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Research Note

Orbital phase variation of X-ray emission from Cyg X-3

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Abstract. The hard X-radiation (20-200 keV) from Cyg X-3 shows a maximum at a phase 0.5 of the observed 4.8 hr modulation, while the soft X-radiation (2-12 keV) shows a maximum at a phase 0.75.Both the emissions show a minimum at a phase 0.0. This behaviour can be explained by considering the X-ray emission both by the compact object and the hot post shock gas left by the passage of the compact object through the dense Wolf-Rayet primary; the attenuation and scattering by the electrons in the hot post shock gas, the Wolf-Rayet wind and the gas in the accretion wake is also used to construct the picture.

Key words: X-rays: stars

1. Introduction

Cyg X-3 was discovered as an X-ray emitting object, which was subsequently found to emit radiation at all wavelengths, starting from radio to high energy gamma rays (Bonnet-Bidaud and Chardin 1988). The X-ray emission shows a periodicity of 4.8 hrs, which is attributed to an orbital period of two objects of a binary system, one of which is a compact object. Recently it was shown (van Kerkwijk 1993; Schmutz, Geballe and Schild 1996; van Kerkwijk et al. 1996) that the primary star is a Wolf- Rayet star. Using the radial velocities of infrared lines, Schmutz et al. (1996) obtained a mass function and from this they suggested that the compact object is a black hole.The X-ray emission is suggested to occur when the black hole accretes gas from the strong wind from the Wolf-Rayet star.

Extensive observations of Cyg X-3 were made in the X-ray band (see Bonnet-Bidaud & Chardin 1988; Hermsen et al. 1987; Matz et al.1996). The phase-intensity diagram was obtained both in the soft X-ray band (2-12 keV) and the hard X-ray band (20-200 keV). In the soft X-ray band the light curve is asymmetric and shows a minimum which is designated as phase zero; the maximum occurs at about phase 0.75 (Bonnet-Bidaud & Chardin 1988). In the hard X-ray band, the minimum also occurs at phase zero, but the maximum occurs at a phase 0.5 (Hermsen et al. 1987; Matz et al. 1996).

The infrared emission from Cyg X-3 also shows the 4.8 hr periodicity (see Bonnet-Bidaud and Chardin 1988 for references) and the minimum of the light curve occurs at the X-ray minimum. The early measurement by Mason, Cordova and White (1986) showed a similarity of the X-ray and infrared light curve. The recent photometric measurement of the infrared curve by van Kerkwijk (1993) shows a flat infrared maximum between phase $\sim$0.4 and $\sim$0.7. The observations of Jones et al.(1994) agree with the result of van Kerkwijk (1993). Infrared spectroscopy was performed on Cyg X-3 by van Kerkwijk (1993), van Kerkwijk et al. (1996), Schmutz et al.(1996) and by Fender, Hanson and Pooley (1999). Line shifts were observed, the maximum blueshift occurring at the time of the infrared minimum and the maximum redshift half an orbit later (van Kerkwijk et al. 1996).

The configuration of the Wolf-Rayet star and the compact object at the time of the X-ray and infrared minima seems to be uncertain. Van Kerkwijk (1993) suggested that the lines which showed the systematic blue shift originate in a region shadowed by the Wolf-Rayet star from the X-radiation of the compact object. This will imply that at the time of the blue shift (X-ray and infrared minimum) the compact star is at the superior conjunction. The phase 0.0 will then correspond to the configuration when the compact object is behind the Wolf-Rayet star along the line of sight. Schmutz et al. (1996) argue that the emission line profiles observed do not show the form predicted by the model of van Kerkwijk (1993).They also point out that at all phases the HeII 1.87 μm line shows the full width of the wind's maximum expansion velocity. Schmutz et al. (1996) further state that this is in "direct conflict, because the HeII 1.87 μm line can only emit over the full width at all phases if it is formed in an accelerating wind in which it remains fully ionised in the region that is in the X-ray shadow". They suggest that the weak lines which show the shifts occur close to the photosphere of the Wolf-Rayet star. The blue shift will then occur when the Wolf-Rayet star is at the descending node and therefore the X-ray and infrared minima, corresponding to phase 0.0 will occur at the ascending node of the compact object. Clearly there is a difference in the interpretations of van Kerkwijk (1993) and Schmutz et al. (1996). This controversy needs to be resolved by further comprehensive study of the origin of the He lines. Pending the resolution of this controversy, in this paper we will use the picture suggested by Schmutz et al. (1996) for two reasons–firstly using their phasing, we have been able to account for the infrared light curve based on emission from a shock produced by the compact object (Apparao 1997), and secondly it is possible to interpret the phase variation of the soft and hard components of X-ray emission as given below. The phases of the minima and maxima of X-ray and infrared emissions are then as shown in Fig. 1.

Several models have been suggested to explain the light curve in the soft X-ray band (see Bonnet-Bidaud and Chardin 1988 for references). In these models, absorption and scattering of the X-radiation, either by the dense wind of WR star or a gas cocoon around the system is suggested to be the cause of the minimum. The absorption is the least at the inferior conjunction, that is at the phase of 0.75 (Fig. 1), and the maximum of intensity should occur at this phase. Similarly the maximum absorption occurs at the superior conjunction and the minimum should occur at phase 0.25. The occurrence of the hard X-ray maximum at phase 0.5 and the occurrence of a minimum at phase zero do not accord with the simple absorption or scattering picture suggested in the earlier models.

We had earlier suggested that infrared emission occurs from the hot post-shock gas produced by the supersonic motion of the secondary through the WR wind (Apparao 1997). This emission causes the observed infrared modulation; the maximum occurs around phase 0.5 when the observer faces the shock, and the minimum occurs at phase zero, when the cooled post-shock gas blocks the infrared radiation from the observer's view.

In order to explain the observed X-ray phase-intensity relation, we suggest that X-ray emission occurs both from the accreting compact object as well as from the hot post-shock gas. Modulation of the X-ray emission occurs due to Compton scattering by electrons inthe wind of the WR star and also by electrons in the hot post-shock gas. In the following we will detail this picture.

2. Structure of the post-shock gas

Apparao (1997) has considered the post-shock structure in the case of Cyg X-3 using the work of Hollenbach and Mckee (1979). He finds the post-shock temperature T_s=4.7×10^7 K and the temperature structure is given by $T^{3/2}$(x)=b-ax, where x is the distance behind the shock front, b=$T_s^{3/2}$ and a=(1/x_0)($T_s^{3/2}$- $T_0^{3/2}$). Here T_0 is the temperature at a distance x_0 and when T_0 is small compared to T_s, x_0≃1.9×10^9 cm and a=1.7×10^2 (Apparao 1997). The density structure is given by n(x)=(16/3)$n_0 T_s$/T(x), where n(x) is the number density at x and n_0 is the pre-shock density at the orbit of the of the black hole and is ≃7×10^{12} He cm^{-3} (the wind of the Wolf-Rayet star is deficient in hydrogen; for simplicity we assume it to contain only helium nuclei and heavier elements in this paper).

Tamm, Fu and Fryxell (1991), while considering accretion of matter on to a compact object passing through the wind of its binary companion find an accretion wake behind the compact object. They find that the shock front is ahead of the compact object at a distance x_1∼0.1r_{acc}. The accretion radius is r_{acc}≃1.1×10^{11} cm (Apparao 1997), so that x_1∼1.1×10^{10} cm.

The picture given above is considerably altered by the presence of the strong X-ray source and also the X-ray emission from the post-shock gas. The determination of the density and

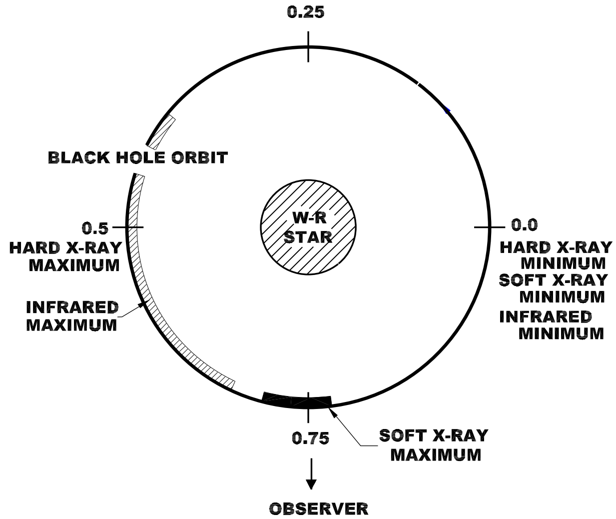

Fig. 1. The orbital phase diagram of Hard X-ray, Soft X-ray and infrared maximum and minimum emissions from Cyg X-3. The soft X-ray maximum occurs in a small band around phase 0.75 (shaded), while the infrared maximum is flat and is between ∼0.4 and ∼0.7 (cross-hatched)

temperature profiles in these conditions is beyond the scope of this work. It may be noted however that the temperature of the post shock gas between the shock front and the compact object can be maintained at a high value by the X-ray irradiation.

3. X-ray emission from post-shock gas

The X-ray emission from the hot post-shock gas can be calculated using the expressions for the density and temperature given above. The X-ray luminosity due to emission by the post-shock gas in the direction of the movement of the shock can be expressed as

$$F_X = 5.4{\times}10^{-39} 4\pi A Z^2 g \int\int n_e n_i T^{-0.5} e^{-h\nu/kT} dx d\nu$$

in ergs s^{-1}; n_e, n_i and T are dependent on x. Here n_i=n_{He}, where n_{He} is the density of helium nuclei (the main constituent of the wind from the Wolf-Rayet star) in the wind and n_e= 2n_i; A is the area of the shock and is ≈2πr_s^2, where r_s is the radius of the shock and is 1.1×10^{11} cm (Apparao 1997). The integrals are over the temperature range and the frequency band. Using the expressions for the density and temperature profiles in the post-shock gas given by Apparao (1997), we have evaluated the X-ray luminosity between 2 and 12 kev and find L_x≃ 10^{38} ergs s^{-1} which is comparable to the observed value(White and Holt 1982; Willingale et al. 1985). Note that T_s given above corresponds to ≃ 4.7 keV, therefore the X-ray emission from the post-shock gas corresponds to the soft component.

4. Scattering and absorption of X-rays from the black-hole by the post-shock gas

The determination of the scattering or absorption optical depth will depend on the structure of the gas density, starting from the shock front to the black hole. Since we have not obtained this density profile, we will estimate the electron scattering optical depth in two steps; 1) the electron scattering optical depth τ_C^s from the profiles given in Sect. (2) and the optical depth τ_C^i due to the gas ionised and controlled by the X-ray irradiation. The electron column density N_c between the black hole and an observer seeing it from the front of the shock due to the hot post-shock gas can be calculated using the density and temperature profiles given above and is $N_c=32\,n_0(T_s^{3/2}/a)$. We find $N_c\simeq4.2\times10^{23}$ cm^{-2}. This corresponds to an electron scattering optical depth of $\tau_C^s\sim0.3$. We have also calculated τ_C^s from the black hole to the observer in a direction perpendicular to the motion of the shock and find it is about the same value. In the Appendix the optical depth for Compton scattering due to the gas ionised by the X-radiation from the black hole τ_C^i, when an observer sees the black hole from the front of the shock, is given for various n_{He}. For helium gas densities greater than 10^{15} cm^{-3} the τ_C^i is large and will scatter and degrade the X-radiation. Since the hard radiation is observed at a high intensity the scattering optical depth τ_C^i must be $\lesssim$1; we will estimate this below. The value of τ_C^i in the direction perpendicular to the motion of the shock at the black hole will be twice the value of that seen from the front, if the shock front is assumed to be in the shape of a parabola. Thus flux of X-radiation from the black hole as seen from the side of the shock will be less than that seen from the front of the shock. The thick accretion wake is however dense enough to attenuate both components when the observer views the black hole from the back of the shock, that is at phase 0.0.

5. Absorption and scattering of X-radiation by the wind of the Wolf-Rayet star

The X-radiation emitted by the black hole as well as that emitted by the post-shock gas has to pass through the wind of the Wolf-Rayet star. A simple estimate of the column density of helium from the position of the compact star at phase 0.75 to the observer (see Fig. 1) gives, $N_{He}\simeq4\times10^{23}$ cm^{-2} [in this calculation, we have taken the mass loss $\dot{M}=4\times10^{-5}$ $M_\odot$ yr^{-1} (van Kerkwijk 1993); the wind velocity law is taken as $v(r)= v_a$ [1-$(R_*/r)]^\beta$ with $\beta\sim1.0$ and v_a=4000 km s^{-1} (Conti and Underhill 1988)] This value will correspond to a hydrogen column density of $\sim4\times10^{24}$ cm^{-2} (corresponding to solar abundances); this is much larger than the observed column density of 7×10^{22} H atoms cm^{-2} (White and Holt 1982; Willingale et al. 1985). However the strong X-ray emission from the compact object and the hot post-shock gas ionises the gas around(Kallman and McCray 1982); the ionisation is complete upto the element Silicon and partial upto the element Iron. In a gas of uniform hydrogen number density n_H (Universal abundances), X-radiation of luminosity L, will ionise a sphere of radius R given by $R^2=L/n_H\xi$. Kallman and McCray (1982) give $\xi\simeq100$ for the ionisation described above.With $L\simeq10^{38}$ erg s^{-1} and $n_H=7\times10^{13}$ cm^{-3} (corresponding to $n_{He}=7\times10^{13}$ cm^{-3}), we find $R\sim1.2\times10^{11}$ cm, giving a column density of $\sim8.4\times10^{24}$H atoms cm^{-2}. In actuality at phase 0.75, the wind density is falling towards the observer giving a lower column density. However comparing this number with the column density estimate due to the wind, suggests that most of the wind in this direction is completely ionised upto at least Silicon and partially ionised upto Iron. Thus the soft X-radiation is not appreciably absorbed by the wind and results in the low hydrogen column density observed. The column density from the compact object to the observer due to the wind at phase 0.5 can also be calculated and is $\pi/2$ times the value at phase 0.75 (see Williams et al. 1990). The Compton scattering optical depth due to the Wolf-Rayet wind $\tau_C^w\simeq2N_{He}\sigma$, where σ is the Compton scattering cross section. At phase 0.75, τ_C^w is about 0.6 and at a phase 0.5 it is $\pi/2$ times this value, that is $\sim$0.9.

6. Modulation of X-rays in Cyg X-3

We can now construct the picture of modulation of hard and soft X-radiation from Cyg X-3, using the above calculations. The observed modulation is due to scattering of radiation by electrons between the X-ray source and the observer. In the case of the hard X-radiation, the radiation comes from the black hole. At phase 0.5 the maximum radiation is seen, when the combined Compton scattering optical depth τ_C^{tot}, due to the post-shock gas, the ionised region due to the X-rays from the black hole and the Wolf-Rayet wind, towards the observer is minimum. $\tau_C^{tot}=\tau_C^s+\tau_C^i+\tau_C^w$. The values of τ_C^s and τ_C^w are given above. The value of τ_C^i is not known. If we use the observed ratio of intensities at phases 0.5 and 0.75 (Hermsen et al. 1987), we can adjust τ_C^i and find $\tau_C^i\sim0.6$ at phase 0.5 and $\tau_C^i\sim1.2$ at phase 0.75. Then $\tau_C^{tot}\sim1.8$ at phase 0.5 and $\sim$2.1 at phase 0.75, resulting in the reduced hard X-ray intensity at phase 0.75. At phase 0.0, the hard radiation is strongly attenuated by the accretion wake and leads to the minimum observed.

The soft X-radiation seen by the observer is a combination of the emission from the black hole and the radiation from the hot post-shock gas. This however is modulated by the attenuation due to the wind of the Wolf-Rayet star.The amount of soft X-radiation emission towards the observer from the hot post shock gas increases from pkase 0.5 to phase 0.75 as the attenuation due to the Wolf-Rayet wind decreases. The soft radiation as seen by the observer quickly drops beyond phase 0.75 due to the combined effects of decreasing solid angle subtended by the hot post- shock emitting region, the attenuation by the post shock gas and the increasing attenuation by the wind of the Wolf-Rayet star. At phase 0.0 the soft X-radiation is completely attenuated by the gas in the accretion wake.

7. Discussion

We have been able to account qualitatively for the phase dependence of the X-ray intensity in the 4.8 hr modulation, using the X-ray emission from the secondary black hole and the emission from the hot post shock gas as well as scattering and attenuation by the post shock gas and the Wolf-Rayet wind. This has been possible by taking the phase 0.0 corresponding to the X-ray minimum to be at the ascending node of the compact object. As mentioned in the introduction there is a controversy as to the

Table 1. The Compton scattering optical depth for the X-ray induced ionisation sphere

n_{He} cm^{-3}	n_H cm^{-3}	R cm	τ_C^i
10^{16}	10^{17}	3×10^{9}	42
10^{15}	10^{16}	10^{10}	14
10^{14}	10^{15}	3×10^{10}	1.54*
10^{13}	10^{14}	10^{11}	0.15*

*In this case R=x_1

configuration of the Wolf-Rayet star and the compact star at the time of the X-ray minimum which needs to be resolved.

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Appendix

Here we calculate the dimension of the ionised sphere due to X-radiation from the black hole for several n_{He}, using the work of Kallman and McCray(1982). We use the X-ray luminosity of the black hole as L=10^{38} ergs s^{-1}. The dimension of the ionised sphere is given $R^2=L/n_H\ \xi$. From Kallman and McCray (1982) $\xi\simeq100$ for fully ionised helium. We use $n_H=10n_{He}$. The values of R for several n_{He} are given in Table 1. The value of the electron scattering optical depth due to the ionised sphere $\tau_C^i=2n_{He}R$. In case of R greater than x_1, x_1 is used in place of R in the expression for τ_C^i.

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