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Optical and infrared modulation in the Be-star/X-ray source LSI+61°303

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Abstract. The Be star X-ray source LSI+61°303 is found to show optical and infrared modulation with its orbital period. We show that this modulation is due to radiation from a shock produced by the companion to the Be star, while it passes through the gas envelope of the Be star in its binary motion.

Key words: stars: emission-line, Be – stars: individual: LSI+61°303 – infrared: stars – X-rays: stars

1. Introduction

Several binary systems contain stars which give out gas either in the form of a dense wind (Wolf-Rayet stars) or in the form of an expanding disk (Be stars), through which the companion star has to traverse in its orbital motion. In such binaries with small periods, the velocity of the companion is supersonic, resulting in a shock. The post-shock gas is hot and emits radiation. By calculating this radiation we have explained the infrared modulation observed in the X-ray source Cyg X-3 (Apparao, 1997), which contains a Wolf-Rayet star. In this paper we consider the infrared and optical modulation in the X-ray source LSI +61°303, which is a binary containing a Be star and a compact object. The Be star sometimes ejects a gas disk,through which the compact object passes and produces a shock.

The presence of a compact object in the system LSI +61° 303 is indicated by the X-ray and gamma ray emission from the source. Using the radio emission, Taylor & Gregory (1982) found the period of the binary system to be 26.5 days. In addition a long term modulation of the radio radiation with a time scale of about 4 years was observed by Gregory et al. (1989). The X-ray emission occurs at a phase of 0.5 (Taylor et al., 1996), using the zero phase defined earlier by Taylor & Gregory (1982). It is suggested that the X-ray emission occurs when the compact object,at its periastron, passes through the gas envelope of the Be star.

Mendelson & Mazeh (1989) found an optical modulation in the V-band with the same periodicity as the radio periodicity. This is confirmed by Paredes et al. (1994); the optical modulation in the V-band is about 0.15 mag. Using an optical extinction corresponding to E(B-V)=0.93 (Hutchings & Crampton, 1981) and a distance of 2.3 kpc to the source, the V-band modulation flux is calculated and is given in Table 1. Paredes et al. (1994) also found the periodic modulation in the IJHK bands. The modulation magnitudes and the corresponding monochromatic luminosities are given in Table 1.

Marti & Paredes (1995) have tried to explain the infrared modulation as due to an eclipse of the emission from the compact object and its accretion disk by the Be star and its gas envelope. They have however not verified if any process near the compact object or the accretion disk can produce the requisite energy to give the increases observed in the modulation. Also the phase of the observed minimum does not follow from the model and the longitude of the periastron is fitted to give the required phase. They assumed super-Eddington accretion of matter on to the compact object, without reconciling this to the fact that the observed X-ray emission is lower than the Eddington limit by several orders of magnitude. Marti & Paredes (1995) did not explain the optical modulation with their model and suggest that a different model is required for the explanation of the optical modulation.

In this note we suggest that the excess optical and infrared emission is from the post shock gas left by the passage of the compact object through the gas envelope of the Be star.

2. Emission from a shock produced by the compact object

The binary period of the LSI+61°303 is 26.5 days (Taylor & Gregory, 1982). Using a mass for the primary Be star (B0V) of 10 $M_\odot$ and a mass of 1 $M_\odot$ for the compact object, the average distance between the stars is 5×10^{12} cm. The velocity of the compact object is $v_r = 2.2\times10^7$ cm s^{-1}. The passage of the compact object through the gas envelope of the Be star is supersonic, resulting in a shock wave. The bow shock is suggested to be at the accretion radius (Frank et al. 1985; see discussion in Apparao, 1997). Here we will use the radius of the bow shock as the accretion radius which is calculated to be $r_s \simeq 5\times10^{12}$ cm.

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

$$T_s = \frac{3\mu_s v_s^2}{16k} \quad (1)$$

where μ_s is the mean mass per particle evaluated behind the shock, k is the Boltzmann constant and v_s is the velocity

Table 1. Observed and calculated modulation emission fluxes

Wave Band	Modulation magnitude Δm	Observed L_ν ergs $s^{-1}Hz^{-1}$	Calculated L_ν $n_0 = 2 \times 10^{11}$ cm^{-3} ergs $s^{-1}Hz^{-1}$	Calculated L_ν $n_0 = 5 \times 10^{11}$ cm^{-3} ergs $s^{-1}Hz^{-1}$
V	0.15	2.3×10^{21}	9.6×10^{20}	2.4×10^{21}
I	0.20	1.8×10^{21}	1.4×10^{21}	3.4×10^{21}
J	0.38	1.5×10^{21}	1.6×10^{21}	4.0×10^{21}
H	0.44	1.1×10^{21}	1.8×10^{21}	4.3×10^{21}
K	0.32	9.6×10^{20}	1.9×10^{21}	4.5×10^{21}

of the shock which is the same as v_r. This can be evaluated in the present case,using a mean mass per particle as 0.6, to give (Hollenbach & Mckee, 1979) $T_s=1.38\times10^5 v_{s7}^2$, where $v_{s7}=v_s/(10^7$ cm s^{-1}). Using the value of v_s given above, $T_s \simeq 6.7 \times 10^5$ K. The post shock density structure is given by Hollenbach & Mckee (1979) and can be simplified for the present case to

$$n(x) = n_0 \frac{16T_s}{3T(x)} \quad (2)$$

where n(x) and T(x) are the number density and temperature at a distance x behind the shock front. n_0 is the pre-shock density; here we take $n_0=2\times10^{11}$ cm $^{-3}$; this denisty is reasonable since the number densities in Be star envelopes range between 10^{11} and 10^{13} cm^{-3} (Doazan, 1982).

The equation given by Hollenbach & Mckee (1979) for the variation of temperature in the post shock region can be integrated to give the temperature T(x) as a function of 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 becomes 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}=(3.3kT)/(nL), where L is the cooling function for energy loss by bremsstrahlung and is $L=1.4\times 10^{-27} Z^2 g T^{1/2}$. Using the value of n_0 given above $x_0=5.7\times10^9$ cm and a=0.096.

The monochromatic luminosity in a given wave band due to the post shock gas can be evaluated and is given by

$$L_\nu = 5.4 \times 10^{-39} 2\pi A Z^2 g \int_0^{x_0} n_e(x) n_i(x) T^{-0.5}(x) \times e^{-h\nu/kT} e^{-\tau} dx \quad (3)$$

in ergs s^{-1} Hz^{-1}. Here $n_e=n_i$ and A the area of the shock is$\simeq 2\pi r_s^2$. g is the Gaunt factor and Z is the average atomic mass; in the present consideration we have taken Z=g=1. τ is given by

$$\tau(x) = \int_0^x \kappa_s(y) dy \quad (4)$$

κ_s is the free-free absorption coefficient and is given by (Allen, 1976):

$$\kappa_s(x) = 1.37 \times 10^{-23} Z^2 g \lambda^3 n_e(x) n_i(x) T^{-1/2}(x) \quad (5)$$

The integral for τ given in (4) can be evaluated using (2) and (5) to give

$$\tau(T) = 4.2 \times 10^{-22} T_s^2 Z^2 g\lambda^3 \frac{1}{a} n_0^2 (\frac{1}{T} - \frac{1}{T_s}) \quad (6)$$

We have calculated the emission L_ν at various wavelengths using(2),(3),(6) and the values of the parameters given above. We have taken $T_0=10^4$ K along with Hollenbach & Mckee (1979). We have also obtained the values of L_ν for n_0= 5×10^{11} cm^{-3} and given them in Table 1. It may be worthwhile pointing out that the emission flux L_ν is approximately proportional to n_0, because of the occurrence of n_0^2 in the integral and the limit x_0 is inversely proportional to n_0.

The radiation flux from the post shock gas is directed towards the direction of motion of the shock and the cooled shocked gas is opaque to the radiation in the opposite direction. The maximum will occur at the descending node of the secondary object (phase∼0.75) and the minimum at the ascending node (phase∼0.25). This agrees with the phases of the minimum and maximum seen in the light curve given by Marti & Parades (1995). However it remains to be established that the zero phase adopted by Taylor & Gregory (1982) from radio observations does correspond to the compact object being in front of the Be star.

3. Discussion

We have considered here the radiation emitted by the gas in the Be star envelope that is shocked by the passage of the secondary star through the envelope. In the case of the Be-star/X-ray source LSI +61°303, the radiation due to the free-free emission from the hot gas is adequate to explain the observed modulation in the infrared (see Table 1). The fact that the modulation monochromatic luminosity in several wavelength bands (expressed as ergs s^{-1} Hz^{-1}) is nearly the same is consistent with the suggestion that the radiation is from free-free emission with very little absorption in the Be star gas envelope. The explanation of the V-band luminosity however requires a higher envelope density than that required for the explanation of the infrared luminosity. This may be due to any of the following reasons: (1) The V-band and the infrared observations were made at different times and it is known that the Be star envelope density varies (2) The data in the V-band light curve given by Marti & Paredes (1995) is very noisy and the value of the modulation magnitude we have taken may be high (3) The value of E(B-V) is smaller than that given by Hutchings & Crampton (1981). The explanation (1) seems most likely because of the variability of the Be star envelope gas density. In the present suggestion the phases of the minimum and maximum flux observed follow (without any assumption of the longitude of the periastron; the orientation of the orbit in the sky plane with respect to the line of sight however is important) from the transparency and opaqueness of the shocked gas in the forward and backward directions of the shock motion respectively; the minimum is at the ascending node of the secondary and the maximum is at the descending node, as observed(see discussion above).

The observed ~4-yr modulation of the radio emission from LSI +61°303 is attributed to a possible quasi-period in the gas emission of the Be star. If this is the case the ~4-yr period should also show in the infrared modulation as this emission is also dependent of the gas in the Be star envelope.

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