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Liu, Q.; Hang, H.; Wu, G.

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# Long-term optical spectral observations of the Be/X-ray binary LSI +61°303: evidence of H $\alpha$ emission associated with the neutron star

Q.Z. Liu<sup>1,2</sup>, H.R. Hang<sup>1</sup>, G.J. Wu<sup>3</sup>, J. Chang<sup>1</sup>, and Z.X. Zhu<sup>1</sup>

<sup>1</sup> Purple Mountain Observatory, Nanjing 210008, P.R. China, National Astronomical Observatories, Chinese Academy of Sciences

<sup>2</sup> Astronomical Institute “Anton Pannekoek”, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

<sup>3</sup> Yunnan Observatory, P.O. Box 110, Kunming 650011, P.R. China, National Astronomical Observatories, Chinese Academy of Sciences

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**Abstract.** We present the optical spectra of the periodic radio star LSI +61°303 with intermediate dispersion. The H $\alpha$  emission line profile and its variation are analyzed. Variability in LSI +61°303 is observed on different timescales. During our observations the equivalent width (EW) of H $\alpha$  line showed long-term variability that is likely to be associated with the 4-year period. We suggest that the long-term variability is connected to the intrinsic behaviour of the Be star.

The H $\alpha$  EW changed strongly around the radio maximum, clearly displayed a maximum at phases between 0.55–0.6, and possibly both another maximum at phases around 1.0 and a minimum between radio phases 0.7–0.9. The only three spectra that showed nearly equal intensities of the two peaks of H $\alpha$  emission line all occurred at radio phases around 0.8. It is interesting to note that the H $\alpha$  emission line in 1995 October showed unusual variation at radio phases around 0.6, where the decrease of the H $\alpha$  emission accompanied by the enhancement of the emission at the red wing. These short-term and periodic phenomena can be fairly explained with the X-ray induced H $\alpha$  emission by employing the orbital solution deduced from near-infrared light curves (Marti & Paredes 1995). Thus provides some evidence for a correlation with the orbital motion of the neutron star.

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

## 1. Introduction

The star LSI +61°303 was identified as the radio counterpart of the radio source GT0236+610 (Gregory & Taylor, 1978). Extensive radio observations yielded a periodic variation with a period of  $26.52 \pm 0.04$  day (Taylor & Gregory, 1982), and a more accurate period of  $26.496 \pm 0.008$  day (Taylor & Gregory, 1984). The period was considered to be a binary period by Taylor & Gregory (1982). Typically, radio outbursts peak around phases 0.6–0.8 (Paredes et al. 1990). Hutchings & Crampton (1981) confirmed the radio period by analysis of three-year observation of radial velocity. They concluded that the optical spectrum

corresponds to a rapidly rotating B0 V star. For a primary mass range 5–10  $M_{\odot}$  the orbital solution yields a secondary mass between 1.1–1.5  $M_{\odot}$ . Periods close to the orbital 26.5 days radio period have been also found by Mendelson & Mazeh (1989) in UBVRI bands, by Paredes et al. (1994; 1997) in the near infrared and X-ray bands. More recently, Zamanov et al. (1999) reported the detection of the similar period in the H $\alpha$  emission line. The radio outburst amplitude and shape appear also to be modulated on a long-term  $\sim 4$  yr scale (Gregory et al. 1989; Paredes et al. 1990; Estalella et al. 1993). The 4-year period is attributed to the periodicity of the Be star giving out a gas ring.

Previous spectral observations displayed the profile of the H $\alpha$  emission line as rapidly variable (Gregory et al. 1979; Hutchings & Crampton, 1981; Paredes et al. 1994; Zamanov et al. 1996; Zamanov et al. 1999). In particular, Paredes et al. (1994) found noticeable variability of the red hump of H $\alpha$  line at or close to the radio maximum, accompanying a decrease of the H $\alpha$  EW. Zamanov et al. (1996), moreover, showed that similar variations exist in the blue hump of the line, at the opposite location of the orbit (at phase  $\sim 0.25$ ). We report in this paper the observational results of LSI +61°303 from 1992 to 1998 during our programme of monitoring long-term variability of Be/X-ray binaries. The spectra display an unusual enhancement at the red wing of H $\alpha$  emission line, while the emission enhancement at radio phases around 1.0 is mainly contributed to the center part of the H $\alpha$  emission line. We also find that quasi-periodic H $\alpha$  EW variation is likely present when we choose the data obtained within same period.

## 2. Observations and reductions

The optical spectroscopic observations were made at Xinglong station of Beijing Astronomy Observatory with a CCD grating spectrograph detector at the Cassegrain focus of the 216 cm telescope. The log of the observations for LSI +61°303, together with the equivalent width of the H $\alpha$  emission line, is shown in Table 1. The typical error for H $\alpha$  measurements is about 10%, due to our high S/N observations, but for few cases the error can reach 15% due to poor weather condition. He- $\alpha$  spectra were taken in order to obtain the pixel-wavelength relations. They were bias subtracted and flat field corrected. All spectroscopic

Send offprint requests to: Q.Z. Liu (qzliu@astro.uva.nl)

data are reduced with the IRAF package on our Sun-4 station with exception of the spectra taken in 1992, which were reduced using the FIGARO/DIPS0 package on the Vax 11/780 computer of Purple Mountain Observatory.

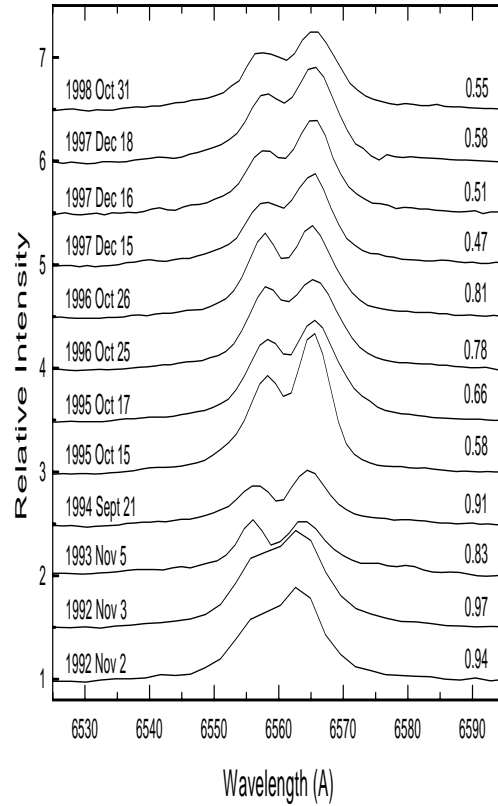
### 3. Spectral results

Various observers have noted that the  $H\alpha$  emission line in LSI +61°303 is highly variable, showing several timescales of variability. These can be briefly classed as long-term variability on timescales of months or years, short-term variability on timescales of days and periodic variability. We discuss below the various timescales of variability and the anomalous behaviour it displays during our observations.

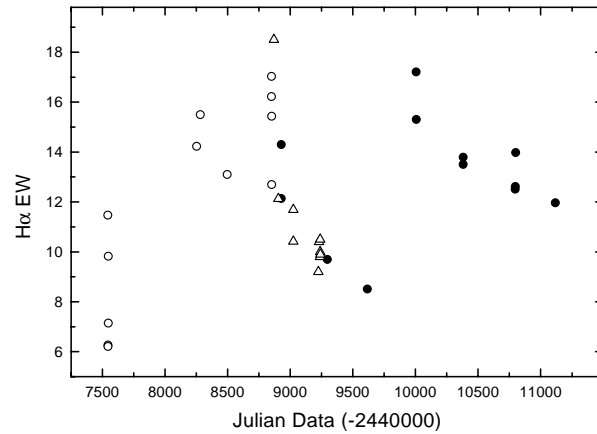
#### 3.1. Long-term variability

The  $H\alpha$  spectra collected during our several observing runs from 1992 to 1998 are shown in Fig. 1. We show our normalized  $H\alpha$  record of LSI +61°303 ordered sequentially with observing time and drawn on the same scale with same offset. The  $H\alpha$  line profile did not change in its main feature over 20 years. The profile is very broad, and there are two clearly separated peaks with an exception of our lower dispersion spectra obtained in 1992. In general, the intensity of the red peak (R) is stronger than that of the violet peak (V) and the FWHM of the red peak is wider than that of the violet peak. However, we also notice that the profiles on 1993 Nov. 5, 1996 Oct. 25 and 26 (all corresponding to radio phases around 0.8) showed that the R and V are nearly the same. Although Zamanov et al. (1999) reported the separation between these two peaks was changed about  $100 \text{ km s}^{-1}$  within a period, it did not change noticeably during our observations (about  $325 \text{ km s}^{-1}$ ), regardless of the  $H\alpha$  line with a higher intensity in 1995 or with a lower intensity in 1994. If the separation between the peaks is indicating the distance from the star at which the  $H\alpha$  emission is originating (Huang, 1972), we have to assume, even if the results from Zamanov et al. (1999) have been taken into account, that the size of the disc did not change greatly between 1992 and 1998. Therefore the annual drop of the EW and intensity of  $H\alpha$  emission line from 1992 to 1994, and then from 1995 to 1998, is different from the variations of the profile due to the dissipation of the envelope, which showing gradual decrease of the separation of the double-peak.

Fig. 2 shows the long-term variability of the  $H\alpha$  EW from 1989 to 1998 as a function of time. Apart from our data during the programme, the combined data set of Paredes et al. (1994) and Zamanov et al. (1996) is included in the figure. Although the object is found to be highly variable, its long-term variation trend is roughly obvious. A minimum of the EW of  $H\alpha$  emission line is present in January 1989 (JD 2447546) with an  $H\alpha$  EW of  $-6.2 \text{ \AA}$ . This faint state is consistent with the decrease in the near-infrared magnitude (Hunt et al. 1994), and likely to be related to a much reduced circumstellar envelope. Maximum of the EW of  $H\alpha$  emission line exists in 1992 August (JD 2448869) with an EW of  $-18.5 \text{ \AA}$ , about three times of the value at minimum. The variation of the  $H\alpha$  emission line during our observations is



**Fig. 1.** The  $H\alpha$  spectra of LSI +61°303 taken during our long-term programme. All spectra have had the continuum level normalized and are offset vertically to allow direct comparison. The corresponding radio phases are given on the right-hand.



**Fig. 2.** Long-term  $H\alpha$  EW variability. The different data sets are denoted by different symbols in the figure: open circles for Paredes et al. (1994), up-triangles for Zamanov et al. (1996) and filled circles for the new data presented in this paper

dramatic. The  $H\alpha$  EW reduced to a relatively low value between 1993 and 1994 after the maximum in 1992, and then it rapidly increased to a relatively high state in 1995. It is interesting to note that the following change of the  $H\alpha$  EW is similar to the variation during 1992–1994 but with a higher  $H\alpha$  emission. In

**Table 1.** Journal of the spectroscopic observations of LSI +61°303.

Date	Julian date (-2440000)	Phase	Exp. time (s)	Resolution (Å/pixel)	H $\alpha$ EW (Å)	Note
92.11.02	8929.2	0.94	7200	2.26	-12.1	single peak
92.11.03	8930.2	0.97	3600	2.26	-14.3	single peak
93.11.05	9297.2	0.83	7200	1.39	-9.7	R $\approx$ V
94.09.21	9617.3	0.91	1800	1.22	-8.5	R>V
95.10.15	10006.3	0.58	2700	1.22	-17.2	R $\gg$ V
95.10.17	10008.3	0.66	2700	1.22	-15.3	R>V
96.10.25	10382.3	0.78	1300	1.22	-13.78	R $\approx$ V
96.10.26	10383.2	0.81	1300	1.22	-13.50	R $\approx$ V
97.12.15	10798.2	0.47	1200	1.22	-12.5	R $\gg$ V
97.12.16	10799.2	0.51	1800	1.22	-12.61	R $\gg$ V
97.12.18	10801.1	0.58	1500	1.22	-13.97	R $\gg$ V
98.10.31	11118.2	0.55	1200	1.22	-11.96	R>V

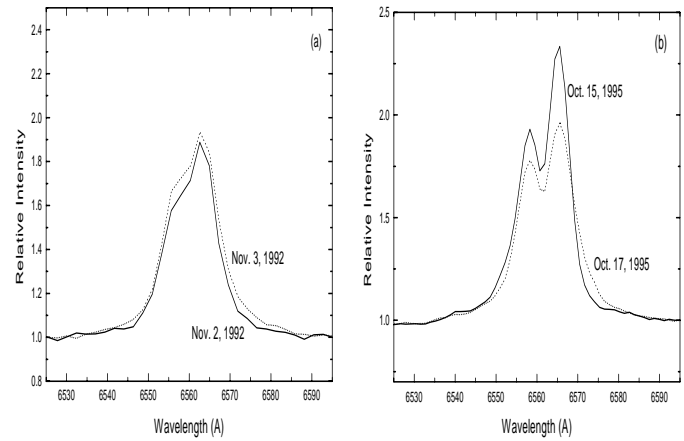
passing we also note that the time interval between the latest two minima or the latest two maxima is all about 4 years.

### 3.2. Short-term variability

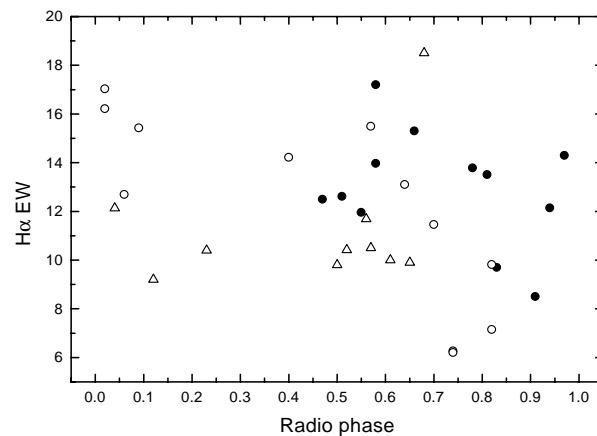
Variations at timescales of days in H $\alpha$  spectra have been reported by Paredes et al. (1994) and Zamanov et al. (1996). Fig. 3 shows the short-term variability during our observations. Both the intensity and the EW of the H $\alpha$  emission line vary considerably within few days. An attempt to search for shorter variations within one day turned out not to be successful in our observing runs. The 1992 November spectra are the only spectra with single peak, although the spectral dispersion is not high. The H $\alpha$  EW was -12.1 Å on November 2, 1992 at radio phase 0.94. It increased about 20 percent and amounted to -14.3 Å one day later (Fig. 3a). The enhancement is at both the humps and the wings of the H $\alpha$  line. We find from Fig. 3b that the change of H $\alpha$  EW in 1995 October at radio phases about 0.6 was also fairly large. It is noteworthy that the decrease of the H $\alpha$  emission in 1995 October accompanied by the enhancement of the emission at the red wing. We are inclined to suggest that the enhancement is real, since it covers more than 10 Å, well beyond the resolution, and the data was carefully reduced repeatedly. The variation in 1997 December was just opposite to that in 1995 October, with an increase of the H $\alpha$  emission accompanied by the decrease of the emission at the red wing, although not as obvious as that in 1995.

### 3.3. Periodic variability

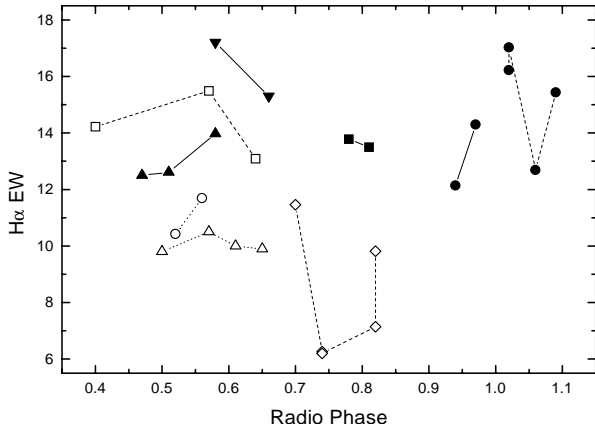
Zamanov et al. (1999) reported the detection of the 26.5 day period in the H $\alpha$  line ratios of LSI +61°303 such as FWHM(V)/FWHM(R), EW(V)/EW(R) and V/R. Fig. 4 illustrates the H $\alpha$  EW of LSI +61°303 as a function of radio phase. The radio phase is calculated on the basis of a 26.496 day period and phase zero has been set at JD2443366.775 (Taylor & Gregory, 1982). Although our data available are somewhat sparse, we find the data have a good coverage over the radio phases 0.5–1.0. Our data confirm that the H $\alpha$  EW changes strongly in



**Fig. 3a and b.** Short-term H $\alpha$  EW variability with timescales of few days. **a** variability in 1992 November. **b** variability in 1995 October. Note the decrease of the line intensity with the enhancement around  $\lambda$  6570 at the red wing



**Fig. 4.** H $\alpha$  EW variations of LSI +61°303 fold on the 26.496 day radio period. The different data sets are denoted by different symbols in the figure: open circles for Paredes et al. (1994), up-triangles for Zamanov et al. (1996), and filled circles for the new data presented in this paper



**Fig. 5.**  $H\alpha$  EW variations of LSI +61°303 fold on the 26.496 day radio period. The data within same cycle are connected with different kind of lines in the figure for the different data sets: dash lines for Paredes et al. (1994), dot lines for Zamanov et al. (1996), and solid lines for the new data presented in this paper. Solid dots at phases around 1.0 are data obtained in 1992 August (Paredes et al. 1994) and in 1992 November (this paper)

correspondence of the radio outburst. The data collected in Fig. 4 are considerably scattered at first glance. This scatter originates partly in the long-term trend of the Be envelope itself, which displays somewhat different behaviour in different cycles (Fig. 2). Such different behaviour can be seen in the radio data as well (Taylor & Gregory, 1982). In order to eliminate the long-term effect of the Be envelope, we select the data within same cycle, which are connected and shown in Fig. 5. An additional data set obtained within several cycles in 1991 (Paredes et al. 1994) is also included in the figure. The separated data immediately exhibit that there is a maximum around radio phases 0.55–0.6. There are possibly both another maximum around phases 1.0 and one minimum between radio phase 0.7–0.9, but the data are too sparse (only cover one cycle) to enable a strong conclusion to be drawn. If the periodic modulation turns out to be true as data will have accumulated, then it differs from the periodic variations of radio flux and optical magnitudes, since the minimum of the  $H\alpha$  EW appeared at the phases where the maxima (phases 0.6–0.8) of radio flux and optical magnitudes occurred (Taylor & Gregory, 1982; Mendelson & Mazeh, 1989). Instead of having a wider minimum lasting for about half an orbital cycle as radio flux and V magnitude, the  $H\alpha$  EW shows a deep minimum at phase about 0.75.

#### 4. Discussion

The multi-timescale variability of the  $H\alpha$  EW presented here offers an opportunity for trying to understand the mechanism behind the variation of LSI +61°303. The most well accepted explanation of the  $H\alpha$  line profiles in Be stars involves a circumstellar disk-like envelope that produces the double-peaked line profile. The quasi-periodic variation of the  $H\alpha$  EW is likely to be caused by the periodic accretion of the neutron star and subsequently the possible formation of an accretion disk, which

resulting in the X-ray emission. An accretion disk is likely to form around the neutron star in Be/X-ray binaries with orbital period less than 100 days (Waters et al., 1989; Li & van den Heuvel, 1996). The neutron star begins to accrete stellar material when it approaches the periastron, resulting in the additional loss of stellar material.

In order to interpret the observed behaviour of the LSI +61°303 near infrared light curves, Marti & Paredes (1995) suggested an eclipse-attenuation model of the secondary emission by the Be primary star and its envelope. They indicated that the accretion rate can exhibit two maxima respectively peaked at phases 0.53 and about 1.0, if suitable initial velocity (e.g.  $2 \text{ km s}^{-1}$ ) was chosen. This model is employed to explain the observed variations. We suggest that both the accretion disk and X-ray heating may be responsible for the small part of the  $H\alpha$  emission. The increase in width of the red hump, as Paredes et al. (1990) reported, could be either due to emission of the accretion disk or due to X-ray induced enhancement in the circumstellar disk (Apparao, 1991; Liu & Hang, 1999). Following the orbital solution of Marti & Paredes (1995), we can expect the increase of the red hump of  $H\alpha$  intensity and the unusual enhancement at red wing as observed in Fig. 3b, when the neutron star moves away from the observer at the phases 0.53 to about 1.0. The radial component of orbital velocity of the neutron star in 1992 November is very small since it is at phase about 1.0 (see Fig. 4 in Marti & Paredes, 1995), so that the X-ray induced enhancement may mainly contribute to the center part of the  $H\alpha$  emission (see Fig. 3a).

We also introduce the mechanism of X-ray heating parts of the normal star facing the X-ray source to interpret the enhancement of optical magnitudes at phases 0.6–0.8 (Mendelson & Mazeh, 1989; Paredes et al. 1994). According to the calculation, an X-ray luminosity of  $5 \times 10^{36} \text{ erg s}^{-1}$  is needed to produce the same enhancement of optical V magnitude, i.e., 0.03 mag for a B0-type star (Apparao, 1991). Such an X-ray luminosity can cause fairly large variations on  $H\alpha$  emission. That is likely the reason why the EW of the  $H\alpha$  emission line in LSI +61°303 varied dramatically while the V magnitude only changed a little. Furthermore, we suggest that the dip observed at the maximum optical luminosities (Mendelson & Mazeh, 1989) may also be related to the dip between the two maxima of the accretion rate, thus the X-ray luminosity. The spectra with nearly same V and R at phases around 0.8, where the minimum of accretion rate occurs (Marti & Paredes, 1995), seem to provide further evidence for this viewpoint.

An alternative explanation is that the 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 orbital motion (Apparao, 1999). This explanation is also associated with the secondary compact object. In the model, the maximum will occur at the descending node of the secondary object and the minimum at the ascending node. This model, however, strongly depends on the structure of the envelope.

It must be noted that in Marti & Paredes' model (1995), they assumed super-Eddington accretion of matter on to the compact object, without reconciling this to the fact that the observed X-

ray luminosity is lower than the Eddington limit by several orders of magnitude. However, Hermsen et al. (1977) reported the detection of  $\gamma$ -ray emission from a source whose position error box includes LSI +61°303 with luminosity of  $10^{37}$  erg s<sup>-1</sup>. It can be explained with that the missing high luminosity emitted at  $\gamma$ -ray band. If the  $\gamma$ -ray source is not associated with LSI +61°303, then the low observed X-ray luminosity is likely to be interpreted with that the high eccentricity is a spurious result or the X-ray emission is unlikely powered with accretion, since high eccentricity will result in high accretion rate thus high X-ray luminosity when the neutron star approaches the periastron.

Variability in LSI +61°303 is observed on different timescales. We suggest that the long-term variability is connected to the intrinsic behaviour of the Be star and the short-term variability and periodic variability to the orbital motion of the neutron star. Some other Be/X-ray binaries were also reported that their mass loss were likely to be associated with the orbital motion of the neutron star (Charles et al. 1983; de Martino et al. 1984; Liu & Hang, 1999). We know from the observations that the H $\alpha$  emission variation due to the long-term change of Be envelope is much larger than that due to the periodic modulation. Since our observations are centered at the range of radio maximum, and there are only a few spectral data at radio minimum, it is necessary to monitor the object within one period or several successive periods, if we want to fully understand the spectral characteristics of the object.

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