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Long-term monitoring of orbital modulation and secondary-star irradiation in Nova Cas 1995 (V723 Cas)

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ABSTRACT

We present optical spectroscopy collected at seven epochs and $BVR_{C}I_{C}$ photometry obtained at 1227 epochs of nova V723 Cas, covering the time interval between 2007 and 2015. The mean magnitude during this period, stable at ∼3 mag brighter than in quiescence, and the continuous presence of strong [Fe X] and other high-ionization emission lines, indicates that the nuclear burning at the surface of the white dwarf is continuing 20 years past the initial outburst. The light curve shows a large amplitude (2 mag) orbital modulation, which is governed by the visibility of the irradiated side of the secondary star. Our observations do not confirm the reported increase with time of the orbital period of V723 Cas, a period of P=16.638 383 ± 0.000 025 h satisfying equally well all available observations in all bands. Our observations also do not confirm the presence of an additional periodicity around P=15.2397 h from which V723 Cas was classified as an intermediate-polar system.

Key words: novae, cataclysmic variables.

1 INTRODUCTION

V723 Cas (Nova Cas 1995) is a classical nova that has been intensively studied, thanks to the favourable position on the sky (circumpolar for many of the Northern hemisphere observatories), peak brightness (V=9.2), and extremely slow evolution. It lingered around maximum for more than a year and experienced several secondary maxima before entering the tediously slow decline that followed.

The outburst of V723 Cas has been densely covered by optical spectroscopic observations in both high- and low-resolution modes. Detailed reports covering different parts of the overall evolutions were presented by Munari et al. (1996), Iijima, Rosino & della Valle (1998), Iijima (2006), and Goranskij et al. (2007). Around first outburst maximum, V723 Cas displayed a typical Fe II-type nova, with remarkably sharp emission lines and very low velocity P-Cyg absorption components. At later times and after the following maxima, higher velocities were attained by both the absorption components and the width of emission lines. V723 Cas took an extremely long period of time to reach the nebular stage, 18 months, surpassed only by nova V1280 Sco that required 50 months (Naito et al. 2012). A striking feature of optical spectra of V723 Cas has been the presence of many strong high-ionization emission lines, especially [Fe VII], and of the coronal line of [Fe X] at 6375 Å, which for many years has been among the strongest emissions. [Fe X] was generally reported as the highest ionization coronal line seen on V723 Cas, while Goranskij et al. (2007) proposed a weak emission line at 6501 Å as due to [Fe XVII].

Large sets of optical photometric data of V723 Cas have been published by Munari et al. (1996), Chochol & Pribulla (1997, 1998), Goranskij et al. (2002, 2007), Chochol et al. (2003), and Shugarov et al. (2005). Apart from the complex behaviour around maximum, these photometric studies show that V723 Cas progressively slowed the decline until in ∼2003 it entered a long-lasting plateau in parallel with persistent supersoft X-ray emission (SSS phase). The plateau is $\Delta B \sim 3$ mag brighter than quiescence and it is characterized by a strong orbital modulation with a period of 16.64 h and an amplitude of ∼2 mag, indicating a large orbital inclination.

Ness et al. (2008) observed V723 Cas with the *Swift* satellite at several epochs during 2006–2007, and found that V723 Cas was still an active SSS X-ray source more than 12 year after the initial outburst, with a temperature of $\sim 4 \times 10^5$ K, and a bolometric luminosity $\geq 1300\,L_{\odot}$, suggesting protracted nuclear burning on the white dwarf (WD). The fuel could be material left on the WD surface after the initial explosion, but there is also the intriguing possibility that it is provided by renewed accretion. In the case of renewed accretion (a scenario favoured by Schaefer & Collazzi 2010), Ness et al. (2008) pointed out the possibility that V723 Cas turn into a stable SSS source, like the prototypes Cal 83 and Cal 87.

Infrared photometry covering the initial 1.5 years of the outburst of V723 Cas was reported by Munari et al. (1996) and Kamath & Ashok (1999), who found no evidence for dust condensation and the IR emission originating from the pseudo-photosphere within the ejecta and free–free transitions in the ionized gas above it. Absence

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Table 1. Journal of spectroscopic observations. Δt is counted from primary optical maximum (1995 December 17), the phase is computed following equation (1).

Date	UT (mid)	Phase (mid)	t (d)	Expt. (s)	Disp (Å pixel^{-1})	Range (Å)	Telesc.
2006 Oct 27	00 18	0.025	3967	3600	4.23	3500–7785	1.82 m+AFOSC
2008 Sep 10	22 50	0.013	4651	3000	2.31	3600–7100	1.22 m+B&C
2009 Aug 27	01 20	0.019	5002	2400	2.31	3600–7100	1.22 m+B&C
2011 Dec 27	18 04	0.991	5854	3600	2.31	3330–7560	1.22 m+B&C
2013 Dec 10	20 04	0.017	6568	3600	2.31	4500–8000	1.22 m+B&C
2014 Nov 03	00 51	0.003	6896	3900	2.31	3350–8050	1.22 m+B&C
2015 Mar 07	19 32	0.989	7020	3600	2.31	3600–7200	1.22 m+B&C

of dust was confirmed by space and ground-based IR observations reported by Evans et al. (2003). The infrared spectrum was initially dominated by H and He recombination lines, and at later times by coronal lines, that Evans et al. (2003) inferred to be results of collisional ionization rather than photoionization. A reddening of $E(B-V)$=0.78 was derived from the H recombination lines by Evan et al. (2003). The intrinsic sharpness of V723 Cas lines, due to the low ejection velocity, allowed Rudy et al. (2002) to identify a large number of new infrared lines. Infrared imaging with *HST*-NICMOS by Krautter et al. (2002) did not detect spatially extended emission around V723 Cas. Spatially resolved, multi-epoch infrared spectra by Lyke & Campbell (2009) allowed them to recover the geometry of the extended nebula around the nova caused by the expanding ejecta, which appears different depending from the emitting ion, from an equatorial ring with polar nodules for [Si VI] and [Ca VIII], to a prolate spheroid for [Al IX]. The distance to the nova was estimated to be $3.85^{+0.23}_{-0.21}$ kpc.

Interferometric radio observations that spatially resolved the ejecta of V723 Cas were presented and modelled by Heywood et al. (2005) and Heywood & O'Brien (2007). Observing limitations did not allow them to firmly establish if – at radio wavelengths – the resolved ejecta were displaying a mainly spherical or aspherical shape. The expansion velocity was found to be $\sim$100 km s^{-1} at the inner edge of the expanding shell, and $\sim$400 km s^{-1} at its outer edge.

Photometric and spectroscopic evolution of V723 Cas after 2006 is basically undocumented. In this paper, we present our long-term $BVR_{\rm C}I_{\rm C}$ photometric monitoring of the nova during the time interval 2007 November 6 to 2015 March 12, that in addition to documenting the protracted plateau phase also provides nicely mapped orbital modulations at five distinct epochs. In addition, we present optical spectra, all obtained at the same orbital phase corresponding to minimum optical brightness, at seven epochs evenly distributed between 2006 October 27 and 2015 March 3, to document the very slow spectroscopic evolution characterizing the protracted plateau phase the nova is experiencing.

2 OBSERVATIONS

To monitor the spectroscopic evolution of V723 Cas, we observed it at seven distinct epochs while it was passing at the photometric minimum during the orbital motion, i.e. always at the same orbital phase to avoid introducing spurious differences due to the changing aspect along the orbital motion. Even if this required much longer exposures, we selected to observe V723 Cas at photometric minima in order to suppress the glare from the irradiated side of the companion star (in full view at photometric maximum) and thus focus on the WD, its wind, the accretion disc and the hotspot where changes were more likely to occur. A log of the spectroscopic observations is presented in Table 1. Low-resolution spectra were obtained with the 1.22 m telescope + B&C spectrograph operated in Asiago by the Department of Physics and Astronomy of the University of Padova. The CCD camera was a ANDOR iDus DU440A with a back-illuminated E2V 42-10 sensor, 2048 × 512 array of 13.5 μm pixels. The spectroscopic observations were obtained in long-slit mode, with the 2- arcsec-wide slit rotated to the parallactic angle. The spectral resolution was close to 2.4 pixels (5.5 Å) on all epochs, corresponding to 340 km s^{-1} at H β. A single low-resolution spectrum was obtained in service mode with AFOSC spectrograph and imager at the Asiago 1.82 m telescope. The slit with was 1.26 arcsec wide, east–west aligned, and the detector a Tektronix 1024 × 1024 CCD.

$BVR_{\rm C}I_{\rm C}$ CCD photometry of V723 Cas was obtained at 1227 distinct epochs over the time interval 2007 November 6–2015 March 12, with the Asiago 67/92 cm Schmidt camera and telescopes N.40 and 164 operated by ANS Collaboration. Technical details of this network of telescopes running since 2005, their operational procedures, and sample results are presented by Munari et al. (2012). Analysis of the photometric procedures and performances, and measurements of the actual transmission profiles for all the photometric filter sets in use with ANS Collaboration telescopes is presented by Munari & Moretti (2012). ANS telescope N.40 is a 0.50 m *f*/8 Ritchey–Chrétien located on top of Mt Zugna (Trento, Italy) and equipped with Optec $UBVR_{\rm C}I_{\rm C}$ filters. The CCD is an Apogee Alta U42 1024 × 1024 array, 13.5 μm pixels ≡ 0.67 arcsec pixel^{-1}, with a field of view of 12 arcmin × 12 arcmin. ANS telescope N.164 is a Meade 0.35 m *f*/10 located in Rovereto (Trento, Italy), equipped with a 1.6 × focal reducer, an SBIG ST-9 CCD camera, 512 × 512 array, 20.0 μm pixels ≡ 1.87 arcsec pixel^{-1}, field of view of 16 arcmin × 16 arcmin and Omega $UBVR_{\rm C}I_{\rm C}$ filters. Asiago 67/92cm Schmidt telescope is operated by INAF (National Institute of Astrophysics) and it is equipped with an SBIG STL-11000MC2 CCD detector, 4048 × 2672 array, 9 μm pixels ≡ 0.86 arcsec pixel^{-1} , field of view of 58 arcmin × 38 arcmin, and Omega $BVR_{\rm C}I_{\rm C}$ filters.

All photometric observations were carried out so that the nova was always measured simultaneously in two (more rarely three or four) distinct bands. This was necessary for the calibration of the instantaneous colour equations necessary to proper transform the local to the standard photometric system. The measurements were carried out with aperture photometry, the long focal length of the telescopes, and the absence of nearby contaminating stars not requiring to revert to PSF fitting. All photometric measurements were carefully tied to the same local $BVR_{\rm C}I_{\rm C}$ photometric sequence calibrated by A. Henden (private communication) against Landolt (1992) equatorial standards. The adopted local photometric sequence is composed by stars about 1 mag brighter than the nova

Table 2. Our 2007 November–2015 March $BVR_{\mathrm{C}}I_{\mathrm{C}}$ CCD photometry of V723 Cas. The total error budget is given. The observing telescope is identified in the last column (the table is published in its entirety electronic only. A small section is shown here for guidance regarding its form and content).

HJD	yyyy-mm-dd	B		V		R_{C}		I_{C}		ID
2455896.36700	2011 11 30	15.694	0.014	15.268	0.016	14.886	0.009	14.585	0.013	160
2455896.38757	2011 11 30	15.555	0.014	15.139	0.012	14.811	0.011	14.535	0.015	160
2455896.40815	2011 11 30	15.473	0.010	15.072	0.009	14.752	0.008	14.453	0.010	160
2455896.42874	2011 11 30	15.433	0.012	15.014	0.009	14.684	0.008	14.399	0.011	160
2455896.45217	2011 11 30	15.346	0.011	14.919	0.008	14.637	0.010	14.332	0.012	160
2455896.47276	2011 11 30	15.309	0.010	14.911	0.010	14.597	0.009	14.323	0.010	160
2455896.49330	2011 11 30	15.257	0.010	14.876	0.011	14.592	0.008	14.300	0.011	160

and covering a wide range in colours for optimal transformation from the local to the standard system. The sequence was intensively tested during the whole observing campaign for linearity of colour equations and for absence of intrinsic variability of any of its constituent stars. The use of the same photometric comparison sequence for all observations at all telescopes ensues the highest homogeneity of the collected data. The median value of the total error budget (defined as the quadratic sum of the Poissonian error on the nova and the formal error of the transformation from the local to the standard system as defined by the local photometric sequence) of the photometric data reported in this paper is 0.013 mag for B and V, and 0.012 for R_{C} and I_{C}. The photometric data are presented in Table 2 (available electronic only via CDS, Strasbourg, at http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/MNRAS/).

3 PHOTOMETRIC EVOLUTION AND ORBITAL MODULATION

The overall B-band photometric evolution of V723 Cas is presented in Fig. 1 (the other photometric bands behaving similarly), where data summarized by Goranskij et al. (2007) are used to cover the initial part (from discovery to early decline), and our data to extend it from 2007 to 2015. Apart from the several distinct maxima and the marked variability affecting the early decline (1998–2000), the most striking feature is the plateau phase where the nova has been trapped during the last dozen years. The shadowed region overlaid to the data points in Fig. 1 is fitting quite well the observed behaviour. It is obtained by adding (in flux) an exponential decline and a constant term at B=15.75, the latter modulated by a sinusoid of total amplitude ΔB=1.95 mag. At the latest observing epochs covered in Fig. 1, the exponential term has essentially nulled its effect, and the system is evolving at constant mean magnitude. This is $\Delta B{\sim}2.8$ mag brighter than quiescence, adopting for it B=18.58 as measured by Goranskij et al. (2007) on DSS Palomar I and II plates. The refusal to return to quiescence makes V723 Cas a member of an exclusive club with other few novae sharing the same behaviour. Schaefer & Collazzi (2010) list among them V1500 Cyg (nova 1975), V1974 Cyg (nova 1992), GQ Mus (nova 1983), CP Pup (nova 1942), V4633 Sgr (nova 1998), RW UMi (nova 1956), and the recurrent nova T Pyx (eight outbursts between 1866 and 2011).

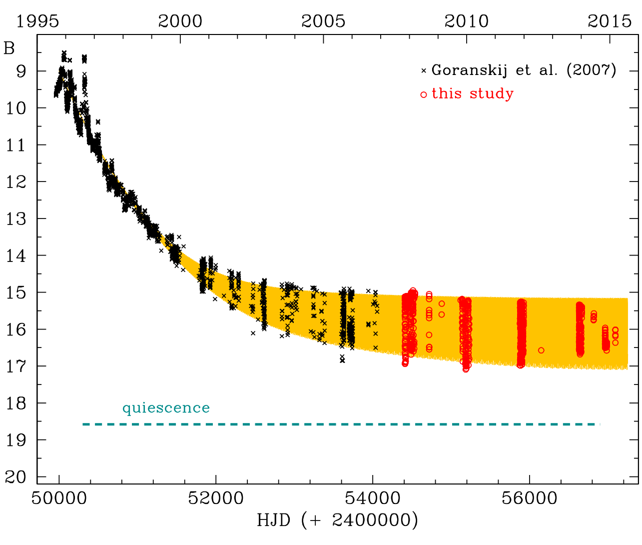

Figure 1. Photometric evolution of V723 Cas in the B band, combining Goranskij et al. (2007) data with ours. The shadowed region is obtained by combining an exponential decline with a sinusoidal modulation centred at B=15.75 and with a total amplitude of ΔB=1.95 mag. The brightness at quiescence (B=18.58) is taken from Goranskij et al. (2007).

As already noted by others (e.g. Shugarov et al. 2005), the light curve of V723 Cas during the plateau phase displays a strong orbital modulation. We have carried out a Fourier analysis of the data in Table 2, separately for the four $BVR_{\mathrm{C}}I_{\mathrm{C}}$ observing bands, which provides a clear detection of the orbital period. Because the observations in the four photometric bands are distributed quite differently in time, the periods obtain from them represents four independent determinations of the true orbital period. Averaging the results for the four bands, we obtain an orbital period of P=16.638 383 ± 0.000 025 h. This is one of the longest orbital period known for classical novae (not considering novae erupting within symbiotic stars where the donor star is a red giant, supergiant or Mira variable). The time of minimum was obtained by fitting Legendre polynomials to the observations in all four bands, which resulted in the following ephemeris for the times of transit through minimum of V723 Cas:

$$T(\mathrm{min}) = 2454\,411.235(8) + 0.693\,266(1) \times E \tag{1}$$

Our observations allow us to densely cover the entire phased light curve of V723 Cas in all four bands at five distinct epochs. The corresponding light curves, phased according to above equation (1), are plotted in Fig. 2. The time intervals (in JD − 245 0000) for these five distinct epochs are: 2007 November 4411 ≤ JD ≤ 4440, 2008 January 4474 ≤ JD ≤ 4538, 2009 December 5117 ≤ JD ≤ 5229, 2011 November 5864 ≤ JD ≤ 5924, and 2013 November 6630 ≤ JD ≤ 6665.

Our determination of the orbital period well compares with previous estimates, that were based on shorter time intervals and noisier data. Goranskij et al. (2000) found a period of 0.693 25 (±0.000 18) days, Goranskij et al. (2002) derived 0.693 265 (±0.000 008), Shugarov et al. (2005) obtained 0.693 26 (±0.000 12), and

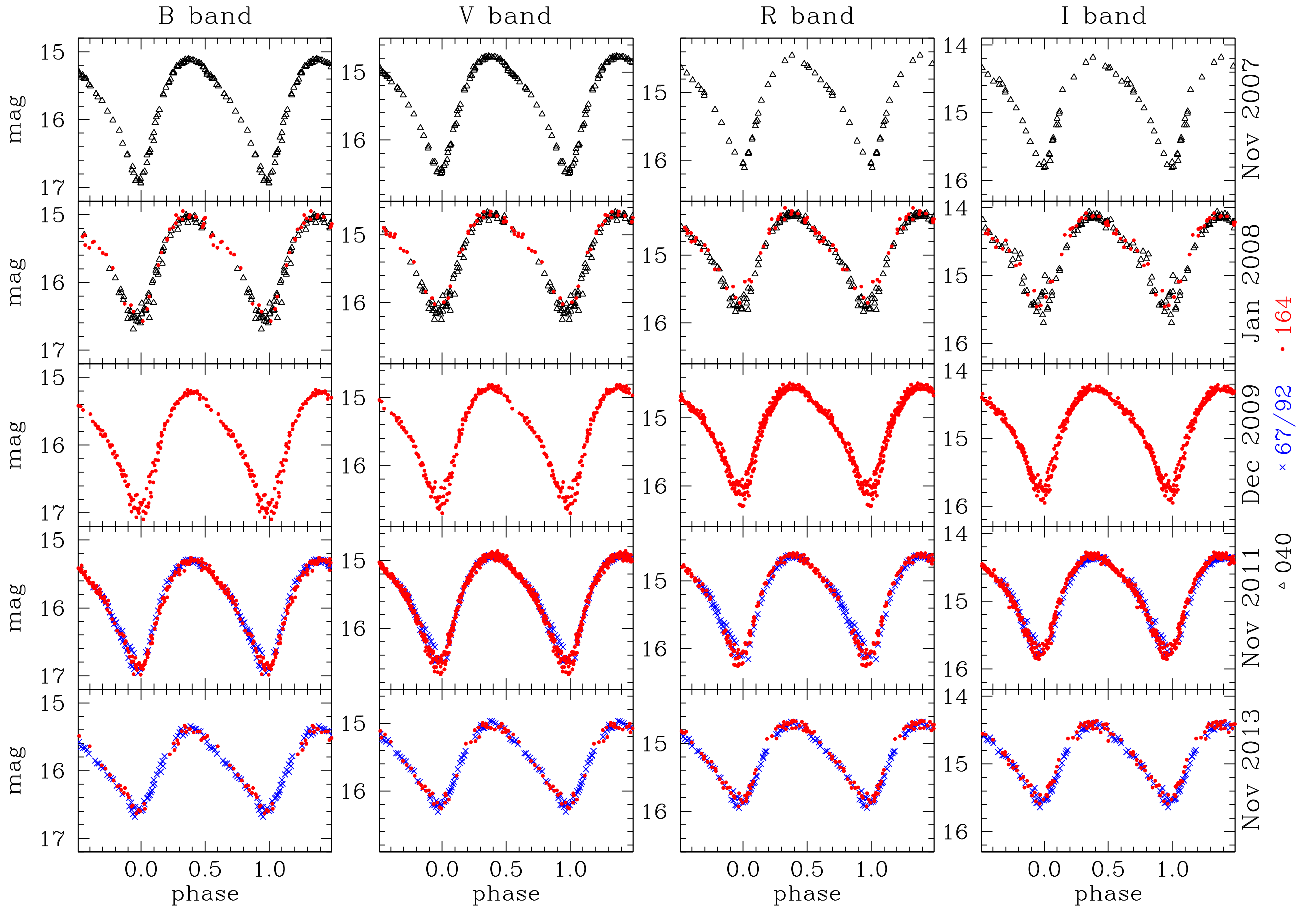

Figure 2. The phased light curves of V723 Cas in the B,V,R_C,I_C bands for the five distinct seasons of our observations (indicated to the right), following equation (1) ephemeris. Different symbols (see legend at the far right) identify the three telescopes used in collecting the data. To facilitate intercomparison, the span on ordinate axis is the same in all panels, and the extrema identical in all panels for a given band.

Goranskij et al. (2007) suggested that different periods apply to different times intervals, from 0.693 265 to 0.693 2773 d.

Goranskij et al. (2007) found a trend in the O−C timing of individual minima, concluding that the orbital period of V723 Cas increased with time during the 1999–2005 interval of their observations. We have checked with our ephemeris (equation 1) the times of 53 individual minima listed by Goranskij et al. (2007), and have found no O−C trend. We conclude that only one and the same orbital period applies to the whole recorded photometric history of V723 Cas. Our observations aimed to uniformly cover the orbital cycle and did not focus on timing of minima. Nevertheless, in a few occasion the data were sufficiently well distributed around a minimum to allow determining its epoch. By spline fitting, we derived the following epochs for eight minima (HJD−245 0000): 4412.623, 4417.468, 4485.404, 5118.369, 5186.316, 5882.335, 5889.274, and 6644.251, with an uncertainty of ±0.011 d for them. They too confirm the absence of any O−C trend.

Chochol & Pribulla (1998) observed V723 Cas during the early decline from maximum, when it was still several years before settling on to the plateau phase. They found a weak periodic signature at P=15.2397 h that produced a poor-looking and noisy light curve resembling that of an eclipsing binary. This period was not found again by later and more extended photometric studies by other investigators. Schaefer & Collazzi (2010), in their comparative analysis of novae struck in long-lasting post-outburst plateau, adopted the P=15.2397 period as real, and from the simultaneous presence of more than one periodicity they concluded that V723 is likely to be an intermediate-polar system. We have searched our data around the additional period proposed by Chochol & Pribulla (1998) but found no trace of it. Phased plots as well as Fourier analysis do not return any statistical meaning for it, either in the direct data or in the residuals after the orbital modulation has been removed. Thus, the additional P=15.2397 period seems spurious.

4 SPECTRAL EVOLUTION

The spectroscopic evolution that V723 Cas followed during the last seven years can be traced with the Asiago spectra plotted in Fig. 3. How the intensity ratio of some diagnostic pairs of lines evolved during this period of time is explored in Fig. 4.

The very high ionization conditions encountered in V723 Cas during the protracted plateau are exemplified by the presence of a strong [Fe X] 6375 Å coronal line. [Fe X] first appeared in 1999 November (Iijima 2006) and has been increasing in intensity afterwards (Goranskij et al. 2007), arguing for protracted nuclear burning at the surface of the WD. Our spectra show that the peak intensity of [Fe X] with respect to nearby Hα and [Fe VII]+[Ca V] 6087 Å was reached during 2008, after which it begun to smoothly decline (cf. Fig. 4). The peak in intensity of [Fe X] should correspond to the time when the pseudo-photosphere around the nuclear burning WD reached its maximum temperature.

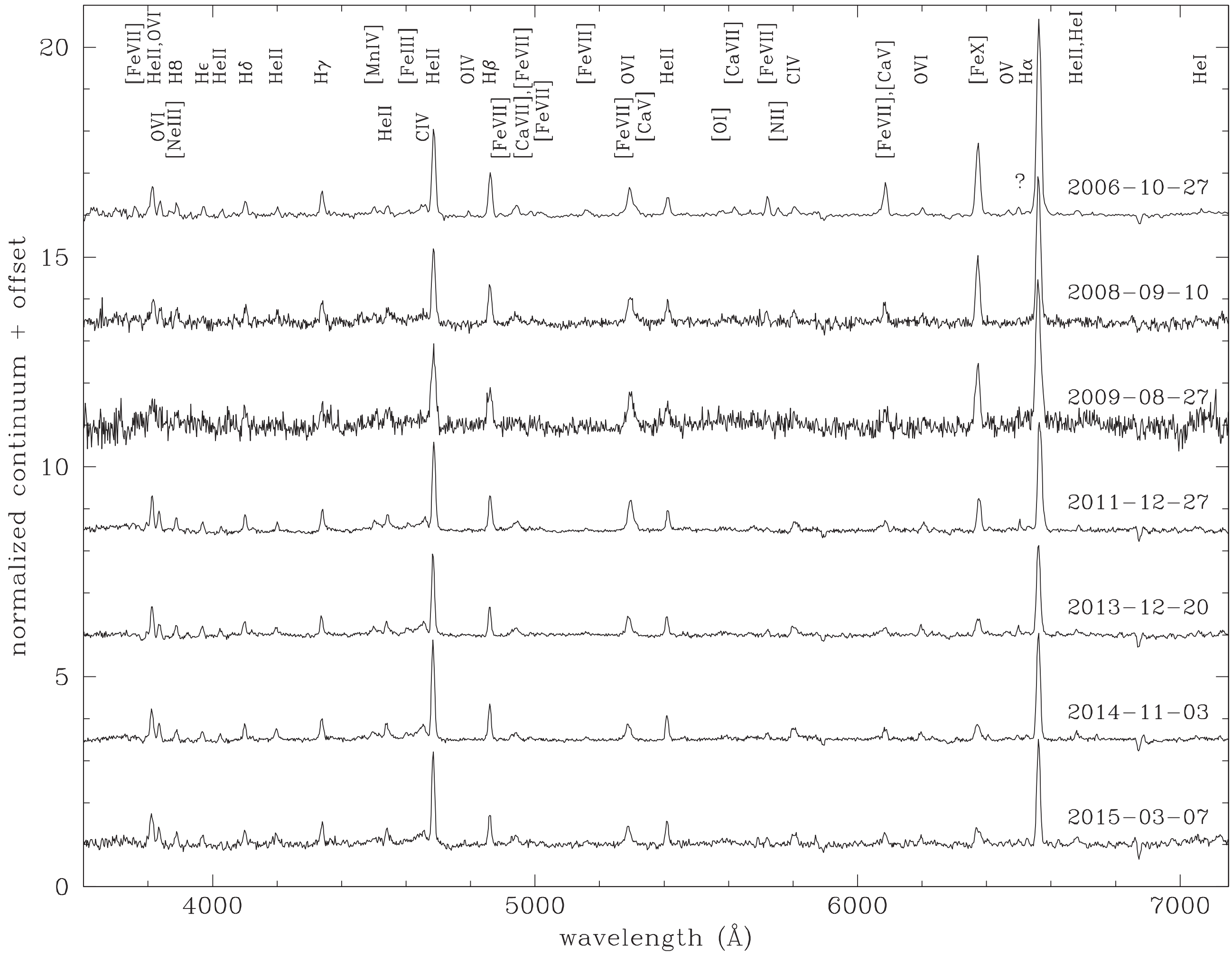

Figure 3. Sequence of Asiago low-resolution, continuum normalized spectra of V723 Cas to highlight the evolution of the nova over the period covered by our photometric observations. To avoid any effect induced by changing orbital aspect, all these spectra have been obtained within 0.025 phase shift (≡30 min) of equation (1) minima.

Overall, the 2006–2015 spectroscopic evolution smoothly followed the preceding recorded history of V723 Cas, with very slow changes that parallel the near constancy of the photometric behaviour. In addition to the rise and fall of [Fe X], our 2006–2015 spectra show a smooth reduction in intensity of high-ionization forbidden lines and a progressively stronger dominance by hydrogen and He II lines, while weak permitted lines from O VI and C IV remained visible throughout. The gradual weakening after 2008 of forbidden lines with respect to permitted ones could be associated with a decrease in the wind blown by the nuclear burning WD. No significant change in profile and width of the emission lines is seen in our spectra in Fig. 3.

The He II 4686/H β ratio has been slowing increasing over the 2006–2015 period, increasing from 1.86 in 2006 to 2.60 in 2015 (cf. Fig. 4). The ratio was 1.00 in 1998, 1.16 in 1999, 1.53 in 2000, 1.43 in 2001 (Iijima 2006), 1.22 in 2002, 1.67 in 2004, and 1.70 in 2005 (Goranskij et al. 2007). This ratio has been used to estimate the surface temperature of the WD under a number of simplifying assumptions, including solar composition. In this way, Iijima (2006) derived an upper limit of 2.0×10^5 K to the temperature of the WD in 1998–1999, that raised to an upper limit of 3.1×10^5 K in 2005 according to Goranskij et al. (2007). Modelling *Swift* X-ray observations for 2006 and 2007, Ness et al. (2008) derived a lower limit to the temperature of $\sim 3.3 \times 10^5$ K. It is worth noticing that the ongoing nuclear burning of H into He at the surface of the WD, should alter the relative abundances of H and He in its envelope and in the blown-off wind. Thus the He II 4686/H β ratio should therefore be used with caution as a proxy for the temperature of the WD, because of the altered chemical partition in the WD wind. Also the possible presence of magnetic fields, strong enough to funnel the accretion towards the magnetic poles and their associated strong shocks, would alter the conditions with respect to the simple photoionization scenario upon which the He II 4686/H β ratio has been used to estimate the temperature.

Goranskij et al. (2007) identified a weak emission line at 6500.5 Å with [Fe XVII]. Our spectra in Fig. 3 show the same line (marked by a '?' symbol) at an essentially constant intensity over the 2006–2013 period, irrespective of the large changes in intensity experienced in parallel by [Fe X]. It is also worth noticing that other coronal lines of an ionization potential intermediate between [Fe X] and [Fe XVII], like [Fe XI] 3987 and [Fe XIV] 5303, are absent from spectra. For these reasons we doubt the identification of the weak emission feature at 6500.5 with [Fe XVII]. This weak emission feature almost disappeared from 2014–2015 spectra.

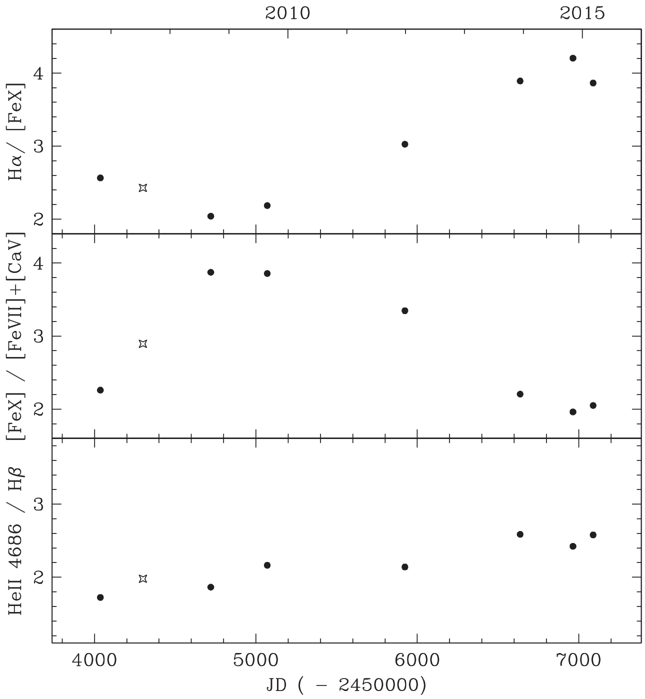

Figure 4. Evolution with time of emission -line ratios from the V723 Cas spectra of Fig. 3 (solid dots). The open symbols are drawn from a spectrum of V723 Cas obtained around minimum brightness on 2007 July 19 with the Russian 6 m telescope (Goranskij, private communication).

5 CONCLUSIONS

Our 2007–2015 photometric monitoring of V723 Cas shows how the system is stable around a mean B=15.75 mag, which is $\Delta B \sim 2.8$ mag brighter than quiescence. As indicated by the persistent presence of coronal emission lines, the WD is still burning hydrogen on its surface 20 years past the nova outburst it underwent in 1995. The light curve is strongly modulated by orbital motion, with a total amplitude of 1.95 mag in the B band, indicating a large orbital inclination. The large amplitude, the stability of minima, and the similarity of the light curves at different epochs and photometric bands suggest that the modulated visibility of the irradiated side of the secondary star is the principal cause for the observed variability.

The marked asymmetry of the phased light curve (the rise to maximum takes ∼1/3 and the decline towards minimum ∼2/3 of the orbital cycle) may easily be ascribed to the hotspot that is displaced from the direction connecting the WD and the secondary star. The high energy deposition on the irradiated side of the secondary may sustain a higher mass transfer and in turn a brighter hotspot compared to the quiescence preceding the nova outburst. The varying intensity of coronal lines indicates that the surface temperature of the WD is varying with time, and consequently the irradiation of the secondary star. Coupled with correlated changes in the mass-transfer rate, which affect the brightness of the hotspot and the accretion disc, they may account for the small differences in the amplitude and minute details of the light curve observed from epoch to epoch.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table_2_electronic_full.dat Our 2007 November–2015 March BVR_CI_C CCD photometry of V723 Cas. (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stv1867/-/DC1).