Late-time Observations of Calcium-rich Transient SN 2019ehk Reveal a Pure Radioactive Decay Power Source

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Abstract

We present multiband Hubble Space Telescope imaging of the calcium-rich supernova (SN) SN 2019ehk at 276-389 days after explosion. These observations represent the latest B-band to near-IR photometric measurements of a calcium-rich transient to date and allow for the first opportunity to analyze the late-time bolometric evolution of an object in this observational SN class. We find that the late-time bolometric light curve of SN 2019ehk can be described predominantly through the radioactive decay of $^{56}$Co for which we derive a mass of $M(^{56}\text{Co}) = (2.8 \pm 0.1) \times 10^{-2} M_\odot$. Furthermore, the rate of decline in bolometric luminosity requires the leakage of $\gamma$-rays on timescale $t_\gamma = 53.9 \pm 1.30$ days, but we find no statistical evidence for incomplete positron trapping in the SN ejecta. While our observations cannot constrain the exact masses of other radioactive isotopes synthesized in SN 2019ehk, we estimate a mass ratio limit of $M(^{57}\text{Co})/M(^{56}\text{Co}) \leq 0.030$. This limit is consistent with the explosive nucleosynthesis produced in the merger of low-mass white dwarfs, which is one of the favored progenitor scenarios in early-time studies of SN 2019ehk.

Unified Astronomy Thesaurus concepts: Supernovae (1668); Type Ib supernovae (1729); White dwarf stars (1799); Nuclear abundances (1128); Nucleosynthesis (1131)

1. Introduction

Calcium-rich (Ca-rich) transients are a peculiar class of thermonuclear transients that were identified almost two decades ago and have been studied extensively ever since (Filippenko et al. 2003; Perets et al. 2010; Kasliwal et al. 2012). These supernovae (SNe) are defined observationally by fast-evolving light curves ($t_e < 15$ days) and low overall luminosities ($M_{\text{peak}} > -16$ mag), both photometric properties being consistent with typical ejecta and $^{56}$Ni mass estimates of $0.5 M_\odot$ and $0.1 M_\odot$, respectively (Taubenberger 2017). The “Ca-rich” naming convention is in part derived from their spectroscopic evolution wherein these transients exhibit prominent [Ca II] emission features in their photospheric and nebular phase spectra compared to [O I] emission ([Ca II]/[O I] > 2; Milisavljevic et al. 2017). However, while Ca-rich transients appear to cool most efficiently through Ca II transitions over O I, it is debated whether these explosions are in fact more abundant in calcium ions than oxygen by mass (Perets et al. 2010; Milisavljevic et al. 2017). As a result, we choose to adopt the nomenclature presented by Shen et al. (2019) and refer to these objects as “calcium-strong transients” (CaSTs) throughout the paper.

The majority of known CaSTs are located in the outskirts of early-type host galaxies (Perets et al. 2011; Kasliwal et al. 2012). However, as the number of confirmed CaSTs increases, there appears to be a substantial spread in their host morphology that includes both disk-shaped and elliptical galaxies (Perets et al. 2010; Perets 2014; Milisavljevic et al. 2017; De et al. 2021). Additionally, CaSTs are typically found in galaxy groups or cluster environments with no evidence of star formation, and their explosion sites are generally associated with old stellar populations (Perets et al. 2010, 2011; Lyman et al. 2014; Foley 2015; Lunnan et al. 2017). Consequently, typical progenitor systems proposed for CaSTs have included a white dwarf (WD) with a neutron star (NS), a black hole (BH), another WD, or a nondegenerate main-sequence star companion (Rosswog et al. 2008; Perets et al. 2010; Metzger 2012; MacLeod et al. 2014; Sell et al. 2015; Margalit & Metzger 2016; Bobrick et al. 2017; Zenati et al. 2019a, 2019b). Nevertheless, the observed diversity in host galaxies and explosion characteristics suggests heterogeneity among CaST progenitors (Milisavljevic et al. 2017). Therefore, increasing the sample size of objects and performing novel studies of new CaSTs will help uncover the origins of this unique explosion class.

On 2019 April 29 (MJD 58602.24), the closest known CaST, SN 2019ehk, was detected in the nearby galaxy NGC 4321 (M100) at 16.2 ± 0.4 Mpc (Jacobson-Galán et al. 2020a; Nakaoka et al. 2020). Observations of SN 2019ehk were acquired as early as ~10 hr after explosion ($t_{\text{exp}} = 58601.8 \pm 0.1$ days, in MJD), which allowed for unprecedented multiwavelength coverage of this event. Fast-cadence observations revealed a double-peaked light curve in optical bands, with the primary peak being temporally coincident with luminous X-ray emission ($L_X \approx 10^{41} \text{erg s}^{-1}$), the first instance of X-ray detections in a CaST. Combined with flash-ionized Hα and He II spectral lines at ~1.5 days after explosion, these observations revealed the presence of dense circumstellar material (CSM) in a compact shell surrounding the progenitor system at the time of explosion. Jacobson-Galán et al. (2020a, hereafter WIG 2020a) also presented deep Hubble Space Telescope...
(HST) pre-explosion imaging of the explosion site that constrained the possible progenitor of SN 2019ehk to be either a massive star in the lowest-mass bin (\(\lesssim 10 M_\odot\)) or a WD in a binary system. Alternatively, Nakaoka et al. (2020) suggest that SN 2019ehk is an ultrastripped SN candidate that arose from an He (or C/O) star + NS binary configuration. The latter scenario, however, is difficult to reconcile with the presence of H-rich material in the local circumstellar environment. Recently, based on derived oxygen mass, De et al. (2020) concluded that the progenitor of SN 2019ehk was a low-mass massive star (\(M_\text{ZAMS} \approx 9-9.5 M_\odot\)) that lost most of its H envelope via binary interaction prior to explosion. We explicitly address the viability of this alternative scenario of a “calcium-rich Type Ib” SN proposed by De et al. (2020) in Section 4.3, and we offer an additional, independent calculation of the oxygen mass parameter.

Photometric observations of SNe at late-time phases (\(t \gtrsim 300\) days) enable the study of explosion power sources and, consequently, the progenitor system responsible for a given transient. To date, only a few CaSts and CaSt candidates have been detected in photometric observations at \(t \gtrsim 250\) days after explosion, e.g., PTFO101uv (Kasliwal et al. 2012), SN 2012hn (Valenti et al. 2014), and SN 2018gwo (De et al. 2021). The close proximity of SN 2019ehk provides the first opportunity to accurately reconstruct the late-time bolometric light-curve evolution of a CaSt using multicolor observations that span from \(H\) band to the near-IR at \(\sim 3\) days after explosion. In Section 2 we present observations and data reduction of SN 2019ehk. In Section 3 we present modeling of SN 2019ehk’s bolometric light-curve evolution and derive physical properties of the radioactive-decay-powered explosion. In Section 4 we discuss how SN 2019ehk compares to other late-time SN light curves and how these new observations constrain the SN progenitor system.

2. Observations

Early-time observations of SN 2019ehk were conducted with a variety of ground-based telescopes from 2019 April 28 to August 2 (\(\sim 0.5-96.2\) days after explosion). Specifics about reduction techniques and instruments used are presented in WJG20a. Following WJG20a, we adopt a host galaxy distance of \(16.2 \pm 0.400\) Mpc, distance modulus \(\mu = 31.1 \pm 0.100\) mag, redshift \(z = 0.005 \pm 0.001\), and time of explosion \(t_{\text{exp}} = 58601.8 \pm 0.1\) days (MJD). The Milky Way color excess along the SN line of sight is \(E(B-V) = 0.0227\) mag (Schlegel et al. 1998; Schlafly & Finkbeiner 2011), and the host galaxy reddening is \(E(B-V) = 0.47 \pm 0.10\) mag (WJG20a), both of which we correct for using a standard Fitzpatrick (1999) reddening law \((R_V = 3.1)\). Understanding whether alternative \(R_V\) values are more appropriate descriptors of the host galaxy extinction is beyond the scope of this paper, and we proceed with \(R_V = 3.1\) so as to remain consistent with other studies on SN 2019ehk.

We obtained additional late-time, ground-based imaging of SN 2019ehk on 2020 January 1 \(\sim 247.2\) days after explosion) in \(r\) and \(i\) band with the Inamori-Magellan Areal Camera and

8 Nakaoka et al. (2020) and De et al. (2020) assume a host galaxy reddening range of 0.5–1.0 mag that is derived from a comparison between SN 2019ehk and two particular SNe. Our adopted color excess from WJG20a lies at the lower end of this range and is based on (i) direct measurements of Balmer decrement of the H ii region from pre-explosion spectroscopy of the SN explosion site and (ii) color comparisons to CaSt and SN Ic samples (e.g., Figure 10 in WJG20a).

Spectrograph (IMACS; Dressler et al. 2011) on the Magellan Baade 6.5 m Telescope. The data were first bias-subtracted and flat-fielded, and then three frames per filter were averaged using PyRAF. From these observations, we measure an \(i\)-band AB magnitude of 21.40 \(\pm 0.06\) mag and derive an \(r\)-band upper limit of \(\gtrsim 23.51\) mag.

Late-time HST imaging of SN 2019ehk was first obtained in F275W, F336W, F438W, F555W, and F814W filters (2000–10000 \(\AA\)) with the Wide Field Camera 3 (WFC3) through HST program PID-15654 (PI Lee) on 2020 January 29 and March 15 (\(\sim 276.2\) and 321.8 days after explosion, respectively). Additional UVIS/IR WFC3 imaging was taken in F555W, F814W, F110W, and F160W filters (0.45...1.7 \(\mu m\)) on 2020 May 21 (\(\sim 389.0\) days after explosion) under HST program PID-16075 (PI Jacobson-Galán). Following methods in Kilpatrick et al. (2018), we reduced all HST imaging using the hst123\(^9\) Python-based reduction package. We downloaded all relevant calibrated WFC3/UVIS and IR images \((flcflt\) frames) from the Mikulski Archive for Space Telescopes.\(^{10}\) Each image was then aligned to a common reference frame using TweakReg. We then drizzled images from common filters and epochs using astrodrizzle. Finally, we performed photometry in the original, calibrated images using dolphot (Dolphin 2000). We present the observed apparent magnitudes (AB system), as well as \(3\) upper limits derived from fake star injection, for all late-time HST filters in Table A1. The late-time false-color RGB image of SN 2019ehk and its host galaxy is shown in Figure 1. The complete multiband light curve of SN 2019ehk is shown in Figure 2(a).

3. Analysis

In Section 3.1 we describe the derivation of SN 2019ehk’s bolometric light curve, which spans \(\sim 0.5-388.8\) days after explosion. In Section 3.2 we apply an analytic formalism for a radioactive-decay-powered emission to fit the late-time light-curve evolution of SN 2019ehk and derive physical parameters of the explosion.

3.1. Pseudo-bolometric Light Curve

At \(t < 97\) days, we construct a pseudo-bolometric light curve of SN 2019ehk through a combination of multiband photometry from multiple ground-based telescopes (see, e.g., WJG20a). For each epoch, luminosities are calculated through trapezoidal integration of SN flux in \(uvBvegoriz\) bands (3000–10000 \(\AA\)). Uncertainties are estimated through a Monte Carlo simulation that includes 1000 realizations of the data. In time intervals without complete color information, we interpolated between light-curve data points using a low-order polynomial spline. This method is different from that used by WJG20a, who created a bolometric light curve of SN 2019ehk through fitting of the spectral energy distribution (SED) with a blackbody model. The two methods lead to consistent luminosities for \(t \lesssim 40\) days. However, the blackbody model overpredicts the total flux at later phases owing to the prominent [Ca ii] and Ca ii line transitions that dominate the SED flux in some bands. As expected, the blackbody model becomes an inadequate description of the observed emission as soon as the SN transitions to an emission-dominated spectrum in the nebular

\(^{9}\) https://github.com/charliekilpatrick/hst123

\(^{10}\) https://archive.stsci.edu/hst/
phase. Therefore, we apply the trapezoidal integration method to determine the bolometric luminosity at all phases for consistency.

For late-time observations at $t > 276$ days, we also perform trapezoidal integration of SN 2019ehk’s SED in HST filters ($0.3–1.7 \mu m$). Because infrared (IR) HST imaging was only taken during the last epoch (+389 days; Figure 2(a)), we extrapolate backward in time in order to apply an IR correction that constitutes $\sim 30\%$ of the bolometric flux to the HST observations at +276 and +322 days after explosion. We proceed with the assumption that such a correction is not necessary for early-time epochs ($t \lesssim 100$ days) where IR contribution is negligible. Furthermore, we note that there may be a small fraction ($\lesssim 5\%$) of UV SN flux that is not taken into account when constructing the late-time bolometric luminosities owing to observed nondetections in the F275W, F336W, and F475W HST filters. The complete bolometric light curve of SN 2019ehk is presented in Table A2 and plotted in Figure 2(b).

### 3.2. Radioactive Decay Model

The late-time light-curve evolution of most SNe is governed primarily by the energy deposition rate of the radioactive decay...
chain $^{56}\text{Ni} \rightarrow^{t_{\text{dec}}=8.77 \text{ days}}^{56}\text{Co} \rightarrow^{t_{\text{dec}}=111.3 \text{ days}}^{56}\text{Fe}$ (Arnett 1982).

The $\gamma$-rays released in this process are then thermalized in the expanding SN ejecta, and, for phases $t \gtrsim 60$ days after explosion, $^{56}\text{Co}$ beta-decay will power the bolometric light curve until the decays of other radioactive species such as $^{57}\text{Co}$ and $^{55}\text{Fe}$ become dominant (e.g., $t \gtrsim 500$ days after explosion; orange dotted–dashed line in Figure 2(b)).

In this section, we describe the components of a purely radioactive-decay–powered model and apply it to fit the bolometric light curve of SN 2019ehk at late times. The total energy generated in each beta-decay can be defined by (i) $\gamma$-rays released in the decay chain, (ii) kinetic energy of emitted positrons, and (iii) $\gamma$-rays produced from electron–positron annihilation. Regardless of the generation process, all $\gamma$-rays produced have a finite probability of escaping the ejecta before depositing their energy. The limiting case where the $\gamma$-ray photons from the $^{56}\text{Co}$ decay are completely trapped and thermalized within the expanding ejecta is shown in Figure 2(b) (green dotted–dashed line). However, observations of Type Ia SNe (SNe Ia) and stripped-envelope Type Ib/c SNe (SNe Ib/c) clearly show more rapid light-curve decays, indicating that a fraction of $\gamma$-rays are able to escape before depositing their energy into the ejecta (Cappellaro et al. 1997; Wheeler et al. 2015).

Following Clocchiatti & Wheeler (1997), the $\gamma$-ray leakage can be parameterized in terms of a trapping timescale, $t_{\text{tr}}$. The kinetic energy from positrons can also be thermalized, and therefore their potential leakage from the SN ejecta can be described by a positron trapping timescale, $t_{\text{e}}$.

To model the late-time light curve of SN 2019ehk, we apply the formalism outlined in the Appendix of Valenti et al. (2008a) for energy deposition from radioactive decay during the nebular phase ($t \gtrsim 60$ days). This model is very similar to the Bateman equation (see, e.g., Equation (16) in Seitenzahl et al. 2014) in how it can be used to derive masses of radioactive isotopes and trapping timescales, $t_{\text{tr}}$ and $t_{\text{e}}$. However, unlike the Bateman formalism, this method self-consistently accounts for the trapping of $\gamma$-rays created through electron–positron annihilation.

The total luminosity generated by radioactive decay of $^{56}\text{Ni}$ and $^{57}\text{Ni}$ during the nebular phase ($t \gtrsim 60$ days) is described by the following expression, originally presented by Sutherland & Wheeler (1984) and Cappellaro et al. (1997) and summarized here for clarity:

$$L_{\text{neb}}(t) = S^{\text{56Ni}}(\gamma) + S^{\text{56Co}}(\gamma) + S^{\text{56Co}}(\gamma) + S^{\text{56Co}}(\gamma) + S^{\text{56Co}}(\gamma) + S^{\text{56Co}}(\gamma),$$

(1)

$S^{\text{56Ni}}(\gamma)$ is the energy deposition due to $^{56}\text{Ni}$ decay:

$$S^{\text{56Ni}}(\gamma) = M^{\text{56Ni}} e^{-t_{\text{tr}}/\tau_{\text{56Ni}}},$$

(2)

where $M^{\text{56Ni}}$ is the mass of $^{56}\text{Ni}$ and $\tau_{\text{56Ni}} = 3.9 \times 10^{10} \text{ erg s}^{-1} \text{ g}^{-1}$ is the energy rate generated by the decay of $^{56}\text{Ni}$ per unit mass and a decay timescale of $\tau_{\text{56Ni}} = 8.77$ days. The remaining terms in Equation (1) constitute the energy deposition rate due to the respective decays of $^{56}\text{Co}$ and $^{57}\text{Co}$.

A total of 81% of the energy released by the $^{56}\text{Co}$ decay is emitted in the form of $\gamma$-rays:

$$S^{\text{56Co}}(\gamma) = 0.81 L_{\text{neb}}(1 - e^{-t_{\text{tr}}/\tau_{\text{56Co}}}),$$

(3)

The term $(1 - e^{-t_{\text{tr}}/\tau_{\text{56Co}}})$ accounts for the trapping probability of the $\gamma$-rays in the ejecta, and $L_{\text{neb}}$ is the rate of energy production from the $^{56}\text{Co}$ decay:

$$L_{\text{neb}}(t) = M^{\text{56Ni}} e^{-t_{\text{tr}}/\tau_{\text{56Ni}}},$$

(4)

where $\tau_{\text{56Co}} = 6.8 \times 10^{9} \text{ erg s}^{-1} \text{ g}^{-1}$ and $\tau_{\text{56Co}} = 111.3$ days.

The remaining 19% of energy from $^{56}\text{Co}$ decay is released via positrons and is partly described by the following expression for energy deposition from $\gamma$-rays created in positron annihilation:

$$S^{\text{56Co}}(\gamma) = 0.164 L_{\text{neb}}(1 - e^{-t_{\text{tr}}/\tau_{\text{56Co}}})(1 - e^{-t_{\text{e}}/\tau_{\text{56Co}}}),$$

(5)

where the terms $(1 - e^{-t_{\text{tr}}/\tau_{\text{56Co}}})$ and $(1 - e^{-t_{\text{e}}/\tau_{\text{56Co}}})$ account for the trapping probabilities of the $\gamma$-rays and positrons, respectively. The remaining source of energy in $^{56}\text{Co}$ decay is kinetic energy from positrons and is expressed by

$$S^{\text{56Co}}(\gamma) = 0.036 L_{\text{neb}}(1 - e^{-t_{\text{tr}}/\tau_{\text{56Co}}}).$$

(6)

Lastly, we consider the contribution of $^{57}\text{Co}$ decay to the bolometric light curve, which we parameterize as follows:

$$S^{\text{57Co}}(\gamma) = M^{\text{57Co}} e^{-t_{\text{tr}}/\tau_{\text{57Co}}},$$

(7)

where $\tau_{\text{57Co}} = 8.9 \times 10^{9} \text{ erg s}^{-1} \text{ g}^{-1}$ for no $\gamma$-ray trapping, $\tau_{\text{57Co}} = 7.0 \times 10^{9} \text{ erg s}^{-1} \text{ g}^{-1}$ for complete $\gamma$-ray trapping, and $\tau_{\text{57Co}} = 392.11$ days. We adopt the energy rate $\epsilon^{\text{57Co}}$ that assumes no trapping of $\gamma$-rays and complete trapping of X-rays and Auger electrons (see, e.g., Seitenzahl et al. 2009; Graur et al. 2016). This description of energy deposition from $\gamma$-rays released in $^{57}\text{Co}$ decay will yield the most conservative estimate on the total $^{57}\text{Co}$ mass in SN 2019ehk. We also ignore any “freeze-out” effects that typically influence the SN light curve at $t > 600$ days (Fransson & Kozma 1993; Fransson & Jerkstrand 2015; Graur et al. 2018).

In this model, free variables include the total masses of $^{56}\text{Co}$ and $^{57}\text{Co}$, as well as the timescales of $\gamma$-ray and positron escape, $t_{\text{tr}}$ and $t_{\text{e}}$, respectively. We do not fit for other physical parameters that define these timescales such as the density profile, opacity, mass, and kinetic energy of the expanding ejecta. These dependencies are discussed in the context of derived trapping timescales in Equations (8) and (9). To fit the bolometric light curve, we use the nonlinear least-squares package curve_fit in scipy (Virtanen et al. 2020). Our final model fit to the late-time light curve is shown as the dashed black line in Figure 2(b).

Using Equation (1), we first attempt to model the bolometric light curve of SN 2019ehk with the inclusion of partial trapping of positrons, e.g., including $t_{\text{e}}$. We find that the model is insensitive to the positron trapping timescale and no meaningful statistical boundary can be constrained. We then model the bolometric light curve under the assumption of complete positron trapping (i.e., $(1 - e^{-t_{\text{tr}}/\tau_{\text{56Co}}}) = 1$) and derive a total $^{56}\text{Co}$ mass of $M^{\text{56Co}} = (2.8 \pm 0.10) \times 10^{-2} M_{\odot}$ and a $\gamma$-ray trapping timescale of $t_{\text{tr}} = 53.9 \pm 1.30$ days. The estimated $^{56}\text{Co}$ mass is consistent with the $^{56}\text{Ni}$ mass of $M_{\text{Ni}} = (3.1 \pm 0.11) \times 10^{-2} M_{\odot}$ derived from photospheric modeling of the SN 2019ehk light curve at $t < 30$ days after explosion (WIG20a). This indicates that the early-time luminosity of SN 2019ehk during its second light-curve peak was primarily powered by radioactive decay and not by additional power sources such as CSM interaction. Conversely, the first light-curve peak at $t < 7$ days after explosion was powered by interaction with dense CSM (WIG20a).
Because SN 2019ehk’s bolometric light curve only extends to \(\sim 400\) days after explosion, the model fit is not fully sensitive to the contribution of \(^{57}\)Co decay to the overall SN luminosity. Consequently, we derive an upper limit on the total mass of \(^{57}\)Co in SN 2019ehk to be \(M(^{57}\text{Co}) < 8.3 \times 10^{-4} M_{\odot}\), which represents a 3\(\sigma\) statistical deviation relative to the late-time light-curve data. Based on these mass estimates, we find a ratio of radioactive isotope masses in SN 2019ehk to be \(M(^{57}\text{Co})/M(^{56}\text{Co}) \leq 0.030\). As previously stated, this mass ratio represents the most conservative limit under the assumption of no \(\gamma\)-ray trapping from \(^{57}\)Co decay. However, for complete \(\gamma\)-ray trapping from this decay chain, the least conservative limit on \(^{57}\)Co mass in SN 2019ehk is \(M(^{57}\text{Co}) < 1.1 \times 10^{-4} M_{\odot}\), which yields a mass ratio of \(M(^{57}\text{Co})/M(^{56}\text{Co}) \leq 0.004\). It is likely that the true \(^{57}\)Co mass and mass ratio limits for SN 2019ehk are within this range given the evidence of partial \(\gamma\)-ray trapping from \(^{56}\)Co decay at late times. Finally, given the uncertainty on SN 2019ehk’s host extinction, we also calculate the \(M(^{57}\text{Co})/M(^{56}\text{Co})\) mass ratio limit after correcting the data for a maximum color excess of \(E(B-V) = 1\) mag as presented in the range by Nakaoka et al. (2020). We find mass ratio limits of \(\leq 0.0044\) and \(\leq 0.034\) for complete and no \(\gamma\)-ray trapping from \(^{57}\)Co decay, respectively. These limits are consistent with those calculated with our preferred host extinction value presented in Section 2. We also note that the estimated mass ratio limits are marginally dependent on the bolometric correction to the IR flux at late times as discussed in Section 3.1.

As shown by Clocchiatti & Wheeler (1997), the trapping timescales of both \(\gamma\)-rays and positrons are physical parameters that are defined based on properties of the SN ejecta. For \(\gamma\)-ray trapping, the expression is

\[
t_{\gamma} = (C(\eta)\kappa_{\gamma}M_{ej}^{2}E_{k}^{-1})^{1/2}, \tag{8}
\]

where the ejecta opacity to \(\gamma\)-rays is \(\kappa_{\gamma} = 0.027 \text{ cm}^{2} \text{ g}^{-1}\), \(M_{ej}\) is the ejecta mass, \(E_{k}\) is the kinetic energy of the ejecta, and the density function \(C(\eta)\), under the assumption of spherical symmetry, is written as

\[
C(\eta) = (\eta - 3)^{2}[8\pi(\eta - 1)(\eta - 5)]^{-1}, \tag{9}
\]

where \(\eta\) defines the density profile of ejecta, i.e., \(\rho_{ej} \propto r^{-\eta}\).

Following Valentí et al. (2008a), we assume that the ejecta is homogeneous and has a flat density profile of \(\eta = 0\) within Equation (9), which then yields \(C(0) = 0.072\). For the known \(\gamma\)-ray energies of the beta-decays, the \(\gamma\)-ray opacity of the ejecta is expected to be \(\kappa_{\gamma} = 0.027 \text{ cm}^{2} \text{ g}^{-1}\) (Colgate et al. 1980; Woosley et al. 1989; Clocchiatti & Wheeler 1997). To check this assumption, we solve for \(\kappa_{\gamma}\) in Equation (8) using \(C(0)\) listed above, \(t_{\gamma}\) from our model fits, and \(M_{ej} = 0.7 M_{\odot}\) and \(E_{k} = 1.6 \times 10^{50} \text{ erg}\) as derived in WJG20a from early-time light-curve modeling. With these values, we estimate a \(\gamma\)-ray opacity of \(\kappa_{\gamma} = 0.026 \pm 0.0019 \text{ cm}^{2} \text{ g}^{-1}\), which is consistent with the fiducial value used in other studies. Furthermore, this agreement suggests that the SN 2019ehk ejecta structure can be consistent with being homogeneous and spherically symmetric, with synthesized Ni located at the center.

4. Discussion

4.1. Comparison to Late-time SN Studies

SN 2019ehk is the only confirmed CaST to be observed long enough after explosion so as to probe the effects of energy deposition from multiple radioactive isotopes on the bolometric light curve. Studying this object at such late times also allows for the first test of \(\gamma\)-ray and positron trapping in an SN that exhibits the typical spectroscopic and photometric evolution of a CaST. As shown in Figure 3(a), the peculiar, “calcium-strong” SN 2016hnk was observed to \(\sim 300\) days after explosion, and Jacobson-Galán et al. (2020b) found that including \(t_{\gamma} \approx 60\) days was necessary to fit the bolometric light curve at late times. However, while SN 2016hnk follows a similar light-curve evolution to SN 2019ehk out to late times, it is not considered a typical CaST given its similarities to “1991bg-like” SNe Ia (Galbany et al. 2019),

With regard to other thermonuclear SN varieties shown in Figure 3(a), SN 2019ehk has a similar overall light-curve evolution out to \(\sim 400\) days after explosion. Compared to normal and subluminous SNe Ia SN 2011fe and SN 2005ke, respectively, SN 2019ehk has a consistent decline rate. As previously stated, this mass ratio represents the most conservative limit on the total mass of \(^{57}\)Co decay, respectively. These limits are consistent with those calculated with our preferred host extinction value presented in Section 2. We also note that the estimated mass ratio limits are marginally dependent on the bolometric correction to the IR flux at late times as discussed in Section 3.1.

4.2. CSM Interaction and Dust Formation

SN 2019ehk represents the first CaST with direct evidence for confined CSM surrounding the progenitor star at the time of
explosion (WJG20a). Shock-ionized spectral lines and luminous X-ray emission revealed that the CSM was H- and He-rich and had a mass of $\approx 7 \times 10^{-3} M_\odot$ and a velocity of $\approx 500$ km s$^{-1}$. These observations jointly confirmed that this compact shell of material extended out to a radius of $r < 10^{15}$ cm from the progenitor and had a density of $n \approx 10^9$ cm$^{-3}$ ($M < 10^{-5} M_\odot$ yr$^{-1}$). Radio observations from $\sim 30$ to $220$ days after explosion indicated a significantly lower density $n < 10^4$ cm$^{-3}$ at larger radii $r > (0.1-1) \times 10^{17}$ cm. Furthermore, there is no evidence of circumstellar interaction in the latest nebular spectrum of SN 2019ehk at a phase of $\sim 270$ days.

Prior to the late-time imaging presented in this analysis, all multiwavelength observations have indicated that the material ejected by the progenitor was dense, small in quantity, and confined to the immediate circumstellar environment. Based on the light-curve modeling in Section 3.2, we find no statistical evidence for a power source in addition to $^{56}$Ni; the same amount of $^{56}$Ni that powers the early-time light curve is enough to account for the entire bolometric luminosity up to 400 days. Here we quantify the contribution of CSM interaction to the late-time light curve, employing a modified version of the simplified formalism by Smith et al. (2010):

$$L_{\text{CSM}} = \frac{1}{2} \epsilon w v_w^3,$$

where $\epsilon$ is the efficiency of conversion of shock kinetic energy into radiation and $v_w$ is the shock velocity. The wind density parameter $w$ is defined by $M/v_w$, where we adopt $v_w \approx 500$ km s$^{-1}$ as estimated in WJG20a. For the explosion parameters of SN 2019ehk ($M_{ej}$ and $E_k$) and a wind-like environment (see WJG20a), the shock velocity is

$$v_w = 10^8 \left[ \frac{M}{1 M_\odot \text{ yr}^{-1}} \right]^{0.12} \left[ \frac{t}{\text{days}} \right]^{0.12} \text{ km s}^{-1}. \quad (11)$$

We treat Equation (10) as an extra energy term to be added to Equation (1), and we derive a $\sigma$ limit on mass loss of $M < 10^{-10} M_\odot$ yr$^{-1}$ for an optimistic efficiency of 80%. This result indicates very low densities in the SN environment of $n < 10^3$ cm$^{-3}$, consistent with the radio nondetections. Our mass-loss estimate suggests a “very clean” environment that is natural in a WD+WD system (WJG20a) but more difficult to reconcile with the environments around massive stars.

Finally, we consider the case of dust formation in SN 2019ehk for completeness. As shown in the optical/IR light curve in Figure 2(a), the late-time SED of SN 2019ehk is gradually being shifted blueward, which is not reflective of dust formation that would induce the opposite effect and is likely an effect of fading CaII emission at redward wavelengths. Furthermore, our WFC3/IR observations at $+389$ days after explosion extend from $\sim 0.9$ to $1.7 \mu$m and would be able to detect emission from a dust shell that typically peaks around $\sim 2 \mu$m. Consequently, we can conclude that there is no evidence for dust formation in SN 2019ehk at phases $\lesssim 400$ days after explosion.

### 4.3. Oxygen Ejecta Mass

The mass of oxygen in the ejecta can constrain the type of progenitor and the explosion mechanism. WJG20a estimated $M_{O} > 0.14 M_\odot$ from O I and [O I] emission lines in the $+72$-day spectrum, and De et al. (2020) found a less stringent...
but consistent mass limit of $M_0 > 0.005 - 0.05 \, M_\odot$ from a spectrum at +270 days using only the [O I] line transition. Both of these analyses assumed temperatures of the emission region (e.g., $T = 5000$ K by WJG20a and $T = 3400 - 4000$ K by De et al. 2020) that were not directly constrained by the data. Here we reanalyze the +72-day spectrum, adding to our analysis the inferences made from an estimated upper limit on the [O I] $\lambda 5577$ luminosity to constrain the temperature and obtain a robust lower limit to $M_0$. We then present two independent estimates of $M_0$ based on the $^{56}$Co mass obtained in this paper.

4.3.1. Lower Limit from +72-day Spectrum

In order to obtain a lower limit to $M_0$ from the +72-day spectrum, we use $L_{5300}$, the [O I] $\lambda 5577$, $5630$, and $6363$ luminosity, and $L_{7774}$, the recombination line luminosity from WJG20a. We add a constraint for the [O I] $\lambda 5577$ line by rescaling to the +44-day spectrum in order to determine the continuum, resulting in a line ratio of $L_{5577}/L_{5300} < 0.2$ and assuming a constant continuum shape between epochs. We note that a change in the line ratio of $\pm 30\%$ would influence the excitation rate in $\lambda 5303$ by $\pm 25\%$, which in turn will modify the final O mass estimate by $\pm 25\%$. We then computed a grid of models over a range of density, temperature, and ionization fraction for various values of the oxygen mass using atomic rates from CHIANTI (Dere et al. 1997). We find that an O mass of $M_0 > 0.08 \, M_\odot$ is required to match the observed line luminosities, which lies in the upper end of the lower limits presented by De et al. (2020). For this minimum mass, the other parameters are constrained to $\log(n_e) = 8.6$, $T = 5530$ K, and $O^+/O \sim 0.25$. For larger $M_0$, wider ranges of the other parameters are allowed. This is a robust lower limit on the O mass because (i) some oxygen could be inside the photosphere at this stage, as the spectrum is not yet fully nebular, and (ii) we assume a single temperature. If, as is likely, a range of temperatures is present and the higher-temperature gas is more highly ionized, then both the neutral mass ($M \propto e^{2/5}T$) and the ionized mass ($M \propto T^{1/2}$) will increase. We note that we cannot confirm the approximate formula by Uomoto (1986) used by De et al. (2020) in CHIANTI. Using the same parameters as De et al. (2020) in CHIANTI, we would infer an O mass that is a factor of 1.6 lower than that reported by De et al. (2020). We speculate that updated atomic parameters of CHIANTI might be responsible for the difference.

4.3.2. Estimate from $L_{7774}$ in +270-day Spectrum

We measure an O I recombination line luminosity $L_{7774} = 1.8 \times 10^{37} \, \text{erg s}^{-1}$ in the +270-day spectrum. It is known that $\sim 37\%$ of the recombinations produce that line, and each recombination must balance an ionization (Julienne et al. 1974). We have shown that the original mass of $^{56}$Co is 0.028 $M_\odot$, but by +270 days, only 0.0025 $M_\odot$ remains. With a 77.2-day half-life, that implies $5.4 \times 10^{48}$ decays per second at $t = 270$ days, each of which carries 2.11 MeV of energy. Victor et al. (1994) computed the number of ionizations per 1000 eV as a particle slows down in pure oxygen gas. They did not include photoionization by emission lines created in the process, and while the O I emission lines cannot photoionize oxygen, O II lines such as those at 834 Å can ionize O I. We use this information to quantify the amount of energy released by $^{56}$Co decay that is channeled solely to O I emission. We note that Ca is excited by a population of electrons at significantly lower energies that would not lead to O emission. Adding in those photoionizations, we find 26–45 ionizations per 1000 eV. For a radius of 6 $\times 10^{15}$ cm based on the expansion speed and phase, the energy flux is $2.7 \times 10^{13} \, \text{MeV cm}^{-2} \, \text{s}^{-1}$, and the absorption cross section based on $\kappa_c = 0.027 \, \text{cm}^2 \, \text{g}^{-1}$ yields (5.1–8.7) $\times 10^{-7}$ ionizations per second. Thus, the observed $\lambda 7774$ luminosity requires $M_0 \approx 0.30 - 0.50 \, M_\odot$. This estimate applies if the $^{56}$Co is located well inside the absorbing shell, but the local $\gamma$-ray flux will be higher if the $^{56}$Co is just inside the absorbing shell (i.e., large degree of mixing). The geometrical correction could reduce the required oxygen mass by as much as a factor of 1.5, and the final estimate is $M_0 \approx 0.20 - 0.33 \, M_\odot$. We also explore the effect of a large host extinction on the SN 2019ehk O mass. Using a color excess of $E(B-V) = 1.0$ mag, we find an O I line luminosity $L_{7774} = 4.3 \times 10^{37} \, \text{erg s}^{-1}$, which yields an O mass range of $M_0 \approx 0.70 - 1.20 \, M_\odot$ by the steps outlined above. While these values violate the total ejecta mass estimates from light-curve modeling and support a lower host extinction value, it is possible that the assumptions made in this analysis do not fully account for all the details of SN physics, e.g., the application of Victor et al. (1994) is technically for pure O gas.

4.3.3. Estimate from Opacity at +270 Days

Figure 2(b) shows that all but $\sim 4\%$ of the radioactive decay energy escapes from the oxygen SN ejecta shell, which indicates an optical depth of $\sim 0.04$. We assume that the source of $\gamma$-rays (i.e., $^{56}$Co) is centrally located. With an opacity $\kappa_c = 0.027 \, \text{cm}^2 \, \text{g}^{-1}$, that implies a mass column of 1.48 g cm$^{-2}$. Multiplying by the area of a $6 \times 10^{15}$ cm shell gives an O mass of $\sim 0.3 \, M_\odot$. WJG20a found that there is a significant amount of He in the ejecta, which would reduce the O mass range to $\sim 0.27 \, M_\odot$. Carbon might be present as well, which could lower the O mass by as much as 1/3.

A further geometric correction should also be considered. The estimate above implicitly assumes that the $\gamma$-rays move radially, and that is a good approximation if the $^{56}$Co is located well inside the absorbing shell. If the $^{56}$Co is located just inside the absorbing shell, a photon will move at some angle to the radial and will encounter more material. The correction factor depends on the thickness of the shell, but for a plausible range of $1.5 < r_{outer}/r_{innershell} < 2$, the mass estimate could be decreased by a factor of 1.5–1.32. If the $^{56}$Co is mixed with the absorbing material, some $\gamma$-rays will escape more easily, bringing the correction factor back toward 1. The mass estimate based on the opacity thus becomes $\sim 0.20 \, M_\odot$. This O mass, as well as other estimates discussed above, is consistent with the O abundances in merging hybrid +C/O WDs (e.g., Zenati et al. 2019b) that WJG20a present as a favored progenitor scenario for SN 2019ehk.

4.4. Progenitor Channels

As the sample of known CaSTs continues to grow, the exact progenitor systems responsible for these SNe remains unknown. While the older stellar environments and significant host galaxy offsets observed for many CaSTs are consistent with a WD origin, the increasing diversity of CaST explosion sites indicates that their progenitors may be heterogeneous and include some types of massive stars. For the progenitor of SN 2019ehk, Nakaoka et al. (2020) conclude that the SN may have arisen from the explosion of an ultrastripped, low-mass He (or C/O) star in a binary system with a companion NS.
As shown in Figure 4, SN 2019ehk is inconsistent with the predicted ejecta masses and nucleosynthesis of CO or ONe WD + NS merger models (A. Bobrick et al. 2020b, in preparation; Zenati et al. 2020). However, the exact unbound ejecta mass produced in these models is uncertain and could match $M_{ej}$ estimated for SN 2019ehk. Nonetheless, most of these models synthesize higher amounts of $^{57}$Co than could be present in SN 2019ehk (Figure 4) and thus are not viable progenitor systems.

An explosion scenario that is consistent with SN 2019ehk is the disruption of a lower-mass CO WD (or hybrid HeCO WD) by a hybrid WD (Zenati et al. 2019b), which can produce fast-rising, faint CaST-like events (Y. Zenati et al. 2020b, in preparation). The explosion model can result in $\sim 0.4$–$0.6 M_\odot$ of ejecta and synthesize low enough masses of $^{57}$Co so as to remain within the limit set by the late-time light-curve modeling. WJG20a also find this progenitor scenario to be consistent with the H- and He-rich CSM composition found in the SN progenitor environment. While this late-time analysis confirms one of the favored models in WJG20a, further tests should be done to understand how well this type of explosion can quantitatively match SN 2019ehk’s early-time light curve and spectra.

Lastly, we compare estimates of $M_{ej}$ and mass ratio values to those predicted by a variety of core-collapse (CC) SN models. In Figure 4, we show that SN 2019ehk is not consistent with both the nucleosynthetic yields and ejecta masses produced in the explosion of massive stars in the lowest-mass bins ($\lesssim 8$–$11 M_\odot$; Wanajo et al. 2018). Similarly, electron-capture (EC) SN models for low-mass progenitors ($8.8 M_\odot$; Wanajo et al. 2018) cannot reproduce the SN 2019ehk observables despite their proposed link to fast-evolving transients such as CaSTs (Moriya & Eldridge 2016; Milisavljevic et al. 2017). Furthermore, we explore the possible connection between SN 2019ehk and ultrastrippped SN (USSN) models. Such a progenitor system was favored by Nakaoka et al. (2020) for SN 2019ehk and involves the explosion of an He or CO star that has had most of its outer H and He envelope removed owing to its NS companion. In Figure 4 we include explosion models for ultrastrippped SNe Ic (Yoshida et al. 2017) and USSNe of varying explosion energies (Moriya et al. 2017). Both models produce less $M_{ej}$ than SN 2019ehk and synthesize too much $^{57}$Co to be consistent with the most conservative mass ratio limit. Nonetheless, additional modeling of USSNe is needed to understand the range of ejecta and isotope masses generated through the explosion of compact, stripped massive stars.

Based on a lower limit on the O mass of $M_O > 0.005$–$0.05 M_\odot$, De et al. (2020) favor a stripped-envelope progenitor ($M_{ZAMS} \approx 9$–$9.5 M_\odot$) for SN 2019ehk with $\gtrsim 0.02 M_\odot$ of H on the stellar surface. The mass of potential photospheric H is based on a qualitative analogy between one peak spectrum of SN 2019ehk and SN IIb models (e.g., Hachinger et al. 2012) despite the overall dissimilarity between the photometric and spectroscopic evolution, as well as explosion parameters, of H-poor SNe compared to SN 2019ehk (Nakaoka et al. 2020; WJG20a). While the O mass lower limit by De et al. (2020) shows consistency with USSN models (e.g., Moriya et al. 2017; Yoshida et al. 2017), such a progenitor scenario is inconsistent with even the most conservative mass ratio limit shown in Figure 4, as well as alternative methods for calculating O mass discussed in Section 4.3. Furthermore, the range of nucleosynthetic yields...
and $M_\text{ej}$ values produced in the CC of normal to ultrastripped, 9–11 $M_\odot$ SN progenitors cannot reproduce those observed in SN 2019ehk.

Additionally, it is difficult to reconcile the specific progenitor scenario proposed by De et al. (2020) with the detection of a dense, confined shell of H- and He-rich CSM in the SN 2019ehk progenitor environment. From X-ray detections and flash-ionized spectral lines, WJG20a derived a CSM H mass of $\sim 3 \times 10^{-4} M_\odot$ around SN 2019ehk’s progenitor, which is incompatible with the estimate proposed by De et al. (2020) of $\gtrsim 0.03 M_\odot$ near or on the surface of the progenitor. Furthermore, the progenitor environment of SN 2019ehk is unlike that of any double-peaked, H-poor SNe with extensive radio observations (see, e.g., Kamble et al. 2016), and the lack of radio detections indicates a low-density environment at distances $r > 10^{16}$ cm, which is inconsistent with a stripped-envelope, massive star progenitor system. Also, our radio limits, as well as the presence of an H-rich CSM, are inconsistent with most of the ultrastripped SN progenitor configurations presented by Matsuoka & Maeda (2020). Nonetheless, SN 2019ehk radio limits and ejecta mass are consistent with two binary models that include a fraction of gas escaping the system $f_\text{eq} = 0.1$ and final orbital separation $a_{\text{eq}} = 1–10 R_\odot$, but these models cannot reconcile the presence of H in the local SN environment. Furthermore, we note the large uncertainties on the efficiency of nonconservative mass transfer in these systems during the Roche lobe overflow stage of binary evolution. It is unclear how mass loss in a stripped, $\sim 9–9.5 M_\odot$ massive star progenitor could allow for the presence of only $\sim 10^{-4} M_\odot$ of dense H-rich material in its local environment ($r < 10^{15}$ cm), while also ejecting several $M_\odot$ worth of H via binary interaction that was not detected in any panchromatic observations of SN 2019ehk out to late-time phases.

5. Conclusions

In this paper, we have presented HST WFC3 imaging of CaST SN 2019ehk at 276–389 days after explosion. Photometric detections in all optical/IR filters enabled the creation of a bolometric light curve that extended out to phases yet unexplored in a CaST. We show that the late-time light-curve evolution can be modeled solely through the radioactive decay of isotope $^{56}$Co with a mass of $M(^{56}$Co) = $(2.8 \pm 0.1) \times 10^{-2} M_\odot$. Additionally, we find evidence for $\gamma$-ray leakage on the timescale of $t_{\gamma} = 53.9 \pm 1.3$ days but do not find statistical evidence for incomplete positron trapping in SN 2019ehk’s ejecta. The bolometric light curve of SN 2019ehk does not extend to late enough phases to precisely quantify the mass of $^{57}$Co synthesized in the explosion, and therefore we derive the most conservative limit on the mass ratio of odd to even isotopes to be $M(^{57}$Co)/$M(^{56}$Co) $\leq 0.03$. We compare this mass ratio limit and the total SN 2019ehk ejecta mass to that predicted by various explosion models involving WDs and stripped, compact massive stars. We show that these observables make SN 2019ehk incompatible with single- and double-degenerate explosion scenarios that typically produce SN Ia-like explosions. Additionally, SN 2019ehk is inconsistent with the projected nucleosynthetic yields of WD+NS binary mergers, as well as CC and EC SNe from normal to ultrastripped massive stars ($M_{ZAMS} \approx 9–11 M_\odot$).

However, these derived values in SN 2019ehk do match the mass ratio and $M_\text{ej}$ produced in the tidal disruption of a low-mass C/O WD by a larger, hybrid WD. Additional modeling of these explosion mechanisms, as well as more late-time observations of nearby CaSTs, will be essential in constraining CaST progenitor systems.

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Facility: Hubble Space Telescope.

Software: scipy (Virtanen et al. 2020), IRAF (Tody 1986, Tody 1993), AstroDrizzle (Gonzaga 2012), photpipe (Rest et al. 2005), DoPhot (Schechter et al. 1993), HOTPANTS (Becker 2015), dolphot (Dolphin 2000).

Appendix

In this section we present data tables for HST imaging (Table A1) and the bolometric light curve (Table A2) of SN 2019ehk. We also include a data table of explosion models (Table A3) used in Figure 4.
Table A1  
HST Imaging of SN 2019ehk

| Instrument | Aperture | Filter | MJD     | Phase (days) | Exp. Time (s) | Proposal No. | Magnitude (mag) | Error |
|------------|----------|--------|---------|--------------|---------------|--------------|----------------|-------|
| WFC3       | UVIS     | F275W  | 58877.92| 321.78       | 2190.0        | 15654        | >26.93         | ...   |
| WFC3       | UVIS     | F275W  | 58923.58| 321.78       | 2190.0        | 15654        | >26.59         | ...   |
| WFC3       | UVIS     | F336W  | 58877.90| 276.10       | 1110.0        | 15654        | >26.65         | ...   |
| WFC3       | UVIS     | F336W  | 58923.58| 321.78       | 1110.0        | 15654        | >26.55         | ...   |
| WFC3       | UVIS     | F438W  | 58877.89| 276.10       | 1050.0        | 15654        | 25.73          | 0.10  |
| WFC3       | UVIS     | F438W  | 58923.57| 321.78       | 1050.0        | 15654        | >26.44         | ...   |
| WFC3       | UVIS     | F555W  | 58877.93| 276.10       | 670.0         | 15654        | 24.38          | 0.04  |
| WFC3       | UVIS     | F555W  | 58923.59| 321.78       | 670.0         | 15654        | 25.26          | 0.08  |
| WFC3       | UVIS     | F555W  | 58990.73| 388.93       | 1500.0        | 16075        | 25.96          | 0.07  |
| WFC3       | UVIS     | F814W  | 58877.89| 276.10       | 836.0         | 15654        | 22.03          | 0.01  |
| WFC3       | UVIS     | F814W  | 58923.57| 321.78       | 836.0         | 15654        | 23.07          | 0.03  |
| WFC3       | UVIS     | F814W  | 58990.70| 388.93       | 900.0         | 16075        | 24.55          | 0.06  |
| WFC3       | IR       | F110W  | 58990.64| 388.84       | 1211.75       | 16075        | 24.88          | 0.05  |
| WFC3       | IR       | F160W  | 58990.64| 388.84       | 1211.75       | 16075        | 24.37          | 0.07  |

Note.  
* All apparent magnitudes in AB system. No extinction corrections have been made for MW or host reddening.

Table A2  
Bolometric Light-curve Data

| MJD   | Phase (days) | Luminosity (erg s⁻¹) | Uncertainty (erg s⁻¹) |
|-------|--------------|----------------------|-----------------------|
| 58602.23 | +0.43        | 1.83e+41             | 1.15e+40              |
| 58603.17 | +1.37        | 5.94e+41             | 2.99e+40              |
| 58603.22 | +1.42        | 6.10e+41             | 3.07e+40              |
| 58603.62 | +1.82        | 6.53e+41             | 3.55e+40              |
| 58604.61 | +2.81        | 7.76e+41             | 4.03e+40              |
| 58605.25 | +3.45        | 1.75e+42             | 9.28e+40              |
| 58606.21 | +4.41        | 1.27e+42             | 7.12e+40              |
| 58606.21 | +4.41        | 1.27e+42             | 7.05e+40              |
| 58606.26 | +4.46        | 1.22e+42             | 6.88e+40              |
| 58607.24 | +5.44        | 8.80e+41             | 5.34e+40              |
| 58607.39 | +5.59        | 8.33e+41             | 5.25e+40              |
| 58607.55 | +5.75        | 7.59e+41             | 7.77e+40              |
| 58608.13 | +6.33        | 5.91e+41             | 3.04e+40              |
| 58609.18 | +7.38        | 5.48e+41             | 2.88e+40              |
| 58612.21 | +10.41       | 6.86e+41             | 3.75e+40              |
| 58612.21 | +10.41       | 6.86e+41             | 3.72e+40              |
| 58614.39 | +12.59       | 7.63e+41             | 4.06e+40              |
| 58615.14 | +13.34       | 7.84e+41             | 4.04e+40              |
| 58615.36 | +13.56       | 8.03e+41             | 4.27e+40              |
| 58616.18 | +14.38       | 8.23e+41             | 4.30e+40              |
| 58617.08 | +15.28       | 7.54e+41             | 4.05e+40              |
| 58619.19 | +17.39       | 5.87e+41             | 3.88e+40              |
| 58619.19 | +17.39       | 5.87e+41             | 3.81e+40              |
| 58622.52 | +20.72       | 4.50e+41             | 2.88e+40              |
| 58626.26 | +24.46       | 3.49e+41             | 1.93e+40              |
| 58628.30 | +26.50       | 3.21e+41             | 1.80e+40              |
| 58631.12 | +29.32       | 2.81e+41             | 1.62e+40              |
| 58632.18 | +30.38       | 2.74e+41             | 2.02e+40              |
| 58633.20 | +31.40       | 2.72e+41             | 1.62e+40              |
| 58633.20 | +31.40       | 2.72e+41             | 1.64e+40              |
| 58633.27 | +31.47       | 2.66e+41             | 1.52e+40              |
| 58634.18 | +32.38       | 2.58e+41             | 1.49e+40              |
| 58636.08 | +34.28       | 2.45e+41             | 1.34e+40              |
| 58636.11 | +34.31       | 2.45e+41             | 1.34e+40              |
| 58636.21 | +34.41       | 2.44e+41             | 1.46e+40              |
| 58636.35 | +34.55       | 2.47e+41             | 1.51e+40              |
| 58639.05 | +37.25       | 2.17e+41             | 1.29e+40              |
| 58639.18 | +37.38       | 2.16e+41             | 1.34e+40              |
Table A2
(Continued)

| MJD   | Phasea (days) | Luminosityb (erg s⁻¹) | Uncertainty (erg s⁻¹) |
|-------|---------------|------------------------|-----------------------|
| 58640.18 | +38.38        | 2.10e+41               | 1.30e+40              |
| 58642.10 | +40.30        | 1.99e+41               | 1.26e+40              |
| 58642.22 | +40.42        | 2.00e+41               | 1.31e+40              |
| 58644.07 | +42.27        | 2.05e+41               | 1.25e+40              |
| 58646.23 | +44.43        | 1.95e+41               | 1.43e+40              |
| 58649.22 | +47.42        | 1.87e+41               | 1.40e+40              |
| 58652.28 | +50.48        | 1.70e+41               | 1.49e+40              |
| 58652.71 | +50.91        | 1.70e+41               | 1.34e+40              |
| 58657.53 | +55.73        | 1.52e+41               | 9.97e+39              |
| 58658.04 | +56.24        | 1.48e+41               | 8.88e+39              |
| 58658.18 | +56.38        | 1.46e+41               | 9.21e+39              |
| 58661.20 | +59.40        | 1.32e+41               | 8.76e+39              |
| 58670.01 | +68.21        | 9.83e+40               | 6.95e+39              |
| 58687.86 | +86.06        | 6.99e+40               | 6.94e+39              |
| 58688.97 | +87.17        | 6.64e+40               | 5.75e+39              |
| 58690.97 | +89.17        | 6.75e+40               | 5.33e+39              |
| 58696.97 | +95.17        | 5.39e+40               | 4.26e+39              |
| 58877.93 | +276.13       | 1.07e+39               | 4.68e+37              |
| 58923.59 | +321.79       | 4.76e+38               | 2.19e+37              |
| 58990.73 | +388.93       | 1.55e+38               | 9.05e+36              |

Notes.

a Relative to explosion.
b Covers wavelength range 3000–10000 Å.

Table A3
Explosion Model Characteristics

| Model            | Description                | SN Type | M0 (M0) | M56(Ni) (M0) | 57Co/56Co | Reference               |
|------------------|----------------------------|---------|---------|--------------|-----------|-------------------------|
| W7               | Deflagration               | SN Ia    | 1.38    | 0.59         | 0.041     | Iwamoto et al. (1999)   |
| ddt_n100         | Delayed Detonation         | SN Ia    | 1.40    | 0.60         | 0.031     | Seitenzahl et al. (2013b) |
| det_1.06         | Detonation                 | SN Ia    | 1.06    | 0.56         | 0.006     | Sim et al. (2010)       |
| doubledet_CSDD-S | Double Detonation          | SN Ia    | 0.79    | 0.21         | 0.044     | Sim et al. (2012)       |
| doubledet_CSDD-S | Pure Deflagration          | SN Ia    | 1.40    | 0.36         | 0.038     | Fink et al. (2014)      |
| det_ONE1e7       | O-Ne WD Detonation         | SN Ia    | 1.23    | 0.96         | 0.009     | Marquardt et al. (2015) |
| gcd_GCD200       | Detonation                 | SN Ia    | 1.40    | 0.74         | 0.025     | Seitenzahl et al. (2016) |
| merger_11 + 09   | Violent Merger             | SN Ia    | 1.95    | 0.10         | 0.024     | Pakmor et al. (2012)    |
| merger_09 + 09   | Violent Merger             | SN Ia    | 1.75    | 0.10         | 0.003     | Pakmor et al. (2010)    |
| merger_09 + 076 Z1 | Violent Merger            | SN Ia    | 1.6     | 0.18         | 0.009     | Kramer et al. (2013)    |
| merger_09 + 076 Z0.01 | Violent Merger         | SN Ia    | 1.6     | 0.18         | 0.003     | Kramer et al. (2016)    |
| 0.55 + 0.63 Carich | WD Merger                  | CaST    | 0.45    | 0.013        | 0.0028    | Y. Zenati et al. (2020, in preparation) |
| 0.52 + 0.63 Carich | WD Merger                  | CaST    | 0.43    | 0.052        | 0.00084   | Y. Zenati et al. (2020, in preparation) |
| 0.50 + 0.58 Carich | WD Merger                  | CaST    | 0.36    | 0.011        | 0.011     | Y. Zenati et al. (2020, in preparation) |
| 03HeWD+14NS      | NS + He WD                | FRRT    | 0.30    | 0.0036       | 0.049     | A. Bobrick (2021, private communication) |
| 06320D+14NS      | NS + CO WD                | FRRT    | 0.63    | 0.0049       | 0.040     | Zenati et al. (2020)    |
| 06320D+20NS      | NS + CO WD                | FRRT    | 0.63    | 0.0061       | 0.058     | Zenati et al. (2020)    |
| 08320D+14NS      | NS + CO WD                | FRRT    | 0.80    | 0.029        | 0.078     | Zenati et al. (2020)    |
| 090NeWD+14NS     | NS + One WD               | FRRT    | 0.9     | 0.023        | 0.120     | A. Bobrick et al. (2020, in preparation) |
| 090NeWD+14NS     | NS + One WD               | FRRT    | 0.9     | 0.026        | 0.11      | A. Bobrick et al. (2020, in preparation) |
| 100NeWD+14NS     | NS + One WD               | FRRT    | 0.9     | 0.029        | 0.11      | A. Bobrick et al. (2020, in preparation) |
| 120NeWD+14NS     | NS + One WD               | FRRT    | 1.1     | 0.046        | 0.093     | A. Bobrick et al. (2020, in preparation) |
| 120NeWD+20NS     | NS + One WD               | FRRT    | 1.2     | 0.054        | 0.11      | A. Bobrick et al. (2020, in preparation) |
| 120NeWD+20NS     | NS + One WD               | FRRT    | 1.2     | 0.034        | 0.068     | A. Bobrick et al. (2020, in preparation) |
| 120NeWD+50BN     | BH + One WD               | FRRT    | 1.2     | 0.010        | 0.044     | A. Bobrick et al. (2020, in preparation) |
| 130NeWD+50BN     | BH + One WD               | FRRT    | 1.3     | 0.090        | 0.072     | A. Bobrick et al. (2020, in preparation) |
| CO145            | CO Star Core-Collapse     | USSN    | 0.098   | 0.0097       | 0.046     | Yoshida et al. (2017)   |
| CO150            | CO Star Core-Collapse     | USSN    | 0.11    | 0.0057       | 0.041     | Yoshida et al. (2017)   |
| ussn_E1e50erg    | Core-Collapse, 10^36 erg   | USSN    | 0.20    | 0.026        | 0.091     | Moriya et al. (2017)    |
| ussn_E2,5e50erg  | Core-Collapse, 2.5 \times 10^36 erg | USSN | 0.20 | 0.030 | 0.085 | Moriya et al. (2017) |
Table A3
(Continued)

| Model      | Description                        | SN Type     | $M_{\odot}$ ($M_{\odot}$) | $^{56}$Ni ($M_{\odot}$) | $^{56}$Co/$^{56}$Co | Reference              |
|------------|-------------------------------------|-------------|---------------------------|------------------------|----------------------|------------------------|
| ussn_E5e50erg | Core-Collapse, $5 \times 10^{56}$ erg | USSN$^a$    | 0.20                      | 0.034                  | 0.080                | Moriya et al. (2017)   |
| e8.8       | Core-Collapse, $M_{ZAMS} = 8.8 M_{\odot}$ | ECSV$^b$    | 0.017                     | 0.0029                 | 0.034                | Wanajo et al. (2018)   |
| e9.6       | Core-Collapse, $M_{ZAMS} = 9.6 M_{\odot}$ | CCSN$^d$    | 0.56                      | 0.0025                 | 0.036                | Wanajo et al. (2018)   |
| u9.1       | Core-Collapse, $M_{ZAMS} = 8.1 M_{\odot}$ | CCSN$^e$    | 0.33                      | 0.0016                 | 0.046                | Wanajo et al. (2018)   |
| s11        | Core-Collapse, $M_{ZAMS} = 11 M_{\odot}$ | CCSN$^f$    | 1.48                      | 0.0039                 | 0.023                | Wanajo et al. (2018)   |

Notes.

- $^a$ Single-degenerate channel.
- $^b$ Double-degenerate channel.
- $^c$ Faint rapid transient.
- $^d$ Ultrasnipped supernova.
- $^e$ Electron-capture supernova.
- $^f$ Core-collapse supernova.

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