

Interacting supernovae and supernova impostors. SN 2007sv: the major eruption of a massive star in UGC 5979

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ABSTRACT

We report the results of the photometric and spectroscopic monitoring campaign of the transient SN 2007sv. The observables are similar to those of type II_n supernovae, a well-known class of objects whose ejecta interact with pre-existing circum-stellar material. The spectra show a blue continuum at early phases and prominent Balmer lines in emission, however, the absolute magnitude at the discovery of SN 2007sv ($M_R = -14.25 \pm 0.38$) indicate it to be most likely a supernova impostor. This classification is also supported by the lack of evidence in the spectra of very high velocity material as expected in supernova ejecta. In addition we find no unequivocal evidence of broad lines of α - and/or Fe-peak elements. The comparison with the absolute light curves of other interacting objects (including type II_n supernovae) highlights the overall similarity with the prototypical impostor SN 1997bs. This supports our conclusion that SN 2007sv was not a genuine supernova, and was instead a supernova impostor, most likely similar to the major eruption of a luminous blue variable.

Key words: galaxies: individual (UGC 5979) - supernovae: individual (SN 2007sv)

1 INTRODUCTION

With the label of *supernova* (SN) *impostors* we refer to a class of objects showing luminous outbursts that mimic the behaviour of real supernovae (SNe; see e.g. Van Dyk et al. 2000, 2012; Maund et al. 2006; Dessart et al. 2009). The most classical SN impostors are thought to be the eruptions of extragalactic luminous blue variables (LBVs, Humphreys & Davidson 1994). They may experience eruptions with comparable energies as those of real SNe, but

the stars survive the eruptive events.

LBVs are evolved, massive stars very close to the classical Eddington limit, showing irregular outbursts and, occasionally, even giant eruptions during which they lose massive portions of their H-rich envelope (up to a few solar masses per episode). In quiescence they are blue stars located in the so called 'S Doradus Instability Strip' of the HR Diagram, namely in the luminosity-temperature range $-9 \leq M_{\text{bol}} \leq -11$ and $14000 \text{ K} \leq T_{\text{eff}} \leq 35000 \text{ K}$ (Wolf 1989). During eruptive episodes LBVs become redder and evolve with a roughly constant bolometric magnitude. However, it has been proposed that they may increase their bolometric

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luminosity during giant eruptions (Humphreys & Davidson 1994). Active LBVs show quite erratic variability and, sometimes, fast optical luminosity declines after the outburst, possibly because of prompt dust formation in the circum-stellar environment. Spectroscopic studies indicate that eruptions are accompanied with relatively high velocity winds, viz. a few hundreds km s^{-1} . Their spectra share some similarity with those of type II_n SNe, with prominent and narrow hydrogen lines in emission (Van Dyk et al. 2000).

SN impostors are believed to be extra-Galactic counterparts of the famous ‘Giant Eruption’ of the galactic LBV η Carinae in the mid-19th century. This, together with the eruption of P Cygni in the 17th century, are the only two major eruptions registered in the Milky Way in recent times. However, weaker eruptions were occasionally observed in the past either in the Milky Way (e.g. AG Car) or in the Local Group (e.g. S Doradus in the LMC, Humphreys & Davidson 1994). These nearby examples are fundamental to our understanding of the nature of eruptive phenomena since their physical parameters are well constrained, and give us the opportunity to demonstrate that these stars survive major eruptions.

It has been argued that a connection may exist between interacting SNe and impostors, mainly based on the observed similarity in the spectra, although they usually have remarkably different photometric properties. Even more importantly, there is evidence (though debated) that LBVs or other massive stars may explode as real interacting SNe soon after major outbursts (e.g. Pastorello et al. 2007; Mauerhan et al. 2013; Margutti et al. 2014; Ofek et al. 2013; Smith et al. 2014) or, at least, that interacting SNe are connected with massive stars compatible with LBVs (Kotak & Vink 2006; Gal-Yam & Leonard 2009, and references therein).

In this context we report the case of SN 2007sv. The transient was discovered on 2007 December 20.912 UT, and was located 6".9 West and 6".7 South of the centre of UGC 5979 (Duszanowicz et al. 2007). The detection was confirmed with an unfiltered CCD image by T. Boles on 2007 December 25.971 UT, whilst there was no source detected at the position of SN 2007sv on an archive image taken on 2007 September 13.093 UT (Duszanowicz et al. 2007).

This article is organised as follows. In Section 2 we report comprehensive information about the host galaxy and in Sections 3 and 4 we present the results of our photometric and spectroscopic observations, respectively. A discussion follows in Section 5, where we remark similarities and differences between 2007sv and other interacting events. Finally our main conclusions are summarized in Section 6.

Hereafter we will refer to SN impostors reporting their names without the ‘SN’ prefix, in order to emphasize their different nature compared to genuine SNe.

2 THE HOST GALAXY

The host galaxy, UGC 5979, is a low-contrast faint (with apparent B magnitude 15.93) dwarf galaxy without a visible

nucleus. Dwarf galaxies are the most common galaxies in the universe. Grebel (2001) considers all galaxies with absolute magnitude fainter than $M_V \simeq -18$ as dwarfs, while according to Tammann (1994) the limit usually is $M_B \simeq -16$. According to their optical appearance they are classified into five different groups: dwarf irregulars (dIs), blue compact dwarfs (BCDs), dwarf ellipticals (dEs), dwarf spheroidals (dSphs) and dwarf spirals (dSs). However, this morphological classification is somewhat arbitrary, and the distinction between different classes is sometimes ambiguous¹.

UGC 5979 is a diffuse (dI) galaxy², located at $RA = 10:52:41.16$ and $Dec = +67:59:18.8$ [J2000], with a radial velocity corrected for the Local Group infall onto the Virgo cluster of about 1376 km s^{-1} ($z = 0.0045$). From the above value of the recessional velocity, we infer a distance for UGC 5979 of about $18.85 \pm 1.03 \text{ Mpc}$, resulting in an absolute magnitude of $M_B = -15.5$ (distance modulus $\mu \simeq 31.38 \pm 0.27 \text{ mag}$, adopting $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

For the foreground Galactic extinction we assumed the value $A_V = 0.048 \text{ mag}$, as derived from the Schlafly & Finkbeiner (2011) recalibration of the Schlegel et al. (1998) infrared-based dust maps available e.g. in NED³. We also adopt no additional host galaxy extinction contribution in the transient direction, since a detailed analysis of the spectra of 2007sv revealed no evidence of narrow absorptions of the NaID doublet at the recessional velocity of the host galaxy.

A rough estimate of the metallicity of the host galaxy can be obtained from the relation of Pilyugin et al. (2004):

$$12 + \log(\text{O}/\text{H}) = 5.80(\pm 0.017) - 0.139(\pm 0.011)M_B \quad (1)$$

that links the integrated absolute B -band magnitude with the average oxygen abundance of the galaxy, providing a value of ~ 8 , which suggests that the environment may have a significantly sub-solar metallicity. A direct measurement of the host galaxy metallicity confirms this result. We spectroscopically observed UGC 5979 with the Nordical Optical Telescope (NOT) equipped with ALFOSC+grism#4. A 1.0" slit was placed on a bright H II region at 19.5" (1.8 kpc) from SN 2007sv. After 1800 sec exposure, we obtained an optical spectrum with clear detection of narrow [O III] $\lambda 5007 \text{ \AA}$, [O III] $\lambda 4959 \text{ \AA}$, Balmer lines up to $H\gamma$, [N II] $\lambda 6584 \text{ \AA}$ and [S II]. Via Balmer decrement we determined an extinction of $E(B - V) = 0.82 \text{ mag}$ at the H II region location and we corrected the spectrum accordingly. We measured the line fluxes by fitting them with Gaussians, as explained in detail in Taddia et al. (2013). The detection of N II, $H\alpha$, $H\beta$ and O III lines allowed us to determine the oxygen abundance via strong line diagnostics, namely with the N2 and O3N2 methods (Pettini & Pagel 2004). Our results are $\log(\text{O}/\text{H})+12$ (N2) = 8.01–8.1 dex and $\log(\text{O}/\text{H})+12$ (O3N2) = 8.00–8.08 dex. The quoted uncertainty is due to

¹ Further sub-classification is based on the revised de Vaucouleurs morphological classification introduced by van den Bergh (1960) and on the luminosity classification introduced by van den Bergh (1960) (and extended by Corwin et al. 1985)).

² <http://leda.univ-lyon1.fr/>

³ <http://ned.ipac.caltech.edu>

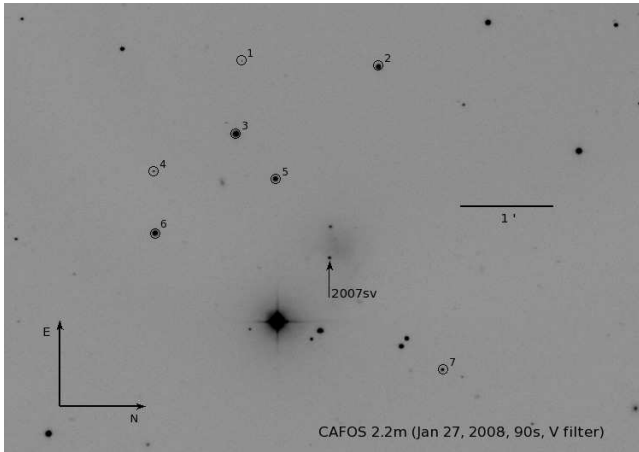


Figure 1. Finding chart of 2007sv. The stars used for the photometric calibration are labelled with a number, the position of the transient is marked with an arrow. Information about the instrumental set-up is also reported.

the error on the flux of N II, which appears rather faint. Sub-solar metallicities may be a rather common characteristic of SN impostor environments (see Habergham et al. 2014) and we are currently investigating this issue for a large sample of impostor environments (Taddia et al. in prep).

3 PHOTOMETRY

Our photometric monitoring campaign started on December 30, 2007 and spanned a period of about 100 days. We also collected sparse observations (mostly unfiltered) from amateur astronomers. Information about the photometric data and the instruments used are reported in Table 1.

All data were pre-processed using standard procedures in IRAF⁴ including bias and flat field corrections. To measure the magnitudes we used a dedicated pipeline developed by one of us (E. C.), that consists of a collection of PYTHON scripts calling standard IRAF tasks (through PYRAF) and other specific analysis tools, in particular SEXTRACTOR for source extraction and star/galaxy separation, DAOPHOT to measure the source magnitude via PSF fitting and HOTPANTS⁵ for image difference with PSF match.

The magnitudes were measured using the PSF-fitting technique, first subtracting the sky background calculated using a low order polynomial fit (typically a 2nd order polynomial). The PSF was obtained by averaging the profiles of isolated field stars. The fitted source is removed from the original frames, then a new estimate of the local background is derived and the fitting procedure is iterated. Finally, the residuals are visually inspected to validate the fit.

Error estimates were obtained through artificial star experiments in which a fake star, of magnitude similar to that of

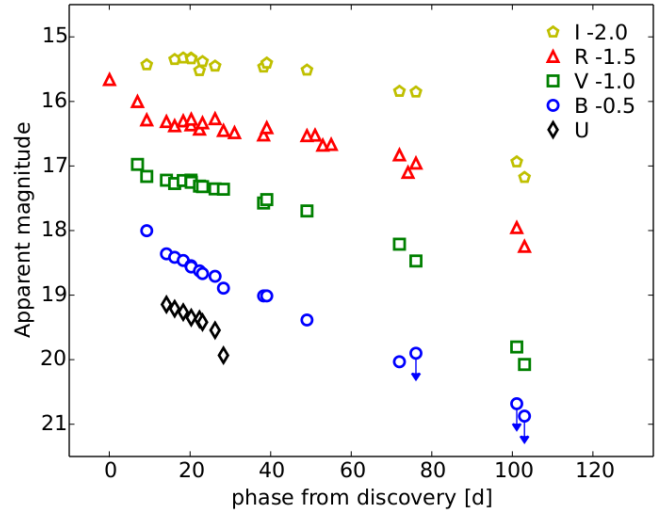


Figure 2. Multi-band light curves of 2007sv. The UBVRI magnitudes are listed in Table 1. The phase is from the discovery.

the SN, is placed in the PSF-fit residual image in a position close to, but not coincident with that of the real source. The simulated image is processed through the PSF fitting procedure and the dispersion of measurements out of a number of experiments (with the fake star in slightly different positions), is taken as an estimate of the instrumental magnitude error. This is combined (in quadrature) with the PSF-fit error returned by DAOPHOT.

The SN photometry was calibrated as follows. Among the observational data, we selected the frames obtained in photometric nights in which standard photometric fields (from the list of Landolt 1992) were observed. These standard frames were used to derive zero points and colour terms for the specific instrumental set-up and to calibrate the magnitudes of selected stars in the SN field (Table 2 and Figure 1). This local sequence was used to calibrate the SN magnitudes in non-photometric nights. The final magnitudes were computed using first-order colour-term corrections.

The resulting magnitudes of 2007sv are reported in Table 1 along with the photometric errors, and the light curves are shown in Figure 2. We remark no observation was obtained in the days before the discovery (December 20, 2007), therefore the epoch of the maximum cannot be precisely constrained. In the following, we adopt the epoch of the discovery (which we assume to be in the proximity of the maximum light) as reference time for the light curve phases.

Adopting for 2007sv the distance modulus and the reddening discussed Section 2, we obtain an absolute magnitude at discovery of $M_R = -14.25 \pm 0.38$, which can be considered as an indicative estimate for the peak absolute magnitude. As shown in Figure 3, this value is similar to that measured for the SN impostor 1997bs (Van Dyk et al. 2000) and the enigmatic transient SN 2008S (light curve in Figure 3 and spectrum in Figure 9 from Botticella et al. 2009), and significantly fainter than that one may expect from a canonical SN IIn such as SN 1999el (Di Carlo et al. 2002). This gives a clue to infer the true nature of 2007sv, although it is not sufficient to rule out alternative SN hypothesis, as we will discuss in Section 5.

⁴ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Associated Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

⁵ <http://www.astro.washington.edu/users/becker/hotpants.html>

Table 1. Optical magnitudes of 2007sv and associated errors.

Date	MJD	U	err	B	err	V	err	R	err	I	err	Instrument
20070913	54356.09	-	-	-	-	-	-	>18.8	-	-	-	SX MX7
20071220	54454.91	-	-	-	-	-	-	17.161	0.261	-	-	SX MX7
20071227	54461.86	-	-	-	-	17.975	0.356	17.502	0.137	-	-	MX916
20071230	54464.15	-	-	18.502	0.077	18.161	0.039	17.786	0.023	17.432	0.023	AFOSC
20080104	54469.04	19.145	0.147	18.860	0.025	18.220	0.014	17.812	0.024	-	-	RATCam
20080106	54471.08	19.211	0.057	18.914	0.042	18.271	0.017	17.877	0.018	17.350	0.020	RATCam
20080108	54473.21	19.264	0.085	18.963	0.025	18.225	0.019	17.802	0.029	17.327	0.020	RATCam
20080110	54475.14	-	-	19.044	0.066	18.219	0.027	17.863	0.028	17.329	0.026	AFOSC
20080110	54475.20	19.348	0.076	19.064	0.024	18.252	0.015	17.776	0.030	17.338	0.017	RATCam
20080112	54477.25	19.373	0.025	19.124	0.024	18.311	0.026	17.929	0.033	17.522	0.032	ALFOSC
20080113	54478.00	19.420	0.081	19.166	0.027	18.319	0.016	17.832	0.032	17.382	0.035	RATCam
20080116	54481.12	19.544	0.138	19.208	0.020	18.354	0.026	17.768	0.029	17.452	0.028	RATCam
20080118	54483.20	19.933	0.213	19.392	0.102	18.359	0.034	17.951	0.127	-	-	RATCam
20080120	54485.94	-	-	-	-	-	-	17.984	0.265	-	-	SX MX7
20080128	54493.16	-	-	19.512	0.109	18.573	0.030	18.020	0.068	17.467	0.085	CAFOS
20080128	54493.95	-	-	19.526	0.037	18.520	0.022	17.907	0.023	17.406	0.024	RATCam
20080207	54503.93	-	-	19.885	0.036	18.696	0.021	18.030	0.025	17.514	0.032	RATCam
20080209	54505.94	-	-	-	-	-	-	18.023	0.179	-	-	Apogee Ap7
20080211	54507.85	-	-	-	-	-	-	18.178	0.210	-	-	SBIG ST-7
20080213	54509.94	-	-	-	-	-	-	18.166	0.218	-	-	SX MX7
20080301	54526.88	-	-	20.532	0.053	19.211	0.028	18.328	0.041	17.843	0.056	RATCam
20080304	54529.01	-	-	-	-	-	-	18.599	0.262	-	-	SX MX7
20080305	54530.98	-	-	>20.4	-	19.471	0.056	18.456	0.067	17.854	0.035	CAFOS
20080331	54556.00	-	-	>21.2	-	20.803	0.057	19.455	0.064	18.936	0.049	ALFOSC
20080401	54557.93	-	-	>21.4	-	21.074	0.047	19.745	0.044	19.177	0.184	RATCam

The observations were carried out using the 2.56 m Nordic Optical Telescope (NOT) with ALFOSC and the 2 m Liverpool Telescope with RATCam (both located at the Roque de Los Muchachos, La Palma, Canary Islands, Spain), the Calar Alto 2.2 m Telescope with CAFOS (Sierra de Los Filabres, Spain) and the 1.82 m Copernico Telescope with AFOSC (Mount Ekar, Asiago, Italy). Additional observations (mostly unfiltered) were obtained by amateur astronomers.

The magnitudes obtained from SX MX7, Apogee Ap7 and SBIG ST-7 were computed from unfiltered images, whose magnitudes were rescaled to R-band.

MX916: 0.45 m f4.5 newtonian telescope with a MX916 CCD Camera, at Mandi Observatory (Pagnacco, Udine, Italy)

SX MX7: 0.32 m f/3.1 reflector and a Starlight Xpress MX716 CCD camera at Moonbase Observatory (Akersberga, Sweden)

Apogee AP7: C-14 Celestron Schmidt Cassegrain reflector and an Apogee AP7 CCD camera (Suffolk, United Kingdom)

SBIG ST-7: 0.44 m f4.43 telescope with a SBIG ST-7 Dual CCD Camera at Sandvretens Observatorium (Uppsala, Sweden)

Table 2. Magnitudes of the stellar sequence used for the photometric calibration. The stars are shown in Figure 1.

label	ra [J2000] (hh:mm:ss)	dec [J2000] (dd:mm:ss)	U	err	B	err	V	err	R	err	I	err
1	10:53:02.62	67:58:18.77	-	-	-	-	20.159	0.056	19.202	0.015	-	-
2	10:53:01.92	67:59:46.33	18.451	0.020	17.110	0.015	15.861	0.029	14.983	0.022	14.214	0.027
3	10:52:54.29	67:58:14.49	15.692	0.009	15.675	0.007	15.127	0.020	14.800	0.016	14.429	0.030
4	10:52:50.03	67:57:21.82	-	-	20.571	0.010	19.113	0.024	18.195	0.015	16.425	0.014
5	10:52:49.13	67:58:39.87	17.682	0.007	17.088	0.011	16.212	0.012	15.688	0.008	15.180	0.012
6	10:52:43.00	67:57:22.46	16.401	0.004	16.329	0.005	15.661	0.010	15.295	0.006	14.887	0.003
7	10:52:27.18	68:00:26.52	-	-	-	-	18.245	0.013	17.770	0.005	17.299	0.015

The $B - V$, $V - R$ and $V - I$ colour curves of 2007sv are compared in Figure 4 with those of the same SNe considered in Figure 3, showing that 2007sv rapidly becomes red (in analogy with other SN impostors) as the temperature of the ejecta decreases (Section 4). On the other hand, the regular type IIIn SN 1999el remains bluer for a longer time. In particular, it has much bluer colours than the other transients at phases later than 100 days.

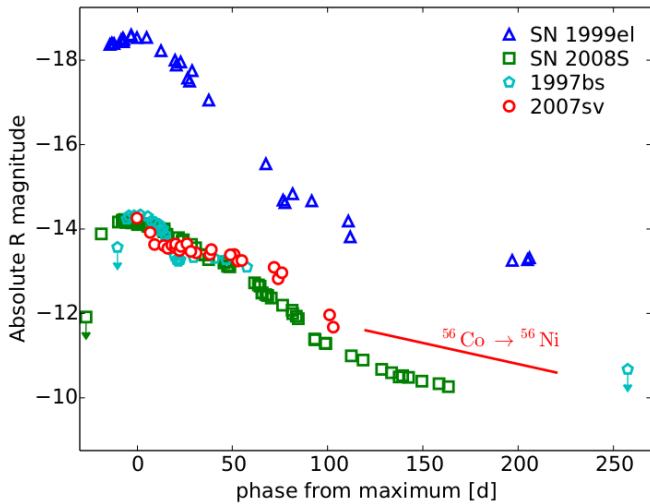
The comparisons shown above highlight some of the similarities between the SN impostors 2007sv and 1997bs

and the peculiar transient SN 2008S, whose nature has not been firmly established yet (genuine electron-capture SN or SN impostor, see Prieto et al. 2008; Botticella et al. 2009; Smith et al. 2009; Thompson et al. 2009; Pumo et al. 2009; Wesson et al. 2010; Kochanek 2011; Szczygiel et al. 2012, and Section 4.3), all showing a fainter maximum and a different evolution in the light curve when compared with the light curve of the interacting SN 1999el.

Table 3. Log of the spectroscopic observations of 2007sv. The phase refers to the discovery.

Date	MJD	Phase (days)	Instrumental setup	Grism or grating	Spectral range (Å)	Resolution (Å)	Exp. times (s)
20071229	54463.96	9	Ekar182+AFOSC	2×gm4	3450-7800	24	2×1800
20080105	54470.05	15	TNG+LRS	LR-B	3600-7770	19.9	2700
20080110	54475.08	20	Ekar182+AFOSC	gm2+gm4	3450-8100	34; 24	2×1800
20080113	54478.26	23	TNG+LRS	LR-R	5070-10100	10.7	1800
20080114	54479.12	24	NOT+ALFOSC	gm4	3300-9100	9.6	1800
20080119	54484.43	30	HET	LRS	4300-7300	6.2	2×1350
20080128	54493.17	38	CAHA+CAFOS	b200	3200-8800	12.3	3600
20080201	54497.12	42	WHT+ISIS	spec	3200-10300	4.8; 9.8	1200
20080301	54526.25	71	HET	LRS	4300-7300	6.0	4×1125
20080308	54533.04	78	CAHA+CAFOS	b200+g200	4800-10700	13.8	2×2400

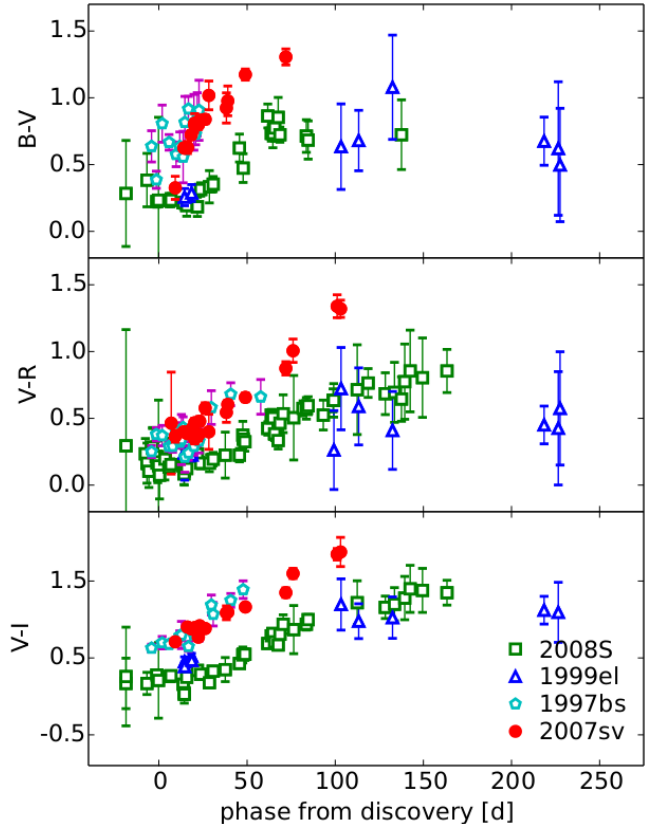
The spectra were obtained using the 1.82 m Telescopio Copernico with AFOSC, the 3.58 m Telescopio Nazionale Galileo (TNG) with DOLoRes (La Palma, Canary Islands, Spain), the 4.2 m William Herschel Telescope with ISIS (La Palma, Canary Islands, Spain), the 2.56 m Nordic Optical Telescope (NOT) with ALFOSC, the Calar Alto 2.2 m telescope with CAFOS and the 11.1x9.8 m Hobby-Eberly Telescope (HET, Mt. Fowlkes, Texas, USA) with LRS.


Figure 3. Comparison of the absolute R-band light curves of the impostors 2007sv and 1997bs, the enigmatic transient SN 2008S, and the classical type II_n SN 1999el. The red line indicates the slope of the ^{56}Co decay.

4 SPECTROSCOPY

Spectroscopic observations were carried out from December 29, 2007 (i.e. 9 days after the discovery) to March 7, 2008 (+78 days from discovery). Basic information on the spectra and the instrumental configurations is reported in the log of spectroscopic observations (Table 3).

All data were processed using standard IRAF tasks in order to perform the pre-reduction analysis (bias, flat and overscan corrections) and the extractions of the mono-dimensional spectra. Wavelength calibration was performed using the spectra of comparison lamps obtained with the same instrumental setup. Flux calibration was performed using the spectrum of standard stars. The accuracy of the wavelength calibration was verified measuring the wavelength of night sky lines (in particular [OI] at 5577.34 Å or 6300.30 Å), and a shift was applied in case of discrepancy. Spectral resolution was measured from the full-width-at-half-maximum (FWHM) of night sky lines, adopting their


Figure 4. Comparison among the $B - V$ (top), $V - R$ (middle) and $V - I$ (bottom) colour curves of the same sample as in Figure 3. All phases refers to the epoch of the maximum, except for 2007sv, in which the phase refers to the discovery.

mean value as final resolution estimate. The final spectral flux calibration was checked against multi-band photometry obtained on the nearest night and, when necessary, a scaling factor was applied. Telluric corrections were applied when spectra of references stars obtained during the same nights were available. The spectral sequence obtained with the above procedures is shown in Figure 5.

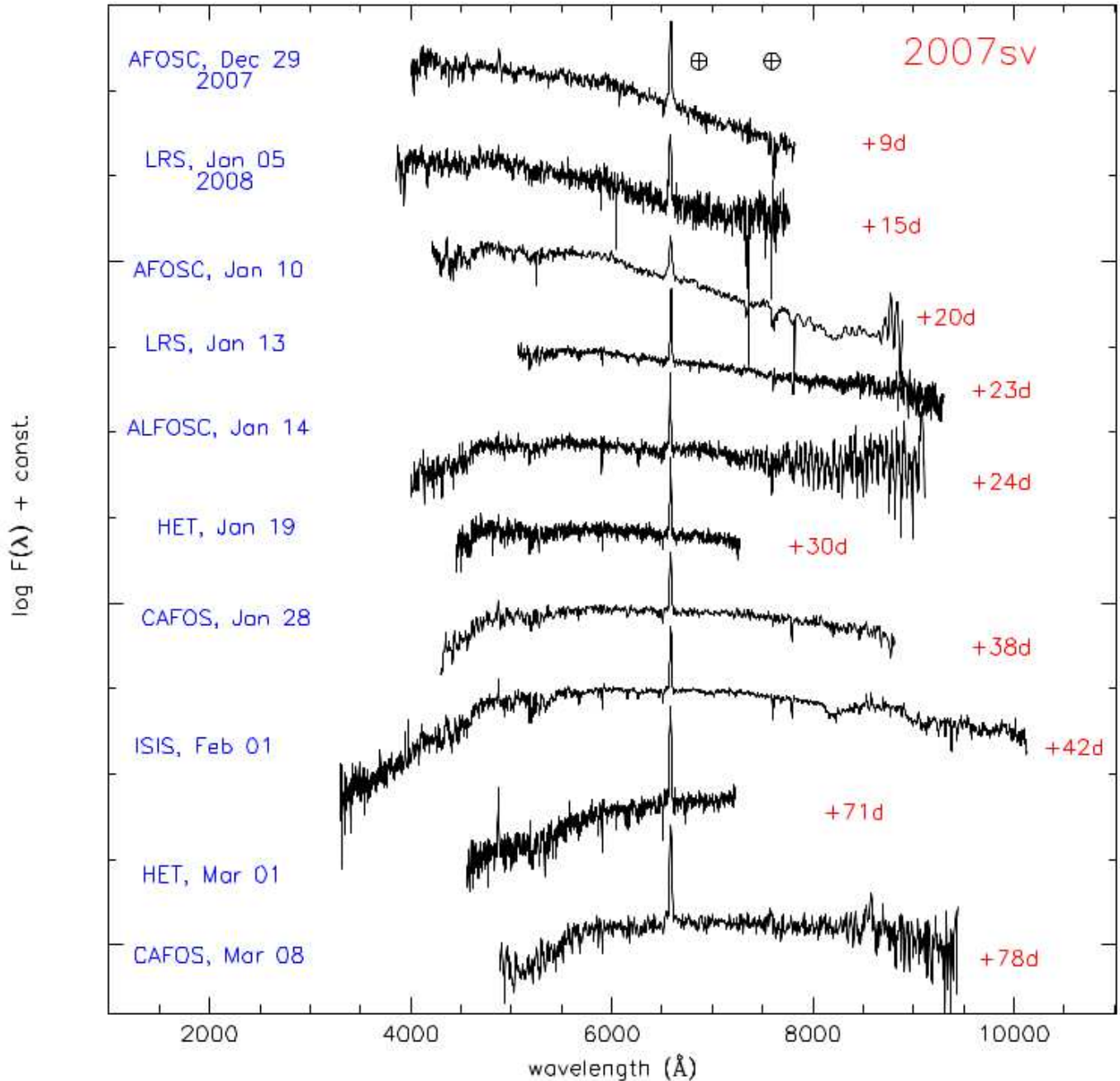


Figure 5. Spectral sequence of 2007sv. The date and the instrumental set-up is reported on the left, the phase (in days after the discovery) is indicated on the right. Spectra are flux-calibrated. The \oplus symbols mark the position of the visible telluric absorptions.

4.1 Spectral evolution and line identification

From Figure 5, we note that all spectra of 2007sv are dominated by a prominent and narrow H_{α} emission line. We also remark that there is relatively little evolution in the spectral features during the almost 80-days coverage window, except for the continuum becoming progressively redder. As the spectra are characterized by a significant continuum contribution to the total flux, we estimated the temperature of the emitting region through a black-body fit. The temperature experienced a rapid decline from $\simeq 8000$ K in the +9d spectrum to $\simeq 4000$ K in the late-time spectra (71-78d; Figure 5,

see also Section 4.2). This evolution is consistent with that of the broad-band colours (Figure 4). As mentioned above, there is little spectral evolution during the almost 80d of spectral coverage. However, it should be noticed that the spectra have relatively poor resolution and low S/N. Therefore, it is difficult to measure evolution in the weak and narrow spectral features. In order to investigate the presence of low-contrast spectral lines, we inspected in detail one of our highest S/N spectrum (ISIS, phase +42d).

The line identification is shown in Figure 6. As a support for the line identification, we compare in Figure 6 the spectrum with that of another SN impostor UGC2773-

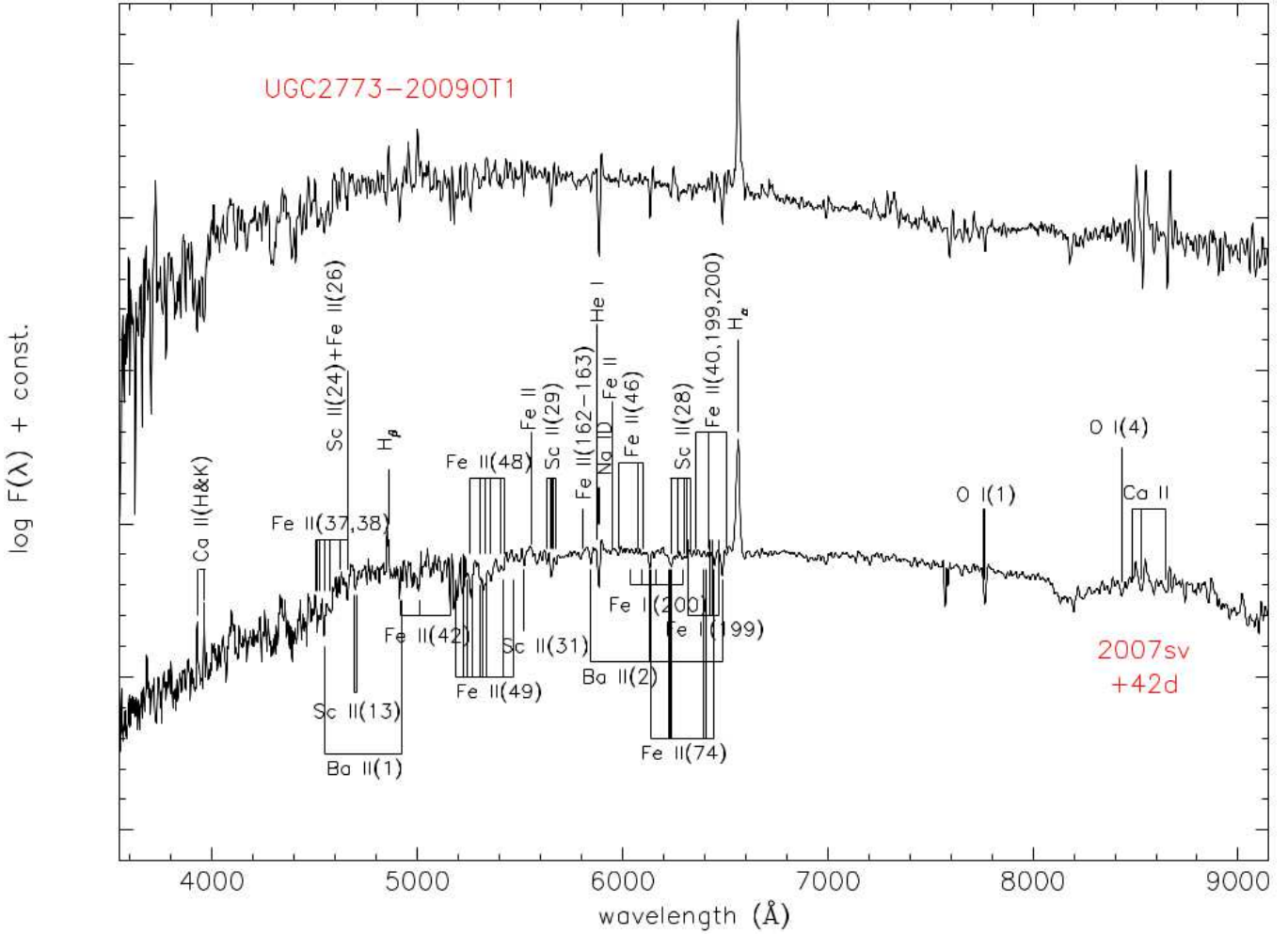


Figure 6. Identification of the lines of the HET spectrum obtained on March 1, 2008. A comparison with the spectrum of the transient UGC2773-2009OT1 obtained with the Telescopio Nazionale Galileo + LRS on Oct 11, 2009 (slightly before maximum, Padova-Asiago SN archive) is also shown. The spectra are flux-calibrated and redshift-corrected.

2009OT1 from the Padova-Asiago SN archive (also shown in Figures 6 and 9, res. 11 Å). A comprehensive line identification for UGC2773-2009OT1 was performed by Smith et al. (2010) and Foley et al. (2011). Figure 6 shows that, despite the different resolution, the spectra of the two transients are very similar, with a number of lines in common (see e.g. Figures 8 to 12 in Smith et al. 2010). We determined an indicative photospheric velocity in the spectrum of 2007sv ($\simeq 500 \text{ km s}^{-1}$) from the blue-shifted absorption component of the Ba II 6496.6 Å line, and the expected positions of all other absorption lines were derived by adopting this velocity for all ions. The lines with strong emission components were identified using their rest wavelengths. We identified H_{α} and H_{β} , He I at 5875.6 Å, O I (multiplets 1 and 4) Ba II (multiplets 1 and 2), Na ID (doublet at 5889.9 and 5895.9 Å), Sc II (multiplets 13, 24, 28, 29, 31), Fe II (multiplets 37, 40, 42, 46, 48, 49, 74, 164, 199, 200), plus other relatively strong, unclassified Fe II lines detected in absorption. We also identified the H&K Ca II lines and the NIR Ca II triplet. These lines show a narrow P-Cygni profile (blueshifted by about

650 km s^{-1}), although a shallow high-velocity component in the NIR triplet cannot be ruled out (see Section 4.3).

4.2 H_{α} profile and evolution of the main observables

The evolution of the H_{α} profile during the almost 80d of spectral coverage is highlighted in Figure 7. We notice that there is no significant change in the wavelength position of the H_{α} emission peak.

The H_{α} line profile is relatively complex. A narrow component is detected in our higher resolution spectra of 2007sv, but a simple Gaussian or Lorentzian line fit does not well reproduce the entire line profile. For this reason, we adopted a combination of multiple line components to improve the accuracy of the spectral line fit. A broad component (decreasing from ≥ 2000 to $\simeq 1700 \text{ km s}^{-1}$) is visible in the two earliest spectra (phases +9d and +15d). This component is only marginally detected in the two subsequent spectra (+20d and +23d), and disappears at later phases. In fact, the broad component is below the detection threshold in the

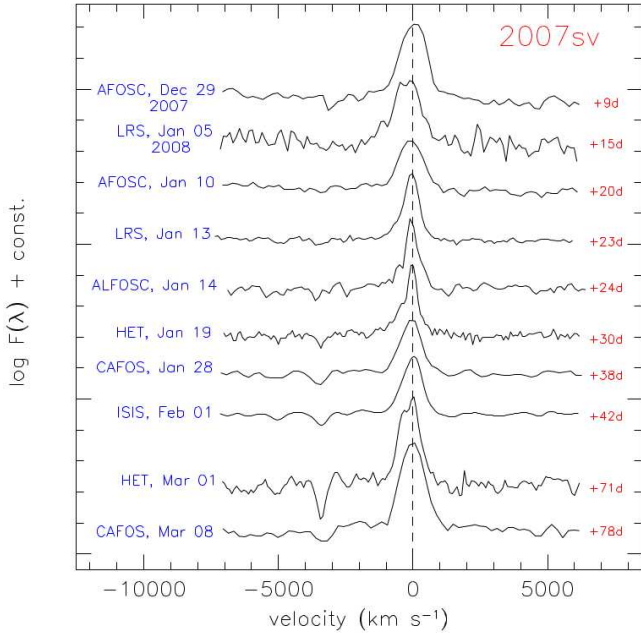


Figure 7. Evolution of the profile of $H\alpha$ in the velocity space.

+24d ALFOSC spectrum. Starting from the LRS spectrum at +23d, we improved our fits by including an intermediate-width (FWHM velocity ≈ 600). While we cannot rule out that the intermediate component was also present at earlier phases, the modest resolution of the +9d to +20d spectra prevents us its discrimination from the narrow component. In the spectra collected at later phases, a two-component (intermediate + narrow) fit well reproduces the observed line profile.

In order to analyze the evolution of the velocity of the different $H\alpha$ components and the total line flux, we first corrected the spectra for redshift (adopting 1116 km s^{-1} as the mean heliocentric radial velocity⁶) and for foreground Galactic extinction (using the values mentioned in Section 2). Then we measured the total line flux, and the full-width-at-half-maximum (FWHM) velocities of the three $H\alpha$ line components. In most spectra the narrow component was unresolved, and even the intermediate component was occasionally below (or near) the resolution limits. In these cases, a multicomponent fit using a combination of Gaussian functions provided good fits. However, in some cases (namely for the two higher resolution HET spectra), we used a Gaussian function for the intermediate component and a Lorentzian profile for the narrow component. Figure 8 (top panel) shows the evolution of the velocity of the ejected material for the three line components.

As mentioned above, the narrow component was unresolved in most cases. When the narrow $H\alpha$ was unresolved, we used the spectral resolution as an upper limit for the velocity of the slowest-moving material.

When the narrow line component was resolved, we first corrected the measured FWHM for the spectral resolution ($width = \sqrt{FWHM^2 - res^2}$) and then computed

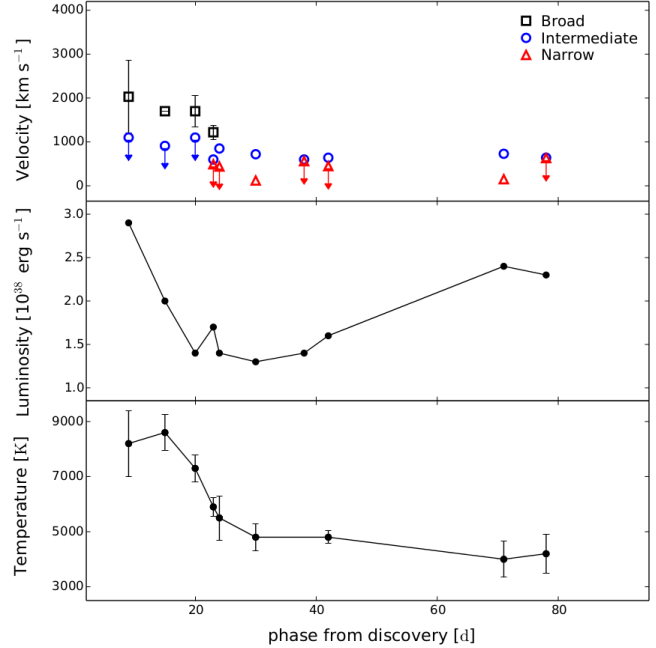


Figure 8. **Top.** FWHM evolution for the broad (black squares, solid line), the intermediate (blue circles) and the narrow $H\alpha$ (red triangles) components. **Middle.** Evolution of the total luminosity of $H\alpha$. We assume a 10% error in the measures, due only to the error in the flux calibration. **Bottom.** Evolution of the spectral continuum temperature.

the velocity ($v = \frac{width}{6562.8} \times c$). In the highest resolution HET spectra at phases +30 and +71d we measured the FWHM of the narrower component as $120 \pm 30 \text{ km s}^{-1}$ and $150 \pm 40 \text{ km s}^{-1}$, respectively. The intermediate component remains at roughly constant velocity around $600\text{--}800 \text{ km s}^{-1}$ at all epochs. Finally, the broad component is characterized by a fast decline from $\approx 2000 \text{ km s}^{-1}$ in our first spectrum to $\approx 1200 \text{ km s}^{-1}$ in the +23d spectrum. We note that these values are significantly smaller than the typical values of $\approx 10000 \text{ km s}^{-1}$ measured in the ejecta of young SNe.

Multiple line components in the spectra of interacting objects are known to arise from different emitting gas shells (see e.g. Turatto et al. 1993). The very small velocities inferred for the narrow $H\alpha$ in the HET spectra ($120\text{--}150 \text{ km s}^{-1}$) are consistent with those expected in the winds of an LBV. The velocity evolution of the broad component is consistent with material violently ejected, and in particular with the velocities observed in the fastest hydrogen-rich material expelled in major eruptions of LBVs (Smith 2008; Pastorello et al. 2010, 2013). More puzzling is the interpretation of the intermediate component. According to the interpretation usually adopted in interacting SNe (see e.g. Chevalier & Fransson 1994), the intermediate velocity component arises in the gas region between the forward shock and the reverse shock. In the case of 2007sv, the relative strength of this component progressively increases with time with respect to that of the narrow component. This would support the idea that a significant fraction of the line flux at late phases arises from the gas interface between the two shock fronts, hence from the shocked gas

⁶ <http://leda.univ-lyon1.fr/>

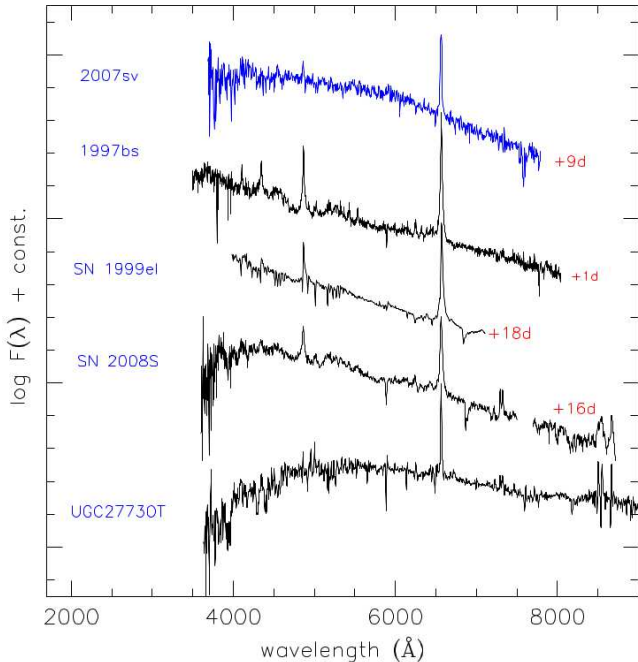


Figure 9. Comparison of early-time spectra of the impostors 2007sv, 1997bs and UGC2773-2009OT1 (spectrum obtained slightly before maximum), the enigmatic transient SN 2008S, and the linearly-declining type IIn SN 1999el. The spectra are flux-calibrated and redshift-corrected.

region. In addition, one may note that the intermediate component is significantly blue-shifted with respects to the narrow one. In the ejecta/CSM interaction scenario, a blue-shifted intermediate component may be explained with an attenuation of the red line wind due to prompt dust formation in a post-shock cool dense shell, as observed in a number of interacting SNe (e.g. 2006jc, Smith et al. 2008; Nozawa et al. 2008; Mattila et al. 2008). Alternatively, very asymmetric and blue-shifted line profiles may be interpreted in terms of a highly asymmetric geometrical distribution of the CSM (see e.g. the interpretation of Stritzinger et al. 2012, for SN 2006jd).

A progressive enhancement of ejecta/CSM interaction emission can be inferred observing the evolution of the total H_{α} flux in the latest spectra (phase > 70 d; Table 4 and Figure 8, middle panel). The flux decreases from about 7×10^{-15} erg s^{-1} to 3×10^{-15} erg s^{-1} during the first ~ 40 days. Later on, we note an increase by a factor almost two in the H_{α} flux, approximately about 5.5×10^{-15} erg s^{-1} in the last two spectra. As mentioned above, this can be interpreted as an increased contribution of the intermediate component arising in a shocked gas region which dominates the flux contribution at late phases over the other line components.

4.3 Spectral comparison with other interacting transients

An important issue is to determine whether the spectroscopy alone allows us to discriminate between genuine type IIn SNe and SN impostors. For this goal, we compare in Fig-

ure 9 the AFOSC early-time spectrum (phase +9d) of 2007sv with spectra of young transients with narrow emissions, viz. the impostors 1997bs (Van Dyk et al. 2000) and UGC2773-2009OT1 (Padova-Asiago SN Archive; Pastorello et al. in preparation), the classical type IIn SN 1999el (Di Carlo et al. 2002) and SN 2008S (Botticella et al. 2009). SN 2008S is the prototype of a small family of intermediate-luminosity transients (see Thompson et al. 2009, and references therein) whose nature has been widely debated. Although many observables of SN 2008S are similar to those observed in SN impostors, the detection of prominent, narrow [Ca II] (7292–7324 Å) lines and, even more, the late-time light curve with a decline rate consistent with that expected from the ^{56}Co decay (Botticella et al. 2009), provide reasonable arguments to support a faint SN scenario. The progenitor star of SN 2008S was detected in mid-infrared archive Spitzer images, whilst there was no detection in deep optical and near-IR pre-explosion frames (e.g. Prieto et al. 2008). This was interpreted as a clear signature that the progenitor was a highly reddened star, embedded in a dusty environment. Although there is general agreement that the progenitor star of SN 2008S was a moderate-mass star⁷, the characterization of the stellar type is somewhat different in the different papers, ranging from a $\sim 9 M_{\odot}$ extreme asymptotic giant branch star (AGB; e.g. Prieto et al. 2008; Khan et al. 2010; Kochanek 2011; Szczygiel et al. 2012) to a $\leq 20 M_{\odot}$ supergiant (Smith et al. 2009). The most debated issue is whether the observed 2008 outburst was a terminal stellar explosion, most likely as an electron-capture SN from a super-AGB star (Pumo et al. 2009; Tominaga et al. 2013) or an LBV-like outburst of a mildly massive star (Smith et al. 2009, 2011).

From the comparison in Figure 9, it is evident that the spectra of all these transients are rather similar, and many spectral lines are in common to all of them. Therefore this is an indication that the spectra alone may not be sufficient to discriminate between impostors and true SNe. As mentioned before, the narrow [Ca II] doublet at 7292–7324 Å is the hallmark feature for SN 2008S-like transients and is sometimes used as an argument to support the non-SN nature of these objects. There is no clear evidence for the presence of [Ca II] lines in the spectra of 2007sv or 1997bs, which is suggestive of a non-SN origin. However, the [Ca II] feature was detected in UGC2773-2009OT1 (which is clearly an impostor, see Smith et al. 2010; Foley et al. 2011). Therefore, the [Ca II] feature is not a good discriminant of the nature of these explosions.

In Figure 10, the 7800–8700 Å wavelength window of the +42d ISIS spectrum of 2007sv is compared with spectra of SN 2008S and UGC2773-2009OT1. In all of them we find the Ca II triplet at 8498.0 Å, 8542.1 Å and 8662.1 Å, which is another very common feature in many types of transients, although some differences in the line strengths and velocities can be appreciated. The three spectra show narrow features with velocities of a few hundreds km s^{-1} , and these mark the presence of slow-moving material. However, a very broad depression with a minimum at about 8200 Å is

⁷ A similar conclusion was also inferred for the detected progenitor of the 2008S-analogous NGC300-2008OT1 (Bond et al. 2009; Berger et al. 2009)

Table 4. Main parameters inferred from the spectra of 2007sv.

Phase (days)	FWHM($H_{\alpha,broad}$) (km s ⁻¹)	FWHM($H_{\alpha,intermediate}$) (km s ⁻¹)	FWHM($H_{\alpha,narrow}$) (km s ⁻¹)	H_{α} Luminosity (10 ³⁸ erg s ⁻¹)	Resolution (km s ⁻¹)
9	2030±830	< 1100	-	2.9	1100
15	1700:	< 910	-	2.0	910
20	1700±360	< 1100	-	1.4	1100
23	1220±160	600±100	< 490	1.7	490
24	-	850±180	< 440	1.4	440
30	-	720±100	120±30	1.3	280
38	-	600±120	< 560	1.4	560
42	-	640±100	< 450	1.6	450
71	-	730±100	150±40	2.4	270
78	-	640±130	< 630	2.3	630

The measured FWHM of the broad, intermediate and narrow components of H_{α} are reported in columns 2, 3 and 4, respectively. The measure marked with the : symbol is uncertain.

The total luminosity of H_{α} is in column 5, the spectral resolution in column 6.

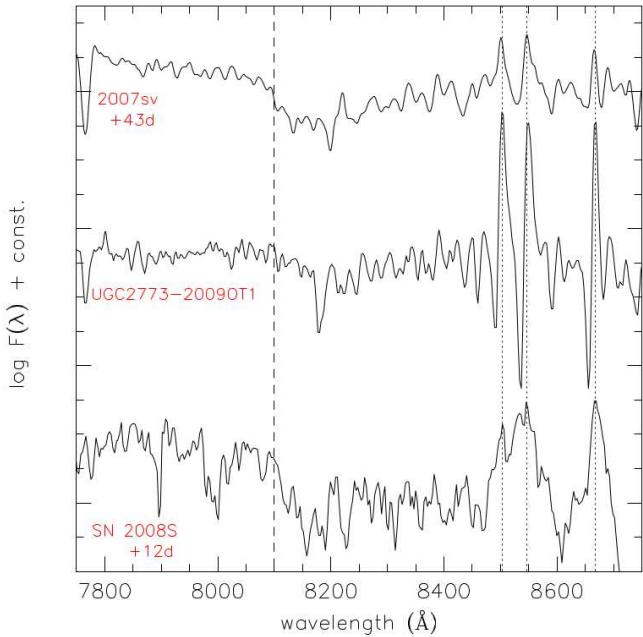


Figure 10. Comparison of the NIR Ca II triplet line profiles in three different types of faint transients, viz. 2007sv, UGC2773-2009OT1 and SN 2008S (from top to bottom). The three dotted lines mark the position of the lines of the Ca II triplet at 8498.0 Å 8542.1 Å and 8662.1 Å. The dashed is an indicative line that marks the velocity close to the terminal velocity of the gas. The spectra are flux-calibrated and redshift-corrected.

visible in all spectra in Figure 10, suggesting that a small amount of material can be ejected at high velocities (above 10000 km s⁻¹) also in SN impostors. The presence of fast-moving material has been also reported in the η Car circumstellar environment (Smith 2008). Therefore, the detection of high-velocity gas alone should not be considered a robust argument to favor a SN scenario⁸.

⁸ We note, however, that this argument is instead used by many authors to favor the SN explosion scenario for the debated SN 2009ip.

5 DISCUSSION

In Sections 3 and 4 the photometric and spectroscopic properties of the optical transient 2007sv have been described. The main goal of the forthcoming discussion is to provide convincing insights on its nature (SN vs. SN impostor). Already from a quick investigation of the spectra of 2007sv, the similarity with the spectra of well-known SN impostors (e.g. 1997bs and UGC2773-2009OT1, Van Dyk et al. 2000; Smith et al. 2010; Foley et al. 2011) is evident. However, some similarity can also be found with the spectra of genuine interacting SNe (such as SNe 1999el and 1995G, Di Carlo et al. 2002; Pastorello et al. 2002). The comparisons shown in Section 4.3 confirm that there are only subtle differences between spectra of LBV-like eruptions and genuine type IIIn SNe, giving evidence that from the spectroscopic analysis alone it is sometimes tricky to discriminate between the two types of transients.

However, from an in-depth inspection of our spectral sequence of 2007sv, we can obtain crucial information on this object. The increased total luminosity of H_{α} and the enhanced strength of the intermediate-velocity component in the late time spectra suggest that the material ejected in the outburst was interacting with the pre-existing CSM. We also found that next to the expected narrow components, H_{α} and the Ca II NIR triplet show broader wings (Figure 10), suggesting an outflow of material at velocities comparable with those observed in SN ejecta. The maximum velocity registered for the outflowing material (dashed line in Figure 10) is about 14000 km s⁻¹ (although it is clear that the bulk of this material is expanding at much lower velocity, viz. \sim 8000 km s⁻¹). The detection of prominent broad spectral features from typical nucleosynthesis products observed in SN ejecta would be a more robust tool to distinguish between SNe and impostors. We do not detect any broad line of α - or Fe-peak elements in the late-time spectra (approx. +80d) of 2007sv, except for the shallow absorption attributed to the Ca II NIR triplet. For this reason, the general spectral properties of 2007sv favor a non-terminal explosion scenario for this transient, although we have to admit that these can not be considered as conclusive proofs to unveil the nature of this interacting transient.

A more robust constraint can be derived from the pho-

ometric analysis. In some cases, impostors were unmasked through their erratic light curves. It is worth mentioning the optical transient observed during the period 2000-2009 in NGC 3432 (aka 2000ch, Wagner et al. 2004; Pastorello et al. 2010) and also the 2009-2012 recurrent transient observed in NGC 7259 (known as 2009ip, Smith et al. 2010; Foley et al. 2011; Pastorello et al. 2013). The latter was followed by a major eruption in mid-2012 that has been proposed to be a terminal SN explosion (Smith et al. 2014, and references therein). However, more frequently impostors reveals themselves through a single episode, characterized by a fast-evolving but regular light curve. A classical example is 1997bs (Van Dyk et al. 2000), whose light curve shape is not trivially discernible from that of a regular SN. And the light curve of 2007sv is remarkably similar to that of 1997bs. However, the colours of 2007sv rapidly become redder as the object evolves, due to the decreasing temperature of the emitting region (this finding is confirmed by the temperature evolution inferred through black-body fits to the spectral continuum). The colour/temperature transition is observed to occur on much shorter timescales than in typical SNe IIn (see e.g. Fig. 4).

Finally, the peak luminosity still remains the most used method to discriminate between SNe and impostors. With a distance modulus of 31.38 ± 0.27 mag, we derive for 2007sv an absolute magnitude of $M_R = -14.25 \pm 0.38$. This value is 4 to 6 magnitudes fainter than the absolute magnitudes typically measured in type IIn SNe (e.g. Richardson et al. 2002).

5.1 Which mechanisms can produce 2007sv-like events?

The faint absolute magnitude at the discovery and the rapid colour (temperature) evolution provide robust evidence for the impostor nature for 2007sv, though some cases of faint transients exist in the literature that have been proposed to be true SNe. In fact, weak SNe can be produced via i) the core-collapse explosion of a peculiar SN through electron capture of a moderate-mass star; ii) the fall back event from a very massive star (Pumo et al. 2009, and references therein). Both mechanisms are believed to produce absolute light curves fainter than those observed in canonical SN types.

In the former scenario the ONeMg stellar core of a 8-10 M_{\odot} super-AGB star collapses generating a weak, low-energy event called electron-capture (EC) SN. The SN ejecta may eventually interact with an H-rich circumstellar environment generated by the stellar mass-loss during the super-AGB phase. As mentioned in Section 4.3, a promising candidate EC SN is SN 2008S (Botticella et al. 2009), an object that shares some similarity with a SN impostor, but has a SN-like shaped light curve, a late-time light curve consistent with the ^{56}Co decay. In the latter scenario, the collapse of a very massive star ($> 25\text{-}30 M_{\odot}$, Zampieri et al. 2003) is followed by the fall-back of the inner stellar mantle onto the stellar core, generating eventually a black hole. In both scenarios a common feature is the faint absolute magnitude, which is generally due to the small amount of radioactive ^{56}Ni in the ejecta. The presence of radioactive material in the ejecta can be revealed from the decline rate of the late-time SN light curve. However, in massive stars the interaction of the ejecta

with the pre-existing CSM can induce a dramatic increase in the radiated energy, and cause significant deviations from the expected luminosity peak and light curve decline rate expected in the radioactive decays, making the detection of ^{56}Co signatures problematic.

Another efficient mechanism proposed to explain transient events with a total radiated energy comparable with those of real SNe is the pulsational pair-instability in very massive stars. Woosley et al. (2007) showed that major instabilities produced by electron-positron pair production (pulsational-pair instability) cause the ejection of massive shells without necessarily unbinding the star (and hence without leading to a terminal SN explosion). These major mass-loss episodes might produce transients currently classified as SN impostors. In addition to this, when a new shell is ejected and collides with pre-existing material, the resulting radiated energy is comparable with that of a core-collapse SN (sometimes even one order of magnitude higher). If the impacting material is H-rich, the shell-shell collisions would produce a SN IIn-like spectrum and a slowly-evolving, luminous light curve that would make the transient practically indiscernible from true SNe IIn. All of this further complicates our attempts of discriminating SNe IIn from eruptive impostors.

A safe discrimination criterion would be the detection of the products of stellar and core-collapse explosive nucleosynthesis through the prominent α -element lines in the nebular spectra. But in many SNe IIn the inner ejecta are covered by the H-rich interaction region sometimes for very long timescales (up to many years), making the detection of the α -element spectral features difficult.

All the clues illustrated so far make us confident that 2007sv was not a terminal SN explosion, but very likely a major eruption mimicking the SN behaviour. If this is true, the progenitor star may have reached again a quiescent stage, returning to the pre-eruptive bolometric luminosity. This can be confirmed through an inspection of deep, high resolution images obtained years after the outburst, for example using the Hubble Space Telescope or the largest ground based telescopes which can deliver sub-arcsecond images. The identification of the quiescent progenitor in such high quality images would be final evidence that the massive star producing 2007sv is still alive. Alternatively, a long timescale monitoring of 2007sv can eventually reveal further outbursts after the one registered in 2007, which would also prove that the 2007 episode was not the final stellar death. This strategy worked well for the 2000 transient observed in NGC 3432 (Wagner et al. 2004) that was recovered after 8 years during a subsequent eruptive phase (Pastorello et al. 2010).

5.2 Is 2007sv heralding a SN explosion?

In order to identify possible further outbursts experienced by the progenitor of 2007sv, we analyzed a number of images of the transient site obtained before and after the 2007 event. These data were mostly collected by two of the co-authors of this paper (T.B. and G.D.), with a few additional observations performed with the 1.82 m Telescopio Copernico of the Asiago Observatory. These observations are listed in Table A1 in Appendix A. The unfiltered observations of T.B. and G.D. were scaled to R-band magnitudes using the

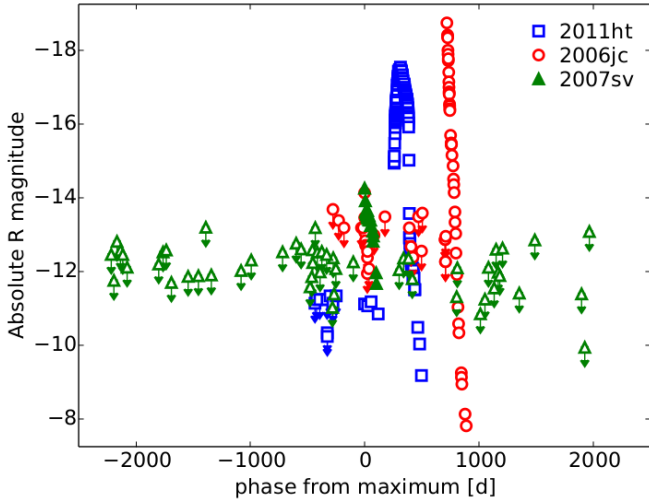


Figure 11. Plot of the photometric limits obtained from November 27, 2001 to January 07, 2014 and the absolute R-band light curve of 2007sv. The absolute light curve of the type Ibn SN 2006jc and the type IIn SN 2011ht are shown for comparison. The phases refers to the first recorded eruption.

magnitudes of reference stars reported in Table 2. These images of the 2007sv site span a period of over a decade. In this temporal window, we did not detect any further signature of a variable source at the position of 2007sv (see Figure 11). The Pan-STARRS1 survey imaged this galaxy on 52 separate nights between Feb. 25, 2010 (MJD 55252.30) and May 17, 2013 (MJD 56429.26) in one of the filters $g_{P1}r_{P1}i_{P1}z_{P1}$ (for a description of the Pan-STARRS1 3π survey, see Inserra et al. 2013; Magnier et al. 2013). No further detection of any outbursting activity was seen, and the magnitude limits of these individual epochs are typically 22.0, 21.6, 21.7, 21.4 and 19.3 respectively for $g_{P1}r_{P1}i_{P1}z_{P1}$ (as reported in Inserra et al. 2013). These magnitudes are in the AB system as reported in Tonry et al. (2012).

Tracing the photometric history of a SN impostor has also another objective. As briefly mentioned in Section 1, there is growing evidence that some interacting SNe may be preceded by large stellar eruptions (i.e. impostor events). A similar sequence of events has been proposed for a number of SNe, from the historical case of SN 2006jc discovered by K. Itagaki (Nakano et al. 2006; Yamaoka et al. 2006; Pastorello et al. 2007) to a few recent type IIn SNe (see Smith et al. 2014, and references therein). In several cases, a lower luminosity outburst was observed few weeks before the brightest event (i.e. the putative SN). However, occasionally a larger time delay was observed between the two episodes (1-2 years). In Figure 11, together with 2007sv, we also show two cases of SNe that were heralded by an outburst with a significant time delay. SN 2006jc is a stripped-envelope SN (of type Ibn) whose ejecta were seen to interact with Herich CSM (Pastorello et al. 2007, 2008; Foley et al. 2007). Its progenitor experienced an outburst 2 years before its explosion as a core-collapse SN, and the magnitude of this impostor ($M_R \simeq -14$) was comparable with that expected in an LBV eruption. SN 2011ht was initially classified as a SN impostor on the basis of its early spectral properties (Pastorello et al. 2011), and was later reclassified as a type

IIn SN after a major spectral metamorphosis (Prieto et al. 2011). However, the nature of SN 2011ht nature is not fully clarified. There are controversial interpretations on its SN-like observables (Roming et al. 2012; Humphreys et al. 2012; Mauerhan et al. 2013; Fraser et al. 2013), since collisions among massive shells might still explain SN 2011ht without necessarily invoking a core-collapse. Interestingly, a posteriori, a weak transient has been observed about one year before the main episode (Fraser et al. 2013). This weak source, (labelled as PSO J152.0441+51.8492 by Fraser et al. 2013) was detected in archival data of the Panoramic Survey Telescope and Rapid Response System 1 (Pan-STARRS1) at an absolute magnitude $M_R \approx -11.8$. Fraser et al. (2013) provided strong arguments that the two sources were physically related. Recent studies (see Ofek et al. 2014) claim that pre-SN eruptions are quite common. Nonetheless, so far only a handful of impostors with solid detections have been observed to be followed by what is believed to be a true SN explosion.

The most intriguing issue is that, although there are some outliers with the absolute magnitudes brighter than -14 (Ofek et al. 2014), most pre-SN outbursts (those with robust detections) have absolute magnitudes close to or fainter than -14, nearly coincident with absolute magnitude of 2007sv. Although there was no further detection of a re-brightening of 2007sv before and after 2007, its overall photometric similarity with the precursors of SN 2006jc and other interacting SNe, may lead to the speculation that impostors such as 2007sv are instability episodes of massive stars (some of them in the LBV stage) that can be followed on short timescales (months to decades) by a terminal stellar explosion, as an ejecta-CSM interacting SN.

6 CONCLUSIONS

In this paper we have reported the results of our follow-up campaign of the transient 2007sv. Our photometric monitoring spans a period of over 100d, whilst our spectroscopy data cover $\simeq 80$ d of the evolution of 2007sv. The spectra are largely dominated by a multi-component H_α line in emission. This spectral characteristic is common to both in SN impostors and in type IIn SNe. As we have widely discussed, although the discrimination between true interacting SNe and SN impostors is a tricky issue, the lack of broad lines from α -elements, the photometric and colour evolutions, and the faint peak magnitude of $M_R \simeq -14.25$ support the scenario that 2007sv was a SN impostor, most likely a major eruption of an LBV.

However, some doubts still remain whether 2007sv was instead a very weak terminal explosion of a massive star. In absence of the detection of further outbursts or a future 'real' SN explosion (as observed in other similar transients), the most promising method to definitely rule out the possibility that 2007sv was a faint interacting core-collapse SN is by obtaining deep and high spatial resolution images of the transient's site (e.g. with HST), in the attempt to detect some signatures from the surviving star. This method, that has been successfully tested to find the progenitors of a number of CC-SNe (see Smartt 2009, and references therein) and may well give the final answer to the enigma of 2007sv.

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APPENDIX A: PHOTOMETRIC LIMITS OF 2007SV

Table A1. Optical detection limits for 2007sv. No source was observed in the position of the transient at any epochs reported in the Table.

Date	MJD	R	Instrument
20011127	52240.11	> 18.96	Apogee AP7
20011220	52263.09	> 19.66	Apogee AP7
20020116	52290.20	> 18.60	Apogee AP7
20020215	52320.81	> 18.85	Apogee AP7
20020307	52340.86	> 18.96	Apogee AP7
20020414	52378.95	> 19.30	Apogee AP7
20030115	52654.91	> 19.22	Apogee AP7
20030222	52692.91	> 18.89	Apogee AP7
20030323	52721.03	> 18.84	Apogee AP7
20030506	52765.91	> 19.72	Apogee AP7
20030930	52912.17	> 19.55	Apogee AP7
20031229	53002.03	> 19.54	Apogee AP7
20040302	53066.83	> 18.22	Apogee AP7
20040419	53114.94	> 19.51	Apogee AP7
20050105	53375.00	> 19.39	Apogee AP7
20050403	53463.98	> 19.11	Apogee AP7
20060103	53738.05	> 18.89	SX
20060305	53899.87	> 18.81	Apogee AP7
20060501	53856.89	> 18.65	Apogee AP7
20060831	53978.90	> 19.84	SX
20060915	53993.00	> 19.56	SX
20060920	53998.95	> 18.83	SX
20060923	54001.87	> 19.18	SX
20061015	54023.78	> 18.23	SX
20061103	54042.08	> 18.89	SX
20061126	54065.91	> 19.43	SX
20061223	54081.06	> 18.88	SX
20070122	54122.88	> 18.96	SX
20070314	54173.86	> 20.39	SX
20070321	54180.88	> 19.05	Apogee AP7
20070328	54187.84	> 20.03	SX
20070413	54203.85	> 19.34	SX
20070913	54356.09	> 19.16	SX
20081017	54756.97	> 19.37	SX
20081125	54795.98	> 19.05	SX
20090107	54838.84	> 19.06	SX
20090209	54871.83	> 19.62	SX
20100304	55259.84	> 20.10	Apogee AP7
20100310	55265.80	> 19.32	SX
20100928	55467.13	> 20.57	SX
20101107	55507.13	> 20.17	SX
20101207	55537.95	> 19.31	SX
20110126	55587.84	> 19.87	SX
20110212	55604.81	> 18.82	Apogee AP7
20110302	55622.86	> 19.44	SX
20110316	55636.87	> 19.53	SX
20110409	55660.94	> 18.79	Apogee AP7
20110903	55807.07	> 20.01	SX
20120117	55943.21	> 18.56	Apogee AP7
20130228	56351.89	> 20.03	ARTEMIS
20130315	56379.86	> 21.48	ARTEMIS
20130320	56371.10	> 21.88	AFOSC
20130507	56419.92	> 18.34	Apogee AP7
20131205	56631.19	> 22.15	AFOSC
20140107	56664.99	> 21.29	AFOSC

The observations provided by T. B. (with a C-14 Celestron Schmidt Cassegrain reflector and an Apogee AP7 CCD camera at the Coddanham Astronomical Observatory, Suffolk, United Kingdom) and G. D. (with a 0.32 m f/3.1 reflector and a Starlight Xpress MX716 CCD camera at Moonbase Observatory (Akersberga, Sweden)) were unfiltered images, which magnitudes rescaled to R-band. Multi-band observations were obtained on March 20, 2013, with the following additional detection limits: U > 19.93, B > 20.94, V > 21.02, I > 21.26.