Exploring the Efficacy and Limitations of Shock-cooling Models: New Analysis of Type II Supernovae Observed by the Kepler Mission

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Received 2016 December 14; revised 2017 August 3; accepted 2017 August 3; published 2017 October 5

Abstract

Modern transient surveys have begun discovering and following supernovae (SNe) shortly after first light—providing systematic measurements of the rise of Type II SNe. We explore how analytic models of early shock-cooling emission from core-collapse SNe can constrain the progenitor’s radius, explosion velocity, and local host extinction. We simulate synthetic photometry in several realistic observing scenarios; assuming the models describe the typical explosions well, we find that ultraviolet observations can constrain the progenitor’s radius to a statistical uncertainty of ±10%–15%, with a systematic uncertainty of ±20%. With these observations the local host extinction (AV) can be constrained to a factor of two and the shock velocity to ±5% with a systematic uncertainty of ±10%. We also reanalyze the SN light curves presented by Garnavich et al. (2016) and find that KSN 2011a can be fit by a blue supergiant model with a progenitor radius of RH < 7.7 + 8.8(stat) + 1.9(sys) R☉, while KSN 2011d can be fit with a red supergiant model with a progenitor radius of RH = 111 ± 89(stat)+49(sys)−21(sys) R☉. Our results do not agree with those of Garnavich et al. Moreover, we re-evaluate their claims and find that there is no statistically significant evidence for a shock-breakout flare in the light curve of KSN 2011d.

Key words: supernovae: general

1. Introduction

Modern surveys such as the Palomar Transient Factory (PTF, iPTF; Law et al. 2009; Kulkarni 2013), the Panoramic Survey Telescope & Rapid Response System (PanSTARRS, Kaiser et al. 2002), the All-Sky Automated Survey for SuperNovae (ASASSN, Shappee et al. 2014), the Subaru HSC Survey Optimized for Optical Transients (SHOOT, Tanaka et al. 2016), and the High Cadence Transient Survey (HITS, Förster et al. 2016) have successfully been discovering and following SNe close to their date of first light. In addition to a handful of individual objects (Pastorello et al. 2006; Quimby et al. 2007; Gezari et al. 2008; Schawinski et al. 2008; Arcavi et al. 2011, 2017; Gal-Yam et al. 2011; Ergon et al. 2014; Valenti et al. 2014; Bose et al. 2015; Gall et al. 2015; Tartaglia et al. 2017), samples with good coverage during the rise of Type II supernovae (SNe II) have only recently been published (Rubin et al. 2016). Garnavich et al. (2016, G16) published data from two SNe discovered in the Kepler mission data. These are extremely well sampled SN II light curves (LCs) and we address them in this paper.

In parallel, theorists have developed models to describe the expected early-time emission from core-collapse SNe. While hydrodynamic models provide a detailed calculation of the explosion, they are computationally expensive. Analytic models are more appropriate for searches of large parameter spaces, such as the ones performed in this work. For recent reviews of SN modeling see Hillebrandt (2011) and also the introduction of Morozova et al. (2016).

Waxman et al. (2007) and Nakar & Sari (2010, NS10) derived similar models describing the post-shock emission from massive envelopes. Rabinak & Waxman (2011, RW11) extended the theory to non-constant opacity, and improved the calculation of the color temperature by taking into account bound-free absorption, which was previously neglected.

Sapir & Waxman (2017, SW17) rederived the analytical results for constant opacity and extended the theory to later times. Shussman et al. (2016b, S16) explored the calibration of analytical models against numerically simulated explosions and progenitors, and also extended the theory to later times when the photosphere has penetrated more deeply into the ejecta. Both S16 and the extended theory in SW17 depend more strongly on the assumptions about the internal structure of the progenitor than the unextended theories. Therefore we limit ourselves to the unextended analytical theories. These theories depend explicitly (or implicitly) on the following assumptions:

1. The ejecta has expanded sufficiently such that it is no longer planar and must be considered in the spherical geometry. NS10 and S16 do not assume this and give solutions for the LC including the planar phase.
2. The emission is from a very thin shell that was initially near the edge of the star, and the photosphere has penetrated only a small fraction of the ejected mass. This is assumed by the unextended theories NS10/RW11/SW17, but not by the extensions in S16/SW17.
3. The temperature is above 0.7 eV and recombination effects are not important. This is assumed by all of the theories.

While NS10 and RW11/SW17/S16 roughly agree on the bolometric luminosity in the spherical phase, RW11, SW17, and S16 included bound-free (the dominant) absorption in the calculation of the color temperature. This can have a dramatic effect on the estimation of the progenitor’s radius. In view of the above considerations we use the unextended models presented in SW17. For a more thorough discussion see Section 1 of SW17.

Several recent works (Gall et al. 2015; González-Gaitán et al. 2015; G16) compared observations to such models, but applied them at times when the models are no longer valid (T < 0.7 eV or when the photosphere has penetrated deep into the ejecta). In those works, the LC parameters were estimated by comparing the time to peak of the model to the rise time of
the light curves. Models with $10–15 \, M_\odot$ ejecta are valid only until \( \sim 5–7 \) days after explosion, while they peak at \( \sim 12–14 \) days depending on the parameters. Rubin et al. (2016) showed that including data beyond the model’s validity range leads to incorrect assessment of the uncertainties and potentially to the acceptance of models that should be rejected.

Here we explore the potential of shock-cooling models to constrain the progenitor’s radius, the explosion velocity, and the local host extinction under simulated observing programs with various facilities. We also revisit the G16 Kepler SNe and reanalyze the data while taking into account the limitations of the models and their uncertainties.

### 2. The Model

In this work we use the recent derivation for constant opacity of SW17. SW17 extended the previous models for low-mass envelopes, where the photosphere penetrates the envelope before the temperature has dropped below 0.7 eV. They found an approximation for the LC at times when Equation (2) (Section 1) no longer holds. However, this approximation depends more strongly on the density structure of the star. In this work we consider stars with massive hydrogen envelopes, therefore we use the unextended model.

The two equations that we use are for the photospheric temperature and bolometric luminosity. They are given in SW17 (their Equation (4)) and are reproduced here:

\[
T_{ph} = 1.61 \left[ 1.69 \left( \frac{v_8 \kappa_{0.34}^{5/4}}{f_6 M_0 \kappa_{0.34}} \right)^{1/3} R_{13}^{1/4} f_{d}^{-1/2} \right] \text{ eV} \tag{1}
\]

\[
L = 2.0 \times 10^{42} \left( \frac{v_8 \kappa_{0.34}^{5/4}}{f_6 M_0 \kappa_{0.34}} \right)^{-2} \frac{v_{8.5} R_{13}}{\kappa_{0.34}} \text{ erg s}^{-1} \tag{2}
\]

where \( \kappa = 0.34 \kappa_{0.34} \text{ cm}^2 \text{ g}^{-1}, \ v_8 = 10^8 v_{8.5} \text{ cm s}^{-1}, \ M = 1M_\odot, \ R = 10^{13} R_{13} \text{ cm}, \ \epsilon_1 = 0.027 [0.016], \ \text{and} \ \epsilon_2 = 0.086 [0.175] \) for \( n = 3/2 [3]. \ v_{8.5} \) is the asymptotic shock velocity, \( M_0 \) is the ejected mass, and \( f_d \) is the time in days.

The model is valid for the following times:

\[
t > 0.2 \frac{R_{13}}{\nu_{8.5}} \max \left[ 0.5, \left( \frac{f_6 \kappa_{0.34} M_0}{v_{8.5}} \right)^{0.2} \right] \text{ day} \tag{3}
\]

\[
t < 3 f_p^{-0.1} \left( \frac{\nu_{8.3}}{M_0} \right) \text{ day} \tag{4}
\]

where the first limit describes the requirement for sufficient expansion (spherical phase) and the second limit describes the requirement that the photosphere has penetrated only a small fraction of the envelope’s mass. Additionally, to ensure fully ionized hydrogen we require

\[
t < \arg(T_{ph}(t) = 0.7 \text{ eV}). \tag{5}
\]

The specific flux is given by

\[
f_\lambda = \frac{L_{bol}}{4 \pi R_{ph}^2} \frac{T_{col}}{h c} g_{BB} \left( \frac{h c}{X T_{col}} \right) \tag{6}
\]

where \( R_{ph} \) is the photospheric radius, \( T_{col} \) is the color temperature, and \( g_{BB} \) is the dimensionless blackbody function.

### 3. Fitting Synthetic Data

In order to estimate the efficacy of shock-cooling models we simulated a synthetic photometry campaign. We explored discovery in the R-band 0.5 days after explosion with follow-up triggered one day later. We synthesized the following follow-up scenarios: photometry in Bessell (1990) \( BV, \ UBVI, \ \text{or} \ UVW1+\text{SWIFT/UVOT} \) UVW2 with a one-day cadence and R-band observation three times per night. We excluded UVW1 and UVW2 due to their known red leaks (Brown et al. 2010). These follow-up scenarios are realistic and are similar to the observational campaign of SN 2013fs (Valenti et al. 2016; Yaron et al. 2017). We simulated SNe with various radii \( (R_e = 50–1000 \, R_\odot) \) and extinction values \( (A_V = 0.1–1) \).

In order to explore what may be achieved with future UV facilities, we also simulated the expected photometry from ULTRASAT (Sagiv et al. 2014). ULTRASAT is a proposed UV satellite observatory that will acquire high-cadence (15 minute) UV photometry at 2500 Å. We simulated photometry in the ULTRASAT filter with 1 hr cadence and pre-explosion photometry (a conservative scenario given the design of 15 minute cadence).

We generated synthetic data from Equations (1) and (2) using the parameters in Table 1. The extinction for each central wavelength was calculated using the prescription of Cardelli et al. (1989). Different redshifts were chosen for the models such that they gave roughly the same observed peak \( R \) magnitude \( (m_{peak} \sim 18) \). All magnitudes reported here are in the AB system unless stated otherwise. The distance moduli were calculated using the cosmology of Planck Collaboration et al. (2015) with \( H_0 = 67.74 \, \text{km s}^{-1} \, \text{Mpc}^{-1}, \Omega_m = 0.31, \) and

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**Table 1**

| Parameter | Value |
|-----------|-------|
| \( n \)   | 3/2   |
| \( \kappa \) | 0.34  |
| \( R_e/R_\odot \) | 50–1000 |
| \( M/M_\odot \) | 10   |
| \( f_\nu \) | 1.0   |
| \( T_{col}/T_{ph} \) | 1.1   |
| \( v_{8.5} \) | 1.0   |
| \( A_V \) | 0.05–1 |
| \( R_V \) | 3.1   |

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SW17 explored numerically several different progenitors with varying mass ratios of core to mantle and found that the density normalization \( f_\nu = 1–3 \) [0.1–0.8] for \( n = 3/2 [3] \) (assuming normal stars with mass ratios of core to mantle of 0.1–1, SW17 Figure 5). Here we take \( f_\nu = 1 \) for \( n = 3/2 [3] \), appropriate for a mass ratio of core to mantle of 1. However, the emission is weakly dependent on \( f_\nu \). SW17 also show that the ratio of the color temperature to the photospheric temperature is well behaved and given by \( T_{col}/T_{ph} = 1.1 [1.0] \pm 0.025[0.05] \) for \( n = 3/2 [3] \) (SW17 Figures 11 and 13). We use these nominal values. See Section 3.3 and Figure 9 for the effect of these systematic uncertainties on the inferred parameters.

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$W = L \times 0.69$. Two examples of the synthetic light curves are shown in Figures 1 and 2.

### 3.1. Noise Model

To get a realistic model of the noise we adopted 5% uncertainties for all filters. We used a limiting magnitude of 22 in all filters, similar to the limiting magnitudes observed in the SN 2013fs campaign. The effective wavelengths and limiting magnitudes used in this work are summarized in Table 2. We converted the limiting magnitude to a flux error $\sigma_f$ and used the following equation to generate noise for the model:

$$\sigma^2 = \sigma_f^2 + (0.05f)^2$$

where $f$ is the model flux. We then drew the synthetic observations from a normal distribution with mean $f$ and variance $\sigma^2$. 

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**Figure 1.** Example of a synthetic light curve generated from SW17 of a star with $R = 500 R_\odot$, $A_V = 0.1$, and the parameters given in Table 1. The error bars are plotted, but are smaller than the markers. The time where the model is no longer valid is marked by the dotted vertical line.

**Figure 2.** Example of a synthetic light curve generated from SW17 of a star with $R = 50 R_\odot$, $A_V = 0.1$, and the parameters given in Table 1. The error bars are plotted, but are smaller than the markers. The time where the model is no longer valid is marked by the dotted vertical line.

$\Omega_L = 0.69$. Two examples of the synthetic light curves are shown in Figures 1 and 2.
Table 2
Filter Parameters Used

| Filter      | Effective Wavelength (Å) | Limiting Magnitude |
|-------------|--------------------------|--------------------|
| UVM2        | 2262.1                   | 22.0               |
| U           | 3605.0                   | 22.0               |
| B           | 4413.0                   | 22.0               |
| V           | 5512.1                   | 22.0               |
| R           | 6585.9                   | 22.0               |
| I           | 8059.8                   | 22.0               |
| ULTRASAT    | 2500.0                   | 22.0               |
| Kepler      | 6416.8                   | ...                |

3.2. Fitting Procedure

Fitting NS10/RW11/SW17 models with a simple log-likelihood test statistic is non-trivial because for different sets of parameters the models are valid for different time durations. One possible solution, which is not satisfactory, is to limit the analysis to a specific window of time. This approach was taken in Rubin et al. (2016), Valenti et al. (2014), and Bose et al. (2015). While this guarantees that all of the explored models are valid in the window, it does not take into account that the models must be valid over their entire range of validity (including data points outside the chosen window). We solve this problem by considering the P-value of each fit. The process is as follows.

1. Choose a set of model parameters.
2. Calculate the time range of validity given the parameters.
3. Calculate the P-value using

\[ P = 1 - \text{CDF}(\chi^2, \nu) \]  

where CDF is the cumulative distribution function, \( \chi^2 \) is the value of the chi-squared statistic of the fit, and \( \nu \) is the number of degrees of freedom (including only those data points that are within the time range of validity).

In this way we can ensure that the accepted fits are fully self-consistent, meaning they fit all of the relevant data and nothing but the relevant data. We defined the critical value to be \( P \)-value > 5%. This means that there is less than a 5% chance that the data came from a rejected model.

We generated models on a grid of \( \nu_{8.5}, R_s, \) and \( A_v \). For each point on the multi-dimensional grid we calculated the \( \chi^2 \) statistic, taking into account only those data points that were at times when the model is valid. For some cases we performed a Markov chain Monte Carlo (MCMC) which confirmed gives equivalent results, but was easier to use to explore the uncertainties. Note that there is a dependence on \( M_0 \), and on \( f_\lambda \) through the small prefactors in Equations (1) and (2). We discuss these in Section 3.3.

To test the ability to discriminate between models with \( n = 3/2 \) and \( n = 3 \), we performed a Monte Carlo where we drew 200 LCs with \( n = 3/2 \) and \( R = 500 R_\odot \), and 200 LCs with \( n = 3/2 \) and \( R = 50 R_\odot \). We then fit each model once assuming \( n = 3/2 \), and once assuming \( n = 3 \) (the incorrect polytropic index). We collected the \( P \)-values of the best fits and compared their distributions.

3.3. Systematic Uncertainties

SW17 models depend to some degree on underlying assumptions about the stellar structure. This appears through two parameters, \( M_0 \) and \( f_\lambda \), which weakly affect the results through the exponents \( \epsilon_1 \) and \( \epsilon_2 \) in Equations (1) and (2) and appear as the degenerate combination \( M_0 f_\lambda \). In addition, the predicted band luminosity depends on the color temperature and its relation to the photospheric temperature. This dependence is degenerate between \( R \) and \( \nu_{8.5} \). This is because the photospheric temperature depends on \( R^{1/4} \) and is practically independent of \( \nu_{8.5} \), while the bolometric luminosity varies like \( \nu_{8.5}^2 R \).

3.4. Results and Discussion

Our results are summarized in Figures 3 and 4. As was observed in Rubin et al. (2016), \( \nu_{8.5} \) (\( E/M \) in their paper) is statistically well constrained. However, in single bands \( \nu_{8.5} \) can only be considered a lower limit because of the unknown local host extinction. The addition of UV coverage reduces the uncertainties significantly. Most of the statistical power is in the
UV, shown by the minor differences between \( R + \text{UVM2} \) and \( \text{BVRI} + \text{UVM2} \). High-cadence UV reduces the uncertainties even more, to below the systematic errors for both large and small radii. It is noteworthy that for smaller radii there is a paucity of data within the valid time ranges—so a continuous, high-cadence campaign is valuable.

In Figures 5 and 6 we show the effect of different radii and extinction \( A_V \) under an observing plan of \( \text{BVRI} + \text{UVM2} \). The relative confidence interval in radius and \( \text{vs} \) is not very sensitive to the radius or extinction for radii above \( 500 \, R_\odot \). For lower radii the relative confidence interval increases, but remains less than a factor of two, indicating that the fit would still reconstruct a small radius. This sensitivity is primarily due to insufficient data in the first few days. Also, for very low values of extinction, the relative error becomes large, but the absolute upper limits are stringent at low extinction.

Figure 7 shows the results of the Monte Carlo simulations testing how well the models can discriminate between models with \( n = 3/2 \) and \( n = 3 \). For large radii the models can be quite easily discriminated between, achieving a plausible fit \((P\text{-value} > 0.05)\) for the incorrect polytropic index \( \sim 50\% \) of the time, with much lower likelihood than the correct polytropic index. However, at lower radii the models cannot be told apart. Note that fitting an \( n = 3 \) model to data drawn from an \( n = 3/2 \) model leads to larger radii (roughly by a factor of two). Figure 8 shows an example of the 95% confidence interval contours for \( R = 500 \, R_\odot, \, \text{vs} = 1, \, A_V = 0.1 \) for an observing program with \( \text{BVRI} + \text{UVM2} \).
correlation between $v_{38.5}$ and the radius, as well as the correlation between the radius and $A_V$, is noteworthy.

We evaluated the systematic uncertainties by exploring how the best fit parameters depend on the values of $T_{col}/T_{ph}$, $f_p$, and $M_{ej}$. The results are shown in Figure 9. For each case we studied we fit the model to the extreme cases of the systematic uncertainties in $T_{col}/T_{ph}$ and $f_p$. We report the most extreme best fit values for the radius and velocity as the systematic uncertainties in $T_{col}/T_{ph}$ and $f_p$. The ejected mass can in principle be constrained from observations (Dessart et al. 2010). Therefore we do not treat it as a systematic error, but we show in Figure 9 the effect of varying the ejected mass between 5 and 20 $M_\odot$. As can be seen, the effect is weak and shifts the best fit value by roughly $\pm 10\%$.

Our interim conclusions can be summarized as follows.

1. Coverage of a single optical band (e.g., R-band) cannot constrain the radius to less than a factor of two. Adding multiband coverage (BVRI or UBVRI) reduces the uncertainty on the radius to 30%–50%, and allows upper limits to be placed on the extinction up to a factor of four to six.

2. High-cadence UV coverage reduces the statistical uncertainty on the progenitor’s radius to $\pm 10\%$. While this is currently dominated by systematics, improved theories and measurements may help to further reduce it. The addition of UV coverage to measurements in the optical bands also allows for the determination of the local host extinction, which is currently challenging to determine, to within 30%–100%.

3. Shock-cooling models can discriminate between progenitors with $n = 3/2$ and $n = 3$ density profiles but this depends on the specific observing plan and cadence. Models with larger radii can be more easily discriminated between.

4. An important caveat is the assumption of a constant reddening law, and specifically $R_V = 3.1$. Poznanski et al. (2009) and more recently Rodríguez et al. (2014) and de Jaeger et al. (2015) showed for samples of SNe II-P that $R_V < 2$, assuming that SNe II are standard candles, which is a topic of debate. Also, $R_V$ for SNe may not be the same as $R_V$ for the Galaxy.

4. Application to KSN 2011a and KSN 2011d

KSN 2011a and KSN 2011d are two SNe II-P recently reported on by Garnavich et al. (2016, G16). The parameters of both SNe are presented in Table 3 (reproduced from G16). G16 analyzed their light curves with RW11 models of red supergiants (RSGs) and reported their best fit parameters to be progenitor radii of $280 \pm 20 R_\odot$ and $490 \pm 20 R_\odot$ for KSN 2011a and KSN 2011d respectively, both with explosion energies of $(2 \pm 0.3) \times 10^{51}$ erg (for $M_{ej} = 15 M_\odot$). Their analysis included LC data until peak magnitude. G16 concluded that KSN 2011a is not consistent with the simple shock-cooling model, but requires the shock breakout to occur from circumstellar material. This is primarily due to the fast rise observed over a few days. KSN 2011d was well fit by the model, and G16 interpreted an excess at the very early time of the LC as a shock-breakout flare. Here we reanalyze the photometry of KSN 2011a and KSN 2011d, taking into account the limitations of the validity of the models.

![Figure 9](image-url)
Photometry of KSN 2011a and KSN 2011d was obtained from P. M. Garnavich (2017, private communication). We binned the data into 2 hr intervals, taking the errors to be $\sigma/\sqrt{N} - 1$ where $\sigma$ is the standard deviation and $N$ is the number of samples in the interval. Because only a single band is available for the Kepler SNe, we assume no host galaxy extinction and treat our $v_{8.5}$ as a lower limit (as did G16).

As G16 noted in their paper, there is correlated excess in the LC of KSN 2011d prior to their “shock breakout.” Therefore, to assess whether there is a significant departure from a smooth rise, it is more reasonable to compare the LC to a smooth function. To describe the smooth function from which the shock breakout may or may not depart, we fit polynomials (third to ninth order) to the day before and day after the “shock breakout,” excluding the 10 points that G16 associated with it. These fits are shown in Figure 10. Our results are not sensitive to the degree of the polynomial.

We evaluated whether or not the shock breakout is significant in two ways. First, we examined the effect of binning on the significance and shape of the departure. The native cadence of Kepler is 30 minutes, while G16 binned their data into 3.5 hr bins. This leaves seven possible phases of binning. We tested how the shape and significance of the departure differ with all possible choices of binning. Second, we measured the probability of departure of all sets of 10 consecutive points in the LC in the data up to two days before the SN explosion. The purpose of this test is to demonstrate the “look elsewhere” effect, which makes a departure of $3\sigma - 4\sigma$ extremely likely when considering a sufficiently large amount of data, as is the case for KSN 2011d.

### 4.1. Results and Discussion

Our results for the fit parameters of KSN 2011a and KSN 2011d are presented in Table 4. We found that KSN 2011a is best fit by an $n = 3$ model, appropriate for the progenitor of a blue supergiant (BSG). We took $f_\mu = 0.1$, $\kappa_{0.34} = 1$, and $T_{col} = 1.0$ (see discussion in Section 2 on the choice of parameters). It was necessary to increase the errors by a factor of $1.85$ in order to achieve a best fit with $\chi^2$/dof = 1. The best fit is shown in Figure 11. We did not find acceptable fits to $n = 3/2$ models appropriate for RSGs. We find $R_s < 7.7 + 8.8\text{(stat)} + 1.9\text{(sys)} R_\odot$ and $v_{8.5} > 4.7 - 12.0\text{(stat)} - 1.4\text{(sys)}$.\footnote{The lower limit is due to the unknown extinction.}

We agree with G16 that a model of an RSG with a large radius does not fit the data. However, we find that a BSG model is consistent with the early-time data and does not require interaction to explain the fast rise.

Our result is in tension with the known association of SNe II-P with RSG progenitors in pre-explosion imaging (Smartt 2009, 2015). However, there is an observational bias against finding stars with small radii because they are fainter. Two additional factors suppress the detection of BSG progenitors: most progenitor detections are made with the Hubble Space Telescope (HST) with red filters (Smartt 2015), and extinction preferentially suppresses blue stars. Half of the SNe II that have high-quality HST pre-explosion data do not show a progenitor (Smartt 2015), moreover the upper limits that have been derived assume RSG progenitors. We conclude that BSGs have not been ruled out by pre-explosion imaging as the progenitors of many SNe II-P.

It is established that many SNe II have circumstellar material (CSM) (Niemela et al. 1985; Phillips et al. 1990; Garnavich & Ann 1994; Leonard et al. 2000; Matheson et al. 2000; Quimby et al. 2007; Gal-Yam et al. 2014; Shivvers et al. 2015; Khazov et al. 2016; Yaron et al. 2017). Some recent works (González-Gaitán et al. 2015; Gezari et al. 2015) argued that interaction with CSM may explain rise times for II-P SNe that are shorter than expected. They suggest that the rise is due to breakout from the CSM as opposed to shock cooling. The shock-cooling models considered in this work assume that CSM contributed negligibly to the LC. While it is plausible that the simplifying assumptions of shock-cooling models may not hold, some SNe II-P (Yaron et al. 2017) do fit the shock-cooling models well. Perhaps the fast-rising SNe in the literature are also associated with progenitors of small radius.

The model is cut off by the rapid drop in temperature ($T = 0.7\text{ eV}$ at $1.7\text{ days}$ for the best fit). Uncertainties relating to recombination, and the internal structure of the star make it difficult to assess whether a progenitor of small radius can or cannot support a plateau of $\sim 100\text{ days}$. From Figure 1 in G16, the LC is at $M \approx -15$ at 130 days, indicating a $^{56}\text{Ni}$ mass of 0.06 $M_\odot$, assuming full gamma-ray trapping. Note that the tail does not appear to follow cobalt decay, and fades at a rate closer to 1 mag per 50 days, which is unusual for an SN II-P.

Following Nakar et al. (2016) we can estimate the energy contributions to the light curve. The total $ET$ (time-weighted energy) from this SN can be roughly estimated by taking the plateau luminosity $M_\alpha = -17 - L_\alpha \approx 1.75 \times 10^{42}\text{ erg s}^{-1}$. Using the method presented in Nakar et al. (2016), we can estimate $ET$ and find that for a plateau luminosity of $1.75 \times 10^{42}\text{ erg s}^{-1}$ lasting for roughly 100 days we get $ET \approx 6 \times 10^{55}\text{ erg s}$. The $ET$ contribution of $^{56}\text{Ni}$ can be readily calculated as $2 \times 10^{55}\text{ erg s}$. This leaves $\sim 4 \times 10^{55}\text{ erg s}$ to be accounted for by cooling envelope emission. We use Equation (10) of Shussman et al. (2016a), which is reproduced here:

$$ ET \approx 0.15E_{\text{exp}}^{1/2}M_{51}^{1/2}R_\odot = 2.85 \times 10^{55}E_{51}^{1/2}M_{51}^{1/2}R_{500}\text{ erg s} $$

(10)
where  \( E_{51} = E / 10^{51} \text{erg} \),  \( M_{15} = M / 15 M_\odot \), and  \( R_{500} = R / 500 R_\odot \). Typical values of  \( ET \) are \(~0.5–7 \times 10^{55} \text{erg s} \) (Nakar et al. 2016). There is a factor of 5–10 uncertainty in the relation from Shussman et al. (2016a). Therefore a radius of 10  \( R_\odot \) induces an increase in  \( ET \) by roughly a factor of 5–10, which must be explained by an increase by a factor of 100 in  \( E_{\text{exp}} M_{\odot} \), i.e.,  \( E_{51} M_{15} = 100 \). One factor of 2 can be absorbed in the ejected mass, leaving a factor of 50 to be absorbed in  \( E_{51} \).

Rubin et al. (2016) found that  \( E_{51}/M_{10} \) spans two orders of magnitude (0.2–20), so such a large energy is not impossible. The relation of Shussman et al. (2016a) depends on MESA progenitors (Paxton et al. 2011), which may not be representative of stellar profiles just before explosion and are highly model-dependent. We therefore conclude that a radius of \(~10 R_\odot \) cannot be rejected based on considerations of energy budget and plateau length.

KSN 2011d is best fit by an \( n = 3/2 \) model, appropriate for an RSG progenitor. We took \( f_\rho = 1 \), \( \kappa_{0.34} = 1 \), and \( T_{\text{col}} = 1.1 \). It was necessary to increase the errors by a factor of 2.0 in order to achieve any reasonable fits. The best fit is shown in Figure 12. We did not find acceptable fits to \( n = 3 \) models appropriate for BSGs. We found that \( R_e = 111^{+89}_{-21} \text{(stat)} \text{–} 1 \text{(sys)} \) \( R_\odot \) and \( v_{8.5} > 1.8 - 0.3 \text{(stat)} - 0.3 \text{(sys)} \).

Our results do not agree with those of G16, but the reason is not entirely clear. We too find that an RSG model is in excellent agreement with the data, but our constraint on the radius excludes their best fit value. We are unable to recover the reported calculations of G16. The peak magnitude of their reported best fit parameters according to Equations (13)–(14) of RW11 (despite being beyond the limit of validity) is \( m_{\text{peak}} = 20.0 \) (including Milky Way extinction); however, using the same parameters, they calculate it to be \( m_{\text{peak}} = 20.23 \). This discrepancy of a quarter magnitude is the primary source of our conflicting results for the radii.

With regard to the claim of shock breakout we find that their result is not statistically significant. We examined all of the seven possible ways to bin 0.5 hr data points into 3.5 hr bins (the bin width used by G16), and present the most and least significant departures from a smooth rise in Figure 13. The most significant binning option closely resembles the data presented in G16, but the least significant looks dissimilar to the shock-breakout model in shape and is much weaker in significance. We find that the shape and significance depend strongly on the choice of binning, and conclude that the G16 result is not robust.

Our second test of significance shows that the Kepler data are so highly sampled that it is very probable to see 3\( \sigma \) and 4\( \sigma \) departures. Figure 14 shows the \( P \)-value of all collections of 10 consecutive points in the LC up to two days before the explosion. Not only are these likely, but in the noise before the SN explosion there are several departures with much lower \( P \)-value (higher significance). Given the number of data points, the probability of a false alarm is too high to warrant a claim of discovery. We conclude that G16’s result is not statistically significant, and more events of this nature must be studied.

### Table 4

| SN          | Progenitor | \( R_e/R_\odot \) | \( v_{8.5} \) | \( t_0 - 2454833.0 \) |
|-------------|------------|-------------------|--------------|----------------------|
| KSN 2011a   | BSG        | \( 90^{+50}_{-15} \text{(stat)} \text{–} 0.8 \text{(sys)} \) | \( >4.7 - 1.2 \text{(stat)} - 1.4 \text{(sys)} \) | 934.35 +0.09 -0.06 |
| KSN 2011d   | RSG        | \( 111^{+89}_{-21} \text{(stat)} \text{–} 1 \text{(sys)} \) | \( >1.8 - 0.3 \text{(stat)} - 0.3 \text{(sys)} \) | 1040.83 +0.09 -0.17 |

![Figure 11](image-url)  
Figure 11. Top: best fit to KSN 2011a. Blue points are the 2 hr binned data. The models are valid only for the times where the best-fit red line is drawn. Bottom: residuals.

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[Diagram with Flux [Arbitrary units] vs t-2455767.150 (Days) and Residuals]
5. Conclusions

We have explored the uncertainties in applying SW17 models of shock cooling to observations. Generating synthetic photometry with a realistic follow-up campaign and noise model, we have shown that ultraviolet coverage is necessary to constrain the progenitor’s radius in a meaningful way. It is clear that ground-based campaigns will be limited in their ability to constrain the progenitor’s radius. Shock-cooling models are discriminative with regards to the polytropic index for large radii. The uncertainties are strongly influenced by the limits of validity of the models, as was explained in Rubin et al. (2016), although several works have not treated them systematically—leading to incorrect conclusions.

Multiband light curves have the potential to constrain the local host extinction—given reasonable assumptions on $R_V$—with the best performance found with high-cadence ultraviolet coverage. A dedicated UV satellite such as ULTRASAT (Sagiv et al. 2014) would provide superior coverage even to that which was explored in this work.

We applied our methods to the SN LCs published recently by G16. Our findings do not agree with theirs. First, we were unable to reproduce G16’s results based on the information provided in their paper. Our estimates of the uncertainties take into account the model’s limitations. We find that an $n = 3$ model can be self-consistently fit to KSN 2011a. This is due in part to the fact that the observed plateau begins after $T = 0.7$ eV—where the model is no longer valid.
6. Summary

1. We have presented a method for comparing shock-cooling models to photometry self-consistently, taking into account the times for which the models are valid.
2. UV coverage at early times is necessary to statistically constrain the progenitor’s radius to within the systematic uncertainties.
3. UV coverage at early times in conjunction with optical bands can constrain the local host extinction under an assumption on $R_V$.
4. The ejected mass is weakly correlated with $v_{8.5}$ and $R_e$.
5. Both KSN 2011a and KSN 2011d can be self-consistently fit with BSG and RSG shock-cooling models respectively.
6. The shock breakout of KSN 2011d reported by G16 is not statistically significant and depends strongly on binning effects.

We thank E. Waxman, N. Sapir, and E.O. Ofek for helpful discussions. We thank P. Garnavich for the Kepler SN data. This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013) and the MATLAB package for astronomy and astrophysics (Ofek 2014). We also made use of the packages emcee (Foreman-Mackey et al. 2013) and corner.py (Foreman-Mackey 2016). A.G.-Y. and A.R. are supported by the EU via ERC grant No. [307260], the Quantum Universe I-Core program by the Israeli Committee for Planning and Budgeting and the ISF; by an ISF grant; by the Israeli ministry of science and the ISA; and by Kimmel and YeS awards.

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