A&A 439, 1131–1134 (2005)
DOI: 10.1051/0004-6361:20052968

Astronomy & Astrophysics

Research Note

X-ray outburst of 4U 0115+634 and ROTSE observations of its optical counterpart V635 Cas

A. Baykal[1], Ü. Kızıloğlu[1], N. Kızıloğlu[1], Ş. Balman[1], and S. Ç. İnam[2]

[1] Physics Department, Middle East Technical University, Ankara 06531, Turkey
e-mail: altan@astroa.physics.metu.edu.tr
[2] Department of Electrical and Electronics Engineering, Başkent University, 06530 Ankara, Turkey
e-mail: inam@baskent.edu.tr

Received 2 March 2005 / Accepted 1 June 2005

Abstract. ROTSE IIId (The Robotic Optical Transient Experiment) observations of the X-ray binary system 4U 0115+634/V635 Cas obtained during 2004 June and 2005 January make it 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 mag 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 rose again and reached the pre-X-ray outburst level. Afterwards, a gradual decrease of the optical brightness followed until a minimum then a gradual increase started again. Qualitatively, the change of the optical lightcurve suggests a precession of the Be star disc of 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. stars: binaries: close – stars: 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 that 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 & Negueruela 2001). Indeed, X-ray radiation in some Be/X-ray binaries arises as a result of accretion of plasma from the 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 causes that give rise to the disc around a 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 s^{-1}). Their X-ray luminosities vary by up to a factor of 10. Most of the Be/X-ray binaries show a 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 a correlation between their orbital periods and spin periods (Corbet 1986; Waters & 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 s^{-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) type II X-ray (or Giant) outbursts ($L_x > 10^{37}$ erg s^{-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 & 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 the 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

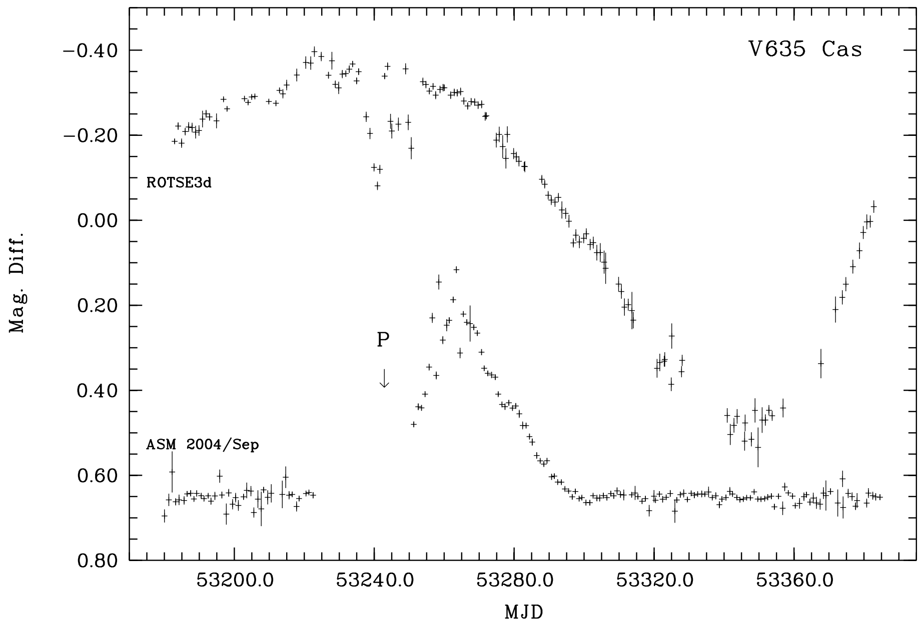

Fig. 1. ROTSE and RXTE/ASM observations of V635 Cas and 4U 0115+634. Inset arrow shows the periastron passage. X-ray observations is plotted in arbitrary count rate units.

was determined by Cominsky et al. (1978) and Johnston et 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 & Crampton 1981) which was subsequently named as V635 Cas (Khopolov et al. 1981). Using the SAS 3 timing observations, pulse period ($P_{\rm pul} = 3.6$ s), orbital period ($P_{\rm orb} = 24.3$ days) and 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 of around ~3–5 years (Negueruela et al. 2001). This kind of activity suggests that losing and reforming a circumstellar disc around a Be star is 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 Kızıloğlu 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 are enhanced significantly after the periastron passage. The sharp decrease of the optical brightness is interpreted as a sign of a mass transfer episode onto 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 0.45 m robotic, automated telescopes situated at different locations on Earth. They are designed for fast (~6 s) 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 × 2048 back-illuminated thinned CCD. These telescopes operate without filters, and have a wide passband that 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 the ROTSE IIId telescope located at the Turkish National Observatory (TUG) site, Bakırlıtepe, Turkey. The observations took place between MJD 53 180 (June 2004) and MJD 53 383 (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.

Figure 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 = $01^{\rm h}17^{\rm m}35\overset{\rm s}{.}7$, $\delta = +63°41'44''$) were plotted. As a check star, we used the one with RA = $01^{\rm h}18^{\rm m}31\overset{\rm s}{.}3$, $\delta = +63°47'30\overset{''}{.}4$.

2.2. RXTE/ASM

The All Sky Monitor (ASM) on board the 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 covers ~70% of the sky every 1.5 h. 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 the optical counterpart V635 Cas.

3. Results and discussion

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 around V635 Cas are quite possible in timescales of (~3–5) years. After each disc-loss episode, the disc starts to reform in less than 6 months. The disc surrounding V635 Cas is truncated at a resonance radius depending on the viscosity parameter by the tidal/resonant interaction with the neutron star (Negueruela & Okazaki 2001; Negueruela et al. 2001). Then the disc becomes unstable to warping, it tilts and starts precessing (Porter 1998).

The typical timescale of optical variations seen in Fig. 1 is much less than a few years. Therefore we consider the variation in the optical brigthening 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 are clearly seen in our observations. The optical brightness sharply decreased by ~0.3 mag during this episode. After this sharp decrease, the optical brightness rose again with small variations on a time scale of several days. The optical brightness returned to its pre-instability value.

If the decrease in the optical brightness is associated with the mass loss episode then the change in optical magnitude ($\Delta m \sim 0.3$) corresponds to a $\dot{M} \sim 10^{-8}$ $M_{\odot}$ yr^{-1} mass loss rate from V635 Cas. This material can be captured by the compact object and forms 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 $\dot{M}_{\rm x} \sim 4 \times 10^{-9}$ $M_{\odot}$ yr^{-1} (Coburn et al. 2004).

Therefore one can 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 a change in light coming from the system. When the denser, elongated part of the disc is in the line of sight, the light output 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.

Negueruela et al. (1998) investigated the ASM light curve between MJD 50 087–50 530. In their analysis, they found that there was type I X-ray outburst activity between MJD 50 295–50 450 and the folded profile showed that a type I X-ray outburst peak $\phi \sim 0.3$ away from the periastron. In order to see the orbital period signature of a type II X-ray outburst, we folded the optical outburst light curve (MJD 53 182–53 353) and the corresponding ASM observations on the orbital period of 24.31 days. As seen from Figs. 2a, b, both folded lightcurves agree with each other. Even if the outburst in X-rays starts a few days after the periastron, peak values of both profiles occur at $\phi \sim 0.25$ (~6 days) before the periastron passage. This suggests that the accretion disk is enhanced ~6 days prior to the periastron passages. Further observations are needed to confirm this behaviour.

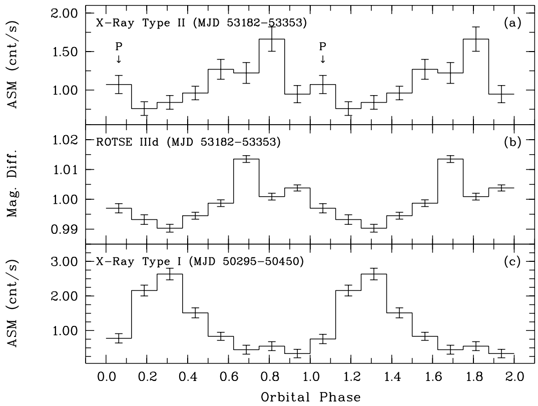

Fig. 2. Folded RXTE/ASM/X-ray lightcurve corresponding to the time span of the optical outburst (~MJD 53 182–53 353) and folded ROTSE IIId lightcurve covering the same time interval are presented in the upper **a)** and middle panels **b)** respectively. The bottom panel **c)** presents the folded light curve during the type I RXTE/ASM/X-ray outburst (MJD 50 295–50 450). Phases 0.0625 and 1.0625 are the periastron passages denoted by the arrow P.

In order to see the statistical significance of these profiles and search for other possible orbital signatures in the ASM light curve, we carried out a χ^2 orbital period search. In this procedure we perform the dynamic period search by calculating χ^2 values from a 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 day orbital period is present. We search for orbital periods between 20 and 30 days and present their χ^2 distributions at the mid value of the time intervals. In Fig. 3, we present the detection contours for the $\Delta\chi^2$ 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). Although orbital period signatures around type II X-ray outburst regions are not significant (around $\sim 1\sigma$ confidence level), as seen in Fig. 2, both optical and X-ray profiles agree with each other during the type II X-ray outburst (MJD 53 182–53 353). On the other hand profiles of type I X-ray and type II X-ray outbursts are phase shifted by ~198 degrees ($\Delta\phi \sim 0.55$) (see Figs. 2a, 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 the extended nature of the Be disc and the high accretion rates are not significantly affected by the eccentric orbit of the binary system. Therefore it is quite

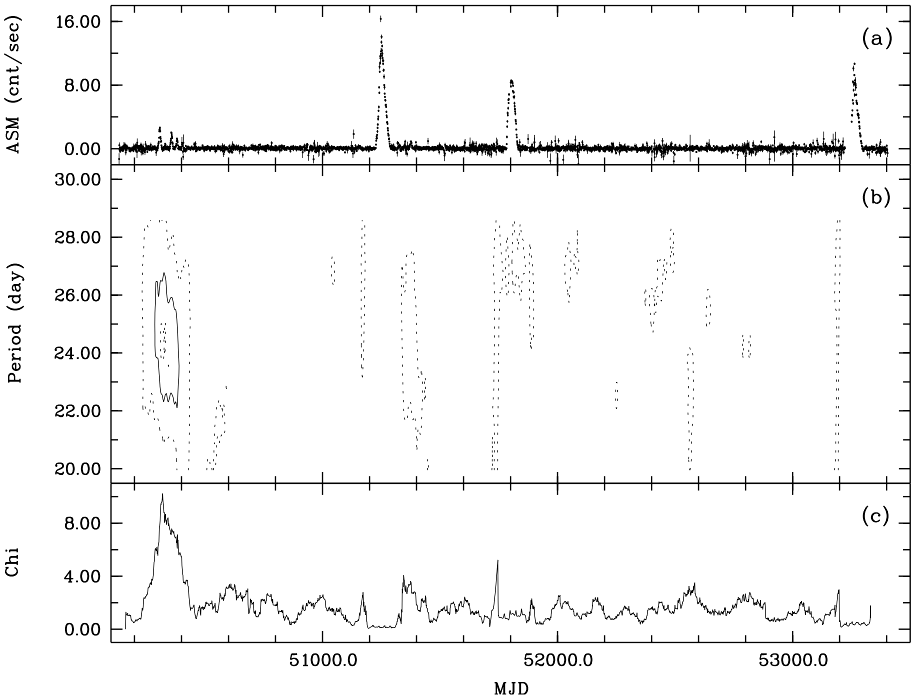

Fig. 3. a) ASM light curve of 4U 0115+634. **b)** Dynamical orbital period search of the ASM light curve. Contour lines denote 1, 3 and 4σ confidence levels. Dashed lines denote 1σ, solid line 3σ and the contour inside 4σ (see the text for details). **c)** Reduced χ^2 values for folding at orbital period 24.31 days (note that 8 phase bins are used for folding).

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 outbursts. During the disc growth phase, the decretion disc becomes unstable and 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 IIId telescope may yield better understanding of the precession and the outburst behaviour of this source.

Acknowledgements. We thank the international ROTSE collaboration and the Turkish National Observatory for the optical facilities. We acknowledge the RXTE-ASM team for the X-ray monitoring data.

References

Akerlof, C. W., Kehoe, R. L., McKay, T. A., 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

Coburn, 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, NY: Woodbury), 57

Giacconi, R., Murray, S., Gurksky, 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., & Okazaki, A. T. 2001, A&A, 369, 108

Negueruela, I., Grove, E. J., Coe, M. J., et al. 1997, MNRAS, 284, 859

Negueruela, I., Reig, P., Coe, M. J., & Fabregat, J. 1998, A&A, 336, 251

Negueruela, I., Okazaki, A. T., Fabregat, J., et al. 2001, A&A, 369, 117

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