High-Cadence, Early-Time Observations of Core-Collapse Supernovae From the TESS Prime Mission

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ABSTRACT

We present observations from the Transiting Exoplanet Survey Satellite (TESS) of twenty bright core-collapse supernovae with peak TESS-band magnitudes ≤ 18 mag. We reduce this data with an implementation of the image subtraction pipeline used by the All-Sky Automated Survey for Supernovae (ASAS-SN) optimized for use with the TESS images. In empirical fits to the rising light curves, we do not find strong correlations between the fit parameters and the peak luminosity. Existing semi-analytic models fit the light curves of the Type II supernovae well, but do not yield reasonable estimates of the progenitor radius or explosion energy, likely because they are derived for use with ultraviolet observations while TESS observes in the near-infrared. If we instead fit the data with numerically simulated light curves, the rising light curves of the Type II supernovae are consistent with the explosions of red supergiants. While we do not identify shock breakout emission for any individual event, when we combine the fit residuals of the Type II supernovae in our sample, we do find a > 5\sigma flux excess in the ~ 0.5 day before the start of the light curve rise. It is likely that this excess is due to shock breakout emission, and that during its extended mission TESS will observe a Type II supernova bright enough for this signal to be detected directly.

Key words: supernovae: general – techniques: photometric

1 INTRODUCTION

Core-collapse supernovae are a broad class of astronomical transients produced by the explosion of high mass (≥ 8M\textsubscript{\odot}) stars at the end of their lives. The most common of these core-collapse subtypes, indeed the most common of all supernova subtypes in a volume-limited sample, are the Type II supernovae (SNe II; Li et al. 2011; Smartt et al. 2009; Holoien et al. 2019a). The progenitors of these explosions are red supergiants with massive hydrogen envelopes that extend out to hundreds of solar radii (e.g., Smartt 2009, 2015), and they are empirically defined by the presence of hydrogen emission lines in their spectra (Filippenko 1997). Some SNe II show evidence of interaction with dense circumstellar material (CSM) in the form of narrow emission features, leading to their designation as SNe IIn (Schlegel 1990; Chugai & Danziger 1994).

While the majority of supernovae in a volume-limited sample will be Type II SNe, about one-fifth of the sample will be comprised of Type Ib and Ic events (SNe Ib/c; Li et al. 2011; Smartt et al. 2009). These are defined by a lack of hydrogen in their spectra, and are further differentiated based on the presence (SNe Ib) or lack (SNe Ic) of strong helium lines. SNe Ib/c, sometimes referred to as stripped-envelope supernovae, are thought to be the core-collapse explosions of massive stars that have lost their hydrogen (and in the case of SNe Ic, helium) envelopes. One particularly interesting subclass of stripped-envelope SNe are the broad-lined SNe Ic (Ic-BL), which exhibit unusually broad absorption features and are associated with long-duration gamma-ray bursts (Galama et al. 1998; Stanek et al. 2003). Further complicating the landscape of core-collapse taxonomy are the Type IIf supernovae that transition from resembling SNe II at early times to exhibiting the narrow helium emission of SNe Ib as they approach maximum light. The nearby SN 1993J is the well-studied archetype of these transitional events (Filippenko et al. 1993; Woosley et al. 1994; Maund et al. 2004; Stevance et al. 2020).

Building a theoretical understanding of the rising light curves of core-collapse explosions has been an area of intense research for some time, in large part because constraining progenitor prop-
euvities through archival observations is difficult (see the reviews by Smartt 2009 and Smartt 2015). Nakar & Sari (2010) and Rabinak & Waxman (2011) explore semi-analytic approaches to this problem, assuming an idealized polytropic density profile for the stellar structure in order to make connections between the rising light curve and properties of the progenitor star. Whether or not these idealized profiles actually occur at relevant depths within the star remains an open question (Morozova et al. 2016), and numerical models provide a means of studying these explosions with fewer restrictive physical assumptions.

Detailed simulations have been used to model observations of particularly well-studied events like SN 1987A (Woosley 1988; Urobin 1993; Urobin et al. 2019), SN 1993J (Nomoto et al. 1993; Dessart et al. 2018), SN 1999em (Baklanov et al. 2005), and SN 2011dh (Bersten et al. 2012). Because these calculations are often tailored for the specific events, it is difficult to generalize their results. To this end, many studies have tried to develop a more general understanding of how characteristics of the progenitor star impact the resultant supernova light curves. Examples include Young (2004), Kasen & Woosley (2009), Dessart et al. (2013), Sukhbold et al. (2016), and Curtis et al. (2020), and we make extensive use of the model light curves from Morozova et al. (2016) here. An excellent overview of our current understanding of core-collapse light curve physics is provided in Chapters 5 and 9 of Branch & Wheeler (2017).

Early-time observations of SNe Ia have become increasingly accessible in recent years (e.g., Shappee et al. 2016; Stritzinger et al. 2018; Yao et al. 2019; Fausnaugh et al. 2019), but due to their lower intrinsic luminosities and faster rise times, the sample of core-collapse supernovae observed at early times remains small. The first expected signature of these explosions occurs as the shock generated by the core-collapse approaches the surface of the progenitor, rapidly heating the photosphere to temperatures \( \gtrsim 10^5 \) K and producing a short-lived outburst of high-energy radiation with a duration comparable to the star’s light crossing time (e.g., Klein & Chevalier 1978; Ensiman & Burrows 1992; Nakar & Sari 2010). This shock breakout emission has been seen by the GALEX satellite in the ultraviolet (UV) for a pair of SNe II (Schawinski et al. 2008; Gezari et al. 2015), and in x-rays by the Swift satellite for the Type Ib SN 2008D (Soderberg et al. 2008; Modjaz et al. 2009). In principle this emission can also be seen in the optical and infrared (IR), but the weakness of the signature at these wavelengths coupled with its short duration (\( \lesssim 30 \) min at peak) makes it difficult to observe for even the highest cadence ground-based surveys.

Observations from the Kepler Space Telescope (Haas et al. 2010) and its extended K2 mission were able to address both of these issues, as the mission provided high quality photometry at an unprecedented 30-minute cadence. In fact, the Kepler observations of the bright SN Ia ASASSN-18bt provide the highest precision light curve of any supernova yet observed (Shappee et al. 2019; Dimitriadi et al. 2019). Two Kepler light curves of SNe II have been published by Garnavich et al. (2016), one of which shows a plausible detection of shock breakout emission.

In both the discovery of transiting exoplanets and the study of extragalactic transients, TESS is the natural successor to Kepler. The high-cadence TESS observations of the bright tidal disruption event ASASSN-19bt help to make it one of the best-studied optical TDEs to date (Holoien et al. 2019b), and Vallety et al. (2019) and Fausnaugh et al. (2019) have used TESS to study the early-time light curves of SNe Ia. In this paper we present observations of twenty bright core-collapse supernovae discovered over the course of the two year TESS prime mission. Although TESS images are deep enough to be competitive with current ground-based discovery surveys, there is a considerable delay between when observations are taken and when they are downlinked from the spacecraft and subsequently made available to the public. This delay is long enough that the mission is not an effective means of discovering bright long-lived transients. As such, all of the events in our sample were discovered by other surveys. It is critical that ground-based surveys quickly detect new transients in the TESS fields in order to enable follow-up spectroscopic confirmation and classification as well as multi-band photometric monitoring.

For this reason, the All-Sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. 2014; Kochanek et al. 2017; Holoien et al. 2019b) has been monitoring the TESS observing fields with increased cadence since the mission began. This monitoring program has proven very successful. ASAS-SN discovered the unusual Type Ia supernova ASASN-18bt, the first extragalactic transient to be studied with TESS data (Vallety et al. 2019), the spectacular tidal disruption event ASASSN-19bt in the TESS continuous viewing zone Holoien et al. (2019b), as well as a large fraction of the bright SNe Ia from TESS Sectors 1–6 studied by Fausnaugh et al. (2019). During the second year of the mission, the Zwicky Transient Facility (ZTF; Bellm et al. 2019; van Roestel et al. 2019) also adopted this practice, and as a result these two surveys are responsible for discovering the majority of the bright transients we study here. Additional discoveries were made during the course of standard operations by the Asteroid Terrestrial-impact Last Alert System (ATLAS; Tonry et al. 2018, 2 SNe), the D < 40 Mpc SN Survey (DLT40; Tartaglia et al. 2018, 2 SNe), the Mobile Astronomical System of TELescope Robots (MASTER; Lipunov et al. 2010, 2 SNe), and from Gaia alerts (Gaia Collaboration et al. 2016, 1 SN).

Table 1 summarizes the observational properties of the events in our sample, including their discovery dates, spectroscopic classifications, redshifts, and V-band Galactic extinctions (Ay; Schlegel et al. 1998; Schlafly & Finkbeiner 2011). The bulk of the sample (12 of the total 20 events) is comprised of normal Type II SNe, and most of our subsequent analysis focuses on these events. The rest of the sample is made up of three Type IIn SNe, and one each of Type Ib, Ic, Ic-BL, and Ibn SNe. For inclusion in this study, we required that events have peak apparent TESS-band magnitudes \( \lesssim 18 \) mag, and the majority of the light curves we present reach peak magnitudes brighter than 17 mag. The most impressive individual light curve in our sample is that of the Type IIn supernova DLT19c (SN 2019esa), which suffers from minimal TESS observing gaps and attains a peak magnitude of \( T_{\text{mag}} = 13.83 \pm 0.01 \).

In Section 2 we describe our TESS image subtraction pipeline. We discuss empirical fits to the observed core-collapse TESS light curves in Section 3. In Section 4 we discuss semi-analytic models for the early-time light curves of the Type II SNe and the resulting estimates of the progenitor radii and explosion energies. We then compare our TESS light curves to the numerically simulated light curves from Morozova et al. (2016) and investigate their use as calibrators for the semi-analytic models. Section 5 discusses shock breakout emission and its likely detection in the stacked light curves of the SNe II in our sample. Finally, we discuss our results in Section 6.

2 TESS IMAGE SUBTRACTION LIGHT CURVE GENERATION

There are a number of challenges associated with the TESS design that complicate the extraction of light curves, and considerable
effort has been expended by the community to develop pipelines to address them. The TESS Science Processing Operations Center (SPOC) pipeline generates calibrated light curves and validation products that are used by the TESS Science Office clearinghouse to identify promising transit candidates for additional follow-up. This pipeline is focused primarily on identifying transiting exoplanet signatures in the 200,000 stars selected for monitoring at 2-minute cadence (Jenkins et al. 2016; Stassun et al. 2018). The TESS Astero-seismic Science Consortium (TASC) has produced its own pipeline, optimized for studying stellar oscillations, which computes light curves for all of the known stellar sources observed by TESS (Lund et al. 2017; Handberg & Lund 2019). While these pipelines are designed to produce light curves for known sources, the open-source ISIS package offers a publicly available tool for producing light curves of any source observed by TESS (Feinstein et al. 2019).

Ultimately, none of these pipelines are ideally suited for studying extragalactic transients with TESS. Because they generally are optimized for high-precision observations of short duration signals associated with bright (T ≤ 15 mag) stellar sources, their corrective procedures often weaken or entirely remove features that evolve on longer timescales. This is a strength when searching for the fleeting flux dip during a planetary transit, but is clearly a problem when trying to study supernovae.

We have developed our own pipeline for the primary purpose of studying transients with TESS. Producing TESS light curves using the image subtraction technique provides a natural means of addressing some of the otherwise troublesome characteristics of TESS images. Most notably, the large 21′′ pixels and undersampled point-spread function (PSF) can make source blending a serious challenge for data reductions based on conventional aperture or PSF photometry techniques. This is not a problem for image subtraction, as light curves produced through this technique are sensitive only to changes in flux relative to the reference image.

We have applied many of the lessons learned over the course of operating the All-Sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. 2014; Kochanek et al. 2017) to develop an image subtraction pipeline optimized for use on the TESS full-frame images (FFIs). As in ASAS-SN data processing, the backbone of our TESS light curve generator is the ISIS image subtraction package (Alard & Lupton 1998; Alard 2000). We work with 750-pixel wide “postage stamps” cut out of the full FFIs. These postage stamps are generally centered on the location of the target, but are off-centered by necessity when the target is less than 375 pixels from a detector edge.

The basic automated image subtraction procedure we use to process the TESS FFIs broadly follows the standard ISIS package usage:

1. Produce 750-pixel postage stamps from each of the FFIs
2. Interpolate all images to the same astrometric solution
3. Select 100 high quality images for building the reference image
4. Scale and subtract this reference image from all postage stamps
5. Perform PSF photometry on the subtracted images

Images used to build the reference image must pass two tests. First, the associated FFI must not have any mission-provided data quality flags. This ensures that we avoid images compromised by momentum dumps and other issues described in the TESS Science Data Product Description Document. Second, the image must have PSF widths and sky background levels at or below the median values measured from all of that sector’s images. This second test is important for excluding images with moderately elevated background counts due to scattered light from the Earth and Moon, as these FFIs are not always flagged by the mission. While they are not used to construct the reference image, these images can still be used in the light curves.

In general, this basic approach is fairly reliable. We used it to produce the first published TESS supernova light curve (Vallely et al. 2019), observe the first promising repeating partial tidal disruption event candidate ASASSN-14ko (Payne et al. 2020), and study a sample of Southern Hemisphere δ Scuti stars (Jayasinghe et al. 2019). However, it occasionally yields inconsistent results or artificial trends. One problem is the undersampled PSF of the TESS images. This makes it useful in some cases to convolve the images with a Gaussian prior to performing the image subtraction. Since this Gaussian smearing is flux-conserving, the only intrinsic drawback of the technique is that it slightly lowers the signal-to-noise ratio of the resulting light curve.

Light curves produced through this Gaussian smearing method have been used to study the tidal disruption event ASASSN-19bt (Holoien et al. 2019b), characterize the short-term variability of ESO-Hs 99’s EXor outburst (Hodapp et al. 2019), and detect an 8.66-hour periodicity in the light curve of V1047 Cen (Aydi et al. 2019). One needs to be careful when using this technique, however. For targets located near other strongly variable sources, for example, applying the additional smearing will exacerbate signal pollution from the neighboring source. Similar issues also arise if the target is close to a bright source, as the subtraction artifacts associated with the bright source can significantly degrade the target light curve after the Gaussian smearing is applied. Given the large pixel scale of TESS, these issues are not uncommon, so care must be taken on a sector-by-sector basis to gauge the utility of this correction.

While the Gaussian smearing technique is useful for mitigating issues with the undersampled PSF, the most significant problem with TESS observations have proven to be background artifacts produced by scattered light from the Earth and Moon (see, e.g., Section 7.32 of the TESS Instrument Handbook) and the “strap” artifacts. These strap artifacts are produced by reflective metal straps located at the base of the silicon depletion region of the TESS detectors, and are most strongly present during epochs of significant scattered light (see Section 6.6.1 of the TESS Instrument Handbook for more details). The basic ISIS image subtraction procedure incorporates a 2-dimensional polynomial sky model to remove differential background variations, but this sometimes proves insufficient for the complex scattered light structures present in TESS images. After a talk by Marco Montalto at TESS Science Conference I, we were inspired to investigate the utility of including an additional round of background filtering in our image processing sequence. Ultimately, this led us to develop the following procedure, which has proven very effective at addressing these two issues.

We implement a procedure that utilizes a one-dimensional median filter, applied once along each axis of the CCD, so that it captures background structure in both the vertical and horizontal directions of the detector. This dual median filtering is a simple, but effective, image processing technique that is applied to each postage
TESS does not reduce four light curves. The first is a basic reduction (see Figure 2). For cases where it is evident that source 2 pixels and we are interested in relatively faint sources, the filtering flux of a point-source is located within a 2 \times 2 pixel area (Ricker et al. 2015). Since the width of the median filter is considerably larger than 2 pixels and we are interested in relatively faint sources, the filtering should not — and does not appear to — remove appreciable amounts of source flux from the image. Whenever possible, the validity of this assumption is confirmed for each target by comparing the light curve measured after median filtering with that of the base-level reduction (see Figure 2). For cases where it is evident that source flux was removed during the median filtering, the procedure is repeated using a median filter of larger width.

For each target, our automated image subtraction pipeline produces four light curves. The first is a basic ISIS reduction with neither of the TESS-specific corrective techniques applied. The second and third are produced by either applying the Gaussian smearing or median filtering corrections separately. The final light curve is produced by applying both techniques simultaneously. All four light curves are subsequently inspected manually, and the most appropriate reduction is selected for further analysis. Due to the reduced signal-to-noise inherent to the technique, the light curves that utilize Gaussian smearing are only considered further if they appear necessary. Our preferred ordering is: 1) basic ISIS reduction, 2) median filtering only, 3) Gaussian smearing only, 4) both Gaussian smearing and median filtering.

Figure 2 illustrates how important these corrective techniques can be, using the light curves of ASASSN-18qk, ZTF19abqlobb, and ASASSN-19or. For all three events the basic ISIS reduction is shown in black, the Gaussian smearing reduction is shown in orange, the median filtering reduction is shown in blue, and the dual correction reduction is shown in green. The importance of the median filtering is particularly evident in ZTF19abqlobb, as the two reductions that do not include this correction are completely dominated by background artifacts. It is not clear, however, that the additional Gaussian smearing utilized in the dual correction reduction mitigates any artifacts not already removed by the median filtering. Thus, for this target we select the median filter only reduction for subsequent analysis.

The differential light curves we produce measure changes in flux relative to the reference image. For transients like the supernovae we study here, one would prefer to build a reference image exclusively using observations obtained long before the transient’s rise. This ensures that no flux from the transient is present in the reference image. However, the relatively short 27 day monitoring window set by the TESS observing strategy means that this is not always possible. We address this concern by measuring the median value of the pre-rise flux measurements for each light curve and subtracting this flux value from all epochs. Introducing this flux offset shifts the entire light curve, ensuring it has a baseline of zero flux prior to the rise of the transient.

For transients observed by TESS over multiple sectors, it is in principle possible to generate a single reference image and then rotate it for use with each new pointing. In practice, however, the large pixel scale of the TESS observations makes this particularly difficult and introduces a large source of uncertainty. As in our prior work (e.g., Vallely et al. 2019; Holoien et al. 2019b; Tucker et al. 2020), we instead choose to construct independent reference images for each sector. When doing so, the flux offset of the first sector is determined from the pre-rise zero point described above. For subsequent sectors, the flux offset is chosen such that linear extrapolations from the last ~ 2 days of the earlier sector and the first ~ 2 days of the later sector match.

In addition to the scattered light and strap artifacts described earlier, TESS images can be compromised by a number of issues, including the spacecraft’s frequent momentum dumps, on board instrument anomalies, or ghost artifacts produced by nearby bright sources. Most of these issues are fairly well understood and are discussed in the TESS Instrument Handbook and TESS Data Release Notes3 documentation. While many of these conditions are noted by the mission provided quality flags that accompany the publicly available FFIs, it is often the case that non-flagged images are still compromised. For instance, the ASASSN-18qk FFI shown in Figure 1 is not flagged by the mission.

The final step of our data reduction process is a manual vetting of the light curves to identify and remove any remaining compromised epochs. This is a somewhat subjective process, in which we examine light curves for epochs dominated by uncorrected systematics and remove them. In practice, these compromised epochs almost always coincide with either momentum dumps or issues with the observations documented in the Data Release Notes for the sector in question. We do not use photometry from these compromised epochs in our analysis, but for completeness they are included, but flagged, in the TESS light curves that we provide in the online supplementary material.

3 https://archive.stsci.edu/tess/tess_drn.html

3  EMPIRICAL ANALYSIS OF LIGHT CURVES

In the literature, light curve rises are commonly characterized using a single-component power-law, \( f(t) \propto t^\alpha \) (See, e.g., Olling et al. 2015). While we prefer a slightly different treatment (described
Figure 1. The image processing sequence for the TESS observation of ASASSN-18qk obtained on JD 2458341.51 by Camera 1/CCD 3. Column (a) shows the FFI as available for download from MAST, column (b) shows the subtracted image produced using the basic ISIS image subtraction, and column (c) shows the image produced after applying the median filtering technique described in Section 2. The images in columns (b) and (c) are shown using the same scale, which has a dynamic range about 25 times smaller than that used in column (a). The top row shows the full 750-pixel wide postage stamps, while the bottom row is now zoomed in on a 100 x 100 pixel region centered on the location of ASASSN-18qk (circled in white). While the basic image subtraction process is able to effectively remove the large scale gradient visible in the FFI by fitting a low order polynomial to the differential background, it is clear that some of this background structure and the strap artifacts (the vertical lines) remain in the initial image subtraction. Both of these contaminants are removed after applying the median filtering technique.

Figure 2. The four light curves produced by our automated image subtraction pipeline for the TESS observations of the supernovae ASASSN-18qk (left), ZTF19abqhobb (middle), and ASASSN-19or (right). In the cases of ASASSN-18qk and, particularly, ZTF19abqhobb, it is clear that incorporating median filtering in the processing sequence greatly improves the light curve quality. In some cases, like ASASSN-19or, however, there is no clear benefit to the additional processing steps.
Figure 3. TESS light curves of the twenty core-collapse events in our sample. For each event, all of the TESS observations are shown in gray, with their rolling 6 hour median shown in black, and the best-fit model (Equation 2) for the rising light curve is shown in red. The two red tick marks at the bottom of each panel indicate the times of first and maximum light for each light curve. All of these light curves are included in machine-readable format in the online supplementary material.
below), to facilitate comparisons with existing studies we first fit the light curves as
\[
f(t) = \frac{h}{(1+z)^2} \left( \frac{t-t_1}{1+z} \right) + f_0. \tag{1}
\]
for \(t > t_1\) and as \(f(t) = f_0\) for \(t < t_1\). Here \(f_0\) is any residual background flux and \(t_1\) is the beginning of the model rise. The factors of \(1+z\) are introduced to account for redshift time-dilation, although this is a relatively small effect for this sample since all of the events are found at low redshift \((z < 0.063)\). Following Olling et al. (2015) and Fausnaugh et al. (2019), we only fit the light curves up to 40% of their peak flux. The resulting fit parameters are shown in Figure 4, and best-fit \(a\) values are presented in Table 2.

A single power law must eventually diverge from the actual light curve, forcing a somewhat arbitrary choice of a time to truncate the single power-law fits. We can minimize this problem by using
curve power-law fits of the form

$$f(t) = \frac{h}{(1+z)^2} \left( \frac{t-t_1}{1+z} \right)^{a_2(1+a_2(1-t_1)/t)} + f_0,$$  \hspace{1cm} (2)

up to (near) the light curve peak. The $t_1$ and $f_0$ parameters are the same, and at early times these fits become a $f \propto t^{-1}$ power-law. The $a_2$ term allows the model to follow the curvature of the light curve towards peak and so minimizes biases in estimates of the early time power-law exponent $a_1$. Mathematically, $a_2$ is related to the rise time, $t_{rise} = t_{peak} - t_1$, between the start of the rise at time $t_1$ and the time of the peak $t_{peak}$ by

$$a_2^{-1} = \ln \left[ 1 + \ln \left( t_{rise} \right) \right].$$  \hspace{1cm} (3)

Fitting $a_2$ or some other variant of $t_{rise}^{-1}$ has better error characteristics than trying to fit a parameter like $a_2^{-1}$ because some fits allow $a_2$ values consistent with zero while the TESS light curve does not include the peak. For our estimates of $t_{rise}$, we actually estimate $t_{peak}$ directly from the light curves as the time of peak flux in a rolling 6 hour binned light curve rather than from the $a_2$ values because we still only fit the curve power laws to near the time of peak and not over the peak – this would require a model with more parameters. Essentially, using the curved power law parameter $a_2$ to determine $t_{rise}$ suffers from the same sorts of biases as using the single power law does for estimates of $a_1$. For most fits, however, the estimates of $t_{rise}$ from $a_2$ are in rough agreement with our more direct estimates.

The curved power-law fits are shown by the red curves in Figure 3, and Figure 5 shows the peak absolute magnitude and rise time measured by TESS for each event as a function of the two curved power-law indexes, $a_1$ and $a_2$. Different colors are used to differentiate between spectroscopic subtypes, although the only clear difference among them is that the CSM-interacting SNe IIa in (shown in blue) exhibit substantially longer rise times. We exclude two events from this comparison: ASASSN-19acc because the TESS observations do not span the full rise to peak brightness, and Gaia19duc because it was already rising at the start of its TESS observations. We still obtain fits for these two events, and for completeness their parameters are reported along with those of the rest of the sample in Table 2. For comparison, Figure 5 also includes the results from fitting the same curved power-law to the numerical model light curves from Morozova et al. (2016). These models are discussed in detail in Section 4.2.

The single-component power-law’s $\alpha$ parameter and the curved power-law’s $a_1$ parameter should be closely related, and Figure 6 compares their best-fit values for the well-observed events in our sample. For light curves where $\alpha$ is well-constrained, the best-fit $\alpha$ values agree very well with the best-fit $a_2$ values. In cases where $\alpha$ is not well-constrained, however, the best-fit $\alpha$ values are consistently and systematically larger than the best-fit $a_1$ values. This suggests that, in addition to the avoidance of an arbitrary end point, curved power-law fits may provide a more robust means of characterizing early-time light curves than the single-component power-law (Equation 1).

There does not appear to be a strong correlation between the empirical light curve fit parameters and their peak luminosities or rise times, at least not in this sample. There is a tendency for larger values of $a_1$ to correspond to brighter peak luminosities in the Morozova et al. (2016) light curves, but this trend is very weak in the observed sample. We see some of the expected correlation between the parameter $a_2$ and the light curve rise time in Figure 5, but the quantitative agreement is poor compared to the uncertainties, confirming the need for a more complex model if the fits are to be used to estimate the rise time.

# 4 COMPARISON TO THEORETICAL MODELS

Next we compare our TESS observations to several theoretical models. First, following Garnavich et al. (2016), we use the semi-analytic treatments of Nakar & Sari (2010) and Rabinak & Waxman (2011). Next, we examine the more detailed numerical simulations of Morozova et al. (2016). Finally, we investigate using the simulated light curves to validate the semi-analytic treatments.

## 4.1 Semi-Analytic Models

We first analyze our TESS data using the same semi-analytic models that Garnavich et al. (2016) used when studying KSN2011a and KSN2011d. The Rabinak & Waxman (2011) and Nakar & Sari (2010) models describe core-collapse explosions as a time-dependent blackbody parameterized by the explosion energy, the density structure and opacity of the ejecta, and the mass and radius of the stellar progenitor. If one makes some reasonable assumptions about the ejecta and assumes a fixed progenitor mass, the models depend primarily on the explosion energy and progenitor radius. The model radius largely determines the light curve rise time, and the explosion energy largely determines the peak luminosity. In principle, these models should be a good tool for estimating these generally inaccessible parameters of the explosion when coupled with high cadence TESS or Kepler light curves.

For our analysis we use semi-analytic models that assume a power-law density structure with an index of $n = 3/2$, appropriate for the efficiently convective envelopes of red supergiant stars (RSGs). For the Nakar & Sari (2010) model these are simply their Equations 29 and 31. Some care must be taken when using the temperature description from Rabinak & Waxman (2011), however, as the unmodified $T_{ph}$ from Equation 13 does not describe the observed blackbody. This is instead described by the color temperature, $T_{col}$, and for the relevant timescales, $T_{col} \approx 1.23 T_{ph}$ (see Rabinak & Waxman’s Figure 1). Thus, for the Rabinak & Waxman (2011) model we use their Equations 13 and 14 and include the 1.23 scaling factor to convert $T_{ph}$ to $T_{col}$. We then assume a fully ionized hydrogen envelope (with opacity $\kappa = 0.34 cm^2 g^{-1}$) and set the normalization of the ejecta density to $f_{p} = 0.1$, a value consistent with RSG progenitors (Calzavara & Matzner 2004). We also assume a progenitor mass of 12.5 $M_\odot$, although we note that there is little difference if we instead use 15 $M_\odot$ like Garnavich et al. (2016).

The results are shown in Figure 7. While these models fit the TESS data well, we find that they require implausibly large explosion energies and small progenitor radii. For example, ASASSN-18gk is best fit with an explosion energy of $35 \times 10^{51}$ erg and a progenitor radius of 22 $R_\odot$ in the Rabinak & Waxman (2011) treatment and with an explosion energy of $46 \times 10^{51}$ erg and a progenitor radius of 29 $R_\odot$ in the Nakar & Sari (2010) treatment. These fits to ASASSN-18gk are shown in the top panel of Figure 7, and the best-fit values for the SNe II sample are shown in the lower panel. The explosion energies estimated from these fits are more than an order of magnitude larger than the typical $\sim 10^{51}$ erg values expected for core-collapse events, and the radii are small compared to the observed 500 – 1000 $R_\odot$ radii of RSGs (see, e.g., Levesque et al. 2005).

Sapir & Waxman (2017) provide a likely explanation for these
Figure 4. Single-component power-law fit parameters compared to rise time and TESS-band absolute magnitude for the core-collapse events in our sample as well as a suite of models computed by Morozova et al. (2016) from which we calculate synthetic TESS observations. The colored points indicate observed data, with SNe II in dark red, SNe IIn in light blue, and SNe Ib/c and IInb in dark green. The shaded points indicate model light curves. Progenitors simulated using MESA are shown as open squares, and those simulated using KEPLER are shown as solid triangles. Explosion energy is indicated by shading, with lighter shades corresponding to higher explosion energy.

Figure 5. Curved power-law fit parameters compared to rise time and TESS-band absolute magnitude for the core-collapse events in our sample as well as a suite of models computed by Morozova et al. (2016) from which we calculate synthetic TESS observations. Marker colors, shapes, and shades have the same meaning as in Figure 4.

results. A fundamental assumption of these semi-analytic models is that the ejecta opacity remains constant over time, meaning that $T$ will depend primarily on $R$. This assumption is reasonable for hydrogen dominated ejecta as long as $T \geq 8100 \, \text{K} = T_{R}$. At lower temperatures, recombination becomes important and modifies the opacity, complicating the relationship between $T$ and $R$ (See Figure 1 of Sapir & Waxman 2017). At longer wavelengths (wavelengths longer than that of the $U$-band (See Section 6.3 of Sapir & Waxman 2017). While Kepler observations use a shorter wavelength filter than TESS, they are not particularly well-suited to this treatment either, as the Kepler bandpass covers 4200–9000 Å, peaking at 5750 Å (Van...
Cleve & Caldwell (2016). In their Rabinak & Waxman (2011) models of the Kepler supernovae KSN2011a and KSN2011d, Garnavich et al. (2016) note that the radii of 280 $R_\odot$ and 490 $R_\odot$ they obtain are also small when compared to those observed for RSGs. Their analysis differs from ours somewhat in that they assume $f_p = 1.0$ and use $T_{ph}$ for their modeling. Note that there is a typo in their text stating that the models were computed using a density parameter of $f_p = 0.1$. If we make the same assumptions as Garnavich et al. (2016), we replicate their results. When we re-fit the KSN2011a and KSN2011d data instead using $T_{col}$ and assuming $f_p = 0.1$, we find that the explosion energy for both events increases from 2.0 to 3.9 x $10^{51}$ erg, and the progenitor radii are reduced by more than 70%, to 80 $R_\odot$ and 140 $R_\odot$, respectively. Morozova et al. (2016) also noted that fitting the semi-analytic Nakar & Sari (2010) model to their synthetic light curves led to overestimates of the explosion energy and underestimates of the progenitor radius. We will explore the question of whether these semi-analytic treatments can be empirically calibrated using the more detailed numerical models in Section 4.3

4.2 Numerical Simulations

Next, we compare our observations to the suite of 126 numerical SNe IIP simulations presented by Morozova et al. (2016). Morozova et al. (2016) used the stellar evolution codes MESA (Paxton et al. 2011, 2013, 2015) and KEPLER (Weaver et al. 1978; Woosley & Heger 2007; Sukhbold & Woosley 2014; Woosley & Heger 2015; Sukhbold et al. 2016) to produce two sets of nonrotating, solar-metallicity red supergiant (RSG) stars to serve as progenitors. To minimize confusion, we will refer to the stellar evolution code as KEPLER and the spacecraft as Kepler.

There are 23 KEPLER models in total, ranging in zero-age main sequence (ZAMS) mass from 9 to 20 $M_\odot$, and 19 MESA models ranging in ZAMS mass from 11 to 20 $M_\odot$, both in increments of 0.5 $M_\odot$. Morozova et al. (2016) explode these progenitor models using the SuperNova Explosion Code (SNEC; Morozova et al. 2015), which also generates both bolometric and filter-specific light curves. Using what is often referred to as the “thermal bomb” mechanism, SNEC initiates the explosions by injecting energy into the inner regions of the progenitor model after excising the innermost 1.4 $M_\odot$ to simulate the newly formed compact object. The amount of energy injected is chosen to yield the desired explosion energy. For each of the 42 progenitor models this process is repeated three times to produce final (asymptotic) explosion energies of $E_{fin} = 0.5$, 1.0, and 2.0 foe, where one foe is $10^{51}$ erg.

For the MESA models with ZAMS masses $\geq 15 M_\odot$, mass-loss is so significant that a larger ZAMS mass does not lead to larger pre-explosion mass. For example, both the 20 $M_\odot$ and 12.5 $M_\odot$ ZAMS mass MESA progenitors have pre-explosion masses of $\sim 11 M_\odot$. 

Figure 6. Comparing the initial rise indices from the single-component ($\alpha$) and curved power-law ($\alpha_1$) forms. The dashed line indicates $\alpha_1 = \alpha$. For well-constrained values of $\alpha$ the two fits agree quite well, but for poorly constrained values the single-component fits are consistently larger than those from the curved power-law fits.

Figure 7. Fits to TESS data using the semi-analytic models of Nakar & Sari (2010) and Rabinak & Waxman (2011). The top panel shows the best-fit models for ASASSN-18qk, a representative example of the fits obtained for the SNe II sample. After assuming a 12.5 $M_\odot$ progenitor, the best-fit Nakar & Sari (2010) model implies a progenitor radius of 29 $R_\odot$ and an explosion energy of $46 \times 10^{51}$ erg, while the best-fit Rabinak & Waxman (2011) model implies a progenitor radius of 22 $R_\odot$ and an explosion energy of $35 \times 10^{51}$ erg. Such implausible combinations of small radii and large explosion energies are a general feature of using these semi-analytic models to fit TESS observations. This can be seen in the lower panel, which shows the best-fit parameters for the 11 well-observed SNe II in our sample. Updated fit parameters for KSN2011a and KSN2011d (shown in magenta) are also included in the lower panel.
Figure 8. Examples of curved power-law fits to synthetic light curves calculated from the simulations of Morozova et al. (2016). The explosion energy and progenitor mass of the models increases from left to right. The left and middle panels show KEPLER progenitors, while the right panel shows a MESA progenitor. For each light curve the synthetic TESS data is shown in black, and the best-fit curve is shown in red. The brief shock breakout spike at the start of the light curves is excluded from the fits.

Figure 9. Peak absolute TESS magnitude and rise time for the synthetic light curves computed by Morozova et al. (2016) compared to the ZAMS mass, pre-explosion mass, and pre-explosion radius of the simulated progenitors. Progenitors simulated using MESA are shown as open squares, and those simulated using KEPLER are shown as solid triangles. Explosion energy is indicated by shading, with lighter shades corresponding to higher explosion energy. Note that a “foe” is equal to $10^{51}$ erg.

This leads to the features seen in several of the Figure 9 panels, and is ultimately a product of the strong de Jager et al. (1988) wind mass-loss prescription used for the MESA models. This prescription is argued to over-estimate the mass-loss rate (e.g., Smith 2014). The KEPLER models use the Nieuwenhuijzen & de Jager (1990) mass-loss prescription, where this effect is only seen for ZAMS masses above 23 $M_\odot$, beyond the range of masses considered by Morozova et al. (2016). We will focus primarily on comparisons to the KEPLER models in our discussion.

The Morozova et al. (2016) analysis focuses on synthetic g-band observations, but since SNEC models supernova emission as a blackbody, we can convert the bolometric luminosity and absolute g-band magnitudes from their work (all of which are available online at https://stellarcollapse.org/Morozova2016) into synthetic...
observations. We use the pyphot package (STScI Development Team 2013) to compute absolute g-band magnitudes and bolometric luminosities for a large sequence of $R_\odot$ blackbodies with 1 K spacing in $T_{\text{eff}}$ from 3,000 K to 303,000 K. To match the Morozova et al. (2016) models we first use

$$
\log[L] = \log[L(T_{\text{eff}}, R_\odot)] + 2\log[R/R_\odot]
$$

(4)

to determine the blackbody radius $R$ necessary to match the bolometric luminosity for each $R_\odot$ blackbody in our grid. We then use

$$
M_g = M_g(T_{\text{eff}}, R_\odot) - 5\log[R/R_\odot]
$$

(5)

to determine which combination of $T_{\text{eff}}$ and $R$ best matches the SNEC data, and this process is repeated for each epoch in the synthetic light curves. Three representative examples of these synthetic TESS observations are shown in Figure 8, and TESS-band versions of all 126 model light curves from Morozova et al. (2016) are included in the online supplementary material.

We fit the curved power-laws to the synthetic data after excluding the shock breakout feature, as SNEC light curves are unreliable for the first ~1/4 days prior to explosion due to the photosphere recedes and becomes better resolved (Morozova et al. 2015). These fits are shown by the red curves in Figure 8, and as was found for the observed light curves, Eqn. 2 fits the rising phases of the model light curves very well. The TESS-band peak absolute magnitude and rise time for all of the Morozova et al. (2016) models are shown in Figure 9 as a function of their ZAMS mass, pre-explosion mass, and pre-explosion radius.

To first order, these synthetic TESS light curves are comparable to the observed sample. Like the observed sample, the model light curves have rise times of order two weeks and peak absolute TESS-band magnitudes of approximately ~18 mag. In detail, however, the two samples differ somewhat. Notably, the Morozova et al. (2016) light curves cluster in relatively confined portions of parameter space compared to the significant diversity exhibited by the observed SNe. This is particularly evident in the $a$ and $\alpha_2$ distributions shown in Figure 4 and Figure 5, respectively. There are also differences in the peak brightness, as even the brightest model light curves only attain absolute TESS-magnitudes of about −18.5 mag, a mark exceeded by several SNe II in our sample.

Examining the relationships shown in Figure 9, a number of trends are readily apparent. First, larger explosion energies and larger progenitors tend to produce slower rising, more luminous light curves, with the peak luminosity being driven primarily by the explosion energy and rise time being driven primarily by the progenitor size, just as in the semi-analytic models. Among the MESA models there is a moderately strong correlation between ZAMS mass and rise time, but the relationship between pre-explosion mass and rise time is complicated by the effects of mass loss. For the KEPLER models there is a tight linear correlation between rise time and both ZAMS mass and pre-explosion mass. Morozova et al. (2016) found that there is a strong correlation between g-band rise time and progenitor radius. The rise times are naturally longer for the redder TESS-band, but the correlations between the rise time and the mass or radius are retained. While we focus our subsequent fits on the KEPLER models, the MESA models follow essentially the same radius-rise time relation.

The tight relation between progenitor radius and rise time for the KEPLER models shown in Figure 9 is well-fit by

$$
R/R_\odot = 85.8 \cdot (t_{\text{rise}}/\text{days}) - 267.6,\quad \text{with a scatter of } \sigma_R = 58.9 R_\odot \text{ in radius.}
$$

(6)

We obtain a similar fit for the KEPLER models between progenitor mass and rise time of

$$
M/M_\odot = 0.897 \cdot (t_{\text{rise}}/\text{days}) + 1.61,\quad \text{with a scatter of } \sigma_M = 0.77 M_\odot \text{ in mass.}
$$

(7)

Figure 10 shows a histogram of the radius estimates for the twelve SNe II in our sample, using the above relations to convert their measured rise times to estimates of their progenitor radii and masses. For comparison, we also include a histogram of the 62 Galactic RSGs for which Levesque et al. (2005) were able to obtain radius estimates from MARCS stellar atmosphere models (Plez 2003; Gustafsson et al. 2003). The two distributions are broadly similar, each with median values near $R \sim 640 R_\odot$ (corresponding to $M \sim 11 M_\odot$). It is worth noting that this result stands in some contrast to the Sloan Digital Sky Survey and Supernova Legacy Survey SNe II sample of González-Gaitán et al. (2015), which favors progenitors smaller than 500 $R_\odot$.

### 4.3 Semi-Analytic Model Calibration

While the physical values inferred from the Nakar & Sari (2010) and Rabinak & Waxman (2011) models are implausible, the fits themselves are quite good (e.g., the top panel of Figure 7). Here we investigate the possibility of calibrating the semi-analytic treatments using the models from Morozova et al. (2016). To do this we fit the rising light curves of all 126 Morozova et al. (2016) models using the Nakar & Sari (2010) and Rabinak & Waxman (2011) treatments, adopting the same fixed 12.5 $M_\odot$ progenitor mass as in Section 4.1 to facilitate consistent comparisons. Repeating this procedure using the true SNEC progenitor mass instead of a fixed value has no significant effect on the results because the semi-analytic models are only weakly dependent on progenitor mass.

The left and center panels of Figure 11 show the progenitor radii and explosion energies inferred by the semi-analytic treatments as a function of the true values in the Morozova et al. (2016) SNEC

![Figure 10](image-url)
simulations. Consistent with our earlier results and the discussion in Morozova et al. (2016), the Nakar & Sari (2010) and Rabinak & Waxman (2011) fits underestimate the true radii and overestimate the true explosion energies by considerable margins. They are, however, reasonably well-correlated.

This allows us to obtain best-fit quadratic curves as a means of calibrating the semi-analytic results. These best-fit curves are shown as the dot-dashed lines in Figure 11. For the Nakar & Sari (2010) treatment, the best-fit calibration curves are

$$R_{NS10} = 26.3 + 0.0375 \cdot R_{SNEC} + 6.64 \times 10^{-5} \cdot R_{SNEC}^2,$$

and

$$E_{NS10} = 0.224 + 2.47 \cdot E_{SNEC} + 0.655 \cdot E_{SNEC}^2.$$  

In these expressions, radii are in units of $R_\odot$ and explosion energies are given in units of $10^{51}$ erg. The residual scatters about the fits are $\sigma_R = 13.4 R_\odot$ and $\sigma_E = 1.3 \times 10^{51}$ erg, respectively. For the Rabinak & Waxman (2011) treatment, the best-fit calibration curves are

$$R_{RW11} = -39.1 + 0.152 \cdot R_{SNEC} + 2.23 \times 10^{-5} \cdot R_{SNEC}^2,$$

and

$$E_{RW11} = 0.559 + 1.41 \cdot E_{SNEC} + 0.153 \cdot E_{SNEC}^2.$$  

The scatters about these fits are $\sigma_R = 24.8 R_\odot$ and $\sigma_E = 0.6 \times 10^{51}$ erg.

We then use these fits curves to calibrate the inferred progenitor radii and explosion energy estimates obtained from the Nakar & Sari (2010) and Rabinak & Waxman (2011) models. Doing so we obtain the right panel of Figure 11. Compared to the non-calibrated model parameters shown in the lower panel of Figure 7, the calibrated parameters are considerably more reasonable, particularly the radius estimates. While improved from the non-calibrated explosion energy estimates (which are in many cases larger than 30 or even $50 \times 10^{51}$ erg), the explosion energy estimates remain about an order of magnitude larger than expected values, even after calibration. The discrepancy in explosion energy may be due to the limited range of explosion energies used by the Morozova et al. (2016) models. This forces significant extrapolation of the calibration curve in order to match the high luminosity observed events.

Figure 11. The semi-analytic models of Nakar & Sari (2010) and Rabinak & Waxman (2011) calibrated using the known progenitor properties of the Morozova et al. (2016) SNEC models. The left and center panels show the model parameters obtained when fitting the rising light curves of the Morozova et al. (2016) light curves using the Nakar & Sari (2010) and Rabinak & Waxman (2011) treatments. The left panel shows the progenitor radii inferred by the semi-analytic models as a function of the actual SNEC progenitor radius, and the center panel shows the inferred explosion energy as a function of its true value. Blue markers indicate the Nakar & Sari (2010) values, and red markers indicate the Rabinak & Waxman (2011) values. Best-fit quadratics to each set of models are shown by the dot-dashed lines. The right panel shows the best-fit parameters for the 11 well-observed SNe II in our sample after calibrating their semi-analytic fit parameters using the best-fit relations for progenitor radius and explosion energy. This procedure leads to more physically reasonable values, although the inferred explosion energies are still quite high.

5 SHOCK BREAKOUT SIGNATURES

One notable feature of the Morozova et al. (2016) models discussed in Section 4.2 that we do not find in the observed sample is the unmistakable shock breakout spikes at the start of the supernova light curves. The strength of this signal varies among the synthetic light curves, but it typically reaches $\geq 30\%$ of the peak brightness (see Figure 8). The time-steps used in the publicly available light curve files from Morozova et al. (2016) are just under 30 minutes, almost identical to the exposure length for a TESS FFI, so we would expect to see a signal of similar strength in the observations. However, visual inspection of the supernovae light curves in Figure 3 shows that this is not the case.

The existence of shock-breakout emission is a robust prediction of core-collapse theory that has been detected previously in observations at shorter wavelengths, so it is very likely present in the TESS data and is merely weaker than the SNEC models predict. That SNEC would simulate shock breakout imperfectly is not surprising. Morozova et al. (2015) note that during shock breakout the photosphere is in the outermost grid cell of the simulation and is spatially poorly resolved, rendering light curves in this early phase unreliable. They also note that the code assumes local thermodynamical equilibrium (LTE), imposing the same temperature for radiation and matter, an invalid approximation during shock breakout.

Shock breakout occurs on a timescale comparable to the progenitor’s light crossing time, $t_{lc} = R_\odot/c$. For the $\sim 640 R_\odot$ progenitors in our sample, this corresponds to a duration of about 30 minutes. Because of this short timescale, averaging over the FFIs may not aid in the detection of the shock breakout peak for an individual SN because it smears the peak out. We can, however, look...
for excess emission near the inferred time of first light, $t_1$ averaged over multiple SNe.

To do this, we stack the fit residuals for the 11 non-CSM interacting SNe II observed by TESS prior to explosion, subtract the best-fit curved power-laws from their observed light curves and combine all of the residuals. The CSM interacting SNe II are excluded from this analysis because the shock breakout signature is expected to be reprocessed and diluted by the dense CSM surrounding these supernovae. Figure 12 shows the resulting median residuals, focused on the timescales where we would expect to find shock-breakout emission and normalized such that the peak flux of the light curve is unity. The horizontal error bars indicate the time interval for each bin, and the vertical error bars show the 1σ uncertainty in the median for the stacked fluxes and residuals from each bin. There is a clear, statistically significant excess visible in the stacked observations clustered just prior to $t = t_1$, the same time where we would expect tofind signatures of shock breakout. We find a 3σ excess at $t - t_1 = -0.1$ days, and this grows to $> 5σ$ significance when we include all of the bins from $t_1 - 1.0$ to $t_1$ days (the shaded region shown above).

The second issue is that while the shock break out peak lasts only approximately the light crossing time $t_{lc}$, it is followed by a slower phase in which the ejecta expand and cool nearly adiabatically before the rise to peak begins. The time scale for this phase of 0.5 to 1.0 days for RSGs is comparable to the transition time scale between the planar and spherical phases of the Nakar & Sari (2010) model. While dimmer than the initial spike, this tail is not negligible and will temporally broaden the signal. Combining these effects, the structure of the residuals does not seem surprising.

We can use the amplitude of the excess to roughly estimate (or limit) the amplitude of shock break out signals in the TESS band. The energy of the excess is $E_{ex} = \epsilon F_{peak} \Delta t$, where $\epsilon = 0.02$ is the amplitude of the excess relative to the peak flux $F_{peak}$ (unity in Fig. 12) and $\Delta t \approx 0.5$ days is the duration of the observed excess. This must be equal to the energy in the break out pulses, $F_{SBO} \Delta t_{SBO}$, where $F_{SBO}$ is the mean flux over time $t_{SBO}$. Combining these, we must have that $F_{SBO}/F_{peak} = \epsilon \Delta t/t_{SBO}$. Clearly we cannot have that most of the shock break out energy is emitted in the light crossing time, since for $t_{SBO} = t_{lc} = 0.5$ hours, $F_{SBO}/F_{peak} \approx 0.5$ would produce signals easily visible in Fig. 3. However, if we spread the emission over the overall time scale of the initial decline, $t_{SBO} \approx 8$ hours, then $F_{SBO}/F_{peak} \approx 0.06$. Such a smaller amplitude signal would be relatively easy to hide for the present sample.

6 DISCUSSION AND CONCLUSIONS

In this work we have presented the first TESS observations of core-collapse supernovae. Due to its large survey area and continuous monitoring, TESS is particularly well-suited for obtaining high-cadence early-time observations of bright extragalactic transients such as these SNe. However, aspects of the TESS images like their large pixel size, the straps, and the many scattered light artifacts likely be smeared over ~ 0.5 days just by the uncertainties in how to temporally align the events.

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can make analyzing these observations difficult. In Section 2 we have described an image subtraction pipeline that addresses the most common issues present in TESS data. We have optimized this pipeline for the study of extragalactic transients, but these techniques would likely be beneficial for other TESS applications as well.

We do not identify any strong trends between the parameters of our empirical light curve fits and the peak luminosities of the SNe. The semi-analytic models of Nakar & Sari (2010) and Rabinak & Waxman (2011) fit the data well, but the resulting estimates of the explosion energies and progenitor radii are not physical, probably because the TESS bandpass is too red. This also appears to be true for Kepler observations. Numerical light curves computed using SNEC yield more plausible estimates, and may provide a means through which the semi-analytic models can be calibrated. We briefly explored this possibility in Section 4.3. Here we simply fit polynomials to convert the semi-analytic energies and radii to better agree with the input models. Doing so produced more physically reasonable radius estimates and improved explosion energies, although even after calibration the inferred explosion energies remained quite high. A similar approach, which we did not explore here, would be to modify the dimensionless factors and perhaps the exponents of the semi-analytic models to achieve the same end.

Broadly speaking, the synthetic TESS light curves produced from the Morozova et al. (2016) models are comparable to what we observe in our sample. The empirical fit parameters for the two data sets are reasonably similar, the rise times are of order two weeks, and the peak absolute TESS-band magnitudes are of order ~18 mag. In detail, however, the Morozova et al. (2016) models appear to differ somewhat from the observed light curves. The SNEC models cluster in relatively confined portions of parameter space compared to the observed light curves, failing to reproduce the full diversity implied by the observations. The observed power law indices found for the rise tend to be shallower but also more diverse. Additionally, even the most energetic SNEC explosions of the most massive model progenitors only reach absolute TESS-magnitudes of about ~18.5 mag. Four of the twelve SNe II in our sample have higher peak luminosities.

A detailed study of these discrepancies is beyond the scope of this work, but we can consider potential explanations. When compared to other numerical models of core-collapse explosions, the Morozova et al. (2016) models are relatively simple. They do not include contributions from radioactive $^{56}$Ni or interactions with CSM, for example. These simplifications allow Morozova et al. (2016) to study a range of models broadly dispersed throughout the progenitor size and explosion energy parameter spaces. In the absence of significant mixing, contributions from radioactive $^{56}$Ni are likely small during the early rise of core-collapse light curves, but subsequent studies by Morozova et al. (2017) and Morozova et al. (2018) have argued that emission enhancement due to CSM interaction is an extremely important aspect of early SNe II light curves. This is, however, inconsistent with pre-supernova observations of Type II progenitors Johnson et al. (2018). A more likely explanation is that SN progenitors do not have the “sharp” edges of stellar evolution models, instead having extensions to their envelopes driven by pulsations, which do not in turn produce high mass density winds. Additional problems may arise from simplifications in the SNEC treatment, like its assumption of LTE throughout the model. Morozova et al. (2018) note that while SNEC’s bolometric light curves generally agree quite well with the multigroup radiation-hydrodynamic code STELLA (Blinnikov & Bartunov 1993, 2011), their synthetic filter light curves do exhibit minor discrepancies. More self-consistent explosion models, like those of the PUSH framework (Perego et al. 2015; Curtis et al. 2020), might also modify the very early light curves.

We find a mean pre-rise flux excess for the Type II SNe of ~2% of the peak flux in the ~0.5 days before the estimated start of the rising light curve which is plausibly due to the shock break out. In this scenario, the excess cannot be dominated by energy from an initial peak lasting only the light crossing time (~0.5 hours), as this would lead to visible peaks in the individual light curve. The energy would have to be emitted over a longer time period. We roughly estimate that the signal should be directly detectable for an SNe II with a peak TESS magnitude brighter than about 15 mag. The switch from a 30-minute cadence to a 10-minute cadence in the extended TESS mission will make searches for such emission from stripped SNe more feasible. In addition to the bright SN Ibn and SN Ib presented here, TESS has already observed multiple SNe Ia (Fausnaugh et al. 2019) and a tidal disruption event (Holoi et al. 2019b) brighter than 15 mag, so it is very likely that TESS will observe a sufficiently bright SN II to allow a direct detection. Even without a direct detection, stacking analyses like that used here will steadily improve.

TESS provides a valuable new means of studying core-collapse supernovae, one that will only become more significant as the sample of early-time TESS observations grows. Better models to interpret the early-time emission are clearly needed. In particular, (semi-analytic) models of both the shock break out peak, its decay and the initial rise appropriate for these redder bands would be very useful, as would methods of using expensive numerical simulations to calibrate simpler models that can be easily fit to the data. With larger numbers of SNe, we would also hope to see clear statistical patterns begin to appear in the distributions and correlations of the parameters describing the initial light curve rises. As a continuing mission, there remains the chance of a spectacularly bright SN that can be followed in detail at the full TESS FFI cadence.

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