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High-Dispersion Spectroscopy of a Be/X-Ray Binary A0535+26/V725 Tau

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Abstract. Classical Be stars (Be stars) are main sequence or non-supergiant B-type stars which have shown Balmer lines in emission at least once. Rapid rotation, which is characteristic of Be stars, is believed to play an important role in forming a circumstellar envelope (called Be-disc). How the disc is formed and disappeared, however, is still disputable. We carried out 'continuous' high-dispersion spectroscopic observations of a Be/X-Ray binary A0535+262/V725 Tau at OAO with the 188 cm telescope and HIDES, aiming at spectral variabilities caused by the tidal interaction between the Be disc and the neutron star which depends on the orbital phase. In 2005, we observed from 24th November to 3rd December (corresponding to the orbital phase 0.68 − 0.79), detecting no variability in the emission line profile of the Be disc near apastron. Our observations were also performed from 6th to 14th November 2007 (corresponding to the orbital phase 0.09 - 0.16) and 2nd and 31st January 2008 (0.50 and 0.86, respectively) at OAO, and in December 2007 at GAO. Observed line profiles of H-alpha only slightly changed in the autumn 2007, which implies that Be disc did not vary even after the periastron. The four-year spectroscopic observations give a suggestion that Be disc has an axi-asymmetric structure.

1. Introduction

1.1. Be stars, Be/X-Ray Binaries

Classical Be stars (hereafter, Be stars) are main-sequence or non-supergiant B-type stars which have shown Balmer lines in emission even once. The most striking feature of Be stars is their high rotation speed (approximately a few of hundreds km/s); they rotate at near critical speed so that the surface gravity balances with their centrifugal force around the equator. The mass ejected from the photosphere forms an Keplarian disc, called Be disc. The Be stars exhibit complicated line profiles containing an absorption component from the photosphere and an emission component from the disc. Recently, Porter & Rivinius (2003) reviewed the Be stars: mainly their properties, variability, and probable mechanisms of the disc formation. The mechanism of the Be-disc formation is still disputable. For instance, Bjorkman & Cassinelli (1993), Cassinelli et al. (2002) and Okazaki (2001) discussed the mechanism of the disc formation, but these suggestions are not conclusive. The common understanding, however, is that the key for the Be-disc formation is high rotation speed of the Be stars. (For further discussion, see Porter & Rivinius (2003) and references therein.)

The emission line profiles, reflecting the Be disc, show many kinds of variability on the timescale from days to several decades: disappearance and regeneration, V/R ratio and line profile variability (LPV).

Be/X-Ray binaries are the systems which consist of a Be star and a compact object (mostly a neutron star, NS) and account for two thirds of high-mass X-Ray binaries (HMXRBs). The system has two discs; a Be disc and an accretion disc around the NS. Generally, the eccentricity of the Be/X-Ray binary is not small ($\gtrsim 0.3$), which implies that the interaction of two stars and the mass accretion from the Be disc into the NS depends on the orbital phase (Okazaki & Negueruela 2001). Therefore, most of the Be/X-Ray binaries are transient; X-Ray outbursts occur in the binary system. The X-Ray outbursts are divided into two types with the luminousity: normal outbursts ($10^{36} - 10^{37}$ erg/s at $1 - 20$ keV) and giant outbursts ($> 10^{37}$ erg/s at $1 - 20$ keV). The normal outbursts (type I outbursts), which last several days, are known to occur around periastron passage of the NS.

Okazaki & Negueruela (2001) presented the simulation of mass transfer in the several Be/X-ray binary systems. They concluded that the normal outbursts occur in the systems with an intermediate eccentricity where the interaction and the mass transfer from the Be disc to the NS are highest near periastron and weakest after apastron.

The giant outbursts (type II outbursts), lasting several ten days, occur independent of the orbital phase, and therefore the detailed mechanism of giant outbursts is less understood.

1.2. A0535+26/V725 Tau

A0535+26/V725 Tau (hereafter, A0535), which discovered by Aliel 5 satellite during a giant outburst (Rosenberg et al. 1975; Coe et al. 1975), is one of the most famous Be/X-Ray binaries. A0535 consists of an X-Ray pulsar of 103s (Caballero et al. 2007) and an O9.7IIIe star (Giangrande et al. 1980). The recurrence time of the normal outbursts and spin-down rate of the pulsar gives orbital elements: the orbital period of 111 days (Motch et al. 1991) and the eccentricity of 0.47 (Finger et al. 1996) and so on. Neither optical photometry nor spectroscopy, however, has yielded the orbital period consistent with X-Ray data (Wang & Gies 1998; Larionov et al. 2001), because the optical data shows very complex variability due to the variability of the Be star. Haigh et al. (2004) ,Grundstrom et al. (2007) and many authors have given spectroscopic long-term observations of A0535. However, since these observations have not been densely carried out, we can not discuss short-term (less than a few weeks) variability.

The mass transfer from the Be disc to the NS and the tidal interaction between them, depends on the orbital phase. Especially, our SPH (Smoothed Particle Hydrodynamics) simulation gives a suggestion that the Be disc in the A0535 system is expected to vary in the orbital phase 0.1 – 0.2, after periastron passage (the orbital phase 0.0).

In this paper, we show both short-term ($\sim$ weeks) and long-term ($\gtrsim$ years) variability of A0535 resulting from an optical high-dispersion spectroscopic monitoring from 2005 to 2008.

2. Observation

We carried out the optical spectroscopic monitoring from Nov. 2005 to Jan. 2008, mainly at Okayama Astrophysical Observatory (OAO) with a 188 cm telescope equipped with HIDES (High Dispersion Echelle Spectrograph). Observations were also performed at Gunma Astronomical Observatory (GAO) with a 1.5 m telescope equipped with GAOES (Gunma Astronomical Observatory Echelle Spectrograph). The observation log is listed in table 1. The typical

Table 1. Observations log. Orbital phase of each day was listed in column 2. The periastron corresponds to the phase 0.0.

Day	Orbital Phase	Telescope
2005 Nov. 24	0.688	OAO
2005 Nov. 25	0.697	OAO
2005 Nov. 27	0.715	OAO
2005 Nov. 29	0.733	OAO
2005 Nov. 30	0.742	OAO
2005 Dec. 01	0.751	OAO
2005 Dec. 03	0.769	OAO
2006 Dec. 18	0.183	OAO
2007 Nov. 07	0.099	OAO
2007 Nov. 08	0.107	OAO
2007 Nov. 09	0.116	OAO
2007 Nov. 10	0.125	OAO
2007 Nov. 11	0.134	OAO
2007 Nov. 13	0.152	OAO
2007 Nov. 14	0.161	OAO
2007 Dec. 16	0.445	GAO
2007 Dec. 19	0.472	GAO
2007 Dec. 20	0.481	GAO
2007 Dec. 26	0.535	GAO
2008 Jan. 02	0.598	OAO
2008 Jan. 31	0.858	OAO

resolution and S/N of our OAO/HIDES data are ∼ 60000 and ∼ 120 in Hα line, respectively. These of our GAO/GAOES data are ∼ 30000 and ∼ 120, respectively.

The Observations in 2005 (in the orbital phase 0.7 – 0.8) were carried out to check the lack of variability of the Be disc after apastron passage. In Nov 2007 (the phase 0.1 – 0.2), we aimed the variability after periastron, when the Balmer line is expected to change, reflecting the tidal interaction between the Be disc and the NS.

3. Results and Discussion

Figure 1 shows all Hα line profiles obtained from 2005 to 2008. The date and corresponding orbital phase are written above each profile. The profiles observed between 24th Nov. and 3rd Dec. in 2005 (in the left frame of figure 1), which were performed after apastron (corresponding to the orbital phase 0.7 – 0.8), showed no variability; this implies that Be disc did not vary at that time. One year later, in Dec. 2006, the Hα emission line had changed in terms of the V/R ratio and the EW (from −6.0 Åto −8.4 Å). Besides, the profile was very different from in Oct. 2006 in Grundstrom et al. (2007); the V/R ratio changed from < 1 to > 1. In Nov. 2007, corresponding to the orbital phase 0.1 – 0.2, when the Balmer emission line is expected to show variability reflecting the interaction between the Be disc and the NS, there was no variability detected in Hα line profiles. The violet component of Hα line, however, clearly weakened between the phase 0.2 and 0.4; the Hα line became red-enhanced single-peaked line. Then, in the end of Jan. 2008, the Hα line profile changed to single-peaked profile.

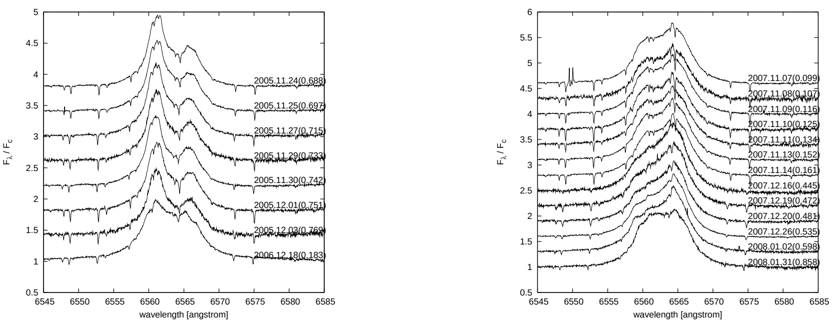

Figure 1. All the Hα line profile of A0535 obtained from 2005 to 2006 (left) and from 2007 to 2008 (right). The date and corresponding orbital phase are written above each profile. Neither after apastron nor periastron, the variability was clearly detected in the Hα emission line. The blue component of the Hα line weakened between Nov. and Dec. 2007. The profile turned to single-peaked by the end of Jan. 2008.

3.1. Short-Term Variability

The observed Hα emission line profiles showed the variability on the time scale from weeks to years.

No variability was detected after apastron in 2005. This is not inconsistent with the suggestion that the tidal interaction between the Be disc and the NS is weakest after apastron passage (Okazaki & Negueruela 2001). However, even after the periastron (the orbital phase 0.1 – 0.2) no variability was detected in the Hα line. This implies that the Be disc showed no change due to the tidal interaction with the NS; it is inconsistent with our simulation. Therefore, it is considered that the tidal interaction in the A0535 system is too week to be observed or that the phase when the interaction effects strongest is different from simulated one. The possibility of the difference of the phase may be caused by the fact that the Be disc plane is not the same as the orbital plane of the NS. The inclination of the orbit of the NS was measured to be $\sim 26°$ (Finger et al. 1996), but the inclination of the Be disc plane has not been estimated because the optical data is too complex. Therefore, we need further observations

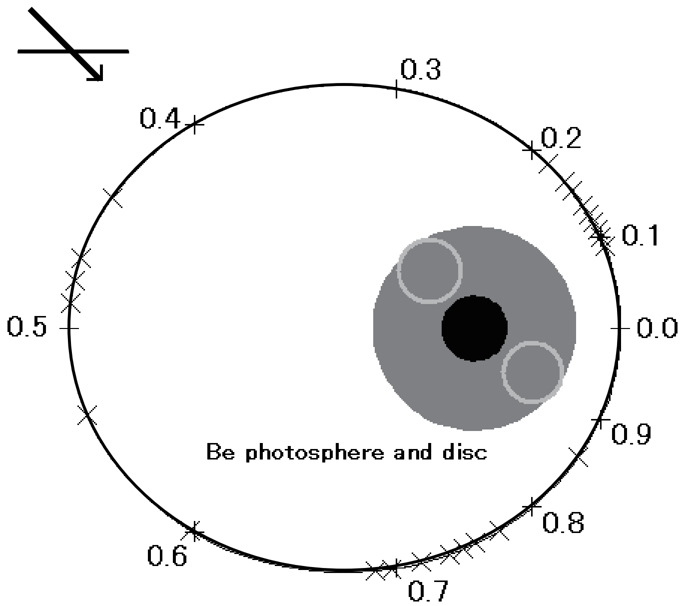

Figure 2. The structure of the Be disc of A0535 suggested by the Hα line profiles from 2005 to 2008. The arrow indicates the line of sight. The black and dark gray circles are the photosphere and the Be disc, respectively, and the elliptical circle is the orbit of the NS (the cross mark indicates the orbital phase when our observation was carried out). The light gray circle in the Be disc is the possible higher temperature or warped region because the centre of the Hα emission line was strong in the orbital phase of 0.1 – 0.2 and ~ 0.8.

to determine the angle of the two plane. The spectropolarimetric observations may gives an evidence.

3.2. Long-Term Variability

In some phase (0.1 – 0.2 and around 0.8), the centre component of the Hα line profile is strong so that the line profile implies that the Be disc is not the Keplarian disc. One the other hand, in the phase 0.4 – 0.8, the Hα line, whose centre component was normally weak, implies the Be disc was the Keplarian one. This suggest that the Be disc is not axi-symmetric; the Be disc has some region with higher temperature or warped.

Figure 2 shows suggested structure of the Be disc. The arrow indicates the line of sight. Black and dark gray circle are the photosphere and the Be disc, respectively. The elliptical circle around the Be star is the orbit of NS, and the cross mark indicates the orbital phase when our observation was carried out. The light gray circle in the Be disc is the possible higher temperature or warped region because the center of the Hα emission line was strong in the orbital phase 0.1 – 0.2 (and around 0.8).

4. Summary

We carried out a high-dispersion spectroscopic monitoring of a Be/X-Ray binary A0535 from Nov. 2005 – Jan. 2008. The results are summarised as these:

1. There was no variability after the apastron passage and this is not inconsistent with (Okazaki 2001).
2. Although the Hα line was expected to vary, we could not observed the variability in the emission line after the periastron.
3. No variability after the periastron is due to the weakness of the tidal interaction or the difference between the orbital plane and the Be disc.
4. There was some phase when the centre of Hα line was strong: this implies that it is possible that the Be disc has a higher-temperature region or warped structure.

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