SN 2018hna: 1987A-like supernova with a signature of shock breakout

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(Received August 3, 2019; Revised August 20, 2019; Accepted August 21, 2019)

ABSTRACT

High cadence ultraviolet, optical and near-infrared photometric and low-resolution spectroscopic observations of the peculiar Type II supernova (SN) 2018hna are presented. The early phase multiband light curves exhibit the adiabatic cooling envelope emission following the shock breakout up to ∼14 days from the explosion. SN 2018hna has a rise time of ∼88 days in the V-band, similar to SN 1987A. A $^{56}$Ni mass of ∼0.087 ± 0.004 M$_\odot$ is inferred for SN 2018hna from its bolometric light curve. Hydrodynamical modelling of the cooling phase suggests a progenitor with a radius ∼50 R$_\odot$, a mass of ∼14–20 M$_\odot$ and an explosion energy of ∼1.7–2.9 $\times$ 10$^{51}$ erg. The smaller inferred radius of the progenitor than a standard red supergiant is indicative of a blue supergiant progenitor of SN 2018hna. A sub-solar metallicity (∼0.3 Z$_\odot$) is inferred for the host galaxy UGC 07534, concurrent with the low-metallicity environments of 1987A-like events.

Keywords: supernovae: general, supernovae: individual: SN 2018hna, galaxies: individual: UGC 07534

1. INTRODUCTION

Core-collapse supernovae (CCSNe) result from the gravitational collapse of stars with a Zero-Age Main Sequence (ZAMS) mass $\gtrsim$ 8 M$_\odot$ (Heger et al. 2003). Type II SNe result from stars that retain their hydrogen envelope at the time of explosion. Theoretical (Grassberg et al. 1971) and observational (Smartt 2009) studies of Type II SNe indicate a Red Super-Giant (RSG) progenitor. However, the nearest naked-eye supernova in the last four centuries, SN 1987A showed that a Blue Super-Giant (BSG) can also be a progenitor of Type II SNe. The presence of a slow rise to the maximum (∼85–100 d) is the distinguishing feature in the light curves of Type II SNe resulting from a BSG (Kleiser et al. 2011). However, extended RSGs can also result in a slow rising
Type II SN if they synthesize a substantial amount of $^{56}\text{Ni}$ ($\sim 0.2 \, M_\odot$) in the explosion (e.g. SN 2004ek, Taddia et al. 2016). Theoretical models have shown that fast-rotation, low-metallicity and/or interaction in a binary system can indeed lead to the explosion of BSGs as SNe (Podsiadlowski 1992).

In the vast expanse of data on Type II SNe, only a handful of SNe have shown similarities to SN 1987A (Hamuy & Suntzeff 1990; Pun et al. 1995). These are SN 1998A (Pastorello et al. 2005), SN 2000cb and SN 2005ci (Kleiser et al. 2011), SN 2006V and SN 2006au (Taddia et al. 2012), SN 2009E (Pastorello et al. 2012), SN 2009nw (Takáts et al. 2016) and SN Refsdal (Rodney et al. 2016; Kelly et al. 2016). These will be referred to as 1987A-like events, whereas, Type II events with an RSG progenitor will be referred to as normal Type II SNe. Analysis of 1987A-like events have shown that these arise from rather compact progenitors (BSG, R < 100 R_\odot) with a higher ZAMS mass, higher explosion energies ($>10^{51}$ erg) and higher synthesized $^{56}\text{Ni}$ ($\sim 0.1 \, M_\odot$) when compared to normal Type II SNe (Pastorello et al. 2012; Taddia et al. 2016).

The collapse of the core in CCSNe is succeeded by a shock wave resulting from the rebound of the in-falling matter on the neutron-degenerate proto-neutron star (collapsed core). A fraction of the energy lost during this collapse is transferred via neutrino heating to the matter on the neutron-degenerate proto-neutron star, releasing energy in X-ray and UV (Falk & Ensman & Burrows 1992). This short-lived (~100s in nuclear time) heating of the outer ejecta. The shock accelerates towards the surface of the star, releasing energy in X-ray and UV (Falk & Arnott 1977) due to its high temperature ($10^7$ K), releasing energy in X-ray and UV (Falk & Ensman & Burrows 1992). This short-lived (~1000s in nuclear time) heating of the outer ejecta is labelled as the “shock” breakout and marks the first electromagnetic signature of a SN explosion.

The cooling emission from the heated envelope as a result of the shock breakout has been seen only in a few Type II SNe such as SN 1987A (Ensmann & Burrows 1992), SNLS-04D2dc (Tomimaga et al. 2009), SN 2010aq (Gezari et al. 2010) etc. The signature of a shock breakout is generally more prominent in Type IIb SNe with extended envelopes, e.g. SN 1993J (Richmond et al. 1994) and SN 2011fu (Kumar et al. 2013). The thermal emission from the heated ejecta peaks in the UV spanning a few hours to a couple of days (Nakar & Sari 2010). The shock breakout may be delayed due to the presence of a circumstellar wind as the shock not only has to escape the outer envelope of the SN ejecta, but also the dense wind surrounding it (Ofek et al. 2013). During the breakout, the energy released scales with the progenitor radius and hence the detection of an early emission helps in directly tracing the progenitor properties.

SN 2018hna was discovered by Koichi Itagaki on 2018 October 23.9 UT (JD 2458414.3) in the galaxy UGC 07534. SN 2018hna lies 31.6°E and 30°N from the nucleus of the host galaxy. A spectrum obtained by Hiroshima One-shot Wide-field POLarimeter (HOWPol, Kawabata et al. 2008) on 2018 October 24.8 UT, displayed a prominent P-Cygni profile of H\alpha categorizing it as a Type II SN (TNS # 2933).

The photometric and spectroscopic evolution of SN 2018hna is presented in this Letter, and discussed in the context of 1987A-like events.

2. DATA ACQUISITION

Optical photometric ($UBVRI$) and spectroscopic observations of SN 2018hna using the 2-m Himalayan Chandra Telescope (HCT), Indian Astronomical Observatory (IAO), Hanle, India began on 2018 October 31.9 UT (JD 2458423.4). The recently installed robotic 0.7-m GROWTH\textsuperscript{1} - India telescope (GIT) at IAO followed up SN 2018hna in the SDSS $g'r'i'$ filters starting 2018 November 15.9 UT. SN 2018hna was also monitored with the 1.5-m Kanata Telescope in the optical and the near-infrared using the HOWPol and the Hiroshima Optical and Near-InfraRed camera (HONIR; Akitaya et al. 2014). Few spectra were also obtained using the Kyoto Okayama Optical Low-dispersion Spectrograph with Optical-Fiber Integral Field Unit (KOOLSFU, Matsubayashi et al. 2019) mounted on the 3.8-m Seimee telescope, at the Okayama Observatory. Data reduction was performed using standard reduction procedures described in Singh et al. (2018). The follow-up of SN 2018hna is supplemented by data from the public archives of Zwicky Transient Facility (ZTF; Bellm et al. 2019) in $g$ and $r$ bands, from Lasair (Smith et al. 2019), and Gaia (Gaia Collaboration et al. 2018) in $g$-band.

The Neil Gehrels Swift Observatory (Gehrels et al. 2004) monitored SN 2018hna with the ultraviolet Optical Telescope (UVOT; Roming et al. 2005) beginning 2018 October 23.6 UT. Data reduction was performed using the UVOT\textsuperscript{1} data analysis software in HEASOFT (see Kumar et al. 2018).

3. PHOTOMETRIC EVOLUTION

The ultraviolet, optical and near-infrared light curves (LCs) of SN 2018hna are shown in Figure 1. The slow rise to the maximum and the broad peak resemble the peculiar Type II SN 1987A. Due to the immediate follow up with Swift, the early LCs in the optical and the ultraviolet bands show a noticeable decline in brightness during the initial phase, followed by a rise to maximum. This drop can be explained as a result of the rapid cooling of the photosphere proceeding the shock breakout, and was also seen in SN 1987A. Hydrodynamic modeling of the early LC constrained the explosion date to be JD 2458411.3, 3 days prior to discovery (see Section 5.1). The peak in the V-band LC of SN 2018hna at ~87.5 d is adopted as the epoch of maximum. This is similar to SN 1987A (~86 days). A Galactic reddening of $E(B-V) = 0.009\pm0.001$ mag along the direction

\textsuperscript{1} Global Relay of Observatories Watching Transients Happen (http://growth.caltech.edu)
1987A-like Type II SN 2018hna

Figure 1. Apparent light curves (LCs) of SN 2018hna. The LCs of SN 1987A were shifted to match the maximum of SN 2018hna. Offsets have been applied for clarity.

of SN 2018hna was obtained from the dust-extinction map of Schlafly & Finkbeiner (2011). This is consistent with the absence of interstellar Na I D absorption in the spectra of SN 2018hna. No trace of Na I D absorption is seen at the redshift of the host galaxy, concurrent with the high offset of SN 2018hna from the center of the host. A net reddening of $E(B-V) = 0.009 \pm 0.001$ mag is adopted assuming no host extinction. A distance modulus of $\mu = 30.52 \pm 0.29$ mag (12.82 $\pm$ 2.02 Mpc) is estimated for the host galaxy UGC 07534 from the mean of the Hubble flow distances provided in NASA Extragalactic Database (NED\(^2\)) and the Tully-Fisher relation (Karachentsev et al. 2013).

4. SPECTROSCOPIC EVOLUTION

The spectral evolution of SN 2018hna is shown in Figure 2A. The first spectrum of SN 2018hna obtained at $\sim 12$ d, shows strong, broad P-Cygni profiles of the Balmer lines, Fe II features, Ca II NIR triplet, and weak Ba II 4554 Å. He I 5876 Å was identified in the early ($\sim 3$ days from explosion) spectrum of SN 1987A. However, the feature around 5740 Å is identified as Na I D instead of He I 5876 Å due to the low color temperature ($< 8000$ K) inferred from the Spectral Energy Distribution (SED).

As the SN evolved towards the maximum, features of Na I D, Fe II, Ca II, Ba II, Sc II, Ti II and Sr II became more prominent. The line identification in the spectrum of $\sim 73$ d is shown in Figure 2E. The features of Ba II (i.e. 4554 and 6142 Å), which are characteristic of 1987A-like events (Mazzali & Chugai 1995) are also evident in the spectra ($> 15$ d) of SN 2018hna. The prominent features during the late nebular phase ($\sim 256$ d) are labelled in Figure 2D. Feature marked “A” ($\sim 8360$ Å) is unidentified and warrants further investigation.

The P-Cygni profile of Hα in SN 2018hna shows a blue-shift in its emission feature during the photospheric phase, which settles onto a constant value of $\sim 600$

\(^2\) https://ned.ipac.caltech.edu
Figure 2. Panel A: Spectroscopic sequence of SN 2018hna. The three different colors depict the cooling envelope (blue), photospheric (black) and nebular phase (red) of the SN. Panels B, C & D: Comparison of SN 2018hna with 1987A-like events. Panel E: Identification of lines in the spectrum of ∼73 d.

km s\(^{-1}\) during the transition to the radioactive decay phase (> 100 d). The blue-shift has been seen in a majority of Type II SNe (including 1987A-like SNe) and has been explained as arising from the steep density profile of the outer SN ejecta (Anderson et al. 2014).

The absorption troughs of H\(\alpha\), H\(\beta\) and Na I D features in the spectra of SN 2018hna show a “kink” (flux excess) beginning ∼37 d (see Figure 3). This feature is strongest in the spectrum of ∼102 d, and disappeared by ∼112 d. The presence of Ba II in the troughs of Na I D and H\(\alpha\) can possibly explain this feature, although, this line blend should be seen as absorption and not an emission during the photospheric phase. This complex fine-structure was also detected in SN 1987A (Hanuschik et al. 1988; Phillips & Heathcote 1989) and comprised of a blue-shifted flux excess and a red-shifted flux deficit, of which only the former is seen in SN 2018hna. The origin of these kinks is likely a result of asymmetry in the line-emitting region. The velocities of these kinks closely follow the photospheric velocity evolution as in SN 1987A and indicate the advent of high-energy radiation from the decay of \(^{56}\)Ni at the photosphere (Phillips & Heathcote 1989).

5. DISCUSSION

SN 2018hna occurred in the outskirts (∼2.5 kpc from the center) of the low-luminosity (\(M_B \sim -17.1\) mag) dwarf irregular galaxy (IBm) UGC 07534. The luminosity-metallicity relation of Tremonti et al. (2004) yields an oxygen abundance of 8.14 ± 0.02 for UGC 07534. This indicates a sub-solar metallicity (∼0.3 \(Z_\odot\)) of the host environment of SN 2018hna and is consistent with
the occurrence of 1987A-like SNe in late-type galaxies (Sc or later; Pastorello et al. 2012) having sub-solar metallicity.

5.1. Cooling envelope emission and explosion parameters

The early LCs (<14 d) of SN 2018hna distinctly show adiabatic cooling of the shock-heated SN ejecta. The early emission in the $B$ and $V$ bands shows a rise towards an initial peak. This is a result of the “temperature effect” resulting from the migration of the SN SED into the optical wavelengths while the net bolometric luminosity is still declining (Fremling et al. 2019).

Prominent signature of cooling emission is generally seen in Type II (distinctly in IIb) SNe, arising from an extended envelope surrounding their compact core. A similar emission can be seen for a compact BSG progenitor, e.g. 1987A-like events. Since the cooling emission is generally stronger for a more extended and/or more massive envelope, one could use this emission to infer the properties of the H-rich envelope (Nakar & Sari 2010; Bersten et al. 2012; Nakar & Piro 2014).

The multi-color light curves of an explosion of a BSG star were computed with the multigroup radiation hydrodynamics code STELLA (Blinnikov et al. 2000). The resultant synthetic SED was convolved with the filter transmission function of the respective bandpasses. The multi-color light curves of SN 2018hna during the cooling phase were well reproduced for a star of pre-SN mass $\sim 16 M_\odot$ (i.e. an ejecta mass $\sim 14 M_\odot$), a radius of $\sim 50 R_\odot$ and an explosion energy of $\sim 1.7 \times 10^{51}$ erg (see Figure 4). The explosion epoch was constrained to 3 days prior to the discovery i.e JD 2458411.3.

Figure 3. Left panel: Line velocity evolution of SN 2018hna. Middle panel: Evolution of $\text{H}_\beta$, $\text{H}_\alpha$ and Na ID up until $\sim 120$ d. Right panel: Evolution of $\text{O I}$, $\text{H}_\alpha$ and $\text{Ca II}$ during the nebular phase.

Figure 4. Comparison of early phase Swift LCs with the hydrodynamic model.
In the case of a compact progenitor, the drop in temperature post the shock breakout reduces once the temperature reaches in the bracket of 6000-8000 K due to the process of recombination. Hence, the luminosity in the redder bands (\(VRI\)) keeps rising as the temperature falls to this bracket, whereas the luminosity in the UV-bands keeps falling as the wavelength evolves to the Wein’s part of the spectrum (Nakar & Piro 2014). The inset in Figure 5A shows the comparison of SN 2018hna with SN 1987A during the cooling envelope phase. The luminosity and time-scale of the cooling emission overlaps between the two SNe. This is indicative of similarity in progenitor properties (like radius and the ratio of ejecta energy to mass) between SN 2018hna and SN 1987A. We rule out the delay of the shock breakout due to an immediate CSM, as no observable feature of such interaction is discernible in the spectral sequence of SN 2018hna.

The long rise-time of 1987A-like events can be explained due to the slow diffusion of radiation from the decay of radioactive \(^{56}\)Ni through the massive envelope of the progenitor. Hence, the time taken for the radiation to diffuse through the ejecta is used to estimate the mass using the relation from Arnett (1979) for radioactively powered SNe. Using \(E_{57A} = 1.1 \times 10^{53} \text{ erg s}^{-1}\) and \(M_{57A} = 14 \text{ M}_\odot\) (Blinnikov et al. 2000), diffusion time, \(t_d \sim 1.02 t_{1987A}^{1.0}\) and a similar mean opacity, an ejecta mass of \(\sim 19.8 \text{ M}_\odot\) and an \(E_{\text{expl}}\) of \(\sim 2.9 \times 10^{53} \text{ erg}\) is inferred for SN 2018hna.

5.2. Comparison with 1987A-like events

The Ba II 6142 \(\AA\) feature in SN 2018hna was identified as early as \(\sim 15\) d, similar to SN 1987A, but much earlier in comparison to normal Type II SNe (seen \(\sim 50\) d). The strength of Ba II features in SN 1987A primarily arises from the over-abundance of Barium in the entirety of its hydrogen envelope due to the faster cooling of the SN ejecta resulting from its compact progenitor (Mazzali & Chugai 1995). Also, slow-expanding ejecta are denser and produce stronger Ba II features in 1987A-like and low-luminosity Type II SNe (e.g. SN 2005cs, Pastorello et al. 2009). SN 2018hna does not show as strong a Ba II feature as in SN 1987A due to its relatively bluer colors along with a faster photospheric velocity (50% faster at \(V\)-band maximum). This is evident in the spectral comparison in Figures 2B, C & D.

The velocity evolution of H\(\alpha\) and Fe II \(\lambda5169\) feature of SN 2018hna indicates an evolution similar to SN 1987A during the early phase, that subsequently flattens out at a higher velocity (see Figure 3). This is possibly a result of the higher explosion energy in SN 2018hna, which leads to broader line profiles throughout its evolution.

The cooling envelope phase in 1987A-like events shows a steep rise in colors as seen in the evolution of \(U-V\) and \(B-V\) colors (Figures 5B and C). Post the cooling phase, the evolution is almost flat. SN 2018hna, SN 2006au and SN 2006V are bluer compared to SN 1987A. This agrees with the fact that 1987A-like events with bluer colors tend to be brighter at maximum (Taddia et al. 2016). SN 2018hna is bluer in \(U-V\) by \(\sim 1.6\) mag and in \(B-V\) by \(\sim 0.4\) mag. Differences in color can partially
be attributed to higher line-blanketing in SN 1987A (see Figure 2C) and/or higher $^{56}\text{Ni}$-mixing in comparison to SN 2018hna and other events. Post maximum, the colors turn redder, and are similar to SN 1987A during the transition to the radioactive decay phase (beyond $\sim 125$ d).

It is seen that the progenitors of 1987A-like events produce higher amount of $^{56}\text{Ni}$ in comparison to normal Type II SNe as majority of them have higher ejecta masses (Taddia et al. 2016). The degree of $^{56}\text{Ni}$-mixing and the net amount of $^{56}\text{Ni}$ synthesized helps change the rise to the maximum. A larger $^{56}\text{Ni}$ mass increases the time taken to rise to the bolometric peak (rise time) and brightens the peak, whereas a higher degree of $^{56}\text{Ni}$-mixing decreases the rise time.

The optical ($UBVRI$) bolometric luminosity of SN 2018hna is higher than SN 1987A during the maximum and the radioactive decay phase (Figure 5A). The bolometric luminosity including NIR contribution ($UBVRIJHKs$) of SN 2018hna is $16 \pm 5\%$ brighter than SN 1987A during the radioactive decay phase ($\sim 150$ d). Hence, the $^{56}\text{Ni}$ synthesized in SN 2018hna is $0.087 \pm 0.004$ $M_\odot$. The rise to the bolometric maximum is steeper in SN 2018hna in comparison to SN 1987A and signifies a slightly lower-degree of $^{56}\text{Ni}$-mixing in its ejecta. The luminosity at maximum of 1987A-like events is roughly $\sim 1.5$ times the luminosity from the radioactive decay (Dessart & Hillier 2019), however, in the case of SN 2018hna it is more than twice ($\sim 2.5$).

Blue-shifted emission lines in the nebular phase have shown to be an indicator of dust formation in the ejecta of SNe (Elmhamdi et al. 2003) as the receding component of ejecta is blocked by the newly synthesized dust (Sarangi et al. 2018). Blue-shifted emission of [O I], Hα and [Ca II] is seen during the nebular phase of SN 2018hna (see right panel in Figure 3). The peak of these emission lines stays at almost a constant velocity of $\sim 1200, 600$ and $1100$ km s$^{-1}$, respectively, throughout the nebular phase. These numbers are consistent with the fact that Oxygen and Calcium are found deeper in the ejecta than Hydrogen. The first overtone of CO emission ($\sim 2.3$ μm) was detected in SN 2018hna in the near-infrared spectrum of $\sim 153$ d (Rho et al. 2019). A similar feature was also detected in SN 1987A around $\sim 136$ d. In all, the signatures above are an indication of dust in the ejecta of SN 2018hna.

6. SUMMARY

A detailed analysis of the photometric and spectroscopic evolution of the SN 1987A-like supernova SN 2018hna is presented in this Letter, based on which the following are inferred:

- signature of shock breakout is seen in the early phase. SN 2018hna is only the second BSG event caught within a few days from shock breakout;
- the rise to maximum is slow, similar to other 1987A-like events, with a peak $V$-band absolute magnitude of $-16.35 \pm 0.32$ mag;
- an explosion energy of $\sim 1.7-2.9 \times 10^{51}$ erg, a BSG progenitor with a radius $\sim 50$ R$_\odot$, and mass $\sim 14-20$ M$_\odot$; and
- a sub-solar metallicity ($\sim 0.3$ Z$_\odot$) for the host galaxy UGC 07534, in coherence with the low-metallicity of other 1987A-like events.

7. ACKNOWLEDGEMENTS

We thank the referee for their positive comments on the manuscript. We thank Masaomi Tanaka for his insightful suggestions. We thank the staff of IAO-Hanle, CREST-Hosakote, Higashi-Hiroshima Observatory and Okayama Observatory who made these observations possible. The facilities at IAO and CREST are operated by the Indian Institute of Astrophysics (IIA), Bangalore. The 0.7m GIT is set up by IIA and the Indian Institute of Technology, Bombay at IAO, Hanle with support from the Indo-US Science and Technology Forum (IUSSTF) and the Science and Engineering Research Board (SERB) of the Department of Science and Technology (DST), Government of India Grant No.IUSSTF/PIRE Program/GROWTH/2015-16. GCA and VB acknowledge the SERB-IUSSTF grants for the same.

DKS and GCA acknowledge DST/JSPS grant, DST/INT/JSPS/P/281/2018. HK thanks the LSSTC Data Science Fellowship Program, which is funded by LSSTC, NSF Cybertraining Grant #1829740, the Brinson Foundation, and the Moore Foundation. PVB’s work on finding parameters of SNe is supported by the grant RSF 18-12-00522. SB is supported by the grant RSF 19-12-00229 in his work on developing codes modeling the radiative transfer in SNe. K.M acknowledges support by JSPS KAKENHI Grant (18H05223) for the initiation of the SN follow-up program with the Seimei telescope. This research has been supported in part by the RFBR-JSPS bilateral program.

This research made use of RedPipe$^3$, an assemblage of data reduction and analysis scripts written by AS. We acknowledge Wiezmann Interactive Supernova data REPository$^4$ (WISeREP; Yaron & Gal-Yam 2012) and ESA Gaia, DPAC and the Photometric Science Alerts Team$^5$.

Facilities: HCT (HFOSC), GIT, KT (HOWPol, HONIR), ST (KOOLS-IFU), Swift (UVOT)

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$^3$ https://github.com/sPaMFouR/RedPipe

$^4$ https://wiserep.weizmann.ac.il

$^5$ http://gsaweb.ast.cam.ac.uk/alerts
**Software:** STELLA, Astropy (v3.1.2), SciPy (v1.3.0), Matplotlib (v3.1.0), Pandas (v0.24.2), PyRAF (v2.1.14), Seaborn (v0.9.0)

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