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著者	Watari Kenya, Fukue Jun
journal or publication title	Publications of the Astronomical Society of Japan
volume	62
number	2
page range	467-474
year	2010-04-25
URL	http://hdl.handle.net/2297/24563

Optical Light Curves of Luminous Eclipsing Black Hole X-Ray Binaries

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(Received 2009 November 3; accepted 2010 February 16)

Abstract

We examined optical V -band light curves in luminous eclipsing black hole X-ray binaries, using a supercritical accretion/outflow model that is more realistic than the formerly used ones. In order to compute the theoretical light curve in the binary system, we did not only apply the global analytic solution of the disk, but also included the effect of optically thick outflow. We found that the depth of eclipse of the companion star by the disk changed dramatically when including the effect of the outflow. Due to the effect of outflow, we could reproduce the optical light curve for typical binary parameters in SS 433. Our model with an outflow velocity of $v \sim 3000 \text{ km s}^{-1}$ could fit the whole shape of the averaged V -band light curve in SS 433, but we found a possible parameter range consistent with observations, such as $\dot{M} \sim 5000\text{--}10000 L_E/c^2$ (with L_E being the Eddington luminosity and c being the speed of light) and $T_C = 10000\text{--}14000 \text{ K}$ for the accretion rate and donor star temperature, respectively. Furthermore, we briefly discuss observational implications for ultraluminous X-ray sources.

Key words: accretion: accretion disks — black holes — stars: X-rays

1. Introduction

The profile of a light curve in an astronomical object includes a wide range of information, i.e., the spatial distribution and dynamical motion of gas, or its radiative processes, etc. Analysis of the light curve has therefore been known to be an important tool from the old days. Especially, in the case of an eclipsing binary system, which has a compact star, it is useful to suppose the brightness distribution of the accretion disk around the compact star. This method can also be applied to black hole candidates. Generally, it is difficult to discern light from the companion star and light from the accretion disk, but if the object has an eclipse it may be possible for the two components to separate. Moreover, black hole candidates show the (partially) eclipsing property, and we could close in on the feature of the accreting gas, or the black hole mass, or spin, etc (Fukue 1987; Watarai et al. 2005; Takahashi & Watarai 2007).

For the last decade, a large number of luminous black hole candidates (BHCs) have been found in nearby galaxies. They are called “ultraluminous X-ray sources (ULXs)”, but their origin is still unknown (Makishima et al. 2000; Roberts et al. 2004). X-ray data analysis has been used for the mainstream study of the ULXs, but other band data will be useful for evaluating other binary parameters. It is no wonder that eclipsing binaries are detected among the BHCs. In fact, several eclipsing black hole binaries have been discovered (Orosz et al. 2007 in M 33; Ghosh et al. 2006 in NGC 4214).

To examine the observational properties of such luminous eclipsing binaries, light-curve fitting will be a powerful tool. The conventional study of a light curve in a binary system applies to a geometrically thin disk, the so-called standard

accretion disk (Shakura & Sunyaev 1973). This model may have applicability to the high/soft state in black hole candidates, but it may not extend to a low/hard state, very high state, or super-critical state, which is a more luminous state than the high soft state. Luminous black hole candidates that exceed the Eddington luminosity seem to accrete a large amount of gas via a companion star, and the disk becomes geometrically thick. This type of accretion flow is called a “slim disk” (Abramowicz et al. 1988; Watarai et al. 2000). The geometrical thickness of this type disk can play an important role in covering a companion star, depending on the angle, and contribute to changing the shape of the light curve. It is necessary to include it in a calculation of a bright binary system properly. Fukue et al. (1997, 1998) performed light-curve analysis in SS 433 using a geometrically thick torus model by Madau (1988), but it is known that the disk model is thermally unstable. Hirai and Fukue (2001) compared the optical light curve in SS 433 with (thermally stable) supercritical accretion disks, but they adopted self-similar solutions even at the disk outer region. We thus adopted a thermally stable, more realistic (appropriate) treatment of the disk model, and compared the model with observations of super-critical accreting objects, such as SS 433 and ultraluminous X-ray sources.

In addition, in previous studies the mass outflow from a supercritical disk was not included, but a naked supercritical disk was considered. Hence, in the present study we consider a supercritical accretion disk with an optically thick outflow from the center.

In the next section, we introduce the assumptions of our model. In section 3, we briefly show the light-curve calculation method. Calculation results are presented in section 4. The final section is devoted to concluding remarks.

2. Model for Accretion and Outflow under Supercritical Accretion Flows

In this section, we calculate the light curve when the binary star system that fills Roche-lobe is assumed, and a supercritical accretion has occurred in the compact star.

Ideas of supercritical accretion were proposed by many authors in the early 1970's (Shakura & Sunyaev 1973; Abramowicz et al. 1978; Jaroczynski et al. 1980; Paczyński & Wiita 1980). Whether accretion that exceeds the Eddington luminosity is possible or not has been doubted for many years. The solution for supercritical accretion had already been obtained in one dimension (Abramowicz et al. 1988). Due to the development of the computer, supercritical accretion is actually known to be reproduced by numerical simulations (Okuda 2002; Ohsuga et al. 2005; Ohsuga & Mineshige 2007). It thus presently becomes impossible for us to deny supercritical accretion any longer. In the next subsections, we briefly introduce our model and assumptions.

2.1. Model for Supercritical Accretion Flows

The photon trapping radius characterizes supercritical accretion at the radius where advective energy transport becomes important (Begelman & Maier 1982; Ohsuga et al. 2002). This radius accords with the radius that the gravity of the disk balances with the radiation pressure, and it has been suggested that an outflow may originate inside it (Shakura & Sunyaev 1973; Lipunova 1999; Fukue 2004; Heinzeller & Duschl 2007).

However, this outflow blows in a very tiny area compared with the size of the whole disk. It actually will not have an influence on computing the optical flux. Recently, Takeuchi et al. (2009) analyzed 2D RHD simulation results by Ohsuga et al. (2005), and rebuilt a one-dimension model, but the effective temperature distribution of the one-dimension model hardly changes. Therefore, we can use a one-dimension model safely without any outflow effect.

2.1.1. Radiation-pressure dominated regime: $\kappa_{es} \gg \kappa_{ff}$

For the radiation-pressure dominated regime, Watarai (2006) constructed analytical formulae that can be applied for a wide range of accretion rates, and it has been shown that these solutions are a good approximation of the numerical solutions. According to Watarai (2006), the scale height of the disk is given by

$$H_a = 3.0 f(\hat{r}, \dot{m})^{1/2} \hat{r}. \quad (1)$$

This solution is characterized by the ratio of the advective cooling rate to the viscous heating rate, i.e., $f = Q_{adv}^- / Q_{vis}^+$, which can be represented by an analytical form dependent on the radius and the mass accretion rate, $f(\hat{r}, \dot{m})$. The radius \hat{r} is normalized by the Schwarzschild radius, and the \dot{m} represents the mass-accretion rate in Eddington units ($\dot{M}_{Edd} = L_E / c^2$). The explicit form of $f(\hat{r}, \dot{m})$ is given by

$$f(\hat{r}, \dot{m}) = \frac{1}{2} \left[D - 2 \left(\frac{\hat{r}}{\dot{m}} \right)^2 + 2 - D \left(\frac{\hat{r}}{\dot{m}} \right) \sqrt{D^2 \left(\frac{\hat{r}}{\dot{m}} \right)^2 + 4} \right], \quad (2)$$

where D is a constant of order unity (e.g., $D \approx 2.18$ for

a polytropic index $N = 3$). The function $f(\hat{r}, \dot{m})$ is close to unity for an advection-dominated regime, and it is close to zero for a radiative cooling-dominated regime (see Watarai 2006 for more details).

The effective temperature distribution is given by

$$T_{eff} \approx 4.48 \times 10^7 f(\hat{r}, \dot{m})^{1/8} m^{-1/4} \hat{r}^{-1/2} \text{ K}. \quad (3)$$

The boundary radius between the radiation-pressure dominated regime and the gas-pressure dominated regime is located at

$$\begin{aligned} \hat{r}_{rad-gas} &= 18(\alpha m)^{2/3} \dot{m}^{16/21} \\ &\approx 601(\alpha/0.1)^{2/3} (m/10)^{2/3} (\dot{m}/100)^{16/21}. \end{aligned} \quad (4)$$

The same equations are posed by Shakura and Sunyaev (1973). We note that analytic solutions shown here are useful for the radiation-pressure dominated regime.

2.1.2. Gas-pressure dominated regime

In the gas-pressure dominated regime, if electron scattering dominates the opacity, the scale height of the disk and the effective temperature distribution are

$$\begin{aligned} H_b &= 2.7 \times 10^3 \alpha^{-1/10} m^{9/10} \dot{m}^{1/5} \hat{r}^{21/20}, \\ T_{eff} &\approx 3.50 \times 10^7 m^{-1/4} \dot{m}^{1/4} \hat{r}^{-3/4} \text{ K}, \end{aligned} \quad (6)$$

with the same formula by Shakura and Sunyaev (1973).

The transition radius where $\kappa_{es} \sim \kappa_{ff}$ is

$$\hat{r}_{gas,out} = 2.5 \times 10^3 \dot{m}^{2/3}, \quad (8)$$

and thus it is a simple function of the mass accretion rate.

The outer region of the disk is dominated by free-free opacity, and the scale height is given by

$$H_c = 1.5 \times 10^3 \alpha^{-1/10} m^{9/10} \dot{m}^{3/20} \hat{r}^{9/8}, \quad (9)$$

with the effective radial dependence of the temperature as in equation (7).

We ignore irradiation by the disk, or the photosphere of the outflow, because the irradiation dominated regime appears at the outer region of the disk, and the temperature and geometrical effects do not contribute to the optical light curves (less than 10%). To avoid confusion of the model, we decided to handle an easier model.

2.2. Model for Massive Wind

Shakura and Sunyaev (1973) proposed massive (supercritical) outflow, which is formed by strong radiation from the disk. The size of the photosphere surface made by the outflow becomes large, and has an influence on the form of the light curve. Thus, we should include the effect of the outflow in our model. We do not include the collimated, relativistic jet component in this paper.

Here, we introduce a simple wind model by Abramowicz et al. (1991), which assumes a spherical symmetry and uniform outflow velocity. The density of the wind, ρ_w , is

$$\rho_w = \left(\frac{\dot{M}_{out}}{4\pi v \gamma} \right) R^{-2}, \quad (10)$$

where \dot{M}_{out} is the mass outflow rate, v is the velocity of the gas, and γ is the Lorentz factor: $(1 - \beta^2)^{1/2}$, where $\beta = v/c$, and R is the distance from the black hole.

The mass outflow rate should be determined by the physics of the interaction between the disk and outflow, i.e., $\dot{M}_{\text{out}} = \eta \dot{M}_{\text{acc}}$, where η is the efficiency of the outflow gas from the accreting gas. In our present study, we assume $\eta = 1.0$ for simplicity. That is, our model simply assumes that all accreting matter changes to the outflow at the disk inner edge ($3r_g$). The location of the boundary layer between the outflow and the disk may have a strong impact on the emerging X-ray spectrum, but it is not expected to have an enormous influence on the optical band, since the optical emitting region of the photosphere is far away from the disk inner edge.

3. Binary Light Curve Calculation

To calculate the V -band flux in a binary system, we adopt the ‘‘Ray-Tracing Method’’. We suppose that the binary star fills the Roche lobe and transports its mass to the compact star. The shape of the companion star reflects the shape of the potential. The photon propagates from an emitting point on the surface of the disk or that of the photosphere of the wind to the distant observer. According to Fermat’s principle, however, the light rays are traced from the observer’s display coordinates (x_s, y_s, z_s) . After the rays arrive at the surface of the disk/wind, we evaluate the geometrical thickness and effective temperature of the disk/wind model presented in the previous section. The observed flux is integrated in each optical band (V, R, I), assuming the blackbody radiation at the surface of the disk, star, and photosphere of the outflow.

The spatial resolution of the calculation is about 1%–0.1% of the binary distance, which equals to $10^4 r_g$ – $10^3 r_g$. This resolution is sufficient to resolve the optical flux from the binary system. Thus, the mesh size of this calculation is at least much smaller than 10% at this radius.

3.1. Location of the Photosphere

The location of the wind photosphere is estimated from the point where the optical depth measured from a distant observer equals to unity, that is,

$$\tau_{\text{ph}} = 1 = \int_{R_{\text{ph}}}^{\infty} \gamma (1 - \beta \cos \theta) \kappa \rho_w ds, \quad (11)$$

where R_{ph} is the location of the last scattering surface of the photon in the disk coordinates, γ is the Lorentz factor, κ is the opacity for electron scattering, β is the velocity of the wind normalized by the speed of light, c , and θ is the inclination angle. Abramowicz et al. (1991) obtained an analytic solution of a moving plasma, and the shape of the photosphere in their model does not have spherical symmetry (see also Sumitomo et al. 2007). We use their formulae in this paper.

In some cases, analytic formulae derived by King and Pounds (2003) are useful to estimate the size of the photosphere. It is given by

$$R_{\text{ph}} \sim \frac{\kappa \dot{M}_{\text{out}}}{4\pi b v}, \quad (12)$$

where R_{ph} is the radius of the photosphere, κ is the opacity for electron scattering, and b is the eccentricity of the photosphere. The value of b is $0.5 \rightarrow 1$, which is fixed at unity throughout this paper.

In this paper, we assume that the mass outflow rate, \dot{M}_{out} , is equal to the mass-accretion rate at the central region. The mass-outflow rate in our model gives the maximum rate. The typical size of the photosphere is given by

$$\frac{R_{\text{ph}}}{r_g} = \frac{\dot{m}_{\text{out}}}{2\beta} = 10^5 \left(\frac{\dot{m}_{\text{out}}}{2000} \right) \left(\frac{\beta}{0.01} \right)^{-1}. \quad (13)$$

As we show later, if the size of the photosphere is much smaller than the disk size, the photosphere does not influence the shape of the eclipsing light curves.

3.2. Temperature and Luminosity at the Photosphere

We evaluate the maximum temperature of the photosphere by using the following procedure. First, we estimate the size of the photosphere of the outflow. Assuming that photons ejected from the disk surface inside the photosphere are conserved until escaping photons from the surface of the photosphere, i.e., all photons are generated inside the disk, not be generated in the wind. The temperature of the wind photosphere, T_w , is then given by

$$\sigma T_w^4 \approx \frac{L_{\text{disk}}}{4\pi (bR_{\text{ph}})^2}. \quad (14)$$

Here, the luminosity of the disk, L_{disk} , is given by

$$L_{\text{disk}} = \int_{R_{\text{in}}}^{R_{\text{ph}}} 2\sigma T_{\text{eff}}^4 \cdot 2\pi r dr. \quad (15)$$

To determine the location of the disk surface or the photosphere of the outflow, we integrated the optical depth from an observer at infinity to the surface of $\tau_{\text{ph}} = 1$ along the line of sight. After the light rays arrived at the surface, we measured the temperature using equation (14) and the geometrical thickness of the disk from the underlying disk/wind models.

4. Optical Flux Images

4.1. Case without Outflow

Let us see the results when only a naked supercritical disk is considered. In figure 1, we show V -band (5.11×10^{14} – 6.61×10^{14} Hz) flux images at different binary phases. The mass-accretion rates is $\dot{m} = 10^3$, the inclination angle is $i = 70^\circ$, the mass ratio is $q = M_X/M_C = 1$, the temperature of the companion star is $T_C = 15000$ K, and the velocity of the wind is $\beta = 0$, respectively. As can be seen in figure 1, the geometrical thickness of the disk is thin compared with the size of the disk. It is understood that the thickness of the disk does not affect the light curve for $\dot{m} = 10^3$. The scale height of the disk weakly depends on the \dot{m} , as can be seen in equations (1), (6), and (9).

Figure 2 is the time-variation of the V -band flux for various inclination angles. The mass-accretion rate is set to be $\dot{m} = 10^3$. When the inclination angle increases, the flux drops at phase 0.5. This is because the disk hides emission from a secondary star. Optical emission from the secondary star is much larger than that from the disk for $\dot{m} = 10^3$.

As the mass-accretion rate increases, the disk becomes as luminous as the companion star (see figure 3). Some previous studies applied a thick-disk model to the optical light curve

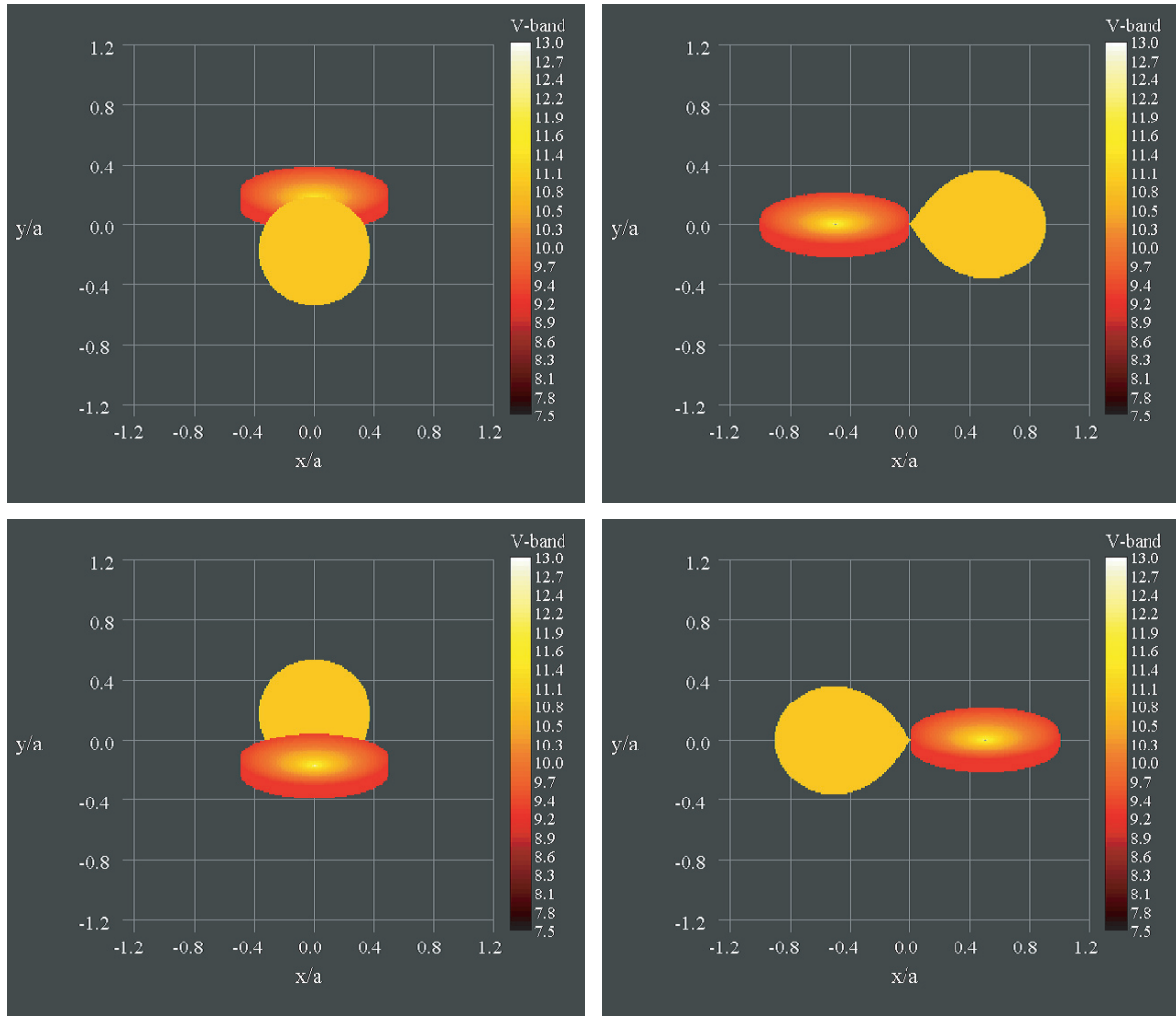


Fig. 1. *V*-band flux images in no-outflow models with various phases (0, 0.25, 0.5, and 0.75). Horizontal and vertical axes are normalized by the binary distance, a . The mass-accretion rate is set to be $1000\dot{M}_{\text{crit}}$, and the mass ratio, $q = M_x/M_c$, is $q = 1.0$. The inclination angle is 70° , and the temperature of the companion star T_c is 15000 K.

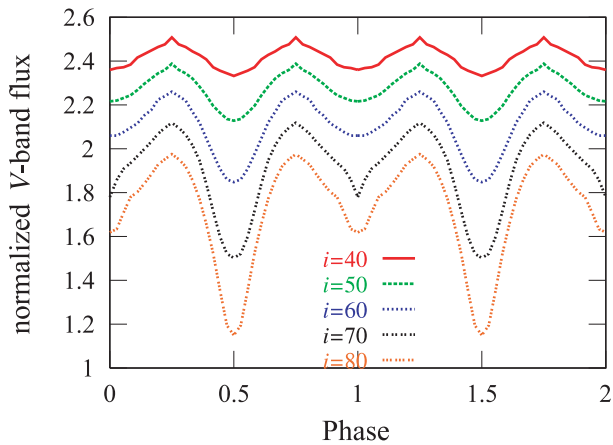


Fig. 2. Theoretical *V*-band light curves expected from our disk model (no wind) with different inclination angles. The inclination angles are $i = 40^\circ, 50^\circ, 60^\circ, 70^\circ$, and 80° from top to bottom. Other parameters are $q = M_x/M_c = 1.0$, $\dot{m} = 10^3$, and $T_c = 15000$ K, respectively.

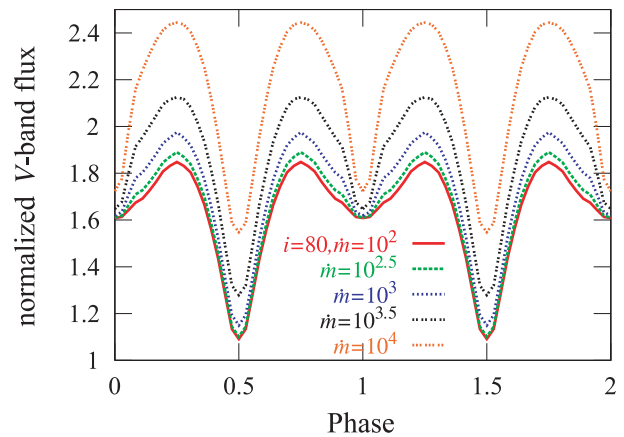


Fig. 3. Same as figure 2, but as a function of the mass-accretion rates (no wind). The mass-accretion rates are $\dot{m} = 10^2, 10^{2.5}, 10^3, 10^{3.5}$, and 10^4 from bottom to top. Other parameters are $q = 1.0$, $i = 80^\circ$, and $T_c = 15000$ K, respectively.

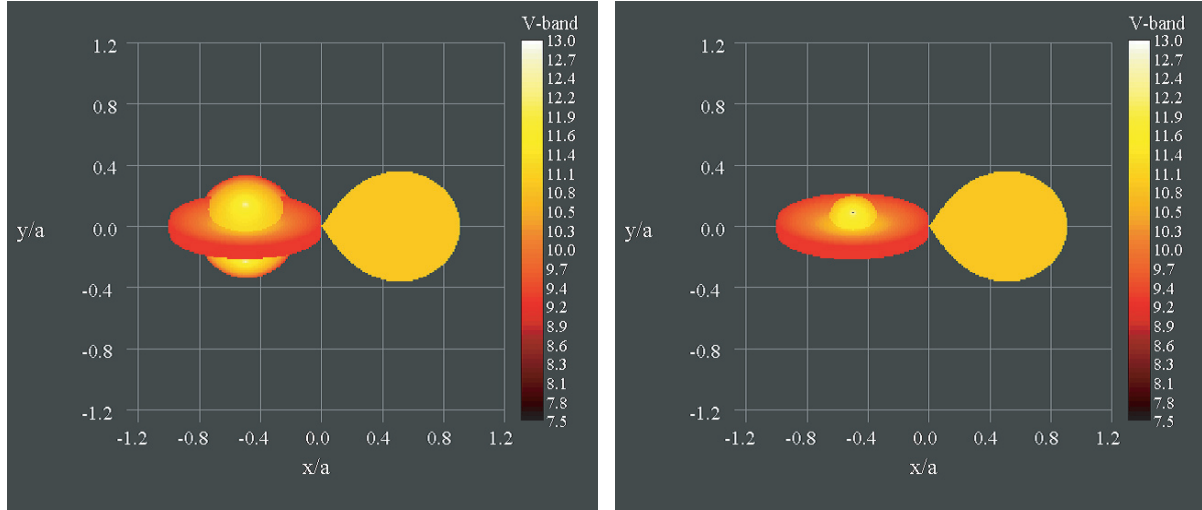


Fig. 4. V -band images including the effect of wind at phase 0.5 with various wind velocity, $\beta = 0.003$ (left) and 0.005 (right). Other parameters are $q = 1.0$, $\dot{m} = 10^3$, $i = 80^\circ$, and $T_c = 15000$ K, respectively.

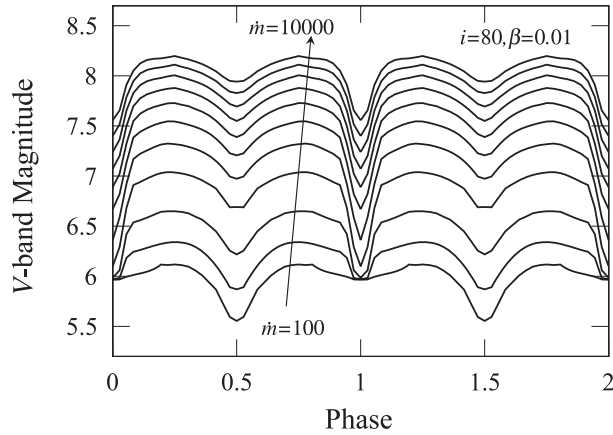


Fig. 5. V -band light curves with various mass-accretion rates. The mass-accretion rates are $\dot{m} = 100, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000$, and 10000 from bottom to top. Other parameters are $q = 1.0$, $\beta = 0.01$, and $i = 80^\circ$.

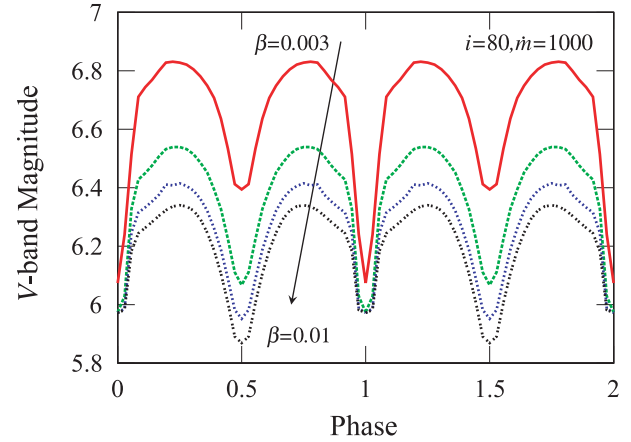


Fig. 6. Same as figure 5, but showing the dependence on the wind velocity, β . The wind velocities are $0.003, 0.005, 0.007$, and 0.01 from top to bottom.

analysis in SS 433 (Sanbuichi & Fukue 1993; Fukue et al. 1997, 1998; Hirai & Fukue 2001). However, their model is called the “thick torus model” (Abramowicz et al. 1978; Madau et al. 1988), and it is thermally/secularly unstable (Kato et al. 1998). Apart from the structure of the inner-most region of the disk, our analytic disk model (i.e., slim disk model) is applicable to the supercritically accreting regime (Watarai 2006). The model can produce a more plausible temperature and scale height. Hence, our model for a bright object is more realistic than that of past research.

4.2. Case with Massive Wind

Figure 4 represents flux images of a model with massive wind. The spherical structure at the central region of the disk is the photosphere by the massive wind. The brightness of the photosphere gradually changes from the central region to the outer region. This is called the limb-darkening effect.

Figure 5 shows the V -band light curves with various

mass-accretion rates for a high inclination angle, $i = 80^\circ$. The most remarkable feature is that a primary minimum and a secondary minimum inversion occur as the mass-accretion rate increases. The V -band magnitude at phase 0 or 1 is larger than the magnitude at phase 0.5 when the mass-accretion rate is relatively small ($\dot{m} = 100$ and 1000). However, an inversion of the flux happens when \dot{m} is large. This is because the optical V -band flux from an accretion disk increases as the mass-accretion rate increases. This feature may be applicable to the observation data of SS 433.

In figure 6, we change the wind velocities with various values. The size of the wind photosphere depends on the velocity of the wind, β . That is, the last scattering surface is inversely proportional to the velocity [see equation (13)]. The low- β outflow therefore makes large photosphere, and thus the geometrical thickness of the wind causes a deep secondary minimum during its eclipse. These features are the main results of the present study.

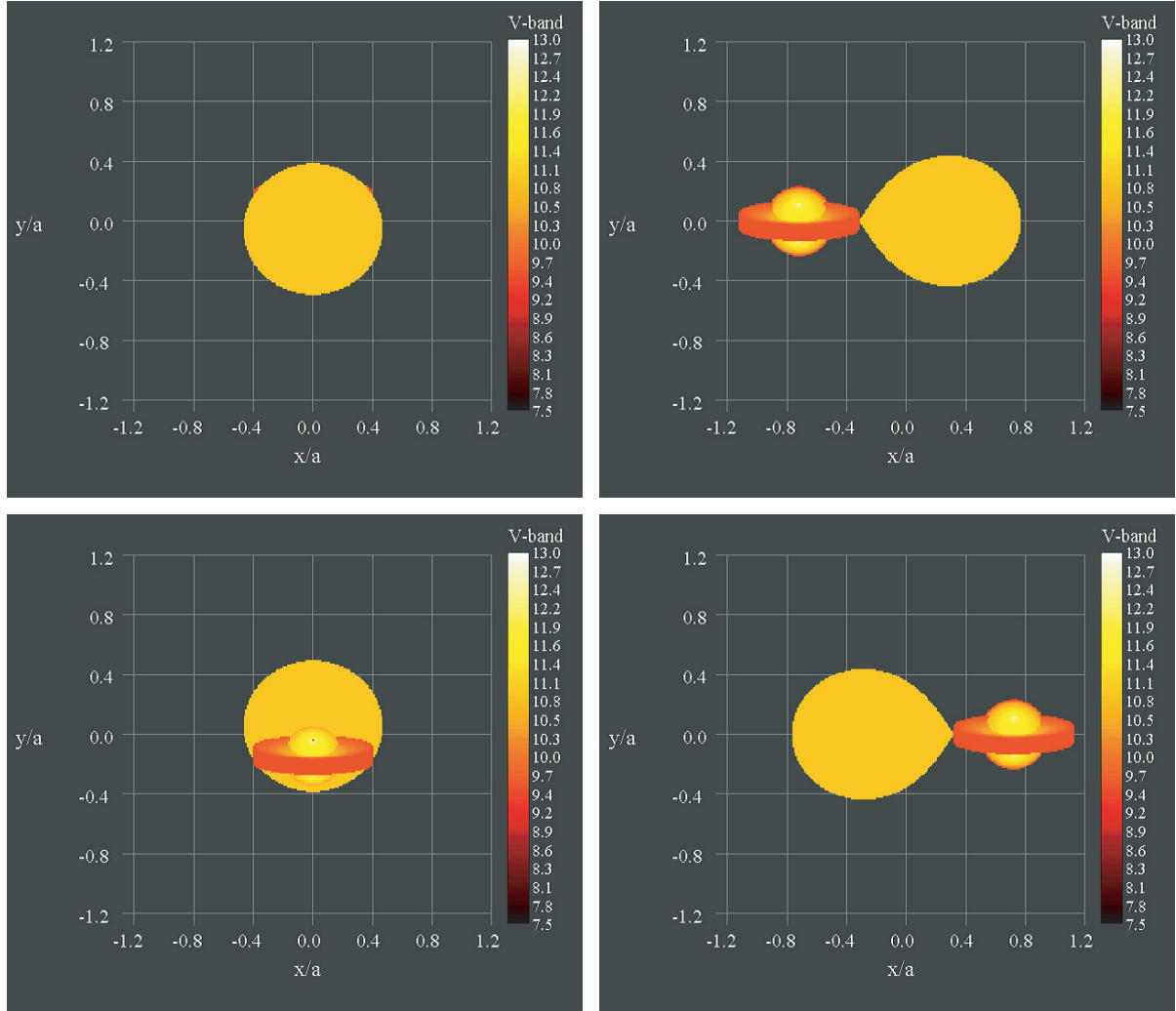


Fig. 7. V -band flux image in SS 433 at various phases (0, 0.25, 0.5, 0.75). The mass-accretion/outflow rate is $\dot{m}_{\text{acc}} = \dot{m}_{\text{out}} = 5000$. The black hole mass is $M_{\text{BH}} = M_{\text{X}} = 4 M_{\odot}$, the mass of the companion star is $M_{\text{C}} = 12 M_{\odot}$, i.e., mass ratio $q = 0.38$. The effective temperature of the companion star is $T_{\text{C}} = 15000 \text{ K}$, and the inclination angle is $i = 78^{\circ}$, whose values are referred from observational results. The velocity of the outflow is fixed at $\beta = 0.01$.

5. Discussion

5.1. Eclipsing Light Curves in SS 433

One difficulty of the optical light curves in SS 433 is interpreting the secondary minimum at phase 0.5, which is made by an eclipse of the companion star by the disk. As we explained in the previous section, it is difficult to fit the optical light curves observed in SS 433 with only the disk model. The theory also supports the massive outflow scenario introduced by observations. The mass-accretion rate in SS 433 is appreciably supercritical, $\dot{M} \sim 10^{-4} M_{\odot} \text{ yr}^{-1}$ (van den Heuvel 1980; Shklovskii 1981; Peres & Blundell 2009). This value corresponds to $\sim 4.5 \times 10^7 \dot{m}$ for a $10 M_{\odot}$ black hole, and it seems to be an upper limit of the mass-accretion rate.

Since its discovery, binary parameters in SS 433 have not yet been confirmed (see recent review by Fabrika 2004). In particular, we could not reach any consensus as to whether the compact object in SS 433 is a neutron star or a black hole. Gies et al. (2002) evaluated the mass of the companion

star via absorption lines of the A7 Ib star to be $19 \pm 7 M_{\odot}$. Recently, Kubota et al. (2010) reported a new constraint on the mass of the compact object by absorption lines taken from SUBARU and Gemini observations. They derived the masses of the compact object and companion star to be $M_{\text{X}} = 4.1^{+0.8}_{-0.7} M_{\odot}$ and $M_{\text{C}} = 12.2^{+0.8}_{-2.1} M_{\odot}$. We applied the mass ratio $q = M_{\text{X}}/M_{\text{C}} = 0.38$ derived by Kubota et al. (2010), and the black hole mass M_{BH} set to be $4.0 M_{\odot}$. This mass ratio is not in conflict with other observation results (Gies et al. 2002; Hillwig et al. 2004).

Figure 7 represents V -band images at various binary phases. We fix the mass ratio $q = 0.38$, inclination angle $i = 78^{\circ}$, and the binary period $P = 13.1 \text{ d}$ based on many former observations. The disk size (radius) is $1.35 \times 10^6 r_{\text{g}} \approx 1.6 \times 10^7 \text{ km}$, which is smaller than the case of $q = 1.0$. The size of the photosphere is comparable to the disk size in the case of $\dot{m} = 5000$.

As for the wind velocity, a quasi-spherical non-relativistic wind from the accretion disk has $3000 \text{ km s}^{-1} \approx 0.01 c$ (Cherepashchuk 2002). Recently, Peres and Blundell (2009)

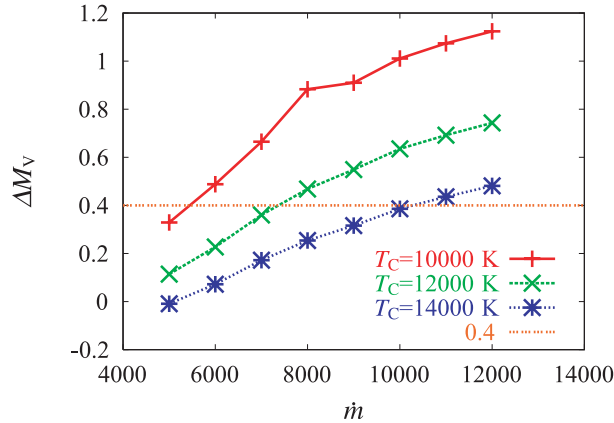


Fig. 8. Difference of the V -magnitude in phase 0 and phase 0.5 as a function of the mass-accretion rate. Other parameters are fixed at $M_{\text{BH}} = 4 M_{\odot}$, $M_{\text{C}} = 12 M_{\odot}$, $\beta = 0.01$, and $i = 78^{\circ}$, respectively.

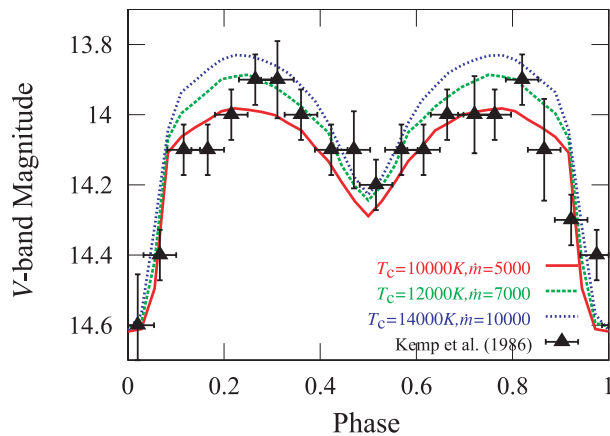


Fig. 9. V -band light curve of SS 433 fitted by our model with several parameter sets. Kemp et al. (1986) showed the averaged optical light curve data of SS 433. We set the numerical data to agree with the observed flux at phase 0. Other fixed parameters are the same as in figure 8.

found a very fast accretion disk wind by near-IR spectroscopy, and its terminal velocity is about 1500 km s^{-1} , which is equivalent to 0.5% of the speed of light. In the fit, we fixed the wind velocity to be $\beta = 0.01$ for simplicity, allowing changes in the other two parameters, namely the mass-accretion rate and the temperature of the donor star.

Before comparing the observational data in SS 433 and our model directly, we infer the possible parameter sets with figure 8. Figure 8 represents the difference of the V -magnitude (ΔM_V) at phase 0 and phase 0.5 as a function of the accretion rate. The definition of the ΔM_V is given by

$$\Delta M_V = M_V(\text{phase } 0.5) - M_V(\text{phase } 0). \quad (16)$$

In the case of SS 433, ΔM_V is about 0.4, which shows that the magnitude of phase 0.5 is larger than that of phase 0. Actually, there are some parameter sets that can fit the observation; we thus could not uniformly determine the best-fit parameter. We tried to fit our model to the V -band average light curve by Kemp et al. (1986). It is clear in figure 9

that our model can fit the whole shape of the light curve, but it does not make any distinction between three cases: (i) $\dot{m} = 5000$, $T_C = 10000 \text{ K}$, (ii) $\dot{m} = 7000$, $T_C = 12000 \text{ K}$, and (iii) $\dot{m} = 10000$, $T_C = 14000 \text{ K}$, respectively.

The mass-donor (companion) star is supposed to be A-type evolved star from absorption line analysis (Gies et al. 2002; Hillwig et al. 2004). On the other hand, some recent observations indicate that the companion star has a lower temperature that is less than 15000 K (Kudritzki et al. 2003; Cherepashchuk et al. 2005). It is an important task for observers to confirm the temperature of the companion star in SS 433.

SS 433 has a precession period of the jet, and the light curve changes at each precession phase. It is necessary to compare the light curve of each precession phase with the model testing.

In addition, X-ray emission in SS 433 comes not only from the photosphere of the wind, but also from non-thermal emission of the jet component (Rose 1995; Krivosheyev et al. 2009; see also Abolmasov et al. 2009). X-ray emission from the outflow depends on the acceleration mechanism, the temperature distribution, and the initial velocity of the outflow launched from the disk surface. If we consider the X-ray emission more seriously, a non-thermal X-ray emitting component (maybe jet component) should be included in our model (e.g., Reynoso et al. 2008; Cherepashchuk et al. 2009). These issues will be our future tasks.

5.2. Comments on Eclipsing ULXs

Considering the probability of eclipse events in the binary system, it is natural that a few eclipsing binaries exist (Pooley & Rappaport 2005). Recently, X-ray eclipsing light curves have been detected in several ULXs. As the data of the ULXs increase, the number of eclipsing ULXs also increases.

M 33 X-7 is one example of an eclipsing black hole X-ray binary discovered in recent years, and an X-ray eclipse has been clearly detected (Pietsch et al. 2004). This object suggests a high-mass X-ray binary, but its luminosity is very large, unlike the famous Cygnus X-1. There are several scenarios to explain the high luminosity. Moreno et al. (2008) pointed out a contradiction of the black hole spin scenario, and proposed a hypercritical accretion scenario in M 33 X-7 based on binary evolution theory. An eclipsing luminous X-ray binary in the dwarf starburst galaxy NGC 4214 has been reported by Ghosh et al. (2006). They clearly detected the X-ray eclipsing feature from this object.

If both optical and X-ray eclipses are observed in an object, we may presume the spatial structure of the accretion disk by using the difference of the emitting region. We are looking forward to waiting for further detections of eclipses in black hole binaries, not only in our Galaxy, but also in galaxies.

6. Conclusion

We have calculated the light curves of eclipsing binaries by handling more realistic accretion-disk models with an optically thick outflow. We also applied the present model to the supercritical accreting object SS 433. Our calculation was somewhat simple, but the geometrical thickness of the accretion disk had not been considered seriously so far. In addition, we clearly showed the change in the shape of the light curve by the wind

using a numerical calculation.

As for the model of wind, because it includes unknown physics (accretion, geometrical thickness, mass loss rate, etc.), we need to evaluate the temperature at the photosphere more seriously. This will be an important issue for observed PG quasars (Young et al. 2007). Modeling of the detailed physics of outflow is our future issue.

Measurements of the wind velocity and the mass-loss rate via observations of the absorption lines will be crucial evidence to confirm our scenario. Fittings with multi-wavelength observational data will be the next step to confirm our model. This is also one of our future tasks.

We would like to thank S. Mineshige for stimulating discussions. We would also like to thank K. Kubota for her helpful comments from an observational viewpoint. The authors would also like to thank T. Suzumori for checking the manuscript. This calculation was supported by Kongo system of the Osaka Kyoiku University Information Processing Center. This work was supported by the Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

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