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Research Note

The peak radio emission phase variations in the Be-star/X-ray source LSI+61°303

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Abstract. The orbital phase of the peak radio emission in the Be star/X-ray source LSI +61° 303 shows variations ranging from 0.5 to 0.9, the weaker emissions showing the larger phase. The delay in attaining peak emission is explained as due to the time required for the relativistic gas bubble responsible for the radio emission, expanding in the hot wind of the Be star, to become large enough in size to become optically thin at the radio frequencies.

Key words: accretion, accretion disks – stars: binaries: general – stars: emission-line, Be – stars: individual: LSI $+61^{\circ}303$ – radio continuum: stars – X-rays: stars

1. Introduction

The Be star/ X-ray source LSI +61° 303 was discovered as a variable radio source GT 0236+610 by Gregory & Taylor (1978). The radio source has been extensively studied and a period of 26.5 days was found (Taylor & Gregory 1982) in the radio emission; this period was suggested to be the orbital period of an object revolving around the optical object LSI +61°303, which was identified as a Be star of spectral type B0-B0.5 V. Modulation of the radio emission with ∼4 yr was also found (Taylor & Gregory 1982). The system was discovered to be an x-ray source (Bignami et al. 1981) indicating that the companion to the Be star is a compact star (white dwarf, neutron star or a black hole). The object was also found to be a gamma ray source (see Tavani et al. 1996 for references). Optical observation (Hutchings & Crampton 1981) confirmed the orbital period found by radio observations and have shown that the orbit is eccentric with an eccentricity of about 0.7. X-ray observations by Taylor et al. (1996) have shown that an x-ray burst occurs at about a phase of 0.5 (phase zero defined by Taylor & Gregory 1982) and it is suggested that the x-ray emission occurs when the compact object passes through the dense envelope of the Be star at its periastron passage.

Measurements of radio emission from LSI +61°303 at several frequencies (Taylor & Gregory 1984; Ray et al. 1997 and references therein) have been fitted with a formula of the form $S \propto \nu^{\alpha}$. The index α is found to systematically change during a burst (Ray et al. 1997), with negative values up to ∼0.5, but reaching positive values in the peak region. Using these observations it is suggested that the radio emission is due to synchrotron emission from relativistic electrons in a bubble containing plasma. This “plasmon” is created near the periastron and expands till it becomes optically thin to the radio emission, when it reaches its peak emission. The subsequent expansion of the bubble leads to a decrease in radio emission. It is also suggested that high energy electrons are injected into the gas bubble over a period of about 2 days (Paredes et al. 1991). VLBI observations detected a double radio source with the source expanding at a rate of about 640 km s^{-1} (Taylor et al. 1992; Massi et al. 1992).

The phase of the peak radio emission is found to vary systematically (see Marti & Paredes 1995; Ray et al. 1997). In a continuous series of observations Ray et al. (1997) find that the phase of the peak radio emission, starting from ∼0.5 reaches a value of ∼0.75 for bursts at the end of the observation. Marti & Paredes (1995) have plotted the normalised peak intensity versus phase and find that the strongest peak occurs at a phase ∼0.6, while the weakest at ∼0.9. This phase difference between the formation of the relativistic gas bubble and the peak emission amounts a time delay of ∼2 days for the stronger bursts and to ∼10 days for the weakest radio bursts.

Two qualitative models have been suggested for the acceleration of relativistic electrons responsible for the radio emission. In one (Taylor & Gregory 1982), supercritical accretion of matter on to the compact object at periastron is suggested to trigger acceleration of relativistic electrons; however no details as to the process of acceleration and the energetics have been given. Also the observed low x-ray luminosity, when supercritical accretion is taking place, is not explained. In the second, Maraschi & Treves (1981) assume a young pulsar as the compact object and suggest the acceleration of the relativistic electrons in the interaction region of the pulsar wind and the gas around it; again no quantitative results are given for comparison with observations. Both these models were proposed before the phase phenomena given above have been established. The relativistic electrons can also result from acceleration of relativistic particles by a shock produced by the secondary in its orbital traversal through the gas envelope of the Be star (Apparao 1999).

In this note we assume that acceleration of relativistic particles takes place near the periastron and a plasmon is formed. We suggest that buoyancy forces force the plasmon in the direction perpendicular to the plane of the orbit and that the plasmon acquires a velocity during its escape from the cool gas disk of the Be star (Sect. 2). We then show that the time delay of the peak emission is due to the time taken for the relativistic gas bubble to expand in the hot wind of the Be star, to reach the size when it becomes optically thin to the radio radiation (Sect. 3).

2. Escape of the plasmon from the cool disk of the Be star

The radio observations indicate the acceleration of high energy particles and the formation of a plasmon containing high energy electrons and gas. Paredes et al. (1991) give the properties of the plasmon (for a high energy radio burst): the initial size $r_i \simeq 2\times10^{13}$ cm, the magnetic field B$\simeq$1 G and the energy of the relativistic gas $E_r \lesssim 4.2\times10^{39}$ ergs.The plasmon expands with a velocity $v_p \simeq 4\times10^7$ cm s^{-1} and reaches the radio peak emission after t$\simeq$ 2 days (Paredes et al. 1991). The size of the plasmon at the peak of radio emission is then, using r_i, v_p and t, $r_m \simeq 2.8\times10^{13}$ cm. When the radio emission is at its peak, the plasmon is optically thin to the radio radiation. Using the condition that it be optically thin at a frequency of 5 GHz (Taylor & Gregory 1984) and the size of the plasmon given above, gives an electron density $n_p \simeq 2.8\times10^6$ cm^{-3} in the plasmon.

Be stars show emission lines, especially H-alpha line, which are interpreted as emission from a cool envelope around the Be star. Ultraviolet observations have also shown the existence of a hot wind (Marlborough 1982; Snow 1982). Several scenarios for the positioning of the cool gas and the hot gas have been suggested (Poeckert 1982). Here we will adopt the model in which the cool gas is confined to the equatorial region of the Be star in the form of a disk (see Apparao 1985), and the hot wind is at the higher latitudes.

The plasmon is formed at the periastron in the equatorial region of the Be star. We will assume the size of the plasmon, when formed, to be $\sim10^{12}$ cm. The number density in this plasmon will then, using the value obtained for the plasmon at the peak of radio emission, to be $n_p \sim 6.1\times10^{10}$ cm^{-3}. This number density is smaller than that in the cool ring of gas emitted by the Be star, which may be assumed to be $n_d \sim 2\times10^{12}$ cm $^{-3}$. [The density in the cool envelope of the Be stars at the peak of H_α emission is estimated to be between 10^{11} and 10^{13} cm^{-3}, with lower values during the decay of the H_α emission (Doazan 1982)]. The density in the plasmon bubble is less than the density in the cool disk which makes the bubble buoyant and makes it rise in the direction perpendicular to the orbit (z-direction). The equation governing the buoyant rise is

$$\frac{dv^2}{dz} = \frac{(\rho - \rho_p)}{\rho_p}\, g sin\theta \tag{1}$$

where v is the velocity of the plasmon at a point P at a height z above the orbital plane. ρ is the density in the cool disk of the Be star and ρ_p is the density in the plasmon. If O is the centre of the Be star then θ is the angle the line OP makes with the orbital plane. g is the acceleration due to gravity of the Be star at the point P. If R is the distance of the periastron point from the Be star, then sinθ=z/$\sqrt{R^2+z^2}$. Also g=GM/(R^2+z^2), where G is the gravitational constant and M the mass of the Be star.

Eq. (1) can be integrated to yield

$$v^2 = \frac{\rho - \rho_p}{\rho_p}(GM)[\frac{1}{R} - \frac{1}{(R^2+z_0^2)^{1/2}}] \tag{2}$$

where z_0 is the thickness of the gas disk. If we use M=20$M_\odot$, R=3$\times10^{12}$ cm (the periastron distance), z_0=0.5R, then using Eq. (2) and the value of ρ_p from above, v can be calculated and is v$\simeq$529 km s^{-1}, which agrees approximately with the observed value of he velocity of the plasmon.

3. Expansion of the plasmon

The plasmon after escaping from the cool disk of the Be star enters the region of the hot wind and will expand. The expansion of a relativistic plasma bubble in a gas was considered by van der Laan (1963). The time t taken by the relativistic gas bubble with an energy E_r in the relativistic particles to expand to a radius r in a gas with a density n_0 is given by

$$t \simeq 1.3\times10^{-12}(n_0/E_r)^{1/2} r^{5/2} \tag{3}$$

in seconds. The above expression is valid when the energy density of the relativistic particles is larger than the magnetic field energy density and when the dimension of the plasmon is much larger than its initial size. With the values of E_r and B given in Sect. 2, the first condition is satisfied; in any case the decrease in radio emission with time implies the expansion of the plasma, which in turn implies that this condition is satisfied. The second condition is valid when r_m is compared to the value of the initial size of the plasmon assumed here near the periastron.

The strength of the wind $\dot{M}$ of the Be star, from UV observations is between 3×10^{-11} and 3×10^{-9} $M_\odot$ yr^{-1} (Snow 1982). The wind velocity V varies between about 600 km s^{-1} near the Be star to a terminal velocity of about 1000 km s^{-1}. If we use $\dot{M} = 2\times10^{-9}$ $M_\odot$ yr^{-1} and V=600 km s^{-1} at a distance of 3×10^{12} cm from the Be star then the particle density in the wind at this point is $n_0 \simeq 2\times10^7$ cm^{-3}. Using this value and the values of the plasmon size (r_m) and energy in relativistic particles given above (E_r), the delay time t can be calculated using Eq. (3). We find that t$\simeq$3.7 days, which is approximately the delay observed. Thus the time delay of the observed peak emission from the time of the periastron passage can be explained as the time taken by the plasmon to become optically thin as it expands in the Be star wind. The radio bursts of the lower intensity will take a longer time to reach the optically thin stage as is seen from Eq. (3). The lowest energy bursts are about a factor of about six lower in intensity than the highest energy burst, leading to a time delay of about 2.5 times the delay for the high energy burst, which is in approximate agreement with observations in view of the variability of the various parameters involved.

4. Discussion

In the scenario outlined in this note we have shown that the plasmon containing relativistic electrons and gas formed near the periastron of the secondary orbit, floats to the top of the Be star cool disk in the polar direction to acquire a sizeable velocity. The plasmon formed at the periastron may split into two bubbles and travel in the two polar directions resulting in the twin blobs observed. The plasmon then expands in the wind of the Be star and takes time to reach the situation when it becomes optically thin at radio frequencies and attain the peak of radio emission. It is well observed (see Doazan, 1982) that the density of the Be star disk, as inferred from H_α observations, increases, reaches a maximum and then decreases. A similar inference is made from the observed sequence of x-ray flares from the Be star/X-ray source A 0538- 66 (Apparao 1993). If the relativistic electron density is proportional to the gas density in the Be star disk, as is natural to assume, then the intensity of radio emission after each subsequent periastron passage decreases in intensity as is observed (Ray et al. 1997). According to the present suggestion the orbital phase delay, which is dependent on the energy in the relativistic electrons, will increase in subsequent radio bursts as observed (Marti & Paredes 1995; Ray et al. 1997). Thus, in each episode of the $\sim$4 yr radio emission cycle,mentioned in the introduction, and which is likely associated with the cycle of emission of cool gas by the Be star, the phase delay will show increasing values in subsequent radio bursts. During the following episode of the $\sim$4 yr cycle, the peak radio phase will again start at the periastron value and will increase. This can be verified in future observations.

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