The Be/X-ray transient 4U 0115+63/V635 Cassiopeiae

III. Quasi-cyclic variability

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ABSTRACT

Context. 4U 0115+63 is one of the most active and best studied Be/X-ray transients. Previous studies of 4U 0115+63 have led to the suggestion that 4U 0115+63 undergoes relatively fast quasi-cyclic activity. However, due to the lack of good coverage of the observations, the variability time scales are uncertain.

Aims. Our objective is to investigate the long-term behaviour of 4U 0115+63/V635 Cas to confirm its quasi-cyclic nature and to explain its correlated optical/IR and X-ray variability.

Methods. We have performed optical/IR photometric observations and optical spectroscopic observations of 4U 0115+63/V635 Cas over the last decade with unprecedented coverage. We have focused on the Hz line variability and the long-term changes of the photometric magnitudes and colours and investigated these changes in correlation with the X-ray activity of the source.

Results. The optical and infrared emission is characterised by cyclic changes with a period of ~5 years. This long-term variability is attributed to the state of the circumstellar disc around the Be star companion. Each cycle involves a low state when the disc is very weak or absent and the associated low amplitude variability is orbitally modulated and a high state when a perturbed disc precesses, giving rise to fast and large amplitude photometric changes. X-ray outbursts in 4U 0115+63 come in pairs, i.e., two in every cycle. However, sometimes the second outburst is missing.

Conclusions. Our results can be explained within the framework of the decretion disc model. The neutron star acts as the perturbing body, truncating and distorting the disc. The first outburst would occur before the disc is strongly perturbed. The second outburst leads to the dispersal of the disc and marks the end of the perturbed phase.

Key words. stars: pulsars: individual: 4U 0115+63 – stars: pulsars: individual: V635 Cas – X-rays: binaries – stars: neutron – stars: binaries: close – stars: emission line, Be

1. Introduction

4U 0115+63 was one of the first Be/X-ray binaries to be discovered. The oldest available X-ray observation dates back to August 1969 when the Vela 5B satellite detected the source as three small outbursts separated by 180 days (Whitlock et al. 1989). Since then about 15 outbursts have been reported (see Table 1). Normally, these outbursts represent an increase in the X-ray luminosity by a factor ~100 and last for about a month. The strongest outbursts reach luminosities close to the Eddington value (~1038 erg cm−2 s−1). The lack of orbital modulation and the relative large increase in luminosity define these outbursts as type II. Only in one occasion, in 1996, has 4U 0115+63 showed orbital modulated, shorter and smaller outbursts, i.e., type I (Negueruela et al. 1998). For a review of the X-ray variability in Be/X-ray binaries see, e.g., Coe (2000) and Ziolkowski (2002).

X-ray pulsations (Pspin = 3.6 s) were soon discovered (Cominsky et al. 1978) and the orbital parameters (Porb = 24.3 d, e = 0.34, αs sin i = 140.1 lt-s) determined (Rappaport et al. 1978). Subsequent detections led to the discovery of one (Wheaton et al. 1979), two (White et al. 1983), three (Heindl et al. 1999) and four (Santangelo et al. 1999) cyclotron resonance scattering features.

The 1978 outburst allowed the identification of the optical counterpart (Johns et al. 1978; Hutchings & Crampton 1981) with a reddened (A V ≥ 5 mag) B-type star that showed Hr in emission, V635 Cas. Extensive studies in the IR/optical (Kriss et al. 1983; Mendelson & Mazeh 1991; Unger et al. 1998; Negueruela et al. 2001) and X-ray (Whitlock et al. 1989; Tsunemi & Kitamoto 1988) bands allowed the determination of the astrophysical parameters – V635 Cas is a V ~ 15 B0.2Ve star located at a distance of ~7–8 kpc – and to the suggestion
of cyclic changes with a quasi-period of 3–5 years. This quasi-
cycling behaviour is closely related to the dynamical evolu-
tion of the viscous circumstellar disc around the Be star. The
Be star loses and reforms the disc on time scales of 3–5 years (Negueruela et al. 2001). At some point during the growing
phase the disc becomes unstable and highly disturbed.

In this paper we present the most complete monitoring of
4U 0115+63. Optical (BVR) photometric observations were obtained from the 235-mm camera and di-
ff erent intermediate-resolution grat-
ings. The WHT spectra were obtained with the red arm of
the Intermediate Dispersion Spectrograph (IDS), fit with
the 235-mm camera and different intermediate-resolution grat-
ings. The WHT spectra were obtained with the red arm of
the Intermediate Dispersion Spectroscopic and Imaging System
(ISIS), equipped with either the R600R or R1200R gratings.

Other observations have been obtained with the 2.6 m Nordic
Optical Telescope (NOT), also located in La Palma, equipped
with ALFOSC; the 1.93 m of the Haute Provence observa-
tory (OHP) in France, equipped with either the R600R or R1200R gratings.

The main source of spectroscopy is the 1.3 m Skinakas tele-
scope (SKI), which was equipped with a 2000 × 800 ISA SiTe
CCD and a 1302 l mm⁻¹ grating, giving a nominal dispersion of
1.04 Å/pixel. Many other spectra were obtained through the
service programme of the Isaac Newton Group at La Palma, ei-
ther with the 2.5 m Isaac Newton Telescope (INT) or the 4.2 m
William Herschel Telescope (WHT). The INT was equipped
with the Intermediate Dispersion Spectrograph (IDS), fit with
the 235-mm camera and different intermediate-resolution grat-
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the Intermediate Dispersion Spectroscopic and Imaging System
(ISIS), equipped with either the R600R or R1200R gratings.

2. Observations

2.1. Optical and infrared photometry

Optical (BVRI) photometric observations were obtained from the
20 cm (before April 2001) and 70 cm (after April 2001) tele-
scopes at the Crimean Observatory (CRI) in Ukraine between
1998–2005 using an ST-7 CCD of the St. Petersburg University.
The array is 765×510 pixels, corresponding to a 8.1′×5.4′ field
of view (0.65′$/\text{pixel}$ scale). The data set consists of about 260 B
and 350 VRI measurements. In order to improve the signal-to
noise ratio, up to 5 images in each colour band were obtained
and co-added to create the final image. The standard technique
of bias and dark subtraction and flat-fielding was used. A cali-
ibrated set of standard stars, located within the same field, was
used to perform aperture photometry using a SExtractor-based
package. The photometric accuracy is usually better than 0.001
in V, R and I and about 0.003 in B.

Near-infrared photometric data (about 200 JHK mea-
surements) were obtained at Campo Imperatore (Italy) with
SWIRCAM NIR camera with the PICNIC 256 × 256 pixel
array, attached to the 1.1 m telescope. The camera’s field of view
is 4.5′ × 4.5′ with a 1.04′$/\text{pixel}$ scale. Each photometric image
was obtained from 5 co-added dithered images, after sky sub-
traction and flat-field correction. The same photometric package
as for the ST-7 data was used to perform photometry.

Table 2 (electronic form only) gives the results of our photo-
metric monitoring.

2.2. Optical spectroscopy

The main source of spectroscopy is the 1.3 m Skinakas tele-
scope (SKI), which was equipped with a 2000 × 800 ISA SiTe
CCD and a 1302 l mm⁻¹ grating, giving a nominal dispersion
of 1.04 Å/pixel. Many other spectra were obtained through the
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ings. The WHT spectra were obtained with the red arm of
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(ISIS), equipped with either the R600R or R1200R gratings.

Other observations have been obtained with the 2.6 m Nordic
Optical Telescope (NOT), also located in La Palma, equipped
with ALFOSC; the 1.93 m of the Haute Provence observa-
tory (OHP) in France, equipped with the Carelèc spectrograph
and the Mt. Ekar 1.82 m Telescope (EKA) of the Padova
Astronomical Observatory (Italy), equipped with AFOSC. One
low resolution spectrum was taken with the blue arm of the
TWIN spectrograph on the 3.5 m of the Calar Alto observatory
(CA) in Spain. Table 3 (electronic form only) gives the log of the
optical spectroscopic observations.

The reduction of the spectra was made using the STARLINK
Figaro package (Shortridge et al. 2001), while their analysis was
performed using the STARLINK Dipso package (Howarth et al. 1998).

3. Results

We have been monitoring 4U 0115+63 spectroscopically since the early 1990’s (Paper II). Photometric data were also occasionally acquired. Since August 1999 the source is being monitored in the UBVRIJHK bands. In this section we present the results of these new observations. The analysis of the historical variability curves will be presented in Sect. 4.

3.1. Photometric variability

Figure 1 shows the evolution of the optical and infrared magnitudes and colours for the period August 2000–June 2006. These observations define a complete cycle of variability. The light curve begins with the photometric bright state that led to the 2000 X-ray outburst. The magnitudes gradually decreased and the colours became bluer. A faint stable photometric state was reached at around MJD 52000 (April 2001). This state extended for more than two years up to ~MJD 52 880 (August 2003). We will refer to this state as the extended photometric low state (ELS). The average BVRI magnitudes during the ELS are $B = 16.93 \pm 0.05$, $V = 15.50 \pm 0.03$, $R = 14.56 \pm 0.03$, $I = 13.55 \pm 0.04$, $J = 12.61 \pm 0.03$, $H = 12.19 \pm 0.03$, $K = 11.86 \pm 0.05$. These values are in complete agreement with those given in Paper I for the previous faint state. Photometrically, the ELS is a quiet state with very low amplitude variations, as can be deduced from the small values of the standard deviation.

The end of the ELS is marked by the gradual brightening of the photometric bands in August 2003. The source enters a new activity state characterised by large amplitude variations in the form of optical eruptions, i.e., the optical/IR brightness alternates between maxima and ELS values. The amplitude of variability is larger at longer wavelengths (e.g. $V$ increased by ~0.5 mag and $K$ by 1.6 mag in about 440 days). In coincidence with the first optical eruption of this state, a new X-ray outburst was observed (September 2004). Note also the constancy of the $(B-V)$ colour throughout the observations.

Baykal et al. (2005) reported ROTSE observations covering the 2004 outburst. They found a sharp drop lasting for about a week (MJD 53235–53242) of ~0.3 mag in the source brightness a few days before the onset of the X-ray outburst and interpreted this result as a sign of mass ejection from the outer parts of the disc of the Be star. We do not observe such drop in our data. Although our observations contain only one point in the narrow interval when the ROTSE drop was seen, it shows very similar values to those of the previous and following observations.

3.2. Spectroscopic variability

Figure 1 also shows the evolution of the equivalent width (EW(Hα)) and the separation of the peaks, in km s$^{-1}$, of the split profiles of the Hα line in the interval 1999–2006. As the EW(Hα) increases the peak separation decreases. This is the expected behaviour of a quasi-Keplerian disk and indicates that as the EW(Hα) increases, the region where the Hα line is produced moves further away from the central star (e.g. Hummel & Vranchen 1995).

In Fig. 2 the Hα profile through the different phases of the variability cycle is displayed. The top panel corresponds to the cycle that began after the 1995 outburst (Paper II), while the bottom panel to that after the 2000 outburst. The emission line profile of the Hα line shows significant richness in variability. Both single- and double-peak as well as symmetric and asymmetric profiles are seen. Symmetric profiles are associated with extreme values, either way, of the EW(Hα). Asymmetric profiles are associated with intermediate values of EW(Hα).

Taking as the starting point of the cycle the X-ray outburst prior to the ELS, the evolution of the Hα profile through the cycle is the following: at the time of the outburst the Hα line shows a single peak profile. The EW(Hα) finds itself in a relative maximum. When the profile is a narrow single peak there is a broad base component on top of which it sits (see e.g. Fig. 2 spectra MJD 51771 and MJD 51801). This component was already noticed in Negueruela et al. (2001) and may be...
3.3. Reddening and distance

In Paper I values of the reddening and distance were derived from the observations showing the bluest colours (those from January 8, 1998). It was then assumed that these observations corresponded to purely photospheric emission. In view of the observations presented here, a revision of these parameters is justified since i) a much longer set of optical photometric observations is available, ii) a longer extended low optical state (MJD 52 000–52 800) is observed, where presumably the underlying B star is exposed and photospheric emission without substantial contribution from the disc is detected and iii) the observations cover a wider wavelength band with (quasi)simultaneous optical and near IR data, which allows us to estimate the reddening by fitting the photometric data to a model atmosphere.

Figure 2 shows the energy distribution of a B0V star (Straizys 1995) and the lowest magnitudes of the ELS. Letting $A_V$ be a free parameter we find that the best fit is achieved for $A_V = 5.17 \pm 0.03$. The distributions with $A_V = \pm 3\sigma$ are also shown.

TAKING into account that $A_K = 0.115 A_V$, that for a B0V the intrinsic $K_0 = -3.25$ (Straizys 1995) and the minimum observed magnitude, $K = 11.89 \pm 0.02$, the distance-modulus is $DM = K - 0.115 A_V - K_0 = 14.55$ or $d = 8.1 \pm 0.1$ kpc. The error in the distance includes the photometric uncertainty only and assumes that neither $K_0$ nor the reddening law are affected by errors – for example, an uncertainty of 0.2 mag in $K_0$ translates into a distance error of about 0.7 kpc.

The assumption of standard reddening may introduce large errors if not verified. In Paper I, it was shown that the use of the extinction law by Fitzpatrick (1999) favours a value of $R$ close to the standard $R = 3.1$. For further verification, we used the CHORIZOS code (Maiz-Apellániz 2004) to study the reddening. The program was used to fit extinction laws from Cardelli et al. (1989) convoluted with the spectral energy distribution of a $T_{	ext{eff}} = 27,500 \text{ K}$, $log g = 4.0$ TLUSTY atmosphere model to our photometry. Although we obtain a slightly lower value for $R$, the derived $A_V = 4.8 \pm 0.1$ is compatible with the value found above at a $3\sigma$ level.
3.4. Power spectrum analysis

In order to search for periodic variations in the photometric light curves we performed a power spectral analysis. The details of the technique employed can be found in Larionov et al. (2001).

The power spectrum and spectral window of the data set were calculated as

\[ P(f) = \frac{1}{N^2} \left| \sum_{j=1}^{N} (m_j - \bar{m}) e^{-2\pi if t_j} \right|^2 \]

and

\[ W(f) = \frac{1}{N^2} \left| \sum_{j=1}^{N} e^{-2\pi if t_j} \right|^2, \quad W(0) = 1, \]

respectively, where \( i = \sqrt{-1}, t_j \) denotes the time of observation, and \( m_j \) and \( \bar{m} \), the individual and mean values of the brightness, respectively.

It is clear from Fig. 1 that in order to judge with sufficient confidence the reality of the orbital plus close and/or related periodicities, one should remove the longer-period component(s) of variability. In our case it is not sufficient to subtract the linear trend, and we need to take into account the slow light variations. We have constructed a smoothed data set using the method of a sliding mean with the window value \( \delta t_j \). The optimal value of the smoothing interval was \( \delta t_j = 0.5 \) mag in \( R \).

The amplitude of the sine-wave obtained is 0.01 mag in \( R \). We calculate the ephemeris of the small-scale optical variations as \( \Delta \text{JD}_{\text{max}} = 2449498(\pm1.0) + 24.41(\pm0.15) \cdot E \), where \( E \) is the epoch number. The most striking (but not unexpected) result is that these values practically coincide, within errors quoted, with the X-ray ephemeris. The position of the optical maximum corresponds to the periastron passage. The orbital period modulation is also present in the time interval MJD 52 850–53 250, but the shape is markedly non-sinusoidal.

No evidence of a 24-day peak was found in the interval MJD 51 400–52 000. Instead, there is a modulation with \( 22.15 \) day period and amplitude \( \Delta \text{JD}_{\text{max}} \). One possible explanation for the 22.15-d period is that it represents the beat frequency between the orbital frequency and precession frequency of the disc. In this case the disc would precess with retrograde motion with a period of about 250 days. After the 2004 X-ray outburst all periodicities are suppressed.

We also applied the same analysis to the V and I bands. For the J band we obtained practically the same results as in R, while in V we were not able to detect any significant modulation close to the orbital period. The fact that the beat frequency is more
apparent in the redder bands gives support to the interpretation of the 22.15-d periodicity as being affected by the precession of the disc, as one would expect the IR magnitudes to be more affected by the disc that the shorter wavelengths.

4. Discussion

4.1. Source states

We have analysed optical light curves and spectra of 4U 0115+63 spanning over more than two decades, the last 10 years with unprecedented coverage. During this period the source exhibited significant photometric and spectroscopic variability, allowing the definition of source states. The intensity of the optical, infrared and X-ray emission highly correlates with the state of the source. Figure 5 shows the historical record (1980–2006) of the R band and Hα equivalent width (EW(Hα)) of V635 Cas. Squares and stars in the top panel of Fig. 5 represent observations taken from Mendelson & Mazeh (1991) and Negueruela et al. (2001), respectively. Squares in the EW(Hα) panel are from Negueruela et al. (2001) and crosses from Kriss et al. (1983). Circles correspond to our new measurements. Vertical dashed lines denote the occurrence of X-ray outbursts. The striking repeatability of the pattern of variability during the periods 1986–1990 and 2002–2005: a photometric faint state is followed by an optical flare with a slow gradual rise (200–300 days) and a fast decay (70–80 days). An X-ray outburst occurs when the source is in a photometric bright state. A second optical eruption separated from the previous one by about 250 days is not accompanied by X-ray activity. This second optical eruption presents a more symmetric profile with a fast rise and equally fast decay. Mendelson & Mazeh (1991) also reported the presence of a small flare after the second eruption, peaking in June 1988 (MJD 47 340) with an amplitude of ~0.3 mag and duration of 50 days. Exactly the same event is seen 17 years after (MJD 53 585). If the source follows the same pattern as in the late 1980’s, then we should expect the source to remain in a low photometric state until spring 2007 and to start a new optical outburst soon after. The overall difference of ~0.25 mag between the Mendelson & Mazeh’s and our data set is most likely due to instrumental as well as calibration (selection of different secondary standard stars) effects, as no attempt to perform absolute photometry was made in Mendelson & Mazeh (1991). The optical/IR/X-ray behaviour of 4U 0115+63/V635 Cas can be understood in terms of the evolution of the equatorial disc around the Be star. Two basic states can be distinguished depending on the presence or absence of the disc.

4.1.1. The low state

The low state would correspond to the complete loss of the disc or to a highly debilitated disc. During the low state, the source shows the weakest magnitudes, the bluest colours and the smallest Hα equivalent widths (EW(Hα)). The source exhibits little variability, with changes in the photometric bands of less than 0.05 magnitudes. Orbital modulation is detected. Since the source can stay in the low state for extended periods (a few years), the term “extended low state” (ELS) is used (Roche et al. 1993). During the low state the source is X-ray quiet. A discless state occurs when the Hα line displays an absorption profile. According to our interpretation of the long-term light curve shown in Fig. 6, 4U 0115+63 would have gone through ELS during MJD 48 600–49 300 (1991–1993), MJD 50 300–50 900 (1996–1998) and MJD 52 000–52 800 (2001–2003).

The issue of whether the disc completely vanishes during the low state or there still exists some residual emission from a highly debilitated disc is a very important question, since in the case of total loss one can decouple the disc emission from that of the central star and hence determine the astrophysical parameters of the underlying star without any interference from the disc (Paper I). Disc-less states in 4U 0115+63 occurred in 1997 and 2001 as the Hα line appeared in absorption. Further support for the complete disappearance of the disc in 2001 comes from the fact that the standard deviation of the photometric magnitudes during this state does not follow any trend as a function of wavelength (see Sect. 3.1). Disc activity is expected to affect the redder magnitudes more than bluer magnitudes, hence making the IR magnitudes appear more variable. Also, from the power spectral analysis we observed that when the disc is present a beat period between the orbital period and presumably the precession period of the disc was found. Then the fact that no such beat frequency is detected during the ELS but only a low-amplitude (~0.01 mag) modulation coinciding with the orbital period seems to indicate the absence of a disc. The 1992 low state would have not been accompanied by the complete loss of the disc as no absorption profile was attained.

The neutron star spins down during the low state. Previous studies have reported spin-up episodes throughout the duration of the X-ray outbursts (see e.g. Tamura et al. 1992). However, the historical record of the spin period hardly shows evidence for variability (see Table 1). Thus, if the neutron star spins up during the outburst, it must spin down in quiescence.

Disc-less phases have been seen in a number of Be/X-ray binaries but only two have been observed frequently enough as to allow a meaningful comparison with 4U 0115+63, namely, A 0535+26 (Lyuty & Zaitseva 2000; Larionov et al. 2001; Clark et al. 1999; Haigh et al. 2004) and X Per (Clark et al. 2001, and references therein). The three systems show extended low states, although its duration differs: ~600 days (MJD 50 700–51 300) for A 0535+26 (Haigh et al. 2004; Zaitseva 2005), ~800 days (MJD 52 000–52 800) for 4U 0115+63 (Fig. 1) and ~1300 days (MJD 47 700–49 000) for X Per (Clark et al. 2001). The long-term photometric light curve of X Per is very similar to that of 4U 0115+63 (cf. Fig. 7 in Clark et al. 2001 with Fig. 1),
The long-term variability of 4U 0115+63 can be summarised as follows: the equatorial disc around the Be star dictates the state of the source. The quasi-cyclic variations coincide with the time scales for disc build-up and loss. X-ray outbursts occur in pairs, although the second one may be missing. Between pairs of outbursts the optical/IR emission and variability is highly suppressed, while in between the outbursts of a given pair the optical/IR emission is highly variable.

This behaviour can be explained within the framework of the truncated decretion disc model (Paper I, Okazaki & Negueruela 2001; Okazaki et al. 2002). Initially, the disc grows gradually like in isolated Be stars. However, in Be/X-ray binaries the surface density of the disc increases more rapidly than that of isolated Be stars, as a consequence of truncation. The truncation of the disc is the result of the resonant torque exerted by the neutron star, which removes angular momentum from the disc. Okazaki et al. (2002) locate the truncation radius of 4U 0115+63 at 0.36−0.39a, where a is the semi-major axis of the orbit, for a wide range of values of the viscosity. The disc becomes optically thick at IR wavelengths and unstable to radiation-driven warping. Eventually, the disc begins to warp, tilt and precess.

The photometric variations observed during the high states (1987−1989, 2003−2005), characterised by large (≥1 mag) and relatively fast (~100 days) amplitude variations, are rather large when compared to typical values seen in isolated Be stars (Dachs et al. 1988). In addition, the brightest magnitudes are accompanied by historic maxima of the EW(Hα). These extreme values of the EW(Hα) correspond to line shapes much narrower than at other times. In the framework of the disc decretion model, the coincidence of very high values of the EW(Hα) with narrow, single-peaked lines and very bright optical and infrared
magnitudes during the high state, leads to the conclusion that extreme values happen because the disk becomes warped and occasionally presents a much higher surface to the observer (see Paper II). Therefore the changes in magnitudes should be the consequence of two different effects: on the one hand, an increase in the disk size or density; on the other hand, a change in the emitting surface observed. They should not be interpreted as fast phases of disc loss and reformation, despite the fact that the photometric magnitudes fall to ELS values. This strongly disturbed phase would begin after the first outburst.

One possible explanation for the difference between the first and second outburst could be the different state of the disc, with the first one occurring when the disc is still in a quasi-stable state while the second one when the disc has been distorted. The distortion of the disc leads to the interaction with the orbiting neutron star. If the interpretation of the 22.15 days period (sect. 3.4) as the beat period between the orbital period and precession is correct, then the time scales associated with the perturbed disc (~250 d) would be a factor ~2 longer than the duration of the optical eruption associated with the missing X-ray outburst (~150 d). In this context the missing outburst would simply reflect the fact that no interaction between the neutron star and the distorted disc took place during the ~6 orbits that the optical eruption lasted.

An alternative explanation for the missing X-ray outburst requires the formation of an accretion disc around the neutron star (Mendelson & Mazeh 1991) and it is based on the centrifugal inhibition at the edge of the neutron star magnetosphere (Stella et al. 1986). In the 1988 and 2005 events the matter accumulated in the disc would not be enough to overcome the propeller effect.

The (B–V) colour index appears as a good indicator to distinguish between the two outbursts. While the (J–K) colour (also (V–R) and (R–I), not shown in Fig 1) follows smoothly the state of the disc, (B–R) is rather insensitive to photometric or spectral changes. Only prior to the destructive outburst of September 2000 does it display high amplitude variability (Fig. 1).

In addition to the missing outbursts, the fact that the first X-ray outburst does not modify, at least dramatically, the strength of the Hα line also needs to be explained. In this respect, one may wonder how much of a disruption an X-ray outburst represents. As an order of magnitude estimate, we can derive the mass content in the disc simply as

\[ M = \int \rho \, dV \]

with \( \rho = \rho_0 (R_*/r)^n \) and \( dV = 2\pi r H dr \). Here \( \rho_0 \) is the density and the inner radius of the disc \( (at \ r \sim R_*) \), \( R_* \) the star radius, \( H \) the disc height and \( n \) an exponent defining the density law. According to Waters et al. (1988) \( n \) varies in the range 2–4 in most BeX.

The typical radius of a B0.2 star, \( R_* = 8 \, R_\odot \) and assuming typical values for the disc radius \( R_d = 5 \, R_* \), and inner density \( \rho_0 = 10^{-10} \, g \) (Telling et al. 1998) cm\(^{-3}\) and \( H = 0.03 \, R_\odot \), (Negueruela & Okazaki 2001) the mass is estimated to be \( 2.6 \times 10^{-5} \, M_\odot \) for \( n = 2 \) and \( 7.8 \times 10^{-11} \, M_\odot \) for \( n = 4 \).

On the other hand, a mean X-ray luminosity of \( 10^{37} \, erg \, s^{-1} \) for about a month requires the transfer of \( M = L_x / (GM) = 5.4 \times 10^{16} \, g \, s^{-1} \) or \( 7 \times 10^{11} \, M_\odot \) month\(^{-1}\), that is just \( \leq 10\% \) of the mass in the disc. This relatively small effect on the mass content of the disc would explain the fact that the strength of the Hα line does not change much after the first outburst (see also Norton et al. 1994).

5. Conclusion

We have presented the results of our monitoring of the Be/X-ray binary 4U 0115+63/V635 Cas. Our 2000–2006 data represent the most complete optical and infrared photometric study of 4U 0115+63/V635 Cas made up to now. The combination of our observations over the last decade with published data allowed us to investigate the correlation between the optical, infrared and X-ray emission. X-ray outbursts, which come into pairs, occur when the source is photometrically bright and the Hα line appears strongly in emission. The equatorial disc around the Be star dictates the state of the source: if the disc is absent the source is in the low state. In the high state large amplitude variation and asymmetric spectral lines denotes a disturbed disc. The time scale for loss and build-up of the equatorial disc is 5 years, approximately 3 of which correspond to the high state and 2 to the low state. However, this quasi-periodic behaviour is broken if one of the X-ray outburst is missing. In this situation the high state covers the entire cycle. Bright magnitudes are observed because the disc warps and presents a larger surface to the observer. The fact that the infrared and optical magnitudes and the Hα equivalent width do not change dramatically after the first outburst may indicate that, at the time of the outburst, the disc had not been distorted yet. It is after the first outburst that the disc becomes unstable, warps and tilts. The second X-ray outburst takes place during this phase of strongly disturbed disc. The disc finally disappears, partly reabsorbed by the B star and partly used up to power the X-ray outburst.

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