Supercritical Accretion Disks with Superwinds

Etsuko Kitabatake and Jun Fukue
Astronomical Institute, Osaka Kyoriku University, Asahigaoka, Kashiwara, Osaka 582-8582
etsuko@cosmos2.cc.osaka-kyoiku.ac.jp, fukue@cc.osaka-kyoiku.ac.jp

and

Katsura Matsumoto
Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima-naka, Okayama 700-8530
katsura@cc.okayama-u.ac.jp

(Received 2001 July 9; accepted 2002 February 5)

Abstract

We construct a model for supercritical accretion disks with winds, where the mass-accretion rate highly exceeds the Eddington rate and a significant fraction of the accreting gas is expelled as a superwind, under a self-similar treatment. The mass-accretion rate $\dot{M}$ decreases with radius $r$ as $\dot{M} \propto r^{s+1/2}$, where $s \geq -1/2$ is some arbitrary constant. The surface density $\Sigma$ and the disk central temperature $T_c$ vary as $\Sigma \propto r^s$ and $T_c \propto r^{s/4-1/2}$, respectively. In spite of such a modification, we found that the scaleheight $H$ and the surface temperature $T$ of such a superdisk with a superwind is very similar to those of a supercritical disk without winds; $H \propto r$ and $T \propto r^{-1/2}$. Furthermore, the optical depth of the wind becomes remarkably smaller than that in the spherical case, because mass loss takes place at various radii on the disk, and the gas distribution in the wind is not concentrated, but diluted in space. Hence, the observational appearances of both superdisks are quite similar, except for the existence of a strong wind, unless the wind mass-loss rate highly exceeds the critical rate. We then apply a superdisk with a superwind to supersoft X-ray sources. In our picture, although the accretion rate in these objects is of the order of $10^{-5} M_\odot$ yr$^{-1}$ at the outer edge of the disk and a sufficiently thick superdisk may be established, most of the gas is expelled by the superwind, and the accretion rate at the center becomes of the order of $10^{-7}$–$10^{-6} M_\odot$ yr$^{-1}$.

Key words: accretion, accretion disks — black holes — supercritical accretion — supersoft X-ray sources — X-rays: individual (CAL 83, CAL 87, SMC 13, RX J0019.8+2156)

1. Introduction

According to a theoretical investigation and the observational discrepancy for the classical picture, we now suppose there are three types of accretion disks around a central object of mass $M$ with the mass-accretion rate $\dot{M}$ (see, e.g., Kato et al. 1998). The criterion is the Eddington rate, defined by

$$\dot{M}_E = \frac{L_E}{c^2} = 1.4 \times 10^{17} \eta^{-1} \frac{M}{M_\odot} \text{ g s}^{-1},$$  

(1)

where $L_E (= 1.25 \times 10^{38} M/M_\odot \text{ erg s}^{-1})$ is the Eddington luminosity and $\eta$ is the efficiency. For a subcritical accretion rate ($\dot{M} \lesssim \dot{M}_E$), the classical standard disk is applied (e.g., Shakura, Sunyaev 1973), while for a very low accretion rate ($\dot{M} \ll \dot{M}_E$), the optically-thin advection-dominated accretion flow (optically-thin ADAF) is proposed (e.g., Ichimaru 1977; Narayan, Yi 1994; Abramowicz et al. 1995; Popham, Gammie 1998). On the other hand, for a supercritical accretion rate ($\dot{M} \gg \dot{M}_E$), the optically-thick advection-dominated disk (optically-thick ADAF or slim disk) may be established (Beigelman, Meier 1982; Abramowicz et al. 1988; cf. Eddum et al. 1988).

In recent years, the accretion disk in the supercritical accretion regime was extensively studied by many researchers (Szuszkiewicz et al. 1996; Beloborodov 1998; Watarai, Fukue 1999; Watarai et al. 2000; Mineshige et al. 2000; see Fukue 2000 and references therein). Abramowicz et al. (1988) called the model a slim disk due to its medium thickness between a thin disk and a fat one. In this paper, based on a physical viewpoint of the accretion rate, we call the accretion disk under supercritical accretion a supercritical accretion disk (or, in short, a superdisk). Superdisks, we believe, play important roles in various astronomical sites: in SS 433 and some galactic black hole candidates in galactic superluminal sources, such as GRS 1915+105 and GRO J1655–40, in narrow-line Seyfert 1 galaxies and luminous quasars, and in supersoft X-ray sources.

Such active objects often exhibit a mass loss in the form of winds and/or jets. Winds from an inner region of a supercritical disk were first investigated by Meier (1979, 1982), under a spherical approximation (cf. Shakura, Sunyaev 1973; Eddum et al. 1988). Recently, several researchers examined supercritical winds (e.g., Becker, Begelman 1986a,b; King, Begelman 1999). In these studies, however, spherical symmetry is usually assumed. Except for a few cases (Eddum et al. 1988; Watarai, Fukue 1999; cf. Shakura, Sunyaev 1973), no one has considered the mass loss and wind from a supercritical accretion disk, without spherical symmetry.

In this paper we examine supercritical accretion disks with wind mass loss, under a self-similar treatment (Watarai, Fukue 1999; Fukue 2000). We also apply such a superdisk with winds to several supersoft X-ray sources.

In the next section we present an accretion-disk model with supercritical accretion and wind. In section 3 we apply the present model to three supersoft X-ray sources. The final
section is devoted to concluding remarks.

2. Superdisks with Superwinds

In this section we describe a model of a supercritical accretion disk which includes wind mass loss. In order to construct a model that is easy to use, we adopt a self-similar treatment for optically-thin ADAFs. According to their approach, Watarai and Fukue (1999) found self-similar solutions for optically-thick supercritical disks (see also Fukue 2000). We here consider the mass loss in the formalism.

2.1. Basic Equations

Let us suppose a gaseous disk, rotating around and infalling onto a central object of mass $M$. The disk is assumed to be steady and axisymmetric. Although the disk is not infinitesimally thin, but has a finite thickness, the physical quantities are assumed to depend only on the radius $r$, and vertically integrated equations are used.

Hence, the continuity equation integrated in the vertical direction is expressed for the present purpose as

$$\frac{1}{r} \frac{d}{dr} (r \Sigma v_r) = 2 \dot{\rho} H,$$

where $\Sigma$ is the disk surface density, $v_r$ the radial velocity, $\dot{\rho}$ the mass-loss rate per unit volume, and $H$ the disk half-thickness.

The momentum equation is

$$v_r \frac{dv_r}{dr} = \frac{v_r^2}{r} - \frac{GM}{r^2} - \frac{1}{\rho} \frac{d}{dr} (\rho c_s^2),$$

where $v_r$ is the rotation velocity and $c_s$ is the sound speed, which is defined as $c_s^2 \equiv p/\rho$, $p$ being the pressure. There is no net momentum gain/loss, associated with the wind.

The angular momentum conservation is

$$r \Sigma v_r \frac{d}{dr} (r v_r) = \frac{d}{dr} \left( \frac{2 \alpha \rho c_s^2 r^3}{\Omega_K} \frac{d\Omega}{dr} \right),$$

where $\alpha$ is the viscous parameter, $\Omega (= v_r/r)$ the angular speed, and $\Omega_K$ the Keplerian angular speed. There is no net angular-momentum gain/loss, associated with the wind.

The hydrostatic balance in the vertical direction is

$$\frac{GM}{r^3} H^2 = \frac{\Pi}{\Sigma} = c_s^2,$$

where $\Pi$ is the vertically integrated pressure. There is no net momentum gain/loss in the vertical direction associated with the wind.

The energy equation becomes

$$\Sigma v_r \frac{dc_s^2}{\gamma - 1} + 2 H c_s^2 \left( \dot{\rho} - \dot{v}_r \frac{d\rho}{dr} \right) = f \frac{\alpha \Sigma c_s^2 r^2}{\Omega_K} \left( \frac{d\Omega}{dr} \right)^2,$$

where $\rho (= \Sigma/2H)$ is the gas density and $f$ is an advection parameter. That is to say, the advection heating $Q_{\text{adv}}$ is assumed to be expressed by the viscous heating $Q_{\text{vis}}$ as $Q_{\text{adv}} = Q_{\text{vis}} - Q_{\text{rad}} = f Q_{\text{vis}}$, $Q_{\text{rad}}$ being the radiative cooling (Narayan, Yi 1994). In this energy equation (6), the term associated with mass loss on the left-hand side comes from the work done by pressure with the help of the continuity equation (2).

2.2. Self-Similar Solutions

Although the simple self-similar model cannot describe the innermost region and outer limb, it well reproduces the overall structures in a non-relativistic regime. In the self-similar model the velocities are assumed to be expressed as follows:

$$v_r(r) = -c_1 \alpha \Omega_K(r),$$

$$v_\phi(r) = c_2 \Omega_K(r),$$

$$c_s^2(r) = c_3 \Omega_K^2(r),$$

where

$$v_K(r) = \sqrt{\frac{GM}{r}},$$

and constants $c_1$, $c_2$, and $c_3$ are determined later. It is straightforward to consider the vertical motion, which associates with the advection motion along the conical disk surface (Fukue 2000; Fukue, Matsumoto 2001). In this paper, however, we neglect the vertical motion since the line spectrum is not of interest.

From the hydrostatic equation (5), we obtain the disk half-thickness $H$ as

$$H/r = \sqrt{c_3} = \tan \delta.$$

Hence, a supercritical disk with winds also has a conical surface, whose opening (half-thickness) angle is $\delta$.

Assuming the surface density $\Sigma$ to be in the form of

$$\Sigma = \Sigma_0 r^s,$$

we obtain

$$\Pi = \Sigma c_s^2 = \Sigma_0 c_3 r^s \frac{GM}{r},$$

$$\rho = \frac{\Sigma}{2H} = \frac{\Sigma_0}{2\sqrt{c_3}} r^{s-1},$$

$$\dot{\rho} = - \left( s + \frac{1}{2} \right) \Sigma_0 c_1 \alpha \sqrt{\frac{GM}{r}} r^{s-3/2}.$$}

It should be noted that, for a self-similar disk without any wind mass loss, the suffix $s$ is $s = -1/2$.

Then, from the momentum, angular momentum, and energy equations [(3), (4), and (6)], we can determine the constants uniquely as follows:

$$c_1 = \frac{1}{3\alpha^2} h(\alpha, \epsilon'),$$

$$c_2 = \frac{2\epsilon'}{9\alpha^2} h(\alpha, \epsilon'),$$

$$c_3 = \frac{2}{9\alpha^2} h(\alpha, \epsilon'),$$

where

$$\epsilon' = \frac{1}{f} \left( \frac{5/3 - \gamma}{\gamma - 1} \right),$$

$$h(\alpha, \epsilon') = \sqrt{\left( \frac{2 - s}{s + 1} + 2\epsilon' \right)^2 + 18\alpha^2 - \left( \frac{2 - s}{s + 1} + 2\epsilon' \right)^2}.$$
When $s$ is $-1/2$, these expressions reduce to those found by Narayan and Yi (1994).

The parameters of the model are the ratio of the specific heats $\gamma$, the standard viscous parameter $\alpha$, and the energy-advection fraction $f$.

Comparing the case with no mass loss ($s = -1/2$) and the case with mass loss ($s > -1/2$), $\varepsilon'$ decreases and $f$ increases. Hence, the effect of mass loss is similar to the advection effect.

### 2.3. Accretion Rates

Using the self-similar solutions, the mass-accretion rate is expressed as

$$ M = -2\pi r \Sigma v_r = 2\pi \Sigma_0 c_s \alpha \sqrt{GMr^{s+1/2}} $$

$$ = \dot{M}_{\text{out}} \left( \frac{r}{r_{\text{out}}} \right)^{s+1/2}, $$

where $r_{\text{out}}$ is the disk outer radius and $\dot{M}_{\text{out}}$ is the accretion rate there. As already stated, for self-similar solutions without winds $s = -1/2$, while $s > -1/2$ for those with winds. Hence, according to the wind mass loss, the accretion rate decreases with radius, as expected.

Using the mass-loss rate per unit volume described in equation (15), the mass-loss rate per unit surface area becomes

$$ 2\rho H = \frac{1}{2\pi r} \frac{dM}{dr} = -\left( s + \frac{1}{2} \right) \frac{M}{2\pi r^2} \left( \frac{r}{r_{\text{out}}} \right)^{s+1/2} $$

$$ = -\left( s + \frac{1}{2} \right) \frac{\dot{M}_{\text{out}}}{2\pi r_{\text{out}}^2} \left( \frac{r}{r_{\text{out}}} \right)^{s-3/2}. $$

### 2.4. Radiation Properties

The surface flux and disk luminosity of the present model are derived as follows.

By assuming a dominance of the radiation pressure, we can write the height-integrated pressure $\Pi (= \Sigma c_s^2)$ and the averaged flux $F$ as

$$ \Pi = \Pi_{\text{rad}} = \frac{1}{3} \sigma T^4_4, $$

$$ F = \sigma T^4_4 \Pi = \frac{3}{8} \sigma \Sigma_0 \sqrt{c_s} G M r^{-2}, $$

where $\sigma$ is the Stefan–Boltzmann constant. The optical thickness of the disk in the vertical direction is

$$ \tau = \frac{1}{\kappa} \Sigma_0 \Sigma_c - \frac{1}{\kappa} \Sigma_0 \rho r, $$

where $\kappa$ is the electron-scattering opacity.

Hence, the effective flux and the effective temperature of the disk surface become, respectively,

$$ \sigma T^4_\text{eff} = \frac{\sigma T^4_4}{\tau} = \frac{3}{4\kappa} \frac{\sqrt{c_s} GM}{r^2} = \frac{3}{4\kappa} \sqrt{c_s} \frac{L_E}{4\pi r^2}, $$

$$ T^4_\text{eff} = \left( \frac{3\sqrt{c_s} L_E}{16\pi \sigma} \right)^{1/4} r^{-1/2}. $$

Finally, the disk luminosity $L_{\text{disk}}$ is evaluated as

$$ L_{\text{disk}} = \frac{2}{4} \sqrt{c_s} L^2_0 \ln \frac{r_{\text{out}}}{r_{\text{in}}}, $$

where $r_{\text{in}}$ is the disk inner radius.

It should be emphasized that the radiative appearance, such as $T^\text{eff}$ and $L_{\text{disk}}$, are not affected by the mass loss, although the pressure $\Pi$ and the average flux $F$ depend on the mass-loss distribution. This can be understood as follows. When there is a wind mass loss from the disk surface, the average flux $F$ decreases all over the disk, compared with the no-wind case. At the same time, the surface density and optical depth decrease for the mass loss case, compared with the no-wind case. That is, we see the deep inside of the disk in the case with mass loss. As a result, the effective temperature of the disk does not depend on the mass loss, and the radiative appearance is similar to that without mass loss.

### 2.5. Wind Optical Depth

If the wind mass-loss rate is sufficiently high, the wind flow becomes optically thick and the disk may be veiled; the disk cannot be seen in its naked form.

Under the spherical approximation, for example, the optical depth $\tau_{\text{wind}}$ of the wind is roughly estimated as

$$ \tau_{\text{wind}} = \int_{r_{\text{in}}}^{r_{\text{out}}} \frac{\kappa \dot{M}_{\text{wind}}}{4\pi r^2 v_{\text{wind}}} dr \sim \frac{\kappa \dot{M}_{\text{wind}}}{4\pi r_{\text{out}} v_{\text{wind}}}, $$

where we have assumed that the mass-loss rate $\dot{M}_{\text{wind}}$ and the wind velocity $v_{\text{wind}}$ are both constant. Hence, in usual cases of supercritical winds the wind optical depth exceeds unity when the mass-loss rate becomes of the order of the critical rate (see, e.g., Meier 1979, 1982; Becker, Begelman 1986a,b).

In the case of superwinds from the disk, this estimate is not always true. It is because winds start from various radii; in other words the mass-loss rate is not constant but depends on radius. As a result, the wind gas is not concentrated at the center, but is diluted over a wide space, and the optical depth is reduced. In the present model, for example, from equation (22), the mass-loss rate per unit surface area is about

$$ 2\rho_0 v_{\text{wind}} = \frac{1}{2} \frac{\dot{M}_{\text{out}}}{2\pi r_{\text{out}}^2} \left( \frac{r_0}{r_{\text{out}}} \right)^{s-3/2}, $$

where $\rho_0$ is the density at radius $r_0$. If the wind density decreases as $\rho_{\text{wind}} \sim (r_0/r)^2 \rho_0$, the wind optical depth becomes

$$ \tau_{\text{wind}} \sim \int_{r_{\text{in}}}^{r_{\text{out}}} \left( \frac{1}{2} \frac{\dot{M}_{\text{out}}}{2\pi r_{\text{out}}^2} \left( \frac{r_0}{r_{\text{out}}} \right)^{s-3/2} \left( \frac{r_0}{r} \right)^2 dr \right) \sim \left( s + \frac{1}{2} \right) \frac{\kappa \dot{M}_{\text{out}}}{4\pi r_{\text{out}} v_{\text{wind}}} \left( \frac{r_0}{r_{\text{out}}} \right)^{s+1/2}. $$

Namely, the wind optical depth depends on $r_0$, and for $r_0 = r_{\text{in}}$ the optical depth reduces by a factor of $(r_0/r_{\text{out}})^{s+1/2}$ in the present case, compared with the spherical estimate.

Hence, as long as the mass-loss rate is not very high, we can expect that the observational appearances, such as the spectra and light curves, of the superdisk with winds may be similar to those of a superdisk without winds (Fukue 2000).

### 3. Application to Supersoft X-Ray Sources

In this section we apply the present picture of a superdisk model with winds to supersoft X-ray sources (CAL 83, CAL 87, and SMC 13).


3.1. Superdisks with Superwinds in Supersoft Sources

Supersoft X-ray sources (or supersoft sources: SSSs) are active objects, which are very luminous in the supersoft X-ray regions, typically at about 20–40 eV (e.g., Kahabka 1995; Rappaport, Di Stefano 1996 for reviews). The bolometric luminosities of SSSs are very large, up to $10^{36}$ erg s$^{-1}$ to $10^{38}$ erg s$^{-1}$, which are of the order of the Eddington luminosity of a solar-mass object. The effective temperature is about $(2-6) \times 10^4$ K ($kT \sim 17-50$ eV), which is higher than that of a usual white dwarf, but lower than that of a typical X-ray binary.

In the current picture of a binary SSS, they consist of a white dwarf and a normal (or slightly evolved) companion (van den Heuvel et al. 1992). Material flowing from the donor filling its Roche lobe forms an accretion disk around the white dwarf, and a steady nuclear burning on the surface of the white dwarf takes place due to the higher mass of white dwarfs of $\sim 1 M_\odot$ and a sufficiently high accretion rate of $\sim (1-6) \times 10^{-7} M_\odot$ yr$^{-1}$. That is, the mass-accretion rate $\dot{M}_{\text{in}}$ at the white-dwarf radius $r_{\text{WD}} (= r_{\text{in}})$ is

$$\dot{M}_{\text{in}} \sim 10^{-7} - 10^{-6} M_\odot \text{ yr}^{-1}.$$ (32)

Since the critical accretion rate of the white dwarf is about $M_{\text{E}} = L_\text{E}/(\eta c^2)$, the desired mass-accretion rate $\dot{M}_{\text{in}}$ is comparable to the critical rate. Hence, in SSSs the usual picture of the traditional standard accretion disk by Shakura and Sunyaev (1973) breaks down.

Observationally, simple geometrically thin disks are also rejected. First, the continuum spectra of SSSs are not interpreted by the geometrically thin standard disks. In order to reproduce the spectrum in optical wavelengths, the irradiation effect (Matsumoto, Fukue 1998) or other processes such as supercritical accretion should be desired. Second, light curves of SSSs are also not explained by a geometrically thin disk. Hence, for typical parameters a superdisk in SSSs is sufficiently optically thick.

On the other hand, from equation (31), the optical depth of the wind is roughly

$$\tau = 65.76 \left( \frac{c_\alpha}{0.1} \right)^{-1/2} \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{\dot{M}_{\text{out}}}{10^{-5} M_\odot \text{ yr}^{-1}} \right) \left( \frac{r_{\text{out}}}{R_\odot} \right)^{-1/2} \left( \frac{r}{r_{\text{out}}} \right)^s.$$ (36)

This discrepancy in the accretion rates between equations (32) and (33) is easily interpreted in the present picture of superdisks with winds. Namely, a significant amount of the accreting gas is flung away via wind mass loss, and 1–10% of $\dot{M}_{\text{out}}$ is ultimately accreted onto the white dwarf. Using the expression for the accretion rate (21), we obtain

$$\dot{M}_{\text{in}} / \dot{M}_{\text{out}} \sim \left( \frac{r_{\text{in}}}{r_{\text{out}}} \right)^{s+1/2}.$$ (34)

Since $r_{\text{in}} \sim 0.01 r_{\text{out}}$ for SSSs, we finally have

$$\dot{M}_{\text{in}} / \dot{M}_{\text{out}} \sim 10^{-2} \quad \text{when} \quad s \sim 1/2.$$ (35)

The optical depth is roughly estimated as

$$\tau = 0.567 \left( \frac{M}{M_\odot} \right)^{-1} \left( \frac{\dot{M}_{\text{out}}}{10^{-5} M_\odot \text{ yr}^{-1}} \right) \left( \frac{v_{\text{wind}}}{5000 \text{ km s}^{-1}} \right)^{-1} \left( \frac{r_{\text{out}}}{0.01 R_\odot} \right) \left( \frac{r}{r_{\text{out}}} \right)^{s+1/2}.$$ (37)

Hence, in the case of the supersoft X-ray sources, the optical depth of wind is of the order of unity.

### Table 1. Observational quantities (Cowley et al. 1998).

<table>
<thead>
<tr>
<th>Name</th>
<th>Period [d]</th>
<th>$m_V$</th>
<th>$M_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAL 83</td>
<td>1.04</td>
<td>16.3–17.5</td>
<td>−1.3</td>
</tr>
<tr>
<td>CAL 87</td>
<td>0.44</td>
<td>19.0–20.8</td>
<td>+0.3</td>
</tr>
<tr>
<td>SMC 13</td>
<td>0.17</td>
<td>20.2–20.6</td>
<td>+1.4</td>
</tr>
</tbody>
</table>

3.2. Accretion Rates in SSSs

The accretion rate of superdisks is supposed to be sufficiently high. In fact, in order to construct a sufficiently thick superdisk, the mass-accretion rate $\dot{M}_{\text{out}}$ at the outer edge of the disk $r_{\text{out}}$ is required to be

$$\dot{M}_{\text{out}} \sim 10^{-5} M_\odot \text{ yr}^{-1}.$$ (33)

This discrepancy in the accretion rates between equations (32) and (33) is easily interpreted in the present picture of superdisks with winds. Namely, a significant amount of the accreting gas is flung away via wind mass loss, and 1–10% of $\dot{M}_{\text{out}}$ is ultimately accreted onto the white dwarf. Using the expression for the accretion rate (21), we obtain

$$\dot{M}_{\text{in}} / \dot{M}_{\text{out}} \sim \left( \frac{r_{\text{in}}}{r_{\text{out}}} \right)^{s+1/2}.$$ (34)

Since $r_{\text{in}} \sim 0.01 r_{\text{out}}$ for SSSs, we finally have

$$\dot{M}_{\text{in}} / \dot{M}_{\text{out}} \sim 10^{-2} \quad \text{when} \quad s \sim 1/2.$$ (35)

The optical depth is roughly estimated as

$$\tau = 65.76 \left( \frac{c_\alpha}{0.1} \right)^{-1/2} \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{\dot{M}_{\text{out}}}{10^{-5} M_\odot \text{ yr}^{-1}} \right) \left( \frac{r_{\text{out}}}{R_\odot} \right)^{-1/2} \left( \frac{r}{r_{\text{out}}} \right)^s.$$ (36)

Hence, for typical parameters a superdisk in SSSs is sufficiently optically thick.

On the other hand, from equation (31), the optical depth of the wind is roughly

$$\tau_{\text{wind}} = 57.6 \left( \frac{s + 1/2}{2} \right) \left( \frac{\dot{M}_{\text{out}}}{10^{-5} M_\odot \text{ yr}^{-1}} \right)^{-1} \left( \frac{v_{\text{wind}}}{5000 \text{ km s}^{-1}} \right)^{-1} \left( \frac{r_{\text{out}}}{0.01 R_\odot} \right)^s \left( \frac{r}{r_{\text{out}}} \right)^{s+1/2}.$$ (37)

when $s = 1/2$. Hence, in the case of the supersoft X-ray sources, the optical depth of wind is of the order of unity.
Roche lobe volume (figure 1). The irradiation effect on the surface of the companion star is considered. The parameters are then the white dwarf mass $M_{WD}$, the white dwarf luminosity $L_{WD}$, the companion mass $M_{\text{comp}}$, the companion initial temperature $T_{\delta}$, the system inclination angle $i$, the disk outer radius $R_{\text{disk}}$, and the half-thickness angle of the disk surface $\delta$.

Figure 2 shows the light curves for CAL 83. The crosses denote the observation (Kahabka, van den Heuvel 1997), while the solid curve means the best fit model. We examined several combinations of parameters: $M_{WD} = 0.75 M_\odot$, $L_{WD} = 0.5 L_\odot$, $M_{\text{comp}} = 2 M_\odot$, $T_{\delta} = 8300 K$, $i = 30^\circ$, and $\delta = 2^\circ$.

Figure 3 shows the light curves for CAL 87. The crosses denote the observation (Alcock et al. 1997; Kahabka, van den Heuvel 1997), while the solid curve means the best-fit model. The parameters are as follows: $M_{WD} = 0.75 M_\odot$, $M_{\text{comp}} = 1.5 M_\odot$, $L_{WD} = 0.1 L_\odot$, $T_{\delta} = 7800 K$, $i = 80^\circ$, and $\delta = 15^\circ$.

The calculated and observed light curves for CAL 87 are shown in figure 3. The observed light curves in the $V$-band are denoted by the crosses (Alcock et al. 1997; Kahabka, van den Heuvel 1997), while the calculated curve is denoted by a solid curve. We examined several combinations of parameters: $0.6 M_\odot \leq M_{WD} \leq 1.2 M_\odot$ in steps of $0.1 M_\odot$ (the primary is assumed to be a white dwarf); $0.5 M_\odot \leq M_{\text{comp}} \leq 2 M_\odot$ in steps of $0.2 M_\odot$; $0.1 L_\odot \leq L_{WD} \leq 1 L_\odot$ in steps of $0.1 L_\odot$ (although $M_{\text{out}}$ is supercritical, $M_{\text{in}}$ is subcritical due to superwind mass loss); $70^\circ \leq i \leq 90^\circ$ in steps of $2^\circ$ (eclipsing system); $5^\circ \leq \delta \leq 20^\circ$ in steps of $5^\circ$. The best-fit parameter set is as follows: $M_{WD} = 0.75 M_\odot$, $M_{\text{comp}} = 1.5 M_\odot$, $L_{WD} = 0.1 L_\odot$, $T_{\delta} = 7800 K$, $i = 80^\circ$, and $\delta = 15^\circ$. As can be seen in figure 3, the primary minimum is well reproduced, but the secondary is not. This is partially because we approximate the companion by a sphere, and ignore the tidally deformed shape of the Roche lobe.

Figure 4 shows the light curves for SMC 13. The crosses denote the observation (Schmidike et al. 1996), while the solid curve means the best-fit model. The parameters as follows: $M_{WD} = 0.8 M_\odot$, $M_{\text{comp}} = 0.16 M_\odot$, $L_{WD} = 0.3 L_\odot$, $T_{\delta} = 3000 K$, $i = 70^\circ$, and $\delta = 10^\circ$, $R_{\text{disk}} = 0.7 R_{\text{out}}$. The calculated and observed light curves for SMC 13 are shown in figure 4. The observed light curves in the $V$-band are denoted by the crosses (Schmidike et al. 1996), while the calculated curve is denoted by a solid curve. We examined several combinations of parameters: $0.5 M_\odot \leq M_{WD} \leq 1.5 M_\odot$ in steps of $0.1 M_\odot$ (the primary is assumed to be a white dwarf); $0.5 M_\odot \leq M_{\text{comp}} \leq 2 M_\odot$ in steps of $0.25 M_\odot$; $0.1 L_\odot \leq L_{WD} \leq 1 L_\odot$ in steps of $0.1 L_\odot$ (although $M_{\text{out}}$ is supercritical, $M_{\text{in}}$ is subcritical due to superwind mass loss); $70^\circ \leq i \leq 90^\circ$ in steps of $2^\circ$ (eclipsing system); $5^\circ \leq \delta \leq 20^\circ$ in steps of $5^\circ$. The best-fit parameter set is as follows: $M_{WD} = 0.8 M_\odot$, $M_{\text{comp}} = 0.16 M_\odot$, $L_{WD} = 0.3 L_\odot$, $T_{\delta} = 3000 K$, $i = 70^\circ$, and $\delta = 10^\circ$. As can be seen in figure 4, the primary minimum is well reproduced, but the secondary is not. This is partially because we approximate the companion by a sphere, and ignore the tidally deformed shape of the Roche lobe.
curve means the best-fit model. We examined several combinations of parameters: \(0.8 M_{\odot} \leq M_{\text{WD}} \leq 1.4 M_{\odot}\) in steps of 0.2 \(M_{\odot}\); 0.16 \(M_{\odot}\) \(\leq M_{\text{comp}} \leq 0.4 M_{\odot}\) in steps of \(\sim 0.2 M_{\odot}\); 0.1 \(L_{\text{E}}\) \(\leq L_{\text{WD}} \leq 1 L_{\text{E}}\) in steps of 0.1 \(L_{\text{E}}\); 60° \(\leq i \leq 80°\) in steps of 5° (eclipsing system); 5° \(\leq \delta \leq 20°\) in steps of 5°. The best-fit parameter set is as follows: \(M_{\text{WD}} = 0.8 M_{\odot}, M_{\text{comp}} = 0.16 M_{\odot}, L_{\text{WD}} = 0.3 L_{\text{E}}, T_{c} = 3000 K, i = 70°,\) and \(\delta = 10°\). \(R_{\text{disk}} = 0.7 R_{\text{out}}\). In this case, we must reduce the disk size; otherwise, the disk is too luminous for any parameter set. The calculated light curve for SMC 13 well reproduces the observed one. In this case the companion star is supposed to be rather small, and the primary minimum is wide.

4. Concluding Remarks

In this paper we proposed supercritical accretion disks (superdisks) with wind mass loss, and applied the model to several SSSs (CAL 83, CAL 87, SMC 13). We found that superdisks exhibit various distinct features, compared with standard thin disks.

For a self-similar superdisk with winds, the surface density \(\Sigma\) and the disk central temperature \(T_{c}\) vary as \(\propto r^{−1/2}\) and \(T_{c} \propto r^{−2}\), respectively, and the mass-accretion rate \(\dot{M}\) decreases with radius \(r\) as \(\dot{M} \propto r^{s+1/2}\), where \(s\) is of the order of 1/2 for SSSs. On the other hand, the scaleheight \(H\) and the surface temperature \(T\) are very similar to those of a superdisk without winds; \(H \propto r\) and \(T \propto r^{−1/2}\). In addition, in contrast to a spherical superwind, the optical depth of the present superwind is of the order of unity. Hence, the observational appearances of both superdisks are quite similar, except for the existence of wind. Optical light curves of CAL 83 and SMC 13 are well reproduced by the present disk model, while there remain some residuals in the case of CAL 87.

Supercritical accretion disks with a strong wind may apply to some X-ray binaries and luminous active galactic nuclei. In the present analysis we did not mention any production mechanism of a strong wind from the disk surface. Whether a central object is a black hole or not, the supercritical accretion rates must lead to a strong mass loss, since the mass-eating rate of the central object is limited.

The authors would like to thank Dr. I. Hachisu for useful comments. They also thank an anonymous referee for several critical comments, especially concerning the problem of wind optical depth, which improved the original manuscript.

References

Fukue, J. 2000, PASJ, 52, 133
Kato, S., Fukue, J., & Mineshige, S. 1998, Black-Hole Accretion Disks (Kyoto: Kyoto University Press), ch. 16