High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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On the nature of the X-ray outbursts in Be/X-ray binaries

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Abstract. Be/X-ray binaries are a major subclass of high mass X-ray binaries. Two different X-ray outbursts are displayed in the X-ray light curves of such systems. It is generally believed that the X-ray outbursts are connected with the neutron star periastron passage of the circumstellar disk around the Be star. The optical emission of the Be star should be very important to understand the X-ray emission of the compact object. We have monitored several Be/X-ray binaries photometrically and spectroscopically in the optical band. The relationship between the optical emission and X-ray activity is described, which is very useful to explain the X-ray outbursts in Be/X-ray binaries.

Keywords. X-rays: binaries, stars: emission-line, Be, Be/X-ray binaries

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1. Introduction

Be/X-ray binaries are composed of a Be star and a compact object, usually a nutron star (Reig 2011). The Be star is a non-supergiant B star whose spectrum has, or had at some time, one or more Balmer lines in emisison (Rivinius *et al.* 2013). The emission lines are attributed to a circumstellar disk around Be star. Neutron star moves around the Be star in an eccentric orbit. When neutron star approaches its periastron point, the material in the circumstellar disk will be accreted onto the surface of the neutron star and a kind of Type I or Type II X-ray outburst may result.

The X-ray activities of the Be/X-ray binaries should be connected with the physical states and evolution of the circumstellar disk. Only the inner part of the circumstellar disk has the contribution to the V-band continuum emission, while the Hα emission comes from the whole disk (Carciofi 2011). Therefore, we can do the optical photometric and spectroscopic observations at the same time to monitor the variability and evolution of the circumstellar disk around the Be star. Okazaki *et al.* (2013) and Reig & Blinov (2018) suggested that the Type II X-ray outbursts in Be/X-ray binaries might be connected with a warped disk around the Be star. Here we summarise our spectroscopic and photometric observational results on several Be/X-ray binaries.

2. Observations

We have been annually monitoring the visual spectra of a number of Be/X-ray binaries since the 1990s. Optical spectroscopic observations were carried out with the 2.16 m telescope at Xinglong Station of the National Astronomical Observatories of China. After 2012, we also carried out spectroscopic observations with Lijiang 2.4m telescope at Yunnan Astronomical Observatory. We do the photometric observations using the small telescopes at Xinglong Station, including 60cm and 80cm telescopes. Data reduction and analysis were introduced in Yan *et al.* (2012a).

After RXTE/ASM was ceased its science operations in January 2012, X-ray activities of the Be/X-ray binaries are monitored by Swift/BAT and MAXI. Combined with our optical data, we can study the relationship between the X-ray variability and its optical emission.

3. Results

We have analysed the optical observational data of five Be/X-ray binaries, including MXB 0656-072, A 0535+26, and BSD 24-491. We summarise the major results for each Be/X-ray binary.

MXB 0656-072 underwent a series of X-ray outbursts between 2007 November and 2008 November. A 101.2-day orbital period was reported for the first time for MXB 0656-072 (Yan *et al.* 2012a). Our optical observations indicate that the strength of the Hα line in our 2006 observations became stronger than that of 2005 and it had an extraordinary strength during our 2007 observations, which were taken just before the first X-ray outburst of 2007 November (see Fig. 8 in Yan *et al.* 2012a). In 2007, our simultaneous optical photometry and spectroscopy on MXB 0656-072 showed an interesting behaviour: while the Hα emission line strongly increased, the source brightness in UBV decreased by 0.2 mag in 2007 compared to the 2008-2009 observations.

We analysed the photometric and spectroscopic data of A 0535+26 from 1992 to 2010. Results indicated that each giant X-ray outburst of A 0535+26 usually occurred in a fading phase of the optical brightness. An anti-correlation between the optical brightness and the Hα intensity was observed during our 2009 observations (see Fig. 2 in Yan *et al.* 2012b): when the brightness of the system showed an obvious decline, the intensity of Hα line kept increasing. 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.

An X-ray outburst from RX J0440.9+4431 was observed between 2010 March 26 and 2010 April 15 by MAXI and the following two small X- ray flares were also detected by Swift/BAT. Several positive and negative correlations between the V-band brightness and the Hα intensity were found from the long-term photometric and spectroscopic observations (see Fig. 1 in Yan *et al.* 2016). When the optical brightness of the system began to decline, the intensity of Hα emission line was still in an increasing phase. The strongest Hα emission line during the last 20 years, with an EW of $\sim$ -12.9Å, was observed during our 2010 observations, which trigged three consecutive X-ray outbursts between 2010 March and 2011 February.

4. Conclusions

V-band photometry and Hα spectroscopy are useful tools to monitor the physical changes in the circumstellar disk. Rivinius *et al.* (2001) suggested that a low density region would be formed in the inner part of Be star disk after a strong mass ejection event, and the circumstellar envelope could change from a disk to rings. The low density region will move outward at a time scale of viscosity. With the movement of the ejected material through the low density region, gas may encounter the compact object. Therefore, the neutron star can be a probe to constrain the structure of the Be star disk.

We have been monitoring a sample of Be/X-ray binaries for a long time. Several anti-correlations between the V-band brightness and the Hα emission have been found in MXB 0656-072, A0535+26, and LS V+44 17. Such similar phenomena are also observed in other Be/X-ray binary systems. X-ray outbursts were usually triggered during a decline phase of the continuum emission. There should be a time lag between the mass ejection events and the X-ray outbursts. We can use this time lag to constrain the mass transportation in the circumstellar disk.

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