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Flaring and modulation of infrared radiation from the X-ray source Cygnus X-3

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Abstract. The modulation of infrared emission from the x-ray source Cyg x-3 is explained as due to free-free emission from gas in the wind given out by the binary companion to the x-ray source, and which is heated by the shock produced by the orbital motion of the compact object responsible for the x-rays. The observed infrared flaring occurs when the shock encounters clumps in the wind.

Key words: stars: Cyg X-3 – X-rays: stars – infrared: stars

1. Introduction

Cyg x-3 was first discovered in x-rays and later found to emit radiation from radio to high energy gamma rays (Bonnet-Bidaud & Chardin 1988). The object is in a heavily obscured region and has been identified in the R and I bands (Wagner et al. 1989,1990). The x-ray emission shows a regular modulation with a period of $\sim$ 4.8 hrs. This period is generally considered to be the orbital period of the compact object responsible for the emission of x-rays, revolving around another star. The nature of the primary star is suggested to be a Wolf-Rayet (WR) star by van Kerkwijk (1993) and van Kerkwijk et al. (1996), using observations of infrared lines. Schmutz et al. (1996), by determining the radial velocities of the infrared lines, obtained a mass function for the binary system. Using a mass range for the WR star of 5-20 $M_\odot$, they find the x-ray emitting object will have a mass in the range 7-40 $M_\odot$, suggesting the compact object is a black hole.

Variable infrared emission from Cyg x-3 has been observed (Fender et al. 1996 and references therein). The 4.8 hour modulation was also seen in the infrared emission and the modulation was found to be variable between 10 and 25 percent. Infrared flares with increase in luminosity of upto a factor of $\sim$3 and duration in the range 100-1000 s was observed (Mason et al. 1986). The quiescent infrared emission was suggested to be emitted by the hot wind from the WR star (van Kerkwijk 1993) further heated by the x-ray emission from the compact star (CO). The shadowing of the x-ray heating by the WR star resulting in a comparatively cooler gas in an orbital sector and also variable free-free absorption by the wind as the stars orbit each other, was suggested to be the origin of the 4.8 hour modulation. The infrared flaring is suggested to be optically thin free-free emission from a hot gas with a temperature T $\gtrsim 5\times10^5$ °K (Mason et al. 1986; Fender et al. 1996); however the origin of this hot gas was not specified. Fender et al. (1996) have also suggested that the infrared flaring emission can be from synchrotron emsission from the relativistic elctrons; again no details were given.

In this paper we suggest that the motion of the CO at supersonic velocity through the wind of the WR star produces a shock which heats the gas to high temperatures, and results in infrared emission which adds to the infrared emission from the wind of the WR star. The orbital motion of the binary system results in the 4.8 hour modulation. Also when the shock goes through clumps of gas in the WR wind, the higher density in the clumps leads to enhanced infrared emission which is observed as infrared flares.

The quiescent infrared flux was given by Fender et al. (1996) to be 16.6±0.4 mJy in the K-band. Using a distance of 10 kPc (Dickey 1983) and an extinction A_K = 2 (van Kerkwijk et al. 1996), the quiescent K-band flux $F_K = 1.1\times10^{22}$ ergs s^{-1}Hz^{-1} . The additional flux needed to produce the 4.8 hour modulation, using a value of $\sim$ 15 percent, is $F_K^m \approx 1.7\times10^{21}$ ergs s^{-1}Hz^{-1}. The Infrared K-band flare flux was also given by Fender et al. (1996) as 49.3±7.4 mJy. This will translate to a flare K-band flux $F_K^f \approx 3.6\times10^{22}$. ergs s^{-1}Hz^{-1}.

2. The 4.8 hr infrared modulation

We will consider here a binary system of a WR star of mass $M_1 = 5M_\odot$ and a CO of mass $M_2=7M_\odot$ as allowed by the mass function given by Schmutz et al. (1996). Using the orbital period of 4.8 hrs. the distance between the stars is a=2.2×10^{11} cm. The velocity of the CO is $v_2=7.4\times10^7$ cm s^{-1}. This velocity is supersonic for the wind from the WR, resulting in a shock. The velocity of the wind from the WR star used here is v_w=1000 km s^{-1} (see van Kerkwijk 1993 and van Kerkwijk et al. 1996). This gives a relative velocity between the CO and the wind as $v_r=1.24\times10^8$ cm s^{-1}. It is suggested that due to the supersonic motion of the CO, a bow shock is formed at the accretion radius (Frank et al. 1985). The numerical simulations of Tamm et al. (1991, and references therein) indicate that the stand-off distance is smaller than the accretion radius; however the radius of the bow shock seems to be about the value of the accretion radius. Here we will use the radius of the bow shock equal to the accretion radius and is r_s=1.1$\times$10^{11} cm.

The mass loss due to the wind from the WR star is taken as $\dot{M}$=4$\times$10^{-5} $M_\odot$ yr^{-1} (van Kerkwijk 1993). We will assume that the gas in the wind is pure helium. This will result in a density of helium at the orbit of the CO as ρ_w=4.6$\times$10^{-11} gm cm^{-3} or a number density $n_{He}\simeq$7$\times$10^{12} cm^{-3}.

The post shock temperature T_s is given by Spitzer (1968) and Hollenbach & Mckee (1979)

$$T_s = \frac{3\mu_s v_s^2}{16k},$$

where μ_s is the mean mass per particle evaluated behind the shock, k is the Boltzman constant and v_s is the velocity of the shock and is same as v_r. This can be evaluated to give T_s= 3.03$\times$10^5v_{s7}^2, where v_{s7}= v_s/ (10^7 cm s^{-1}). Using the value of v_s given above $T_s\simeq$4.7$\times$10^7°K. The post shock density structure has been worked out by Hollenbach & Mckee (1979). The formula can be simplified in the present case to give

$$n(x) = n_0 \frac{16T_s}{3T(x)}$$

where n (x) and T (x) are the number density and temperature at a distance x behind the shock front. n_0 is the post shock density and is the same as n_{He}.

The equation given by Hollenbach & Mckee (1979) for the variation of temperature with time in the post shock region can integrated to give the temperature T (x) as a function of the distance x from the shock front to give $T^{3/2}$ (x)= b-ax. With the condition T=T_s at x=0 and T=T_0 at some distance x=x_0, we get b=$T_s^{3/2}$ and a= (1/x_0) ($T_s^{3/2}$-$T_0^{3/2}$).

The gas behind the shock cools and the distance at which the temperature is much less than T_s is given by x_0=$v_s t_{cool}$. Using the expression given by Hollenbach & Mckee (1979), in the present case, t_{cool}= (9kT)/ (n_eL), where L is the cooling function for energy loss by bremsstrahlung and is L=1.4$\times$10^{-27} Z^2 g $T^{1/2}$. Here Z=2 and the Gaunt factor g=1.4 (Fender et al. 1996). and n_e= 2 n_{He}. Using the values of T_s and n_{He} we find $x_0\approx$1.9$\times$10^9 cm.

The infrared flux in the K-band due to the post shock gas can now be evaluated and is

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

in ergs s^{-1} Hz^{-1}.
Here n_i=n_{He} and n_e=2n_i ; A is the area of the shock and is $\approx$2πr_s^2. The integral can be evaluated using the expressions for n_{He} (x) and T (x) given above. We have done this and using the numerical values given above, we find F_k = 2.2 $\times$10^{21} ergs s^{-1} Hz^{-1}. This value adequately explains the observed modulation flux F_K^m given in Sect. 1.

The modulation of the infrared flux is caused by the aspect of the shock with respect to the line of sight. The front of the shock is transparent to the infrared radiaton due to the high temperature, while the back of the shock is opaque due to the lower temperature and higher density of the gas . The linear free-free absorption coefficient for small (hν/kT), as is the case here, is given by (Allen 1976):

$$\kappa_s = 1.98\times10^{-23} Z^2 \lambda^2 n_e n_i T^{-3/2}$$

where λ is the wavelength of radiation in cm. The attenuation of the infrared radiation in the shock emitting region towards the front of the shock can be estimated by evaluating $\int_0^{x_0} \kappa_s dx$. We have calculated this value using the expressions and values given above and find it less than 0.1. On the other hand the the cooler part of the postshock region, makes it opaque for the emitted infrared radiation towards the back of the shock. Consequently the minimum of the infrared flux occurs at the ascending node of the CO, which corresponds to the blue shift of infrared lines associated with the WR star; this is as observed by Schmutz et al. (1996). It must be mentioned however, that the shock front is not exactly perpendicular to the direction of motion of the compact object; the angle between them is arctan (v_2/v_w) which is about 36°. Therefore the infrared minimum will not occur exactly at the ascending node, but before it reaches the ascending node. This can be verified in future more accurate measurement of the infrared modulation curve.

We have mentioned earlier that van Kerkwijk (1993) has explained the modulation, by suggesting that the region of the wind from the WR on the side of the x-ray object has a higher temperature than the region shadowed by the WR. By assuming a contrast in the temperatures of the x-ray heated and the shadowed regions, van Kerkwijk (1993) has been able to explain the infrared modulation. However it needs to be shown that the required heating and the assumed temperature contrast actually occurs.

3. Infrared flare emission

The occurence of clumpiness in winds of early type stars has been considered by Owocki et al. (1988). The clumpiness is given by [$< \rho^2 >/< \rho >^2$] $\simeq$6 and the dimension of the larger clumps is $r_C\sim$10^{11}.

We suggest that the infrared flaring observed in Cyg x-3 occurs, when the shock due to the CO encounters a clump of gas in the WR wind. The procedures in the previous section can be used again to evaluate the the number density of He nuclei in the clump n_{He}^c needed to explain the infrared flare flux in the K-band given in Sect. 1 (F_K^f= 3.6$\times$10^{22} ergs s^{-1} Hz^{-1}). We find that the clump density $n_{He}^c\approx$4.5$\times$ n_{He}^w.This density is withing the range usually considered. Thus it seems possible that the infrared flares can result from the hot gas formed due to the passage of the shock due to the CO through the clump.

4. Discussion

We have shown above that the modulation and flaring of infrared flux from Cyg x-3 can result from passage of the shock due to the compact object in the system through the wind of the Wolf-Rayet star. In the above considerations we have used the composition of the gas in the wind as pure helium; it turns out the assumption of pure hydrogen gives essentially the same value as calculated for helium. Schmutz et al. (1996) have suggested $M_1 \approx 13\ M_\odot$ and $M_2 = 17 M_\odot$. These are higher than the values used in our considerations. However use of these values reduces the emission obtained above by only a factor of $\sim$1.4, which does not alter our conclusions in view of the uncertainties in A_K and other values.

No correlation between enhancements of x-rays and infrared flares has been observed (Mason et al. 1986). In the present suggestion of the origin of the infrared flares, a correlation is not expected, firstly because of the time taken by the infrared flare emitting gas to travel the from the shock region to the CO and secondly because of the time delay between the arrival of the gas at the outer region of the accretion disk around the CO and the arrival at the surface of the CO from where x-ray emission takes place.

Finally, acceleration of particles takes place near the shock front; these high energy particles may lead to the observed radio emission. This aspect will be presented elsewhere.

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References

Allen, C.W., 1976, Astrophysical Quantities, The Athlone Press,London.
Bonnet-Bidaud, J.M. and Chardin,G., 1988, Physics Reports,170,325.
Dickey, J.S., 1983, ApJ, 273, 688.
Fender, R.P., Bell-Burnell, S.J., Williams, P.M. and Webster,A.S.,1996, MNRAS, 283, 798.
Frank,J., King,A.R. and Raine,D.J., 1985, Accretion Power in Astrophysics, Cambridge University Press, Cambridge.
Hollenbach, D. and McKee, C.F., 1979, ApJ Suppl., 41,555.
Mason, K.O., Cordova, F.A. and White, N.E.,1986, ApJ, 309, 700.
Owocki, S.P., Castor, J.I. and Rybicki, G.R., 1988, ApJ, 235, 914.
Schmutz, W., Geballe, T.R. and Schild, H., 1996, A&A, 311, L25.
Spitzer, L. 1968, Diffuse Matter in Space (Interscience, New York).
Taam, R.E., Fu,A. and Fryxell, B.A., 1991, Ap.J., 371, 696.
van Kerkwijk, M.H., 1993, A&A,276, L9.
van Kerkwijk, M.H. et al., 1996, A&A, 314, 521.
Wagner,R.M.,Kreidel,T.J.,Bus,S.J. and Williams, W.,1989, ApJ, 346, 971.
Wagner,R.M.Kreidel,T.J.,Martell,P.J. and Beaver,J., 1990, ASP conference Ser 8., CCDs in Astronomy, Ed. G.H.Jacoby, Astron.Soc.Pacific, San Francisco, p.361.

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