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HeI doubled emission lines from A0535+26 ≡ HDE 245770

A possible interpretation

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ABSTRACT

We report results of the spectroscopy for V725 Tau (HDE 245770, BD +26°883), commonly known as Flavia's star, which is the optical counterpart of the X-ray pulsar A0535+26, carried out at the 1.5 m Loiano telescope during one run of observations of this star spread over a period of years. The HeI emission lines clearly show doubling, which is good evidence for the presence of a disc. In this paper we critically discuss the possibility that this disc is a temporary accretion disc around the neutron star, a view that contrasts to the usual interpretation, which considers that this sort of doubling in the HeI emission lines is due to a disc formed by gas expelled from the Be star. In the former case the outer radius of the accretion disc could range from 5.9×10^{10} cm to 2.1×10^{11} cm, taking the most probable range into account for the orbital inclination of the binary system, from 35° to 39°. The presence of such a temporary accretion disc around the neutron star was predicted by Giovannelli & Ziółkowski (1990).

Key words. X-rays: binaries – accretion, accretion disks – stars: emission line, Be – stars: binaries: close

1. Introduction

A 0535+26/HDE 245770 is a typical X-ray/Be runaway system (van Oijen 1989), whose components are a 104 s X-ray pulsar (Rosenberg et al. 1975) and an O9.7 IIIe star (Giangrande et al. 1980). The X-ray pulsar is spinning up with a pulse period derivative $\dot{P}/P = -4.9 \times 10^{-4}$ yr^{-1} (Coe et al. 1990), with alternating phases of spin-down during X-ray outbursts. The X-ray pulsar A0535+26 has a magnetic field of $\sim 10^{13}$ G (Grove et al. 1995). The orbital period has been determined by many authors with different methods: $111\overset{\mathrm{d}}{.}0 \pm 0\overset{\mathrm{d}}{.}4$ (Priedhorsky & Terrell 1983), $111\overset{\mathrm{d}}{.}38 \pm 0\overset{\mathrm{d}}{.}11$ (Motch et al. 1991), and $110\overset{\mathrm{d}}{.}3 \pm 0\overset{\mathrm{d}}{.}3$ (Finger et al. 1994) from X-ray data, and recently $110\overset{\mathrm{d}}{.}0 \pm 0\overset{\mathrm{d}}{.}5$ (Coe et al. 2006) from the increasing of X-ray activity associated with the periastron passage of the neutron star. These values agree with that reported by Guarnieri et al. (1985) from long-term optical photoelectric data ($109\overset{\mathrm{d}}{.}8 \pm 2\overset{\mathrm{d}}{.}0$). The orbital eccentricity of the system is 0.47 (Finger et al. 1994). The terminal velocity of the stellar wind from the star with significant optical output is ~ 630 km s^{-1} (Giovannelli et al. 1982), and its mass loss rate is $\sim 10^{-8}$ $M_{\odot}$ yr^{-1} (Giovannelli et al. 1984; de Loore et al. 1984).

The X-ray pulsar is close to its equilibrium state (Bisnovatyi-Kogan 1991; Li & van den Heuvel 1996), which could be a reason why some of the expected X-ray outbursts have failed to occur. This was noted at the end of the eighties, as discussed by Giovannelli & Ziółkowski (1990, and references therein), or in the mid-nineties, as found by the RXTE satellite (see http:// space.mit.edu/XTE). The O9.7 IIIe companion does not normally fill its Roche lobe (de Loore et al. 1984), although a temporary accretion disc can be formed around the neutron star when it is close to periastron (Giovannelli & Ziółkowski 1990).

Complete reviews of this system can be found in the papers by Giovannelli et al. (1985), Giovannelli & Sabau-Graziati (1992), and Burger et al. (1996).

Ever since its discovery, several groups performed observations in order to search for the optical counterpart of the 104 s X-ray pulsar. After the discovery of the association of HDE 245770 with the X-ray pulsar A 0535+26 (Bartolini et al. 1978), Giovannelli et al. (1982) initiated multi-frequency monitoring of the system, which has carried on without interruption until the present epoch. The photometric and spectroscopic behaviour of HDE 245770 are typical of a Be star, in spite of the neutron star companion in the binary system (see e.g. Piccioni et al. 1985; Guarnieri et al. 1985; Piccioni et al. 2000).

In this paper we will discuss one of the most interesting observations of this system: the appearance of a doubling in the HeI emission lines, during the period when HDE 245770 was recovering its "normal" Be state after a disc-loss phase, as demonstrated by the renewed presence of H_{α} and HeI in emission (Giovannelli et al. 1999). This event might be associated with the formation of a temporary accretion disc around the X-ray pulsar, during the periastron passage ($\varphi^{\circ}_{\mathrm{orb}} \sim 0.997$).

2. October 1999 observations

The observations were performed on October 9th, 10th, and 12th, 1999 using the Bologna Faint Object Spectrometer and Camera (BFOSC, Merighi et al. 1994) mounted at the

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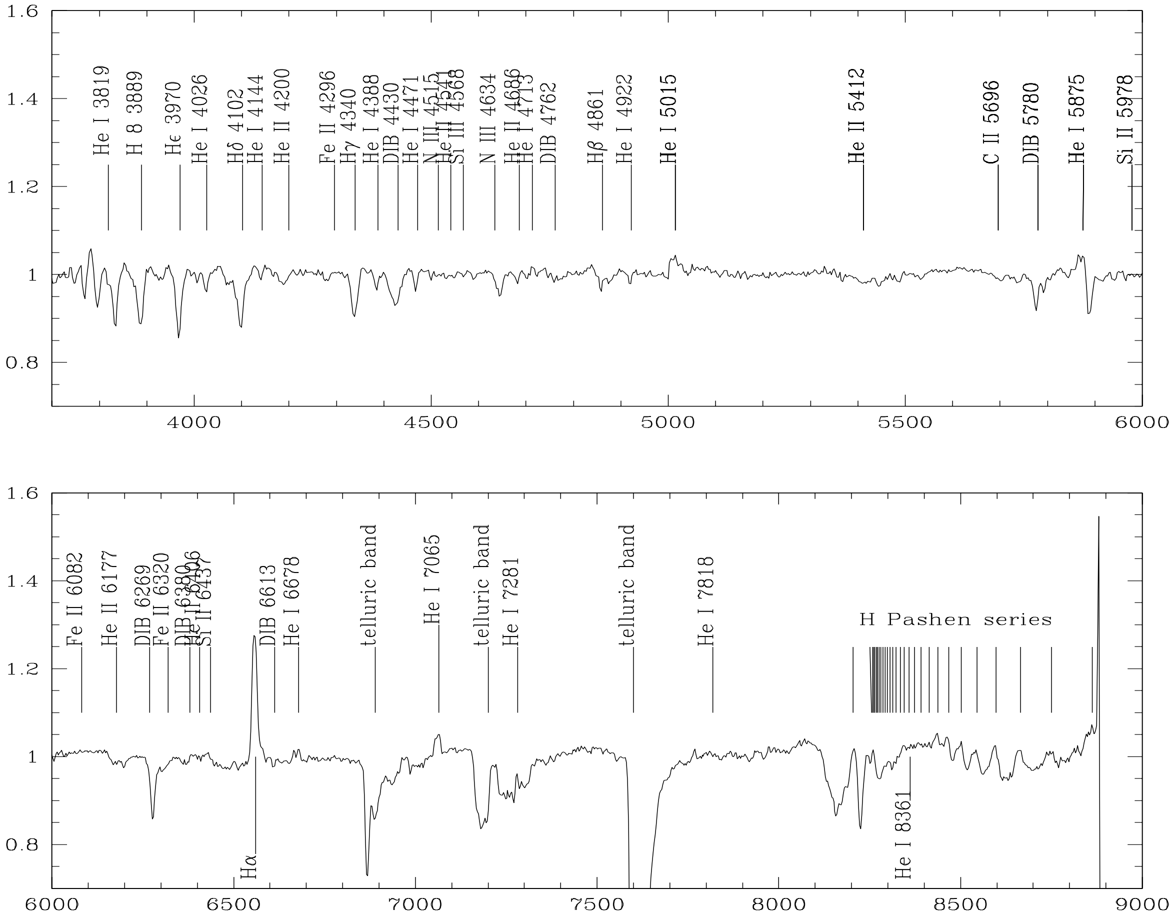

Fig. 1. Spectrum of HDE 245770, normalised to the continuum, taken on October 9, 1999.

Cassegrain focus of the 1.52 m "Cassini" Telescope of the Loiano Observatory of the Bologna Astronomical Observatory. BFOSC is equipped with a 2048 × 2048 Loral CCD detector (pixel size 15 μm, FOV 13 × 13 arcmin^2, pixel scale 0.5 arcsec/pixel) employing a grism with resolving power 5.7 Å, corresponding to $\Delta\lambda$/pixel of 2.8 Å and covering a spectral range of 3500–9000 Å.

Figure 1 shows the spectrum of HDE 245770 from ~3700 Å to ~8900 Å taken on the night of October 9, 1999. The spectrum has been normalised to the continuum and divided into two parts for better presentation. To assist with the interpretation, the main lines are marked on the plot. Similar spectra were taken on October 10 and 12, 1999. By examination of the spectrum in Fig. 1 we can see that the HeI lines that appear in emission (i.e. $\lambda\lambda$ 5015 Å, 5875 Å, 6678 Å, and 7065 Å) show doubling in their profiles. The same doubling is seen in the spectra from Oct. 10 and 12, as can be seen in Fig. 2 where we present an expansion of the three longer wavelength lines. The line at λ 5015 Å is not as well-defined, since it is weak and close to the FeII (m42) line at λ 5018 Å. In spite of this, the values of the velocity splitting, $v_{\rm obs}$ for this line, lie within the range inferred from the other three lines.

In order to measure the line doubling, we fitted the observed profiles of all the HeI lines in emission with sets of Gaussians. The numerical values of the splittings are shown in Table 1, together with the corresponding velocities. Photometry of HDE 245770 carried out on October 9 and 11, 1990 gave values for B of 9.78 ± 0.04 mag and 9.77 ± 0.04 mag, respectively. The long-term light curve in B has a continuous trend

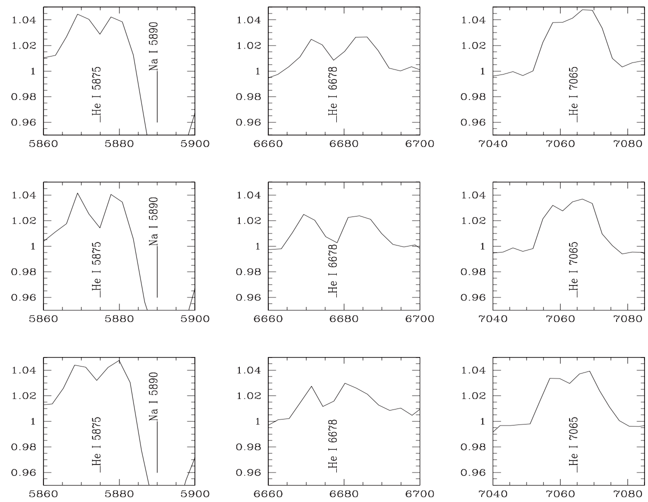

Fig. 2. The HeI emission lines profiles of HDE 245770. *Upper*, *medium*, *lower panels* refer to the spectra taken on October 9, 10, and 12, 1999, respectively.

from ~9.5 mag to ~10 mag during the past 15 years. This trend is now reversing.

3. The temporary accretion disk

Normally the HeI lines observed in emission from HDE 245770 are single-peaked. When they appear broadened and split, the standard assumption is that they originate in a rapidly rotating

Table 1. Separation ($\Delta\lambda$) of the split lines and the relative Keplerian velocities (v_d) inferred from the four observed lines at λ 5015 Å, λ 5875 Å, λ 6678 Å, and λ 7065 Å in the spectra of HDE 245770/A 0535+26 system, taken on Oct. 9, 10, and 12, 1999.

Date yymmdd		HeI 5015 Å	HeI 5875 Å	HeI 6678 Å	HeI 7065 Å
991009	$\Delta\lambda$ (Å)	8.8 ± 1.4	11.6 ± 1.4	13.5 ± 1.4	10.0 ± 1.4
	v_d (km s^{-1})	263 ± 42	296 ± 36	303 ± 31	213 ± 21
991009	$\Delta\lambda$ (Å)		11.3 ± 1.4	13.5 ± 1.4	10.3 ± 1.4
	v_d (km s^{-1})		288 ± 36	303 ± 31	219 ± 21
991009	$\Delta\lambda$ (Å)		11.3 ± 1.4		
	v_d (km s^{-1})		288 ± 36		
991010	$\Delta\lambda$ (Å)	9.3 ± 1.4	11.4 ± 1.4	13.9 ± 1.4	9.5 ± 1.4
	v_d (km s^{-1})	278 ± 42	291 ± 36	313 ± 31	202 ± 21
991010	$\Delta\lambda$ (Å)	8.2 ± 1.4	11.5 ± 1.4	13.4 ± 1.4	9.7 ± 1.4
	v_d (km s^{-1})	245 ± 42	293 ± 362	301 ± 31	206 ± 21
991012	$\Delta\lambda$ (Å)		11.4 ± 1.4	12.9 ± 1.4	10.3 ± 1.4
	v_d (km s^{-1})		291 ± 36	290 ± 31	219 ± 22
991012	$\Delta\lambda$ (Å)		11.6 ± 1.4	11.7 ± 1.4	10.2 ± 1.4
	v_d (km s^{-1})		296 ± 36	263 ± 31	217 ± 21

Keplerian disc. One explanation for the presence of such a disc is that it is an "excretion disc" around the Be star, due to the expulsion of matter from the star. However, in this scenario there are some difficulties in explaining the lack of correlations between HeI (6678 Å), H_α, and H_β lines (e.g. Clark et al. 1998). Therefore we argue that the HeI line splitting is evidence of an accretion disc around the X-ray pulsar, but is temporary since such splitting disappeared on a time scale of about a month. Indeed, after 43 days from the last October 12 observations, not only did the doubling disappear, but the HeI lines were also mixed up with the noise. Figure 3 shows the spectra taken on October 12 (lower) and November 24, 1999 (upper) around H_α, where the HeI lines (5875, 6678, and 7065 Å) are included.

Assuming that the matter in the disc is rotating with a Keplerian velocity distribution, we can derive the geometrical parameters of the disc from the line profiles. With almost complete independence of the radial distribution of the emitting material, one half of the velocity separation of the peaks gives, to within an uncertainty of 15%, the projected rotational velocity ($v_d \sin i$) (where i is the inclination angle of the orbit of the disc with respect to the plane of the sky) of the outer edge of the annular zone within the disc where the given emission line is formed (Smak 1969, 1981; Huang 1972). For v_d we use:

$$v_d^2 = GM_{NS}/R_d \quad (1)$$

where M_{NS} is the mass of the neutron star and R_d the outer radius of the disk.

We detected only minor variations in the line profiles from one night to another during the observing run, so we can use the mean value of the splitting for each line. The mean measured separation of the peaks in HeI $\lambda\lambda$ 5015, 5875, 6678, and 7065 Å are 8.8 Å, 11.4 Å, 13.1 Å, and 10.0 Å, respectively. These values correspond to values for $v_{obs} = v_d \sin i = 263 \pm 42$, 291 ± 36, 295 ± 31, and 213 ± 21 km s^{-1}, respectively (see Table 1). Using Eq. (1) we obtain

$$R_d = [GM_{NS}/v_{obs}^2] \times \sin^2 i, \quad (2)$$

and in differential form,

$$\Delta R_d = \frac{2GM_{NS} \times \sin^2 i}{v_{obs}^3} \times \Delta v_{obs}. \quad (3)$$

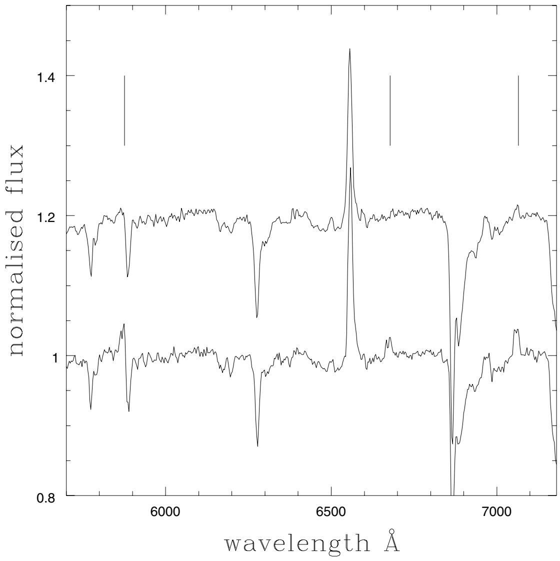

Fig. 3. Spectra of HDE 245770 taken on October 12 (*lower*) and November 24, 1999 (*upper*). The flux of the upper spectrum is multiplied by 1.2 for a better representation.

An average value for the neutron star mass in binary X-ray/Be(OB) systems is $1.5 \pm 0.3\ M_\odot$ (Joss & Rappaport 1984; Thorsett et al. 1993; van Kerkwijk et al. 1995). Taking this value for the mass of the neutron star, we can plot the radius of the accretion disc against the orbital inclination angle for the minimum and maximum values of v_{obs}, i.e. 213 ± 21 and 295 ± 31 km s^{-1} as shown in Table 1. The results are shown in Fig. 4.

There have been a number of determinations of the inclination angle i by different research groups. The earliest gave a lower limit of 50° using line broadening and an upper limit of 86° from the absence of X-ray eclipses (Hutchings 1984). The second determination constrained the value of i to between 40° and 60° with the mass of the primary between 9 $M_\odot$ and 17 $M_\odot$ (Janot-Pacheco et al. 1987). This mass range includes the value of 15 $M_\odot$ reported earlier by Giangrande et al. (1980) based on optical spectroscopic data. The third determination of the inclination angle, based on radial velocity measurements from high dispersion IUE spectra of HDE 245770 gives a range in i of

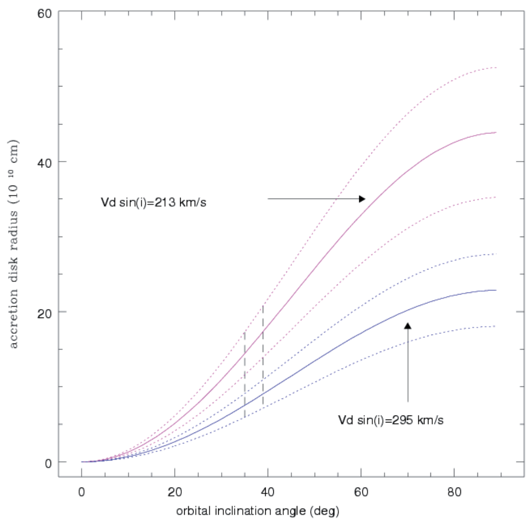

Fig. 4. Accretion disc radius vs orbital inclination angle for HDE 245770. The red curves are for $v_{\rm obs} = 213 \pm 21$ km s^{-1} and the blue curves for $v_{\rm obs} = 295 \pm 31$ km s^{-1}, the minimum and maximum values, respectively, derived from the observed HeI line splittings. Blue dashed vertical lines refer to the minimum and maximum values of i to between 35° and 39°, as derived in this paper.

26°–40° with the mass of the primary between 8 $M_\odot$ and 22 $M_\odot$ (Wang & Gies 1998). The fourth determination yielded values for i of $38.^\circ6 \pm 2.^\circ5$ or $36.^\circ1 \pm 1.^\circ7$ depending on whether the HeI line used was at λ 4713 Å or λ 4471 Å (Haigh et al. 2004). The latter values were derived from the photospheric spectra obtained just after the loss of the "excretion disc".

Using our own classification of O9.7IIIe for the visible star HDE 245770 (Giangrande et al. 1980) and the rotational broadening of 230 ± 45 km s^{-1} derived from the HeII absorption line at λ 1640 Å (Giovannelli et al. 1982), which agree with the values derived by Giangrande et al. (1980) for the λ 4471 Å HeI line, we can derive a value for the inclination angle of 37° ± 2° after carefully deconvolving the instrumental broadening and using results from Conti & Ebbets (1977), Fukuda (1982), and Penny (1996). The corresponding equatorial rotational velocity is $\sim 382 \pm 40$ km s^{-1}, in agreement with determinations by Haigh et al. (2004) and by Wang & Gies (1998).

We can use this result to constrain the values of the radius of the hypothetical accretion disc radius around the X-ray pulsar A0535+26, using range limits for i of 35° to 39°, which include the errors in the determination of $v_{\rm obs}$.

The value of the accretion disc radius can range from $(5.9 \pm 0.1) \times 10^{10}$ cm to $(2.1 \pm 0.1) \times 10^{11}$ cm. This possible spread includes of the different zones of the accretion disc where HeI λ 7065 Å and λ 6678 Å form. For any orbital inclination angle, the radius of the formation zone in the accretion disc is smaller for higher velocities $v_{\rm obs}$. All these conclusions assume that the accretion disc is coplanar with the orbit of the neutron star. If this assumption is not valid, some modifications to the limits of the accretion disc radius should be applied. Finally, further small adjustments would be needed if improved determinations of the masses of the neutron star and the O9.7IIIe star were obtained.

Up to now good observational evidence has not been available on which to base a serious discussion of these effects, but assuming that the spin axis and the orbital axis are parallel, the mass function derived from the orbit of the neutron star, $f(M) = M_{\rm Be}^3 \sin^3 i/(M_{\rm Be} + M_{\rm NS})^2 = 1.64 \pm 0.23\ M_\odot$ (Bildsten et al. 1997) yields an upper limit on the mass of the Be star ($M_{\rm Be} < 22\ M_\odot$), given a neutron star mass of 1.5 $M_\odot$ (Wang & Gies 1998). It is possible for the spin and orbital axes to be misaligned, if the neutron star acquired a substantial asymmetric impulse velocity at birth, but this velocity would have to be in the range of at least 400–500 km s^{-1} (Fryer et al. 1998). However, this is not the case for the present object, as the neutron star A0535+26 received a natal impulse velocity of no more than ~160 km s^{-1} (Giovannelli & Sabau-Graziati 2000). This result is strengthened by the more general model predictions of Fryer (2004) who discusses asymmetries in the core of a massive star just prior to collapse. Neutrinos carry away momentum, and the asymmetric collapse leads to asymmetries in the neutrino distribution. However even in the most extreme cases of asymmetric collapse, the resulting neutron star velocities do not exceed 200 km s^{-1}, so the hypothesis that the accretion disc and the orbit are coplanar has a high degree of probability.

4. Discussion

As discussed by Giovannelli & Ziółkowski (1990), it is possible for a temporary accretion disc to form in the system A0535+26/HDE 245770. The possibility of the formation of accretion discs around the neutron stars in X-ray/Be binaries has been thoroughly debated for several decades, and in recent times this possibility is a well-accepted one within the working community (Ushomirsky & Routledge 2001; Okzaki et al. 2002; Wilson et al. 2002; Ziółkowski 2002; Clark et al. 2003; Haigh et al. 2004; Hayasaki & Okazaki 2004).

Doubts about this idea came from the theoreticians (Davies & Pringle 1980; Livio et al. 1986a,b; Anzer et al. 1987) who suggested that matter accreted directly from the stellar wind of the Be star should have very low specific angular momentum with respect to the neutron star, which would make the formation of an accretion disc impossible. However the observations suggested a different scenario: that the matter accreted by X-ray pulsars associated with Be stars (and therefore accreted from their winds) has in fact very high specific angular momentum compared to that required by a Keplerian disc (Rappaport & Joss 1977; Ziółkowski 1985).

Indeed, during X-ray outbursts, (when spin-up times are measured), the accretion onto the pulsar A0535+26 is disc-fed, so that (at least temporarily) an accretion disc must be present during the X-ray active phases (see e.g. Finger et al. 1996). Whether remnants of the disc are still present near apoastron remains an open question.

The presence of a temporary accretion disc is also supported by some measurements, presented but not interpreted by Hutchings et al. (1978) who reported the variability of the HeII (λ 4686 Å) absorption line and its appearance in emission on two occasions in A0535+26/HDE 245770 system. These were only 8 days apart, and the line was observed in absorption between these occasions. This HeII emission line is a clear indicator of the presence of an accretion disc around compact stars in X-ray binaries (e.g. Hutchings 1974; Crampton et al. 1976; Hutchings et al. 1977; Val Baker et al. 2005).

The possible values of the accretion disc outer radius, ranging from 5.9×10^{10} cm to 2.1×10^{11} cm, if we take into account that the most probable range of values of the orbital inclination angle (35°–39°) are consistent with the dimensions of the binary system.

A natural question to put here is why the system A0535+26/HDE 245770 did not show an X-ray outburst during the period October 9, 10, and 12, 1999 when our optical measurements were performed. The explanation could be either that the system was not at periastron or that the pulsar, although at periastron, is rotating with its equilibrium period. The orbital phase at which the measurements were performed merits a comment. Following the most reliable determinations by Motch et al. (1991) of the X-ray period and the initial epoch ($P_{XR} = 111\overset{d}{.}38 \pm 0\overset{d}{.}11$ and T_0 = JD 2, 446, 734.3 ± $2\overset{d}{.}6$), the orbital phase corresponding to the beginning of our measurements is $\varphi_{orb} \sim 0.44$. Hence, on this basis we would have been measuring quite close to apoastron.

Recently, by using the increase X-ray activity associated with the periastron passages, Coe et al. (2006) derived the ephemeris of the system as ($P^{\diamond}_{XR} = 110\overset{d}{.}0 \pm 0\overset{d}{.}5$ and $T^{\diamond}_0$ = JD 2, 450, 094 ± 1^{d}), in complete agreement with what was derived by Guarnieri et al. (1985) ($P_{orb} = 109\overset{d}{.}8 \pm 2\overset{d}{.}0$) from long-term optical photoelectric photometry. If the orbital period is $110\overset{d}{.}0$, the orbital phase corresponding to our October 12, 1999 measurements is $\varphi^{\diamond}_{orb} \sim 0.997$, i.e. at the periastron passage.

The pulse period behaviour of A0535+26 (see e.g. Giovannelli & Sabau-Graziati 1992) indicates that in its normal state the pulsar becomes "slow" ($P_{spin} > P_{eq}$) during the active phases, i.e. close to periastron, and "fast" ($P_{spin} < P_{eq}$) during the quiescent phase, i.e. close to apoastron. The alternation between the slow and fast phases is due to the oscillatory behaviour of the instantaneous equilibrium period, which in turn tracks the variable accretion rate. The value of the equilibrium period P_{eq} is related directly to the instantaneous accretion rate $\dot{M}$ by $P_{eq} \propto \dot{M}^{-3/7}$ (Davidson & Ostriker 1973; Ziółkowski 1985).

From observations over a number of years, A0535+26 was, on average, found to be spinning up with a timescale of ~2000 yr (Giovannelli et al. 1984; Coe et al. 1990; Giovannelli & Sabau-Graziati 1992). It is possible, either due to an unusually quiet state of the Be star (which implies a low value for $\dot{M}$ and so a long P_{eq}) or to its long-term average spin-up (a progressive reduction in P), that the pulsar can acquire a state in which it remains fast ($P < P_{eq}$) during the whole orbital cycle, including its periastron passage, as occurred, for instance, in 1985–86 (Giovannelli et al. 1986) and perhaps also during the period of the observations reported in the present paper.

The unusually quiet state of the Be companion HDE 245770 started in early 1997 and developed until late 1998. It has been reported and discussed by Haigh et al. (1999) and by Piccioni et al. (1999, 2000). During this type of phase, when the excretion disc of the Be star is lost, X-ray pulsations from A0535+26 have in fact been detected (Neguerela et al. 2000). Ikhsanov (2001) discussed the possible origin of this X-ray emission from the X-ray pulsar during the quiescent phase of the Be companion and concluded that this emission, with a pulse period of 103 s and with luminosity 4×10^{33} erg s^{-1} during the "disc-loss" state in August-November 1998, can be interpreted within the canonical model of spherical accretion onto a magnetized neutron star (Elsner & Lamb 1984). During this period the neutron star was the accretor. The estimated magnetospheric radius at which the magnetic field begins to dominate the dynamics of the inflow is $r_m \sim 9.3 \times 10^9$ cm. The corotation radius is $r_c \simeq 3.7 \times 10^9$ cm (Stella et al. 1986), so that $r_m > r_c$ and the neutron star must be in the centrifugal inhibition regime. These are the same conditions obtained by Mukherjee & Paul (2005) from BeppoSax measurements of A0535+26 on 2000 September 4, October 5, and March 5, 2001.

Doubling of the HeI emission lines was detected by Clark et al. (1998). The separation of the HeI (λ 6678 Å) peaks ranges from 7.0 ± 1.0 Å on October 16, 1995, to 11.0 ± 0.5 Å on November 1, 1994. The first is below our value, and the second is roughly comparable. We can comment that our values have been obtained during a short run of observations (October 9–12, 1999), whilst those of Clark et al. (1998) were obtained during a couple of years. If they would have measured in the nights around November 1, 1994, the obtained values of the separation of the HeI (λ 6678 Å) peaks would have been roughly around 11.0 ± 0.5 Å, as noted by those authors who stated that there are similarities in two pairs of spectra taken on adjacent days. Under our hypothesis that an accretion disc around the neutron star is responsible for the doubling of He I lines, the lower values reported by Clark et al. (1998) would move the upper limit of the radius of the accretion disc to $\sim 3.2 \times 10^{11}$ cm instead of the upper value found with our data, namely $\sim 2.1 \times 10^{11}$ cm.

However Clark et al. (1998) did not attribute the doubling to the presence of an accretion disc around the neutron star, but to a circumstellar disc. They observed the onset of long-term cyclic V/R variability of H_α, as well as of H_β, between December 1993 and September 1994, coincident with the longest photometric minimum observed in a decade of their observations.

That H_β is expected to be produced closer to the star than H_α shows that the symmetry in the disc extends to smaller radii than the H_α emission zone; however, no correlation was observed with the HeI λ 6678 Å line. Since this is expected to be emitted close to the star, it either sets an inner limit to the predicted density wave pattern, or implies a different origin for the splitting in the HeI line, i.e. in the accretion disc around the neutron star. The inner edge of the disc does not extend to the stellar surface, but is instead detached of $\geq 0.2\ R_*$ ($R_* \sim 9.7 \times 10^{11}$ cm for $R_* = 14\ R_\odot$ and $M_* = 15\ M_\odot$ (Giangrande et al. 1980 values).

If we do adopt the assumption that the HeI emission is formed in the excretion disc around the Be star, the splitting could give an estimate of the inner radius of the disc. If we use a mass for the Be star $M_{Be} \simeq 15\ M_\odot$ (Giangrande et al. 1980), the inner radius could range between 2.1×10^{12} cm and 5.9×10^{11} cm. But the radius of the Be star is $R_{Be} \simeq 14\ R_\odot = 9.7 \times 10^{11}$ cm (Giangrande et al. 1980). This means that – although the upper limit for the inner disc radius, 2.1×10^{12} cm, derived from the HeI line at λ 7065 Å, would then be compatible with the radius of the Be star – the lower value of 5.9×10^{11} cm, derived from the HeI line at λ 6678 Å, is clearly incompatible with the stellar radius.

One could choose to argue here that the mass of the Be star may not be so well determined at 15 $M_\odot$. Using the range $9\ M_\odot \leq M_{Be} \leq 17\ M_\odot$, as suggested by Janot-Pacheco et al. (1987), the pairs of limit values for the inner radius of the excretion disc will be 2.4×10^{12} cm and 6.7×10^{11} cm for $M_{Be} = 17\ M_\odot$, while 1.3×10^{12} cm and 3.5×10^{11} cm for $M_{Be} = 9\ M_\odot$. The radii for Be stars of 17 $M_\odot$ and 9 $M_\odot$ are $\sim 1.1 \times 10^{12}$ cm and $\sim 5.8 \times 10^{11}$ cm, respectively. In both cases the lower values for the inner radius of the excretion disc are incompatible with its presence around the Be star with the given radius.

Figure 5 shows in a single diagram the values of the radius of the Be star, and upper and lower limits for the radii of the formation regions of the HeI emission lines $\lambda\lambda$ 6678 and 7065 Å in a hypothetical excretion disc around the star. The mass range we have used in Fig. 5 includes the value of 15 $M_\odot$ from Giangrande et al. (1980), the range of 9 $M_\odot$ to 17 $M_\odot$ suggested by Janot-Pacheco et al. (1987), and an upper limit value of 22 $M_\odot$ from Wang & Gies (1998). It is clear that an excretion disc cannot exist within the body of the star, so that the shaded red area in Fig. 5 is forbidden. This result implies that it is unlikely that

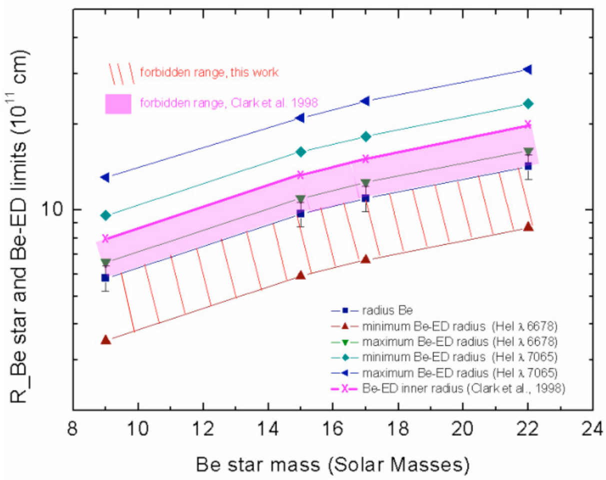

Fig. 5. Selected values for the radii of Be stars in the mass range from 9 $M_\odot$ to 22 $M_\odot$ (blue squares). It shows the lower limits (red triangles) and upper limits (green inverse triangles) to the radius of formation of the HeI λ 6678 Å line in emission from a hypothetical excretion disc around the Be star. Lower limits (light blue lozenges) and upper limits (blue triangles sideways on) to the radius of formation of the HeI λ 7065 Å line in the excretion disc. The dashed area is forbidden for the formation of the HeI λ 6678 Å line. The magenta area is forbidden for the formation of any emission lines, being the inner radius of the excretion disc $R_{\mathrm{in-AD}} = 1.2 \times R_*$ (magenta X).

the HeI lines are in fact formed in the excretion disc, although a thin allowed shell exists just very close to, but above, the Be star surface.

However, Clark et al. (1998) found that the inner edge of the excretion disc around the Be star does not extend to the stellar surface, but is instead detached. The separation between the circumstellar disc and star is $\geq 0.2\ R_*$. Therefore, the band between the radius of the Be star and the radius of the inner edge of the circumstellar disc is forbidden for the production of any emission line. Thus, this forbidden band excludes the thin allowed shell for the formation of HeI (6678 Å) we have found. Therefore, this is strong evidence against the origin of HeI lines in the circumstellar disc and then in favour of their origin in an accretion disc around the neutron star.

Finger et al. (1996) use BATSE X-ray data obtained during the outburst of February-March 1994 to find a spin-up rate at the maximum of the outburst of $\sim 1.2 \times 10^{-11}$ Hz s^{-1}, which strongly suggests the presence of an accretion disc around the neutron star. Clark et al. (1998) put forward the view that one of the emission components detected in their optical spectra taken during the outburst might well correspond to emission from this kind of disc. Finger (1998) analysed quasi-periodic oscillations (QPO's) from the A0535+26 X-ray pulsar, using the dependence of the radius r_0 of the inner edge of an accretion disc given by Pringle & Rees (1972), to constrain the ratio of r_0 to the Alfvén radius, providing new information on the accretion-disc magnetosphere boundary region.

Clark et al. (1999), in searching for the long-term variability of the system HDE 245770/A0535+26 do not find a positive correlation between the optical and the X-ray light curves. They therefore exclude models for the X-ray behaviour in which accretion is directly fed from the dense circumstellar wind of the primary. X-ray outbursts are triggered by discrete mass ejection events from the primary. This possibility had already been discussed by Giovannelli & Sabau-Graziati (1992) in the context of "noisy" or "anomalous" outbursts, while during "normal" outbursts, i.e. those that are symmetric around the periastron, optical and X-ray correlations do exist. However Clark et al. (1999) do not exclude the presence of an accretion disc around the neutron star after the X-ray QPO's observed during the outburst of February 1994. It is important in this context to determine whether the accretion disc is a transient or a permanent feature of the system.

A detailed study of the geometry of the accretion flow in the system HDE 245770/A0535+26 shows the need for the formation of an accretion disc around the neutron star to yield any kind of flares at periastron passage (Ikhsanov et al. 2001). They suggest that the missing outburst phenomenon can be attributed to a property of the spherically symmetrical accretion onto the interchange-stable magnetosphere of the neutron star. Larionov et al. (2001), analyzing a large set of optical photometric data, found a modulation period of 103 days, which they attribute to the beating between the orbital period of the system and a precession period of ≈1400 days, which can be assigned either to an accretion disc around the neutron star, or a warped excretion disc around the Be star.

Romero et al. (2001) have suggested the possibility that HDE 245770/A0535+26 system may be identified with the otherwise unidentified variable EGRET gamma ray source 3EG J0542+2610, assuming the existence of a temporary accretion disc around the neutron star, i.e. during the February 1994 X-ray outburst. The gamma-ray emission seems to have been quenched exactly when the accretion disc was well-formed and rotating maximally.

Ziółkowski (2002) put forward the scenario of temporary accretion discs around neutron stars and included a discussion of the possible excretion disc around Be stars in Be/X-ray binary systems. The presence of the accretion disc around the neutron star can be directly inferred from the observed spin-ups of neutron stars during "noisy" or "casual" outbursts. The time scales of the spin-ups and their correlation with the X-ray luminosities indicate that the accreted angular momentum corresponds to the orbital angular momentum at the inner edge of the disc.

The best-studied case is the major February 1994 casual outburst of A0535+26 (Finger et al. 1996; Bildstein et al. 1997), during which a spin-up on a time scale of ~25 yr was seen at the peak of the outburst. The same outburst provided independent evidence of an accretion disc, based on the interpretation of the QPO detected during that event. Both the frequency of the QPO, interpreted as the Keplerian frequency at the inner edge of the disc, and its correlation with the spin-up rate and with the X-ray luminosity fully support the model based on the accretion disc. The accretion discs must also be present during most of the "normal" outbursts. The system A0535+26 demonstrated spin-ups on time scales of ~100 yr during many normal outbursts (Ziółkowski 1985; Giovannelli & Sabau-Graziati 1992). Similar spin-ups were observed during all normal outbursts of 2S 1845-024 (Finger et al. 1999) or at least during some normal outbursts of many other X-ray/Be systems (e.g. 4U 0115+63, GS 0834-430, 2S 1417-62, EXO 2030+375, 4U 1145-61 – Bildstein et al. 1997). The neutron stars of these systems are in an accretor phase ($P > P_{\mathrm{eq}}$); however, neutron stars in many X-ray/Be systems experience spin-downs during outbursts. They enter a propeller phase ($P < P_{\mathrm{eq}}$) (Ziółkowski 2002). For the system A0535+26, the time scales of these spin-downs are of ≈1000 yr (Ziółkowski 1985; Giovannelli & Sabau-Graziati 1992). In principle the accretion disc may survive during the propeller phase. However, such accretion discs seem not to be persistent. Clark et al. (1999) vainly searched for the optical-infrared contribution from the accretion disc in A0535+26 during the quiescent phase (propeller state) after the February 1994 outburst. They found no significant contribution, which implied that the accretion disc was either absent or, if present, as an extremely weak remnant.

5. Conclusions

With the measurements presented in this article and for the first time with optical observations, we believe that we have demonstrated the presence of a temporary accretion disc around the 104 s period X-ray pulsar A0535+26, the companion of the O9.7IIIe star, "Flavia's Star". We have detected the presence of the disc via the temporary doubling of the HeI lines in emission. How long this accretion disc remains is a subject for further investigation. However we can give a tentative, very rough upper limit to its duration. We detected the presence of the doubling of the HeI emission lines on Oct. 9, 10, and 12, 1999, but it was absent on Nov. 24, 1999 (see Fig. 3). This implies that the disc did not survive for a time interval as long as $T_{\rm AD-presence} = 43$ days, i.e. an upper limit of 0.38 in orbital phase. We are not able to supply any information about the onset of the formation of this temporary disc. Observations of this type might increase this duration period by a factor of up to 2.

We consider that the question of the presence of a temporary accretion disc around the X-ray pulsar A0535+26/HDE 245770 is of considerable importance, and it merits considerable effort to resolve it. We suggest further monitoring of A0535+26/HDE 245770 both in X-rays and in the optical range, with enhanced spectral resolution. This would be aimed at verifying if indeed the accretion disc forms around the neutron star and if it correlates with its periastron passage. We have to admit, though, that any correlation will be complicated by other factors, notably the intrinsic behaviour of the Be star and the possible presence of an excretion disc around it, which may be fed by ejection due to a steady wind, more sporadic puffs, and/or from a shell. This makes it crucial to carry out long-term monitoring of the binary system over several entire orbital periods, in both the optical and X-ray ranges, to detect X-ray flaring activity, its variation with different X-ray quiescent phases, and the properties of the correlated optical emission.

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