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LETTER

Letter to the Editor

First correlation between compact object and circumstellar disk in the Be/X-ray binaries

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Abstract. A remarkable correlation between the Hα emission line and the radio behaviour of LS I+61°303 over its $\sim$4 yr modulation is discovered. The radio outburst peak is shifted by a quarter of the $\sim$4 yr modulat ion period (about 400 days) with respect to the equivalent width of the Hα emission line variability. The onset of the LS I+61°303 radio outbursts varies in phase with the changes of the Hα emission line, at least during the increase of Hα equivalent width. This is the first clear correlation between the emission associated to the compact object and the Be circumstellar disk in a Be/X-ray binary system.

Key words: stars: individual: – X-rays: stars – radio continuum: stars – stars: emission-line, Be

1. Introduction

The Be/X-ray binaries are the major subclass of massive X-ray binary systems in which a neutron star accretes material from the wind of an early type Be star. The Be stars are known to exhibit emission in the Balmer lines and infrared excess, which are attributed to the presence of cool circumstellar disk. Correlation between the changes of the Be circumstellar envelope and the emission of the compact object can be expected, as a result of the compact object interaction with the surrounding matter. However, no clear correlation has been detected till now – only loose correlations between the optical/infrared properties of the Be circumstellar disks and the X-ray emission of the neutron star have been reported to exist (e.g. Corbet et al. 1985; Coe et al. 1994; Negueruela et al. 1998).

LS I+61°303 (V615 Cas, GT 0236+610) is a radio emitting X-ray binary which exhibits radio outbursts every 26.5 d. The radio outburst peak and the outburst phase are known to vary over a time scale of $\sim$4 yr (Gregory et al. 1989; Gregory, 1999). Hereafter, we will use the latest values reported and we will refer to these radio periods as $P_1 = 26.4917$ d and $P_2 = 1584$ d. Phase zero for both has been set at JD2443366.775 (Gregory, Peracaula & Taylor, 1999). The 26.5 d period is believed to be the orbital period. The $\sim$4 yr modulation has been discovered on the basis of continued radio monitoring. Both relativistic jet precession or cyclic variability in the Be star envelope have been proposed as a possible origin of the long term modulation (Paredes, 1987; Gregory et al. 1989), with the second interpretation being the most likely one. This suggestion is supported by the fact that the Hα emission line varies on the same (4 yr) time scale (Zamanov et al. 1999). However, these authors were not able to derive what is the connection between the radio and Hα parameters.

In this letter we report an intriguing correlation between the synchrotron non-thermal radio emission, associated with the compact star, and the Be circumstellar disk visible in the $H\alpha$ emission line. This is the first clear connection between the Be circumstellar disk variability and the emission from the neutron star in the Be/X-ray binaries.

2. $H\alpha$ and radio observations

The new $H\alpha$ spectroscopic observations used in this paper are obtained with the 2-m RCC telescope of the Bulgarian National Astronomical Observatory 'Rozhen' during the last two years. They are analyzed together with the previously published data (Paredes et al. 1994; Zamanov et al. 1999). The Hα parameters which vary with the $\sim$4 yr modulation are the equivalent width of Hα, EW(Hα), and the distance between the peaks, $\Delta V_{\rm peak}$ (Zamanov et al. 1999).

The radio observations during the previous 6 years were retrieved from the Green Bank Interferometer, which is a facility of the USA National Science Foundation operated by NRAO in support of the NASA High Energy Astrophysics program. From this data, we measured the radio outburst peak flux density and the beginning of every outburst. As onset of the outburst, we adopted the time when the radio flux density achieved a value equal to 1/3 of the maximum flux observed for every orbital period. Whenever possible, the onset of the outburst was measured separately from the 2.25 GHz and 8.3 GHz observations and the average value is used in the analysis.

In terms of the Ejector-Propeller model of LS I+61°303, the outburst onset better represents the time of the transition of the

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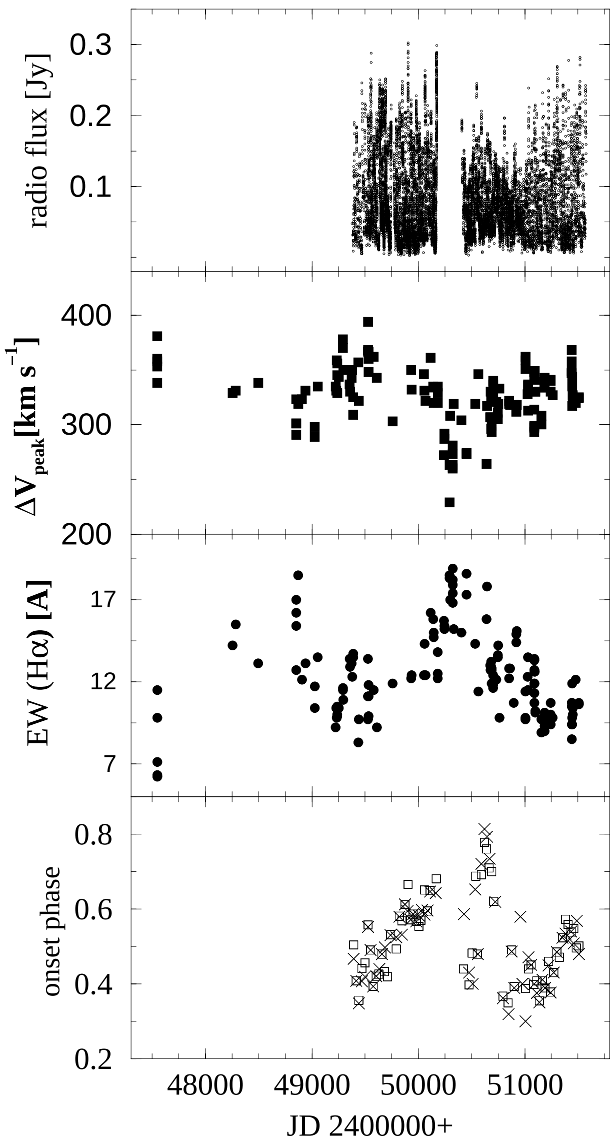

Fig. 1. $H\alpha$ and radio observations over the period 1989 - 2000. The regular Hα observations cover more than 2500 days. From top to bottom are plotted the radio flux density at 2.25 GHz, the ΔV_{peak} of Hα, the EW(Hα), and the onset phase of the outburst relatively to the orbital (P_1) period. In the bottom panel, the squares refer to 2.25 GHz and ($\times$) - to 8.3 GHz. The traces of the $\sim$4 yr modulation are visible in all panels.

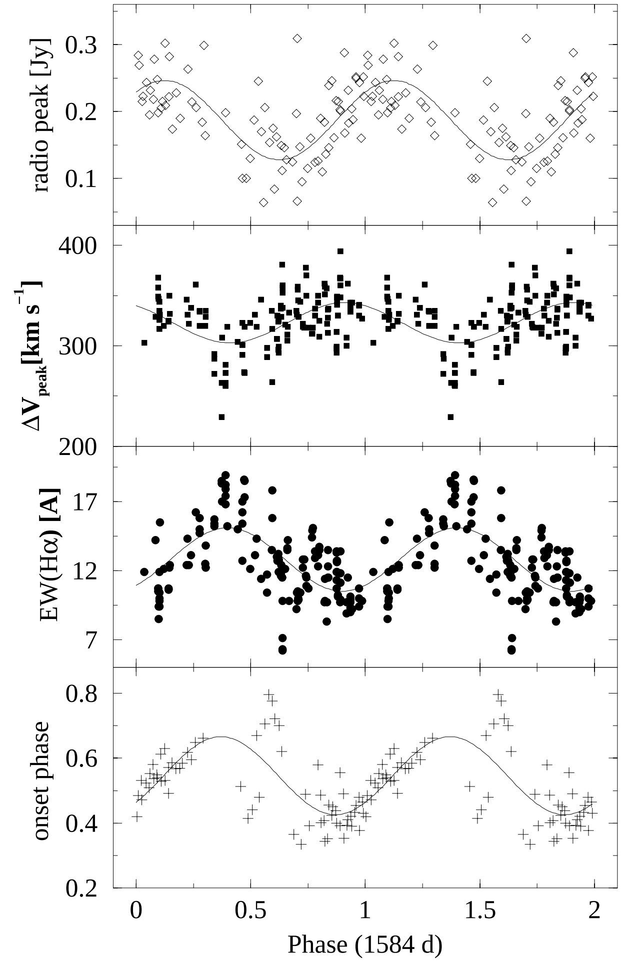

Fig. 2. The radio and Hα parameters folded on P_2=1584 day period with phase zero at JD2443366.775. The upper panel represents the radio outburst peak flux. The Hα panels are the same as in Fig. 1. The bottom panel represents the averaged values of the onset phase from 2.25 GHz and 8.3 GHz.

neutron star from propeller to ejector and the appearance of the expanding radio emitting plasmon (Zamanov, 1995).

3. Relation between circumstellar disk and radio outbursts

The radio and $H\alpha$ observations obtained during the last years are plotted in Fig. 1. It is clearly visible that all these parameters vary over a time scale of $\sim$4 yr. Following the predictions of Gregory (1999) the radio outburst peak achieved a new maximum at the end of 1999. Big changes in the radio outburst peak flux from values less than 0.150 Jy at JD2451000 to values more than 0.250 Jy at JD2451400 are observed (Fig. 1). At the same time, the parameters of the Be circumstellar disk $EW(H\alpha)$ and ΔV_{peak} do not exhibit extreme values in their behaviour. This suggests that the radio peak flux density and the $H\alpha$ parameters do not vary in phase nor in anti-phase.

To understand this behaviour we plotted all the data folded on the P_2=1584 d period. Every parameter was fitted separately with a cosine function. Our attempts to use more complicated functions (e.g. three term truncated Fourier fit containing sine and cosine terms with half and quarter orbital periods) showed that, with this scatter of the points, the significance of other terms is negligible and we used simple cosine waves in the form: $y = A + B\,cos(2\pi(\phi + \phi_0))$. The best fit parameters are listed in Table 1 and plotted as solid lines in Fig. 2.

From Table 1 and from Fig. 2 the following correlations can be seen:

a) The Hα parameters, EW($H\alpha$) and ΔV_{peak}, vary in anti-phase. This is a relationship well known for the Be stars, reflecting the fact that the the size of the disk grows as the EW(Hα) increases (Hanushik, Kozok & Kaizer, 1988).

Table 1. Fitted parameters, $y = A + B\, cos(2\pi(\phi + \phi_0))$.

parameter	A	B	ϕ_0
Radio peak [Jy]	0.187±0.003	0.059±0.003	0.125±0.010
Onset phase*	0.548±0.005	0.12±0.01	0.62±0.01
EW($H\alpha$) [Å]	12.8±0.01	2.3±0.1	0.60±0.01
$\Delta V_{\rm peak}$ [km s^{-1}]	323±1	−20±2	0.59±0.01

* the phase of the beginning of the radio outburst calculated relative to the orbital period

b) At the same time, a strange phase shift can be seen between the radio outburst peak flux and the Hα parameters. This shift is about 0.25 in phase. So, if the parameters really vary as simple cosine functions on average, this means that the radio peak varies with the first derivative of the $H\alpha$ emission line parameters.

c) The beginning of the radio outburst is in phase, or only slightly shifted, relative to the Hα variability, at least on the ascending branch.

Ray et al. (1997) have shown that the outburst peak is slowly shifting in phase during the time interval from JD2449400 to JD2450100. In the same interval the outburst peak flux achieved maximum values and began to decline. This is one more confirmation that the variability of the outburst peak and the time of the outburst are phase shifted one to another over the 1584 day period.

Although the scatter of the points in Fig. 2 is considerable, all evidences (the cosine fit, the behaviour observed by Ray et al. (1997), the behaviour during the last radio outburst maximum) show that the radio outburst peak is shifted relatively to the behaviour of the circumstellar disk, although the start of the radio outburst is in phase (or almost in phase) with the circumstellar disk changes.

4. Discussion

A successful modeling of the radio outburst of LS I+61°303 is based on the synchrotron radiation from relativistic particles injected into an expanding plasmon (Paredes et al. 1991). The genesis of the plasmon can be a result of the transition of the neutron star from propeller to ejector state (Zamanov, 1995), or in other words from accretion onto the magnetosphere to "young radio pulsar" every orbital period.

In such a picture, the start of the outburst will correspond to the moment when the neutron star emerges from the denser parts of the circumstellar disk. Therefore, the bigger the disk the later the outburst can be expected. This can be seen on Fig. 2. At phases 0–0.25 we observe increase of the EW(Hα), decrease of the $\Delta\ V_{\rm peak}$ and slow shift of the onset of the outburst. The behaviour of the beginning of the outburst on the increasing branch (phases 0–0.25) is stable, but on the decreasing branch (phases 0.25–0.5) the scatter of the points is considerably bigger. The stable behaviour at phases 0.25–0.5 is observed twice at about JD 2449800 and JD 2451400 (Fig. 1) so it is unlikely to be a data artifact. Probably this is a result that, during the disk build-up, the increase of the material of the Be disk is feeded only from one source - the B star equatorial region. In contrast the disk-decline can be in two directions - accretion onto the B star or slow dissipation outwards. The behaviour of the start of the outburst points that the disk build up is a stable process and the disk-decline is a more complicated and probably unstable process, or may be it suggests formation of structures like the double disk observed in X Persei (Tarasov & Roche, 1995).

In context of the propeller-ejector transition the surrounding matter will basically influence the expansion velocity of the plasmon, affecting in this way the intensity of the radio outbursts. The remaining plasmon physical parameters (initial magnetic field, injection rate of relativistic particles, etc.) are not expected to vary significantly from one to another outburst. The expanding plasmon calculations predict that there will be weaker outbursts for higher expansion velocities. By expanding faster, the energy losses of the electrons due to the adiabatic expansion are more important and less electron energy is available to be radiated. In addition, the faster decrease of the magnetic field will also contribute to less synchrotron radiation being produced. Supposing that the plasmon is a result of the propeller-ejector transition, the expanding plasmon will appear when the neutron star is receding from the periastron and the plasmon will expand outside of the Hα emitting disk. The size of this disk is about 40-65 $R_\odot$ (Zamanov & Martí 2000) and the apastron separation between components is about 150 $R_\odot$ (Hutchings & Crampton 1981). The enigmatic behaviour of the outburst peak flux density (its phase shift with 0.25 or $\sim$400 days) indicates that the conditions outside the Hα disk vary in a different way compared to the changes inside the Hα emitting disk.

The X-ray emission of LS I+61°303 is observed to exhibit maximum every orbital period and the X-ray outburst is shifted relatively to the radio outburst (Taylor et al. 1996, Harrison et al. 2000). In terms of the ejector-propeller model, the X-ray maximum is due to the propeller action and higher mass accretion rate onto the magnetosphere at the periastron passage (Zamanov & Zamanova, 1997). In this sense it will be very interesting to see what is the behaviour of the X-ray maximum observed in the high-energy emission of LS I+61°303 over the $\sim$4 yr modulation.

Another possible origin of the $\sim$4 yr modulation may be the precession of the Be star. Lipunov & Nazin (1994) have demonstrated that this value is in rough agreement with the expected period ($\sim 10^3$d) for precession of the B star. The precession of the B star can be expected, because after the supernova kick the neutron star orbital plane may be different from the Be disk plane (e.g. Bradt & Podsiadlowski, 1995). Our attempts to model the behaviour of the outburst phase as a result of the precession are unsuccessful till now but it can be due to of insufficient data sample, because the systematic radio observations cover about 6 yr (1.5 periods) with considerable gaps and scatter inside the data set. In this context, it deserves to be noted that if the Hα variability is a result of a precessing disk seen at different inclination angles, this will imply an inclination angle $i > 60°$

and a precession angle $\Delta i > 6°$ (this estimate is obtained using the values from Table 1 and assuming everywhere an optically thick in Hα disk).

To conclude, the behaviour of LS I+61°303 radio and Hα emission is evidence that the picture of the interaction between the neutron star and the circumstellar disk in the Be/X-ray binaries is not as simple as generally expected. We need long series of observations over different wavelengths to better understand the behaviour of the Be stars and the Be/X-ray binaries.

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