PTF 13EFV – AN OUTBURST 500 DAYS PRIOR TO THE SNHUNT 275 EXPLOSION AND ITS RADIATIVE EFFICIENCY

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ABSTRACT

The progenitors of some supernovae (SNe) exhibit outbursts with super-Eddington luminosities prior to their final explosions. This behavior is common among Type IIn SNe, but the driving mechanisms of these precursors are not yet well understood. SNHunt 275 was announced as a possible new SN during May 2015. Here we report on pre-explosion observations of the location of this event by the Palomar Transient Factory (PTF) and report the detection of a precursor about 500 days prior to the 2015 May activity (PTF 13efv). The observed velocities in the 2015 transient and its 2013 precursor absorption spectra are low (1000–2000 km s\(^{-1}\)), so it is not clear yet if the recent activity indeed marks the final disruption of the progenitor. Regardless of the nature of this event, we use the PTF photometric and spectral observations, as well as \textit{Swift}-UVOT observations, to constrain the efficiency of the radiated energy relative to the total kinetic energy of the precursor. We find that, using an order-of-magnitude estimate and under the assumption of spherical symmetry, the ratio of the radiated energy to the kinetic energy is in the range of \(4 \times 10^{-2}\) to \(3.4 \times 10^3\).

Subject headings: stars: mass-loss — supernovae: general — supernovae: individual: PTF 13efv, SNHunt 275

1. INTRODUCTION

Some supernova (SN) progenitors exhibit vigorous variability or possible explosive outbursts shortly (weeks to years) prior to the SN explosion (Foley et al. 2007; Pastorello et al. 2008; Groh 2014; Yaron et al. 2015). It is possible that these flash-ionized SNe have lower CSM mass, and/or a CSM that is confined to short distances from the progenitor (e.g., Gal-Yam et al. 2014; Shivvers et al. 2015; Smith et al. 2015; Khazov et al. 2015; Yaron et al. 2015). It is possible that these flash-ionized SNe have lower CSM mass, and/or a CSM that is confined to short distances from the progenitor (e.g., Gal-Yam et al. 2014; Groh 2014; Yaron et al. 2015).

Ofek et al. (2014a) systematically searched for pre-explosion outbursts (precursors) among a sample of 16 SNe IIn in which the hydrogen Balmer lines persist at least until the SN maximum light. Five possible precursors were found. Based on this analysis, they conclude that precursor events among SNe IIn are common: assuming a homogeneous population, at the one-sided 99% confidence level, more than 98% of all SNe IIn have at least one pre-explosion outburst that is brighter than \(3 \times 10^7 L_\odot\) (absolute magnitude \(-14\)) that takes place up to 2.5 yr prior to the SN explosion. The average rate of such precursor events during the year prior to the SN explosion is likely larger than one per year (i.e., multiple events per SN per year), and fainter precursors are possibly even more common. They also find possible correlations between the integrated luminosity of the precursor, and the SN total radiated energy, peak luminosity, and rise time. These correlations are expected if the precursors are mass ejection events, and the early-time light curve of these SNe is powered by interaction of the SN ejecta with optically thick CSM. No precursors were found in a similar search among five SNe IIn, recently...
reported by Blininki et al. (2015). They do not provide the absolute-magnitude-dependent search time of their sample, so direct comparison of the two surveys is not straightforward.

The nature of the SN precursors is unknown, although several theoretical mechanisms have been suggested to explain this high mass loss in the final stages of stellar evolution. These include the pulsational pair instability (e.g., Rakavy et al. 1967; Woosley et al. 2007; Waldman 2008; Moriya & Langer 2015), bursty shell oxygen burning (Arnett & Meakin 2011), binary evolution (e.g., Chevalier 2012; Soker & Kashi 2013), and internal gravity waves excited by core convection (Quataert & Shiode 2012; Shiode & Quataert 2013). In addition to the nature of the engine driving the precursors, another relevant question is how the mass loss arises and the origin of the radiated luminosity. In the context of luminous blue variables (LBVs) and η Carinae in particular, one can envision mass loss to arise from explosions — i.e., shock waves accelerating material at the surface, later converting the kinetic energy to radiation through the interaction of the freshly ejected material with previously ejected mass (e.g., Smith 2013). In this case, we expect the radiated energy to be less or comparable to the kinetic energy of the ejecta. In an opposite scenario, a super-Eddington radiative field drives mass through radiation pressure. Here we expect the radiated energy to be larger than the kinetic energy of the ejecta (Shaviv 2000; 2001).

SNhunt 275 (PSN J09093496+3307204) was discovered by Howerton et al. Classification of the transient (Elias-Rosa et al. 2015) by the Asiago Transient Classification Program using a spectrum taken on 2015 Feb 9.93 (UTC dates are used throughout this paper) revealed a narrow P-Cygni Hα line with an emission width of about 900 km s$^{-1}$ and an expansion velocity, derived from the absorption component, of 950 km s$^{-1}$. The P-Cygni profile is superposed on broad Hα emission having a full width at half-maximum intensity (FWHM) of $\sim 6800$ km s$^{-1}$. Elias-Rosa et al. (2015) also reported on the detection of a possible source at the transient location in Hubble Space Telescope (HST) images with apparent magnitudes of 22.8, 21.5, and 22.5 (F606W filter) on 2009 Feb. 9, 2008 Mar. 30, and 2009 Feb. 25, respectively. These correspond to absolute magnitudes of about $-9.7, -11.0$, and $-10.0$, respectively. Observations on 2015 Mar. 9, Apr. 9, and Apr. 14 showed that the transient brightness had increased (de Ugarte Postigo et al. 2015a, b, c). Furthermore, spectroscopic observations on 2015 Apr. 14 (with resolution $R \approx 500$) did not detect the P-Cygni absorption component. Vinko et al. (2015) reported that the absolute magnitude of the transient reached $-17$ on 2015 May 18, and suggested that the transient has exploded as a SN.

Here we present PTF observations of the field of this transient in the years prior to its recent discovery and the detection of a precursor event reaching an absolute magnitude of about $-12$ (Duggan et al. 2015). We use these observations to put limits on the ejected mass and the radiative efficiency of the precursor. The radiative efficiency is defined here as the ratio of the radiated energy to the kinetic energy. Although the results have an uncertainty of several orders of magnitude, they provide the foundations for better future measurements.

We assume a distance to the transient of about 30 Mpc and a Galactic reddening of $E_B-V = 0.023$ mag (Schlegel et al. 1998). In Fig. we present our photometric and spectroscopic observations as well as Swift observations. The results are discussed in § and summarized in §.

2. OBSERVATIONS

The Palomar Transient Factory (PTF and iPTF; Law et al. 2009; Rau et al. 2009), using the 48-inch Oschin Schmidt telescope, observed the field of SNhunt 275 starting in March 2009. On 2013 Dec. 12, PTF detected a new source at the location of the event, and the transient was named PTF 13efv (Figure 1). Spectroscopic classification obtained on 2013 Dec. 13 suggested that this is a “SN imposter” (e.g., Van Dyk & Matheson 2012). All of the PTF observations are reduced using the PTF-IPAC pipeline (Lafer et al. 2014) and the photometric calibration and magnitude system are described by Ofek et al. (2012a, b).

Photometry of the source was derived using point-spread function (PSF) fitting photometry on the subtracted images (see, e.g., Firth et al. 2015 for details). Three images obtained between 2014 Jan. 23 and 2014 Apr. 25 were used as a reference. The PTF $R$-band photometry is listed in Table § and the light curve is presented in Fig 1. The $R$-band light curve clearly shows a precursor detected toward the end of Nov. 2013. The first detection of this outburst was on 2013 Nov 26. The next observations, about 2 weeks later, do not show an indication for flux variations. Therefore, it is possible that the outburst started much earlier than Nov 26. Observations obtained on 2013 Dec 21 indicate that the source returned to the levels of the reference image. We note that our PTF $g$-band light curve includes a single non-detection on 2013 Apr. 22 with a limiting magnitude of 21.1. The precursor disappeared in the third week of Dec. 2013. We note that in Figure there is a single point, on 2009 Sep 10, that looks like an outburst. In order to test its reality, we ran the newly developed image subtraction code (Zackay, Ofek, & Gal-Yam 2016) on the images, where we constructed a reference image using the optimal image coaddition algorithm described in Zackay & Ofek (2015a, b). This image subtraction code is optimal, in the background dominated noise limit, and unlike the popular image subtraction methods it is numerically stable, returns a subtraction image with uncorrelated noise, and preserves the shape of cosmic rays and bad pixels. We found out that the residual causing the detection on 2009 Sep 10 has a sharp shape, indi-

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indicating that it is likely a bad pixel or radiation hit event. Therefore, we conclude it is not an outburst.

We note that there are 21 observations obtained between 2010 Feb 13 and 16. All these observations have negative fluxes and their weighted mean count is $-68 \pm 9$, where the error was estimated using the Bootstrap method (Efron 1982). This is likely due to real variability of the progenitor, specifically a decline in luminosity relative to the reference image. We note that the formal error on the mean (12 counts) is consistent with the bootstrap error. This consistency indicates that our error estimate is reasonable. For additional tests regarding systematics in our image subtraction and photometry we refer the reader to Ofek et al. (2014a).

Most of the optical spectra (see Table 2) were obtained with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck-1 10 m telescope, although a few spectra were also taken with the DEep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on the Keck-2 10 m telescope, the Kast spectrograph (Miller & Stone 1993) on the Shane 3 m telescope at Lick Observatory, and the Gemini-North Multiobject Spectrograph (GMOS; Hook et al. 2004) on the 8 m Gemini-N telescope. Spectral reductions followed standard techniques (e.g., Matheson et al. 2000; Silverman et al. 2012). All spectra are publicly available online via the Weizmann Interactive Supernova Data Repository, WISEREP (Yaron & Gal-Yam 2012). The spectra are presented in Figure 3 and a close-up view of the Hα line is shown in Figure 1.

![Fig. 2 — The PTF light curve at the position of SNHunt 275 prior to its May 2015 event. Black filled symbols represent the PTF measurements. Circles mark individual measurements which are 3 times above the noise level, while squares represent measurements which are consistent with 3 times the noise. The triangle marks a Swift/UVOT U'M2 upper limit. We note that the weighted mean of the counts during the 2013 outburst is 326 ± 18.](http://wiserep.weizmann.ac.il/)
shows the Na I absorption doublet (5890, 5896 Å) at zero redshift and at the host-galaxy redshift. The equivalent width of the Na I doublet at the host-galaxy redshift is about 2.3 times stronger than the Galactic Na I absorption line. Therefore, it is likely that there is host-galaxy extinction in the direction of this event.

The Hα line luminosity as measured in the Keck/DEIMOS spectrum on 2015 May 20 is about $1.2 \times 10^{40}$ erg s$^{-1}$. This is over an order of magnitude stronger than the luminosity during the 2013 outburst. We verified the flux calibration is correct by calculating the $V_{\text{UVOT}}$-band synthetic magnitude from the spectrum and comparing it with the Swift-UVOT photometry.

SNHunt 275 exploded in NGC 2770, which has been the home of several SNe (e.g., Thöne et al. 2009), among which was SN 2008D (Soderberg et al. 2008; Modjaz et al. 2009). Thus, the host galaxy has been observed many times and by various instruments. Specifically, since 2008, it was observed by the Ultra-Violet/Optical Telescope (UVOT; Roming et al. 2005) onboard the Swift satellite (Gehrels et al. 2004). Some of these observations have already been reported (e.g., Campana et al. 2015). The data were reduced using standard procedures (e.g., Brown et al. 2009). Flux from the transient was extracted from a 3″-radius aperture, with a correction applied to transform the photometry on the standard UVOT system (Poole et al. 2008). The resulting measurements, all of which have been converted to the AB system (Oke & Gunn 1983), are listed in Table 3 and displayed in Figure 5. Since there are no UVOT detections of the object prior to $t_0$ (= 2457157.36, see definition below), Figure 5 shows only measurements taken after $t_0$. We note that the contribution from the host galaxy was subtracted by removing the (coincidence-loss corrected) mean count rate observed prior to January 2015.

We used the UVOT observations to construct the bolometric light curve of the transient. This was done by correcting the measurements for Galactic reddening of $E_{B-V} = 0.023$ mag (Schlegel et al. 1998; Cardelli et al. 1989), and fitting a black-body continuum to all of the observations in one-day bins (only in bins having observations in more than three bands). The fitted bolometric light curve, effective temperature, and radius are presented in Figure 6 while the fitted measurements are listed in Table 3. Figure 7 presents the UVOT spectral energy distribution, along with the best-fit blackbody curve, on three epochs, 1.8, 4.5 and 14.3 days after $t_0$. The uncertainties were estimated using the bootstrap method (Efron 1982) applied to each time bin. Following Ofek et al. (2014c), we further estimated the rise timescale of the event by fitting the luminosity ($L$) with an exponential rise of the form

$$L = L_{\text{max}}(1 - \exp[-(t - t_0)/t_{\text{rise}}]),$$

where $L_{\text{max}}$ is the fitted maximum luminosity and $t_0$ is
ual observations, is given in Table 1. The source flux (Moretti et al. 2004). The background count rates were estimated in an annulus around the transient location, with an inner (outer) radius of 50′′.

The spectra were obtained at the parallactic angle, and were corrected for airmass-effects using the mean atmospheric extinction curve.

Note. — MJD is the modified Julian day. The temperature and radius are based on fitting a black-body continuum to the spectra (excluding the Hβ and Hα regions). Since the temperatures may be affected by metal absorption, they should be regarded as lower limits. Similarly, the radii should be regarded as upper limits. “Setup” indicates the grating name, or (respectively) the blue grism and red grating. The spectra were obtained at the parallactic angle, and were corrected for airmass-effects using the mean atmospheric extinction curve for each site. We note that the Galactic reddening (E_B-V = 0.023 mag) is taken into account in the effective temperature calculations. However, we ignored the unknown host extinction. If the host extinction is indeed a factor of 2 larger than the Galactic extinction, as suggested by the Na I absorption doublet, then the lower limit on the effective temperature will be 300 to 1000 K higher than listed in the Table.

Table 2

| Telescope     | Instrument | Setup       | MJD        | Temp. (K) | Radius (cm) |
|---------------|------------|-------------|------------|-----------|-------------|
| Gemini-N      | GMOS       | R400/G5305  | 56629.8    | 5820      | 4 × 10^{14} |
| Keck-I        | LRIS       | 400/3400, 400/8500 | 57158.3    | 10,800    | 6 × 10^{14} |
| Keck-I        | LRIS       | 400/3400, 400/850 | 57162.3    | 9230      | 4 × 10^{14} |
| Keck-II       | DEIMOS     | 1200G       | 57162      | 9030      | 7 × 10^{14} |
| Keck-I        | LRIS       | 400/3400, 400/850 | 57186.3    | 6010      | 1 × 10^{15} |
| Keck-I        | LRIS       | 600/4000, 1200/7500 | 57189       | ∙ ∙ ∙      | ∙ ∙ ∙        |
| Lick 3 m      | Kast       | 600/4310, 300/7500 | 57191       | 5960      | 1 × 10^{15} |

Note. — Time is given relative to \( t_0 = 2457157.36 \). The counts are background subtracted, where the background is estimated as the mean of all the observations in a given filter obtained before 2015 Jan. 1. The subtracted backgrounds are 0.892, 1.496, 0.743, 0.085, 0.206, and 0.146 counts for the V, B, U, UVW1, UVW2, and UVW2 filters, respectively. The zero points to convert these counts to AB magnitudes are 17.88, 18.99, 19.36, 18.97, 18.53, and 19.07 mag, for the V, B, U, UVW1, UVW2, and UVW2 filters, respectively. This table is published in its entirety in the electronic edition of ApJ. A portion of the full table is shown here for guidance regarding its form and content.

Table 3

| Filter | JD - \( t_0 \) (day) | Counts | Counts error |
|--------|-----------------------|--------|--------------|
| V      | -2685.8316            | -0.016 | 0.054        |
| V      | -2682.2874            | 0.087  | 0.074        |
| V      | -2680.7415            | -0.007 | 0.040        |
| V      | -2679.6697            | 0.004  | 0.052        |
| V      | -2678.8016            | 0.000  | 0.047        |

Note. — Time is given relative to \( t_0 = 2457157.36 \). The counts are background subtracted, where the background is estimated as the mean of all the observations in a given filter obtained before 2015 Jan. 1. The subtracted backgrounds are 0.892, 1.496, 0.743, 0.085, 0.206, and 0.146 counts for the V, B, U, UVW1, UVW2, and UVW2 filters, respectively. The zero points to convert these counts to AB magnitudes are 17.88, 18.99, 19.36, 18.97, 18.53, and 19.07 mag, for the V, B, U, UVW1, UVW2, and UVW2 filters, respectively. This table is published in its entirety in the electronic edition of ApJ. A portion of the full table is shown here for guidance regarding its form and content.

FIG. 6. — Fitted bolometric luminosity (upper panel), effective temperature (middle panel), and effective radius (lower panel) as a function of time since the fitted \( t_0 \). See text for details. The gray line shows the best fit exponential rise timescale.

FIG. 7. — From left to right, we present the UVOT spectral energy distribution of SN Hunt 275, on three epochs: 1.8, 4.5 and 14.3 days after \( t_0 \), respectively. The gray lines represent the best-fit blackbody curve.
within the Swift-XRT energy range.

Throughout this paper we assume a distance to SNHunt 275 of 30 Mpc (distance modulus 32.38 mag). The reduction and analysis presented here is based mainly on tools available as part of the MATLAB astronomy and astrophysics package (Ofek 2014).

3. DISCUSSION

Here we briefly review the properties of the 2013 event (§3.1), and discuss the question of whether SNHunt 275 marks the final disruption of the star (§3.2). Furthermore, by analyzing the properties of the 2013 precursor and the latest explosion (May 2015), we attempt to constrain the physical setup of this explosion, and specifically the radiative efficiency of the precursor explosions (§3.3). In §3.3 we discuss the question of whether the possible mass loss is driven by a radiation field, or the radiation is generated by the mass-loss interaction with previously emitted material.

3.1. The 2013 event

To summarize – the 2013 outburst took place about 500 days prior to the May 2015 main event and reached a peak absolute magnitude of about −11.9 in R-band ($\approx 1.7 \times 10^{40}$ erg s$^{-1}$). The duration of this outburst was longer than 20 days, hence the integrated radiated energy in R-band is $> 2.4 \times 10^{46}$ erg. An interesting fact is that the outbursts decayed fast, on less than a week time scale. A spectrum taken during the outburst revealed Balmer lines with P-Cygni profile with a velocity of about 1000 km s$^{-1}$. These properties are summarized in Table 4.

In terms of peak absolute magnitude, and the total radiated energy this event is at the low end of the precursor event population reported in Ofek et al. (2014a). However, this is a clear selection bias. One of the most well studied SN showing multiple precursor events is SN 2009ip (Smith et al. 2010; Mauerhan et al. 2013; Ofek et al. 2013b; Pastorello et al. 2013; Prieto et al. 2013; Fraser et al. 2015). Interestingly, SN 2009ip likely showed four events, prior to its presumably final explosion on September 2012 (e.g., Smith et al. 2010). These events took place at about $−25$, $−660$, $−710$ and $−1060$ days prior to the latest explosion. The activity of SNHunt 275 on time scales of tens to hundreds of days prior to the presumably final explosion is similar to the one observed in SN 2009ip. One difference is that the peak luminosity of the outbursts seen in SN 2009ip was about an order of magnitude higher than that of SNHunt 275. One key question that is not yet clear in the cases of SN 2009ip and SNHunt 275 is if we saw the final death of the star, or the latest events are just other, brighter than average, outbursts.

3.2. The Nature of the 2015 Event

A close-up view of the evolution of the Hα line is presented in Figure 3. An interesting fact is the appearance of a single P-Cygni absorption feature during the 2013 outburst, and two absorption features in spectra taken about one month after the May 2015 event. This double P-Cygni absorption feature, with $\sim 1000$ and $\sim 2000$ km s$^{-1}$ velocities, is seen in all of the Balmer lines in the spectrum.

This can be interpreted in several ways; here we mention two obvious possibilities. First, the absorption at $2000$ km s$^{-1}$ can be produced by material ejected after the 2013 outburst but before the May 2015 event (e.g., during the Feb. 2015 rebrightening). At early times during the May 2015 event, the $2000$ km s$^{-1}$ gas is hot and generates the $2000$ km s$^{-1}$ wide emission lines. Later on this relatively dense gas cools, and we detect a P-Cygni absorption feature, with $\sim 1000$ and $\sim 2000$ km s$^{-1}$ velocities, is seen in all of the Balmer lines in the spectrum.

Alternatively, it is possible that the May 2015 event released material at $2000$ km s$^{-1}$ that at early times is seen in emission and later in absorption. If this scenario is correct, we predict that X-ray and radio emission will not be detected, since the shock velocity is too low. The current X-ray nondetection, the reddening (cooling) of the spectra, and lack of broad spectral features suggest that the star has not exploded yet.

The scenarios we discuss do not cover all possibilities. For example, breaking the spherical symmetry gives

### Table 4

| JD $− t_0$ (day) | $L_{bol}$ ($10^{42}$ erg s$^{-1}$) | Temp. (K) | Radius ($10^{14}$ cm) |
|------------------|----------------------------------|-----------|----------------------|
| 1.860            | 1.14 ± 0.05                      | 11,500 ± 600 | 4.9 ± 0.5           |
| 4.540            | 1.78 ± 0.02                      | 12,200 ± 100 | 4.4 ± 0.1           |
| 5.176            | 1.79 ± 0.36                      | 12,300 ± 600 | 4.4 ± 1.7           |
| 7.325            | 1.98 ± 0.04                      | 12,100 ± 200 | 4.7 ± 0.2           |
| 10.260           | 1.81 ± 0.03                      | 10,900 ± 200 | 5.5 ± 0.2           |
| 11.416           | 1.67 ± 0.04                      | 10,200 ± 200 | 6.1 ± 0.3           |
| 12.582           | 1.54 ± 0.04                      | 10,000 ± 300 | 6.1 ± 0.4           |
| 13.257           | 1.43 ± 0.04                      | 9800 ± 200  | 6.1 ± 0.3           |
| 14.335           | 1.32 ± 0.05                      | 9200 ± 300  | 6.8 ± 0.5           |

*Note.* — Bolometric luminosity, effective temperature, and radius estimated from a black-body fit to the Swift-UVOT observations (Table 3) corrected for Galactic extinction. Like in Table 3, the temperature measurements should be regarded as lower limits on the effective temperature. Assuming the host extinction is twice as large as the Galactic extinction (i.e., as suggested by the Na I absorption doublet) the lower limit on the temperature will be higher by up to about 1000 K.

### Table 5

| JD $− t_0$ (day) | Exp. time (s) | Source (counts) | Background (counts) |
|------------------|---------------|-----------------|---------------------|
| $−2685.835$      | 9995.4        | 2               | 38                  |
| $−2682.295$      | 4563.3        | 1               | 55                  |
| $−2680.750$      | 2864.9        | 3               | 124                 |
| $−2679.740$      | 1428.2        | 2               | 28                  |
| $−2678.811$      | 15785.9       | 0               | 65                  |

*Note.* — Source is the number of counts in a 9″-radius aperture of the source position and in the 0.2–10 keV band. Background is the number of counts in the 0.2–10keV band, in an annulus of inner (outer) radius of 50″ (100″) around the source. The ratio between the background annulus area and the aperture area is $92.59$. This table is published in its entirety in the electronic edition of *ApJ*. A portion of the full table is shown here for guidance regarding its form and content.
rise to a large number of scenarios. However, these are very hard to constrain given the limited information at hand. We stress that the observations are hardly conclusive, and it is still not clear what the nature of the May 2015 transient is. We note that future HST observations, taken after the transient light fades away, may check if the progenitor is still visible, and hence whether the May 2015 event marked the final explosion of the star.

3.3. The Radiative Efficiency of Precursors

Table lists the measured properties of the precursor and the possible SN explosion. These properties were estimated based on the PTF light curve, the spectra, the Swift-UVOT data, and the HST observations (Elias-Rosa et al. 2015). Next, we use these properties to estimate the radiative efficiency of the precursor. The goal of this section is to roughly estimate the CSM mass ejected in the 2013 outburst, and to estimate the ratio between the radiated luminosity and kinetic energy of the precursor. This measurement has the potential to resolve the key question: what drives the CSM ejection? For example, a ratio much smaller than one, favors moderate, and it is still not clear what the nature of the May 2015 event is. We note that future observations are hardly conclusive.

The CSM mass can be expressed as

\[ M_{\text{CSM}} = (\frac{1}{\epsilon_R}) \left( \frac{2}{v_{\text{CSM}}} \right) \langle L \rangle \Delta t \]  

(2)

Here \( \epsilon_R \) is the precursor luminosity as a function of time \( t \), \( \Delta t \) is the precursor duration, \( M_{\text{CSM}} \) is the precursor ejecta mass, and \( v_{\text{CSM}} \) is the precursor ejecta velocity. The CSM mass can be expressed as

\[ M_{\text{CSM}} = (\frac{1}{\epsilon_R}) \left( \frac{2}{v_{\text{CSM}}} \right) \langle L \rangle \Delta t \]  

(3)

The radiative efficiency allows us to relate between the observed luminosity integrated over time, the CSM velocity, and mass. Furthermore, the exact value of the radiative efficiency likely depends on the CSM ejection mechanism, and therefore it may be useful for testing some theoretical ideas regarding the precursor physical mechanism (see Figure 2).

However, our derivation is an order-of-magnitude estimate that relies on several assumptions, which are not necessarily correct. For example, we assume that the CSM has spherical symmetry and is not heavily clumped. Nevertheless, as far as we know, this is the only existing estimate for the radiative efficiency of a precursor.

The distance the precursor ejecta can travel during its 20-days ejection is

\[ r_{\text{CSM}} \approx \frac{1.7 \times 10^{14} (\frac{v_{\text{CSM}} \Delta t}{1000 \text{ km s}^{-1}}) \left( \frac{\Delta t}{20 \text{ days}} \right)}{10^4} \text{ cm}, \]

(4)

where \( \Delta t \) is the duration of the precursor (\( \geq 20 \text{ day} \)). An order-of-magnitude estimate of the mean density of the ejected CSM (during its ejection) is

\[ n \approx \frac{M_{\text{CSM}}}{\epsilon_R \mu m_p 4\pi r_{\text{CSM}}^3} \approx 2.7 \times 10^{11} (\frac{1}{\epsilon_R}) \left( \frac{v_{\text{CSM}}}{1000 \text{ km s}^{-1}} \right)^{-2} \left( \frac{\Delta t}{20 \text{ day}} \right)^{-2} \left( \frac{\mu}{0.6} \right)^{-1} \left( \frac{1}{10^4 \text{ cm}^2 \text{ g}^{-1} \text{s}^{-1}} \right) \text{ cm}^{-3}. \]

(5)

Here \( \mu_p \) is the mean molecular weight (assumed to be 0.6).

Another constraint comes from the fact that the precursor radiation disappeared on a timescale shorter than one week (Figure 2), thus, the cooling timescale is \( \lesssim 1 \text{ week} \). The Bremsstrahlung cooling timescale, which gives an upper limit on the cooling timescale, is given by

\[ t_{\text{cool}} \lesssim 1.76 \times 10^{13} \left( \frac{T}{10^4 \text{ K}} \right)^{1/2} \left( \frac{n}{1 \text{ cm}^{-3}} \right)^{-1} \left( \frac{Z}{1} \right)^{-2} \text{ s}. \]

(6)

where \( T \) is the gas temperature and \( Z \) is the atomic number (number of protons), and this can be translated to a lower limit on the density of the emitting region. If we require that \( t_{\text{cool}} < 7 \text{ days} \), and assume \( (Z) \approx 1.7 \text{ and } T \approx 10^4 \text{ K} \), we find that \( n \approx 7 \times 10^7 \text{ cm}^{-3} \). Combining this limit on \( n \) along with Equation 5 and the fact that \( \Delta t \geq 20 \text{ day} \), we get

\[ \epsilon_R \lesssim 3.4 \times 10^{-3}. \]

Next, an order-of-magnitude estimate for the photon diffusion timescale (e.g., Popov 1993; Padmanabhan 2001) is given by

\[ t_{\text{diff}} \approx 0.32 \left( \frac{1}{\epsilon_R} \right) \left( \frac{\kappa}{0.34 \text{ cm}^2 \text{ g}^{-1} \text{s}^{-1}} \right) \left( \frac{\langle L \rangle}{10^3 \text{ erg s}^{-1}} \right) \left( \frac{v_{\text{CSM}}}{10^3 \text{ km s}^{-1}} \right) \left( \frac{\Delta t}{20 \text{ day}} \right)^{-3} \left( \frac{\mu}{0.6} \right)^{-1} \left( \frac{10^4 \text{ cm}^2 \text{ g}^{-1} \text{s}^{-1}}{\kappa} \right) \text{ day}, \]

(8)

Assuming that \( t_{\text{diff}} \lesssim 7 \text{ day} \), we can set the following lower limit:

\[ \epsilon_R \gtrsim 0.04. \]

(9)

Until now, our constraints on the radiative efficiency are based on the properties of the precursor. Next, we will use the properties of the May 2015 event to derive additional constraints.

Assuming \( v_{\text{CSM}} \approx 1000 \text{ km s}^{-1} \), after 500 days (i.e., the time between the Dec. 2013 precursor and the May 2015 event), the CSM traveled a distance of \( r_{\text{CSM}} \approx 4 \times 10^{15} \text{ cm} \). Since the rise time of the May 2015 event is about 2 days (Table 6), we can use the diffusion timescale (Eq. 8) to set an order-of-magnitude upper limit on the mass of the CSM:

\[ M_{\text{CSM}} \lesssim 0.4 \left( \frac{t_{\text{diff}}}{2 \text{ day}} \right) \left( \frac{r_{\text{CSM}}}{4 \times 10^{15} \text{ cm}} \right) \left( \frac{\kappa}{0.34 \text{ cm}^2 \text{ g}^{-1} \text{s}^{-1}} \right)^{-1} \text{ M}_\odot. \]

(10)
Inserting this limit on $M_{\text{CSM}}$ into Equation\(^\text{12}\) gives

$$\epsilon_R \gtrsim 0.007 \left( \frac{\Delta t}{20 \text{ day}} \right) \left( \frac{v_{\text{CSM}}}{1000 \text{ km s}^{-1}} \right)^{-2}.$$ \hspace{1cm} (11)

We note that currently we also have the following upper limit on the duration and luminosity of the precursor. Since we did not find a transient at the location of PTF 13efv in the Catalina Real Time Survey (CRTS; Drake et al. 2009), and assuming CRTS can detect magnitude 19 transients, we can conclude that the luminosity of the precursor was not larger by more than factor of about four than the observed luminosity of $1.7 \times 10^{48}$ erg s\(^{-1}\) seen during December 2013. Furthermore, the PTF $g$-band nondetection prior to the December 2013 event sets an upper limit of about 240 days on $\Delta t$. Since the precursor was not detected in the UV (Table 6), the bolometric correction is likely small.

To conclude, combining all the constraints, we set the following limits on the radiative efficiency:

$$0.04 \lesssim \epsilon_R \lesssim 3400.$$ \hspace{1cm} (12)

We stress that this is an order-of-magnitude estimate and it includes several assumptions that are not necessarily correct. Therefore, the results of this analysis should be viewed with caution. Since we cannot determine whether the efficiency is smaller or larger than unity, we cannot point definitively toward one of two types of scenarios: kinetic energy converted into radiation or radiation-driven mass loss. However, with improved observational constraints this analysis can be used in the future to obtain better estimates of the radiative efficiency of precursors.

### 3.4. What Drives the Mass Loss and Radiation?

In the case that the 2013 event is caused by a super-Eddington continuum-driven wind, we expect it will satisfy a mass-loss vs. luminosity relation. In this case, Shaviv (2001) has shown that the total mass loss is given by

$$M \approx W \frac{L - L_{\text{Edd}}}{c c_s} \Delta t,$$ \hspace{1cm} (13)

where $W$ is a dimensionless constant that empirically was found to be of order a few, $c_s$ is the speed of sound at the base of the wind (estimated to be $60 \text{ km s}^{-1}$), and $L_{\text{Edd}}$ is the Eddington luminosity. For $L \gg L_{\text{Edd}}$ we can write

$$M \approx 4 \times 10^{-5} \frac{W}{5} \left( \frac{L}{1.7 \times 10^{40} \text{ erg s}^{-1}} \right) \left( \frac{\Delta t}{20 \text{ day}} \right) M_\odot.$$ \hspace{1cm} (14)

This estimate is below the derived upper limits on the CSM mass, and hence we cannot rule out this model.

The second option we would like to consider is that the radiation is generated from conversion of the kinetic energy of the ejected mass to radiation via interaction with previously emitted material (e.g., Smith et al. 2014). One possible problem with this scenario is that the interaction will produce mostly hard X-ray photons (e.g., Fransson 1982; Katz et al. 2011; Murase et al. 2011, 2014; Chevalier & Irwin 2012; Svirski et al. 2012). Presumably, it is possible to convert these X-ray photons to visible light by Comptonization or bound-free absorption (e.g., Chevalier & Irwin 2012; Svirski et al. 2012). Comptonization requires larger than unity Thompson optical depth, while the bound-free absorption will need neutral CSM mass with column densities above $\sim 10^{22} \text{ cm}^{-2}$. We note that in the current observations there is no evidence for a large Thompson optical depth, but we cannot rule out strong bound-free absorption. Moreover, this scenario may still work, if we introduce large departures from the spherical symmetry we have assumed so far.

### 4. SUMMARY

We present observations of a precursor, peaking at an absolute magnitude of about $-12$, $\sim 500$ days prior to the SN Hunt 275 May 2015 event. Also included are Swift-UVOT observations of the May 2015 event that peaked at an absolute magnitude of $-17$. We discuss the nature of the May 2015 event, and conclude that it is not yet clear whether this event signals the final explosion of the progenitor or is still another eruption. If the latter, then we may detect a SN taking place within months to a few years.

Finally, we use the observations to constrain the ratio of the radiated energy to the kinetic energy of the precursor (i.e., the radiative efficiency). Under some simplistic assumptions, our order-of-magnitude estimate suggests
that the radiative efficiency of PTF 13efv is $\gtrsim 0.04$. However, this still does not necessarily mean that all precursors have similar radiative efficiencies.

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Margutti, R., Millisalievich, D., Soderberg, A. M., et al. 2014, ApJ, 780, 21
Matheson, T., Filippenko, A. V., Ho, L. C., Barth, A. J., & Leonard, D. C. 2000, AJ, 120, 1499
Mauerhan, J. C., Smith, N., Filippenko, A. V., et al. 2013, MRNAS, 430, 1801
Miller, J. S., & Stone, R. P. S. 1993, Lick Observatory Technical Report 66 (Santa Cruz, CA: Lick Obs.)

REFERENCES

Arnett, W. D., & Meakin, C. 2011, ApJ, 741, 33
Benetti, S., Cappellaro, E., Turatto, M., Taubenberger, S., Harutyunyan, A., & Valenti, S. 2006, ApJ, 653, L129
Bilinski, C., Smith, N., Li, W., et al. 2015, MRNAS, 450, 246
Brown, P. J., Holland, S. T., Immler, S., et al. 2009, AJ, 137, 4517
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Campana, S., Thone, C. C., Leloudas, G., Acciutino, F., & Postigo, A. d. U. 2015, The Astronomer’s Telescope, 7517, 1
Chevalier, R. A. 2012, ApJL, 752, L2
Chevalier, R. A., & Irwin, C. M. 2012, arXiv:1201.5581
Chugai, N. N. 1999, MRNAS, 298, 173
Chugai, N. N. 2001, MRNAS, 326, 1448
Chugai, N. N., Cumming, R. J., Blinnikov, S. I., et al. 2003, arXiv:astro-ph/0309226
Corsi, A., Ofek, E. O., Gal-Yam, A., et al. 2014, ApJ, 782, 42
Drake, A. J., Djorgovski, S. G., Mahabal, A., et al. 2009, ApJ, 696, 870
Duggan, G., Bellm, E., Leloudas, G., et al. 2015, The Astronomer’s Telescope, 7515, 1
Efron, B. 1982, CBMS-NSF Regional Conference Series in Applied Mathematics, Philadelphia: Society for Industrial and Applied Mathematics (SIAM)
Elias-Rosa, N., Benetti, S., Tomassina, L., et al. 2015, The Astronomer’s Telescope, 7042, 1
Fabian, A. C., Fabian, T., Hill, R. L., et al. 2007, Proc. of SPIE, 4841, 1657
Fassia, A., Meikle, W. P. S., Chugai, N., et al. 2001, MRNAS, 325, 907
Filippenko, A. V. 1991, European Southern Observatory Conference and Workshop Proceedings, 37, 343
Filippenko, A. V. 1997, ARAA, 35, 369
Firth, R. E., Sullivan, M., Gal-Yam, A., et al. 2015, MRNAS, 446, 3895
Foley, R. J., Smith, N., Ganeshalingam, M., et al. 2007, ApJ, 657, L105
Fransson, C. 1982, A&A, 111, 140
Fraser, M., Magee, M., Kotak, R., et al. 2013, ApJ, 779, L8
Fraser, M., Kotak, R., Pastorello, A., et al. 2015, MRNAS, 453, 3886
Gal-Yam, A., Arcavi, I., Ofek, E. O., et al. 2014, Nature, 509, 471
Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005
Groh, J. H. 2014, A&A, 572, L11
Hook, I., Jorgensen, I., Allington-Smith, J. R., Davies, R. L., Metcalfe, N., Murovinski, R. G., & Crampton, D. 2004, PASP, 116, 425
Immler, S., Modjaz, M., Landsman, W., et al. 2008, ApJL, 674, L85
Khazov, D., Yaron, O., Gal-Yam, A., et al. 2016, ApJ, 818, 3
Katz, B., Sapir, N., & Waxman, E. 2011, arXiv:1106.1898
Kiewe, M., Gal-Yam, A., Arcavi, I., et al. 2012, ApJ, 744, 10
Lafer, R. R., Surace, J., Grillmair, C. J., et al. 2014, PASP, 126, 674
Law, N. M., Kulkarni, S. R., Dekany, R. G., et al. 2009, PASP, 121, 1395
