X-ray outburst of 4U 0115+634 and ROTSE Observations of its Optical Counterpart V635 Cas

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Abstract. ROTSE IIIid (The Robotic Optical Transient Experiment) observations of X-ray binary system 4U 0115+634/V635 Cas obtained during 2004 June and 2005 January make possible, for the first time, to study the correlation between optical and type II X-ray outbursts. The X-ray outburst sharply enhanced after periastron passage where the optical brightness was reduced by 0.3 magnitude for a few days. We interpret the sharp reduction of optical brightness as a sign of mass ejection from the outer parts of the disc of the Be star. After this sharp decrease, the optical brightness healed and reached the pre X-ray outburst level. Afterwards, gradual decrease of the optical brightness followed a minimum then a gradual increase started again. Qualitatively, change of optical lightcurve suggests a precession of the Be star disc around a few hundred days. We also investigate the periodic signatures from the archival RXTE-ASM (Rossi X-ray Timing Explorer - All Sky Monitor) light curve covering a time span of ~9 years. We find significant orbital modulation in the ASM light curve during the type I X-ray outburst.

Key words. binaries: close – pulsars:general – stars:Emission line, Be – stars:individual: 4U 0115+634, V635 Cas – X-rays:stars –

1. Introduction

A "Be" star is an early type star which is close to the main sequence. Be stars show Balmer emission lines and strong infrared excess in their spectra (Slettebak 1988). Unlike normal B type stars, these properties suggest that circumstellar material can form in a disc structure around the Be star (Okazaki and Negueruela 2001). Indeed X-ray radiation in some Be/X-ray binaries arises as a result of accretion of plasma from Be star to the compact object (Bildsten et al., 1997, Negueruela 1998, Baykal et al. 2002). Fast rotation of the Be star, non-radial pulsations, and magnetic loops have been suggested as the causes that give rise to the disc around Be star, but it is not clear that any of them can explain the observed transient nature of Be/X-ray binaries. Hanuschik (1996) suggested that discs around Be stars are rotationally dominated and their motions are quasi-Keplerian, however mechanisms for outflow from Be stars are needed to explain the X-ray emission from Be/X-ray binaries (Waters et al., 1988).

Some of the Be/X-ray binaries are persistent and relatively low luminosity X-ray sources ($L_x \sim 10^{34}$ erg sec$^{-1}$). Their X-ray luminosities vary up to a factor of 10. Most of the Be/X-ray binaries show sudden (more than a factor of 10) increase in their X-ray luminosities and are called Be/X-ray transients.

Be/X-ray transients show correlation between their orbital periods and spin periods (Corbet 1986, Waters and van Kerkwijk 1989) and exhibit two different kinds of outburst:

i) X-ray outbursts of low luminosity transients ($L_x \sim 10^{36}-10^{37}$ erg sec$^{-1}$) generally occur close to the periastron passages (type I X-ray outburst). The duration of these outbursts in most cases is related to the orbital period (Okazaki & Negueruela 2001). ii) On the other hand type II X-ray (or Giant) outbursts ($L_x > 10^{37}$ erg sec$^{-1}$) last several weeks or even months. In most cases type II X-ray outbursts start after the periastron passage but do not show any other correlation with orbital parameters (Finger and Prince 1997).

The X-ray transient 4U 0115+634 (X0115+634) is an extensively studied Be/X-ray binary system (Campana 1996; Negueruela et al. 1997; Negueruela & Okazaki 2001; Negueruela et al. 2001). The source was reported during the Uhuru satellite survey (Giacconi et al. 1972; Forman et al. 1978). It was also observed by Vela 5B data base (Whitlock et al., 1989). Using the observations of SAS 3, Ariel V and HEAO-1 satellites, the precise position of the X-ray source was determined by Cominsky et al., (1978) and Johnston et
Fig. 1. ROTSE and RXTE/ASM observations of V635 Cas and 4U 0115+634. Inset arrow shows the periastron passage. X-Ray observations is plotted in arbitrary count rate units.

al., (1978). This location is used to identify the strongly reddened Be star with a visual magnitude $V \sim 15.5$ (Johns et al., 1978, Hutchings and Crampton 1981) which was subsequently named as V635 Cas (Khopolov et al., 1981). Using the SAS 3 timing observations, the pulse period ($P_{\text{pul}}=3.6$ seconds), orbital period ($P_{\text{orb}}=24.3$ days) and the eccentricity ($e=0.34$) were found (Rappaport et al., 1978, see also Tamura et al., 1992).

Multiwavelength long term monitoring observations of the optical counterpart V635 Cas have shown that the emission lines and photometric magnitudes of the Be star undergo quasi cyclic activity around $\sim 3-5$ years (Negueruela et al., 2001). This kind of activity suggests that losing and reforming a circumstellar disc around the Be star are possible. After each disc loss episode, the disc starts to reform and expands until it becomes unstable. The warping disk tilts and starts precessing.

In this work we present new ROTSE observations of V635 Cas (see also Kızılçğlu et al. 2005 for preliminary results) and compare our results with RXTE/ASM observations of 4U 0115+634. The comparison of light curves of the optical and X-ray data have shown that type II outbursts in X-rays enhanced significantly after the periastron passage. The sharp decrease of the optical brightness is interpreted as a sign of mass transfer episode to the compact object. The disk around the neutron star is formed in a few days after the periastron passage. This is the first clear evidence of a correlation between optical brightness and X-ray outburst.

2. Observations

2.1. ROTSE

The Robotic Optical Transient Experiment (ROTSE-III) consists of four 0.45m worldwide robotic, automated telescopes situated at different locations on Earth. They are designed for fast ($\sim 6$ sec) responses to Gamma-Ray Burst (GRB) triggers from satellites such as Swift. Each ROTSE telescope has a 1.85 degree of view imaged onto a Marconi 2048 $\times$ 2048 back-illuminated thinned CCD. These telescopes operate without filters, and have wide passband which peaks around 550 nm (Akerlof et al. 2003). ROTSE III telescopes are scheduled to observe optical transients when there are no GRB events. In this
work, we present optical observations of V635 performed by ROTSE IIId telescope located at Turkish National Observatory (TUG) site, Bakrltlepe, Turkey. The observations took place between MJD 53180 (June 2004) and MJD 53383 (January 2005).

A total of about 1850 CCD frames were analyzed. After finding the instrumental magnitudes (Bertin & Arnouts, 1996) ROTSE magnitudes were calculated by comparing all the field stars to the USNO A2.0 R-band catalog. All the processes were done in sequential automated mode. Barycentric corrections were made to the times of each observation by using JPL DE200 ephemerides.

Fig. 1 shows the daily averages of data for V635 Cas obtained with ROTSE IIId telescope. The difference in ROTSE magnitudes of V635 Cas and the comparison star (RA = 01°17′35.7″, δ = +63°41′44″) were plotted. As a check star, we used the one with RA = 01°18′31.3″, δ = +63°47′30″.4.  

2.2. RXTE/ASM

The All Sky Monitor (ASM) on board of Rossi X-ray Timing Explorer (RXTE) satellite consists of three wide-angle Scanning Shadow Cameras (SSCs). These cameras are mounted on a rotating drive assembly, which cover ~70% of the sky every 1.5 hours. A detailed information of the ASM can be found in Levine et al., (1996). ASM data products can be found in the public archive in three different energy bands (1.3-3.0, 3.0-5.0, 5.0-12.0 keV). In Fig. 1, we present the ASM light curve of 4U 0115+634 in the 5.0-12.0 keV energy band together with the light curve of optical counterpart V635 Cas.

3. Results and Discussion

In this work, we present RXTE/ASM observations of 4U 0115+634 and its optical counterpart V635 Cas. A general view of the evolution of the unfiltered optical and RXTE/ASM light curve is shown in Fig. 1.

Negueruela et al (2001) showed that the general optical, infrared and X-ray behaviour of this system can be explained by the dynamical evolution of the viscous circumstellar disc around V635 Cas. The evolution of emission lines and photometric magnitudes indicated that losing and reforming a circumstellar disc starts precessing (Porter 1998). Therefore it is quite resonable to explain the observed light curve as a sign of the precession of the disc around the Be star. Due to the precession of the warped disc, projection of the disc on to the plane of the sky changes giving rise to the change of light coming from the system. When the denser, elongated part of the disc is in the line of sight, light output coming from the system is less. Close to the periastron passages, the outer edge of the precessed disc may cause type II X-ray outbursts. Otherwise the disc continues to precess without causing any type II X-ray outburst.

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In Fig. 2, Folded RXTE/ASM/X-ray lightcurve corresponding to time span of the optical outburst (~ MJD 53182 - 53353) and folded ROTSE IIId lightcurve covering the same time interval are presented at the upper (a) and middle panels (b) respectively. Bottom panel (c) presents the folded light curve during the type I RXTE/ASM/X-ray outburst (MJD 50295-50450). Phases 0.0625 and 1.0625 are the periastron passages denoted by arrow P.

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Typical timescale of optical variations seen in Fig. 1 is much less then a few years. Therefore we consider the variation in the optical brightening as being closely related to the precession of circumstellar disk. However some of the short time scale variations could be related to the dynamical instabilities of the viscous circumstellar disc around V635 Cas. Indeed, the interaction of the disc with the neutron star causes small variations in the light curve which is clearly seen in our observations. The optical brightness sharply decreased by ~ 0.3 magnitude during this episode. After this sharp decrease, the optical brightness healed with small variations on a time scale of several days. It is interesting to note that the optical brightness resumed its pre-instability value.

If the decrease in the optical brightness associates with the mass loss episode to compact object then the change in optical magnitude (Δm ~ 0.3) corresponds to $M \sim 10^{-8} M_\odot yr^{-1}$ mass loss rate from the V635 Cas. This material can be captured and form an accretion disk as suggested by Negueruela et al., (2001) to produce the observed type II X-ray outburst with a mass accretion rate of $M_x \sim 4 \times 10^{-9} M_\odot yr^{-1}$ (Coburn et al., 2004).

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Negueruela et al. (1998) investigated the ASM light curve between MJD 50087-50350. In their analysis, they found that there was type I X-ray outburst activity between MJD 50295-
Fig. 3. (a) ASM light curve of 4U 0115+634. (b) Dynamical orbital period search of ASM light curve. Contour lines denote 1, 3 and 4σ confidence levels. Dashed lines denote 1σ, solid line 3σ and the contour inside 4σ. (see the text for details). (c) Reduced χ² values for folding at orbital period 24.31 days. (note that 8 phase bins are used for folding) are shown in the lower panel.

50450 and folded profile showed that type I X-ray outburst peak φ ∼ 0.3 away from the periastron. In order to see orbital period signature of a type II X-ray outburst, we folded the optical outburst light curve (MJD 53182-53353) and the corresponding ASM observations on the orbital period of 24.31 days. As seen from Fig. 2a,b, both folded lightcurves agree with each other. It is interesting to note that even if the outburst in X-rays starts a few days after the periastron, peak values of both profiles occur at φ ∼ 0.25 (∼ 6 days) before the periastron passage. This suggests that accretion disk enhances ∼ 6 days prior to the periastron passages. Further observations are needed to confirm this behaviour.

In order to see the statistical significance of these profiles and search for other possible orbital signatures in the ASM light curve, we apply χ² orbital period search. In this procedure we compute dynamic period search by calculating χ² values from 150 days (∼ 6 orbital cycle) interval with a new interval beginning every 1 day. The resulting orbital search is not independent since the data segments overlap, but this method identifies the range of times for which the 24.31 days orbital period is present. We search orbital periods between 20 and 30 days and present their χ² distributions at the mid value of time intervals. In Fig. 3, we present the detection contours for Δχ² statistics. As seen in Fig. 3, statistically significant orbital period modulations are only present around the type I X-ray outburst region as suggested by Negueruela et al. (1998). Eventhough orbital period signatures around type II X-ray outburst regions are not significant (around ∼ 1σ confidence level), it is important to note that, as seen in Fig. 2, both optical and X-ray profiles agree with each other during the type II X-ray outburst (MJD 53182-53353). On the other hand profiles of type I X-ray and type II X-ray outbursts are phase shifted by ∼ 198 degrees (Δφ ∼ 0.55) (see fig. 2 a,c). This phase shift and weak orbital signature strongly suggest that the accretion mechanisms of the two types of outburst are geometrically different. In type I X-ray outbursts accretion is moderate while in type II X-ray outbursts extended nature of the Be disc and the high accretion rates are not affected significantly by the eccentric orbit of the binary system. Therefore it is quite natural to see stronger orbital modulation in type I X-ray outbursts relative to the type II X-ray outbursts.
In ROTSE observations, the change in the optical brightness is related to the dynamical evolution of the viscous decretion disc surrounding the Be star V635 Cas. Some of the disc loss and reformation cycles cause type II X-ray outburst. During the disc growth phase, decretion disc becomes unstable and the radiation driven warping starts (Porter 1998). As the disc warps, the tilt of the outer regions increases and the disc starts to precess. The precession period for this source is suggested to be of the order of 100 days (Negueruela et al., 2001).

Future monitoring of V635 Cas with the ROTSE IIIId telescope may yield better understanding of the precession and the outburst behaviour of this source.

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References

Akerlof, C.W., Kehoe, R/L/, McKay, J.A., Rykoff, E.S., et al., 2003, PASP, 115, 132
Baykal, A., Stark, M., Swank, J., 2002, ApJ, 569, 903
Bertin, E., Arnouts, S., 1996, A&AS, 117, 393
Bildsten, L., Chakrabarty, D., Chiu, J., et al., 1997, ApJS, 113, 367
Campana, S., 1996, ApJS, 239, 113
Coberman, W., Kalemci, E., Kretschmar, P., et al., 2004, Atel, 337, 1C
Cominsky, L., Clark, G.W., Li, F., et al. 1978, Nature, 273, 367
Corbet, R.H.D., 1986, MNRAS, 220, 1047
Forman, W., Jones, C., Cominsky, L., et al., 1978, ApJS, 38, 357
Finger, M.H., Prince, T.A., 1997, Proc. Fourth Compton Symp. 1(AIP, Woodbury, NY), 57
Giacconi, R., Murray, S., Gurksy, H., et al., 1972, ApJ, 178, 281
Hanuschik, R.W., 1996, A&A, 308, 170
Hutchings, J.B., Crampton, D., 1981, ApJ, 247, 222
Johns, M., Koski, A., Canizares, C., et al., 1978, IAUC, 3171
Johnston, M., Bradt, H., Doxsey, R., et al., 1978, ApJ, 223, L71
Khopolov, P.N., Samus, N.N., Kukarkina, N.P., Medveddeva, G.I., Perova, N.B., 1981, IBVS, 2042
Kızıloğlu, Ü., Baykal, A., Kızıloğlu, N, 2005, IBVS, 5590
Levine, A.M., Bradt, H., Cui, W., et al., 1996, ApJ, 469, L33
Negueruela, I., 1998, A&A, 338, 505
Negueruela, I., Grove, E.J., Coe, M.J., et al., 1997, MNRAS, 284, 859
Negueruela, I., Reig P., Coe, M., Fabregat, j., 1998, A&A, 336, 251
Negueruela, I., Okazaki, A.T., 2001, A&A, 369, 108
Negueruela, I., Okazaki, A.T., Fabregat, J., Coe, M.J., Munari, U., Tomov, T., 2001, A&A, 369, 17
Okazaki, A.T., Negueruela, I., 2001, A&A, 377, 161
Porter, J.M., 1998, A&A, 348, 512
Rappaport, S., Clark, G.W., Cominsky, L., Joss, P.C., Li, F., 1978, ApJ, 224, L1
Slettebak, A., 1988, PASP, 100, 770
Tamura, K., Tsunemi, H., Kitamoto, S., et al., 1992, ApJ, 389, 676
Waters, L.B.F.M., van den Heuvel E.P.J., Taylor, A.R., et al., 1988, A&A, 198, 200
Waters, L.B.F.M., van Kerkwijk, M.H., 1989, A&A, 223, 196
Whitlock, L., Roussel-Dupre, D., Priedhorsky, W., 1989, ApJ, 338, 381