Searching for the Expelled Hydrogen Envelope in Type I Supernovae via Late-Time Hα Emission

J. Vinko1,2,3, D. Pooley4, J. M. Silverman1, J. C. Wheeler1, T. Szalai3, P. Kelly5, P. MacQueen1, G. H. Marion1, and K. Sárneczky2

1 Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA
2 Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Konkoly Thege ut 15-17, Budapest, 1121, Hungary
3 Department of Optics & Quantum Electronics, University of Szeged, Dom ter 9, Szeged, 6720, Hungary
4 Department of Physics and Astronomy, Trinity University, One Trinity Place, San Antonio, TX 78212, USA
5 Department of Astronomy, University of California at Berkeley, 501 Campbell Hall, Berkeley, CA 94720-3411, USA

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Abstract

We report the first results from our long-term observational survey aimed at discovering late-time interaction between the ejecta of hydrogen-poor Type I supernovae (SNe I) and the hydrogen-rich envelope expelled from the progenitor star several decades/centuries before explosion. The expelled envelope, moving with a velocity of ~10–100 km s⁻¹, is expected to be caught up by the fast-moving SN ejecta several years/decades after explosion, depending on the history of the mass-loss process acting in the progenitor star prior to explosion. The collision between the SN ejecta and the circumstellar envelope results in net emission in the Balmer lines, especially Hα. We look for signs of late-time Hα emission in older SNe Ia/Ibc/Ib/Ib with hydrogen-poor ejecta via narrowband imaging. Continuum-subtracted Hα emission has been detected for 13 point sources: 9 SN Ibc, 1 SN Iib, and 3 SN Ia events. Thirty-eight SN sites were observed on at least two epochs, from which three objects (SN 1985F, SN 2005kl, and SN 2012bh) showed significant temporal variation in the strength of their Hα emission in our Direct Imaging Auxiliary Functions Instrument (DIAFI) data. This suggests that the variable emission is probably not due to nearby H II regions unassociated with the SN and hence is an important additional hint that ejecta–circumstellar medium interaction may take place in these systems. Moreover, we successfully detected the late-time Hα emission from the Type Ib SN 2014C, which was recently discovered as a strongly interacting SN in various (radio, infrared, optical, and X-ray) bands.

Key words: supernovae: general – shock waves – stars: winds, outflows – H II regions

1. Introduction

All stars are thought to lose mass during their main-sequence and subsequent evolution. This can range from a paltry stellar wind like that from the Sun (10⁻¹⁴ M☉ yr⁻¹) to the slow, dense winds of red giants (10⁻⁸–10⁻⁷ M☉ yr⁻¹) to brief, violent, η Carinae–like expulsions of tens of solar masses from very massive stars. At different stages of evolution, a star will undoubtedly have different modes of mass loss. Binary evolution will play a role in many cases.

While it is impossible to study these different modes of mass loss in an individual star in real time, we can do so by studying individual supernovae (SNe) for years and even decades after explosion. The fast-moving SN shock is effectively a time machine, encountering material shed earlier in the life of the pre-SN star.

Recent years have seen a new focus on the circumstellar media (CSM) surrounding SN sites and the interaction of SN ejecta and shocks with the CSM. Well-known CSM-interacting SN types are Type IIP (Chugai et al. 2007), which arises in red supergiant progenitors that blow nearly steady-state winds into which the star explodes, and Type Ibn (SN Ibn) events, which have long been recognized as showing narrow emission lines that reveal dense CSM (e.g., Filippenko 1997). In addition, the great luminosities of superluminous supernovae (SLSNe) are also thought to be powered, in some cases, by ejecta-CSM interaction (Chatzopoulos et al. 2013).

The various types of stripped-envelope SNe are also of great interest in this respect because, though these events have little or no hydrogen on the progenitor at the time of explosion, the progenitors must have once been normal hydrogen-rich stars. Such events include the SNe Ibc, in which the hydrogen envelope has been partly expelled prior to explosion, as well as the SNe Ibn, which essentially lost their H-rich envelope. The mechanism of these processes is poorly understood: it could be due to winds (Heger et al. 1997; Puls et al. 2008), episodic ejection (Smith & Owocki 2006; Pastorello et al. 2007; Shiode & Quataert 2014), or binary interactions, including common-envelope formation and ejection (see the reviews by Taam & Sandquist 2000; Smith 2014). Even some SNe Ia, referred to as SNe Ia-CSM, show strong Hα emission, a clear sign of CSM interaction, in their late-phase optical spectra (Silverman et al. 2013a; Inserra et al. 2016).

The collision between the fast-moving SN ejecta and the slow-moving CSM creates the well-known double-shock pattern with the forward shock (FS) propagating into the CSM and the reverse shock (RS) propagating back into the ejecta (e.g., Chevalier & Fransson 2003, p. 171, and references therein). The acceleration of free electrons results in strong nonthermal emission, from X-rays to radio, coming from the interaction site. Massive SN progenitors (M ≳ 20 M☉) can produce strong, fast-moving winds prior to explosion, which can create a low-density cavity around the explosion site surrounded by a relatively dense CSM shell consisting of previously expelled (H-rich) material (e.g., Chevalier & Liang 1989). When the SN ejecta hit this dense shell, it drives a strong RS into the ejecta, which leads to strong X-ray radiation from the region between the RS and the ejecta-CSM interface (Nynmark et al. 2006). The hard X-rays produced by the RS are mostly absorbed by the cool, dense CSM shell,
causing strong ionization in this medium. Subsequent recombination in this H-rich CSM shell results in emergent emission in the hydrogen Balmer lines, mostly Hα (Chugai & Chevalier 2006). This mechanism is thought to produce intermediate-width (FWHM $\sim$ 2000–3000 km s$^{-1}$) emission lines, mostly due to multiple scattering on free electrons within the shell and, to a lesser extent, bulk motion caused by the acceleration of the shell by the expanding SN ejecta at the beginning of the interaction phase. The FS propagating into the CSM can also ionize the surrounding material, which may produce additional, narrow (FWHM $\lesssim$ 100 km s$^{-1}$) Hα emission from the preshock CSM in front of the FS. The appearance of the Balmer emission can be especially interesting in the case of stripped-envelope SNe, since in such cases the ejecta contain only very low or negligible amounts of H. Thus, the emerging Balmer emission is a very strong indication that the ejecta have overrun the cavity and plunged into the H-rich CSM shell.

The natural expectation that the fast-moving SN ejecta must overtake the previously expelled H-rich envelope has been beautifully demonstrated in the case of the Type Ibc SN 2001em, where strong radio (Stockdale et al. 2004) and X-ray (Pooley & Lewin 2004) emission was discovered $\sim$3 years after explosion. These discoveries generated further interest in SN 2001em, because the radio luminosity ($L_{\text{radio}} \approx 2 \times 10^{28}$ erg s$^{-1}$ Hz$^{-1}$ at 6 cm) and X-ray luminosity ($L_{\text{X}} \approx 10^{41}$ erg s$^{-1}$) were far above anything seen from other SNe Ibc at an age of several years. Since some fraction of SNe Ibc give rise to gamma-ray bursts (GRBs) where the jet is aimed in our direction, it was hypothesized by Granot & Ramirez-Ruiz (2004) that SN 2001em may have been an off-axis GRB. Pooley & Lewin (2004), however, suggested the strong interaction between the SN ejecta and a dense CSM as an alternative mechanism that can also produce the exceptionally strong X-ray luminosity as observed by Chandra. Indeed, the late-time optical spectrum of SN 2001em, which revealed strong Hα emission (Soderberg et al. 2004), added strong support to the ejecta-CSM interaction scenario. Chugai & Chevalier (2006) explained all the unusual late-time X-ray, radio, and optical properties, as well as the failure to resolve a possible jet via Very Long Baseline Interferometry (VLBI) observations (Bietenholz & Bartel 2005; Schinzel et al. 2009), by suggesting that the SN ejecta had finally caught up with the cast-off hydrogen envelope of the progenitor star and that strong interaction was taking place.

A similar phenomenon is invoked in the case of PTF 11kx (Dilday et al. 2012; Silverman et al. 2013b), a Type Ia-CSM, where strong Hα emission developed $\sim$40 days after maximum in an otherwise normal-looking SN Ia.

Motivated by the examples above, we started an observational survey to monitor several years-to-decades-old H-deficient SNe in order to catch signs of the starting (or ongoing) ejecta-CSM interaction. Our concept is that numerous SNe Ia and/or Ibc may show detectable CSM interaction at such late phases because their CSM shells may have reached greater distances from the explosion site than in those well-known cases in which the interaction started within a few hundred days after explosion. Assuming that the H-rich envelope travels with a speed between 10 and 100 km s$^{-1}$ (Chugai & Chevalier 2006), the interaction with the fast-moving ejecta ($v_{\text{SN}} \sim 10,000$ km s$^{-1}$) is expected to start roughly a decade after SN explosion if the expulsion of the envelope ended $\sim$10$^4$–10$^5$ yr before core collapse, depending on wind speed.

The aim of our observations is the direct detection of the Hα emission due to the collision between the H-poor SN ejecta and the surrounding H-rich CSM via imaging the SN sites through narrowband filters centered on the (redshifted) wavelength of Hα. In Sections 2 and 3, we give details of the observations and our methodology of detecting Hα emissions. Section 4 shows our early results, which are further discussed in Section 5. Section 6 summarizes our conclusions.

### 2. Observations

We utilized the 2.7 m (107 inch) Harlan J. Smith Telescope equipped with the Direct Imaging Auxiliary Functions Instrument (DIAFI) at McDonald Observatory to conduct the imaging survey. We applied a narrowband (FWHM = 7 nm) Hα filter centered on the redshift of the Virgo cluster ($z = 0.0033$, $\lambda = 6585$ Å) and another similar filter at an off-line position ($\lambda = 6675$ Å) as a guardband filter to measure the continuum flux near the Hα line. In the following, we refer to these filters as Hα-on and Hα-off, respectively.

We have selected a subsample of the full list of 3662 known SNe I (SNe Ia, SNe Ibc) and SNe IIb discovered before 2014 based on the following selection criteria:

1. decl. higher than $-30^\circ$;
2. distance less than 200 Mpc.

This resulted in 747 potential candidates. These are sampled further, concentrating on the closest ($D \lesssim 30$ Mpc) events. The number of SNe in the restricted sample is 178.

Besides observability from the northern hemisphere, the reasons for these selection criteria were twofold: (i) to have the Hα line redshifted into the transmission band of the Hα-on filter, and (ii) to be able to reach a signal-to-noise ratio ($S/N$) of $\sim$50 for $L(\text{H}\alpha) \sim 10^{39}$ erg s$^{-1}$ (i.e., a signal similar to that of SN 2001em) within $\sim$1 hr exposure time with DIAFI.

We started our multiseason observing campaign in 2014 using both the Hα-on and the Hα-off filters on the SNe with $D < 30$ Mpc. Since then, we have imaged 76 galaxies hosting 99 SNe, i.e., $\sim$55% of the total sample. The journal of the observations can be found in Table 1.

The Hα emission produced by SN-CSM interaction is likely to be variable in time. This offers an opportunity to distinguish between the “real” interaction-produced emission and the flux coming from the immediate vicinity of the SN site but not related to the SN blast wave (e.g., from a nearby H ii cloud), because the latter sources are expected to remain roughly constant in time. Thus, instead of maximizing the number of observed SNe, we aimed at taking multiple images of those SNe that were detected as Hα emitters at significantly different

| Start Date | End Date | No. of Observed SN Hosts |
|------------|----------|--------------------------|
| 2014 Feb 27 | 2014 Feb 28 | 22 |
| 2014 May 03 | 2014 May 04 | 17 |
| 2014 Sep 30 | 2014 Oct 02 | 23 |
| 2015 Mar 14 | 2015 Mar 16 | 27 |
| 2015 May 20 | 2015 May 20 | 7 |
| 2015 Aug 23 | 2015 Aug 23 | 4 |
| 2016 Jun 07 | 2016 Jun 10 | 17 |
epochs. This effort resulted in 38 SNe (in 32 different host galaxies) imaged at least twice, separated by a 3-month-long or longer temporal baseline.

3. Method

The frames taken with DIAFI were reduced and calibrated in the following way. Three frames per filter were collected for each SN. Following standard bias subtraction and flat-field division, the frames obtained through the same filter were geometrically registered by applying the IRAF task \texttt{xregister}, then they were median-combined to filter out the numerous cosmic-ray hits. The median-combined frames were then transformed to the World Coordinate System (WCS) by using the \texttt{SExtractor} and \texttt{WCSTools} codes. With the combined images properly registered in both filters, the \texttt{HOTPANTS} code was applied to subtract the H\textalpha-off frames from the H\textalpha-on frames to produce the continuum-subtracted difference images. These images were used to look for any H\textalpha-emitting source in the immediate vicinity of the SN, as described below.

Flux calibration was performed via observing spectroscopic flux standard stars. We measured the observed count rates on the median-combined H\textalpha-on and H\textalpha-off frames via aperture photometry using the YODA \texttt{code} (Yet anOther object Detection Application) (Dror 2003). The diameter of the circular aperture was chosen as $d_{ap} = 15$ pixels ($\sim 0.61$ arcsec), and the fluxes within this aperture were integrated. The subtracted background flux was estimated within an annulus with an inner diameter and a width of 20 and 5 pixels, respectively, around each object. The correction for the atmospheric extinction was computed using the wavelength-dependent Kitt Peak National Observatory (KPNO) extinction function as tabulated in IRAF, although this was found to be negligible compared to other uncertainties. For the observed spectroscopic standard stars, the true H\textalpha fluxes were calculated as the integral of their known spectral flux densities within the spectral bandpasses of the applied filters. Finally, the conversions between the observed count rates (CRs, in ADU s$^{-1}$) and the true H\textalpha fluxes for both filters have been determined by fitting the following simple relation to the data:

$$ F_{\text{H\alpha}} \times 10^{13} \text{ (erg s}^{-1} \text{ cm}^{-2}) = K \cdot \text{CR (ADU s}^{-1}) $$

Figure 1 illustrates the quality of the fit. The $K$ scaling factors obtained this way turned out to be $1.03 \times 10^{-2}$ and $1.26 \times 10^{-3}$ for the H\textalpha-off and H\textalpha-on filters, respectively. The uncertainties of the flux calibration, estimated from the scatter of the residual plots in the bottom panel of Figure 1, are $1.89 \times 10^{-2}$ and $2.38 \times 10^{-2}$ erg s$^{-1}$ cm$^{-2}$.

The continuum-subtracted H\textalpha flux at the position of every target SN was estimated by the combination of two approaches. First, aperture photometry (using the same parameters as above) was computed with YODA at the SN position on the continuum-subtracted difference frames produced by HOTPANTS. If the total flux in the aperture exceeded the local sky level, the S/N was estimated by dividing the total flux by its uncertainty reported by YODA. Objects with S/N $> 4$ were selected as detection candidates. Second, the detection candidates were examined by computing the same aperture photometry as before but on the final, median-combined H\textalpha-on and H\textalpha-off frames. After transforming the measured CRs to physical fluxes (applying Equation (1)), the net H\textalpha flux was computed by subtracting the calibrated fluxes of the H\textalpha-off frames from the fluxes measured on the H\textalpha-on images. Again, uncertainties were estimated by adopting the values as reported by YODA. Only those candidates that showed S/N $> 4$ after this step were retained as detections. This way, it was possible to filter out some bogus detections, which were due to numerical artifacts on the difference images given by HOTPANTS.

For those objects that were observed on more than one epoch, the effect of different atmospheric transparency was corrected for in the following way: the photometry of the bright, unsaturated stellar sources on the H\textalpha-off (continuum) frames was computed, and their instrumental magnitudes obtained on the second night were scaled to those taken on the first night. A similar transformation was then computed for the H\textalpha-on frames as well. This resulted in consistent relative photometry on the two data sets within an error of a few percent. These data were used to construct the H\textalpha “light curves” to look for temporal variability among the detected sources (see Section 4).

4. Results

We have detected (using the criterion of S/N $> 4$) continuum-subtracted H\textalpha emission from 27 SN sites (see Table 2). At least 14 of these detections ($\sim 50\%$) are clearly from diffuse H\textalpha-emitting sources, probably nearby H\textbeta areas. The others look like point sources in our DIAFI frames, but some of them appear slightly off-center with respect to the expected SN position and thus could just be nearby compact H\textbeta clouds. Figures 2 and 3 show the collection of positive detections.

\[\text{Figure 1. Flux calibrations for the H\textalpha-on (blue squares) and H\textalpha-off (red circles) filters.}\]
The third column of Table 2 contains the average of the redshift-independent distances taken from the NASA Extragalactic Database\textsuperscript{11} (NED). Based on these distances and the Milky Way extinction coefficient in the R-band from Schlafly & Finkbeiner (2011), the logarithms of the calculated H\textalpha luminosities and their uncertainties (expressed in erg s\textsuperscript{-1}) are shown in the fourth and fifth columns of Table 2. The (likely underestimated) uncertainties are pure photometric errors described above and do not contain any other effects, e.g., the uncertainty of the distances or any in-host extinction.

In Figure 4, we give an example of a strong (S/N > 200) detection on the continuum-subtracted image. SN 2005kl is the strongest H\textalpha-emitting object in our sample. Its H\textalpha luminosity, $L(H\alpha) \sim 7 \times 10^{41}$ erg s\textsuperscript{-1} (Table 2 and Figure 5), is about an order of magnitude greater than that of the largest H II clouds (Kennicutt 1984), which strongly suggests that the detected H\textalpha emission is (at least partly) due to SN-CSM interaction.

Figure 5 shows the plot of the derived H\textalpha luminosities as a function of distance. It can be seen that, on average, point sources tend to be brighter than diffuse sources (the median luminosities for the two groups are $8 \times 10^{38}$ erg s\textsuperscript{-1} and $2 \times 10^{38}$ erg s\textsuperscript{-1}, respectively), but both types of sources can be found at all luminosity levels, except for the exceptionally bright point source SN 2005kl.

Further hints of the possible presence of ejecta-CSM interaction may be gained from the temporal variability of the detected H\textalpha sources. SN-CSM interaction usually produces variable H\textalpha emission on the timescale of $\sim 100$ days (Mauerhan & Smith 2012; Fransson et al. 2014), although there are known cases, e.g., SN 1988Z, a strongly interacting Type IIn (Aretxaga et al. 1999), showing nearly constant H\textalpha luminosity over $\sim 500$ days. Nevertheless, we imaged 38 SNe on at least two epochs separated by at least 90 days to detect any variability in the net H\textalpha emission from the SN site.

In Figure 6, we plot the light curves of 10 detected H\textalpha emitters that were observed at least three times. It can be seen that six of them do not show any change that exceeds the uncertainties, although SNe 1981B, 2013dk, and 2014C exhibited continuous variation (either increase or decrease) during our observations. Flux changes exceeding the photometric errors significantly (i.e., larger than 3\sigma) were found in the case of SNe 1985F (Ib, 3.7\sigma), 2005kl (Ic, 8.1\sigma), 2010gi (Ib, 3.3\sigma), and 2012fh (Ic, 5.6\sigma). SN 2010gi, a SN Ib, is a diffuse source (Figure 3) that is more affected by the changing atmospheric conditions because the applied flux-scaling method that corrects for changing atmospheric transparency (see above) works reliably only for point sources. Thus, we do not believe that the variability detected at the position of SN 2010gi is real; instead, we attribute this to an instrumental effect. The other three objects are SNe Ibc, and they are all point sources; thus, their variability is more convincing. Again, variability of the H\textalpha-line flux alone cannot be considered as proof of ejecta-CSM interaction, but it might give additional support for this hypothesis—for example, in the case of the extremely strong H\textalpha emitter SN 2005kl, which is also a strongly variable source.

\textbf{5. Discussion}

Even though it is difficult to prove the existence of ejecta-CSM interaction from only narrowband imaging, without spectroscopic and/or multiwavelength (X-ray and/or radio) observations, our data at hand strongly suggest that CSM interaction is the likely explanation for the H\textalpha emission in at least a few of the SNe in our sample. The collision between the SN blast wave and the expelled, slowly moving H envelope can certainly produce H\textalpha emission in the same order of magnitude as observed, as already demonstrated by SN 2001em (Section 1).

SN 2004dk (Type Ib) is another example in which SN-CSM interaction was detected in X-rays by \textit{XMM-Newton} shortly after explosion (Pooley 2007) and by radio observations at late phases (Stockdale et al. 2009; Wellons et al. 2012). Although Wellons et al. (2012) concluded that “it is unlikely that the shockwave is interacting with a H-rich common envelope” based on a single nebular spectrum of SN 2004dk that showed only a weak, narrow, unresolved H\textalpha emission feature attributed to the interstellar medium (ISM) (Maeda et al. 2008), our solid (S/N $> 50$) detection of a strong point source at the SN position may suggest that the blast wave has finally reached the expelled H-rich envelope. The lack of variability (Figure 6), however, does not strengthen this interpretation; thus, follow-up observations will provide important constraints for this case.

A more recent example occurred during the progress of our project. After emerging from solar conjunction, the Type Ib SN 2014C started to show strong H\textalpha emission $\sim 110$ days after explosion, even though H was absent from its spectrum during the photospheric phase (Milisavljevic et al. 2015). Accompanied by contemporaneous strong X-ray and radio emission,

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
SN & Type & $D$ & log $L(H\alpha)$ & Unc. & Remark \\
& & (Mpc) & (erg s$^{-1}$) & (dex) & \\
\hline
1937D & Ia & 11.0 & 37.8135 & 0.0277 & point source \\
1979B & Ia & 17.0 & 37.9868 & 0.0070 & diffuse \\
1981B & Ia & 17.7 & 37.7577 & 0.0868 & diffuse \\
1983I & Ic & 14.0 & 38.6929 & 0.0048 & diffuse \\
1984L & Ib & 18.8 & 38.5064 & 0.0341 & diffuse \\
1985F & Ib & 7.6 & 38.6909 & 0.0121 & point source \\
1997br & Ia & 27.5 & 38.3376 & 0.0374 & diffuse \\
2000E & Ia & 23.9 & 38.8246 & 0.0231 & point source \\
2000cr & Ib & 57.6 & 39.5134 & 0.0272 & diffuse \\
2000ew & Ic & 17.6 & 39.6804 & 0.0647 & diffuse \\
2004ao & Ib & 26.9 & 38.0196 & 0.0664 & diffuse \\
2004dk & Ib & 22.8 & 39.1888 & 0.0272 & diffuse \\
2004gn & Ic & 14.4 & 38.2218 & 0.1629 & diffuse \\
2004gt & Ic & 21.4 & 40.0318 & 0.0109 & point source \\
2005V & Ib & 22.4 & 40.5150 & 0.0095 & diffuse \\
2005kl & Ic & 21.6 & 41.8452 & 0.0020 & point source \\
2007Y & Ib & 19.1 & 38.7186 & 0.0272 & diffuse \\
2007af & Ia & 24.3 & 38.7417 & 0.0676 & diffuse \\
2007gr & Ic & 8.2 & 38.4519 & 0.0120 & diffuse \\
2007uy & Ib & 30.0 & 39.2632 & 0.0115 & diffuse \\
2008ha & Ia & 20.0 & 38.2445 & 0.0684 & point source \\
2010gi & Ib & 10.2 & 38.4090 & 0.0635 & diffuse \\
2011jm & Ic & 22.2 & 39.5923 & 0.0030 & diffuse \\
2012fh & Ic & 16.4 & 38.8490 & 0.0008 & point source \\
2012P & Ib & 25.7 & 39.4327 & 0.0070 & point source \\
2013dk & Ic & 21.4 & 38.8910 & 0.0799 & point source \\
2014C & Ib & 14.3 & 38.8262 & 0.0527 & point source \\
\hline
\end{tabular}
\caption{List of Detected Objects and Their H\textalpha Luminosities (Computed in erg s$^{-1}$ Using the Distances in the Third Column)}
\end{table}

Note. See text for details.

\textsuperscript{11} http://ned.ipac.caltech.edu
this remarkable metamorphosis was explained by ejecta-CSM interaction (Margutti et al. 2017), the same mechanism for which we search.

We detected the appearance of the Hα emission from SN 2014C on our DIAFI frames taken between 2015 May and 2016 June (∼500 and ∼900 days after explosion, respectively). Figure 7 shows the continuum-subtracted DIAFI frames obtained on 2015 May 19 and 2016 June 07 (left and right panels, respectively), with the object circled in green. Its Hα luminosity (Table 2) is in agreement with the independent spectroscopic measurements given by Milisavljevic et al. (2015). This source seems to show continuously decreasing net (i.e., continuum-subtracted) Hα flux (see Figure 6), but, due to the relatively large error bars of its photometry, the detected overall flux change did not exceed 2σ during the ∼1 yr baseline of our observations.

More recently, SN 2014C was also detected as a variable point source in mid-IR bands with the Spitzer Space Telescope by the SPIRITS project (Tinyanont et al. 2016). Note that Tinyanont et al. (2016) observed an increase of the mid-IR fluxes from SN 2014C between 200 and 600 days after explosion, while our observations span only the later (t > 500 days) phases. The latest Spitzer observations from the SPIRITS project, partly published by Tinyanont et al. (2016), show a slow but continuous decline of mid-IR fluxes between ∼600 and ∼1000 days in both the 3.6μ and the 4.5μ bands, in agreement with our Hα observations.

Tinyanont et al. (2016) explained the observed rebrightening of SN 2014C in the mid-IR as due to shock heating (either radiative or collisional) of preexisting dust around SN 2014C, which is in good agreement with the observations in other bands, including our Hα detections. This highlights the importance of simultaneous observations in nonoptical bands in order to detect additional tracers of ejecta-CSM interaction that may discriminate between the different mechanisms producing the contemporaneous Hα emission.

The relatively low number of detected Hα-emitting point sources (13 out of 99 SNe, i.e., ∼13%) is more or less consistent with the recent estimate for the rate of the SN 2001em/2014C–like events published by Margutti et al. (2017) based on late-time rebrightening in the radio. From 41 SNe Ibc having radio coverage at t > 500 days after explosion, Margutti et al. (2017) found 4 cases (SN 2001em, SN 2003gk, SN 2007bg, and SN iPTF11qj, ∼10% of the sample) in which luminous radio rebrightening was observed years after core collapse. Since radio light curves are usually attributed to SN-CSM interaction, the emergence of radio fluxes at such late phases is a very strong sign of the ejecta-CSM collision. Their result (∼10%) is consistent with our detection rate (∼13%) when taking into account that at least some of our detected Hα emitters could also be compact H II areas very close to the SN site; i.e., the detected emission may not be due to ejecta-CSM interaction in every case.

Variability in the detected Hα-line emission can be another tracer for SN-CSM interaction, because H II clouds are usually close to ionization/recombination equilibrium and do not show noticeable variation in their emission-line strengths. On the contrary, existing models of ejecta-CSM interaction (e.g., Chugai & Chevalier 2006; van Marle et al. 2010) predict several forms of variability in the produced radiation. The most commonly accepted scenario is the close link between the X-rays produced by the RS and the Hα-line emission coming from the H-rich dense shell between the FS and the RS (see Section 1). Since the main source of the escaping Hα-line

**Figure 2.** Detections of significant (S/N > 4) Hα emission from the sample SN sites. Each stamp is a 0.7 × 0.7 arcmin² subset of the continuum-subtracted DIAFI frame centered on the SN position. The photometric aperture and annulus are indicated by the red and blue circles, respectively.
photons are the X-rays absorbed by the shell, any kind of variation in the absorbed X-rays can imply a change in the emergent Hα flux. At the beginning of the interaction, the models predict a relatively quick rise (∼500 days) of the X-ray flux (Chugai & Chevalier 2006) followed by a slower decline after the FS passed through the dense shell and the shell got accelerated by the SN ejecta piling up from behind (Chevalier & Liang 1989). The deceleration of the RS, $v_{\text{RS}} \sim t^{-1/(n-2)}$, where $n$ is the power-law index of the density profile in the outer part of the SN ejecta, is also partly responsible for the decrease of the Hα luminosity, since $L_X \sim v_{\text{RS}}^{-3}$ (Chevalier & Fransson 2003; Nymark et al. 2006) and $L_{\text{H} \alpha} \sim \eta L_X M_S^{9/40}$, where $\eta \sim 0.1$ is the efficiency of converting the X-ray flux to Hα photons and $M_S$ is the mass of the dense CSM shell (Chugai & Chevalier 2006). In addition, at later phases, the shell gets diluted by expansion, reducing the X-ray optical depth and causing a further decrease in the produced Hα radiation.

In Figure 6, there are examples of increasing (e.g., SN 1981B and SN 2012fh) and decreasing (SN 2005kl and SN 2014C) Hα luminosities. In the simple interaction scenario described above, the increasing Hα fluxes might be connected with an
the declining Hα luminosity, is especially interesting, since it is the only SN Ia in our sample that shows such a phenomenon. Since the baseline of our survey is still less than 1000 days, and we have only a few measured points for each SN, it is premature to draw any definite conclusion based on such details. Future observations will be useful to decide whether these SNe are indeed subject to ejecta-CSM interaction.

6. Conclusions

Our narrowband imaging survey of old, H-deficient (Type Ib,c, Ia, and IIb) SNe through Hα filters resulted in the following:

1. detection of continuum-subtracted Hα emission from 27 SN sites (see Table 2), 13 of which are point sources at our resolution;
2. detection of significant variation (exceeding 3σ) of the Hα emission from three SNe: SN 1985F, SN 2005kl, and SN 2012fh (all SNe Ib,c and point sources); SN 2010gi, a diffuse source around a SN IIb, also shows some sort of variability, but its reality is more uncertain;
3. a strong, variable Hα emitter, SN 2005kl (SN Ic), for which the Hα luminosity exceeds that of the typical H II regions by an order of magnitude;
4. detection of Hα emission from the known late-time interacting SN 2004dk and SN 2014C;
5. possible variation in the Hα emission from SN 1981B (Ia), SN 2012P (IIb), SN 2013dk (Ic), and SN 2014C (Ib).

We conclude that, in the case of the three variable Hα emitters (i.e., SN 1985F, SN 2005kl, and SN 2012fh), the source of the net Hα emission is likely the ongoing ejecta-CSM interaction. The robustness of our methodology is demonstrated by the successful detection of the well-known interacting SN 2004dk and SN 2014C. The number of detected point-source Hα emitters, 13 out of 99 SNe, is consistent with the recently estimated rate (~10%) of such events (Margutti et al. 2017).

In addition to continuing our narrowband imaging for all nearby SNe I, we plan to obtain spectroscopic and multi-wavelength data, from radio to X-ray bands, for the SNe listed in Table 2 to confirm and characterize the ejecta-CSM interaction. We are also investigating the archival radio and X-ray coverage of these SNe (D. Pooley et al. 2017, in preparation).

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