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Multiple major outbursts from a restless luminous blue variable in NGC 3432

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ABSTRACT

We present new photometric and spectroscopic observations of an unusual luminous blue variable (LBV) in NGC 3432, covering three major outbursts in 2008 October, 2009 April and 2009 November. Previously, this star experienced an outburst also in 2000 (known as SN 2000ch). During outbursts the star reached an absolute magnitude between −12.1 and −12.8. Its spectrum showed H, He I and Fe II lines with P-Cygni profiles during and soon after the eruptive phases, while only intermediate-width lines in pure emission (including He II λ4686) were visible during quiescence. The fast-evolving light curve soon after the outbursts, the quasi-modulated light curve, the peak magnitude and the overall spectral properties are consistent with multiple episodes of variability of an extremely active LBV. However, the widths of the spectral lines indicate unusually high wind velocities (1500–2800 km s^{-1}), similar to those observed in Wolf–Rayet stars. Although modulated light curves are typical of LBVs during the S-Dor variability phase, the luminous maxima and the high frequency of outbursts are unexpected in S-Dor variables. Such extreme variability may be associated with repeated ejection episodes during a giant eruption of an LBV. Alternatively, it may be indicative of a high level of instability shortly preceding the core-collapse or due to interaction with a massive, binary companion. In this context, the variable in NGC 3432 shares some similarities with the famous stellar system HD 5980 in the Small Magellanic Cloud, which includes an erupting LBV and an early Wolf–Rayet star.

Key words: supernovae: general – supernovae: individual: 2000ch – galaxies: individual: NGC 3432.

1 INTRODUCTION

Luminous blue variable (LBV) stars are debated subjects of modern astrophysics, because they signify a key stage in the fate of

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the most massive stars. Such stars may experience an unstable post-main-sequence LBV stage before becoming Wolf–Rayet (WR) stars. LBVs lose most of the hydrogen (H) envelope rapidly (typically $10^{-5}\,M_{\odot}\,yr^{-1}$, up to $10^{-4}\,M_{\odot}\,yr^{-1}$; see, e.g. Humphreys & Davidson 1994), forming massive circumstellar nebulae like the spectacular *Homunculus* surrounding η-Car. Later massive stars eventually explode as type Ib/c supernovae (SNe) (see the case of SN 2001am, Schinzel et al. 2009). However, there is increasing evidence that even LBVs can *directly* explode producing core-collapse SNe (Kotak & Vink 2006; Gal-Yam et al. 2007; Smith et al. 2007, 2008; Trundle et al. 2008; Agnoletto et al. 2009; Gal-Yam & Leonard 2009).

An attempt to characterize LBVs was made by Humphreys & Davidson (1994). However, LBVs do not form a homogeneous group of stars, since they span quite a large range of magnitudes and variability types. Some of them show an S-Dor variability type. During this phase, the star expands and contracts with some regularity over time-scales of years, varying its apparent temperature (and, as a consequence, spectral type). Its bolometric luminosity is generally not thought to change significantly (but see Clark et al. 2009; Groh et al. 2009) and the upper limit to the luminosity/mass ratio for static stellar atmospheres (the so-called 'Eddington limit') is not violated. With S-Dor, other classical examples of this variability type are AG Car in the Galaxy and R 127 in the Large Magellanic Cloud (LMC). As mentioned by van Genderen (2001), the S-Dor variability has typical periods of a few years (*short S-Dor phase*) or decades (*long S-Dor phase*). Other LBVs occasionally experience giant eruptions, during which they increase their luminosity and can reach $M \approx -14$ (4–6 mag brighter than their typical quiescence magnitudes), temporarily exceeding the Eddington limit. The most popular giant eruption of an LBV in our Galaxy is that of η-Car during the nineteenth century.

Spectra of LBVs' giant eruptions are characterized by incipient narrow (with full-width-at-half-maximum velocity, $v_{\rm FWHM}$, lower than $1000\,km\,s^{-1}$) H lines in emission, resembling those of type IIn SNe. For this reason and their relatively high peak luminosities, they are occasionally misclassified as real SN explosions. However, since the stars survive the eruptions, they are labelled *SN impostors* (van Dyk et al. 2000). Well-studied cases are SN 1954J (also known as V12 in NGC 2403, Tammann & Sandage 1968; Smith, Humphreys & Gehrz 2001; van Dyk et al. 2005), SN 1997bs (van Dyk et al. 2000) and SN 2002kg (Weis & Bomans 2005; Maund et al. 2006, 2008).[1] The first registered outburst of the variable star in NGC 3432 discussed in this paper was designated as SN 2000ch (Papenkova & Li 2000; Wagner et al. 2004a). Hereafter, this transient will be dubbed NGC 3432 2000-OT. Contrary to genuine SNe IIn, SN impostors are less luminous and their spectra do not show clear evidence of broad lines (>3000–$4000\,km\,s^{-1}$) produced by SN ejecta. SN impostors will hereafter be referred to without the misleading 'SN' label.

In this paper we will analyse the 2008 October, 2009 April and 2009 November outbursts of the same variable in NGC 3432 that was responsible for NGC 3432 2000-OT (see the wide discussion in Wagner et al. 2004a). We attempt to reconstruct the variability history of this star and derive information on its nature. The paper is organized as follows: in Section 2 we introduce the variable in NGC 3432 and describe its environment. In Sections 3 and 4 photometric and spectroscopic evolutions are presented, while in Section 5 we analyse the evolution of the spectral energy distribution (SED) of the variable. A discussion on the nature of the star follows in Section 6.

2 THE LUMINOUS VARIABLE IN NGC 3432 AND ITS ENVIRONMENT

NGC 3432 is a well-studied irregular galaxy (see, e.g. Ho, Filippenko & Sargent 1997) interacting with a low-surface brightness dwarf companion (UGC 5983), which is located south-west of the main galaxy (Fig. 1). This interacting system is included in Arp's catalogue (Arp 1966) with the label Arp 206. English & Irwin (1997) noted the presence of an extended arm of the galaxy in the north-east direction, which ends with a luminous clump in which the variable star lies. The disturbed morphology of NGC 3432 and the presence of an extended north-east region detached from the main body of the galaxy likely result from the tidal interaction of NGC 3432 with UGC 5983 (see also Swaters et al. 2002; van der Kruit 2007).

Lee et al. (2009) determined for NGC 3432 a star formation rate (SFR) of $0.49\,M_{\odot}\,yr^{-1}$ from UV data, and of $0.32\,M_{\odot}\,yr^{-1}$ from Hα luminosity. Interaction between galaxies is well known to trigger star formation, and the relatively low SFR observed in NGC 3432 may appear as an inconsistency. However, a starburst episode may occur with a significant delay (10^8–10^9 yr) with respect to the major tidal distortions (Mihos & Hernquist 1994). According to English & Irwin (1997) Arp 206 is consistent with this scenario, and would currently be in a pre-starburst phase.

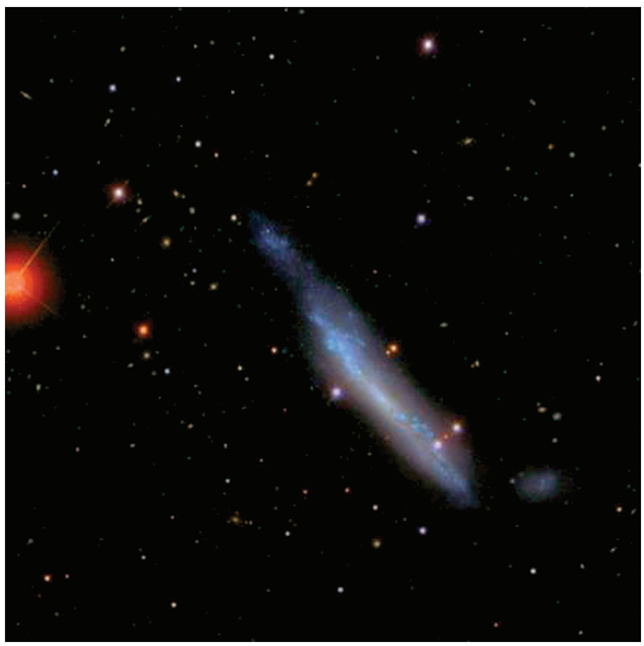

Figure 1. SDSS colour image (http://cas.sdss.org/astrodr6/en/tools/chart/) of the interacting galaxy system Arp 206. The main galaxy is NGC 3432, while the dwarf companion UGC 5983 is located south-west of it. The field of view is about 11 arcmin × 11 arcmin. North is up, east is to the left.

[1]Many other transients have been proposed to be SN impostors, including SN 1999bw (Filippenko, Li & Modjaz 1999; Li et al. 2002), SN 2001ac (Matheson & Calkins 2001), SN 2003gm (Maund et al. 2006), SN 2006fp (Blondin et al. 2006), SN 2007sv (Harutyunyan et al. 2007), SN 2009ip (Foley et al. 2010; Smith et al. 2010). In addition, the controversial SN 1961V, whose nature (SN explosion or LBV outburst) is still debated (Utrobin 1984; Branch & Cowan 1985; Fesen 1985; Cowan, Henry & Branch 1988; Goodrich et al. 1989; Filippenko et al. 1995; Stockdale et al. 2001; van Dyk, Filippenko & Li 2002; Chu et al. 2004), deserves to be mentioned.

Measuring the intensity of the [O II] λλ 7320, 7330 doublet and the intensity ratio of strong [O II] λ 3727 and [O III] λλ 4959, 5007 lines in H II regions, Pilyugin & Thuan (2007) estimated an average O abundance of 12 log (O/H) = 8.3 ± 0.1 dex for NGC 3432 which is comparable to the metallicity of the LMC (∼8.35 dex, Hunter et al. 2007). However, the metallicity in the region of the variable star might be significantly different from this average value.

The distance of the galaxy system is computed through the recessional velocity corrected for Local Group infall into Virgo.[2] The Hyperleda data base[3] gives $v_{\rm Vir} = 779\,{\rm km\,s^{-1}}$, providing a distance of 10.8 ± 1.2 Mpc (distance modulus $\mu = 30.17 \pm 0.56$ mag, adopting $H_0 = 72 \pm 8\,{\rm km\,s^{-1}\,Mpc^{-1}}$, Freedman et al. 2001).

Schlegel, Finkbeiner & Davis (1998) quote a Galactic reddening of $E(B - V) = 0.013$ in the direction of NGC 3432, while the peripheral position of the objects in the host galaxy suggests a modest internal reddening. This is also indicated from the lack of narrow interstellar absorption lines in the spectra of the variable star (see Section 4). Therefore, hereafter we will adopt a total reddening of $E(B - V) = 0.013$ mag, in agreement with Wagner et al. (2004a).

The discovery of a variable star in NGC 3432 on 2000 May 3 UT was reported by Papenkova & Li (2000) at the position $\alpha = 10^{\rm h}52^{\rm m}41\overset{\rm s}{.}40$ and $\delta = +36^\circ40'08\overset{''}{.}5$ (equinox J2000.0), which is 123 arcsec east and 180 arcsec north of the nucleus of the host galaxy. The transient had an unfiltered peak magnitude of $m = 17.4$. A KAIT image was obtained 4 d prior to this on 2000 April 29, showing nothing brighter than $m = 19$ at the position of the variable (Wagner et al. 2004b). The low luminosity and the spectra dominated by narrow Balmer lines were consistent with an SN impostor (e.g. van Dyk et al. 2000). Wagner et al. presented optical plus near-infrared light curves of NGC 3432 2000-OT covering a period of ∼3 months, and noted a somewhat erratic variability over very short time-scales (of the order of weeks). Additional sparse archive observations led these authors to conclude that no major outburst was previously observed, and the likely quiescent magnitude of the LBV was around $R = 19.4 \pm 0.4$ mag. They also registered a deep magnitude minimum ($R \sim 20.8$) soon after the luminosity peak, and interpreted it as the result of dust formation, occultation or eclipse phase. We will show in Section 3 that the star has been detected (occasionally) at a magnitude even fainter than $R \approx 21$ in subsequent follow-up observations.

Another transient was announced on 2008 October 7.12 UT by Duszanowicz, Nakano & Itagaki (2008) at a position $\alpha = 10^{\rm h}52^{\rm m}41\overset{\rm s}{.}33$, $\delta = +36^\circ40'08\overset{''}{.}9$ (equinox J2000.0), very close (but apparently not coincident) to that of the 2000 outburst (Fig. 2). The new transient (labelled NGC 3432 2008-OT in this paper) had an apparent peak magnitude ($R = 17.5$) similar to that of 2000-OT. Its faint absolute magnitude ($M_R \approx -12.7$) was again consistent with that of an SN impostor.

In order to prove that the position of 2008-OT was coincident with that of 2000-OT, relative astrometric calibration was performed using as template a good-quality image of the 2008 transient and as target image the discovery frame of the 2000 transient obtained with the 0.76-m KAIT telescope (Filippenko et al. 2001). In order to align the two images, we identified 15 sources in common to both images and measured their centroid positions. This allowed us to derive a geometric transformation for the two images (implying a shift, a scaling to a common pixel scale and a rotation) using the IRAF package GEOMAP. To employ a general non-linear transformation, we selected a second-order polynomial model that computes the geometric alignment function. The images were finally registered to the target image using GEOTRAN. The accuracy of the alignment is 0.145 px in the x-axis and 0.154 px in the y-axis. Accounting for the pixel scale of the target image, the rms errors of the transformation in the two axes are 116 and 123 mas. We measured the position of the transients in the two images with aperture photometry and found in the transformed images a discrepancy in the position of the two transients of $\Delta x = 0.039$ px (31 mas) and $\Delta y = 0.013$ px (10 mas), which are well below the uncertainty of the transformation. We are therefore confident that the two transients were two major outbursts of the same stellar source (Fig. 2).

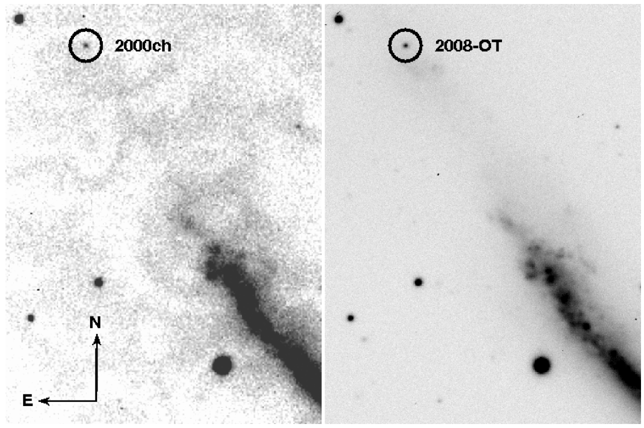

Figure 2. Comparison between an unfiltered KAIT image of NGC 3432 2000-OT (2000ch) obtained on 2000 May 4 and an R-band image of the 2008 transient obtained at TNG on 2008 October 25. The position of the two transients is coincident, within the errors. This allows us to conclude that the two outbursts were produced by the same star.

More precise coordinates than those previously reported for the NGC 3432 variable, as determined from Sloan Digital Sky Survey (SDSS) images, are $\alpha = 10^{\rm h}52^{\rm m}41\overset{\rm s}{.}256$ and $\delta = +36^\circ40'08\overset{''}{.}95$ (equinox J2000.0). Unfiltered amateur images showing the region of the variable star at four epochs during the period 2006–2008 are shown in Fig. 3. Finally, two further outbursts of the variable in NGC 3432 were registered in 2009 April (hereafter labelled as 2009-OT1) and 2009 November (2009-OT2), during routine monitoring observations of the star.

3 PHOTOMETRY

After the discovery by Duszanowicz et al. (2008), we started a systematic monitoring of the variable in the optical bands. At the same time, we collected a number of pre-discovery images of NGC 3432 from amateur astronomers and professional telescopes available through science data archives. The calibration of the optical photometry obtained with standard Johnson–Bessell filters has been performed using the local standard star magnitudes presented in Wagner et al. (2004a) for the B, V and R bands, while the U and I band data have been calibrated independently. The calibration of the Sloan filter photometry was performed using the SDSS photometry catalogue.[4]

[2] The Local Group infall velocity here adopted is $v_{\rm LG-infall} = 208 \pm 9\,{\rm km\,s^{-1}}$ (Terry, Paturel & Ekholm 2002).
[3] http://leda.univ-lyon1.fr/

[4] Sloan Digital Sky Survey web site: http://www.sdss.org/. The SDSS filter definition can be found in Fukugita et al. (1996), while the photometric system is defined in Smith et al. (2002).

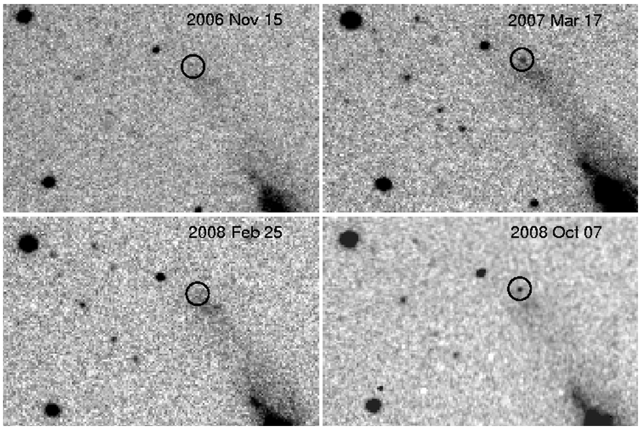

Figure 3. Unfiltered images of NGC 3432 obtained with a 32-cm reflector in Akersberga (Sweden). The four images show the evolution of the variable star, whose position is marked with a circle, on 2006 November 15 (top-left), 2007 March 17 (top-right), 2008 February 25 (bottom-left) and 2008 October 7 (bottom-right). The transient is clearly visible in the March 2007 and October 2008 images, while in the other two images it is below the detection limit. North is up, east is to the left.

Johnson–Bessell and Sloan magnitudes (or magnitude limits) of the variable in NGC 3432 are reported in Tables 1 and 2. The light curves, including the photometry of Wagner et al. (2004a) and spanning a period of almost 16 yr, are shown in Fig. 4. The right-hand panels show in detail the evolution of the variable during the four major outbursts: from top to bottom 2009-OT2, 2009-OT1, 2008-OT and 2000-OT. As already mentioned, the outbursts showed comparable peak magnitudes ($R \approx 17.5$–18.5 mag) and a number of subsequent luminosity fluctuations, although the post-peak evolution is somewhat different in the four cases. This is clearly visible when the R-band absolute light curves of the four outbursts are plotted together (Fig. 5). While 2000-OT showed a fast post-peak decline, with a deep minimum reached after a few days, 2008-OT and 2009-OT1 reached the minimum 2–3 months after maximum. We can summarize the photometric evolution of the four outbursts as follows.

(i) 2000-OT. During this outburst, the star reached a peak magnitude of $R = 17.4$ ($M_R \approx -12.8$) on 2000 May 3. The maximum was followed by a steep decline of 3.5 mag in about a week (but an observation obtained 2 d after maximum already showed the transient being 2.9 mag fainter than at peak). A sequence of secondary peaks was also observed (at magnitude around 18.6), with a temporal distance of about 12–15 d between each other (Wagner et al. 2004a, and Fig. 4, bottom-right panel).

(ii) 2008-OT. During this eruptive episode, the variable arrived at a maximum magnitude of $R = 17.5$ ($M_R \approx -12.7$, 2008 October 7), and experienced a rebrightening ($R \approx 18$) at ∼18 d after the main maximum. The rebrightening was followed by a large luminosity drop (more than 3 mag). Although the light curve is poorly sampled in this period, the star probably remained fainter than $R \sim 20.5$ ($V \sim 21.5$) for about 1 month. Then its luminosity increased again, reaching a peak of $R \sim 18.6$ at about 70 d after the main outburst. Finally, the luminosity slowly declined and leveled off at $R \approx 19.5$ (see Fig. 4, right, second panel from bottom).

(iii) 2009-OT1. Surprisingly, about 200 d after the previous outburst the variable brightened again. In this episode the peak magnitude (on 2009 April 22) was around $R \sim 17.9$ ($M_R \sim -12.3$). The primary peak was followed by a number of magnitude

Table 1. A small sample of unpublished Johnson–Bessell photometry of the variable star in NGC 3432. The full photometry available for the variable star in NGC 3432 is listed in a machine readable table online (see Supporting Information). The numbers in brackets are the errors associated with the SN photometry, and include both measurement and photometric calibration uncertainties. Observations marked with the symbol '⋆' are unfiltered images, and have all been rescaled to R-band magnitudes according to the prescriptions of Pastorello et al. (2008). The epochs and magnitudes of the first maxima of the major outbursts are in boldface.

Date	avg. JD	U	B	V	R	I	Source
2009 April 14	245 4935.62		20.82 (0.04)	20.59 (0.03)	19.73 (0.03)	20.03 (0.02)	NOT⋆
2009 April 15	245 4937.49			20.06 (0.01)	19.45 (0.01)	19.67 (0.02)	NOT
2009 April 22	245 4943.58	17.58 (0.02)	18.58 (0.01)	18.45 (0.01)	18.04 (0.01)	18.00 (0.02)	NOT
2009 April 22	**245 4944.41**			**18.33 (0.05)**	**17.92 (0.04)**		SO
2009 April 24	245 4945.55		18.60 (0.01)	18.50 (0.02)	18.05 (0.01)	18.01 (0.02)	TNG
2009 April 24	245 4946.44				18.11 (0.11)		BH⋆

NOT = 2.56-m Nordic Optical Telescope + ALFOSC (La Palma, Canary Islands, Spain);
SO = 0.44-m f/4.4 Newton Telescope + SBIG ST-7E Dual CCD (Obs. L.H., Sandvreten Obs., Uppsala, Sweden);
TNG = 3.58-m Telescopio Nazionale Galileo + Dolores (Fundación Galileo Galilei-INAF, La Palma, Canary Islands, Spain);
BH = Meade LX200 12" f-6.3 telescope + SBIG ST-10 Dual CCD Camera (Obs. B. Häusler, Rimpar, Germany).

Table 2. A small sample of our Sloan-filter photometry of the variable star in NGC 3432 and associated errors. The full photometry available for the variable star in NGC 3432 is listed in a machine readable table online (see Supporting Information).

Date	JD	u	g	r	i	z	Source
2003 April 26	245 2755.72	20.39 (0.09)	19.99 (0.04)	19.20 (0.03)	19.57 (0.08)	19.54 (0.10)	SDSS
2004 March 16	245 3080.89	>22.37	22.26 (0.29)	21.46 (0.13)	21.51 (0.17)	21.23 (0.37)	SDSS
2008 November 09	245 4779.69		21.87 (0.32)	20.67 (0.14)	>21.37	>20.90	LT
2008 November 19	245 4789.66		22.02 (0.24)	20.90 (0.10)	21.54 (0.19)	>21.89	LT
2008 November 24	245 4794.66		22.12 (0.20)	21.31 (0.11)	21.52 (0.10)		LT
2008 December 10	245 4810.61			18.79 (0.06)	19.17 (0.05)		LT

SDSS = 2.5-m Sloan Digital Sky Survey Telescope + TK2048E CCDs (Apache Point Observatory, New Mexico, USA);
LT = 2.0-m Liverpool Telescope + RatCAM (La Palma, Canary Islands, Spain).

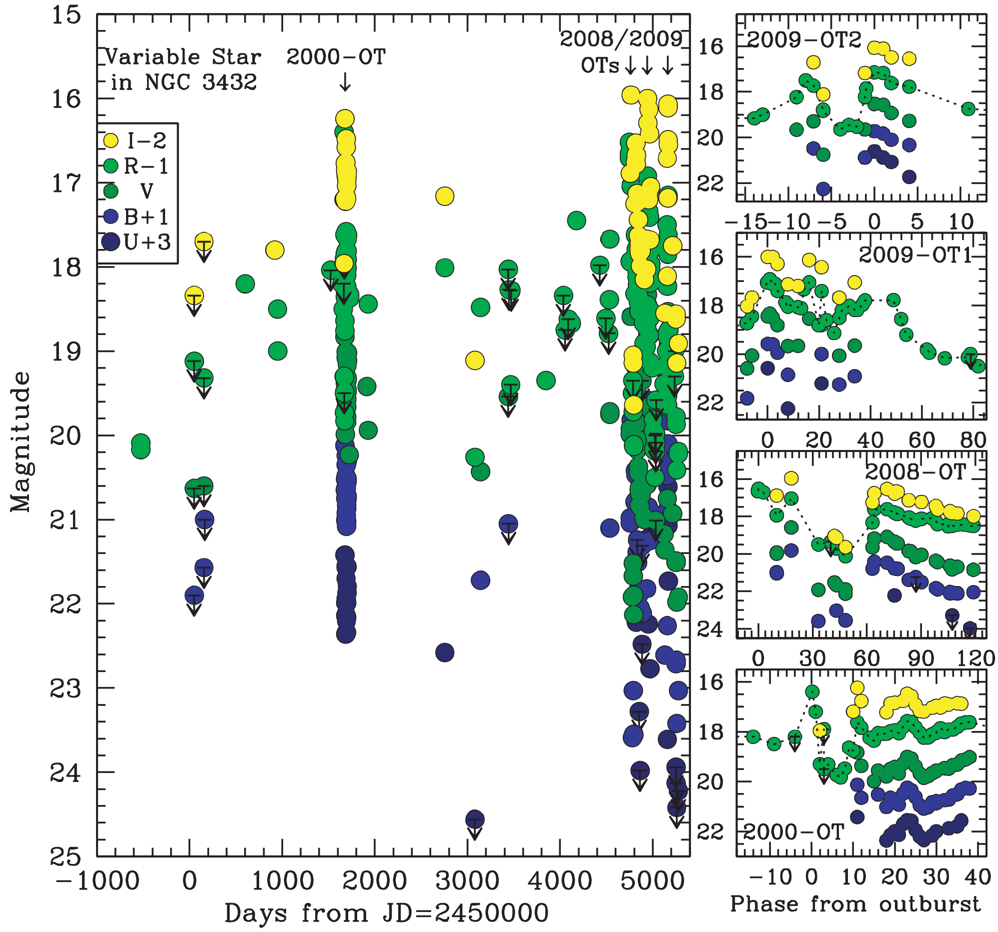

Figure 4. Main panel: 15-yr multiband optical light curve of the variable in NGC 3432. Blow-ups with the detailed light curves of 2000-OT (the data are from Wagner et al. 2004a), 2008-OT, 2009-OT1 and 2009-OT2 are shown in the panels on the right. Sloan u′, r′ and i′ magnitudes were scaled to Johnson–Bessell U, R and I magnitudes applying a correction of $\Delta U = -0.81$, $\Delta R = -0.18$ and $\Delta I = -0.41$ mag, computed comparing the photometry of the local sequence stars in the Sloan and Johnson–Bessell photometric systems. To guide the eye, *R*-band data points in the inserts are connected by a dotted line.

oscillations that occurred on shorter time-scales than those observed in 2008-OT. They were followed by a dramatic drop of $\Delta R \geq 3.3$ mag from the peak to the minimum (Fig. 5).

(iv) 2009-OT2. A further rebrightening of the variable in NGC 3432 was finally registered in 2009 November, again ∼200–210 d after the previous episode. This might be either a coincidence in the luminosity fluctuations or, alternatively, might suggest some periodicity in the major episodes of stellar variability. The consequences of this latter scenario will be discussed in Section 6. Interestingly, the first maximum of 2009-OT2 reached $M_R \sim -11.7$, but was followed after 8 d by a second peak that was even slightly brighter ($M_R \sim -12.1$, see Fig. 5). After the second peak, the luminosity of the star dropped down by more than 2 mag in ∼1 month.

The comprehensive light curve (period 1994–2009; see Fig. 4, main panel) shows a rather erratic evolution. Luminosity peaks occur on unusually short time-scales and the range of spanned magnitudes ($\Delta m \sim 4$ mag, Fig. 5) are atypical for an S-Dor-like event. Together with the main peaks we also note a few sparse detections at magnitudes 18.5–19.5, and some minima (e.g. at JDs 244 9475 and 245 3081). Such optical deficits can be possibly due to post-outburst dust formation episodes (as proposed by Wagner et al. 2004a). The implications of this unusual photometric evolution in constraining the nature of the variable star will be discussed in Section 5.

In Fig. 6 we compare the *R*-band absolute light curve of the variable in NGC 3432 during the period from 2008 October to 2009 June with those of the SN impostors 1997bs (van Dyk et al. 2000) and 2009ip (Smith et al. 2010), the 2004 luminous eruption in UGC 4904 that heralded SN 2006jc (hereafter UGC 4904 OT 2004-1, Pastorello et al. 2007a) and two additional underluminous transients whose nature (core-collapse SN, LBV outburst, peculiar luminous nova) is still debated: M85 OT 2006-1 and 2008S (Kulkarni et al. 2007; Pastorello et al. 2007b; Rau et al. 2007; Ofek et al. 2008; Prieto et al. 2008a; Botticella et al. 2009; Smith et al. 2009; Thompson et al. 2009; Wanajo et al. 2009). The peak magnitudes of the NGC 3432 variable (in the range of −12.1 to −12.8) are much fainter than those of 1997bs ($M_R \approx -15.3$) and 2009ip ($M_R \approx -14.6$), marginally fainter than those of 2008S and UGC 4904 OT 2004-1 ($M_R \approx -13.7$). However, they are comparable with the maximum magnitude of M85 OT 2006-1 (Kulkarni et al. 2007), although the two transients have different photometric evolution. M85 OT 2006-1, indeed, presents a slowly evolving light curve with a sort of plateau, while the variable in NGC 3432 has a fast evolution, characterized by steep post-peak luminosity declines and subsequent rebrightenings similar to those observed in 2009ip (Smith et al. 2010) and other SN impostors (Maund et al. 2006).

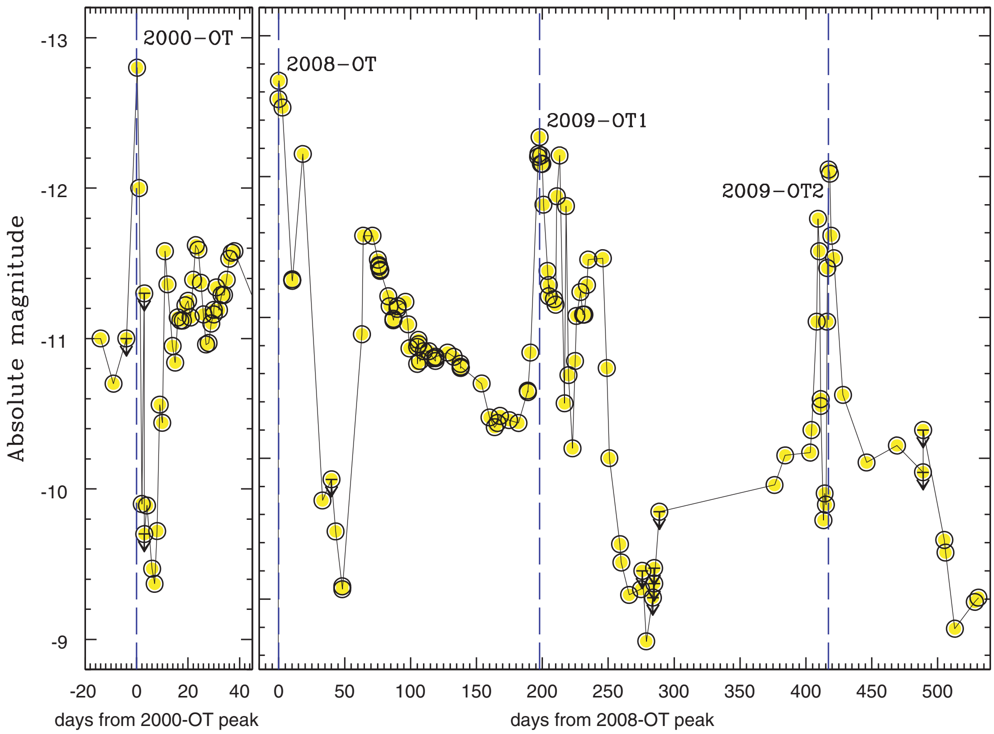

Figure 5. Comparison of the *R*-band light curves of the variable star in NGC 3432 covering the 4 major outbursts: 2000-OT (Wagner et al. 2004a); 2008-OT, 2009-OT1, 2009-OT2 (this paper). SDSS *r*-band magnitudes were scaled to Johnson-Bessell ones by applying a zero-point shift of $\Delta R = -0.18$ mag (see caption in Fig. 4). The epochs of the main luminosity peaks for the four outbursts are marked with vertical blue dashed lines.

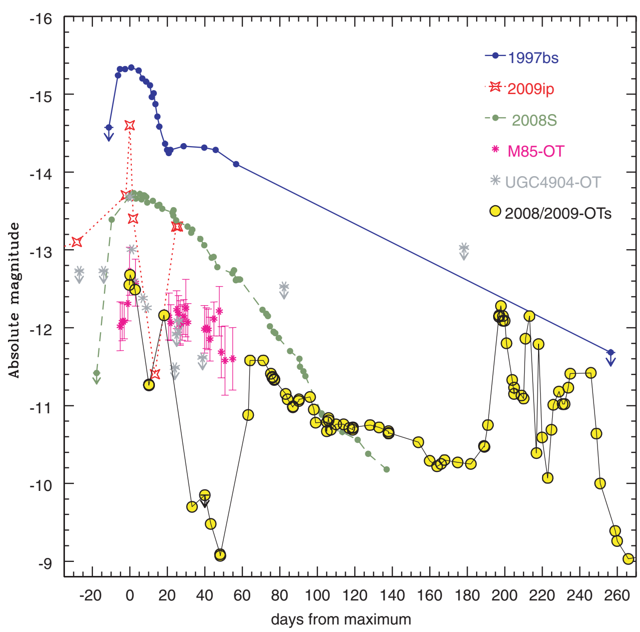

Figure 6. Comparison of the *R*-band absolute light curve of the variable star in NGC 3432 (period october 2008 to June 2009) with those of some well-studied transient events: 1997bs (van Dyk et al. 2000), 2009ip (Smith et al. 2010), the 2004 outburst preceding SN 2006jc (UGC 4904 OT 2004-1, Pastorello et al. 2007a), 2008S (Botticella et al. 2009) and M85 OT 2006-1 (Kulkarni et al. 2007). SDSS *r*-band magnitudes of the variable in NGC 3432 were rescaled to Johnson–Bessell magnitudes by applying a zero-point shift of $\Delta R = -0.18$ mag (see caption in Fig. 4).

In Fig. 7 long-term light curves of the NGC 3432 variable and a few well-monitored LBVs and SN imposters are shown: η Car,[5] S-Dor and HD 5980,[6] 1997bs (van Dyk et al. 2000), 2002kg (Weis & Bomans 2005; Maund et al. 2006, 2008), 2009ip (Smith et al. 2010), UGC 4904 OT 2004-1 (Pastorello et al. 2007a). Remarkably, even though some modulation in the light curve of the variable star in NGC 3432 may suggest an S-Dor-type variability, its overall characteristics are reminiscent of those of major outbursts. Some similarity can be found, indeed, with the years-long outburst of η Car during the nineteenth century, and – more marginally – with the eruption in 1993–1994 of the stellar system HD 5980 (see Koenigsberger 2004, and references therein). We will better address the latter similarity in the forthcoming sections.

4 SPECTROSCOPY

Spectra of the luminous variable in NGC 3432 were obtained after the 2008 October outburst using the 4.2-m William Herschel Telescope (WHT) equipped with ISIS, the 3.58-m Telescopio Nazionale Galileo (TNG) with LRS, the 2.56-m Nordic Optical Telescope (NOT) with ALFOSC and the 2.2-m telescope of the Calar Alto Observatory plus CAFOS. Information on the spectra obtained during the period from 2008 October to 2009 November is reported in Table 3. The best signal-to-noise (S/N) spectra of the star witnessing the evolution of the 2008-OT and 2009-OT1 outbursts,

[5] Historical observations of η Car's Great Eruption in the 1840s were kindly provided by Frew (2004), while the collection of the normalized V-band photometric studies of the η Car's variability after 1952 are from S. Otero (private communication). Extensive light curves of η Car can be found at the following URL: http://varsao.com.ar/Curva_Eta_Carinae.htm
[6] Data from AAVSO International Data Base: http://www.aavso.org

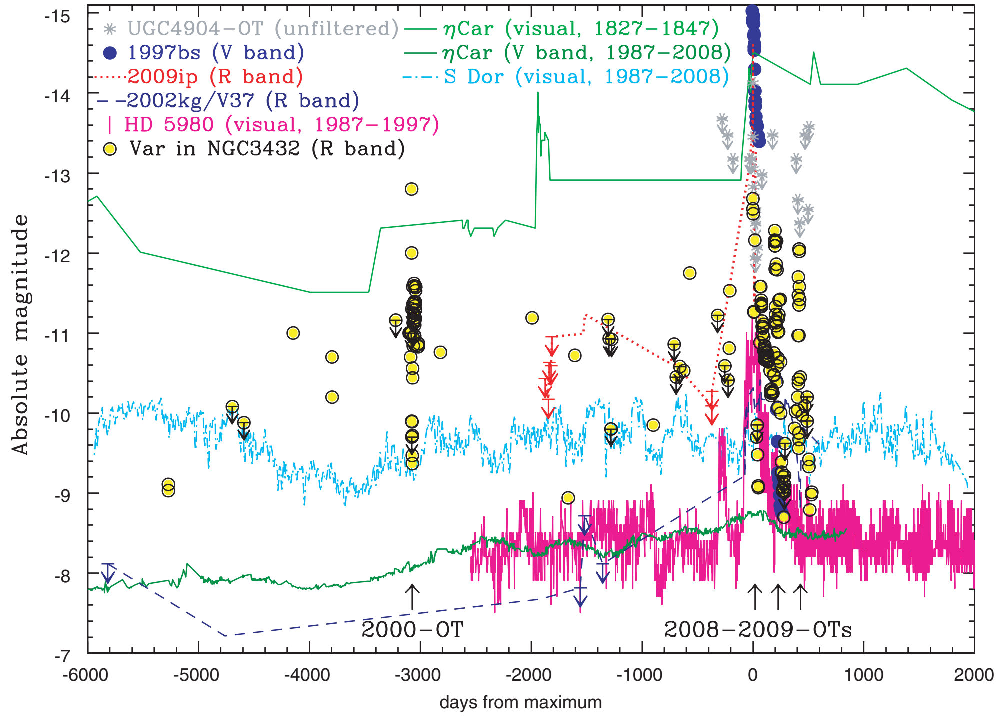

Figure 7. Long-term photometric monitoring of a few famous LBV outbursts – SN impostors: 1997bs, 2000kg/V37, 2009ip, 2000/2008/2009-OTs in NGC 3432 and UGC 4904 OT 2004-1 (references in the text). The Sloan *r*-band magnitudes of the variable in NGC 3432 were rescaled to Johnson–Bessell magnitudes adopting the prescriptions mentioned in the caption of Fig. 5. A boxcar filter of size = 5 d was applied to the light curve of S-Dor (AAVSO data base). The modulated variability of S-Dor, and the light curve of the LBV/WR system HD 5980 in the SMC (including photometry of the eruption in 1993–1994, magenta crosses, AAVSO data base) are also shown. Visual magnitudes of η Car during the Great Outburst of the 1840s are visualized with green circles (see Frew 2004, and references therein), while V band magnitudes of η Car from 1987 to the present days (S. Otero, private communication) are shown with green-olive dots. The light curve of the Great Eruption of η Car has been corrected for a total extinction of $A_V = 1.7$ mag (e.g. Davidson & Humphreys 1997), while for the light curve in more recent decades we accounted for circumstellar dust, and therefore adopted a significantly higher extinction ($A_V = 6.1 \pm 0.6$ mag, according to Davidson et al. 1995).

Table 3. Basic information on new spectra of the luminous variable in NGC 3432.

Date	JD	Instrument	Grism/grating	Exposure time (s)	Range (Å)	Resolution (Å)
2008 October 14	245 4753.75	WHT+ISIS	R300B, R158R	2×2400	3250–5410,5140–10150	5.4,6.3
2008 October 17	245 4756.71	CAHA2.2m+CAFOS	b200	2727.3	3400–8770	10.5
2008 October 17	245 4756.74	TNG+LRS	LRB	2700	3700–7990	15
2008 December 21	245 4821.75	NOT+ALFOSC	gm4	3600	3300–9050	18
2008 December 22	245 4822.63	TNG+LRS	LRR	3600	5050–9800	13
2009 January 22	245 4853.64	TNG+LRS	LRB	3600	3560–7920	12
2009 February 22	245 4884.56	NOT+ALFOSC	gm4	2×2700	3400–8100	18
2009 March 22	245 4912.52	TNG+LRS	LRB	2×2700	3370–7930	15
2009 April 24	245 4945.60	TNG+LRS	LRB	3600	3260–7940	11
2009 May 12	245 4964.49	TNG+LRS	LRB	2700	3280–7940	11
2009 May 19	245 4971.41	TNG+LRS	LRB	2700	3400–7930	11
2009 November 27	245 5162.67	CAHA2.2m+CAFOS	b200	2700	3500–8730	12

but also the subsequent quiescent phases, are shown in Fig. 8 together with spectra obtained in 2000/2001 (2000-OT) from Wagner et al. (2004a). The spectra of the variable obtained soon after 2008-OT are characterized by prominent H lines in emission (see line identifications in Fig. 9). He I lines are also clearly visible with $v_{\rm FWHM} \approx 2000\,{\rm km\,s^{-1}}$, which is only slightly lower than that of Hα ($v_{\rm FWHM} \approx 2300\,{\rm km\,s^{-1}}$). The spectra of the 2008 episode display significant differences compared with those of 2000-OT described in Wagner et al. (2004a; also shown in the top part of Fig. 8). In the 2000 event the He I lines were weaker and the FWHM velocities measured for Hα were slightly lower, being in the range of 1600–1800 km s^{-1}. Such differences in line velocities may suggest a more powerful outburst (but we cannot confirm it on the basis of our photometric data) or less envelope mass ejection in the 2008 outburst. However, the integrated flux of Hα obtained averaging the flux measured from the three available spectra of 2008 October is about 4×10^{-14} erg cm^{-2} s^{-1},which is a factor of 2 more than the flux reported by Wagner et al. (2004a) for the 2000 event, implying that the 2008 event had an Hα luminosity twice that of the 2000 event. Adopting the same relation between the Hα luminosity and the radius (R) of the emitting region and the same assumptions as Wagner et al., we obtain R(Hα) = 0.25 pc (from the Hα luminosity computed from

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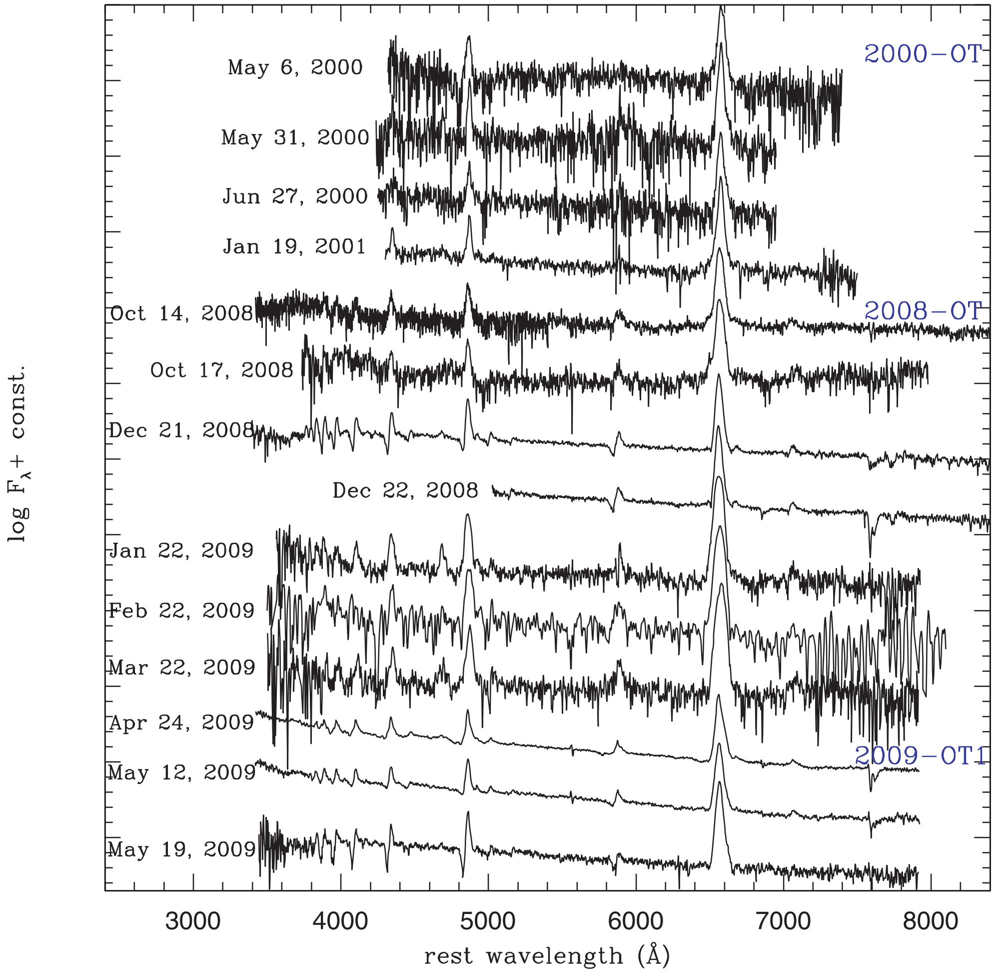

Figure 8. Optical spectra of the variable in NGC 3432 from Wagner et al. (2004a) (relative to the 2000 eruptive episode) and new spectra of the 2008/2009 outbursts. Only the best S/N spectra are shown. The second-order contamination from the NOT spectra has been removed following the prescriptions of Stanishev (2007). The noisy spectrum obtained on 2009 February 22 was slightly smoothed. The apparent narrow P-Cygni feature visible at the position of He I λ5876 in the 2009 January 22 spectrum is in reality a spike due to a poorly removed hot pixel. Some spectra have been cut at the blue wavelengths because of the modest S/N.

the 2000 May 14 spectrum, $R(\mathrm{H}\alpha) = 0.2$ pc was determined by Wagner et al. 2004a). Remarkably, the peak of the Hα line is asymmetric and slightly blue-shifted. This phenomenon is visible also in the late-time spectra of some core-collapse SNe and is expected when newly formed dust extinguishes the light coming from the receding hemisphere (see e.g. SN 1999em, Elmhamdi et al. 2003).

High S/N spectra were then obtained on 2008 December 21–22, showing a remarkable evolution. The continuum is very blue, and prominent P-Cygni profiles are now visible. It is worth noting that P-Cygni profiles were marginally detected (especially in Hβ) also in the 2000-OT spectrum of 2000 May 6 (Wagner et al. 2004a). Together with H and He I, Fe II lines of the multiplet 42 and Ca II H & K[7] are clearly detected (see Figs 8 and 9). Now Hα does not show a P-Cygni profile and its v_{FWHM} is about 2000 km s^{-1}, consistent with the velocity deduced from the position of the minimum of Hβ. Other Balmer lines show significantly lower P-Cygni velocities (about 1600 km s^{-1}), very close to those of He I lines (∼1500–1550 km s^{-1}). Finally, unblended Ca II λ 3934 and Fe II λ 5169 P-Cygni lines have absorption components which are blue-shifted by about 1250 km s^{-1}. Comprehensive line identification is shown in Fig. 9.

A further spectrum of the variable was obtained on 2009 January 22. Within one month, the spectrum of the variable has evolved significantly. P-Cygni profiles are no longer visible, He I and Fe II lines are marginally detected, while a prominent He II λ4686 line is now visible in emission (see insert in Fig. 9). The same line was visible also in the second spectrum of 2000-OT (2000 May 31) presented by Wagner et al. (2004a) and, marginally, also in the 2001 January 19 spectrum. The presence of this line would indicate high temperatures of the emitting material. He II lines in emission are common features in He-rich, hot Wolf–Rayet stars and early O-type supergiants, and are only rarely detected in LBVs during quiescence (e.g. in AG Car, Stahl 1986). Finally, two spectra were collected on 2009 February 22 and March 22, and the object did not show any further evolution. We noted only a weakening of the He II line. The linewidths are very similar to those measured in the January spectrum, viz. $v_{\mathrm{FWHM}} \approx 2750$ km s^{-1}.

The spectra obtained during the 2009-OT1 event (2009 April–May, see Fig. 10) show prominent P-Cygni lines of H, He I and Fe II, and share striking similarities with the 2008 December spectra,

[7] The identification of Ca II is unequivocal, being the line at λ 3934 Å unblended in the Nordic Optical Telescope spectrum of 2008 December 21.

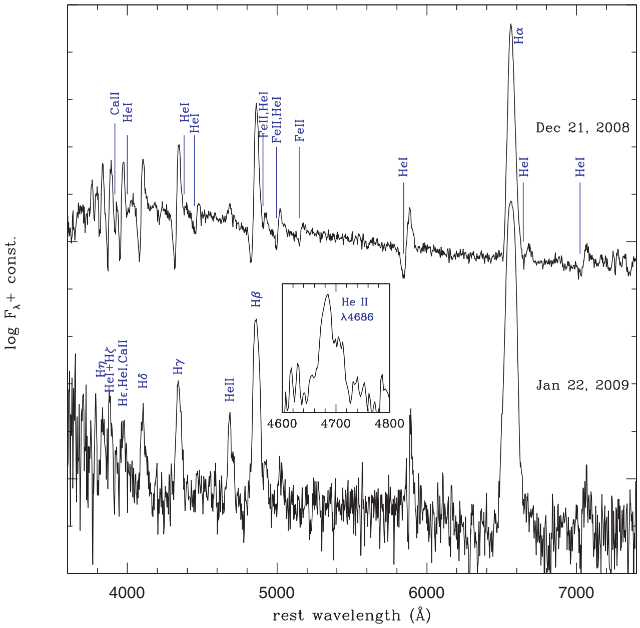

Figure 9. Line identification in the spectra obtained on 2008 December 21 and 2009 January 22. The apparent narrow P-Cygni feature visible at the position of He I λ5876 in the 2009 January 22 spectrum is in reality a spike due to a poorly removed hot pixel. The insert shows in detail the complex structure of the He II λ4686 line in the January 22 spectrum.

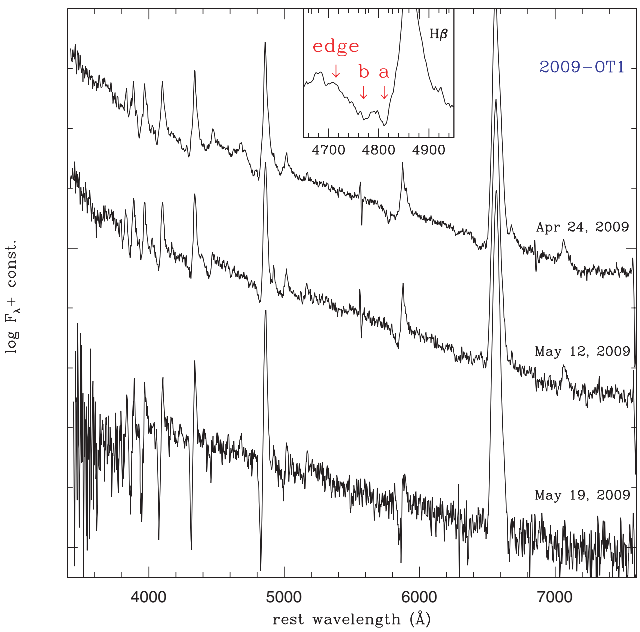

Figure 10. Spectroscopic evolution of the April–May 2009 outburst (2009-OT). A zoom-in of the Hβ region of the April 24 spectrum is shown in the insert. Individual features mentioned in the main text are labelled.

although the continuum is now significantly bluer. This is probably due to the fact that these spectra were obtained closer to the epoch of the outburst onset. From May 12 to May 19, the continuum temperature decreases significantly and the spectral lines show more prominent P-Cygni absorption components. The H and He I lines in the first spectrum of Fig. 10 (2009 April 24) show two-component absorption profiles. We identify a lower-velocity trough (labelled a in Fig. 10) which is blue-shifted by about $v_a \approx 3000\,\mathrm{km\,s^{-1}}$, and another absorption component (labelled b) with a core velocity v_b of about 5300 km s^{-1}. The broad wings of the absorption feature extend up to a velocity of $v_{\rm edge} \approx 9000\,\mathrm{km\,s^{-1}}$. As H$\beta$ is not saturated, $v_{\rm edge}$ is not a perfect indicator for the terminal wind velocity (v_∞). Prinja, Barlow & Howarth (1990) found that $v_{\rm edge}$ overestimates v_∞ by 20–25 per cent ($v_\infty \approx 0.8 v_{\rm edge}$), and we can therefore more accurately estimate the terminal velocity of Hβ as 7200 km s^{-1}.

This peculiar line profile is remarkably similar to those observed by Trundle et al. (2008) in SN 2005gj. The similarity of this absorption line splitting in the SN spectra with those of well-known LBVs (Stahl et al. 2001, 2003) led Trundle et al. (2008) to conclude that the progenitor of SN 2005gj was likely an LBV that experienced a mass-loss episode a few decades before the SN explosion. In the spectrum of 2009-OT1 we measure velocities which are more than one order of magnitude higher than those reported by Trundle et al. (2008), very different to those of ordinary LBV winds. The higher-velocity trough (b) is only marginally detectable in the subsequent spectrum of 2009-OT1 (May 12, 2009), while the lower-velocity one is still visible and has $v_a \approx 2000$–$2200\,\mathrm{km\,s^{-1}}$. The whole absorption feature extends to blue wavelengths corresponding to $v_{\rm edge} \approx 6000$–$7000\,\mathrm{km\,s^{-1}}$ ($v_\infty \approx 4800$–$5600\,\mathrm{km\,s^{-1}}$). The last spectrum of the variable in Fig. 10 (2009 May 19) shows P-Cygni lines with a single absorption component, though with a slightly asymmetric profile. The minimum of the absorption indicates $v_a \sim 2000\,\mathrm{km\,s^{-1}}$, but with the blue wing extending to $v_{\rm edge} \approx 3000$–$3500\,\mathrm{km\,s^{-1}}$ ($v_\infty \approx 2400$–$2800\,\mathrm{km\,s^{-1}}$).

The last spectrum of the variable in NGC 3432 (see Table 3) was obtained at the time of the 2009-OT2 outburst (2009 November 26), but it is not shown in Fig. 8 because of its poor S/N. It showed a blue continuum and narrow H lines, with $v_{\rm FWHM}$ of about 1300–1400 km s^{-1}, still consistent with the lower line velocities displayed by this variable during all the earlier outbursts.

Vink & de Koter (2002) suggested that oscillations in the wind velocity (and mass-loss rate) similar to those we observe in the spectra of the variable in NGC 3432 can be associated with changes in the efficiency of line driving, as a result of variations in the Fe ionization of the wind (bistability in the wind velocity in early-type stars; see Lamers, Snow & Lindholm 1995; Vink, de Koter & Lamers 1999). We note that also Koenigsberger et al. (2006) invoke the bistability mechanism to explain the changes in wind velocity of HD 5980 (see Section 6). Despite the high degree of variability, the wind velocities of the variable in NGC 3432 remain remarkably high both during outbursts and in quiescence, making an ordinary LBV scenario for this object rather problematic.

4.1 Comparison with luminous stars and stellar outbursts

During the LBV phase, massive stars vary their apparent temperatures and, as a consequence, spectral types. The high degree of variability of LBVs is generally evident in their spectra. During the quiescent phase, LBVs tend to have blue spectra often similar to those of B supergiants. However, a number of LBVs such as AG Car and HD 269582 (Stahl 1986) show Opfe/WN9 spectra during quiescence. In this phase, these objects also have strong He II in emission, that disappears during outburst when the spectra display prominent P-Cygni profiles. Nevertheless, the remarkably high velocities measured in the spectra of the variable in NGC 3432 both during outburst and in quiescence are unusual.

In order to better constrain the nature of this variable, we compare its spectra with those of well-known classes of luminous stars or other types of transients. In Fig. 11 (panel A) a spectrum of the variable star during the quiescence after 2008-OT is shown along

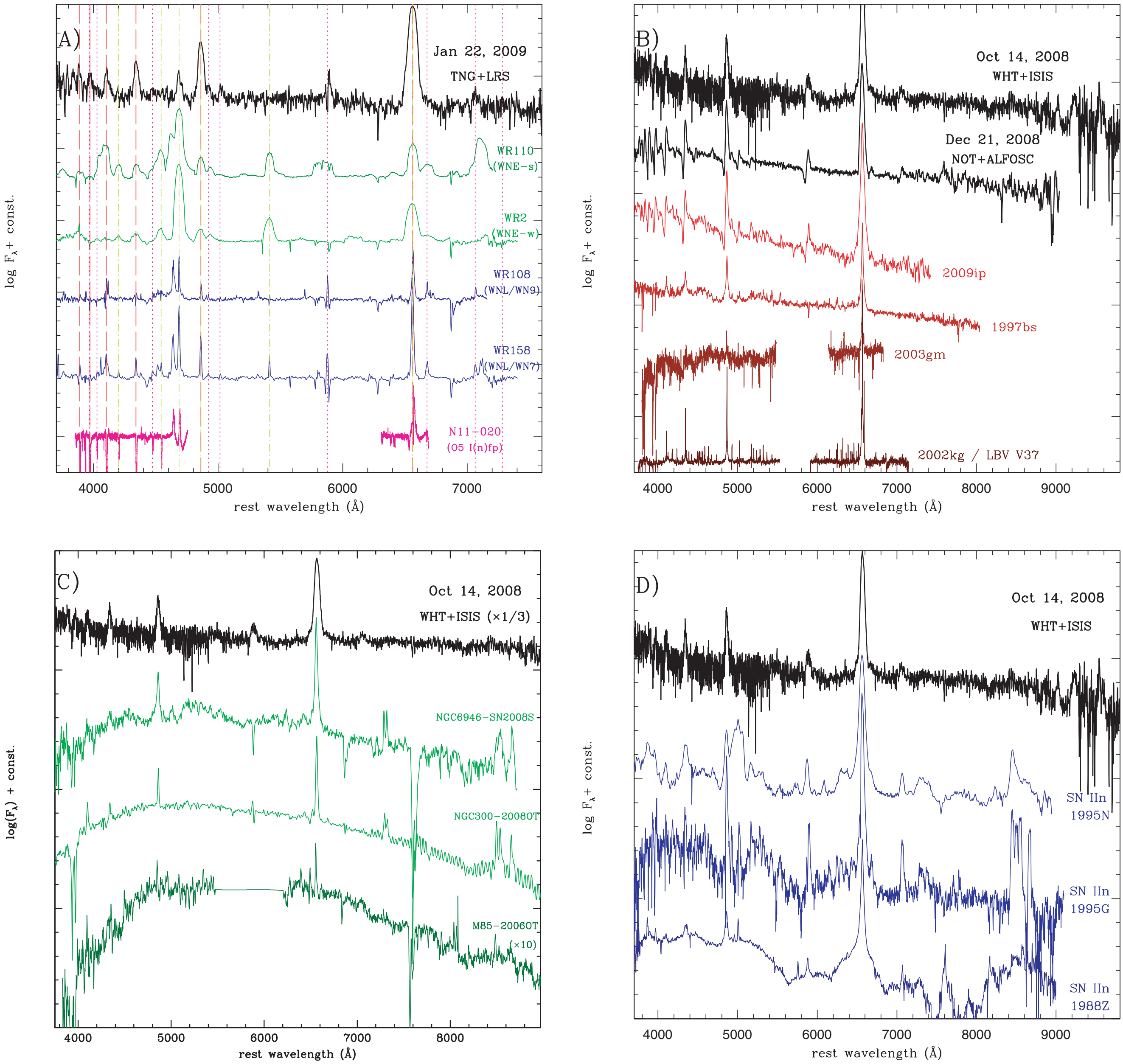

Figure 11. Comparison of spectra of the variable in NGC 3432 with those of different families of objects. (A) Comparison of a spectrum of the variable in quiescence (2009 January 22) with those of a few Wolf–Rayet (WN) stars and an Oe-type star: WR 110 (WNE with strong lines; WN6-s, see Hamann et al. 1995a), WR 2 (WNE with weak emission lines; WN2-w), WR 108 (WNL; WN9), WR 158 (WNL, WN7), and the O5-type N11-020. The positions of the most important H lines are marked with red dashed lines, those of He I features are indicated with magenta dotted lines and those of He II with bright green dot-dashed lines. Note that WR 2 and WR 110 do not show clear signature of H lines, and the features at the positions of Hα and Hβ are mostly due to He II. All spectra of WN stars shown in the figure are from Hamann, Koesterke & Wessolowski (1995b), that of N11-020 from Evans et al. (2006). The narrow spike at the position of He I 5876 Å in the spectrum of 2008-OT is due to a poorly removed hot pixel. (B) Comparison of two spectra of the variable in NGC 3432 with those of other well-known SN impostors: 2009ip (ESO-NTT spectrum obtained on 2009 October 22; Padova-Asiago Supernnova Archive), 1997bs (van Dyk et al. 2000), 2003gm and 2002kg (Maund et al. 2006). All these transients are thought to be luminous eruptions of LBVs. (C) Comparison of the spectrum of the variable in NGC 3432 after the 2008 outburst (2008 October 14) with those of a sample of enigmatic transients whose nature is still debated (see text). The spectrum of (SN) 2008S is from Botticella et al. (2009), that of the optical transient in NGC 300 is from Pastorello et al. (in preparation), and that of M85 OT 2006-1 is from Kulkarni et al. (2007). (D) Comparison of the October 14 spectrum of the variable in NGC 3432 with those of luminous, interacting core-collapse SNe: the type IIn SNe 1995G, 1995N and 1988Z (from Pastorello et al. 2002, 2005; Turatto et al. 1993, respectively).

with those of a number of Wolf–Rayet (of WN type) stars. While early WN (WNE) stars show relatively broad emission lines with an FWHM which is quite consistent with that observed in the spectrum of the variable in NGC 3432, their spectra are characterized by prominent He II emission lines, which dominate over the H features. (Unblended He II line at 4686 Å is visible only in the 2009 January 22 spectrum, when the star was quiescent, and its intensity was much lower than that observed in spectra of WNE stars.) Late WN (WNL) stars have instead more intense H lines, but very narrow. In addition, lines such as N III, N IV, C III, C IV which are prominent in

WN stars, are not visible in the spectra of the variable (see Hamann, Koesterke & Wessolowski 1995a; Crowther et al. 1995a; Crowther, Hillier & Smith 1995b,c; Nota et al. 1996, for a detailed information on the subclassification of WN stars). The spectrum of the variable in NGC 3432 shares some similarity with those of other luminous hot stellar types, such as Be, Oe stars and O-type supergiants. Although Be stars show conspicuous Hα lines in emission, sometimes the line profiles are double-peaked, suggesting the presence of a disc.[8]

Finally, Oe and O-supergiant stars still show prominent H lines, and He II features are weak (usually weaker than He I lines). This is the case of N11-020, classified as O5 I(n)fp by Evans et al. (2006; see also Fig. 11, bottom of panel A), whose spectral lines are relatively broad, but still too narrow in comparison with those of the variable. In addition, lines of other ions visible in all stellar types described above (N II, N III, C III, C IV, Si IV) *are not visible* in the spectra collected so far for the luminous star in NGC 3432.

In Fig. 11 (panel B) two spectra of the variable in NGC 3432 are compared with those of the SN impostors 1997bs (van Dyk et al. 2000), 2009ip (Padova-Asiago Supernova Archive), 2003gm (Maund et al. 2006) and 2002kg (Maund et al. 2006). It is worth noting that the spectral lines of the NGC 3432 variable are broader than those of the other SN impostors. Hα is indeed dominated by an intermediate-width component ($v_{\mathrm{FWHM}} \approx 2300\,\mathrm{km\,s^{-1}}$) and weak, marginally detectable broader wings.

The other SN impostors shown in Fig. 11 have FWHM velocities of Hα that typically are $\leq 1000\,\mathrm{km\,s^{-1}}$, similar to that measured for 2001ac ($v_{\mathrm{FWHM}} \approx 900\,\mathrm{km\,s^{-1}}$, Matheson & Calkins 2001). Only 2009ip competes with the variable in NGC 3432 in linewidths (see also the discussion in Foley et al. 2010; Smith et al. 2010), although its spectrum does not show He II λ4686. The spectrum of 1997bs presented by van Dyk et al. (2000) and shown in Fig. 11 (panel B) has a two-component emission profile, with a narrow component ($v_{\mathrm{FWHM}} \approx 500\,\mathrm{km\,s^{-1}}$) atop a broader one, with $v_{\mathrm{FWHM}} \approx 1500\,\mathrm{km\,s^{-1}}$. In this context, the spectral lines of the major outbursts of the variable in NGC 3432 are broader by a factor of 1.5–3, with FWHM velocities which are close to those observed in the intermediate components of some interacting SNe (see Fig. 11, panel D). Nevertheless, the most important spectral features observed in the variable in NGC 3432 (due to H, He I and Fe II transitions) are commonly observed also in the spectra of SN impostors (see e.g. Maund et al. 2006). The only exception is the He II λ4686 line visible in the quiescent spectrum of the variable, which is rarely observed in spectra of erupting LBVs.

We compare in Fig. 11 (panel C) the 2008 October 14 spectrum of the NGC 3432 variable with those of a sample of enigmatic transients whose overall similarity was first discussed by Prieto et al. (2008b) and Thompson et al. (2009). The nature of this group of transients, which includes SN 2008S (Prieto et al. 2008a; Smith et al. 2008; Botticella et al. 2009), NGC 300 2008-OT (Berger et al. 2009; Bond et al. 2009) and M85 OT 2006-1 (Kulkarni et al. 2007), is still debated. According to Smith et al. (2008), Bond et al. (2009) and Berger et al. (2009), these transients are likely SN impostors caused by the luminous eruptions of massive (10–20 $\mathrm{M_{\odot}}$) stars. While the progenitors of SN 2008S and NGC 300-OT were identified as dust-enshrouded massive stars in archive *Spitzer* images (of about 10 $\mathrm{M_{\odot}}$, according to Prieto et al. 2008a; Botticella et al. 2009; Thompson et al. 2009), the star producing M85 OT 2006-1 was never detected, and the outburst was associated with the merging of low-mass stars by Kulkarni et al. (2007), Rau et al. (2007) and Ofek et al. (2008). Pastorello et al. (2007b) questioned both the mass limit derived for the progenitor of M85 OT 2006-1 and the nature of the outburst itself, proposing that it was the underluminous core collapse of an $\sim$8 $\mathrm{M_{\odot}}$ star. Finally, Botticella et al. (2009) discussed the possibility that SN 2008S, and probably also the other transients of this group, were electron-capture SNe from super-AGB stars (see also Pumo et al. 2009; Wanajo et al. 2009). H, He I and Fe II lines are detected both in the spectra of the luminous star in NGC 3432 and in objects of the family. However, the latter objects show a prominent [Ca II] feature at about 7300 Å (not visible in our spectra of the NGC 3432 variable), narrower spectral lines and a much slower photometric evolution.

Our first spectrum after the October 2008 outburst is finally compared in Fig. 11 (panel D) with those of three type IIn SNe (1995G, 1995N, 1988Z; see Turatto et al. 1993; Pastorello et al. 2002, 2005). The spectra of SNe 1995G and 1995N were obtained more than one year after their explosions, while that of SN 1988Z is probably earlier. The FWHM of the lines in the spectrum of the variable in NGC 3432 is similar to that of the intermediate-velocity line components of the three type IIn SNe (see Turatto et al. 1993; Aretxaga et al. 1999; Fransson et al. 2002; Pastorello et al. 2002; Zampieri et al. 2005). In interacting SNe these line components are thought to originate from the shocked complex circumstellar medium (CSM).

All these comparisons indicate that the spectra alone do not allow us to discriminate between the different types of explosions. Additional information provided by the photometry (specifically the low peak luminosity, the fast luminosity evolution of the outburst, the variability history of the star) makes us confident in identifying the 2000/2008/2009 transients in NGC 3432 as the most recent episodes of a long series of major mass-loss events in this exceptional, restless variable.

4.2 Evolution of the line profiles

A view of the spectral sequence in Fig. 8 suggests that two types of spectra were observed during follow-up observations of the variable in NGC 3432 (October 2008 to June 2009).

(i) A few spectra (marked with 1, 8, 9, 13, 14, 15 in Fig. 12) show a blue continuum with prominent P-Cygni lines of H, He I and (although weak) Fe II. On average, the FWHM velocity of the emission features is around 1600–2200 $\mathrm{km\,s^{-1}}$. In these spectra there is no clear evidence for the presence of He II lines. The reason why the spectral energy distribution (SED) peaks at the blue wavelengths during outbursts will be addressed more in detail in Section 5.

(ii) Other spectra (e.g. 2, 3, 4, 10, 11, 12) show a much redder continuum and lines of H and He I in pure emission. The FWHM velocities are significantly higher (2400–2800 $\mathrm{km\,s^{-1}}$).[9] In these spectra, the He II λ4686 feature is unequivocally detected.

In order to understand the reasons of the rapid variability of the spectra, we have visualized in Fig. 12 the evolution of the profile of the most important H lines, and correlated the spectra with the phases of the three outbursts. In particular, for each spectrum in Fig. 12 (left panels) we have assigned an identification number. The phases of the light curves reported in the right panels of Fig. 12

[8] Note, however, that only linear spectropolarimetry can unveil the real geometry of a stellar system. Vink et al. (2009), indeed, recently questioned the disk-hypothesis for Oe stars due to the lack of polarimetric proofs.

[9] In the spectra of the variable obtained during the period 2000–2001, the FWHM velocities were slightly lower, between 1600 and 2100 $\mathrm{km\,s^{-1}}$ in the post-outburst phases.

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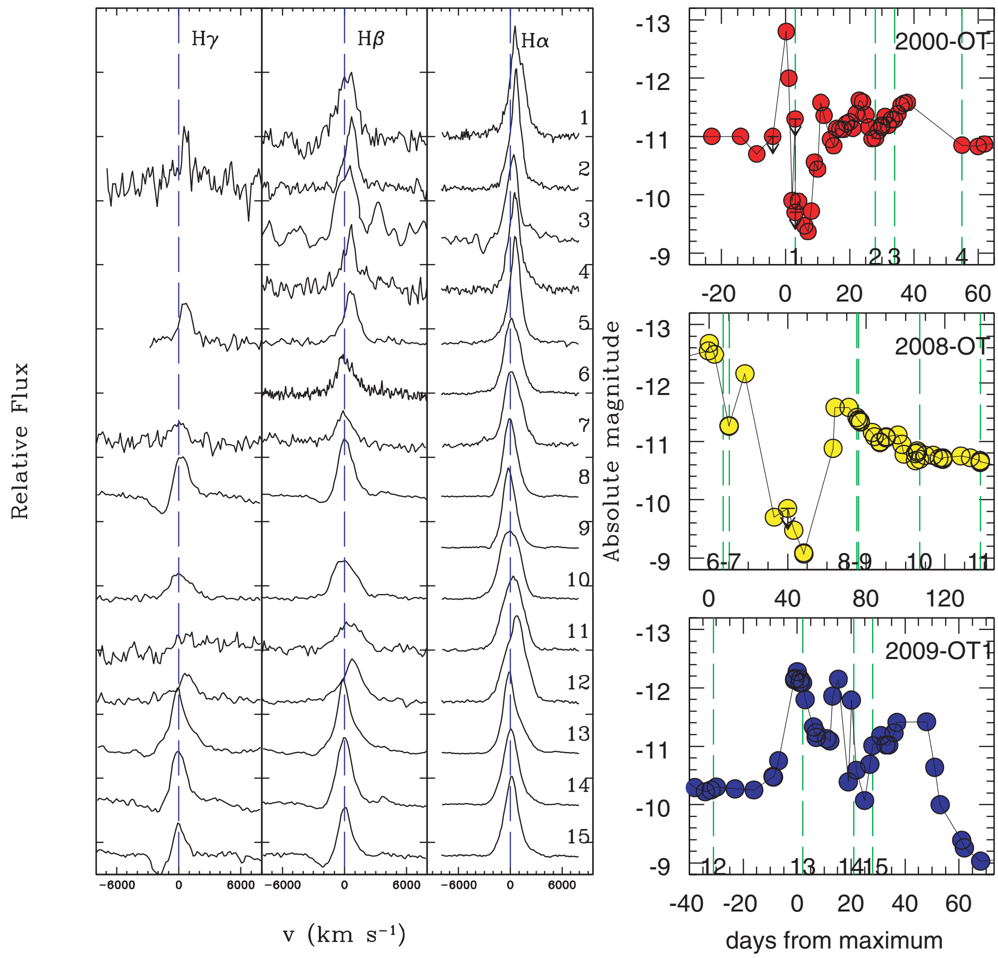

Figure 12. The profiles of Hγ, Hβ and Hα in the spectra of the luminous variable in NGC 3432 between 2000 and 2009 (left panel). The numbers in the panel of Hα allow us to date the spectra in the light curves of the three outbursts shown in the panels on the right: 2000-OT (top), 2008-OT (middle), 2009-OT1 (bottom). The vertical green dashed lines mark the epochs at which spectra are available: 2000 May 6 (1); 2000 May 31 (2); 2000 June 5 (3); 2000 June 27 (4); 2001 January 19 (5); 2008 October 14 (6); 2008 October 17 (7); 2008 December 21 (8); 2008 December 22 (9); 2009 January 22 (10); 2009 February 22 (11); 2009 March 22 (12); 2009 April 24 (13); 2009 May 12 (14); 2009 May 19 (15). Some spectra have been cut at the blue wavelengths because of the poor S/N. The epoch of the 2001 January 19 spectrum (labelled with number 5, Wagner et al. 2004a) is not marked on the right-hand panels because the spectrum was obtained several months after 2000-OT. The low S/N spectrum of 2000 June 5 (Wagner et al. 2004a) was slightly smoothed.

are relative to the epoch of the outburst peaks. We have marked the epochs of the individual spectra with vertical dashed lines. We note that the low S/N spectrum marked with 1 (2000 May 6), which shows evidence of Hβ with P-Cygni profile, was captured when the object was in the deep, post-maximum decline (R > 20.5) but still very close in time (~3 d) to the epoch of the outburst. Other spectra obtained soon after the outburst episodes show an excess at blue wavelengths and clear P-Cygni profiles. On the other hand, spectra with pure emission lines, including He II 4868 Å, were mostly obtained in periods of relative quiescence (R between 19 and 20). In addition, counter-intuitively, we found that $v_{\rm FWHM}$ of the line components in emission is lower immediately after outbursts than when the star is quiescent.

In other words, close to the outburst epochs, the spectra of the variable in NGC 3432 are reminiscent of those of regular erupting LBVs, while in quiescence the spectrum acquires some resemblance to those of young WRs. As mentioned above, although spectra of some LBVs may show He II lines during quiescence (e.g. AG Car, Stahl 1986), the velocity of the material ejected by the variable in NGC 3432 (as deduced from spectroscopy) is too high for a single LBV eruptor. As an alternative, supported by marginal evidence of modulation in the light curve, one may propose a multiple-system scenario. During outburst the total flux is dominated by the LBV eruptor, while in quiescence we start to see a WR companion. This scenario, similar to that proposed for the famous stellar system HD 5980 (see e.g. Koenigsberger 2004, and references therein), is discussed in detail in Section 6.

5 SPECTRAL ENERGY DISTRIBUTION

The evolution of the SED for the variable in NGC 3432 is shown in Fig. 13. The four panels show the SED at three epochs representative of crucial phases in the evolution of each major outburst: 2000-OT (top-left panel), 2008-OT (top-right), 2009-OT1 (bottom-left) and 2009-OT2 (bottom-right). We account only for epochs in which multiband observations of the source are available and, typically, close to a light curve maximum, a minimum and in quiescence.

As mentioned in Section 3, the light curve peak and the subsequent minimum after 2000-OT are extremely sharp, and multiband observations are available only from day +11 (Wagner et al. 2004a), when the transient is in the post-minimum rise. The SEDs at this and subsequent epochs (phases ~ +18 and +33; Fig. 13, top-left

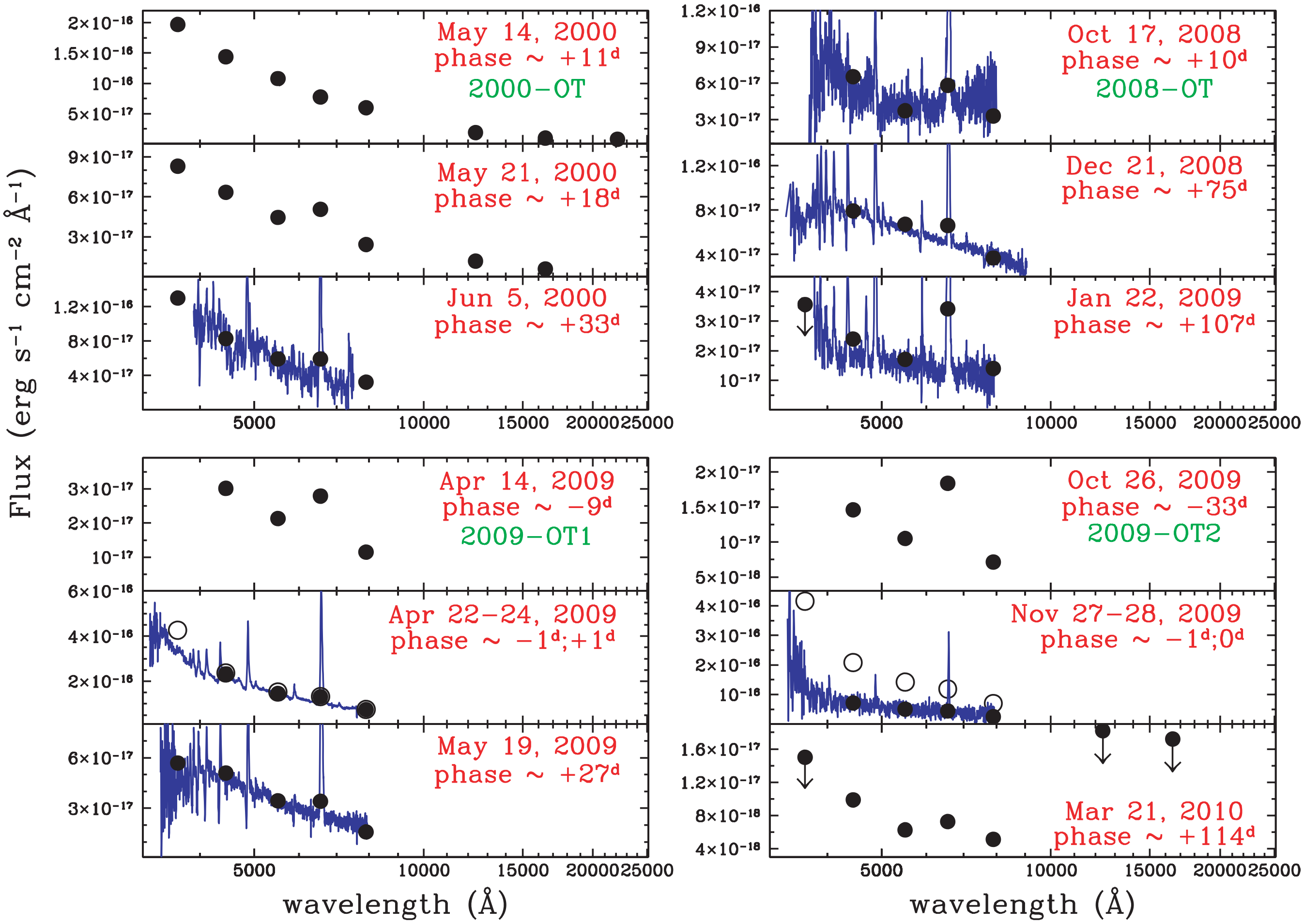

Figure 13. Evolution of the SED of the variable in NGC 3432 at 12 representative epochs (labelled on the right). Coeval spectra have also been shown as a comparison at seven epochs. The spectrum and the SED of 2009 April 24 (filled circles) are shown together with the SED computed 1 d before the maximum of 2009-OT1 (2009 April 22; open circles). Analogously, the spectrum and the SED of 2009 November 27 (filled circles) have been shown together with the SED computed at the epoch of the peak of 2009-OT1 (2009 November 28, open circles).

panel) are extremely blue, with a strong U-band flux contribution (the reddening-corrected $U-B$ ranges from -0.6 to -0.8 during this period).

The evolution of the SED after the 2008-OT eruptive episode is shown in the top-right panel. Again, multiband observations of the luminosity peak are missing. However, at day +10 from the main outburst (in coincidence with a sharp minimum) the source shows a redder SED ($V-I \approx 1$), with a clear R-band excess probably due to the flux contribution of Hα. The SED is then computed at +75 d when it becomes again much bluer ($U-B \approx -0.6$; $V-I \approx 0.5$), which is probably the result of a secondary eruptive event.[10] Finally, at +107 d from the main event, the absolute magnitude of the object is about $M_R \approx -10.7$, close to that expected during the quiescence. In this phase, there is a huge R-band (Hα) excess and the colour is still very red ($V-I \approx 1$).

In Fig. 13 (bottom-left panel, upper insert) we report the SED of the star at ~9 d before the peak of the 2009-OT1 outburst, when the luminosity of the object is rising after a deep minimum, and is close to the magnitude at the quiescence. The SED is quite similar to that computed on 2008 October 17. The central insert shows the SED around maximum light, which is extremely blue ($U-B \approx -1, V-I \approx 0.4$). In the subsequent epoch (+27 d) the SED is computed during a sharp luminosity minimum, but still with the object being in a very active, eruptive phase. Consequently, despite the faint absolute magnitude ($M_R \approx -10.3$), the variable still showed a moderately blue SED ($U-B \approx -0.5, V-I \approx 0.4$).

The last panel in Fig. 13 (bottom-right) shows the SED evolution before (−33 d, in a deep magnitude minimum, with $M_R \approx -9$), during and after (+114 d) the 2009-OT2 outburst. The evolution of the SED is similar to that shown for 2009-OT1 (bottom-left panel). At day −33 there is still a huge R-band excess and the SED is very red ($V-I \approx 0.8$), then it becomes blue during outburst ($U-B \approx -0.9, V-I \approx 0.45$) and finally redder again in quiescence ($V-I \approx 1$ at day +114). Unfortunately, the U, J and H band limits reported at phase ~ +114 d are not stringent.

The observed SED is dominated by the U-band emission at all epochs that are relatively close in time to an eruptive episode. This is clearly visible around and soon after the 2009 episodes (2009 April 22–24 and November 27–28), but also on 2008 December 21 when possibly a secondary eruptive episode occurred after 2008-OT. In our attempts to fit the SED around the time of the outbursts with a single blackbody, we obtain reasonable fits to the fluxes in the B, V, R, I bands with temperatures of 8500–9500 K, whilst we fail to simultaneously fit the U band flux, which shows a clear excess.

[10] There is a rebrightening in the light curve at day ~60 after the peak of 2008-OT that is clearly visible in Fig. 12, middle-right panel, for example.

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At these epochs, the spectra show prominent and narrow P-Cygni features, and there is no evidence for the presence of He II λ4686. After the outbursts, the SED evolution suggests a decline of the temperatures (in agreement with Wagner et al. 2004a, who fitted the optical SED of 2000 May 14, i.e. +11 d from the outburst, with a $T = 7800$ K blackbody).

In quiescence or in pre-outburst phases (e.g. 2008 October 17, 2009 January 22, April 14, October 26) the SED indicates somewhat cooler temperatures, and a clear excess in the R-band flux can be noted. At these phases, the spectral lines are broader and in pure emission, He II λ4686 becomes strong and Hα contributes significantly to the R-band flux.

The SED of an LBV is expected to shift from the UV to the optical during outbursts. This appears to be in contradiction with what we observe for the variable in NGC 3432 which, in outburst, moves its SED to bluer wavelengths (i.e. higher temperatures). On the other hand, during quiescence, the variable in NGC 3432 shows moderate temperatures ($V - I \sim 1$ would imply $T_{\rm eff} \approx 5300$ K, Drilling & Landolt 2000) that are typical of yellow (G-type) supergiants, and are inconsistent with early spectral types that LBVs are expected to show during quiescence (e.g. Wolf & Kaufer 1997).

The large U-band emission displayed by the variable in NGC 3432 during and soon after the eruptive events might provide key information. Lacking UV observations, we can only speculate on the nature of the U-band excess. A plausible scenario is that the observed SED is in reality due to two variable contributions: a very hot component which peaks in the UV domain associated with the outburst, plus a warm component that peaks in the optical and declines in temperature with time after the outburst, possibly due to the hypergiant star. A detailed study on the UV variability of the source appears to be crucial to understand the nature of the luminous star in NGC 3432. Spectral modelling of the continuum and the strong stellar outflow would also give estimates for $T_{\rm eff}$ and $\log L$ of the star during its transitional phases, to determine if the observables are consistent with our ideas of LBVs expanding and cooling during outbursts.

Nevertheless, a further stellar component is still necessary to account for the presence of the He II λ4686 line in the spectra of the variable and the high-velocity wind observed during quiescence. These observables would be more consistent with a scenario involving also a hot Wolf–Rayet star (see Section 6).

6 THE NATURE OF THE VARIABLE IN NGC 3432

The luminous variable in NGC 3432 is one of the most intriguing stars discovered in the local Universe. It experienced at least four luminous outbursts within a decade, but a number of minor rebrightenings were also observed (e.g. Fig. 7). Since the three most recent outbursts occurred with intervals of about 200–210 d, one may suggest that subsequent eruptive events occur with some periodicity, although the modulation of the light curve is not regular enough to support this claim. In quiescence the object has an unusually high intrinsic luminosity ($M_R \approx -10.8$), consistent with that of a luminous LBV. Also, to our knowledge, its spectra are unprecedented. Prominent H Balmer lines, dominating over other spectral lines (e.g. He I, Fe II), are typical of LBVs. However, the velocity of the ejected material, 1500–2500 km s^{-1}, is high (by a factor of ∼5–10) for erupting LBVs, and are more consistent with velocities expected in winds of Wolf–Rayet stars (or in some very hot stars, see Cassinelli & Lamers 1987, that are not expected to produce prominent H lines like those observed in the spectra of the NGC 3432 variable). In addition, the presence of He II during the quiescent phase is indicative of high gas temperatures, which is unusual in LBVs, and is commonly observed in Wolf–Rayet stars (including Ofpe/WN9 transition types; see Morris et al. 1996; Nota et al. 1996). However, in all these stars the He II lines (in particular that at 4686 Å) are expected to dominate over all the other lines. This is not the case for the variable in NGC 3432, in which He II λ4686 is always less prominent than Hβ. A relatively weak He II λ4686 line was occasionally observed in quiescent LBVs (Stahl 1986), but always at much lower velocities than those observed in the spectra of the variable in NGC 3432.

In addition, the asymmetric profile (double-peaked, see insert in Fig. 9) of the He II λ4686 line is puzzling. It is currently unclear if this peculiar profile is due to a blend with other spectral lines or if it is an intrinsic asymmetry of the He II line. A similar profile in the He II λ4686 feature was observed also in the spectra of the luminous OB supergiant S18 in the Small Magellanic Cloud (SMC), classified as a B[e] type (Nota et al. 1996). In that case, the line asymmetry and its variability with time were interpreted as a signature of accretion on to a hot companion inside a complex, two-component circumstellar wind (a hot, high-velocity polar wind plus a cooler, dense equatorial disc; see Shore, Sanduleak & Allen 1987; Zickgraf et al. 1989). However, S18 has a moderate photometric variability,[11] it is slightly fainter ($M_{\rm bol} \approx -9.2$ to -9.4, Zickgraf et al. 1989) and the spectral lines are narrower than those observed in the spectra of the variable in NGC 3432. Nevertheless, despite the evident differences between the variable in NGC 3432 and S18 in SMC, a scenario involving a companion star and a CSM might explain both the quasi-modulated variability in the light curves and the variability of the He II λ4686 line.

The large photometric variability of the luminous star in NGC 3432 is another characteristic that is difficult to explain. A variability of 4–5 mag is not unusual for an LBV outburst. However, the frequency of these episodes is puzzling. According to Humphreys & Davidson (1994), different types of variability, in terms of magnitude amplitudes and time-scales, are observed in LBVs, as follows.

(i) *Giant eruptions*, like that of η Car during the 1840s, are rare and expected to occur in intervals of hundreds to thousands of years. During these outbursts the star increases its magnitude by more than 2 mag and ejects a significant amount of its envelope. Erratic individual brightenings have short life, although the phase of intense activity may last even a few years. This phase of major activity is then followed by a long period of quiescence.

(ii) *Eruptions* are much more frequent, being usually observed over time-scales of decades. In these episodes the star brightens by less than 2 mag, although the bolometric luminosity remains almost constant, and the eruptive phase may last for months to years, followed by a luminosity minimum of similar duration. AG Car experienced this kind of variability during the 1980s (Bateson 1988-2000; Stahl et al. 2001).

(iii) *Smaller oscillations* ($\Delta m \leq 0.5$), or even *microvariations* ($\Delta m \leq 0.1$), are also frequently observed in LBVs on time-scales from weeks to several months.

It is evident that the variable in NGC 3432 has unique characteristics, since it does not match any of these variability scenarios.

[11] The variability of S18 is <1 mag, according to van Genderen & Sterken (2002), while most of the B[e]-type stars do not show significant magnitude oscillations.

Although modulated light curves (e.g. Fig. 7) are typical of LBVs during the S-Dor phase, the fact that the variable in NGC 3432 experienced at least four major outbursts in 9 yr plus a few further minor episodes in a very short period of the stellar evolution (around 15 yr) is unexpected and probably cannot be connected to an S-Dor type of variability. Smith et al. (2001) noted some similarity with the erratic fluctuations of the light curve of V12 in NGC 2403 during the period 1949–1954 (Tammann & Sandage 1968; Humphreys, Davidson & Smith 1999), and suggested that these oscillations may be typical of LBVs prior to and during a giant eruption.

Another possibility is that we are observing a very massive star in the latest stages of its life, which experiences a major phase of instability. Frequent ejections of H-rich shells through a pulsational pair instability mechanism, followed by their collisions, have been proposed to explain the properties of the overluminous type IIn SN 2006gy (Woosley, Blinnikov & Heger 2007). A similar scenario has been proposed for another type IIn event, SN 1994W (Dessart et al. 2009).[12] In both cases, the shell–shell interaction was able to fully explain the observed properties of these events, even without the need to invoke an additional contribution from radioactive ^{56}Ni (e.g. Smith et al. 2007).

As mentioned above, the spectral lines identified in 2008-OT are consistent with those of LBVs. The spectra of the variable in NGC 3432 are indeed reminiscent of those of LBV NGC 2363-V1 presented in Petit, Drissen & Crowther (2006). The spectral lines and their evident P-Cygni profiles are remarkably similar in these two objects, but the derived velocities are about one order of magnitude lower in the LBV NGC 2363-V1. LBVs in eruption may have significantly higher velocities, but usually without reaching the extreme values registered in the cases of the major outbursts of the variable in NGC 3432 (see Fig. 11 panel B and discussion in Section 4).

The recurrent mass ejections observed in the variable in NGC 3432 are then expected to produce an increasingly He-rich CSM, stripping the star of its massive envelope. The above scenario, as suggested by Woosley et al. (2007), may also explain the sequence of events preceding SN 2006jc and the formation of its dense, He-rich CSM (Nakano et al. 2006; Pastorello et al. 2007a). Remarkably, the FWHM velocity of the H and He I lines in recent spectra of the variable in NGC 3432 ($\sim$2300 km s^{-1}) is very close to that reported by Pastorello et al. (2007a) for the He I circumstellar lines of SN 2006jc (about 2200 km s^{-1}). This wind velocity (as mentioned above) is significantly higher than that expected of eruptions of LBVs, and more consistent with that of a Wolf–Rayet wind. However, H is still the most prominent spectral feature. The N and He II lines which characterize spectra of young Wolf–Rayet stars (of WN type, Crowther et al. 1995a; see also Section 4) are relatively weak (He II λ4686) or not detected. In addition, the progenitor stars of the variable in NGC 3432 and SN 2006jc were different. In the case of SN 2006jc, a young Wolf–Rayet star[13] was proposed as progenitor (Foley et al. 2007; Pastorello et al. 2007a), while the variable in NGC 3432 is significantly less evolved, since the spectra are still dominated by H lines. This would suggest that it is in a transitional phase of its evolution, possibly approaching the Wolf–Rayet stage. In the light of all of this, the frequent outbursts of the NGC 3432 variable star may possibly herald a similar fate as the precursor of SN 2006jc and an imminent SN explosion.

As an alternative to the pulsational instability, these oscillations in the light curve may indicate another plausible scenario, in which the NGC 3432 variable is a member of a close binary stellar system (like S18 in SMC, Zickgraf et al. 1989) in a complex circumstellar environment. Binarity could enhance the LBV instability. In that case, bipolar structures can be expected in the ejected material. This might be verified through high-resolution spectroscopic observations or with (spectro)polarimetry, both of them unfortunately still out of reach for the variable in NGC 3432.

Another object which the luminous star in NGC 3432 may share some similarity with is the stellar system HD 5980 in SMC (see Koenigsberger 2004, for a review). HD 5980 is one of the best-studied stellar objects, and the brightest source (with integrated magnitude $M_V = -7.3$, Breysacher & Perrier 1991) in the SMC. However, there is substantial evidence that it is not a single exceptionally massive star, but is a triple system comprising of a massive erupting LBV/WR (usually labelled *star A*), an early Wolf–Rayet (*star B*) and, possibly, an O-type companion[14] (*star C*). The three stars have, in quiescence, individual absolute magnitudes of about $M_V \sim -6$ (Foellmi et al. 2008). *Star A* (with a mass of about 50 M$_\odot$, Niemela et al. 1997) and *star B* ($M \approx 28\,$M$_\odot$)[15] constitute a rather close, eclipsing binary system with a period of about 19 d and a rather eccentric orbit ($e = 0.3$). During past decades HD 5980 gradually changed its absolute magnitude and its spectroscopic properties. This was because *star A* entered a very active phase of variability, during which it changed its spectrum from that of a Wolf–Rayet star (of WN4-type, in the early 1980s; Niemela et al. 1997) to that of an LBV (at the time of the eruption, in 1993–1994; see Koenigsberger et al. 1996, and references therein) and back to a WN type in more recent years. During the late 1970s to the early 1980s, the spectrum of HD 5980 showed strong, high-velocity ($v_\infty \approx$ 2000–3000 km s^{-1}) He II lines which are traditionally seen in WN-type Wolf–Rayet stars. However, at the time of the outburst of *star A*, HD 5980 increased its luminosity by about 3 mag, and the spectrum started to show prominent and narrower lines of H and He I (Bateson, Gilmore & Jones 1994; Barbá et al. 1995; Koenigsberger et al. 1995) that are typical of LBV eruptions. At the time of the major eruption, the minimum wind velocities measured from the spectra of HD 5980 were about 500 km s^{-1}, but they rapidly increased in the subsequent few months to about 1000–1300 km s^{-1} (Koenigsberger et al. 1998). It is generally assumed that in the pre-outburst phase the spectrum of HD 5980 was dominated by the Wolf–Rayet features attributed to *star B*, while during outburst the spectrum was dominated by the lower-velocity LBV-like features of *star A*. However, it is still puzzling how *star A* could be a hot WN star before (and after) its eruption as an LBV. The pieces of evidence (1) that the spectra of HD 5980 show strong H lines (with line velocities that are, however, too high for an LBV) and (2) that only one eruption has been registered so far, suggest that *star A* is not a Wolf–Rayet star in the classical sense, but it is in a sort of

[12] Data for SN 1994W were presented by Sollerman, Cumming & Lundqvist (1998). The SN was extensively modelled also by Chugai et al. (2004) who interpreted its observed properties to result from the SN ejecta interacting with a dense and extended CS envelope ejected in a violent event of the progenitor star just $\sim$1.5 yr before its explosion.

[13] Alternatively, Tominaga et al. (2008) proposed that the precursor of SN 2006jc was a more evolved WCO star.

[14] According to Foellmi et al. (2008), we cannot exclude the fact that the membership of *star C* to the stellar system HD 5980 is only a mere line-of-sight coincidence.

[15] We should note that Foellmi et al. (2008) revised the classical mass estimates of Niemela et al. (1997) proposing significantly higher masses for both *star A* and *star B*, being 58–79 M$_\odot$ and 51–67 M$_\odot$, respectively.

pre-LBV evolutionary phase (Foellmi et al. 2008). It is interesting to note that also a few other luminous, H-rich Wolf–Rayet stars are observed in the SMC (Foellmi, Moffat & Guerrero 2003).

In this context, the observables of the variable star in NGC 3432 appear rather similar to those of HD 5980 during the eruptive phase. This might indicate that the variable in NGC 3432 is in a similar evolutionary path as *star A*, i.e. in an initial LBV stage. This might explain the high wind velocities in an otherwise LBV-like spectrum. But it does not explain the strength and the variability of the He II line. In addition, one can speculate that some of the photometric and spectroscopic variability observed in the luminous variable in NGC 3432 can in some way be related to the close interaction with a companion WR star, in analogy to that observed in the stellar system HD 5980. Interestingly, both NGC 3432 and SMC have quite low oxygen abundances, of $12 + \lg(O/H) = 8.3$ (see Section 2) and 8.0 (Hunter et al. 2007; Trundle et al. 2007), respectively.

Long-term monitoring of the hyperactive variable in NGC 3432 is required to understand the configuration of the stellar system, the reasons of its peculiar variability and if the observed properties are an indication of a forthcoming SN explosion.

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SUPPORTING INFORMATION

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

Table 1. Unpublished Johnson–Bessell photometry of the variable star in NGC 3432.
Table 2. Sloan-filter photometry of the variable star in NGC 3432 and associated errors.

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