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X-Ray Light Curves of Low Mass X-Ray Binaries

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X-ray light curves during the eclipse of a geometrically thin accretion disk surrounding a neutron star are calculated theoretically. In comparison with that of the accretion disk around a black bole, which exhibits conspicuous asymmetry due to the relativistic Doppler effect by the disk rotation, the asymmetric nature of the light curve in the present case is not so prominent, since the contribution of the central neutron star on the total X-ray flux is signicicant. This means that the light curve analysis enables us to know whether the object located at the center of the relativistic accretion disk is a black hole or a neutron star.

The dependences of light curves on the inclination angle of the disk and on the X-ray wavelength bands are also examined. Due to the influence of the curvature of the companion rim, ingress and egress of light curves take place rapidly in a higher inclination angle. Moreover, as wavelength bands become soft, the duration of ingress and egress becomes long, since light from the outer part of the disk contributes the total X-ray flux. This wavelength-depencence behavior of light curves depends on the disk model adopted and hence it can help us to discriminate various disk models.

I Introduction

Toward the "bi-decennial" of an *Accretion Disk* after Lynden-Bell [1], the existence of accretion disks in various astronomical objects is now well-established through photometric and spectroscopic observations and their theoretical interpretations.

For example, the spectroscopic observations of cataclysmic variables show double peaked broad Balmer and HeI lines, which originate in a large accretion disk surrounding a white dwarf [2] ~ [4]. Formation of such emission lines is also examined theoretically [5], [6].

Furthermore, Mitsuda et al. [7] reported the X-ray spectrum of low mass X-ray binaries observed by the X-ray astronomical satellite *Temma*. For these spectra, they proposed the two component model, which consists of a nonvarying soft component showing a black-body spectrum of ~1keV and a varying hard one of ~2keV. The soft component is interpreted to originate mainly from the inner accretion disk and therefore to show the multicolor spectrum, whereas the hard component comes from the neutron star surface where the disk gas accretes. On the other hand, theoretical spectra from the relativistic accretion disk around a nonmagnetized neutron star have been studied by Czerny et al. [8]. Calculating the spectra under two component model, they have taken into account the irradiation effect of the inner disk by the boundary layer between the disk and the neutron star.

Malkan [9] claimed that the UV bumps in the spectra of several quasars are due to the relativistic accretion disk surrounding a Kerr black hole located at their active nuclei, which was studied theoretically by Cunningham [10] . Theoretical spectra were also discussed by Collin-Souffrin [11] .

In addition to these spectroscopic studies, the photometric behavior of the accretion disk has been extensively investigated.

For instance, light curves during eclipse of the accretion disk around a white dwarf in cataclysmic variables were obtained by many observers [12] ~ [18] and examined by many theoreticians [19] ~ [22] .

Moreover, X-ray eclipses of low mass X-ray binaries have been detected [23] ~ [25] . In relation to this, Mason [25] identified three kinds of orbital modulation in the X-ray light curves of low mass X-ray binaries ; (i) eclipses of the central X-ray source by the companion ; (ii) smooth, quasi-sinusoidal modulations of the X-ray flux ; and (iii) irregular dips in the X-ray flux. Of these, smooth sinusoidal modulations, he interpreted, represent an eclipse of an extended accretion disk corona (ADC) by an outer part of the accretion disk. On the other hand, dips are periodically caused by the obscuration of the point-like X-ray source that lies at the center of the disk by the outer rim of the accretion disk.

At the present stage, however, the theoretical study of light curves of accretion disks around a neutron star or a black hole is rather limited.

An asymmetric nature of light curves of relativistic disks was pointed out by Fukue [26] and examined by Fukue and Yokoyama [27] . Such an asymmetry is caused by the Doppler effect of the disk rotation. That is, the radiation emitted from the inner part of the disk shifts strongly blueward or redward corresponding respectively to whether the emitting part approaches to or recedes from an observer when the observer is located inclining to the disk plane. As a result, the disk has asymmetric appearance, and therefore, light curves become asymmetric between the ingress phase and the egress one. In these studies, the black hole is postrated as the central object.

Thus the purpose of this paper is to compute the expected light curves during the eclipse of a geometrically thin accretion disk around a neutron star in low mass X-ray binaries. In addition, the simulation of the eclipse is improved in comparison with the previous work where the calculation of the eclipse was done under the approximate treatment for simplicity.

In the next section, situations and coditions supposed in this paper are summarized. Procedures to obtain light curves during the eclipse are also presented in the same section. Results are shown and discussed in section 3. Final section is devoted to conclusions.

II Situations and Procedures

In the present analysis, the eclipse of an accretion disk around a neutron star in close binary systems such as low mass X-ray binaries is examined. In the followings, I shall briefly explain in turn the situations considered and the procedures to calculate light curves.

II-1 Situations

a) Neutron Star

The present paper concerns low mass X-ray binaries which involve a neutron star at the center of an accretion disk, in contrast to the previous work [27] where considerd the black hole as a central object. As mass M_x of the neutron star, it is set that $M_x = 1.4 M_\odot$.

The neutron star is assumed to be non-rotating for simplicity. This allows us to treat the space-time as Schwarzschildian. I further set the radius of the neutron star r_{NS} as $r_{NS} = 2r_g$, where r_g is the Schwarzschild radius and $r_g = 2GM_x/c^2$, G being the gravitational constant and c the light speed. The smaller radius of the neutron star will diminish more or less its contribution to the total flux, although the final results does not depend so much on r_{NS}.

Furthermore, the neutron star is supposed to be non-magnetized. This means that the accretion disk can extend very close to the surface of the neutron star and the matter in the disk may accrete onto the equatorial region of the neutron star to overspread it. Let us assume that the gas which settles down on the surface of the neutron star emits the black body spectrum of an appropriate temperature. Question is then arised : what fraction of the surface of the neutron star brightens ? Czerny et al. [8] restricted the emitting region on the surface of the neutron star within an accretion belt near the equatorial plane and examined the effect of the width of the spectrum.

Although we can not reject such a possibility, I will assume that the overall surface of the neutron star brightens as a black body with temperature T_{NS} in order to avoid entering the additional parameter such as the width of the accretion belt. The surface temperature of the neutron star is set as $T_{NS} = 3.28 \times 10^7$K (2.83keV). The observed temperature at infinity is suffered from the gravitational redshift $(1 + z)^{-1} = (1 - r_g/r_{NS})^{1/2}$ to become 2keV and reproduces the hard component observed in the spectrum of low mass X-ray binaries by the *Temma* satellite [7] .

b) Accretion Disk

As a disk which surrounds the neutron star, here is supposed the standard disk [28] ~ [30] ; that is, the disk is geometrically thin and optically thick. And the rotational velocity of the disk is relativistic Keplerian. The surface of the disk radiates a black body spectrum with temperature T_{AD} depending on the distance R from the center in the disk plane [30] as

$$T_{AD} = (F/\sigma)^{1/4}, \tag{1}$$

where

$$F = \frac{3GM\dot{M}}{8\pi r_g^3} \frac{1}{(R-3/2)R^{5/2}} \left[R^{1/2} - 3^{1/2} + \frac{(3/2)^{1/2}}{2} \ln \frac{R^{1/2} + (3/2)^{1/2}}{R^{1/2} - (3/2)^{1/2}} \frac{3^{1/2} - (3/2)^{1/2}}{3^{1/2} + (3/2)^{1/2}} \right], \tag{2}$$

is the net flux emitted from the disk surface and σ is the Stephan-Boltzmann constant. In equation (2), the radial distance R is measured in units of the Schwarzschild radius r_g and $\dot{M}$ is the accretion rate.

This disk temperature T_{AD} has the maximum at about $4.8r_g$. I set the maximum temperature of the disk $T_{AD,max} = 10^7$K, similar to Fukue and Yokoyama [27] . As already shown by Luminet [31] , the inner region of the disk where the flux and temperature are maximum is suffered from the significant Doppler effect due to disk rotation. Particularly, the approaching part is blueshifted by the amount of $(1 + z) \sim 0.85$ for typical case. Thus when $T_{AD,max}$ is about 10^7K, the apparent temperature of te blueshifted part observed at infinity with typical parameters becomes about 1keV, which corresponds to the soft component in the two component model [7] . It should be noted, however, that the accretion rate required for this value is about critical rate [see equation (3) of Fukue and Yokoyama [27]] .

Due to the general relativistic effect, there is an inner edge of the disk at $3r_g$, inside which the disk gas falls freely onto the surface of the neutron star.

c) Binary System

For the present purpose, it is reasonable to presume that the companion star fills its Roche lobe, otherwise disk accretion will not take place and the accretion disk may not be formed.

Although the real figure of the Roche lobe is rather complicated, I assume that the shape of the companion is a sphere which has the same volume as the Roche lobe. The equivalent radius R_2 of the companion with mass M_2 is expressed [32] as

$$R_2/a=\begin{cases}0.46224\ [q/(1+q)]^{1/3} & \text{for}\quad 0<q<0.523, \qquad (3a)\\ 0.38+0.2\log q & \text{for}\quad 0.523\leq q<20, \qquad (3b)\end{cases}$$

where a is the binary seperation and q is the mass ratio $q = M_2/M_x$. At $q = 0.523$, R_2/a calculated from expression (3a) equals that from expression (3b).

The binary orbital period P, which specifies the binary system, is left as a free parameter.

Finally, the binary orbital plane is assumed to coincide with the disk plane.

d) Observer

An observer (or unmanned explorer) is located at (r_0, δ_0) in the Schwarzschild coordinate (r, θ, ϕ) whose equatorial plane is taken to coincide with the disk the plane. That is, r_0 is the observer's distance from the center and set to be $10^7 r_g$ throughout this paper. δ_0 is the declination angle of the observer measured from the disk plane and left as a free parameter. This declination angle δ_0 is equal to ($\pi/2-$inclination angle i_0 of the binary system) when the disk plane coincides with the orbital plane of the binary system as considered here.

In addition, the accretion disk as well as the companion rotates counter-clockwise against the line-of-sight of the observer.

Ultimately, parameters left freely are q, P, and i_0 (or δ_0).

II-2 Procedures

a) Photographs

Under foregoing situations, photographs of the accretion disk and the neutron star in the specified X-ray wavelength region have been taken at first. In the curved space-time, photon trajectory is traced from the photographer (observer) to the point where it originates [27]. The apparent bolometric flux and thereby the apparent temperature after being suffered from a redshift due both to the disk rotation and to the gravitational field of the neutron star are then determined. Finally, the blackbody spectrum having this apparent temperature is integrated in the specified wavelength region to give an apparent brightness of that point.

In order to take into account the contribution of the flux from the outer disk to the total flux, appropriate size of photos is adopted.

As already known, the images of accretion disks are significantly modified due to the Doppler effect by disk rotation and to the gravitational lensing effect around the central object [31], [27]. This leads to the light curve asymmetry discussed by Fukue [26] and Fukue and Yokoyama [27].

b) Eclipse

With the image of the accretion disk around the neutron star, light curves are calculated by occulting it. Although, in the previous work [20], light curves are computed by occulting the image by the vertical obstacles, here I have obtained them more precisely, using simple geometry as follows.

Let (x, y) be the coordinates on the projection plane of the image, whose origin is located at the center of the neutron star (i.e., at the center of the accretion disk).

At the specified binary phase φ ($\varphi = 0$ at mid-eclipse), the center of the projection circle representing the companion rim is ($a \sin \varphi$, $-a \cos \varphi \cos i_0$) in this coordinate, if the observer is located at far from the center. Hence regions satisfying the condition

$$(x - a \sin \varphi)^2 + (y + a \cos \varphi \cos i_0)^2 \leq R_2^2 \quad (4)$$

on the projection plane are occulted by the companion.

In the actual calculation, the observed flux is obtained numerically as follows. The projection plane is divided into 41×41 (through 121×121) mesh. In each mesh, the observed flux is calculated and evaluated whether it is occulted or not by use of equation (4). Then the integrated X-ray flux of the disk is computed by summing contributions from all mesh which are not eclipsed by the the companion. Thus we can obtain the integrated observed flux as a function of φ for a given inclination angle i_0.

It should be noted that the center of the disk (i.e., the neutron star) is not occulted unless

$$i_0 \geqq i_{cr} = \cos^{-1}(R_2/a). \quad (5)$$

When the center is occulted (that is, the total eclipse occurs), the phase φ_e of ingress or egress is related to the inclination angle and the radius of the companion by

$$\cos \varphi_e \sin i_0 = [1 - (R_2/a)^2]^{1/2}. \quad (6)$$

Since φ_e is the observed quanity, the equation (6) relates i_0 with R_2/a as will be used in the next section.

III X-Ray Light Curves

III-1 Typical Case

A typical example of a light curve during the eclipse of a neutron star and an accretion disk by the companion is shown in figure 1 by a solid curve. For comparison, the light curve of the accretion disk without the neutron star (that is, the light curve of the disk around a black hole) is plotted by a dashed curve.

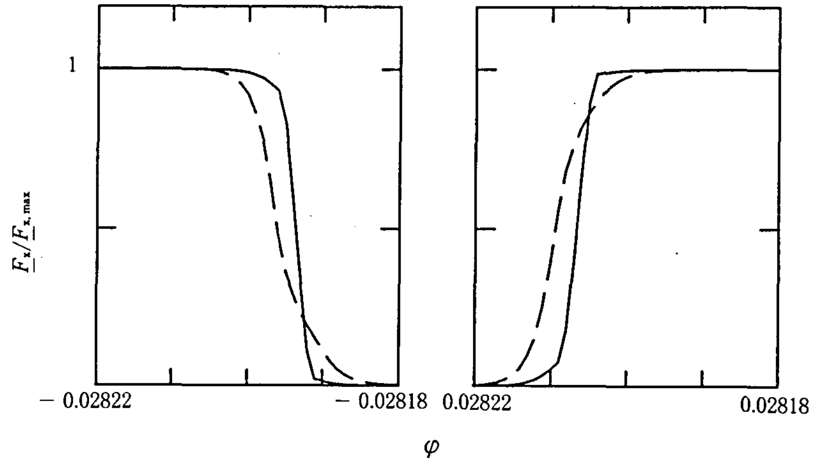

Fig. 1. The typical X-ray light curve of a geometrically thin, relativistic disk around a neutron star during eclipse by the companion (solid curve). For comparison, the light curve of the disk around a black hole is also shown by the dashed curve Parameters are $i_0 = 70°$, $q = 1$, and $P =$ 6 hr. The X-ray wavelengths are 2-30keV.

In figure 1, the abscissa is an orbital phase φ of the binary system, while the ordinate denotes the ratio of the observed X-ray flux to the maximum observed flux at the uneclipsed phase. The left panel shows the ingress phase whereas the right represents the egress phase.

The parameters taken for this standard case are the inclination angle $i_0 = 70°$, the mass ratio $q = M_2/M_x = 1$ (therefore $R_2/a = 0.38$), and the binary orbital period $P = 6$ hr. Furthermore, the X-ray wavelengths are taken as 2–30keV corresponding to the LAC aboard *Ginga* [33] .

The asymmetric nature of the light curve can be also seen in the case of eclipse of the accretion disk around the neutron star, although it is not so prominent in comparison with that in the case of the accretion disk around the black hole.

This is because in the present case the contribution from the neutron star to the total X-ray flux is significant in comparison with that from the disk which produces the asymmetry in light curves. For instance, in the X-ray wavelength region of 2–30keV, the fraction of the X-ray flux from the neutron star in the total flux is 0.53 for $i_0=60°$, 0.57 for $i_0=70°$, and 0.63 for $i_0=80°$.

Using this difference in the asymmetric nature of light curves between the neutron star-case and the black hole-case, we can discriminate the central object of the relativistic accretion disk through light curve analysis.

III-2 Parameter Dependence

As stated in the previous section, the parameters left freely are i_0, q (or equivalently R_2/a), and P. Of these, i_0 and q can not be observed explicitly, although P is observable. However, as noted in equation (6), i_0 is related to R_2/a (hence q) through the phase φ which is observable. Hence, if we fix observable paraneters φ_e and P, then there is left only one parameter ; e. g. , i_0.

Figure 2 shows the dependence of the profiles of light curves on the inclination angle i_0. In figure 2, the observable parameters are selected as $\varphi_e=0.0182$ and $P=3.8$ hr. The wavelength

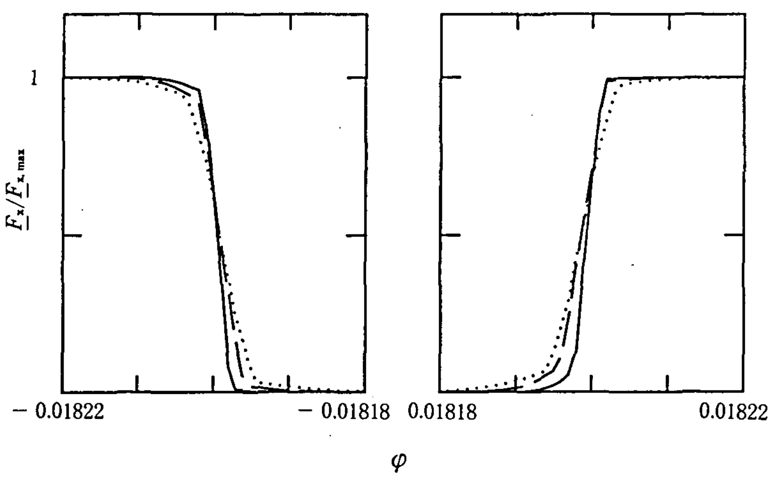

Fig. 2. The dependence of X-ray light curves on the inclination angle i_0. The observable parameters are selected as $\varphi_e=0.0182$ and $P=3.8$ hr. The X-ray wavelength band is 2–30keV.

A solid curve represents the case of $(i_0, q, R_2/a) = (85°, 0.031, 0.143)$, a dashed one (75°, 0.291, 0.281), and the dotted one (65°,1.886, 0.435).

band is 2–30keV.

Moreover, the inclination angle, the mass ratio, and the radius of the companion are (i_0, q, R_2/a) = (85°, 0.031, 0.143), (75°, 0.291, 0.281), and (65°, 1.886, 0.435). These three cases are respectively plotted by a solid curve, a dashed one, and a dotted one.

As can be seen from figure 2, the duration of ingress and egress becomes shorter for higher inclination angle (i. e. for greater mass ratio and therefore for larger companion radius) and vice versa. This is due to the curvature effect of the companion rim. That is, when the inclination angle is high, the equatorial part of the rim of the companion occults the disk and the neutron star. Thus the occulted edge is just like a vertical obstacle which occults the disk quickly. On the other hand, when the inclination angle is low, the system is occulted by the upper part of the rim ; i. e. , by the oblique obstacle. Thus it takes long to occult the system.

Next wavelength dependence of light curves is shown in figure 3. The parameters taken are $i_0=70°$, $q=1$, and $P=6$ hr.

The light curve in 2–5keV is plotted by a solid curve, that in 1–2keV by a dashed one, that in 0.5–1keV by a chain-dotted one, and that in 0.1–0.5keV by a dotted one.

It is seen from figure 3 that the eclipse ingress and egress become gradual as the wavelength band softer, while they become rapidly as it harder. This property is understood as follows ; softer and softer the band becomes, more and more the outer part of the disk contributes to the total X-ray flux. It is demonstrated that the detailed profiles of light curves depend on the disk model adopted.

III-3 Remarks

X-ray eclipses in the transient X-ray burst source EXO0748-676 have been discovered recently [34] , [25] . There exists the residual emission in the "total" eclipse at the level of 4% of the 2-6keV uneclipsed flux and this supposed to originate from an extended accretion disk corona. In this object, the binary orbital period is 3.82 hr and the duration of X-ray eclipse is 8.3

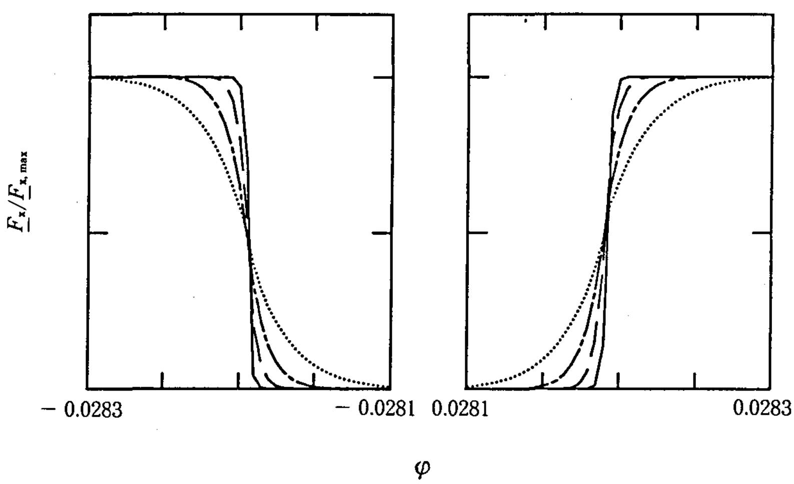

Fig. 3. Wavelength dependence of light curves. The parameters taken are $i_0=70°$, q = 1, and P = 6 hr. The X-ray wavelength bands are 2–5keV (solid curve), 1–2keV (dashed one), 0.5–1keV (chain-dotted one), and 0.1–0.5keV (dotted one).

min ; therefore the ingress and egress phase is $\varphi_e = \pm 0.036$. Furthermore, the eclipse ingress and egress have a duration of ~6s and this means the corresponding phase width is about 0.0004. This width is longer by one order than that for the typical case of the present results (e. g. , see figure 1). Parmar et al. [34] suggested that they are seeing absorption effects in the atmosphere of the companion star. However, there are some arguments against their suggestion.

A linear dimension of the comanion atmosphere that smears the point source by the absorption effect is evaluated as follows. First, the radiation which travels in the radial direction of the companion is roughly absorbed when the optical depth measured in the radial direction.

$$\kappa \rho H$$

becomes unity. Here κ is the opacity. ρ the typical density, and H the depth measured from the surface of the companion.

In the present case, however, we should consider the radiation which travels perpendicular to the radial direction of the companion and almost parallel to the companion surface. Along the trajectory which passes through at the depth h from the companion surface, the optical depth along the line-of-sight is roughly.

$$2\kappa\rho \ [h \ (2R_2 - h)] \ , \tag{8}$$

where R_2 is the radius of the companion. If the optical depth expressed by equation (8) becomes unity, the radiation from the point source is absorbed by the companion atmosphere. This is just the limb darkening effect.

From equations (7) and (8), the depth h is expressed as $h \sim H^2/8R_2$ for $h << R_2$. This is rather small in comparison with the depth H in the radial direction. For example, in the solar type star, H in the optical region is several hundreds km while h is smaller than 0.1km. Due to this limb darkening, we may treat the companion limb as an opaque obstacle.

Of course, in spite that the absorption effect of the companion is the case for EXO0748–676 or not, the timescale of the eclipse in this object is too long to apply the present model. It is desired for further observations of total eclipses in other low mass X-ray binaries.

IV Conclusions

In the present paper, I have investigated expected X-ray light curves during the eclipse of a geometrically thin accretion disk around a neutron star, bearing in mind low mass X-ray binaries.

It is found that the light curve exhibits an asymmetric profile between the ingress phase and the egress one for typical values of parameters, although the asymmetry is not so prominent in comparison with that of the accretion disk around the black hole. This difference of the asymmetric nature of light curves will enable us to distinguish the neutron star and the black hole as a central object.

Inclination angle dependences of light curves are examined by fixing observable parameters ; binary orbital period and the phase that the ingress and egress take place. For higher inclination angle, the width of ingress is short and vice versa. This is due to the effect of the curvature of the companion rim.

Wavelength dependences are also studied. The softer the observed wavelength bands are, the broader the width of ingress and egress becomes. This depends on the disk model adopted, especially, on the temperature distribution on the disk surface. Thus the fine analysis of light curves will reveal the temperature distribution on the disk.

These photometric approach in X-ray wavelengths — X-photo counting approach — as well as spectroscopic one is increasing their potential importance when *Ginga* is now in operation.

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低質量X線連星のX線光度曲線

（福　江　　純）

中性子星周辺の幾何学的に薄い降着円盤が伴星に隠される際の，X線光度曲線を理論的に計算した。ブラックホール周辺の降着円盤が隠される際の光度曲線は，降着円盤の回転にともなう相対論的ドップラー効果によって，食の前後で大きく非対称性なものとなる。それと比較して，中性子星周辺の場合は，X線輻射に対する中性子星からの寄与が大きいため，非対称性はあまり顕著でない。これらのことから，X線光度曲線を解析すれば，相対論的降着円盤の中心天体が，ブラックホールか中性子星かの判別をすることが可能になると思われる。

降着円盤の傾斜角に対する光度曲線の依存性と波長領域での違いも調べた。伴星の縁の曲率の影響によって、傾斜角が大きい場合には，食の入りと食の出で光度曲線は急峻になる。さらに波長帯が軟X線になるにしたがい，X線輻射に対する降着円盤の外周領域からの寄与が大きくなるので，食の入りと出の幅は長くなる。光度曲線の波長依存性は，降着円盤のモデルによって変わるので，波長依存性を調べればモデルの妥当性も検証できる。