ASASSN-15no: the supernova that plays hide-and-seek

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ABSTRACT

We report the results of our follow-up campaign of the peculiar supernova ASASSN-15no, based on optical data covering ~300 days of its evolution. Initially the spectra show a pure blackbody continuum. After few days, the HeI λ 5876 transition appears with a P-Cygni profile and an expansion velocity of about 8700 km s⁻¹. Fifty days after maximum, the spectrum shows signs typically seen in interacting supernovae. A broad (FWHM ~8000 km s⁻¹) Hα becomes more prominent with time until ~150 days after maximum and quickly declines later on. At these phases Hα starts to show an intermediate component, which together with the blue pseudo-continuum are clues that the ejecta begin to interact with the CSM. The spectra at the latest phases look very similar to the nebular spectra of stripped-envelope SNe. The early part (the first 40 days after maximum) of the bolometric curve, which peaks at a luminosity intermediate between normal and superluminous supernovae, is well reproduced by a model in which the energy budget is essentially coming from ejecta recombination and ⁵⁶Ni decay. From the model we infer a mass of the ejecta Mₑj = 2.6 M☉; an initial radius of the photosphere R₀ = 2.1 × 10¹⁴ cm; and an explosion energy Eₑxp = 0.8 × 10⁵⁸ erg. A possible scenario involves a massive and extended H-poor shell lost by the progenitor star a few years before explosion. The shell is hit, heated and accelerated by the supernova ejecta. The accelerated shell+ejecta rapidly dilutes, unveiling the unperturbed supernova spectrum below. The outer ejecta start to interact with a H-poor external CSM lost by the progenitor system about 9 -- 90 years before the explosion.

Subject headings: supernovae: general — supernovae: ASASSN-15no

1. INTRODUCTION

The final core-collapse (CC) of massive stars can produce a wide variety of events in terms of luminosity: luminous stripped-envelope (SE) supernovae (SNe) with M brighter than −18.5 mag [Mazzali et al. 2013], very weak Supernovae (e.g., fainter than ∼−14 mag; Pastorello et al. 2004 Botticella et al. 2009 Spiro et al. 2014) or even failed SNe - when the star directly collapses onto a black hole without significant mass ejection (Heger et al. 2003 Adams et al. 2016 Reynolds et al. 2015).

Another class of very luminous transients, named super-luminous supernovae (SLSNe, with M < −21 mag; Gal-Yam 2012), has been identified in recent years. These can occasionally reach a peak absolute magnitude exceeding −23.5 mag (Dong et al. 2016 Benetti et al. 2014). SLSNe sometimes show spectral signatures of H in their spectra (SLSNe-II), but in most cases their spectra are H-free (SLSNe-I) and they resemble those of stripped-envelope SNe at late phases (Pastorello et al. 2010 Quimby et al. 2011). The mechanism that supports the tremendous energy released in SLSNe is not yet understood, but the most promising central engines are: a) either a spinning-down magnetar (e.g. Kasen & Bildsten 2010 Woosley 2010 Inserra et al. 2013) or an accreting black hole (Dexter & Kasen 2013); b) the shock of the ejecta into a circumstellar shell (which can be H rich/poor) expelled by the progenitor star some time before the explosion (e.g. Blinnikov & Sorokina 2010 Chevalier & Irwin 2011 Wheeler et al. 2017); or c) the radioactive decay of a large amount of nickel produced in a pair-instability explosion (Gal-Yam et al. 2009) but see Moriya et al. 2010; Young et al. 2010; Nicholl et al. 2013).

The luminosity gap between normal and superluminous SNe is mostly populated by objects that show signs of interaction between fast expanding ejecta and a pre-existing circumstellar medium (CSM). The interacting system may be H rich, producing Type Ibn SNe (Schlegel 1990 Filippenko 1997, Turatto et al. 2007) or H rich, producing the so-called Type Ibn SNe (Pastorello et al. 2016) and references therein).

The events populating this luminosity gaps can be very different as testified by the very recent supernova SN 2017dio (Kuncarayakti et al. 2017), showing early spectra typical of a SE-SN, whose ejecta soon collide with a H-rich CSM, showing for the first time the transition
from a Type Ic to a bright Type II in just few weeks.

In these objects the overall luminosity output include input from the ejected $^{56}\text{Ni}$ (which was shown to scale with the kinetic energy, Terreran et al. 2017), plus the conversion part of the kinetic energy of the ejecta into radiation in the interaction process, which depends on the physical properties of the CSM shell (such as density and radius). Assuming that the photosphere radiates as a black-body, the luminosity increases with the radius, and/or with the photospheric temperature.

In the following sections, we will discuss the physical properties of ASASSN-15no, an object in the luminosity gap between normal SNe and SLSNe.

Our object was discovered by the ASAS-SN survey [Shappee et al. 2014] on 2015 August 3.26 UT (Holoien et al. 2015, 2017), and initially reported as an old Type Ic SN by Balam & Graham (2015). Actually, as we will show in this paper, the spectrum eventually developed broad H lines later on, that classifies the event as a Type II SN, caught at very early age. The redshift of the faint ($g = 18.57$ from SDSS DR10), cigar shaped, host galaxy (SDSS J153825.20+465401.4) measured from unresolved emission lines in our Gran Telescopio Canarias (GTC) spectra (see Section 4), is $z = 0.03638 \pm 0.00008$. Assuming $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Riess et al. 2016) and a flat cosmology with $\Omega_m = 0.31$ (Planck Collaboration et al. 2015), we obtain a luminosity distance $D_L = 153.5 \text{ Mpc}$, hence a distance modulus of $\mu = 35.93$ mag. For the foreground Galactic extinction, we adopt $A(V) = 0.045$ mag (Schlafly & Finkbeiner 2011). Instead, since there is no evidence in the spectra of ASASSN-15no for the presence of a narrow Na I D absorption feature at the recessional velocity of the parent galaxy, we assume negligible host galaxy extinction.

2. OBSERVATIONS AND DATA REDUCTION

The follow-up campaign of ASASSN-15no was carried out using several facilities, namely the 1.82 m Copernico Telescope equipped with AFOSC (located at Mount Ekar, Asiago, Italy); the 10.4 m GTC with OSIRIS; the 2.56 m Nordic Optical Telescope (NOT) with ALFOSC; Telescopio Nazionale Galileo (TNG) with Dolores (these telescopes are located at the Observatorio del Roque de los Muchachos, La Palma, Spain); and the Telescopio Joan Oró with MEIA2 located at Mount Montsec, Catalonia, Spain. Additional $V$ photometry has been supplied by the ASAS-SN telescopes.

Spectroscopic and photometric data were pre-processed in the standard manner (performing overscan, bias and flat-field corrections) using IRAF,[12] tasks. For the photometric measurements, the SNOOPY (Cappelaro 2014) package was used, which allowed to extract the magnitude of the SN with the point-spread-function (PSF) fitting technique (Stetson 1987) for the BVRI frames, and the template subtraction technique for the ugriz frames (no deep template frames were available for BVRI bands). Indeed, ugriz template frames from the SDSS survey were obtained on June 2012, three years before the SN break out. The SN magnitudes were then calibrated with reference to the magnitudes of field stars retrieved from the SDSS catalog (DR9). For the BVRI filters, we converted the SDSS catalog magnitudes to Johnson/Cousins, following Chonis & Gaskell (2008). The magnitudes of the Johnson/Cousins bands are thus given in the Vega system, while the SDSS ones are calibrated in the AB system.

Spectra of comparison lamps obtained with the same instrumental set-up were used for the wavelength calibration and standard stars observed in the same nights were used as reference for the flux calibration. The wavelength calibration was checked using night sky lines. The flux calibration was verified against the broad band photometry, and a scaling factor was applied when necessary. Finally, we corrected the spectra of ASASSN-15no for the Galactic foreground extinction and for the redshift of the host galaxy.

3. PHOTOMETRIC ANALYSIS

The ugriz and BV light curves are shown in Figure 1, while the magnitudes in all bands (those shown in Figure 1 plus URI) are reported in the online Tables 2 and 3.

The pre-discovery limit and discovery $V$ magnitudes reported by Holoien et al. (2015) have been revised using deeper, higher quality reference images, and are shown in Figure 1. No deep pre-discovery observations are available for BRI bands. This allows to constrain the $V$-band maximum to 2015 August $1 \pm 2$ d (MJD=57235) and to infer that the rise time, in this photometric band, could have been relatively short.

The $u$ to $z$ light curves have very similar shapes, showing relatively fast declines from the peaks lasting about 20-40 days (we do not have a dense temporal coverage of this phase). Later on, the light curves settle on a slower linear decline up to about 100 days after maximum, with rates only mildly depending on the passband (e.g. $1.15 \pm 0.06$ mag (100d)$^{-1}$ in $u$; $1.24 \pm 0.14$ mag (100d)$^{-1}$ in $r$; and $0.75 \pm 0.04$ mag (100d)$^{-1}$ in $z$). After 100 days, all light curves show a more rapid decline rate especially in blue bands (e.g. $> 2.41$ mag (100d)$^{-1}$ in $u$; $2.30 \pm 0.08$ mag (100d)$^{-1}$ in $r$; and $1.98 \pm 0.10$ mag (100d)$^{-1}$ in $z$). The latest $r$, $i$ and $z$ points at $\sim 300$ days suggest a possible flattening, but the large uncertainties in the measurements prevent us

![Figure 1. $BV$ (Vega) and ugriz (AB mag) light curves of ASASSN-15no. The phase is in the observer's frame.](http://iraf.noao.edu/)
from a robust statement.

4. SPECTROSCOPIC ANALYSIS

The journal of the spectroscopic observations is reported in Table 1, along with the information on the instrumental configurations used and spectral resolutions. The results of the spectroscopic follow-up campaign of ASASSN-15no are shown in Figure 2. The spectra are shown in the observer’s frame and are not corrected for the Galactic extinction.

The spectra at early phases are characterised by a blue continuum. The temperature (estimated through a black-body fit) initially very high, 13300 ± 300 K at +6 d, rapidly drop to 8200 ± 300 K at +23 d, and stays nearly constant hereafter (see Section 6.1). The first feature clearly seen in the spectra beginning at +11 d onwards is a line with a broad and shallow P-Cygni profile probably due to He I 5876.4 Å. The expansion velocity deduced from the minimum of its absorption is about 8700 km s\(^{-1}\). At the same time a broad (FWHM ∼ 8000 km s\(^{-1}\)) Hα emission begins to grow. On day +37, the spectrum starts to show a growing blue continuum component blue-ward of ∼ 5600 Å, which increases with time. This blue pseudo-continuum is often seen in interacting supernovae (Turatto et al. 1993; Smith et al. 2009) and is due to the blending of Fe line emissions. By day +56, the spectrum shows very broad Hα and CaII-IR emissions. The Hα profile is complex, consisting of a broad base with a half width at zero intensity of ∼ 23000 km s\(^{-1}\) for the blue wing and ∼ 13000 km s\(^{-1}\) for the red wing. An intermediate (FWHM ∼ 12000 km s\(^{-1}\)) component, blue-shifted by ∼ −2000 km s\(^{-1}\) with respect to the Hα rest frame wavelength, is superimposed to the broad emission. Starting from day +72 a broad Hβ absorption begins to appear and by day +92 an expansion velocity of about 7400 km s\(^{-1}\) is derived from its minimum.

The CaII-IR emission has instead a triangular shape, with a FWHM ∼ 15400 km s\(^{-1}\) centered at almost its rest-frame position (see Figure 2). This feature remains visible until late phases, with an almost constant FWHM. However, in the last two spectra, the FWHM decreases to ∼ 13700 km s\(^{-1}\) at day +235, and ∼ 11800 km s\(^{-1}\) at day +289, caused by a fading of the red wing, and a simultaneous blueshift of the whole emission by ∼ 70 Å. This could be an indication of dust formation in the shocked ejecta. Hα shows a constant profile until +146 d after maximum, and then fades. In the last three spectra it appears as a relatively faint, broad and boxy emission blended with a now dominant [OI] doublet. The last spectra are reminiscent of those of some stripped envelope SNe, although contaminated by narrow emissions of the parent galaxy, (see Section 6.3). Besides the broad, shallow emissions, the spectra later than ∼ +50 days show a persistent blue pseudo-continuum, typically seen in interacting SNe.

5. ABSOLUTE MAGNITUDES AND BOLOMETRIC LIGHT CURVE OF ASASSN-15no

With the values adopted for distance and extinction in Section 1 (using the Cardelli et al. 1989 extinction law), we obtain $M_V \sim -19.6 \pm 0.3$ mag at maximum light. Similar magnitudes are inferred for the $r$ and $B$ bands at maximum. These values are similar to those derived for some interacting SNe, such as SN 1997cy (Turatto et al. 2000) and SN 1999E (Rigon et al. 2003).

The pseudo-bolometric light curve of ASASSN-15no has been computed by integrating its multi-colour $uBgVriz$ photometry, neglecting any possible contribution in other spectral ranges. The UV contribution, however, is expected to be significant especially at early stages. For each epoch and filter, we derived the flux at the effective wavelength. We adopted as reference the epochs of the $r$-band measurements (except for the first two epochs, for which we used the $V$ band as reference). Missing fluxes in other filters were estimated through interpolation or, if necessary, by extrapolation from the closest available epoch assuming a constant colour with respect to adjacent bands. The flux measurements for all filters, corrected for extinction, give the spectral energy distribution at each epoch, which is integrated with the trapezoidal rule, assuming zero flux at the integra-

| Date          | Rest phase | Instrumental set-up | Grism or grating | Spectral range (Å) | Resolution (Å) |
|---------------|------------|---------------------|------------------|--------------------|----------------|
| 20150806      | +6         | Ekar182+FOSC        | gm4              | 3400 – 8250        | 13.5           |
| 20150809      | +9         | Ekar182+FOSC        | gm4              | 3400 – 8250        | 13.5           |
| 20150810      | +10        | Ekar182+FOSC        | gm4/VPH6         | 3400 – 9280        | 14             |
| 20150811      | +11        | Ekar182+FOSC        | gm4              | 3400 – 8250        | 13.5           |
| 20150812      | +12        | Ekar182+FOSC        | gm4              | 3400 – 8250        | 13.5           |
| 20150817      | +16        | TNG+LRS             | LRB/R            | 3230 – 9650        | 15             |
| 20150824      | +23        | NOT+ALFOSC          | gm4              | 3450 – 9020        | 18             |
| 20150829      | +28        | GTC+OSIRIS          | R1000B/R         | 3640 – 9390        | 7              |
| 20150830      | +29        | TNG+LRS             | LRB              | 3300 – 8080        | 11.0           |
| 20150907      | +37        | Ekar182+FOSC        | gm4/VPH6         | 3500 – 9300        | 14             |
| 20150927      | +56        | GTC+OSIRIS          | R1000B/R         | 3640 – 10390       | 7              |
| 20151014      | +72        | TNG+LRS             | LRB/R            | 3400 – 9640        | 16             |
| 20151104      | +92        | Ekar182+FOSC        | gm4/VPH6         | 3500 – 9300        | 14             |
| 20151204      | +121       | Ekar182+FOSC        | gm4              | 3400 – 8240        | 13.5           |
| 20151229      | +146       | NOT+ALFOSC          | gm4              | 3350 – 9070        | 18             |
| 20160208      | +184       | GTC+OSIRIS          | R1000B/R         | 3630 – 10400       | 7              |
| 20160401      | +235       | GTC+OSIRIS          | R1000B/R         | 3640 – 10390       | 7              |
| 20160526      | +289       | GTC+OSIRIS          | R1000R           | 5100 – 10390       | 8              |

| Note. — The rest phases are relative to the V band maximum (2015 August 1). |
Fig. 2.— Spectroscopic evolution of ASASSN-15no. The wavelength scale is set in the observer’s frame and are not corrected for the Galactic extinction. The ordinate refers to the first spectrum, and the others have been arbitrarily shifted downwards. For the sake of clarity, the flux counts in the last five spectra have been multiplied by the numbers given in parenthesis. Residuals from the atmospheric absorption corrections have been marked with the ⊕ symbol.
tion limits. The observed flux was then converted into luminosity. The resulting pseudo-bolometric light curve is shown in Figure 3 (upper panel), along with those of a sample of SNe that includes SNe IIn with similar luminosity and spectral evolutions, the peculiar Type II SN 2009kf, and a few stripped envelope SNe, because of the similarity of the late time spectra of ASASSN-15no with this SN type (see Section 6.3).

A "true" bolometric light curve is also reported in Figure 3. To construct it, we had to estimate the bolometric correction for each phase. This was performed by fitting with a blackbody the $B_g V r i z$ SED (we didn’t consider the $u$ band because of the heavy line blanketing affecting this spectral region) derived in epochs where the SN had multi-band detections, and then adding the missing flux, measured from 0 to $\infty$, to the optical luminosities. We remark that the BB temperatures derived from the photometric SED are in close agreement with those derived from the spectral fitting (see Section 6.1). Because of the blue pseudo continuum seen in later time spectra of ASASSN-15no due to ongoing interaction, the blackbody fit of the SED could lead to an incorrect estimation of the temperature and accordingly to an overestimation of the bolometric correction. The "true" bolometric luminosity is used for the modelling discussed in Section 6.2.

The luminosity of ASASSN-15no is intermediate between those of the Type IIn SNe 2005gj, 1997cy, and 1999E, and a few dex higher than that of the energetic stripped envelope (SE) SN 1998bw. The pseudo bolometric light curve shows a regular decline from the peak to $\sim 40$ days after maximum, followed by a slightly flatter decline up to about +100 d, similar to the comparison Type IIn SNe and SN 2009kf. However from $\gtrsim 40$ d onwards ASASSN-15no shows a luminosity excess with respect to SN 2009kf. After $\gtrsim +100$ d the decline rate of ASASSN-15no increases again.

6. DISCUSSION

6.1. Photospheric temperature and radius evolution

The photometric and spectroscopic monitoring of the optical transient ASASSN-15no can be used to derive some physical properties of the transient, such as the evolution of the photospheric radius and temperature. We performed a blackbody fit to our early time spectra (phase $< +100$ days), after correcting for the adopted reddening and redshift values (see Section 1). The fits were done selecting the portions of the spectra free of emissions. The fit errors, depend on a number of parameters (including the wavelength extension of the spectra, the line contamination, the uncertainty in the flux calibration and the assumed extinction) and have been estimated to be of the order of 300 K. The temporal evolution of the temperature is shown in Figure 3 bottom panel (blue triangles). Adopting the true-bolometric light curve of Figure 3 (upper panel), spherical symmetry and constant velocity expansion which is believed to be a thermonuclear explosion in a H-rich CSM (Dilday et al. 2012), but other events were proposed to belong to this group, including SNe 2002ic, 2005gj and 2012ca (Hamuy et al. 2003, Prieto et al. 2007, Fox et al. 2015). We remark, however, that other authors suggested an alternative scenario with an energetic CC engine for these transients (Benetti et al. 2009, Trundle et al. 2008, Inserra et al. 2016).

13 These three SNe share similarities with the so-called Type Ia-CSM events. A prototypical event of this class is PTF11Ex, which is believed to be a thermonuclear explosion in a H-rich CSM (Dilday et al. 2012), but other events were proposed to belong to this group, including SNe 2002ic, 2005gj and 2012ca (Hamuy et al. 2003, Prieto et al. 2007, Fox et al. 2015). We remark, however, that other authors suggested an alternative scenario with an energetic CC engine for these transients (Benetti et al. 2009, Trundle et al. 2008, Inserra et al. 2016).
Fig. 4.— Comparison of ASASSN-15no spectra at three key phases with those of reference objects. In the top panel (from top): SN 2005gj (IIn, Prieto et al. 2005; Aldering et al. 2006), ASASSN-15no, SNe 1993J (IIb, Barbon et al. 1995, and references therein), 2004aw (Ic, Taubenberger et al. 2006; Modjaz et al. 2014), 1998bw (BL-Ic, Patat et al. 2001) and 1997ef (BL-Ic, Iwamoto et al. 2000). The main Si II (6355 Å doublet and 5058 Å), and Fe II (4924, 5018, 5169 Å) absorption blends normally seen in Type Ic SNe are marked (e.g. Mazzali et al. 2000). In the middle panel a +52 days spectrum of SN 2009kf (II, Botticella et al. 2010) has been also included. In the bottom panel, SN 2005gj is replaced by SN 1997cy (IIn, Turatto et al. 2000). In this panel the ASASSN-15no spectrum is shown as observed (solid line) and with a BB continuum subtracted (lighter, lower line; see text for details).
try and a filling factor of 1, we calculated the evolution of the blackbody radius (bottom panel in Figure 3), up to 100 days past $V$ maximum.

The photosphere around maximum is hot, with $T_{BB} \sim 13300$ K, then shows a steep decrease to about 8200 K at a phase of +25 d. Hereafter until day +56 the temperature remains constant, but then it smoothly increases up to 9000 K. The late temperature behaviour (later than day $\sim +40$) is likely an artefact due to the contamination on the blue region of the spectra that we attribute to the on-set of ejecta-CSM collision. The photospheric radius, in the same time interval, steeply increases from $8 \times 10^{14}$ cm to about $18 \times 10^{14}$ cm (at a phase of +25 d), and then linearly decreases to about $10 \times 10^{14}$ cm at about +90 -- +100 d (see Figure 3 bottom). It is interesting to note that the photospheric expansion rate in the first 25 d after maximum is about $6.64 \times 10^{13}$ cm day$^{-1}$, which corresponds to about 7700 km s$^{-1}$. This is very similar to the expansion velocity measured from the He I line visible in the spectra from +7 days after maximum (see Section 3). We deduce that for about 20 days the photosphere was locked to the same layer in the expanding ejecta, because the ejecta are highly ionised and thus opaque, and only after 20 days when the temperature is low enough to start the recombination the photosphere moves inwards in mass coordinate.

6.2. Modelling of the light curve

In order to better understand the early phases of the supernova and retrieve information about the physical properties of its progenitor at explosion, we compared the true-bolometric curve of ASASSN-15no with that predicted by the simulations described in Zampieri et al. (2003) and Zampieri (2007). This code solves the energy balance equation for ejecta of constant density in homologous expansion and yields the best fit model by simultaneously comparing the computed bolometric light curve, photospheric gas velocity and temperature with the corresponding observed quantities. Although it is less accurate than a full radiative-hydrodynamic treatment (see e.g. Pumo & Zampieri 2011, 2013), it is able to provide reliable estimates of the physical conditions of the ejected gas and has been successfully applied to a number of SNe II (either to directly model the SN ejecta or to constrain the parameter space for fully hydrodynamical calculations: see e.g. Zampieri et al. 2003; Pumo et al. 2017; Zampieri 2017 and references therein). The early photospheric temperature evolution (lower panel of Figure 3) is well fitted during the first 40 days past maximum by the model assuming that the first energy input occurred 15 days before maximum light (with an uncertainty of about 5 days, found analysing the quality of the model best fits), and the early photospheric gas velocity is constant at a value close to 6300 km s$^{-1}$. This is 2000 km s$^{-1}$ lower than the expansion velocity deduced from the minimum of the He I 5876 Å transition seen in ASASSN-15no spectra ($\langle v_{He I} \rangle = 8400 \pm 500$ km s$^{-1}$ for phases $< +75$ days), and after applying a $v$(Fe II 5169 Å)/$v$(He I 5876 Å) correction derived from SN 1993J spectra, a prototype of a SE supernova.

In fact, the photospheric velocity is usually best traced using Fe and/or Sc lines (Zampieri et al. 2003; Pumo & Zampieri 2011) which, however, are not evident in the ASASSN-15no spectra.

As shown in Figure 3, the model well matches the bolometric light curve only for the first $\sim 40$ days after the $V$ maximum when the input energy is dominated by the recombination and radioactive decay. The physical parameters derived from the model are the following: mass of the ejecta, $M_{ej} = 2.6$ $M_\odot$; initial radius of the photosphere, $R_0 = 2.1 \times 10^{14}$ cm; explosion energy, $E_{expl} = 0.8 \times 10^{51}$ erg. The $^{56}$Ni mass, $M_{Ni}$, and recombination energy are fixed at 0.15 $M_\odot$ and 6000 K, respectively. The values of these parameters are reasonable for a typical CC explosion, except for the radius. The derived radius of $\sim 3000$ $R_\odot$ would be consistent only with a very extended supergiant star (see e.g. Levesque et al. 2005, on Galactic red supergiant stars properties).

It is reassuring to note that the initial radius deduced from the model is in agreement with the measurements from spectrophotometry (see Figure 3 bottom panel).

The radius and, in general, the best-fitting model parameters (e.g. the low ejecta mass) are difficult to reconcile with the collapse of a single star, compared to a scenario involving a massive star in a binary (or multiple) system.

It is of interest to compare the physical parameters deduced for ASASSN-15no with those derived for SN 2009kf (Botticella et al. 2010). In fact SN 2009kf share many physical properties (e.g. spectroscopic type, peak luminosity, early photometric evolution) with ASASSN-15no. Modelling the physical parameters of SN 2009kf, Utrobin et al. (2010) found a somewhat lower initial radius (2000 $R_\odot$), but a much higher ejecta mass ($28.1$ $M_\odot$), explosion energy (22 foe) and $^{56}$Ni mass (0.4 $M_\odot$). The differences regarding ejecta mass and total energy are understood considering that in SN 2009kf the photospheric phase lasts 90 days and is only supported by the ejecta recombination and radioactive decay, while in ASASSN-15no lasts only $\sim 55$ days according to our scenario.

6.3. Spectroscopic comparison with a sample of Core Collapse SNe

We already mentioned that the ASASSN-15no light has a BB-like energy distribution at maximum, in analogy with other SNe (e.g. 2005gj and 1993J, see top panel of Figure 4). Instead, the near-maximum spectra of energetic SNe Ic, despite of being dominated by a strong continuum, show also broad Fe II and Si II features.

The temperature of the emitting photosphere reaches its minimum value, when the radius of the photosphere is maximum, then the temperature remains almost constant, while the radius steadily decreases, and the recombination front recedes inward through the ejecta. However, the late time temperature evolution could be affected by the increasing strength of the blue pseudo-continuum, probably arising from a cool dense shell, the region where the ejecta-CSM interaction take place (Smith et al. 2009).

Overall the observations suggest the following scenario. Initially ASASSN-15no ejecta is in free expansion, but $\sim 40$ d after maximum it starts to interact with a close-by CSM. This is confirmed by the spectroscopic comparison shown in the middle panel of Figure 4, where the spectrum of ASASSN-15no shows remarkable differ-
ences when compared with that of SN 2009fj. Hα is faint and broad, while in SN 2009fj it has a P-Cygni profile typically seen in non-interacting SNe. The ASSASN-15no spectrum shows a blue pseudo-continuum typically seen in the spectra of interacting SNe. Still, the maximum expansion velocity (∼18000 km s⁻¹, assuming an average Ca II IR triplet wavelength of 8579.1 Å [Mazzali et al. 2005] derived from the broad Ca II IR features of ASSASN-15no and SN 1998bw is comparable. After +100 d, the bolometric luminosity decline becomes steeper (upper panel of Figure 3) which correspond to a phase of fading interaction. If, as assumed in our modelling, the explosion of ASSASN-15no has ejected a 56Ni mass of about 0.15 M⊙ similar to the amount of 56Ni ejected in other CC SNe, by ∼+250 days the contribution due to interaction reaches a minimum (see Figure 3 upper panel). By this time, the spectrum is thus a combination of the emission coming from the interaction, and the emission from the non-interacting SN. This is best seen in the bottom panel of Figure 4 where we show the ASSASN-15no spectrum as observed and with a subtracted BB contribution (assumed coming from the interaction and estimated from the flux difference from the ASSASN-15no bolometric luminosity with respect to that of the SE SNe, see top panel of Figure 3). The second (subtracted) spectrum shows typical nebular features of a SE SN with a weak Hα. The simultaneous presence of interaction and ejecta features in the spectra likely indicates that the CSM is clumpy, or that its geometry and/or density structure are highly asymmetric.

6.4. 6300-64 Å - [OI] lines

Following [Taubenberger et al. 2009], we have de-blended the [OI] 6300-64 Å and Hα lines on the last three ASSASN-15no spectra. However, in ASSASN-15no spectra the de-blending is complicated by the presence of the broad Hα. The central position of the 6300 feature is similar to that observed in the SN Ib/c sample presented in Taubenberger et al. and it also experiences a similar red-ward shift with time shown by the SN Ib/c sample. The FWHM is large (5000 - 7000 km s⁻¹ at +184 days, 5400 - 6500 km s⁻¹ at +235 days and 5100 - 5900 km s⁻¹ at +289 days, depending from the assumed Hα width) and very similar to the widths shown by the [OI] 6300 Å line in the more energetic SE-SNe (see Figure 8 of Taubenberger et al. 2009).

Hα, which is blended with the [OI] doublet, has a composite profile. At +186 days, it consists of a broad (FWHM ∼10000 km s⁻¹) component, blue-shifted by ∼4000 km s⁻¹ (similar to that observed in early spectra, see Section 4), and an intermediate one (FWHM ∼3800 km s⁻¹), redshifted by ∼1100 km s⁻¹. At +294 d, while the broad component does not show a clear evolution with time, the intermediate one is found almost at the rest wavelength with a FWHM ∼1700 km s⁻¹.

6.5. The progenitor scenario

In an attempt to address all the observed evidences, we sketch the following scenario. The stripped envelope C/O core of a massive star, undergoes a likely asymmetric (see below) explosion which is initially masked by an opaque H-poor/He-rich, detached shell having an inner radius of ∼3000 R⊙.

Such a shell could have been lost by the SN progenitor during a common-envelope mass loss episode with a companion star, although the uncertainties on the common-envelope evolution prevent us from having precise information on this type of episodes (see e.g. Ivanova et al. 2013; Tauris et al. 2017 and references therein).

Assuming an average expansion velocity of ∼15000 km s⁻¹ for the ejecta and the initial radius deduced from the modelling (∼3000 R⊙), we can estimate that the ejecta travelled about 1.7 days before hitting the shell (likely expanding at low velocity, < 100 km s⁻¹). When the outer ejecta collide with the shell, a fraction of the kinetic energy of the ejecta heats the gas, and speeds up the shell itself. If the velocity deduced from the expanding photospheric radius (7700 km s⁻¹ cfr. Section 5) is in fact an indication that the ejecta plus swept-up shell is expanding with that velocity, this is about half of the velocity of the SN ejecta alone.

Assuming that the explosion of ASSASN-15no was similar to that of SN 1993J, whose observables were well fitted by models of Woosley et al. (1994) and Blinnikov et al. (1998), with ejected mass as low as 1.54 M⊙ (assuming binarity and the formation of a remnant of 1.55 M⊙ we can estimate that the mass of CSM shell enclosing the ASSASN-15no progenitor was as high as 1 M⊙ from our modelling the mass of the SN ejecta plus swept-up up material is 2.6 M⊙, see Sect. 6.3).

This scenario involving the ejecta-shell collision could be a scaled down (both in mass and radius of the shell) version of those proposed as a possible explanation for some SLSNe-II. As an example, in the H-rich SLSN CSS121015:004244+132827 (Benetti et al. 2014) the initial radius has been estimated to be ≲ 2×10⁸ cm and the shell mass to be ∼8.5 M⊙, making this SLSN at least 1.0 dex more luminous than ASSASN-15no.

The ejecta plus swept-up shell material begin a mild interaction with an outer CSM about 40 days after maximum. This outer CSM has probably high density and is H-poor. We get to these conclusions because in the early spectra there is no sign of low velocity Balmer recombination lines. The faint narrow Hα line seen in early spectra mostly comes from an underlying H-II region which contaminates the spectra at all phases (see also the presence of the [S II] doublet in the last two spectra of Figure 2). We can use simple arguments to constraint the geometry of the system. Assuming a velocity of ∼10 – 100 km s⁻¹ for the CS shell, and an initial radius of the massive shell of Rsh = 2.1×10¹⁴ cm, as suggested by the modelling, the inner shell must have been lost by the progenitor star ∼7 – 0.7 years before the explosion. We can also compute when the outer CSM has been expelled by the progenitor through the formula:

\[ t_0 = \frac{R_{sh}^n + (v_{sh} - v_{CSM}) \times t_{int}}{v_{CSM}} \]

where \( R_{sh}^n = 2.1 \times 10^{14} \) cm is the initial radius of the inner shell, \( v_{sh} = 6300 \) km s⁻¹ is the photospheric expansion velocity of the swept-up shell+ejecta, \( v_{CSM} = 10 – 100 \) km s⁻¹ is the assumed expansion for the CSM (similar to the expansion velocity of the massive shell before the collision with the ejecta), \( t_{int} = 50 \) days is the time after which the swept-up shell+ejecta starts to interact with the CSM (taking as reference the time of the first contact
of the ejecta with the shell). The result is that the outer CSM has been lost by the progenitor star about 90 – 9 years before the SN explosion.

At phases later than +100 days, the CSM surrounding the SN is almost swept-up and the radiation is coming from the inner part of the SN ejecta, however, as seen from the presence of the intermediate-width Hα, some residual CSM interaction is still ongoing. Because of the pronounced blueshift of the broad Hα emission seen at all phases, we suggest that the SN ejecta are asymmetric, with the asymmetric axes pointing in the observer’s direction.

In summary, we propose that what we initially observe in ASASSN-15no is the result of the collision between the SN ejecta (not visible early on) with a pre-existing, massive shell. Since the late time spectra turn out to be very similar to the nebular spectra of SE-SN, we propose that the shell could be the result of mass loss due to a common envelope phase in a binary system. This is in fact the favoured channel proposed for stripping the outer H-He mantle of massive stars before their explosion as SE SNe (Podsiadlowski et al. 1992; Yoon et al. 2010; Eldridge et al. 2013). In binary systems, the SN progenitors may also be surrounded by dense CSM because of the mass loss triggered by non-conservative mass transfer along the final phases of the progenitor evolution (Ouchi & Maeda 2017).

Alternatively, a massive binary system composed by a H-poor LBV-like star that expelled a shell ∼ 7 – 0.7 years before a Wolf-Rayet companion star exploded as ASASSN-15no, could also explain the observations. A similar progenitor configuration has been proposed by Pastorello et al. (2007) to explain the output of the type Ibn SN 2006jc (however, this scenario has been questioned by Maund et al. 2016).

7. CONCLUSIONS

Extensive photometric and spectroscopic observations of ASASSN-15no for slightly less than a year of its evolution are presented. The light curve show a slow evolution early on, which is followed by a faster evolution 100 days after maximum, with the V light curve reaching an absolute magnitude peak of M_V ~ −19.6.

The spectra up to ~ 10 days after maximum are featureless with BB temperature dropping from 13300 K at maximum to 8200 K 17 days later. At phase of +11 d, a He I 5876 Å transition with a P-Cygni profile appears, with an expansion velocity of about 8000 km s^-1. At phases later than +40 days from the V maximum, the blue region of the spectra are dominated by a blue pseudo-continuum frequently seen in interacting supernovae. Meanwhile, a broad Hα becomes more and more intense with time up to ~ 150 days after the V band maximum and quickly declines later on. At the same phases an intermediate Hα component appears, which becomes narrower and fainter with time. The spectra at latest phases look very similar to the nebular spectra of stripped-envelope supernovae.

The early photometric evolution (the first 40 days after the V maximum) of the bolometric light curve is well reproduced by a model in which the post-explosive evolution is dominated by the expanding ejecta and the energy budget is essentially coming from ejecta recombination and 56Ni decay. From this we infer, a mass of the ejecta, M_ej = 2.6 M_⊙; an initial radius of the photosphere, R_0 = 2.1 × 10^{14} cm; and an explosion energy, E_{expl} = 0.8 foe. The blue pseudo-continuum and the intermediate Hα component are, instead, clues that ejecta-circumstellar medium interaction starts from about 40 days after maximum.

A possible scenario which accounts for all the observables involves a massive and extended H-poor shell lost by the progenitor star (1 – 7 years before explosion), probably during a common envelope episode with a companion. The shell is heated and accelerated by the collision with the ejecta and its emission models the early bolometric light curve. The accelerated shell+ejecta rapidly dilutes unveiling the unperturbed supernova spectrum below. Meanwhile, the shell+ejecta start to interacts with a more H-poor external circumstellar material lost by the progenitor system about 9–90 years before the explosion. This interaction should occur in clumps or in highly asymmetric CSM, because only in this scenario, the inner ejecta are exposed.

This scenario involving the ejecta-massive shell collision could be a scaled down (both in mass and radius of the shell) version of those proposed for modelling some SLSNe.

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### TABLE 2

*u*gri*z* photometry (AB system) of ASASSN-15no.

| MJD       | rest phase | u (err)      | g (err)      | r (err)      | i (err)      | z (err)      | Instrument  |
|-----------|------------|--------------|--------------|--------------|--------------|--------------|-------------|
| 57240.96  | +6         | 16.36 (0.08) | 16.47 (0.06) | 16.59 (0.09) | ...          | ...          | AFOSC       |
| 57243.93  | +9         | 16.65 (0.02) | 16.32 (0.05) | 16.44 (0.06) | 16.50 (0.08) | 16.52 (0.04) | AFOSC       |
| 57244.93  | +10        | 16.62 (0.05) | 16.45 (0.04) | 16.48 (0.06) | 16.58 (0.06) | 16.62 (0.03) | AFOSC       |
| 57245.92  | +11        | 16.69 (0.05) | 16.38 (0.05) | 16.48 (0.06) | 16.63 (0.10) | 16.63 (0.06) | AFOSC       |
| 57258.97  | +23        | 17.28 (0.03) | 16.75 (0.05) | 16.63 (0.04) | 16.71 (0.04) | 16.70 (0.04) | ALFOSC-FASU |
| 57263.91  | +28        | ...          | 16.84 (0.19) | ...          | ...          | ...          | OSIRIS      |
| 57272.89  | +37        | 17.50 (0.07) | 17.01 (0.04) | 17.00 (0.08) | 16.78 (0.05) | ...          | AFOSC       |
| 57292.86  | +56        | ...          | 17.18 (0.01) | ...          | ...          | ...          | OSIRIS      |
| 57309.87  | +72        | 17.91 (0.06) | 17.45 (0.07) | 17.45 (0.05) | ...          | ...          | LRS         |
| 57330.79  | +92        | 18.12 (0.09) | 17.74 (0.07) | 17.77 (0.10) | 17.27 (0.04) | ...          | AFOSC       |
| 57342.71  | +104       | ...          | 17.89 (0.20) | 18.07 (0.11) | 17.70 (0.06) | ...          | AFOSC       |
| 57359.22  | +120       | 19.16 (0.17) | 18.34 (0.07) | 18.26 (0.07) | 18.14 (0.05) | ...          | AFOSC       |
| 57866.22  | +146       | 19.89 (0.14) | 18.88 (0.07) | 18.74 (0.05) | 18.57 (0.07) | ...          | AFOSC-FASU  |
| 57426.23  | +185       | ...          | 19.84 (0.03) | ...          | ...          | ...          | OSIRIS      |
| 57429.19  | +187       | >20.66 (0.36) | 20.09 (0.11) | 20.13 (0.19) | 19.37 (0.09) | ...          | AFOSC       |
| 57464.19  | +221       | >21.48 (0.51) | 21.08 (0.15) | 20.95 (0.20) | 20.03 (0.20) | ...          | LRS         |
| 57479.18  | +236       | ...          | 20.89 (0.50) | ...          | ...          | ...          | OSIRIS      |
| 57488.02  | +244       | ...          | 21.48 (0.06) | 21.06 (0.10) | 21.23 (0.08) | ...          | LRS         |
| 57534.06  | +289       | ...          | 21.59 (0.66) | 21.53 (0.70) | 21.17 (0.70) | ...          | OSIRIS*     |

**Note.** — *i* and *z* measurements synthesised from the spectrum after normalising it to the *r* photometric measurement. The rest phases are relative to the *V* band maximum (2015 August 1).

### TABLE 3

*UBVRI* photometry (Vega system) of ASASSN-15no.

| MJD       | rest phase | U (err)     | B (err)     | V (err)     | R (err)     | I (err)     | Instrument |
|-----------|------------|-------------|-------------|-------------|-------------|-------------|------------|
| 57233.31  | -2         | ...         | ...         | ...         | >17.10      | ...         | ASASSN     |
| 57237.26  | +2         | ...         | ...         | ...         | 16.46 (0.09) | ...         | ASASSN     |
| 57241.24  | +6         | ...         | ...         | ...         | 16.50 (0.13) | ...         | ASASSN     |
| 57242.28  | +7         | ...         | ...         | ...         | 16.62 (0.09) | ...         | ASASSN     |
| 57243.93  | +9         | ...         | ...         | ...         | 16.55 (0.05) | 16.47 (0.05) | ...         | AFOSC      |
| 57244.28  | +9         | ...         | ...         | ...         | 16.57 (0.08) | ...         | ASASSN     |
| 57244.92  | +10        | ...         | ...         | ...         | 16.55 (0.06) | 16.54 (0.04) | ...         | AFOSC      |
| 57245.92  | +11        | ...         | ...         | ...         | 16.70 (0.08) | 16.50 (0.05) | ...         | AFOSC      |
| 57246.26  | +11        | ...         | ...         | ...         | 16.79 (0.10) | ...         | ASASSN     |
| 57250.26  | +15        | ...         | ...         | ...         | 16.68 (0.09) | ...         | ASASSN     |
| 57255.25  | +20        | ...         | ...         | ...         | 16.68 (0.10) | ...         | ASASSN     |
| 57258.96  | +23        | ...         | 17.01 (0.03) | 16.69 (0.03) | ...         | ...         | ALFOSC-FASU |
| 57316.80  | +79        | 17.17 (0.11) | 17.65 (0.07) | 17.49 (0.06) | 17.22 (0.06) | 16.95 (0.05) | MEIA2      |
| 57317.80  | +80        | 17.20 (0.12) | 17.71 (0.09) | 17.44 (0.05) | 17.36 (0.06) | 16.99 (0.07) | MEIA2      |
| 57330.79  | +92        | 17.92 (0.06) | 17.63 (0.04) | ...         | ...         | AFOSC       |
| 57342.71  | +104       | ...         | 18.19 (0.09) | 17.92 (0.09) | ...         | ...         | AFOSC      |
| 57359.23  | +120       | ...         | 18.57 (0.10) | 18.20 (0.05) | ...         | ...         | AFOSC      |
| 57386.21  | +146       | ...         | 19.05 (0.07) | 18.80 (0.07) | ...         | ...         | ALFOSC-FASU |
| 57429.20  | +187       | ...         | 20.10 (0.15) | 19.88 (0.19) | ...         | ...         | AFOSC      |
| 57488.04  | +244       | ...         | 21.76 (0.18) | 21.38 (0.19) | ...         | ...         | LRS        |

**Note.** — The rest phases are relative to the *V* band maximum (2015 August 1).