Mon. Not. R. Astron. Soc. 317, 205–210 (2000)

Correlated *V/R* and infrared photometric variations in the Be/X-ray binary LS I +61° 235/RX J0146.9+6121

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Accepted 2000 April 19. Received 2000 April 14; in original form 2000 January 4

ABSTRACT

We report on the long-term variability of the Be/X-ray binary LS I +61° 235/RX J0146.9+6121. New optical spectroscopic and infrared photometric observations confirm the presence of global one-armed oscillations in the circumstellar disc of the Be star, and allow us to derive a V/R band quasi-period of 1240 ± 30 d. Pronounced shell events, reminiscent of the spectacular variations in Be stars, are also seen. We have found that the *J*, *H* and *K* infrared photometric bands vary in correlation with the spectroscopic V/R variations, implying that the one-armed disc oscillations are prograde. The effect of the oscillations is not only seen in the Hα line but is also seen in the He I λ6678 and Paschen lines. As these lines are formed at different radii in the equatorial disc of the Be star, such effects confirm the global nature of the perturbation. The Keplerian disc has been found to be denser than the average for a sample of isolated Be stars, which may be indicative of some kind of interaction with the compact companion. Finally, from a *Rossi X-ray Timing Explorer* observation we derive a spin period of the neutron star of 1404.5 ± 0.5 s.

Key words: binaries: general – stars: emission-line, Be – stars: individual: LS I +61° 235 – pulsars: individual: RX J0146.9+6121 – infrared: stars – X-rays: stars.

1 INTRODUCTION

RX J0146.9+6121 is one of the slowest high-mass X-ray pulsar systems (Mereghetti, Stella & Vogt 1993; Hellier 1994). Its optical counterpart is the $V = 11.2$ B1 III–V star LS I +61° 235, located at an estimated distance of 2.3 ± 0.5 kpc (Coe et al. 1993; Motch et al. 1997; Reig et al. 1997, hereafter R97). R97 derived the astrophysical parameters of the optical counterpart and reported V/R variations with a quasi-period of ~3 yr. The line profile variability was attributed to the prograde precession of a one-armed mode confined in the disc of the Be star.

Be/X-ray binaries comprise approximately 70 per cent of the more general class of high-mass X-ray binaries, the other ~30 per cent containing evolved (luminosity class I and II) primaries. In a Be/X-ray binary the optical companion, a Be star, is characterized by an emission line spectrum and an infrared excess when compared with normal B-type stars of the same spectral type. These two observational properties originate in the cool gaseous quasi-Keplerian disc that lies on the equatorial plane of the central star. A neutron star revolves around the 10–20 $M_\odot$ primary in a rather eccentric orbit ($e \sim 0.2$–0.8) and accretes material expelled by the Be star from the disc – in the form of a low-velocity, high-density equatorial wind – giving rise to the X-rays.

The physical properties of the disc of the Be star in Be/X-ray binaries have traditionally been considered to be the same as the properties of isolated Be stars. Indeed, the long-term variability, characterized as disc-loss phases and V/R variations, have been seen in both isolated and Be/X-ray binaries (Okazaki 1997; Negueruela et al. 1998). However, it is not yet clear which role the compact companion in Be/X-ray binaries may play in the onset, and subsequent development, of the perturbation that gives rise to the asymmetric profiles, or in the formation and loss of the disc. There is growing evidence that the circumstellar disc surrounding isolated Be stars and the Be star in an X-ray binary may not share, on average, the same physical properties (Reig, Fabregat & Coe 1997; Negueruela et al. 1998, 1999).

In this paper we analyse optical, infrared and X-ray data and search for correlations between the characteristics of the radiation

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Table 1. Journal of spectroscopic observations and spectral parameters for the Hα line. Errors are $\lesssim$8 per cent.

Date	MJD	Telescope	Range (nm)	EW (Å)	ΔV (km s^{-1})	Profile
17-08-94	49582	BNAO^a	650–662	−8.4	252	$V > R$
08-06-96	50243	BNAO^a	650–662	−9.6	257	$V < R$
09-06-96	50244	BNAO^a	650–662	−10.1	258	$V < R$
01-08-96	50297	INT^a	610–700	−10.1	316	$V < R$
26-08-96	50322	BNAO^a	650–662	−10.2	298	$V < R$
13-11-96	50401	CAO	653–660	−10.3	259	$V < R$
12-12-96	50430	CAO	653–660	−10.3	251	$V < R$
01-02-97	50481	INT^a	580–740	−11.9	288	$V < R$
21-08-97	50682	INT^a	610–700	−12.1	242	$V > R$
18-09-97	50710	CAO	653–660	−12.0	223	$V > R$
10-10-97	50732	BNAO^a	650–662	−10.7	233	$V > R$
28-10-97	50750	JKT	638–673	−11.8	258	$V > R$
10-02-98	50855	INT	640–680	−11.2	235	$V > R$
01-10-98	51088	BNAO^b	650–670	−11.0	337	$V > R$
04-10-98	51091	BNAO^b	650–670	−11.3	333	$V > R$
08-10-98	51095	WHT	649–661	−11.5	336	$V > R$
22-07-99	51382	CAO	653–660	−10.8	298	shell
25-07-99	51385	SKI	555–756	−11.9	312	shell
26-07-99	51386	SKI	555–756	−11.6	325	shell
19-08-99	51410	INT^b	624–680	−11.2	298	shell
17-09-99	51439	BNAO^b	650–670	−12.2	286	shell
19-09-99	51441	BNAO^b	650–670	−11.7	285	shell

Notes to table.
BNAO^a: ISTA 580 × 400 + 632 l mm^{-1} 0.2 Å pixel^{-1}
BNAO^b: Photometrics 1024 × 1024 + 632 l mm^{-1} 0.2 Å pixel^{-1}
CAO: Electronix 1024 × 260 CCD + 600 l mm^{-1} 0.06 Å pixel^{-1}
JKT: TEK4 + RBS + 2400 l mm^{-1} 0.4 Å pixel^{-1}
INT^a: TEK3 + IDS + 235 mm + R1200 l mm^{-1} 0.8 Å pixel^{-1}
INT^b: EEV10 + IDS + 500 mm + R1200 l mm^{-1} 0.2 Å pixel^{-1}
WHT: UES + 31 l mm^{-1}, R = 54000 0.06 Å pixel^{-1}
SKI: ISA608 2000 × 800 + 1300 l mm^{-1} 1 Å pixel^{-1}

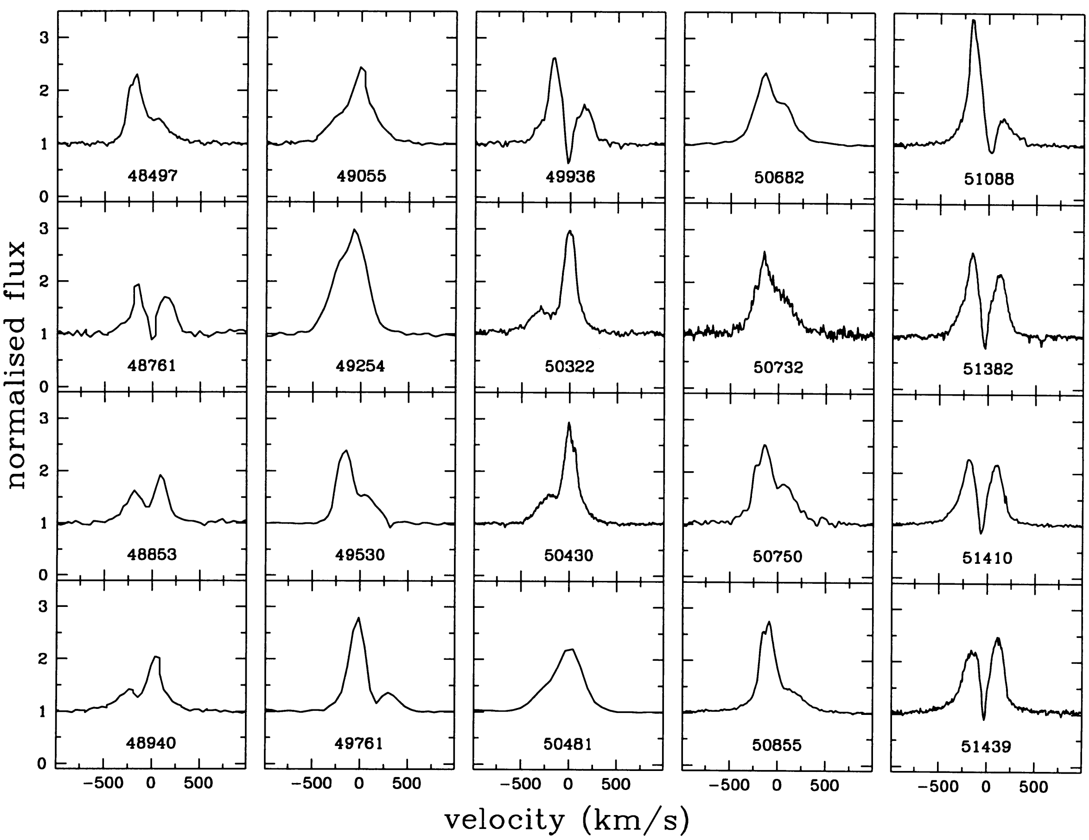

Figure 1. Evolution of the Hα line profile over the period from 1991 August 28 to 1999 September 17 (MJD 48497–51439).

at these wavelengths. Our ultimate goal is to assess the validity of the global one-armed oscillation model, and whether the compact companion has any effect on the V/R variability.

2 OBSERVATIONS AND RESULTS

2.1 Optical data

Optical spectroscopic observations were made with: the 2.6-m telescope at the Crimean Astronomical Observatory (CAO); the 2.0-m Ritchey–Chrétien Couder telescope of the Bulgarian National Astronomical Observatory 'Rozhen' (BNAO); the 1.3-m telescope of the Skinakas Observatory (SKI), in Crete (Greece); the 1.0-m Jacobus Kapteyn Telescope (JKT); the 2.5-m Isaac Newton Telescope (INT) in service mode and the 4.2-m William Herschel Telescope (WHT). The last three telescopes are located at the Observatorio del Roque de Los Muchachos (La Palma, Spain). Table 1 shows the journal of the observations and the instrument set-up. For a description of the observations not mentioned in the table see R97.

Fig. 1 shows a selected sample of Hα line profiles of LS I +61° 235 covering the period from 1991 August to 1999 September. Part of the new data (all observations taken after 1996 February plus those from Rozhen BNAO) are plotted together with some of the spectra presented in R97. The evolution of the V/R ratio can be seen in Fig. 2(a). Different shapes of the line have been represented by different symbols. Stars are used for $V > R$ points, triangles for $V < R$ phases, dots for single-peak lines and squares for shell profiles (i.e. when the central absorption goes beyond the continuum). Note that the shell phase is very brief and always occurs during the transition from $V > R$ to $V < R$. In contrast, the transition from $V < R$ to $V > R$ is separated by single-peak profiles. Strictly speaking, there are no symmetric single-peak lines in our observations (as observed in pole-on stars) as one can always see flank inflections revealing a second peak. Nevertheless, we will refer to the profiles seen during the transition $V < R$ to $V > R$ as a single-peak phase. By fitting a sine function to the V/R curve we refined the V/R quasi-period to a value of 1240 ± 30 d.

We have also measured the separation of the blue and red peaks by fitting two Gaussian functions to the line profile (Fig. 2f). The peak separation gives a measure of the velocity field, assuming it to be Keplerian. The blue-dominated profiles seem to sample a wider range of velocities than red-dominated profiles: $V > R$ points spread over a velocity range 220–360 km s^{-1}, whereas $V < R$ points distribute around 250–320 km s^{-1}. Also, blue-dominated profiles with high values of the peak separation occur only at the end of the $V > R$ cycle, just before the shell phase.

The density wave does not only affect the Hα line but also the Paschen series and He I λ6678 (Fig. 3). As these lines are formed in different regions inside the equatorial disc, the perturbation must extend over a very wide region, hence confirming its global nature.

2.2 Infrared data

The infrared observations were taken with the continuous variable filter (CVF) infrared photometer using the 1.5-m Carlos Sánchez telescope (TCS), located at the Teide Observatory in Tenerife (Spain). The data were reduced following the procedure described by Manfroid (1993). Instrumental values were transformed to the TCS standard system (Alonso, Arribas & Martínez 1998). Table 2

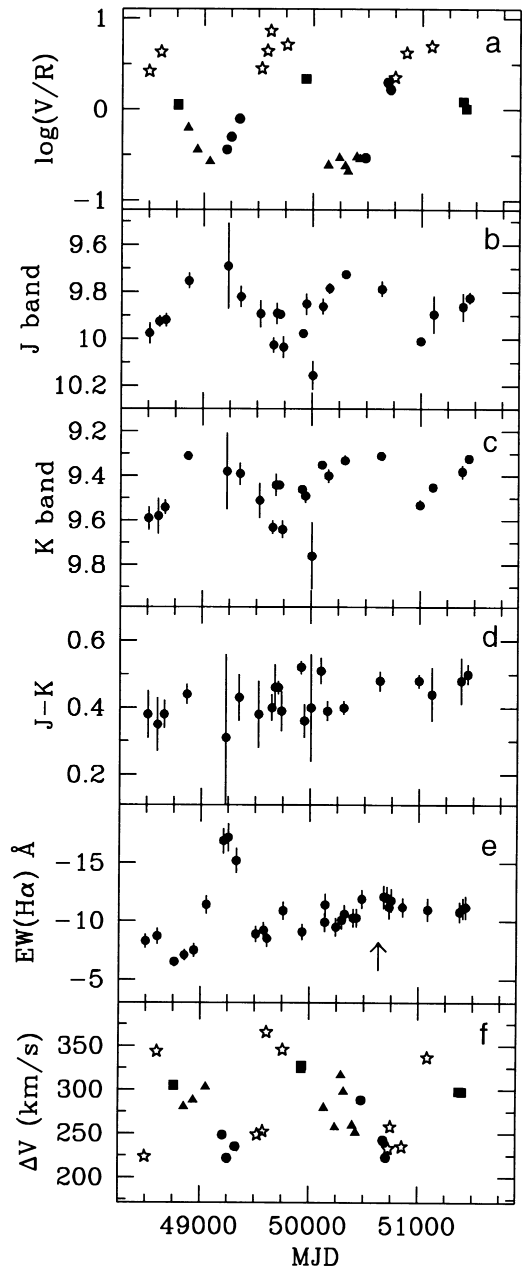

Figure 2. Panels (a)–(f) are as follows: (a) the evolution of the V/R ratio; (b) the J band; (c) the K band; (d) the $J - K$ index; (e) the Hα equivalent width and (f) the peak separation. A correlation between the V/R cycle and the infrared emission is apparent. The arrow in panel (e) indicates the X-ray outburst.

shows the results of the infrared observations. For earlier observations the reader is referred to R97.

The combination of the old and new infrared data yields a very interesting result, namely the correlation between the V/R variations and the infrared magnitudes. Figs 2(b) and (c) show the J and K light curves and the evolution of the colour index $J - K$ (Fig. 2d), covering the period from 1991 August to 1999 October. The light curves were re-binned into 30 d bins. The errors were calculated from the photometric errors depending on the number of points, N, in each bin: when the corresponding bin contained only one point we simply took the observation error, if

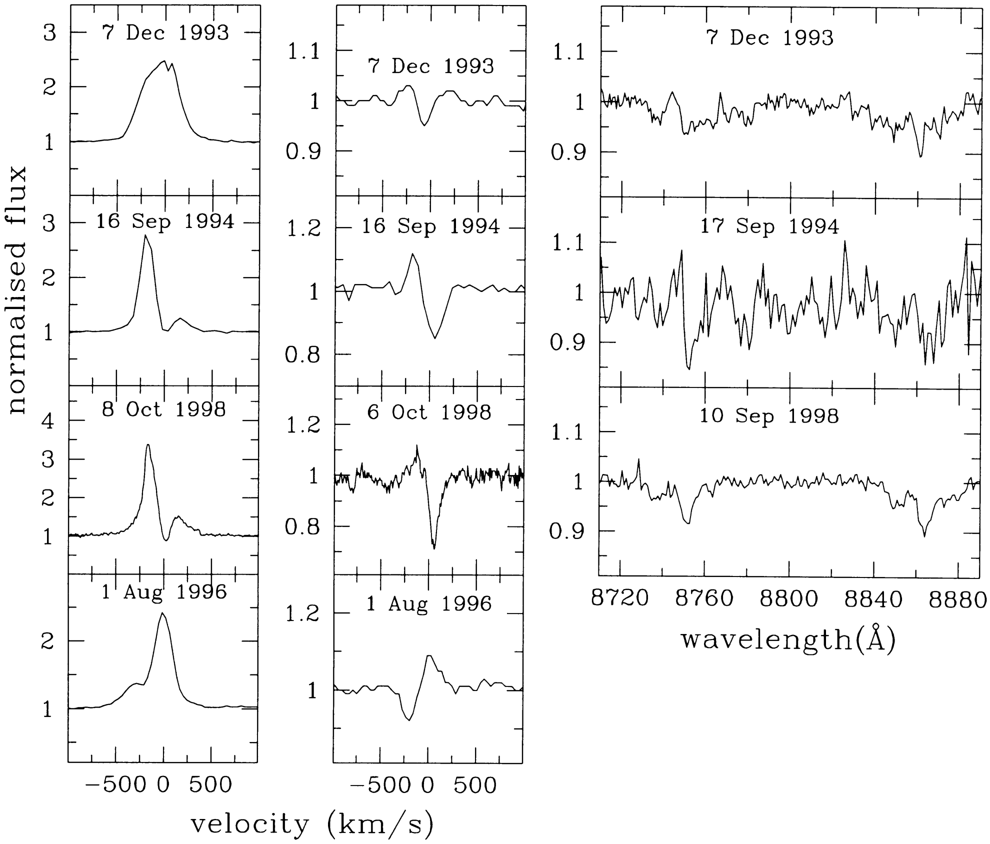

Figure 3. The V/R oscillations are not only seen in Hα (left-hand panel), but also in He I λ6678 (middle panel) and the Paschen lines Pa11 (λ8863) and Pa12 (λ8750) (right-hand panel).

Table 2. Journal of infrared observations.

Date	MJD	J	H	K
13-01-96	50096.42	9.86 ± 0.03	9.58 ± 0.02	9.35 ± 0.02
19-03-96	50162.36	9.78 ± 0.02	9.60 ± 0.01	9.40 ± 0.02
28-07-96	50293.68	9.73 ± 0.05	9.51 ± 0.06	9.34 ± 0.04
29-07-96	50294.65	9.73 ± 0.10	9.51 ± 0.09	9.31 ± 0.08
18-07-97	50648.65	9.83 ± 0.02	9.56 ± 0.02	9.32 ± 0.02
19-07-97	50649.66	9.77 ± 0.01	9.52 ± 0.01	9.32 ± 0.01
21-07-97	50651.66	9.76 ± 0.02	9.53 ± 0.02	9.29 ± 0.02
17-06-98	50982.72	10.01 ± 0.01	9.81 ± 0.02	9.53 ± 0.02
27-10-98	51114.42	10.01 ± 0.02	9.69 ± 0.02	9.48 ± 0.02
28-10-98	51115.67	9.82 ± 0.02	9.66 ± 0.02	9.45 ± 0.02
28-10-98	51115.67	9.85 ± 0.02	9.65 ± 0.02	9.44 ± 0.02
26-07-99	51386.72	9.80 ± 0.02	9.58 ± 0.02	9.37 ± 0.02
27-07-99	51387.66	9.96 ± 0.03	9.67 ± 0.02	9.43 ± 0.02
29-07-99	51389.63	9.85 ± 0.02	9.61 ± 0.02	9.36 ± 0.02
30-07-99	51390.66	9.81 ± 0.02	9.58 ± 0.02	9.34 ± 0.02
01-08-99	51392.64	9.90 ± 0.04	9.63 ± 0.03	9.41 ± 0.02
02-10-99	51454.49	9.79 ± 0.02	9.54 ± 0.02	9.33 ± 0.02
03-10-99	51455.60	9.86 ± 0.02	9.58 ± 0.02	9.32 ± 0.02
04-10-99	51456.56	9.82 ± 0.02	9.57 ± 0.02	9.31 ± 0.02

$1 < N \leqslant 5$ then we defined the error as $\sum |x_i - \bar{x}|/N$ and if $N > 5$ we then considered the standard deviation $\sqrt{(x_i - \bar{x})^2/N}$.

As can be seen in Fig. 2, there is a distinct modulation with an amplitude, from maximum to minimum, of ~0.3 mag. The period of this modulation is 3.1–3.8 yr, in good agreement with the optical V/R variability of 3.4 yr. Interestingly, the infrared maxima occur in coincidence with the optical (~MJD 49250) and X-ray (~MJD 50630) outbursts. On the other hand, the infrared colours do not change drastically over the period of the observations. That is, the slope of the infrared continuum remained the same over the time covered by the observations.

2.3 X-ray data

LS I +61° 235 is a persistent low-luminosity Be/X-ray binary. These systems are characterized by long pulse periods, low X-ray variability ($L_{max}/L_{min} \lesssim 10$) and low but permanent levels of X-ray emission (Reig & Roche 1999).

RX J0146.9+6121 was observed with the *RXTE* Proportional Counter Array (PCA) on 1998 March 21 (02:01–11:54 UT). Good time intervals were defined by removing data taken at low Earth elevation angles (<10°) and during times of high particle background. An offset of only 0°.02 between the source position and the pointing of the satellite was allowed, which ensured that any possible short stretch of slew data at the beginning and/or end of the observation was removed. All five PCA units were functioning during the entire observation. The total net exposure was 19 223 s. Owing to the relatively wide field of view of the PCA instrument (1° FWHM), the nearby X-ray source 4U 0142+61 (White et al. 1996) also contributed to the total flux. After correcting for collimator efficiency, the contribution of 4U 0142+61 to the total observed flux in the energy range 2–30 keV was estimated to be of ~10 per cent. As a result, no X-ray spectral analysis was attempted.

The pulse period was determined by correcting the data to the solar system barycentre and using the epoch folding technique, i.e. we folded the data over a range of periods and searched for a maximum χ^2 as a function of period. The pulse period found was 1404.5 ± 0.5 s, which is virtually the same as the 1404.2 ± 1.2-s pulse period obtained in another *RXTE* observation nine months earlier (Haberl, Angelini & Motch 1998).

3 DISCUSSION

3.1 Global $m = 1$ oscillations

In R97 we investigated the different models that had been put forward to explain the V/R variability in Be stars, and concluded that the model which best accounted for the observational data in LS I +61° 235 was the global one-armed oscillation model (Okazaki 1991, 1997; Papaloizou, Savonije & Henrichs 1992). This model suggests that the long-term V/R variations are caused by global $m = 1$ oscillations in the cool equatorial disc of the Be star. In other words, an enhanced density perturbation develops on one side of the disc, which slowly precesses. The precession time being the time associated with the V/R quasi-period. The density perturbation is confined within a few stellar radii in the disc and the precession period turns out to be fairly insensitive to the size of the disc (Savonije & Heemskerk 1993).

One prediction of the model is that no changes in the slope of the infrared continuum are expected. The reason is that the V/R variations are not the result of changes in the radial gradient of the circumstellar gas. The slope of the infrared continuum is a measure of the radial density distribution but, as matter in the disc does not move radially, no changes in the shape of the infrared continuum are expected. This is exactly the behaviour that we find in the case of LS I +61° 235. While the individual infrared photometric bands changed ($\Delta J \approx \Delta H \approx \Delta K \sim 0.3$ mag) the infrared colours remained unchanged (Fig. 2).

In principle, the issue of whether the motion of the perturbation occurs in the same sense (prograde rotation), or opposite sense (retrograde rotation), to the stellar rotation can be found out from the observations. Telting et al. (1994) realized that a prograde revolution implies that the $V > R$ phase must be followed by a shell profile, and a similar profile but with a much less pronounced absorption feature (or possibly a single peak line if the inclination is low) during the transition from $V < R$ to $V > R$. These characteristic line shapes must translate into noticeable photometric variations. According to Mennickent, Sterken & Vogt (1997), we should expect a minimum of brightness when $V = R$ *prior* to the $V < R$ phase if the motion is prograde, and $V > R$ *after* $V = R$ if the motion is retrograde. In LS I +61° 235 the minimum of brightness in the infrared photometric bands occurred during the shell phase ($V = R$) before the $V < R$ phase began, confirming the prograde nature of the precession inside the disc.

However, models of one-armed global density waves cannot reproduce strong shell–non-shell transitions like the ones seen in LS I +61° 235, which are reminiscent of the so-called *spectacular variations* (Doazan et al. 1983). Such shell events seem to be a rare phenomenon and have only been reported for three Be stars: γ Cas, 59 Cyg and Pleione (Hummel 1998, and references therein), all of which are either binaries or suspected binaries. One possible explanation might be a *thick* disc in the region where the perturbation lies. When the perturbation is behind the star, and for the appropriate inclination angle, no shell event is seen because the disc in between the central star and the observer is thin and does not occult the star or the perturbation. The shell phase would occur when the perturbation is at an inferior conjunction, as the thicker disc would hide the central star from the observer. An alternative explanation is given by Hummel (1998), who suggested a tilted or warped circumstellar disc with precessing nodal line in addition to the density wave (see also Porter 1998).

3.2 A dense circumstellar disc in LS I +61° 235

The work of Dachs et al. (1986) and Hanuschik, Kozok & Kaiser (1988) have shown that the equivalent width of the Hα line emission for Be stars increases with the effective disc radius. As, for rotationally dominated profiles, $\Delta V/(2v \sin i)$ can be regarded as a measure of the radius of the Hα emitting region (Huang 1972), we expect a correlation between the peak separation and the Hα equivalent width. Hanuschik et al. (1988) derived the following law:

$$\log\left(\frac{\Delta V}{2v \sin i}\right) = a \log[\mathrm{EW(H\alpha)}] + b, \tag{1}$$

where $v \sin i$ is the projected rotational velocity and the Hα equivalent width, EW(Hα), is given in angstroms. a and b are related to the rotational law index $a = -j/2$ ($j = 0.5$ for Keplerian rotation and $j = 1$ for conservation of angular momentum) and with the electron density of the disc, respectively. A least-squares fit to the LS I +61° 235 data gave $a = -0.23 \pm 0.10$, i.e. $j \approx 0.5$ and $b = +0.1 \pm 0.1$. These values are to be compared with the average values $a = -0.4$ and $b = -0.1$, found by Hanuschik et al. (1988), for a sample of 26 isolated Be stars. The higher value of b in LS I +61° 235 implies a denser disc than those of isolated Be stars.

The main (and probably only) difference between a Be/X-ray binary and an early-type isolated Be star is the presence of a neutron star in the former. It therefore seems natural to attribute the dissimilarity in the properties of the circumstellar envelopes to the influence of such a compact companion. The neutron star trims the disc to a certain radius and prevents free growth of the disc thereby making it denser. Disc truncation has been suggested in other Be/X-ray binaries like V0332 + 53 (Negueruela et al. 1999). This idea would support the hypothesis that the neutron star plays a fundamental role in the evolution and properties of the equatorial disc in Be/X-ray binaries, as proposed by Reig et al. (1997).

3.3 X-ray/optical/infrared correlations

In R97 the observation of an optical outburst around 1993 September–October (MJD ~ 49260) was reported. During the outburst the EW(Hα) changed by ~ 10 Å, in about 270 d, decreasing to pre-outburst values (~ -8 Å) in around the same period of time (Fig. 2e). This increase coincided with a single-peak phase of the Hα profile. The question of whether this outburst was an isolated event or was associated with the V/R cycle remained open as a consequence of the short coverage of the data. The new observations show no new EW(Hα) maximum. After the outburst the EW(Hα) increased slowly up to a level of -12 Å, considerably lower than the peak of 1993 September. The new single-peak phase should have occurred during 1997 March–May. Unfortunately, the star was too close to the Sun to be observed. However, we notice that EW(Hα) seems to have reached a maximum value just before and after the period when we would expect the single-peak phase (around MJD 50500). Thus, we are inclined to think that the higher EW(Hα) associated with single-peak profiles, as reported in R97, may reflect the fact that the fluxes of both components are adding up and are not affected by the absorption feature present in the other profiles. In this context, therefore, the increase in EW(Hα) is real and would be an event related to the motion of the density pattern in the disc, rather than an isolated episode.

In 1997 July (MJD 50634) LS I +61° 235 underwent a small X-ray outburst (Haberl et al. 1998). The X-ray luminosity increased by nearly a factor of five in one week reaching 3.45×10^{35} erg s^{-1} in the energy range 0.5–10 keV. This outburst is marked with an arrow in Fig. 2(e). Interestingly, the outburst occurred at the time of the expected infrared and EW(Hα) maxima. One is then tempted to attribute this correlated X-ray/optical/infrared behaviour to the high density perturbation where most of the Balmer emission is formed. If the inclination of the system is less than 90°, when the high-density part of the equatorial disc is behind the star, it offers the largest geometric area (especially so if the disc is thicker in this region) and the highest optical and infrared emission. If the neutron star happens to be close to the Be star it will accrete from this high-density material and the X-ray emission will be enhanced. New optical and X-ray observations around the next expected maximum are needed to solve this issue.

4 CONCLUSION

Optical spectroscopic observations confirm the presence of global one-armed oscillations in the circumstellar disc of LS I +61° 235. These oscillations manifest themselves as quasi-periodic variations in the shape of the Hα line, the asymmetric double peak profile of which alternates between red- ($V < R$) and blue-dominated ($V > R$) emission. The system also goes through Be–Be shell transitions, which might indicate an asymmetric vertical structure of the disc in the form of a thick or a tilted disc. The V/R quasi-period is determined to be $\sim 1240 \pm 30$ d. We have found a correlation between the infrared emission and the V/R variations. This is the first time that such a correlation is reported in a Be/X-ray binary. From the pattern traced by the infrared light curves in relation to the V/R ratio we conclude that the one-armed disc oscillations are prograde. The disc of the Be star in LS I +61° 235 is found to be denser than isolated Be stars, which may be connected to the presence of the neutron star. From an *RXTE* observation we derive a spin period of the neutron star of 1404.5 ± 0.5 s.

ACKNOWLEDGMENTS

We thank Chris Moran for providing us with one of the INT spectra and Dr E. V. Paleologou for helping us with the spectroscopic observations at the Skinakas Observatory. The Skinakas Observatory is a collaborative project of the University of Crete, the Foundation for Research and Technology (Hellas) and the Max-Planck-Institut für Extraterrestrische Physik. PR acknowledges support from the European Union Training and Mobility of Researchers Network Grant ERBFMRX/CT98/0195. IN is supported by an European Space Agency external fellowship. RZ acknowledges support from the Dirección general de relaciones culturales y científicas, Spain. Some observations were taken as part of the ING service observing programme. We are grateful to the referees, Dr D. Baade and Dr T. Rivinius, for useful comments.

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