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DISCRETE MASS EJECTIONS FROM THE Be/X-RAY BINARY A0535+26/HD 245770

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ABSTRACT

We present long-term optical spectroscopic observations on the Be/X-ray binary A0535+26 from 1992 to 2010. Combined with the public *V*-band photometric data, we find that each giant X-ray outburst occurred in a fading phase of the optical brightness. The anti-correlation between the optical brightness and the Hα intensity during our 2009 observations indicates a mass ejection event had taken place before the 2009 giant X-ray outburst, which might cause the formation of a low-density region in the inner part of the disk. The similar anti-correlation observed around 1996 September indicates the occurrence of the mass ejection, which might trigger the subsequent disk loss event in A0535+26.

Key words: stars: emission-line, Be – stars: individual (A0535+26) – stars: neutron – X-rays: binaries

1. INTRODUCTION

Be/X-ray binaries represent a major subclass of high-mass X-ray binaries in our Galaxy (Liu et al. 2006). A neutron star moves in a wide and eccentric orbit around the Be star, which is a non-supergiant rapidly rotating B-type star and shows Balmer emission lines at least once in its life (Porter & Rivinius 2003). There are two different disks in a Be/X-ray binary: a circumstellar disk around the Be star and an accretion disk around the neutron star (see Reig 2011 and references therein).

A0535+26 was found by *Ariel V* in 1975 during a giant X-ray outburst (Rosenberg et al. 1975). Its optical counterpart was identified as the Be star HD 245770 with a classification of O9.7 IIIe (Giovannelli & Graziati 1992). A neutron star with a 103 s spin period (Caballero et al. 2007) moves around the primary star in an eccentric orbit ($e = 0.47 \pm 0.02$; Finger et al. 1994). A 111.1 day orbital period was found from the periodic Type I X-ray outbursts around the periastron passage of the neutron star. Since the first giant outburst in 1975, another six giant X-ray outbursts have been observed in 1975 April, 1980 October (Nagase et al. 1982), 1983 June (Sembay et al. 1990), 1989 March (Makino et al. 1989), 1994 February (Finger et al. 1994), 2005 May (Tueller et al. 2005; Coe et al. 2006; Caballero et al. 2008), and 2009 December (Wilson-Hodge et al. 2009; Reynolds & Miller 2010).

The long-term variability of optical and IR photometry was discussed by Hao et al. (1996), Clark et al. (1998, 1999), Haigh et al. (1999, 2004), and Lyuty & Zaitseva (2000). The variability of the Hα emission line is related to physical changes in the circumstellar disk around the Be star. A disk loss event took place in the system in 1998 and the Hα line changed from emission to absorption (Haigh et al. 2004; Grundstrom et al. 2007). Recent short-term and long-term optical spectral variabilities were reported by Moritani et al. (2010).

In this paper, we present our optical spectroscopic and photometric observations on A0535+26. Combined with the public data on the *V*-band magnitude and the Hα equivalent widths (EWs), we discuss the optical variability of the system and unveil the nature of X-ray outbursts.

2. OBSERVATIONS

We obtained optical spectra of HD 245770 with the 2.16 m telescope at Xinglong Station of National Astronomical Observatories, China (NAOC) from 1992 to 2010. The optical spectroscopy with an intermediate resolution of 1.22 Å pixel^{-1} was made with a CCD grating spectrograph at the Cassegrain focus of the telescope. We took both blue and red spectra covering the wavelength ranges 4300–5500 and 5500–6700 Å, respectively, at different times. All spectra were reduced with the IRAF[3] package. The data were bias-subtracted and flat-field corrected, and the cosmic rays were removed. Helium–argon spectra were taken in order to obtain the pixel–wavelength relation. To improve this relation, we also used the diffuse interstellar bands 6614 and 6379 Å observed in the spectra. The short-term and long-term variability of the emission line profile will be discussed in another paper (Q. Z. Liu et al., in preparation). In this paper, we concentrate only on the long-term evolution of the intensity of the Hα line in the spectra of A0535+26. All the spectra have been normalized to the neighboring continuum. The EW of the Hα line has been measured by selecting a continuum point on each side of the line and integrating the flux relative to the straight line between the two points using the procedures available in IRAF. The measurements were repeated five times for each spectrum and the error estimated from the distribution of values obtained. The EW(Hα) typical error is within 3%. This error arises due to the subjective selection of the continuum.

On 2010 October 13, we performed systematic Johnson–Cousin *UBVRI* photometric observations on A0535+26 with the 80 cm Tsinghua–NAOC Telescope (TNT) at Xinglong Station of NAOC. TNT is an equatorially mounted Cassegrain system with a focal length of $f/10$, made by AstroOptik, funded by Tsinghua University in 2002 and jointly operated with NAOC. The telescope is equipped with the Princeton Instrument 1340×1300 thin back-illuminated CCD. The photometric data reduction was performed using standard routines and aperture photometry packages in IRAF, including bias subtraction and flat-field correction. In order to calibrate the instrumental magnitudes of A0535+26, we also observed a sample of Landolt standards in *UBVRI* bands. The average *UBVRI* magnitudes of A0535+26 are 8.6 ± 0.03, 9.6 ± 0.03, 9.2 ± 0.02, 8.9 ± 0.02, and 8.5 ± 0.02, respectively.

[3] IRAF is distributed by NOAO, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperation with the National Science Foundation.

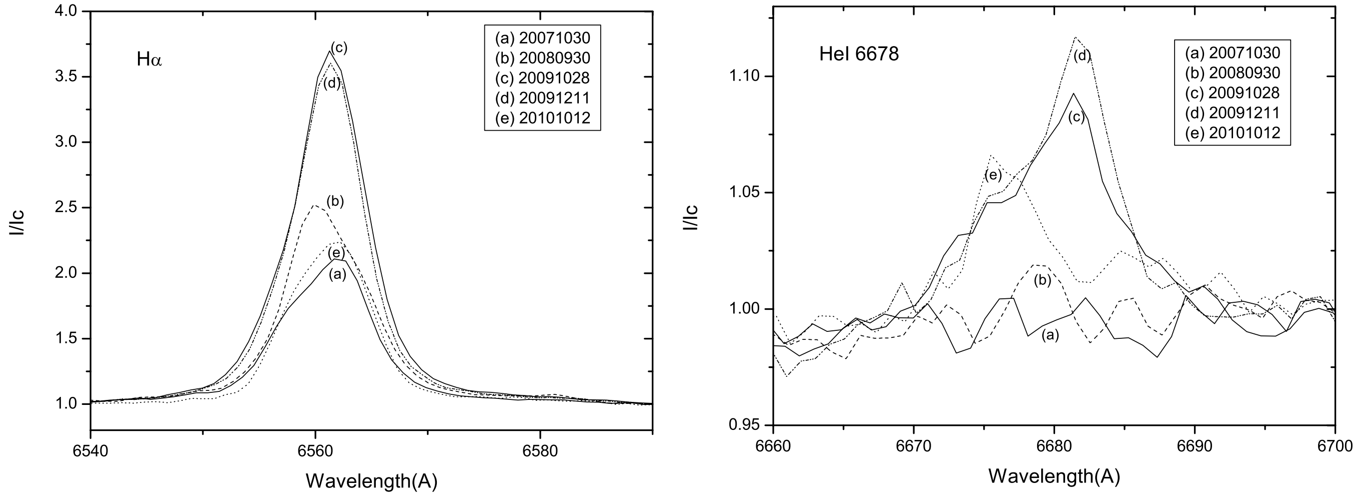

Figure 1. Typical line profiles during our 2007–2010 observations in Hα (left) and He I λ6678 (right) regions, respectively. The insets are the observational dates for each spectrum in the format of YYYYMMDD.

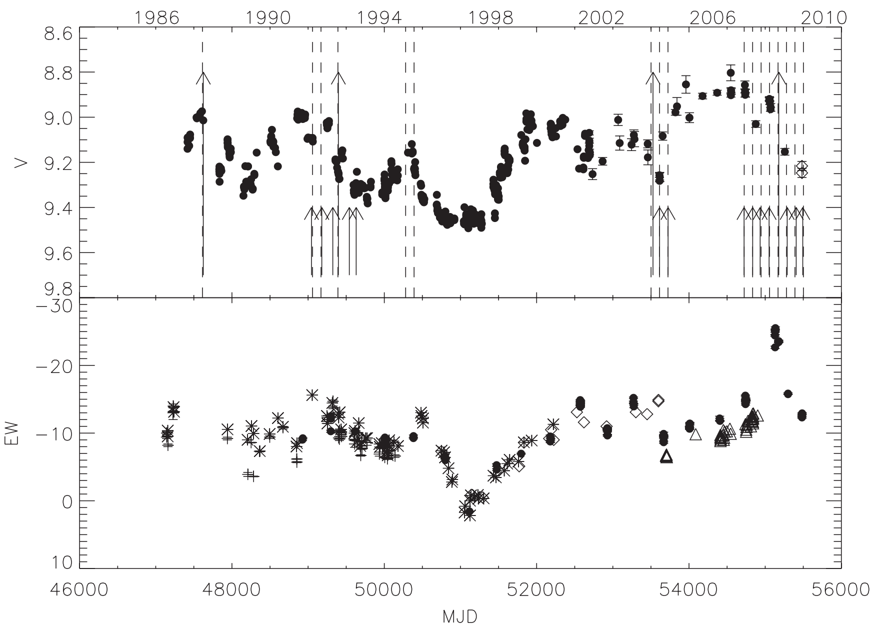

Figure 2. Optical observations of A0535+26. The top panel shows the V-band magnitudes from the literature and our observations (diamonds); the bottom panel shows the EWs of the Hα emission line from the literature and our observations (solid circles). The long and the short arrows in the top panel correspond to the median times for the giant X-ray outbursts and the normal Type I X-ray outbursts, respectively. The dashed lines indicate the times of the neutron star periastron passages.

3. ANALYSIS

3.1. Line Variability During Our 2007–2010 Observations

In order to study the optical line variability before, during, and after the 2009 giant X-ray outburst, we plot the representative spectra of Hα and He I λ6678 during our 2007–2010 observations in Figure 1. The Hα emission line shows an asymmetric single-peaked profile during our 2007 observations. The peak intensity of the Hα became stronger during the 2008 observations, which were made just after a small X-ray outburst (see Figure 2). Our 2009 October observations were performed just before the 2009 giant X-ray outburst of A0535+26 and the Hα emission showed the strongest intensity of the last 20 years. The Hα profiles on 2009 December 11 (MJD 55176), which were observed during the rising phase of the 2009 giant X-ray outburst, showed a subtle change relative to their structure before the outburst. Moreover, the wings of the Hα lines in 2009 also became much broader than those in 2007 and 2008. About one year later, the Hα emission line returned to its normal level, but its peak intensity was still stronger than that in 2007 while its wings were a bit narrower.

As shown in Figure 1, the He I λ6678 line nearly lost its emission feature during our 2007 observations and showed a weak double-peaked profile with $R/V > 1$ during the 2008 observations. Like the Hα line, He I λ6678 showed the largest intensity during our 2009 October observations which were obtained before the 2009 giant X-ray outburst. The difference is that the He I λ6678 line became stronger during our 2009 December 11 observations and a double-peaked profile was still evident in 2010.

3.2. Long-term Optical Variability in Different X-Ray States

In this work we also make use of some public V-band photometric data (Lyuty & Zaitseva 2000; Zaitseva 2005; also the *INTEGRAL*/Optical Monitoring Camera (OMC) V-band

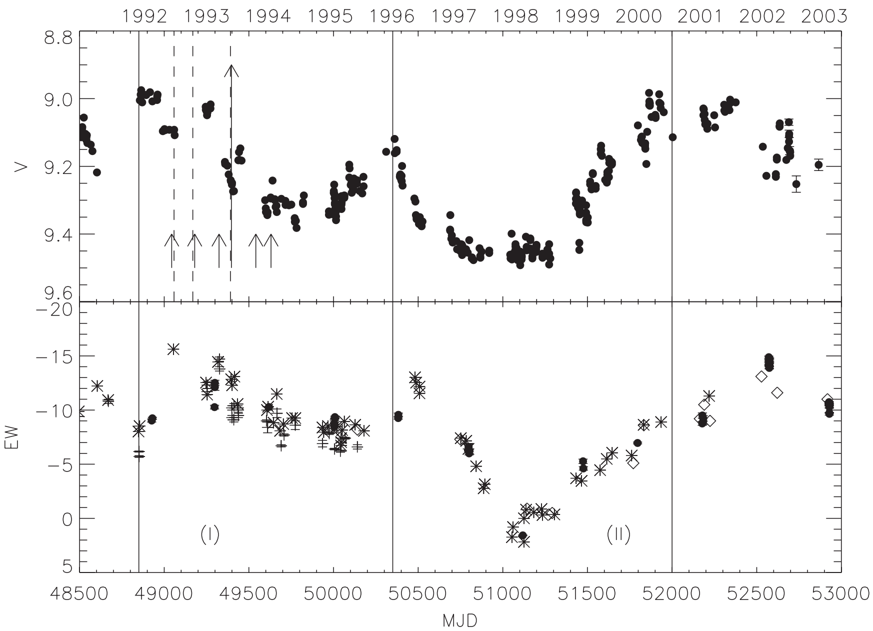

Figure 3. Zoomed Figure 2 in Cycle I and Cycle II regions.

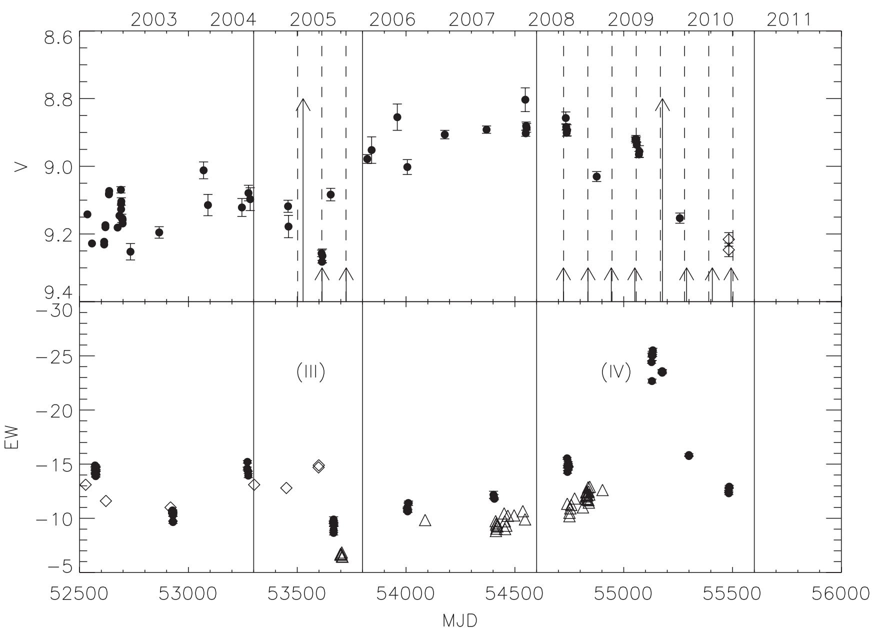

Figure 4. Zoomed Figure 2 in Cycle III and Cycle IV regions.

photometric data, rebinned with a time of 2 days, from the OMC Archive at LAEFF[4]) and the Hα EW data (Clark et al. 1998; Haigh et al. 2004; Coe et al. 2006; Moritani et al. 2010). Our optical photometric and spectroscopic results and all these public data are plotted in Figure 2. The long and short arrows in the top panel of Figure 2 represent the median times of the giant and normal X-ray outbursts in A0535+26, respectively. The times for periastron are also plotted with vertical dashed lines in Figure 2, at the ephemeris of MJD 53613.0+111.1E (Finger et al. 1996). In order to better study the relationship between the optical brightness, Hα emissivity, and X-ray activity, we divide Figure 2 into Figures 3 and 4. Here we focus on the optical variability during the X-ray outbursts and the phase of the disk loss and renewal around the Oe star; this can be divided into four activity cycles.

1. *Cycle I* (MJD 48850−50350). A series of X-ray outbursts were observed by BATSE before and after the giant X-ray outburst in 1994 February (Finger et al. 1996). Haigh et al. (2004) have discussed the multi-wavelength variability of A0535+26 in this cycle. As shown in Figure 3, the first normal X-ray outburst during this cycle took place in an optical brightness decline phase. The *V*-band apparent magnitude of A0535+26 began to increase around MJD 48850 and reached a magnitude of $M_V \sim 9.1^m$ around MJD 49050. However, the EWs of the Hα emission line showed an obvious increase in this time interval. After that, the brightness of the system kept increasing and reached a maximum around

[4] http://sdc.laeff.inta.es/omc/index.jsp

MJD 49250. The second X-ray outburst was observed during this optical brightening process. The following normal and giant X-ray outbursts were detected in an abrupt decline phase of the optical emission. Another two normal X-ray outbursts also occurred in such a phase. The strength of Hα kept declining after the giant X-ray outburst. After MJD $\sim$ 49,800, the optical brightness of A0535+26 began to increase and reached a magnitude of $M_V \sim 9.1^m$ around MJD 50350. In the phase of the optical brightening, the Hα EWs did not change considerably.

2. *Cycle II* (MJD 50350−52560). During this cycle, A0535+26 underwent the events of disk loss and renewal. After MJD 50350, the *V*-band magnitudes increased until MJD 50550, while the strength of the Hα line became stronger during this time. It is hard to imagine what had happened in the system between MJD 50550 and MJD 50650 due to the bad coverage of the *V*-band data. But we could deduce from Figure 3 that the optical brightness of A0535+26 was still declining after MJD 50650, and this decline phase is different from the former one. After MJD 50550, the strength of Hα decreased continually. When the apparent magnitude of A0535+26 reached a maximum around MJD 50800, the Hα intensity still kept declining and reached a minimum around MJD 51050. Then the optical brightness and the intensity of the Hα line kept increasing and a new circumstellar disk was reforming around the Oe star. When the *V*-band brightness reached a stable state around MJD 52000, the intensity of the Hα emission line was still in an increasing phase and it reached a maximum around MJD 50350.
3. *Cycle III* (MJD 53300−53800). During this cycle, a giant X-ray outburst occurred in 2005 May/June after 10 years of inactivity of the Be/X-ray binary A0535+26. Two subsequent normal X-ray outbursts were also observed in the system. As shown in Figure 4, the 2005 giant X-ray outburst took place during the increasing phase of the *INTEGRAL*/OMC *V*-band magnitudes and the first normal X-ray outburst occurred at the time when its *V*-band brightness showed a minimum around MJD 53615. The next normal X-ray outburst was observed in the following optical decline phase. In the increasing phase of the *V*-band magnitude, the strength of the Hα emission line became slightly stronger. It is interesting that the strength of the Hα line dropped abruptly when the optical brightness began to increase.
4. *Cycle IV* (MJD 54600−55600). Eight continuous normal and one giant X-ray outburst were observed during this cycle. Though the time resolution of the *V*-band observations is not very good, one can still see from Figure 4 that the first four normal X-ray outbursts occurred during the fading and brightening phases of the optical brightness between MJD 54700 and MJD 55100, which is similar to the first two normal X-ray outbursts occurring in Cycle I (see Figure 3). The 2009 December giant X-ray outburst and subsequent three normal X-ray outbursts were observed during another fading phase of the optical brightness. According to our 2010 optical photometric observations, the optical brightness of A0535+26 was still at a low level. The *V*-band magnitudes and EWs of the Hα emission line were in a stable level for a long time before Cycle IV. The strength of Hα began to increase when the optical brightness started to fade around MJD 54600, and it reached an unprecedented maximum, with an EW of $\sim$–25 Å, during our 2009 October observations, which were obtained just before the 2009 giant X-ray outbursts. Our observations on 2009 December 11 (MJD 55176, during the rising phase of the giant X-ray outburst) indicate that the strength of Hα was at a slightly lower level than that in our 2009 October observations (also see Figure 1). Our 2010 observational results indicate that the Hα intensity had decreased to the level before Cycle IV.

4. DISCUSSION

Clark et al. (1999) found that the X-ray outbursts in the Be/X-ray binary A0535+26 usually occurred after a period in which the optical light curve had been seen to fade. Our analysis in Section 3.2 also indicates that the recent 2005 and 2009 giant X-ray outbursts were also observed during a fading phase of the optical brightness (see Figure 2). It is interesting that the intensity of the Hα line in the spectra of A0535+26 showed an obvious increase during the fading of the optical brightness in Cycle IV of Figure 4. A similar observational phenomenon was also observed in Cycle I of Figure 3. To explain the anti-correlation between the optical brightness and the Hα intensity in A0535+26, we must first know the physical origin of the optical continuum and Hα emission in the system.

The optically thick Hα emission line in a Be star is generally believed to be formed in the entire circumstellar disk (Slettebak et al. 1992), while only the innermost part of the disk contributes significantly to the continuum flux. Due to the higher ionization potential energy, the formation region of the He I λ6678 line should be smaller than the nearby continuum region (Stee et al. 1998). The strength of the Hα line became stronger during our 2009 observations, while its *V*-band brightness kept fading during that period. The increase of the Hα emission might be caused by the decrease of the optical continuum around the Hα region. In fact, our optical observations in 2010 indicate that even though the optical brightness was still in a fading phase, the strength of the Hα emission line had declined to its level in our 2007 observations. Therefore, we suggest that the obvious increase of the Hα intensity during our 2009 observations was not only caused by the decrease of the optical continuum in A0535+26. The correlation between the *V* magnitude and the $(B - V)$ color in A0535+26 (Clark et al. 1999) indicates that the variability in the *UBV* photometric observations was connected with the changes in the emission from the circumstellar disk around the Oe star (Janot-Pacheco et al. 1987). Therefore, the only source for the variability of the *V*-band brightness is the circumstellar disk around HD 245770. The decrease of the *V*-band brightness during Cycle IV might indicate that great changes had taken place in the inner region of the disk. The strong Hα emission during our 2009 observations might be due to the formation of a larger circumstellar disk before the giant outburst in 2009. Figure 1 shows that the He I λ6678 became much stronger during our 2009 observations and it still had a strong emission during our 2010 observations, which may be attributed to a denser inner part of the disk formed before the 2009 giant X-ray outburst. It seems to be contradictory that the optical brightness became faint when a dense inner disk was formed, if we assume the optical excess comes from the disk around the Oe star.

A unified model should be assumed to explain all the observed features in A0535+26. Observational results (Rivinius et al. 2001) and theoretical calculations (Meilland et al. 2006) suggest that after an outburst in a Be star a low-density region seems to develop above the star. The nature of the outburst is beyond the scope of this paper. Rivinius et al. (2001) and Meilland et al. (2006) suggested that the outburst might be connected with the increased mass loss or mass ejection from the Be star. Some weeks to months after the outburst, the stellar radiation pressure gradually excavates the inner part of the disk and a low-density region could develop around the Be star and slowly grow outward (Rivinius et al. 2001). With the evacuation of the inner disk, the optical continuum emission decreases and an increase in UBV magnitudes will be observed. As shown in Figure 4, the V-band magnitude began to increase at the beginning of Cycle IV. The decrease of the V-band continuum emission indicates that a mass ejection event from the Be star had taken place before MJD 54600. After the mass ejection, a low-density region was forming around the Be star. The He I λ6678 appeared after the mass ejection and became stronger when the optical continuum emission was decaying, which indicated that a larger quantity of material close to the stellar surface should be presented when a low-density region was developing in the inner part of the disk. The new disk material might be ejected from the star by the subsequent mass ejection or re-acreted into the inner region after the supply of material from the star to the disk has been turned off (Clark et al. 2001). Moreover, a lot of material would be transferred into the disk after the mass ejection event and the outer part of the disk would move outward. A more extended circumstellar disk should correspond to a stronger Hα emission. This may explain the detected increasing behavior of Hα emission presented in Figure 4.

The V-band brightness did not show a continuous decline during Cycle IV. The optical brightness of A0535+26 began to decrease around MJD 54600 and showed an increase during the following four normal X-ray outbursts. The increase in the optical emission indicated that a subsequent outburst had taken place and the cavity region was replenished by the ejected material. With the outward motion of the ejected material, a secondary inner circumstellar disk would be formed around the star and a ring-like structure was developing in the disk. When the disk expanded to a certain extent, the neutron star would come inside the circumstellar envelope of the Be star and accrete matter, becoming a transient source. This may account for the first four normal X-ray outbursts in Cycle IV. A considerable fraction of the angular momentum would be transferred onto the neutron star in the system, which may account for the simultaneous spin-up detected by *Fermi*/Gamma-ray Burst Monitor (GBM) (Camero-Arranz et al. 2011). It is interesting that a distinguished double-peaked profile was observed by *Swift*/Burst Alert Telescope (BAT) in the fourth X-ray outburst during Cycle IV (see Figure 5). The profile of the outburst might be connected with the accreting environment of the neutron star. There should be a low-density region in the circumstellar disk when the neutron star was approaching the periastron point around MJD 55057.3 (the vertical dashed line in Figure 5). This low-density region might be the low-density ring structure discussed above. Assuming the circumstellar disk of A0535+26 dissipated on a viscous timescale, we can estimate the viscosity parameter α (Shakura & Syunyaev 1973) using Equation (19) of Bjorkman & Carciofi (2005):

$$t_{\text{diffusion}} = (0.2\,\text{yr}/\alpha) * (r/R_*)^{0.5}, \quad (1)$$

where $t_{\text{diffusion}}$ is the diffusion time of the low-density region from the surface of the Oe star to the periastron point and r is the radial distance from the Oe star to the periastron point of the neutron star. We assume that the time for the formation

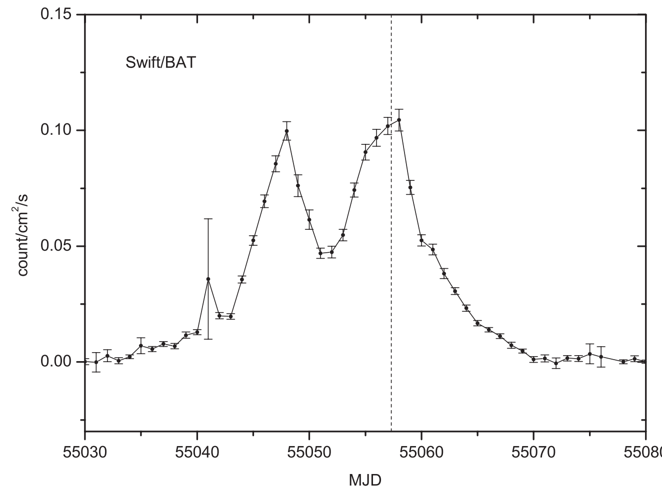

Figure 5. Double-peaked X-ray outburst of A0535+26 observed by *Swift*/BAT in the 15–50 keV energy band from MJD 55030 to MJD 55080. The vertical dashed line indicates the time for the periastron passage of the neutron star.

of the low-density region corresponds to the initial moment of the optical brightness decrease, ∼MJD 54600. Thus, $t_{\text{diffusion}}$ is about 457.3 days. Given that the mass M_* and the radius R_* of the Oe star HD 245770 are 14 $M_\odot$ and 15 $R_\odot$ (Giangrande et al. 1980), respectively, and the typical mass for a neutron star is 1.4 $M_\odot$, the value of r/R_* is approximately 8.6, for an orbital period of 111.1 days with an eccentricity of ∼0.47. Therefore, the viscosity parameter estimated by Equation (1) is $\alpha \sim 0.47$. This result indicates that the circumstellar disk around the Oe star in A0535+26 will be truncated at the 4:1 resonance radius (Okazaki & Negueruela 2001), which will allow enough mass accretion onto the neutron star at the periastron passage to cause the X-ray outburst in the system during Cycle IV.

Very strong Hα emission was observed during our 2009 observations, when the V-band brightness showed an obvious decrease, which indicated a strong mass ejection had taken place before our 2009 observations and a lot of material was replenished in the circumstellar disk. An extended and dense circumstellar disk caused the strong X-ray outburst during Cycle IV. After the 2009 strong X-ray outburst, the disk around the Oe star could also be truncated by the neutron star in A0535+26 and the strength of the Hα emission line showed a rapid decline. One year later, the emission of the Hα line had returned to its level in the quiescent state.

Figure 3 shows that the V-band light curve during Cycle I has the same variability as that during Cycle IV. The decrease of the optical brightness during the first stage of Cycle I might also be caused by the discrete mass ejection from the Oe star. The second abrupt decrease of the optical brightness indicated a lot of material was filled in the disk, which caused the 1994 giant X-ray outburst. The anti-correlation between the optical brightness and the strength of the Hα emission line was also observed during the first decrease of the V-band brightness. However, the Hα did not display a very strong emission during the subsequent abrupt decrease of the optical brightness. With the extension of the decretion disk, it will be truncated by the gravitational interaction of the neutron star (Okazaki & Negueruela 2001). The efficiency of the truncation depends strongly on the gap between the truncation radius and the inner Lagrangian point and the viscosity of the disk. When the neutron star passes the periastron point, the decretion disk will be truncated efficiently. We can see from Figure 4 that after the giant X-ray outbursts, the intensity of the Hα decreased rapidly, which meant that the outer part of the decretion disk had been truncated by the neutron star. Lines formed in the inner region of the decretion disk, such as He i λ6678, could not truncated by the neutron star even around the periastron. Figure 1 in Haigh et al. (2004) indicates that when the Hα intensity showed a gradual decrease after the 1994 giant X-ray outburst, the He i λ6678 still had a strong emission. Our observational results shown in Figure 1 also indicate that the He i λ6678 during our 2010 observations was still in strong emission even though the Hα had decreased to its 2007 level.

A0535+26 underwent disk loss and subsequent renewal events during Cycle II in Figure 3. The anti-correlation between the optical brightness and the Hα intensity was observed between MJD 50350 and MJD 50550. Due to bad coverage of the *V*-band magnitude and the Hα EWs in the following 100 days, we do not know when the optical brightness decreased to its minimum and the intensity of Hα reached its maximum. In Cycle II, both the optical and the Hα line emission kept fading after MJD 50670. It seems that the decay timescales of the optical brightness are different during the increasing and decreasing phases of the Hα intensity. They should have different physical origins. The optical fading between MJD 50350 and MJD 50550 might be caused by the mass ejection from the Oe star, and the subsequent fading of the optical brightness should be the indicator for the dilution of the decretion disk around the Oe star. The increase of the Hα intensity at the beginning of Cycle II means the ejected mass had been transferred into the decretion disk. After the mass ejection event, a low-density region would be formed around the Oe star. With the extension of this low-density region, the decretion disk will be a ring-like structure. If there was no mass ejection taking place in the system, the disk around the Oe star would be lost. Because the inner region of the disk makes a major contribution to the optical continuum emission while the Hα emission could be formed in the entire disk, the optical brightness of A0535+26 reached a stable faint state around MJD 50800 before the Hα line turned from emission into absorption around MJD 51100. The subsequent disk renewal phase may be caused by the discrete mass ejections from the Oe star. Due to the smaller emission region for the optical continuum, the intensity of Hα still kept increasing when the *V*-band brightness showed a stable level during Cycle II.

The 2005 giant X-ray outburst in Cycle III of Figure 4 was also observed during the fading phase of the optical brightness in A0535+26. The intensity of the Hα line did not show an obvious increase before the 2005 giant X-ray outburst. However, it shows an abrupt decrease after the giant X-ray outburst, which might be caused by the truncation of the neutron star. A pre-outburst structure was observed in the following normal X-ray outburst around MJD 53600 (Caballero et al. 2008), which might also be connected with the low-density region formed after the mass ejection.

5. CONCLUSIONS

The *V*-band optical light curve of A0535+26 indicates that each giant X-ray outburst occurred during a fading of the optical brightness in the system. The anti-correlation between the *V*-band magnitudes and the Hα EWs during our 2009 observations indicated a mass ejection event had taken place before the 2009 giant X-ray outburst, which caused the formation of a low-density region in the disk. According to the diffusion time of the low-density region from the Oe star to the periastron point, the viscosity parameter is estimated to be ∼0.47. The rapid decrease of the Hα emission after each giant X-ray outburst might be connected with the truncation of the outer disk by the neutron star in the system. The mass ejection that occurred around 1996 September might trigger the subsequent disk loss event.

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