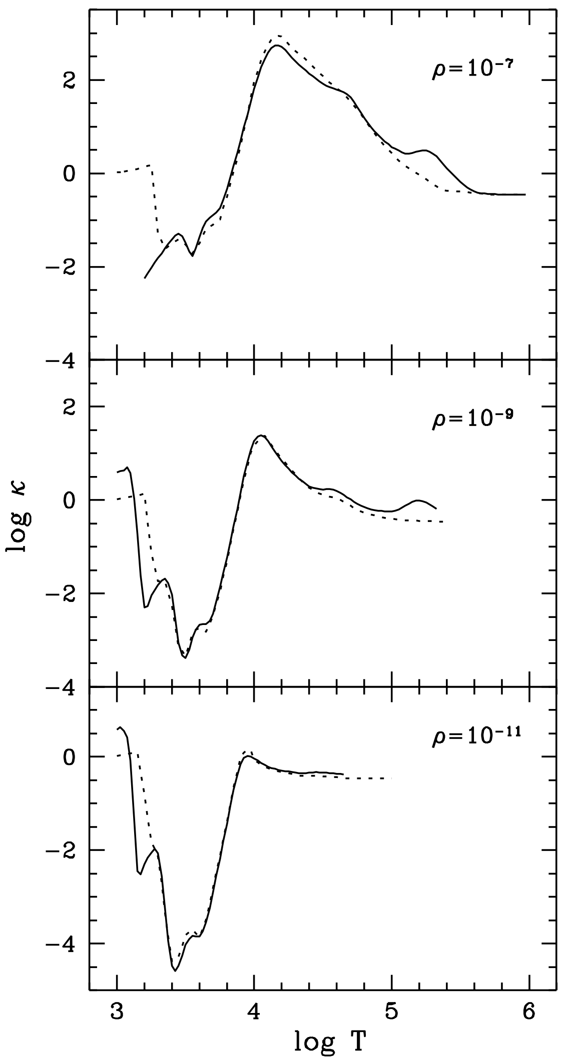

Fig. 1. Opacity κ vs. temperature T(K) for three values of the density, $\rho(\mathrm{gcm}^{-3})$ = 10^{-7}, 10^{-9}, and 10^{-11}. The solid curves represent OPAL-AF opacities, dotted curves the combined opacities taken from Cox & Stewart (1969) and Alexander (1975)

table (Rogers et al. 1996) which is consistent with the OPAL opacities. For temperatures below 5000 K not included in these tables we used the SAHA equation, as before, to determine the degree of ionization and the thermodynamic functions necessary to solve the differential equations for pressure, temperature, and vertical energy flux.

We compare the new results with the old results computed with a version of our code used by Duschl (1986). The opacities were taken from Cox and Stewart (1969) for $\log T > 4.0$, from Alexander (1975) for $\log T < 3.8$, and interpolated values for $3.8 \leq \log T \leq 4.0$. Correspondingly for $\log T > 4.0$ the SAHA equation was used, for the low temperatures tables of Sharp (1981) for c_p and tables of Alexander (1975) for μ. The chemical composition was slightly different, X = 0.739, Y = 0.240, and molecular weight μ_0 = 1.235.

In Fig.1 we compare these new OPAL-AF opacities with the old values from Cox and Stewart (1969) and Alexander (1975) for three values of density ρ (gcm^{-3}) = $10^{-7}, 10^{-9}, 10^{-11}$. This covers the range of densities occurring in disks in cataclysmic variables (compare Fig.2). Obviously the opacities from about 3000K to 10000K are almost unchanged. Differences appear for high and also for very low temperatures.

3. Numerical results from vertical structure computations

3.1. The vertical structure

For our computations we took a white dwarf mass of $1M_\odot$ and the viscous parameter α = 0.1.

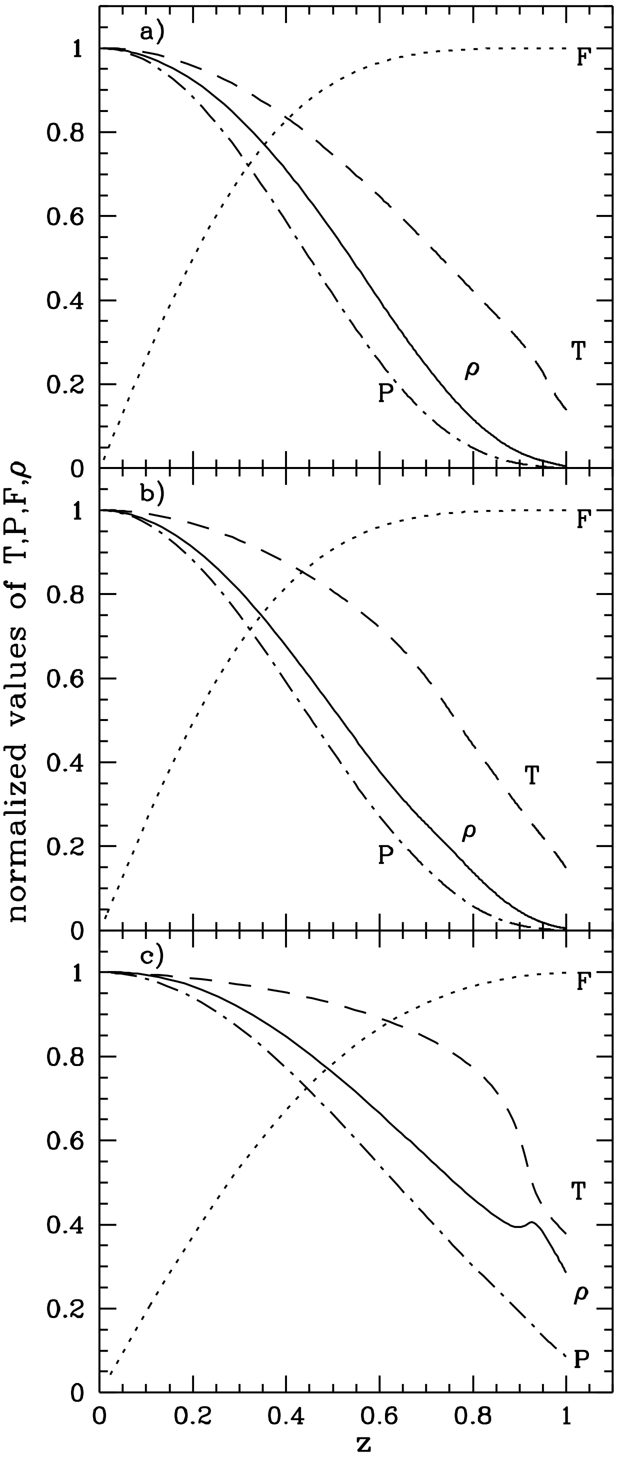

Fig. 2. Vertical structure of the disk with mass flow rate $\dot{M} = 10^{-9} M_\odot/\mathrm{y}$ and $\alpha = 0.1$, Shown are the variations of the normalized quantities temperature T, density ρ, pressure P, and vertical energy flux F from midplane (z = 0) to photosphere (z = 1) at three distances from the white dwarf, $\log r$ = 9.5 (a), $\log r$ = 10 (b), $\log r$ = 10.5 (c)

Table 1. Values from vertical structure computations (standard units)

$\log \frac{\dot{M}}{M_\odot/\mathrm{y}}$	$\log r$	$\log z_0$	$\log T_e$	$\log P_{ph}$	$\log \rho_{ph}$	$\log F_{ph}$	$\log T_c$	$\log P_c$	$\log \rho_c$
	9.5	8.120	4.437	4.639	-7.917	13.558	5.292	7.824	-5.619
-9	10.	8.664	4.062	3.318	-8.806	12.000	4.888	6.524	-6.501
	10.5	8.753	3.687	4.490	-7.000	10.498	4.106	5.544	-6.464
	9.5	7.949	4.187	3.983	-8.294	12.558	4.960	6.987	-6.106
-10	10.	8.133	3.812	4.770	-6.846	11.999	4.220	5.929	-6.312
	10.5	8.334	3.437	4.362	-6.879	9.470	3.557	4.847	-6.514

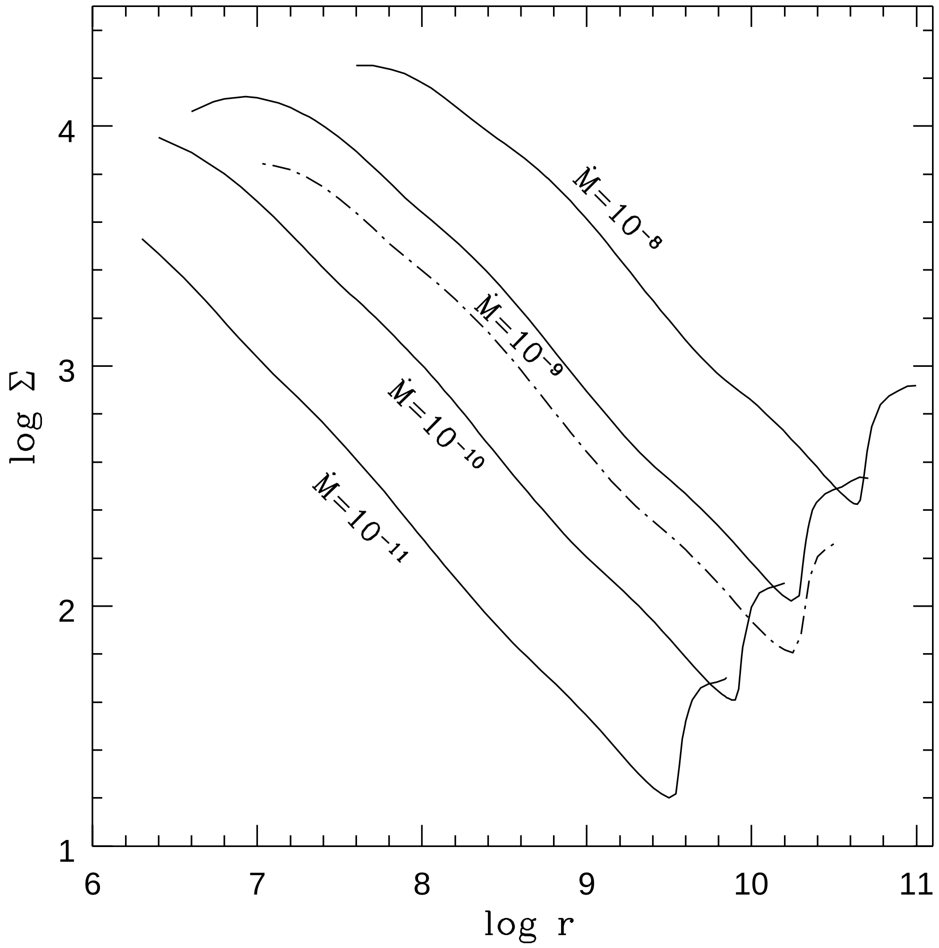

Fig. 3. Surface density Σ vs. distance r from central object for different accretion rates in $M_\odot/\mathrm{y}$, α = 0.1. A dot-dashed curve for α = 0.2 shows the influence of the viscous parameter ($\dot{M}$ = $10^{-9} M_\odot/\mathrm{y}$)

In Fig. 2 we show the variation of temperature T, density ρ, pressure P, and vertical energy flux F from midplane to photosphere at different distances r from the white dwarf, based on the OPAL-AF opacities. The upper diagram for $\log r$ = 9.5 represents a radiative zone, the lowest one for $\log r$ = 10.5 a fully convective zone, and the middle one for $\log r$ = 10 a zone with an interior radiative and an outer convective part. In Table 1, we list the disk height z_0, the effective temperature T_e, the pressure P_{ph} and the density ρ_{ph} at the photosphere, and in the midplane, T_c, P_c, ρ_c, as well as the energy flux from the photosphere F_{ph} of the disk. We give these values for three distances and two mass flow rates. From both Table 1 and Fig. 2 we can see that for a stationary disk the values of T_c and P_c decrease from inner region to outer region, the radiation flux is highest in inner region. For a low mass accretion rate (e.g. $\dot{M}$ = $10^{-10} M_\odot/\mathrm{y}$), the disk is cooler, and convection becomes more important for energy transport.

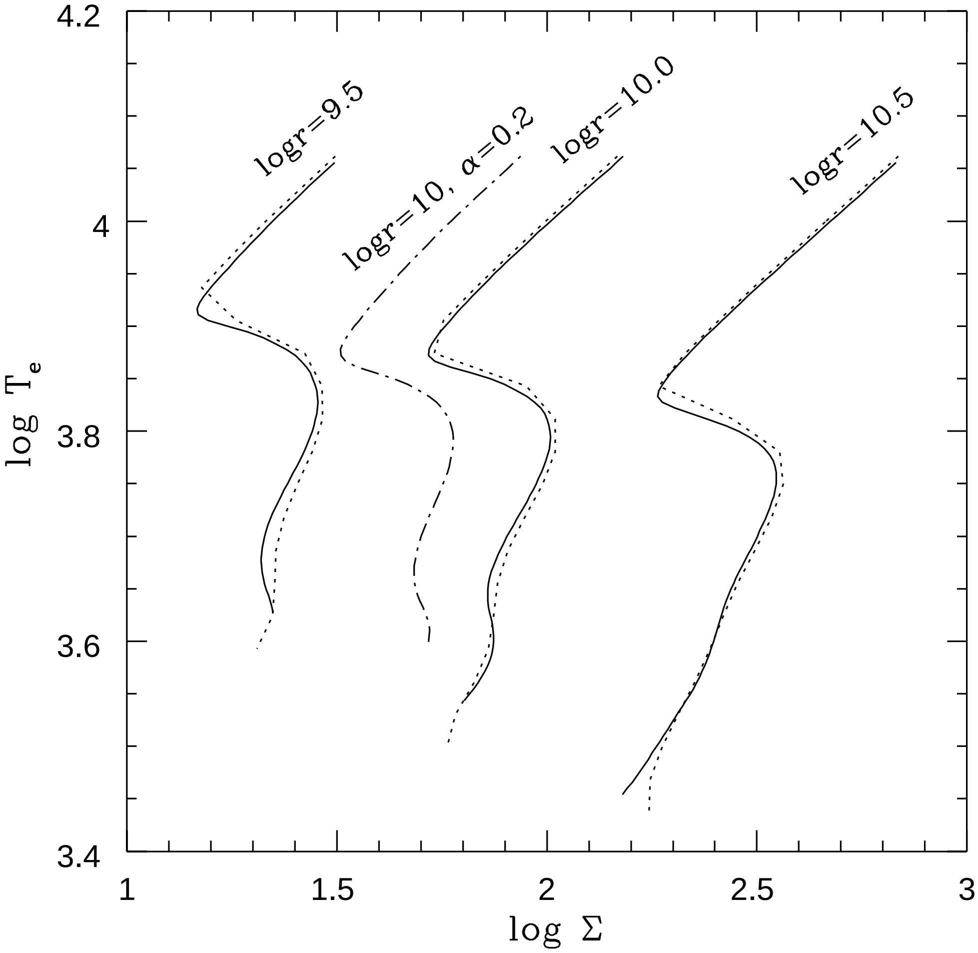

Fig. 4. Effective temperature vs. surface density for three annuli of the disk with radius as indicated and α = 0.1. The influence of different opacity is shown: solid curves are based on OPAL-AF opacity data and OPAL EOS, dotted curves on Cox & Stewart (1969) and Alexander (1975) opacities and corresponding EOS, dot-dashed curve: viscous parameter α = 0.2 (OPAL-AF opacity data and OPAL EOS)

In Fig. 3 we show the surface density distribution in the disk for four mass flow rates, one example for a different viscosity is given. Test computations for the old opacities show no large difference to the new one except for small changes caused by the opacity bump at temperature around $10^{5.3}$K.

3.2. The viscosity-surface density relation

The vertical structure yields the surface density Σ at each distance from the white dwarf for the given parameters,

$$\Sigma = \int_{-z_0}^{z_0} \rho dz \tag{1}$$

The effective temperature T_e at the photosphere is related to the viscosity integral and the mass accretion rate $\dot{M}$,

$$\sigma T_e^4 = \frac{9}{8}\frac{GM}{r^3} f = \frac{3}{8\pi}\frac{GM\dot{M}}{r^3} \tag{2}$$

with

$$f = \int_{-z_0}^{z_0} \mu dz, \tag{3}$$

where $\mu = \frac{\sqrt{2}}{3}\alpha c_s \rho H_p$ is the effective viscosity (H_p pressure scale heigh, c_s sound velocity). The latter relation in Eq. (2) holds for stationary disks away from the inner boundary.

Figure 4 shows the effective temperature-surface density relation for new and old opacities and corresponding EOS in three regions of the disk, $\log r = 9.5, 10, 10.5$. Since the midplane temperatures are mostly below 10^5K for disks around white dwarfs considered here, the bump of the new opacity around $T \sim 10^{5.3}$K has no influence on the $T_e - \Sigma$ relation. If we consider the $T_e - \Sigma$ relation for lowest temperature we find that for decreasing effective temperature an increasing part of the mass is located in the atmosphere until finally the disk is optically thin. This happens earlier for higher α values. For $\alpha = 0.1$ the lowest temperature is around 3000K. We then assume an optically thin disk structure. Therefore the relatively large deviations between the old and the new opacities do not enter in our computations. The small differences between the curves in Fig. 4 should originate from the slight differences between the new and old opacities. Test computations show that OPAL EOS leads to practically the same vertical structure as the SAHA equation. The differences in opacity mainly influence the disk structure for the very low effective temperatures. In addition Fig. 4 shows that the $T_e - \Sigma$ relations for the two sets of opacities differ near the lowest temperature of the hot branch though the opacities do not differ there. The turning point is connected with the onset of ionization and convection and a shift might be due to the slightly different hydrogen content (compare Sect. 1).

To show the effect of changes of α, we included for $\log r = 10$ the results for $\alpha = 0.2$, this curve is roughly parallel to the one for $\alpha = 0.1$.

3.3. Effects of the parameterization

The pressure scale height H_p enters in the mixing length $l_{mix} = \lambda H_p$ (in convective region) and in the effective viscosity $\mu = \frac{\sqrt{2}}{3}\alpha c_s \rho H_p$. In the midplane gradients become zero and the pressure scale height formally becomes infinite. The particular way in which H_p is limited there affects the mixing length and with this the efficiency of convection and also the viscosity. Ludwig et al. (1994) had shown, using the same computing code as here, that smaller λ leads to smaller Σ due to the reduced efficiency of convection. On the other hand, μ decreases with smaller H_p. So the two effects counteract. A test computation where we limited H_p to the disk height z_0 following the concept that the vertical extension of the disk determines the maximal movement of the blobs, results in an increase of Σ by a factor of about 1.2 for a temperature $T_e \approx 4000$K. Cannizzo & Wheeler (1984) limited their pressure scale height to the disk height z above midplane.

This uncertainty leads to larger differences in the $f - \Sigma$ relation than the changes between old and new opacities.

4. Discussion and Conclusions

We found that the improvements of EOS and opacity only lead to smaller differences of the accretion disk structure and the viscosity–surface density relation. The uncertainty arising from the particular way of reducing the pressure scale height towards the midplane (done in a different way by different authors) is large. Since this reduction mostly affects the structure of cool disk regions it can influence the slope of the lowest part of the cool branch of the $f - \Sigma$ relation. It may be important since a partly negative slope could explain a sudden rise of the disk temperature shortly before the onset of an outburst as observed by Hassall (1984) for VW Hydri.

Since the opacity improvement has little influence on the structure for outburst modelling, the $f - \Sigma$ relations derived by Ludwig et al. (1994) are not affected.

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