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Multifrequency study of the very slow nova V723 Cas

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Abstract Multifrequency behaviour of the very slow nova V723 Cas is reviewed. The long-term photometry of the object revealed the orbital period 0.693265 days of the binary, quasi-periodic oscillations in the envelope of the outbursted white dwarf and 182 days periodicity of activity due to the mass transfer bursts from the red to the white dwarf probably caused by a periastron passage of the third body. The photometry at the maximum of brightness was used to calculate the velocity $v = 210\,\mathrm{km\,s^{-1}}$ of ejection of an expanding supergiant photosphere — main inner envelope of the nova. The emission line profiles in nebular stage show multiple peaks formed in an expanding equatorial ring and polar blobs of this envelope. The He I line profile and radio observations suggest the existence of the outer envelope, shaped and accelerated by the spherical and polar winds, detected as absorption components of the H I and He I P Cygni type line profiles. Radio observations allowed to determine ejected mass $2.5\times10^{-4}\,\mathrm{M_\odot}$ and confirmed the clumpy structure of the ejecta.

Key words: stars: novae – cataclysmic variables – circumstellar matter: individual: V723 Cas

1 INTRODUCTION

Outburst of a classical novae occur in binary systems and are caused by a thermonuclear runaway of a hydrogen-rich material on the surface of a white dwarf accreting matter from a Roche lobe filling red dwarf companion.

Classical nova V723 Cas (Nova Cas 1995) was discovered by Yamamoto (1995) on August 24, 1995 at visual magnitude of about 9. It gradually brightened over the next few months reaching the maximum brightness of $V_{\mathrm{max}} = 7.09$ and $B_{\mathrm{max}} = 7.59$ on December 16, 1995 (JD 2450068.4). Since then its slow decline in brightness has been characterized by a number of sharp peaks in brightness, some of them exceeded 2 mag. On the basis of the light curve behaviour and early spectra V723 Cas has been classified as a very slow classical nova of HR Del type although it possesses some properties of the symbiotic novae (Munari et al. 1996; Chochol & Pribulla 1997).

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2 PHOTOMETRY

Our photoelectric $UBVR$ observations gathered with the 0.6 m telescopes at the Skalnaté Pleso (SP) and Stará Lesná (SL) Observatories of the Astronomical Institute of the Slovak Academy of Sciences, during the period 1995 – 2000, were complemented by the photoelectric and CCD photometry from other sources. For the references see the papers Chochol & Pribulla (1997), Chochol & Pribulla (1998) and Goranskij et al. (2000). Available UBV observations of V723 Cas are presented in Fig. 1.

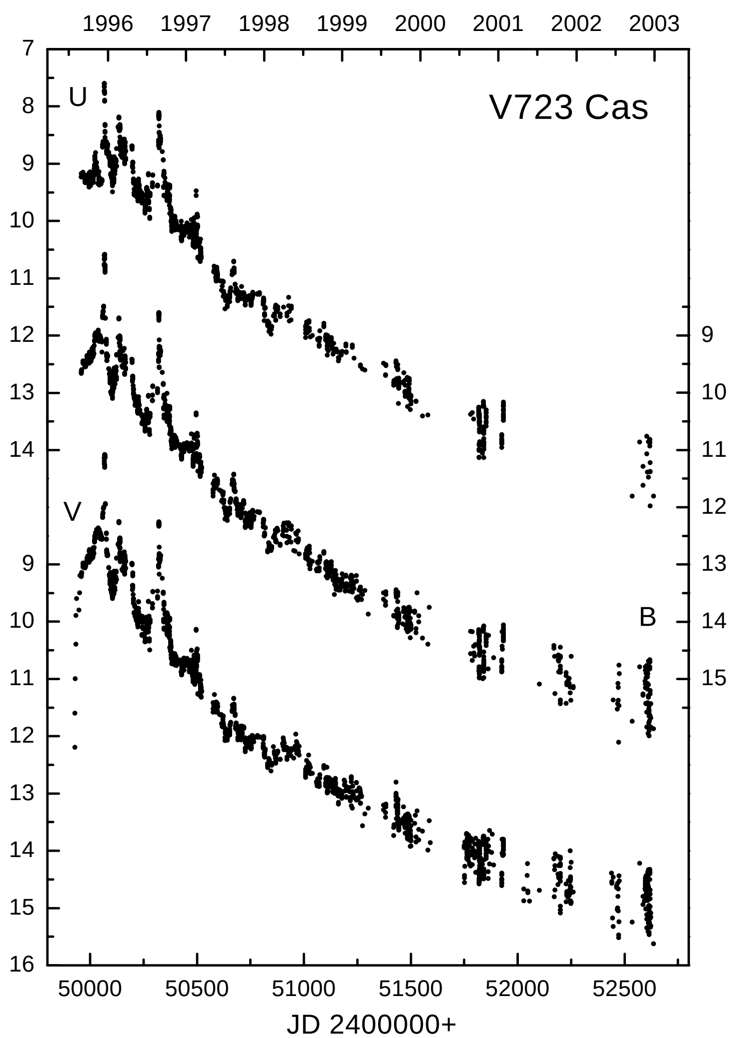

Fig. 1 The U, B, V light curve of V723 Cas.

From the V and B light curves of the nova Chochol & Pribulla (1997) calculated a rate of decline $t_{3,V} = 173{\pm}5$ days and $t_{3,B} = 189{\pm}5$ days and derived (from the maximum magnitude - rate of decline relation) absolute magnitudes of the nova at maximum of $MV_{\rm max} = -6.70{\pm}0.23$ and $MB_{\rm max} = -6.49{\pm}0.32$. They determined the colour excess $E(B-V) = 0.57{\pm}0.01$, in good agreement with $E(B-V) = 0.60$ determined by Gonzales -Riestra et al. (1996) from the strength of 220 nm feature, and estimated the distance to the nova $d = 2.39{\pm}0.38$ kpc. Iijima et al. (1998) estimated the distance and absolute magnitude of the nova at maximum as $d = 2.95{\pm}0.7$ kpc and $MV_{\rm max} = -6.1{\pm}0.5$, respectively. The mass of the white dwarf, calculated from the absolute brightness at maximum using the relation of Livio (1992), is $0.66{\pm}0.05\,{\rm M}_\odot$ (Chochol & Pribulla 1997) and $0.58{\pm}0.07\,{\rm M}_\odot$ (Iijima et al. 1998).

Chochol & Pribulla (1998) studied the evolution of V723 Cas in the two-colour diagram (see Fig. 2) using the $U-B$, $B-V$ colour indices (corrected for reddening) as well as supergiant and blackbody sequences (Flower 1996; Duerbeck & Seiter 1979). They investigated this evolution in the context of an expansion of the supergiant due to a TNR on the white dwarf. The luminosity at maximum exceeded the Eddington luminosity of $24000\,{\rm L}_\odot$ corresponding to a WD mass of 0.66 ${\rm M}_\odot$ The radius of the expanding photosphere reached 67 ${\rm R}_\odot$ at JD 2450069.4 and 109 ${\rm R}_\odot$ ($T_{\rm eff} = 7500$ K, F1 I) at JD 2450071. The derived velocity of expansion of the supergiant atmosphere of $210\,{\rm km\,s}^{-1}$ is in agreement with the velocity of expansion of the main envelope of the nova found from the spectra in nebular stage.

The orbital period of the binary 0.69325 days was determined by Chochol et al. (2000). The ephemeris for brightness minima is:

$$JD_{\rm min} = 2\,450\,421.4801(7) + 0.69325(18)\times E. \qquad (1)$$

As seen in Fig. 3, the observations in 1996 showed only quasi-periodic oscillations. Since September 1997 the amplitude of the orbital period variations gradually increased. In 1999 the orbital R light curve was strongly asymmetric with the maximum at the phase 0.45 and secondary minimum at the phase 0.6 suggesting that V723 Cas is a highly inclined eclipsing binary. New observations taken by Goranskij et al. (2002) allowed to improve the orbital period of V723 Cas to 0.693265 days. They interpreted the oscillations with the period 0.062 days, seen on the 1999 light curve near the maximum light by radial pulsations of the white dwarf's envelope. The radial pulsations in the envelopes of classical novae were predicted by Schenker (2002).

Chochol & Pribulla (1998) found that the brightness maxima (excluding the main maximum in December 1995) follow the ephemeris:

$$JD_{\rm max} = 2\,450\,136\ (5) + 182\ (2)\times E. \qquad (2)$$

The minima of brightness preceded the maxima by 43±8 days. Observed stages of activity are probably caused by an increase of mass transfer rate in the binary during the periastron passage of the third body in the system with the orbital period 182 days.

3 SPECTROSCOPY

The evolution of the nova was unusually slow. During the long pre-maximum stage, which lasted from August to December 1995, most of the emission lines were accompanied by P Cygni type absorptions. The mean blue shift of the absorption components with respect to the emissions was about $-126\,{\rm km\,s}^{-1}$ in September 1995 and $-96\,{\rm km\,s}^{-1}$ in December 1995 (Iijima et al. 1998). A pure F-type supergiant spectrum appeared at maximum brightness on December 19, 1995.

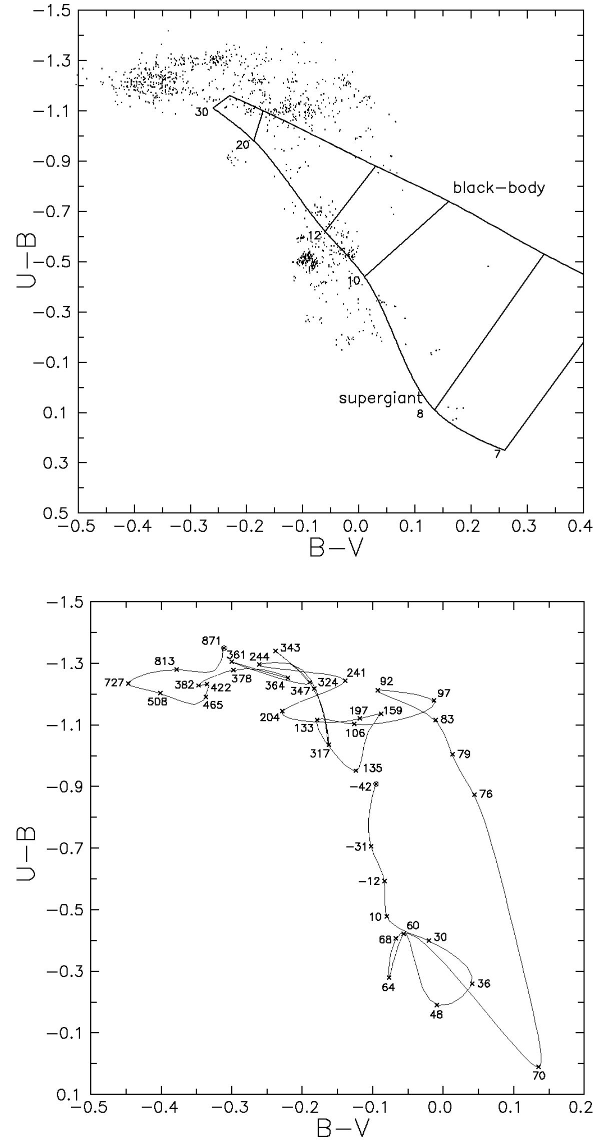

Fig. 2 The two-colour diagram for dereddened indices. The blackbody and supergiant sequences are connected by the isothermal lines corresponding to indicated temperatures $\times 10^3$K (top). The evolutionary path was constructed using two-day averages and the cubic spline. The important dates are given in JD−2 450 000 (bottom).

UV IUE spectroscopic observations were obtained on September 22, 1995; December 22 and 23, 1995 and January 6 and 17, 1996. The first spectrum showed a sloping continuum increasing toward longer wavelengths characteristic of the fireball phase. The spectrum during optical flare in December 1995 showed a dramatic increase of the iron peak absorption shortward of 170 nm. High-resolution spectra taken at January 6, 1996 show a weak emission feature at Mg II 280 nm with a broad P Cygni absorption extending to $-500\,\mathrm{km\,s^{-1}}$. The [N III] 175 nm and [C III] 191 nm appeared, characteristic of the prenebular phase (Gonzales- Riestra et al. 1996).

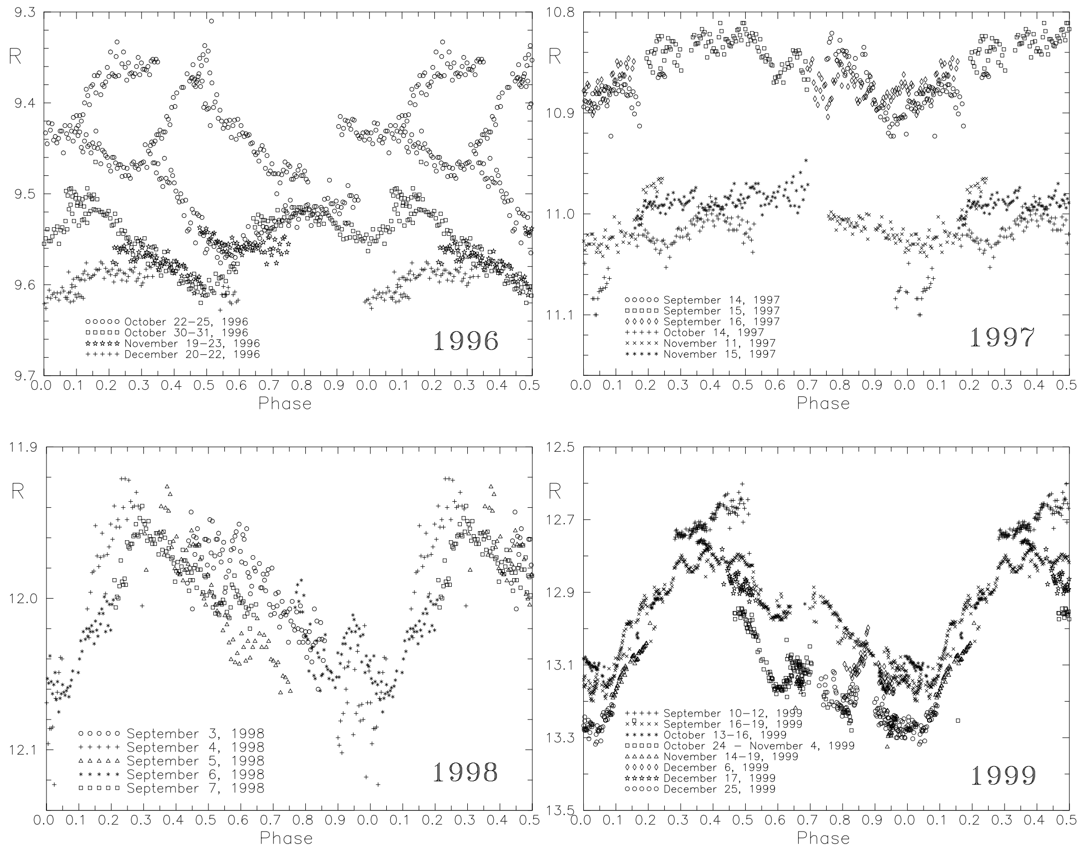

Fig. 3 1996 to 1999 evolution of the orbital R light curve of V723 Cas. The 1996–1998 R data are in the instrumental system. The phases were calulated using the ephemeris (1).

Our spectroscopic observations were taken with the 2.5 m Isaac Newton and 4.2 m William Herschel Telescopes on La Palma, Canary Island, the 6 m and 1 m telescopes at the Special Astrophysical Observatory, Russia and 1.82 m telescope at the Asiago Astrophysical Observatory, Italy, in the period December 1995 – November 2000.

The behaviour of the line profiles was described by Chochol et al. (2000) using the kinematic model of an expanding envelope derived by Chochol et al. (1997) for the nova V1974 Cyg. The spectra of V723 Cas in opticaly thick stage exhibited broad H I and He I emissions accompanied by P Cygni absorptions suggesting the presence of a stellar wind with terminal velocity of 1600 – 2000 $\mathrm{km\,s^{-1}}$ which appears to consist of two components (spherical and polar). Between August 1996 and March 1997 their radial velocities changed from $-1080\,\mathrm{km\,s^{-1}}$ to $-1600\,\mathrm{km\,s^{-1}}$ and from $-690\,\mathrm{km\,s^{-1}}$ to $-800\,\mathrm{km\,s^{-1}}$, respectively. In August 1996, an outer envelope was detected in He I 6678 nm line. The profile consists of two emission peaks on the red side of the emission line profile with radial velocities 280 $\mathrm{km\,s^{-1}}$ and 470 $\mathrm{km\,s^{-1}}$. Both components are detected also as P Cygni absorptions on the blue side of the profile. The emission line profiles of H I, He I and [N II] in nebular stage (after June 1997) show multiple peaks formed by an expanding equatorial ring and polar blobs of the main inner envelope. The ring expands with velocity 210 $\mathrm{km\,s^{-1}}$, corresponding to the ejection velocity of the expanding supergiant photosphere found from the photometry. Kinematic model suggests a large inclination angle of the underlying binary system. During the mini-outburst, detected photometrically in August 1997, the spectra exhibited very broad C III and C IV WR features accompanied by the broadening of He II and disappearance of [Fe V-VII] emission. Before, during and after the mini-outburst the spectra also exhibit typical emission features of an expanding envelope.

We suggest that the physical nature of the brightness increases differs during the various stages of activity. The main outburst in 1995, when the white dwarf evolved to F supergiant, was caused by a strong degenerate flash (a TNR). However the mini-outburst in August 1997 (and by inference perhaps the other flares seen during the decline), when the spectra in maximum showed some features seen in Wolf-Rayet spectra, was caused by a non-degenerate flash on the hot white dwarf.

Near-infrared spectroscopy (0.8–2.5 microns) of V723 Cas was done on August 29, 1999 and July 20, 2000 with the 3 m Shane reflector of the Lick Observatory (Lynch et al. 2000, Rudy et al. 2002). The spectrum resembled that of a late-type classical nova, displaying forbidden lines of single and double ionized sulphur and neutral nitrogen and lines H I, He I and He II. The strongest feature was He I 1.083 microns. Very strong coronal lines of [Si IV] at 1.9629 microns, [Ca VIII] at 2.3214 microns, [Si VII] at 2.4827 microns and new coronal line [Ti VII] 2.2050 microns were detected. The underlying continuum decreased toward the red and was indicative of a free-free emission.

4 RADIO OBSERVATIONS

Radio observations were taken by MERLIN (Multi-Element Radio-Linked Interferometer Network), Jodrell Banks array of 6 observing stations that form a powerful telescope with an effective aperture of over 217 km. At a wavelength 6 cm MERLIN has a maximum resolution of 40 miliseconds of arc (comparable to the HST). Between December 13, 1996 and October 26, 2001 nova V723 Cas was observed by MERLIN interferometer in nine epochs at a wavelength 6 cm and one at 18 cm.

The typical mechanism for the production of radio emission in novae is a thermal free-free process. The radio light curve undergoes an initial rise followed by a turnover (in V723 Cas occurred 940 days after visual maximum) and then a decline. During the first optically thick phase the shell expands with the radio photosphere coincident with the outer boundary of the shell. The second phase starts when the source becomes partially optically thin and the outer shell begins to lag behind the outer edge of the expanding shell. During the final phase the shell is optically thin.

Physical parameters of the V723 Cas shell were obtained by Heywood et al. (2002) fitting its radio light curve by the solution of radiative transfer equations for the model of Hjellming et al. (1979). After the outburst the outer edge of an isothermal sphericall shell of ejecta with the temperature 23 000 K and mass $2.5\times10^{-4}\,M_\odot$ expanded with constant velocity $v_2 = 370\,\mathrm{km\,s^{-1}}$. Ejection terminated at switch-off time $t_s = 145$ days. An inner boundary to the shell was formed which subsequently expanded with the velocity of $v = 210\,\mathrm{km\,s^{-1}}$.

The radio maps of V723 Cas at 6 cm, published by Heywood et al. (2002), can be described as follows. The initial observation on December 13, 1996 found an unresolved point. The source started to be resolved on March 4, 1998 and it was well resolved on December 7, 1998. The angular extent of the shell at these epochs was larger than predicted size for the accepted distance 2.4 kpc and ejected velocity $210\,\mathrm{km\,s^{-1}}$ of the main inner envelope. It means that the more extended outer envelope was detected at these epochs. Further expansion of the shell and transition to the partly optically thin phase II was evident on February 27, 2000. Predicted size of the main inner envelope was consistent with the observed extent of the radio emission.

The inner envelope started to reveal its internal structure - density enhancements connected with the equatorial ring and polar blobs. Two components aligned on north-south were visible on April 16, 2000. The radio map from January 29, 2001 showed two components aligned on east-west. Thereafter, the emission gradualy faded.

The radio data are important for the study of initial phases of remnant ejection and shaping. The interaction within the ejecta and with the binary companion, combined with accretion disk shadowing, could help to understand the structures revealed in radio maps.

5 SUMMARY

The long-term $UBVR$ photometry of the classical very slow nova V723 Cas allowed to determine the orbital period 0.693265 days of the binary consisting of the red dwarf filling the Roche lobe and the white dwarf with the mass $0.66\,M_{\odot}$. The outburst of the nova in 1995 was caused by the degenerate flash on the surface of the white dwarf. The photometry of the main maximum in December 1995 was used to calculate the ejection velocity $210\,\mathrm{km\,s^{-1}}$ of the expanding supergiant photosphere. The 182 days periodicity of flares, seen on the post-outburst light curve, can be explained by the mass transfer bursts from the red to a white dwarf and are probably caused by the periastron passage of the third body in the system. The quasi-period oscillations of brightness, detected in the post-outburst light curve, can be explained by the radial pulsations of the white dwarf envelope.

The optical spectra of V723 Cas revealed the structure of the expanding shell of the nova. The broad H I and He I emissions accompanied by P Cygni absorptions in optically thick stage suggest the presence of a spherical and polar winds which shaped and accelerated the outer envelope detected in He I 6678 nm line profile in August 1996. The equatorial ring and polar blobs of the inner envelope was detected as multiple peaks in emission HI, He I and [N II] line profiles in nebular stage (after June 1997). The ring expanded with velocity $210\,\mathrm{km\,s^{-1}}$, corresponding to the ejection velocity of the expanding supergiant photosphere found from the photometry. Kinematic model suggests a large inclination angle of the underlying binary system. During the flare (mini-outburst), detected photometrically in August 1997, the spectra exhibited very broad C III and C IV WR features accompanied by the broadening of He II and disappearance of [Fe V-VII] emission. The mini-outburst was caused by a non-degenerate flash on the hot white dwarf.

The radio observations taken between 1996 and 2001 revealed an expanding non-uniform shell with varying optical depth. A radiative transfer model was applied to the radio light curve to determine the basic physical parameters of the shell as the ejected mass $2.5\times10^{-4}\ M_{\odot}$ or the outer and inner shell velocity $370\,\mathrm{km\,s^{-1}}$ and $210\,\mathrm{km\,s^{-1}}$, respectively. The radio observations confirmed the clumpy structure of the ejecta.

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DISCUSSION

J.H. BEALL: Regarding the February 2000 Merlin data, can you comment on its structure.

D. CHOCHOL: The 6cm MERLIN radio map of the nova V723 Cas, taken on February 27, 2000, showed that the expanding shell became partly optically thin and started reveal its non-uniform internal structure. The density enhancements arised in an equatorial ring and polar blobs of the main inner envelope.