Late-time Circumstellar Interaction of SN 2017eaw in NGC 6946

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Abstract

SN 2017eaw, the tenth supernova observed in NGC 6946, was a normal Type II-P supernova with an estimated 11–13 M⊙ red supergiant progenitor. Here we present nebular-phase spectra of SN 2017eaw at +545 and +900 days post-max, extending approximately 50–400 days past the epochs of previously published spectra. While the +545 day spectrum is similar to spectra taken between days +400 and +493, the +900 day spectrum shows dramatic changes both in spectral features and emission-line profiles. The Hα emission is flat-topped and boxlike with sharp blue and red profile velocities of ≃−8000 and +7500 km s⁻¹. These late-time spectral changes indicate strong circumstellar interaction with a mass-loss shell, expelled ∼1700 yr before explosion. SN 2017eaw’s +900 day spectrum is similar to those seen for SN 2004et and SN 2013ej observed 2–3 yr after explosion. We discuss the importance of late-time monitoring of bright SNe II-P and the nature of presupernova mass-loss events for SN II-P evolution.

Unified Astronomy Thesaurus concepts: Core-collapse supernovae (304); Type II supernovae (1731); Circumstellar matter (241); Ejecta (453)

Supporting material: data behind figure

1. Introduction

Supernovae (SNe) play an important role in chemical enrichment of the interstellar medium and in the evolution of their host galaxies, including the creation of neutron stars and stellar-mass black holes. Core-collapse SNe arise from the death of massive stars (≥8 M⊙), and those with hydrogen in their spectrum are classified as Type II events (Filippenko 1997; Arcavi 2017; Gal-Yam 2017).

Further subclassifications are based on light-curve evolution. Historically, Type II-plateau SNe (SNe II-P) have a plateau phase following peak brightness which lasts of order 2–3 months before a linear decline, while Type II-linear SNe (SNe II-L) decline linearly almost immediately after reaching peak brightness. However, recent studies have suggested a more continuous distribution of SNe II based on light-curve decay rates rather than a bimodal distribution, where the length of the plateau is related to the mass of the progenitor, with lower-mass progenitors having longer plateaus (Anderson et al. 2014; Valenti et al. 2016; Gutierrez et al. 2017).

Archival images showing the progenitors of supernovae prior to explosion have led to the identification of red supergiants (RSGs) for the progenitors of SNe II-P (e.g., Van Dyk et al. 2003; Smartt et al. 2004; Maund & Smartt 2009; Fraser et al. 2012, 2014; Maund et al. 2014a, 2014b). The initial masses of these RSG progenitors are typically inferred to be between 9.5–16.5 M⊙ (e.g., Smartt et al. 2009; Smartt 2015). This mass range is supported by models of SN II-P nebular-phase spectra (Jerkstrand et al. 2012, 2014).

As SNe evolve, they become more optically transparent, due to decreased ejecta density, which leads to an increasingly emission-line dominated nebular phase starting ∼150–200 days after peak brightness. This nebular phase can provide valuable insights into the kinematic and elemental properties of a SN’s ejecta, as well as information about the SN’s circumstellar (CSM) environment. Bright supernovae are especially valuable for these studies, as they can be observed longer in the nebular phase.

One of the brightest recent SN II-P was SN 2017eaw in NGC 6946, the tenth supernova in this galaxy in the past century. SN 2017eaw was discovered on 2017 May 14.238 UT (Dong & Stanek 2017; Wiggins 2017) and reached a peak V magnitude of 12.8. Its light curve and spectroscopic evolution followed that of a normal SN II-P (Cheng et al. 2017; Tomasella et al. 2017; Xiang et al. 2017; Tsvetkov et al. 2018; Buta & Keel 2019; Szalai et al. 2019; Van Dyk et al. 2019).

Archival Hubble Space Telescope (HST) and Large Binocular Telescope images of NGC 6946 enabled the identification of SN 2017eaw’s progenitor as an estimated 11–13 M⊙ RSG (Van Dyk et al. 2017; Johnson et al. 2018; Kilpatrick & Foley 2018; Rui et al. 2019). In addition, archival Spitzer imaging also showed that the progenitor was surrounded by a dusty T = 960 K shell at 4000 R⊙ (Kilpatrick & Foley 2018).

Late-time, nebular-phase CSM interactions have been reported for a few SNe II-P. The optical signature of a SN’s interaction with surrounding CSM is the appearance of a boxlike or horned Hα emission feature as the outer layers of hydrogen-rich ejecta are heated by radiation from the forward shock colliding with the CSM (Chevalier & Fransson 2003, 2006, 2017; Milisavljevic et al. 2012). Boxlike or flat-topped emission profiles result from ejecta colliding with shells of CSM, while horned profiles result from collisions with CSM disks (Gerardy et al. 2000; Jerkstrand 2017). The timescale at which the collision occurs allows one to determine the radius of the CSM shell or disk, while the Hα velocity width gives information about the CSM density, as denser CSM will decelerate the ejecta more resulting in narrower emission (e.g., Kotak et al. 2009; Andrews & Smith 2018).

Signatures of ejecta–CSM interactions have been observed in a few SNe II-L/P before ∼500 days: SN 2007od (Andrews
et al. 2010), SN 2004dj (Andrews et al. 2016), PTF11iqb (Smith et al. 2015), SN 2011ja (Andrews et al. 2016), SN 2013by (Black et al. 2017), and SN 2017gmr (Andrews et al. 2019). However, boxlike emission profiles indicating ejecta–CSM interaction with CSM shells have only been observed for four SNe II-P, and in these cases the ejecta–CSM interaction was observed after ~785 days: SN 2004et (Kotak et al. 2009; Maguire et al. 2010), SN 2008jb (Prieto et al. 2012), SN 2013ej (Mauerhan et al. 2017), and iPTF14hls (Andrews & Smith 2018; Sollerman et al. 2019).

Boxlike and horned profiles have been observed more commonly in other types of core-collapse supernovae; for example in Type IIn: SN 1998S (Gerardy et al. 2000), SN 2005ip (Smith 2017), and SN 2013L (Andrews et al. 2017), Type I Ib: SN 1993J, (Matheson et al. 2000a, 2000b), SN 2011dh (Shivvers et al. 2013), and SN 2013df (Maeda et al. 2015) and Type II-L: SN 1980K (Fesen & Becker 1990). SN 1993J, the prototypical SN Ibb, shows boxy Hα emission starting at day +669 which lasts until at least day +2500 (Matheson et al. 2000a, 2000b).

In this paper we present optical spectroscopy of SN 2017eaw at +545 and +900 days after explosion. We found significant changes in spectral evolution between these two epochs indicative of late-time ejecta–CSM interaction. The observations are presented in Section 2 with the results and discussion presented in Section 3. Our conclusions are summarized in Section 4.

2. Observations

As part of an optical survey of recent core-collapse SNe in nearby galaxies, we obtained photometric and spectroscopic observations of SN 2017eaw in NGC 6946. Using the Hiltner 2.4 m telescope at MDM Observatory equipped with the Ohio State Multi-Object Spectrograph (OSMOS; Martini et al. 2011) and an ITL 4064 × 4064 CCD, R-band photometry was obtained on 2018 November 7, December 14 and 2019 May 3. Additional photometric observations using an R-band filter that approximately matches the HST WFPC2 F675W filter were obtained on 2019 September 30 and October 28. The F675W is a broadband red continuum filter covering the majority of the same emission features as a standard R-band filter, but with greater sensitivity of the weak, broad [Ca II] and [O II] emission blend. Below, we treat F675W images as roughly equivalent (±0.25 mag) to images taken in R band. Observations were reduced using the OSMOS4 imaging reduction pipeline in Astropy (Astropy Collaboration et al. 2013, 2018). Standard methods of aperture photometry were followed in combination with data from Buta & Keel (2019) to calibrate our images and measure magnitudes of SN 2017eaw.

Optical spectra of SN 2017eaw were taken on 2018 November 7–9 using OSMOS and a 1″ wide slit with a red volume phase holographic (VPH) grism. Exposure times were 3000 s or 4000 s. Observations were reduced using the OSMOS spectral reduction pipeline in Astropy (Astropy Collaboration et al. 2013, 2018) and calibrated using Hg and Ne lamps and spectroscopic standard stars (Oke 1974; Musse & Gronwall 1990). To improve the signal to noise of the final spectrum, three individual observations were combined to a single 11,000 s exposure. We adopted a time since explosion of +545 days, using the average date of the three individual exposures: 2018 November 8.

R-band images of NGC 6946 taken in early Fall 2019 revealed SN 2017eaw was still visible. Using the MMT 6.5 m telescope equipped with Binospec (Fabricant et al. 2019), we obtained a spectrum on 2019 October 29, approximately +900 days after explosion. Observations consisted of 3 × 1260 s exposures with a 1″ slit and the 270 line grating with 1″23 seeing and thin cirrus. Data were reduced using the Binospec pipeline (Kansky et al. 2019) and calibrated with Ne lamps and night sky lines, and flux calibrated with standard star observations.

3. Results and Discussion

SN 2017eaw’s evolution followed that of a standard Type II-P supernova before day ~+500 with similar photometric and spectroscopic properties to SN 2004et (Rho et al. 2018; Tsvetkov et al. 2018; Buta & Keel 2019; Rui et al. 2019; Szalai et al. 2019; Tnyanont et al. 2019; Van Dyk et al. 2019). There was little evidence of CSM interaction for SN 2017eaw in all previously published results, which cover SN 2017eaw’s evolution up to day +594. A small and brief magnitude increase was observed in the optical light curve of SN 2017eaw 6–10 days after explosion, similar to that observed in SN 2012aw, which has been attributed to CSM interaction (Szalai et al. 2019). There was also a weak narrow Hα emission feature which only appeared in the 1.4 day spectrum (Rui et al. 2019).

The +545 day nebular-phase spectrum of SN 2017eaw shown in Figure 1 is dominated by ejecta emission lines with strong Hα 6563 Å, [O I] 6300, 6364 Å, and blended [Ca II] 7291, 7323 Å and [O II] 7320, 7330 Å emission. The spectral shape and observed emission lines closely resemble the +482 and +490 day spectra, but the flux has decreased by approximately 50% (Szalai et al. 2019; Van Dyk et al. 2019). Other strong line emissions are marked in Figure 1, which agree with other nebular-phase emission spectra for SNe II-P (e.g., Jerkstrand et al. 2012; Silverman et al. 2017; Van Dyk et al. 2019).

The [O I] and blended [Ca II] + [O II] emission are asymmetric with blueshifted emission profiles. The [O I] 6300 Å emission peaks on the blue side at −600 km s⁻¹ while on the red side the peak is at 3000 km s⁻¹. For the blended [Ca II] + [O II] feature, the emission peaks at −1600 km s⁻¹, with a red component at approximately 2000 km s⁻¹. Modeling this blended profile as two components, one red and one blue, the blue component contained 60% of the total flux. The asymmetries and the shifted emission profiles indicate the presence of dust in the oxygen-rich ejecta layers, in agreement with dusty progenitors suggested by Khan (2017), Kilpatrick & Foley (2018), Szalai et al. (2019), and Van Dyk et al. (2017, 2019).

Further evidence for dust in SN 2017eaw’s ejecta is indicated by Spitzer infrared observations up to +560 days post explosion, from which dust masses of 10⁻⁴ M☉ of silicate dust and 10⁻⁵ M☉ of carbonaceous dust were estimated.

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4 https://github.com/jrthorstensen/thorosmos

5 We adopted an expansion date of 2017 May 12.2 (JD 2,457,885.7, Van Dyk et al. 2019) throughout this paper, which is approximately one day earlier than the value used in Rui et al. (2019) and Szalai et al. (2019).
Tinyanont et al. 2019). This amount of dust is 100–10,000 times smaller than model predictions for SNe II-P. However, more dust may form over time and/or the dust may have formed quickly and currently be obscured such that the observed dust mass would increase over time as it becomes more optically thin (Tinyanont et al. 2019).

3.1. Ejecta–Circumstellar Interaction

Our +900 day spectrum shown in Figure 1 revealed a drastic change in the supernova’s optical spectrum. The Hα emission now appears broad and boxlike, while the [O I] and [Ca II] + [O II] blend have broadened but decreased in relative strength compared with Hα. The Hα emission may have some contamination from [N II] 6548, 6583 Å, although we view this as unlikely for a Type II-P (see Section 3.2). In addition, weak, blended, and broad Hβ and [O III] emission are also present. The narrow emission features from the blends of Fe II below 6000 Å are no longer visible and neither is the blend of Fe I, Fe II, Ba II at approximately 6100 Å. The significant changes to the Hα and [O I] emission profiles is highlighted in Figure 2.

The boxy Hα profile is strong evidence of ejecta–CSM interaction. The emission extends between approximately −8000 and +7500 km s$^{-1}$. The fact that this boxlike feature is so broad (HWZI $\sim$ 8000 km s$^{-1}$) suggests that the highest velocity ejecta are running into high-density CSM before the ejecta become optically thin. Further, the flat-top of this feature indicates the CSM is a thick shell rather than a disk or torus which would have horn-like emission profiles with increased emission at the highest velocities (Gerardy et al. 2000; Jerkstrand 2017).

The larger bumps in the otherwise flat-topped Hα profile appear to be real, as they are stronger and wider than simply noise on top of the flat emission profile. These features may indicate either clumpy ejecta interacting with a thick shell of CSM material, or smooth ejecta interacting with a clumpy shell of CSM emission (Gerardy et al. 2000; Jerkstrand 2017).
We can constrain the approximate epoch for ejecta–CSM interaction via the R-band light-curve evolution, as shown in Figure 3. The late-time nebular-phase R-band evolution between days +290 and +564 followed a decay rate of $1.469 \pm 0.031$ mag (100 day)$^{-1}$ (Buta & Keel 2019). However, at +721 days, SN 2017eaw had an observed R-band magnitude of 21.73 $\pm$ 0.25 indicating a change in the decay rate. Between +720 and 871 days the light curve was flat with a slight decrease $\approx 0.1$ mag between +871 and +899 days. No observations were obtained between +590 and +721 days, as SN 2017eaw was behind the Sun. Pre-explosion HST images of the SN 2017eaw site indicate that no bright optical sources are located within a radius of 2\" (Van Dyk et al. 2019), meaning that late-time measurements do not have significant contributions from underlying host emission.

One can calculate the electron density, $n_e$, of the ionized hydrogen ejecta, from the recombination time $\tau_r = (\alpha_{A} n_{e})^{-1}$, where $\alpha_{A}$ is the recombination coefficient of hydrogen. Assuming a temperature of 10,000 K and a recombination time of 100 days, the electron density is $2.77 \times 10^{5}$ cm$^{-3}$. We choose a recombination time of 100 days, as the light-curve data indicates a flattening between day +581 and +721. However, as we have no spectral data between day +545 and +900, the recombination time could be somewhat longer.

We can also estimate the mass within the ionized hydrogen using

$$M_{\text{H}} = \frac{m_p4\pi d^2F_c(H_\alpha)}{h\nu_{H_\alpha}\alpha_{\text{eff}}(H_0, T_e)N_e},$$

where $m_p$ is the mass of the proton, $F_c(H_\alpha)$ is the extinction corrected H$\alpha$ flux, $h\nu_{H_\alpha}$ is the energy of an H$\alpha$ photon, and $\alpha_{\text{eff}}(H_0, T_e)$ is the effective recombination coefficient of H$\alpha$ (Melnik & Copetti 2013). Using the electron density found from recombination, the extinction corrected flux of 2.3 $\pm$ 0.3 $\times$ 10$^{-14}$ erg s$^{-1}$ cm$^{-2}$, a distance to NGC 6946 of 7.73 $\pm$ 0.78 Mpc (Van Dyk et al. 2019), we estimate $\sim 1.9 M_\odot$

of ionized hydrogen ejecta. This estimate is in agreement with SNe II-P/II-L hydrogen mass envelope estimates which range from 1 to 10 $M_\odot$ (Cappellaro & Turatto 2001), while more recent classifications have defined SN II-P explosions as having hydrogen envelope masses as low as $M_H \geq 0.3 M_\odot$ (Limongi 2017). This is a lower limit on the mass of the hydrogen envelope as we assumed the entire hydrogen envelope was fully ionized to make the initial density estimate. If, however, it is only partially ionized, then the mass of the hydrogen envelope would be higher.

3.2. Similarities to SN 2004et and SN 2013ej

A few other SNe II-P observed late in the nebular phase have also shown boxlike H$\alpha$ profiles indicating ejecta–CSM interactions. These include SN 2004et (Kotak et al. 2009; Maguire et al. 2010), SN 2008jb (Prieto et al. 2012), SN 2013ej (Mauerhan et al. 2017), and iPTF14hls (Andrews & Smith 2018; Sollerman et al. 2019). Boxlike emission profiles were first observed on day +823 for SN 2004et, on day +788 for SN 2008jb (Prieto et al. 2012), on day +807 for SN 2013ej (Mauerhan et al. 2017), and on day +1153 for iPTF14hls (Andrews & Smith 2018).

Figure 4 shows a comparison SN 2017eaw’s spectrum at day +900 with SN 2004et at day +933 (top panel) and SN 2013ej at day +807 (bottom panel), while Figure 5 shows the H$\alpha$ emission feature for these three SNe in terms of radial velocity. The spectra of SN 2017eaw and SN 2004et showed nearly identical width broad, boxlike H$\alpha$ emission with the same relative strength of [O I] relative to continuum. In addition, the [O I] emission profiles have very similar widths and similar blueshifted emission profiles. For SN 2013ej, its H$\alpha$ emission on the red side was broader than SN 2017eaw and its [O I]/H$\alpha$ ratio was stronger than that observed for SN 2017eaw. SN 2004et had an H$\alpha$ emission profile with a HWZI of $\sim 8500$ km s$^{-1}$ (Kotak et al. 2009), while SN 2013ej had a HWZI of $\sim 9000$ km s$^{-1}$ (Mauerhan et al. 2017). iPTF14hls and SN 2008jb, (not shown in these figures) had HWZI’s of $\sim 1500$ km s$^{-1}$ (Andrews & Smith 2018) and $\sim 8000$ km s$^{-1}$ (Prieto et al. 2012), respectively.

SN 2017eaw’s boxy H$\alpha$ emission also resembles the boxy emission from the Type Iib SN 1993J at day +975 (Matheson et al. 2000a, 2000b) as shown in Figure 6. Compared with SN 2017eaw, SN 1993J’s oxygen-rich ejecta emission are weaker compared with its H$\alpha$ emission. For SN 1993J the boxy H$\alpha$ emission was clearly observed as early as day +300 (Finn et al. 1995), when [O I] and H$\alpha$ emission were equal in strength. The [O I] emission faded more rapidly compared with the H$\alpha$ emission in SN 1993J. The H$\alpha$ emission of SN 1993J is slightly wider than that observed for SN 2017eaw, but also relatively flat.

We note that SN 1993J’s boxlike H$\alpha$ emission feature has been modeled as having a significant contribution from [N II] at these late times due to the low hydrogen envelope mass in SN Iib events (Jerkstrand et al. 2014). However, we do not believe SN 2017eaw’s H$\alpha$ emission profile is likely due to [N II] 6548, 6583 $\AA$ emission as the hydrogen envelope is more massive for Type II-P events than a stripped envelope SNe like SN 1993J, and it is this outer H-rich layer that would be interacting with the CSM rather than the He and N rich ejecta as in the case of a SN Iib.
We now focus on comparing SN 2017eaw with SN 2004et and SN 2013ej, which show comparable expansion velocities and time frames for CSM interaction. Unlike what is observed for both SN 2004et and SN 2013ej, the Hα profile of SN 2017eaw appears virtually flat, with no hint of decreased flux on the receding red side compared with those on the near blue facing side (e.g., Mauerhan et al. 2017). This suggests that there is not a significant amount of dust in the CSM or ejecta which would absorb the emission from the far side of the supernova. Furthermore, SN 2017eaw does not show multiple broad peaks in its Hα profile like those observed for SN 2004et and SN 2013ej (Kotak et al. 2009; Mauerhan et al. 2017).

The Hα luminosity of SNe II-P can be used to determine the ejecta nickel mass based on the well-modeled exponential decay rate in the nebular phase (e.g., Chugai 1990). Following the plateau phase, the Hα luminosity of SN 2017eaw, SN 2004et, and SN 2013ej exponentially declined until CSM interaction is observed in their spectra; see Figure 7. The Hα luminosities were measured from previously published spectra of SN 2004et (Sahu et al. 2006; Kotak et al. 2009) and

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6 We choose not to include SN 2008jb in our comparison, as the +788 day spectrum had a chip gap fall in the middle of the Hα profile (Prieto et al. 2012).

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Figure 4. A +900 day spectrum of SN 2017eaw (black) compared with late-time spectra of the other two SN II-P showing boxlike profiles: SN 2004et (top blue, Kotak et al. 2009) and SN 2013ej (bottom red, Mauerhan et al. 2017). The spectra have been normalized and a small constant was added to SN 2013ej so that the normalized continuum emission below 6000 Å was approximately equal to SN 2017eaw. SN 2004et and SN 2013ej spectra were obtained from the WISEREP (Yaron & Gal-Yam 2012).

Figure 5. Hα line emission relative to expansion velocity for SN 2017eaw (black), SN 2004et (blue, dashed) and SN 2013ej (red, dashed–dotted). All three SNe have boxlike Hα emission profiles that rise at \( \sim -8000 \) km s\(^{-1}\). SN 2017eaw and SN 2004et emission extends to \( \sim 7500 \) km s\(^{-1}\), while SN 2013ej extends further to the red to approximately 10,000 km s\(^{-1}\). Note that the blue side of the Hα emission feature overlaps with the red side of the [O I] 6300, 6364 Å emission.

Figure 6. Hα line emission relative to expansion velocity for SN 2017eaw (black) and the Type IIb, SN 1993J (red, Matheson et al. 2000a, 2000b). The spectra have been normalized such that continuum emission to the red of Hα is approximately equal. Note: the blue side of the Hα emission feature overlaps with the red side of the [O I] 6300, 6364 Å emission. The SN 1993J spectrum was obtained from the WISEREP (Yaron & Gal-Yam 2012).
Interestingly, the size of this CSM shell is similar to the $8 \times 10^{16}$ cm shell estimated for SN 2004et (Kotak et al. 2009). Assuming a typical RSG wind speed of 10 km s$^{-1}$, the mass-loss episode responsible for this material would have had to occur $\sim$1700 yr before SN 2017eaw exploded.

Due to long-term monitoring of NGC 6946 for SNe or failed supernovae, there exists archival optical and infrared images of SN 2017eaw’s progenitor for nine years prior to explosion. The progenitor showed little variability, ruling out eruptive mass-loss episodes for approximately a decade prior to explosion (e.g., Johnson et al. 2018; Tinyanont et al. 2019). The CSM around SN 2017eaw was likely sculpted by photoionized trapped RSG wind with similar to structure to that observed around Betelgeuse, with estimated mass-loss rates of $M \sim (0.9–5) \times 10^{-6} M_{\odot}$ yr$^{-1}$ for SN 2017eaw (Kilpatrick & Foley 2018; Tinyanont et al. 2019).

To exhibit boxlike emission features, the cooling time must be shorter than the adiabatic timescale to enable the formation of the CDS behind the reverse shock (Chevalier & Fransson 2003, 2006, 2017; Kotak et al. 2009). From an analysis of SN 2017eaw, like that done for SN 2004et, we estimate the cooling time as $t_c = 4.6 \times 10^{-3} (M_5/\nu_{w1})^{-1} v_{sa}^{3.4} d^{2}$ days, where $M_5$ is the mass-loss rate in units of $10^{-5} M_{\odot}$ yr$^{-1}$, $\nu_{w1}$ is the wind velocity in units of 10 km s$^{-1}$ and $v_{sa}$ is the ejecta velocity in units of 10$^4$ km s$^{-1}$ (Chevalier & Fransson 2003; Kotak et al. 2009). Since the boxlike emission was present in SN 2017eaw’s day $+900$ spectrum, the shock must still be radiative. Using the width of the H$\alpha$ emission for units of $10^5$ km s$^{-1}$ and the typical RSG wind speeds of $10^4$ km s$^{-1}$, we estimate the mass-loss rate of the progenitor as $M \approx 3 \times 10^{-6} M_{\odot}$ yr$^{-1}$ in agreement with previous results derived from X-ray luminosities shortly after outburst and progenitor SED analysis (Kilpatrick & Foley 2018; Tinyanont et al. 2019).

### 3.4. Frequency of SNe II-P Showing Late-time CSM Interactions

Analysis of 38 SNe II-P in the nebular phase up to day $+500$ did not find any showing boxlike emission profiles (Silverman et al. 2017). This raises the question of whether bright Type II-P objects like SN 2004et, SN 2008jb, SN 2013ej, and SN 2017eaw, which have observations past day $+500$, are unique in showing interaction or if there is simply an underlying observational bias of too few very late-time observations.

Since the majority of SNe II-P are not observed 2–3 yr after explosion, some or maybe most, may undergo similar CSM interactions and we simply have not realized it due to a lack of very late-time observations. To answer the question, more SNe II-P events need to be studied in the 2–3 yr time frame. We note that all four cases where late-time CSM interactions were observed, the SNe II-P were relatively bright which helped the feasibility of late-time ground based optical follow-up: SN 2017eaw reached $V = 12.8$ mag, SN 2013ej reached 12.5 mag, SN 2008jb reached 13.6 mag, and SN 2004et reached 12.6 mag.

Consequently, it is worthwhile to photometrically and spectroscopically follow the next bright SN II-P event. Moreover, as SN 2004et is still visible (Long et al. 2019), other bright SN II-P events with similar ages should be looked at again to investigate if they might also still be visible. Although any late-time emission, if present, will be quite faint, such
additional late-time detections will give us useful information to better understand the CSM environments around SNe II-P.

4. Conclusions

SN 2017eaw’s optical spectrum dramatically evolved between day +545 and +900, developing a boxlike, flat-topped Hα emission profile, indicative of ejecta–CSM interaction. The Hα emission at day +900 dominated the spectrum relative to the oxygen-rich ejecta emission which was strong in earlier phase spectra. SN 2017eaw is just the third SN II-P with observed ejecta–CSM interaction with boxlike emission profiles after +500 days. However, unlike the other late-time SNe II-P spectra, SN 2017eaw showed a fairly flat-topped profile indicating little dust is present in the CSM shell.

Given the similarity of SN 2017eaw’s evolution with that of SN 2004et up to day +900, we can predict some of SN 2017eaw’s future spectroscopic evolution. Spectra of SN 2004et taken at 10.2 yr resembled its day +933 spectrum, in that broad, boxlike Hα emission was still observed while oxygen emission increased in relative strength to the Hα (Long et al. 2019). It is therefore likely that the broad Hα profile observed in the +900 day spectrum of SN 2017eaw will also still be sustained for several years to come. In any case, even if SN 2017eaw’s luminosity fades below practical spectroscopic levels, continued photometric monitoring of its evolution would be worthwhile.

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