Dust Formation and the Binary Companions of Supernovae

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ABSTRACT

Supernovae (SNe) should both frequently have a binary companion at death and form significant amounts of dust. This implies that any binary companion must lie at the center of an expanding dust cloud and the variable obscuration of the companion as the SN remnant (SNR) expands will both unambiguously mark the companion and allow the measurement of the dust content through absorption rather than emission for decades after the explosion. However, sufficiently hot and luminous companions can suppress dust formation by rapidly photo-ionizing the condensable species in the ejecta. This provides a means of reconciling the Type IIb SNe Cas A, which lacks a luminous companion and formed a significant amount of dust ($M_d \approx 0.1 M_\odot$), with the Type IIb SNe 1993J and 2011dh, both of which appear to have a luminous companion and to have formed a negligible amount of dust ($M_d \lesssim 10^{-3} M_\odot$). The Crab and SN 1987A are consistent with this picture, as both lack a luminous companion and formed significant amounts of dust. An unrecognized dependence of dust formation on the properties of binary companions may help to explain why the evidence for dust formation in SNe appears so contradictory.

Key words: stars: massive – supernovae: general – supernovae: individual: SN 1993J, SN 2011dh, Cas A, SN 1987

1 INTRODUCTION

The role of binaries and dust formation are two of the perennial questions and challenges for understanding the properties of supernovae (SNe) and their consequences. Binaries are common (e.g., Sana et al. 2012, Duchêne & Kraus 2013, Kobulnicky et al. 2014, Moe & Di Stefano 2016) and can modify stellar evolution, likely invalidating many expectations for the properties of SN and their progenitors based on the evolution of isolated stars (e.g., Eldridge et al. 2008, Sana et al. 2014). Their role would be much better understood if it were possible to cleanly survey SNe, their progenitors, or their remnants for binary companions and to then well-characterize the overall population. SNe are also believed to be an important source of dust, along with asymptotic giant branch (AGB) stars, particularly early in the universe where there is little time for stars to evolve to the AGB (e.g., Gall et al. 2011, Cherchneff 2014). However, where dust formation in AGB stars is relatively easy to measure, both the amount of dust formed in SNe and the fraction of that dust which survives to be mixed into the interstellar medium remain open questions.

Searches for stellar companions to SN have largely focused on Type Ia SN as a means of distinguishing the single and double degenerate models (see the review by Maoz et al. 2014). The original picture was relatively simple: in the single degenerate model there should always be a companion and in the double degenerate model there should never be a companion. The prevalence of triple systems and the potential role of Kozai-Lidov oscillations in producing double degenerate Type Ia SN complicates the latter case since it means that double degenerate Ia’s may be genuinely associated with non-degenerate (tertiary) companions (e.g., Thompson 2011, Kushnir et al. 2013).

Searches for companions can either be direct, simply observing the companion, or indirect, observing other consequences of the companion’s existence. Direct searches for companion stars to Type Ia SNe include examining the pre-explosion data for SN 2011fe (Li et al. 2011a, Kelly et al. 2012) and looking in supernova remnants (SNR) such as Tycho (Ruiz-Lapuente et al. 2004, Ihara et al. 2007), SN 1006 (Schweizer & Middleditch 1980, González Hernández et al. 2012) and SNR 0509–67.5 (Schaefer & Pagnotta 2012). Indirect searches include the effects of close companions on early-time SN light curves (e.g., Kasen 2010), searches for narrow hydrogen emission lines from material stripped from the companion (e.g., Leonard 2007, Shappee et al. 2013a), and searches for radio emission as the SN shock passes through the wind from a non-degenerate companion (e.g., Chomiuk et al. 2011).
Far less observational attention has been given to the binary companions to core collapse SN (ccSN), although Kochanek (2009) estimated that 50-80% of ccSN are probably members of a stellar binary at death. More generally, most massive stars are in binaries and many ccSN progenitors should be the remnants of stellar mergers, have undergone mass transfer or simply have a binary companion (e.g., Sana et al. 2012, Kobulnicky et al. 2014, Moe & Di Stefano 2015). For example, the numbers of stripped Type Ib SNe and the limits on their progenitor stars both suggest that many are stripped through binary mass transfer rather than simply wind (or other) mass loss (e.g., Eldridge et al. 2008, Smith et al. 2011, Eldridge et al. 2013). Most theoretical studies (e.g., Yoon et al. 2010, Yoon et al. 2012, Yoon et al. 2017, Claews et al. 2011, Benvenuto et al. 2013, and Kim et al. 2013) have focused on the binary properties of the stripped ccSN classes (Type Ibb, Ib and Ic) as cases where binary evolution is modifying the outcomes. As with the Type Ia SN, companions can modify the early-time light curves of the SN (e.g., Kasen 2010, Moriya et al. 2016). For example, the numbers of stripped Type Ibc SNe and the Type IIP SN 2005cs (Maund et al. 2005, Li et al. 2006), and SN 2008ax (Mattila et al. 2008). All the claimed detections are blue, which is expected for most binary companions (Kochanek 2009). However, in the presence of dust formation, early-time limits on the existence of binary companions are problematic, as we discuss below.

For either SN class, the challenge is to prove that any candidate is a real binary companion with the further complication of triples, particularly for the single versus double degenerate debate. Pre-supernova light curves can identify close binaries, but data of adequate depth and cadence are only beginning to exist (e.g., Kochanek et al. 2012, Kochanek et al. 2016) and any detections depend on rare, favorable geometries. Stars identified after the SN may be distinguishable due to being shock heated and hence over-luminous (e.g., Marietta et al. 2003, Shanpee et al. 2013, Pan et al. 2014). Other signatures may be peculiar kinematics (Ruiz-Lapuente et al. 2004), chemical abundances (e.g., Hara et al. 2007, Gonzalez Hernandez et al. 2009, Kerzendorf et al. 2009, Kerzendorf et al. 2013) or fast rotation rates (e.g., Kerzendorf et al. 2009, Pan et al. 2012, Kerzendorf et al. 2013, Pan et al. 2014). Finally, the supernova ejecta can produce broad absorption lines in the spectra of stars either inside or behind the SN (e.g., Wu et al. 1993), for the star behind SN 1006 identified by Schweizer & Middleditch (1980) and the remnant of SN 1885 in M31 found by Pesen et al. (1989). All these spectroscopic tests can also be applied to the companions of ccSN even though they have been discussed almost exclusively in the context of Type Ia SN. All spectroscopic tests are, however, challenging to apply in an extragalactic context because they require high resolution, high signal-to-noise spectra of the candidate star. Ideally, we need a time variable signature for a binary companion that can be carried out with broad band photometry for decades after the SN.

Dust formation is predicted for most SN, with the total amount produced diminishing with decreasing ejecta masses and increasing explosion energies because these lead to higher velocities and more rapidly dropping densities (e.g., Dwek 1988, Kozasa et al. 1989, Todini & Ferrara 2001, Cherchneff & Dwek 2010, Nozawa et al. 2010, Nozawa et al. 2011, Sarangi & Cherchneff 2015). Typical theoretical estimates are that ccSN produce $M_d \sim 0.1-1 M_\odot$ of dust while Type Ia produce $M_d \sim 10^{-3}-0.1 M_\odot$ of dust. These predictions appear to be consistent with late time observations of SNR but such high dust masses are rarely seen shortly after a SN (see the reviews by Gall et al. (2011) or Cherchneff (2014)). Ignoring SN with strong circumstellar interactions, evidence for dust in SN is usually found roughly a year or two after the explosion as either a blue shift of the emission lines or a mid-IR excess due to the presence of hot dust. Examples include SN 1987A (Wooden et al. 1993), SN 2003gd (Sugerman et al. 2006), and SN 2004et (Kotak et al. 2009).

Observations of SNR at much later times (decades or longer), particularly at longer wavelengths corresponding to emission by cooler dust, generally find dust masses more compatible with theoretical predictions. Recent examples include SN 1987A (Matsuura et al. 2011, Indebetouw et al. 2014, Matsura et al. 2015), Cas A (Barlow et al. 2014, De Loore et al. 2016) and the Crab (Temim & Dwek 2013, Owen & Barlow 2013). These high dust masses may not be universal, as Temim et al. (2010) find only a few $10^{-2} M_\odot$ of dust in the pulsar wind-containing remnant G54.1+0.3. There is little evidence for cold dust in the Tycho or Kepler Type Ia remnants ($M_d < 10^{-2} M_\odot$, Gomez et al. 2012). A fundamental problem for all these estimates is that they depend on identifying dust by emission. Observations during the SN are generally only sensitive to hot dust because they depend on observations at relatively short mid-IR wavelengths (e.g., the Spitzer 3.6 and 4.5µm bands), while searches for cold dust require observations at long wavelengths where the combination of luminosities and sensitivities usually restrict the searches to the Local Group or just to the Galaxy and Magellanic Clouds.

In theory, these two problems can solve themselves –

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In and binary companions at the sites of SN limited only by the time of the SN, permitting relatively large surveys for both dust and binary companions. The observations are also feasible for decades after the SN. There is, however, a caveat. As we discuss in §3, a sufficiently hot and luminous binary companion can suppress dust formation, which may explain the difference between the Type IIb SNe Cas A (lots of dust and no luminous companion) and SN 1993J (no dust and a luminous companion). The observations are also feasible for decades after the SN, permitting relatively large surveys for both dust and binary companions. The observations are also feasible for decades after the SN. There is, however, a caveat. As we discuss in §3, a sufficiently hot and luminous binary companion can suppress dust formation, which may explain the difference between the Type IIb SNe Cas A (lots of dust and no luminous companion) and SN 1993J (no dust and a luminous companion). In §4 we use the simple model for binary companions to SNe from Kochanek (2000) to illustrate the effects of dust on the detectability of binary companions. We end in §5 with a general discussion and potential observations.

2 MODELS

We consider a simple self-similar (e.g., Chevalier 1982) model for the SN ejecta density distribution,

$$\rho(r, t) = \frac{15M_e}{32\pi v_0^2 t^3} \left(\frac{r}{v_0 t}\right)^{-x}$$

(1)

where $x = 0 \ (x = 8)$ for $v < v_0 \ (v > v_0)$ or, equivalently, $r < v_0 t \ (r > v_0 t)$. The total kinetic energy of the debris of $E = M_e v_0^2/2$ is determined by the ejecta mass $M_e$ and the velocity scale $v_0$. By mass, 5/8 of the ejecta lies in the interior region and 3/8 lies in the exterior region. For an energy scale of $E = 10^{51} E_{51}$ erg and a mass of $10M_\odot \ (1.4M_\odot)$, the characteristic velocity is $v_0 \approx 3200 \ km/s \ (v_0 \approx 8500 \ km/s)$ for a Type IIP (Type Ia) SN. We adopt these simple models with $E_{51} = 1$ for our standard results. The break radius scale is

$$r_0 = v_0 t = 9.5t_{100} v_{3000} \times 10^{17} \ cm$$

(2)

where $t = 100t_{100}$ years and $v = 3000v_{3000} \ km/s$. The size of the ejecta cloud grows sufficiently rapidly that we can simply view any binary companion as lying at the center of the dust distribution.

If the ejecta contains dust with a total mass of $M_d = 0.1M_\odot$, which is uniformly mixed with the gas and has a constant opacity of $\kappa = 10^4 \kappa_4 \ cm^2/g$, then the optical depth scale is

$$\tau_0 = \frac{15\kappa M_d}{32\pi v_0^2 t^3} = 0.33\kappa_4 M_{d0.1} v_{3000} t_{100}^{-2}.$$  

(3)

Alternatively, we can replace the ejecta velocity with the kinetic energy to find that

$$\tau_m = \tau_0 \left(\frac{r}{r_0}\right) = \tau_0 \left(\frac{v}{v_0}\right)$$

(5)

and the optical depth from radius $r_0 = v_0 t$ outwards to radius $r \geq r_0$ is

$$\tau_{out} = \frac{\tau_0}{7} \left[1 - \left(\frac{r_0}{r}\right)^7\right] = \frac{\tau_0}{7} \left[1 - \left(\frac{v_0}{v}\right)^7\right].$$

(6)
If one puts all the material with \( v > v_a > v_0 \) into a thin shell at radius \( v_a t \), the optical depth of the shell is

\[
\tau_{\text{shell}} = \frac{70}{6} \left( \frac{m_0}{v_a} \right)^{7/3}.
\] (7)

This shows that the detailed arrangement of the outer material has little effect on the optical depth. Other changes in the density profile will produce similar, modest changes in the dimensionless prefactors of these expressions and are unimportant compared to changes in the opacity, mass, energy, velocity or age of the ejecta.

The dust opacity is obviously a key quantity, with

\[
\kappa(\lambda) = \frac{3}{4\rho_a} \frac{Q(a, \lambda)}{a}
\] (8)

where \( \rho_a \) (\( \approx 2.2 \) and \( 3.5 \) g cm\(^{-3}\) for graphitic and silicate dusts) is the bulk density of a grain, \( a \) is the grain size, and \( Q(a, \lambda) \) is the usual efficiency factor. Figure 4 shows the visual absorption and scattering opacities, \( \kappa_a \) and \( \kappa_s \), for standard graphitic and silicate dust as a function of grain size (Draine & Lee 1984, Laor & Draine 1993). The total opacity is \( \kappa_t = \kappa_a + \kappa_s \) and the effective absorption opacity is \( (\kappa_a \kappa_t)^{1/2} \) due to the increase in path lengths created by scattering. More or less independent of composition or grain size, the scale of the V-band opacity is of order 10\(^{-4}\) cm\(^2\)/g, as used in the optical depth scalings given above. We will treat \( S \) and \( \tau \) simply as changes in the dust mass or opacity, which is why we refer to changes in the dust mass or opacity, which is why we can conservatively use a limit on the dust masses of \( M_d \approx 0.1M_\odot \) and Type Ia SNe likely produce less.

The simple \( \tau \propto t^{-2} \) power law dictated by expansion will fail at early times \( (t \lesssim 2 \) years) when the dust properties are still evolving. It will also fail at late times as the reverse shock begins to destroy dust (e.g., Bianchi & Schneider 2003, Nozawa et al. 2007), although this likely only matters on longer time scales than we consider here. This model also excludes any dust that might form in the contact discontinuity (a “cold dense shell”) between the shocked ejecta and the shocked CSM (e.g., Chevalier & Fransson 1994, Pozzo et al. 2004).

In Figure 2 we have also roughly marked where various sources, many of which we introduced in §1, should lie given our fiducial parameter assumptions. For ccSNe, we show the Type IIb SNe 2011dh and 1993J, where there are arguments for the detection of a companion, along with the much older Type IIb remnant Cas A. We also show SN 1987A, the Crab and G54.1+0.3. For Type Ia SNe, we show the very recent SN 2011fe (Nugent et al. 2011), along with the SN 1885

(see Fesen et al. 1983, Fesen et al. 2015), Tycho, Kepler, and SN 1006.

The first point to note from Figure 2 is that SNR should be optically thick to dust for their first

\[
t_{\tau > 1} = 55\kappa_4^{-1/2}M_{d,0.1}^{1/2}M_{10}^{-1/2}E_{51}^{-1/2}
\] (9)

if the amount of dust formed in anyway corresponds to theoretical expectations. For the ccSNe, the theoretically predicted dust mass can be ten times larger. For the Type Ia SNe, the time scale is \( t_{\tau > 1} \approx 20\kappa_4^{-1}M_{d,0.1}^{1/2} \) years, where the theoretically predicted dust mass might also be a ten to a hundred times smaller. Overall, core collapse SNRs should be optically thick for decades up to a century, and Type Ia SNRs should be optically thick for years up to a decade.

The SN 1987A remnant should still be very optically thick given the recent Herschel and ALMA estimates that the cold dust mass is \( M_d \approx 0.1 \) M\(_\odot\) (Matsuura et al. 2011, Indebetouw et al. 2014, Matsuura et al. 2013). Graves et al. (2005) in their limits on any surviving binary companion, used much lower optical depth estimates based on dust masses estimated from the ratio of optical/UV to mid-IR emission found by Bouchet & Danziger (1993). 2172 days after the explosion. Apparently, much of the dust must have formed at slightly later times (see, e.g., Wesson et al. 2015). Another important point is that the bulk of the dust appears to have expansion velocities of \( v \lesssim 1400 \) km/s, putting it well inside the expanding shock between the ejecta and the surrounding medium. This might be expected because the outer layers of the ejecta are the least likely to form dust both because they have the lowest metal fractions (i.e. Type IIIP envelopes) and because they have the highest expansion velocities and so the most rapidly dropping densities (e.g., Kozasa et al. 1983). This means that the reverse shock does not start to destroy newly formed dust until late in the evolution of the SNR.

The best cases for the detection of binary companions to ccSNe are the Type IIb SN 1993J and SN 2011dh. Maund et al. (2004) report the spectroscopic detection of a early-B supergiant as the putative binary companion to SN 1993J 9.9 years after the explosion, and Fox et al. (2014) argue that new HST observations taken in early 2011 and early 2014 (so ∼ 19 years post explosion) confirm the result. Both use an estimated extinction of \( A_V \simeq 0.6 \) mag derived from photometry of nearby stars in Maund et al. (2004). If we fit the F218W, F275W and F336W magnitudes from Fox et al. (2014) to the Solar metallicity PARSEC models (Bressan et al. 2012), focusing only on temperature and extinction, we find a slightly smaller estimate \( A_V \simeq 0.3 \pm 0.1 \) mag, but there is unmodeled contamination from SN emission that introduces additional systematic uncertainties. With a Galactic extinction of roughly \( A_V \simeq 1.2 \) Schlegel & Finkbeiner (2011), we can conservatively use a limit that \( A_V \lesssim 0.4 \) mag at both epochs corresponding to \( \tau_V \lesssim 0.4 \). For an elapsed time of 10 or 19 years, we would expect \( \tau_V \approx 30 \) and 8.2k\( \kappa_4^{-1}M_{d,0.1}^{-1}E_{51}^{-1} \) respectively, implying limits on the dust masses of \( M_d \lesssim 0.0013 \) and 0.0049E\(_{51}\)\( \kappa_4^{-1}M_{d,0.1}^{-1} \). The source also appears to have faded, presumably due to decaying emission by the SN, without evidence that the contribution from the putative companion has increased as it should if veiled by dust formed in the SN.
Figure 3. Fraction of all ccSNe with secondaries brighter than $M_V$ assuming no SN dust (heavy black solid, $\tau_V = 0$). The dashed black lines show the effect of including our standard absorption model for times 20, 30, 50 and 100 years after the SN. The heavy red dotted line shows the integral magnitude distribution of the primaries when they explode for comparison. This model assumes that all systems were binaries ($F = 1$), so the fraction with stellar companions at death is 70%. The time scale can be converted to other parameter choices following Equation (1). The upper scale shows the corresponding apparent magnitudes for a source at a distance of 10 Mpc.

Because SN 2011dh is so much younger, the constraints are correspondingly tighter. Folatelli et al. (2014) and Maund et al. (2015) analyze the same HST data taken in August 2014, 3.2 years after the explosion. Folatelli et al. (2014) adopt an extinction of $A_V = 0.3$ mag as found for nearby stars by Murphy et al. (2011) and argue for the presence of the blue, B star predicted in binary models for the production of SN 2011dh by Benvenuto et al. (2013). Maund et al. (2015) agree with the photometry but argue that some or all of the observed flux could still be due to the SN. The expected optical depth at this epoch is $\sim 290\kappa_4 M_{\text{ej}0.1} M_{\odot}^{-1} t_4^{-1}$, so a detection of the binary companion with $A_V = 0.3$ mag implies $M_d \lesssim 10^{-4} E_{51} M_{\odot}^{-1} M_{\text{ej}0.1} M_{\odot}$. This leaves a puzzle as to why some Type IIb SNe form dust (Cas A), while others apparently do not (SN 1993J and potentially, SN 2011dh).

3 THE EFFECTS OF A HOT BINARY COMPANION ON THE DEBRIS

One way to reconcile visible companions in SN 1993J and SN 2011dh with dust formation in Cas A, is that the presence of a luminous blue companion in SN 1993J and SN 2011dh suppresses dust formation. If the binary companion can photoionize the key elements for dust formation (Mg, Al, Si, S, Fe and C) sufficiently rapidly, then presumably dust formation will be suppressed even as the gas becomes cool enough to allow condensation.

Consider the Type IIb dust formation model of Nozawa et al. (2010). When the star explodes, it is a 4.5$M_\odot$ star which then ejects 2.9$M_\odot$ of material. The inner regions of the ejecta will form grains based on Mg (0.11$M_\odot$, $A = 24$, 7.6 eV), Al (0.01$M_\odot$, $A = 27$, 6.0 eV), Si (0.11$M_\odot$, $A = 28$, 8.2 eV), S (0.03$M_\odot$, $A = 32$, 10.4 eV) and Fe (0.08$M_\odot$, $A = 56$, 7.9 eV), while the outer regions will form grains based on carbon (0.11$M_\odot$, $A = 12$, 11.3 eV). The numbers give the mass of the element in the ejecta, the atomic mass of the most common isotope, and the first ionization energy. “Mixed” with the heavier elements is 1.6$M_\odot$ of oxygen ($A = 16$, 13.6 eV), mixed with the carbon is roughly 1.5$M_\odot$ of helium (24.6 eV) and there is roughly 0.08$M_\odot$ of residual hydrogen in the surface layers. While masses are not reported, nitrogen (14.5 eV) and neon (21.6 eV) will also have significant abundances but are important only to the extent that they absorb UV photons. Note that dust formation can be blocked by photoionization without needing to ionize the most abundant elements (H, He, O) or the other common, but “inert”, elements (N, Ne) because all these elements have higher ionization energies than the key dust forming elements.

We can approximate the structure by putting $0.34M_\odot$ of silicon in the inner region ($r < r_0$) and 0.11$M_\odot$ of carbon in the outer region. Using silicon ($A = 28$, 8.2 eV) roughly matches the number of atoms and the number-weighted mean ionization energy of the Mg/Al/Si/S/Fe mixture. The first requirement is that the ejecta must be optically thick when neutral. For an element with mass $M_i = 0.1M_{\text{ej}0.1} M_\odot$ in the ejecta, the photoionization optical depth scale is

$$\tau_p = \frac{15M_i M_{\alpha} \sigma_p}{64\pi E \sigma p_{\alpha}} \approx 10^{5} M_{\text{ej}0.1} M_{10} \sigma_{17}^{-1} E_{51} A_{28} t_4^{1}$$

(10)
where \( \sigma_0 \sim 10^{-17} \sigma_{17} \text{ cm}^2 \) is a typical photoionization cross section near threshold, \( A = 28 A_{28} \), and \( t = t_1 \) years. This means that in the early phases we can assume that every ionizing photon is absorbed. As the photosphere retreats, these metal atoms will initially be neutral, so a spectrum of any binary companion should show a strong absorption edge near 8 eV (1600 Å). That the UV spectra of the companion of SN 1993J from Fox et al. (2014) do not show such an edge strongly suggests that the Mg, Si, etc., have all been photoionized.

Absent other sources of ionizing photons, the companion will form a photoionized region at the center of the SNR. The ionizing flux needed to balance recombination interior to \( r_0 \) is

\[
Q_0 = \frac{75 \alpha M_i^2}{256 \pi A^2 m_p e^2 n_i^4} \simeq 2 \times 10^{47} \alpha_{13} M_i^2 M_{10}^{3/2} E_{28}^{3/2} t_1^3 \text{s}^{-1} \quad \tag{11}
\]

where \( \alpha = 10^{-13} \alpha_{13} \text{cm}^3/\text{s} \) is the recombination rate. This assumes that the elements included in \( M_i \) are either neutral or singly ionized and that any other elements in the inner region are little ionized. This is likely true given the higher ionization potentials of helium, nitrogen, oxygen and neon. Photoionizing the outer region \((r > r_0)\) requires 3/13 of this flux.

A black body produces

\[
Q_\star = \frac{15L}{\pi k T} \gamma \left( \frac{h \nu}{kT} \right) \quad \text{where} \quad \gamma(u) = \int_u^\infty du u^2 (u^2 - 1)^{-1} \quad \tag{12}
\]

photons with energies above \( h \nu \). Since we are interested in the photoionization of heavy elements with ionization potentials below that of hydrogen, the large deviations of stellar spectra from black bodies beyond 13.6 eV are not of great importance. The overall scale is \( 15L/\pi kT = 4.3 \times 10^{30} L_5 T_4^{-1} \text{s}^{-1} \) for a luminosity \( L = 10^5 L_5 L_\odot \) and temperature \( T = 10^4 T_4 \text{ K} \). For a temperature of 20000 K, \( \gamma(u) = 0.030, 0.083, 0.29, \) and \( 0.66 \) for H (13.6 eV), C (8.2 eV), and Al (6.0 eV). Equating Equations 11 and 12 with the UV photons from the companion can balance recombination over the full inner region after time

\[
t_r \simeq 3.4 \alpha_{13} M_i^{1/3} M_{10}^{2/3} M_{28}^{1/3} E_{51}^{1/3} \gamma_{10}^{1/3} \gamma_{28}^{1/3} \text{ years} \quad \tag{13}
\]

where \( \gamma(u) = 0.17 \gamma_{10} \). For comparison, the time scale for the companion to produce ionizing photons equal in number to the number of target atoms in the inner region is

\[
t_p = \frac{4 \pi m_p \rho_{\odot}}{Q_\star A} = \frac{15 M_i}{8 A Q_\star} \simeq \frac{0.060 M_{0.1} T_4}{A_{28} \gamma_{10} L_5} \text{ years} \quad \tag{14}
\]

This means that if dust formation occurs on times scales of order a year, a sufficiently luminous, hot companion can photoionize the condensible material before dust formation begins.

We can model the growth of the ionized region using the usual simple model for the growth of a Strömgren sphere (Osterbrock 1989) modified for the expansion of the medium. For example, the growth rate of the photoionized zone in the inner \((r < r_0)\) region expressed in comoving coordinates \( \hat{r} = r/r_0 \) is

\[
\frac{d\hat{r}}{dt} = \frac{1}{r^2 t_p} - \frac{1}{t_p} \left( \frac{t}{t_1} \right)^3 - \frac{\hat{r}}{t} \quad \tag{15}
\]

which has no simple solution. The first term of the photoionized region due to the injection of ionizing photons, the second term is the losses due to recombination, and the third term is a Hubble expansion term from working in terms of \( \hat{r} \) instead of \( r \). The solution can be extended beyond \( r_0 \), but the expressions become more complicated. In practice, we considered a model with a \( L = 10^5 L_5 \) and \( T = 20000 K \) black body source ionizing an inner region containing \( 0.34 M_5 \) of silicon \((A = 28, \gamma = 0.29)\) to be ionized, and an outer region containing \( 0.11 M_5 \) of carbon \((A = 12, \gamma = 0.083)\). Using silicon is a reasonable proxy for the actual mixture of Mg/Al/Si/Fe/S. We assume that the silicon and carbon are either neutral or singly ionized and that all other elements with their higher ionization potentials are nearly neutral. In this model, the remnant is photoionized in 530 days starting from neutral gas. The inner region is photoionized in 200 days, while the photoionization of the outer region is slowed because of the higher ionization potential of carbon and the overestimation of the recombination rate created by putting all the carbon in the outer region. With one-third the luminosity, it takes four years and with three times the luminosity it takes 240 days.

The real evolution would be more complex since we should follow the ionization of all the species. We have also neglected the emission by the SN itself, which includes a locally ionizing component because of the radioactive decays, the evolution of the photosphere, collisional ionization, and any ionizing radiation from the expanding shocks. Most of these effects should accelerate the photoionization of the ejecta by the secondary because it means the ejecta are either starting from a partially ionized state or there are additional sources of ionization. Simply starting the process later (e.g., at the end of the plateau phase) has almost no effect on the time at which photoionization is complete because the faster initial growth due to the lower densities compensates for the lost time at the start. For example, solutions to our simple photoionization model started 90 days after the start of the expansion simply merge onto the previous solution.

We chose these parameters because they roughly match the estimated properties of \( T \simeq 10^{4.3 \pm 0.1} K \) and \( L \simeq 10^{5.0 \pm 0.3} L_\odot \) for the companion to SN 1993J (Maund et al. 2004). Fox et al. (2014) agree with this temperature estimate but provide no independent estimate of the luminosity. Folatelli et al. (2014) do not directly estimate a temperature and luminosity for their proposed companion to SN 2011dh but compare to the models of Benvenuto et al. (2013). In these models the secondary ranges from \( T \simeq 22000 K \) and \( L = 10^{4.8} L_\odot \) if the accretion efficiency is low to \( T_r \simeq 30000 K \) and \( L = 10^{5.8} L_\odot \) for high accretion efficiencies. Folatelli et al. (2014) favor the lower efficiency solutions with the lower luminosity and temperature companion. A star with the estimated properties of the companion to SN 1993J or those of the hotter more luminous models for SN 2011dh would photoionize the most important dust producing species on the time scales that Nozawa et al. (2010) find for dust formation in Cas A (300-350, 350-500 and 600-700 days for the carbon, silicate/oxide, Si/FeS grains, respectively). The cooler, lower luminosity models for SN 2011dh probably could not do so. The SN 1993J remnant would also be photoionized well before Fox et al. (2014) obtained their UV HST spectra in 2012, which would...
explain why the are no signs of strong absorption bluewards of $\sim 1600\text{Å}$.

4 AN ILLUSTRATIVE MODEL

In [Kochanek 2009] we considered a simple model for the expected properties of binary companions to ccSNe ignoring binary interactions. Here we take one of these cases to illustrate the consequences of the evolving dust distribution. We assume that the distribution of primary masses $8M_\odot < M_p < 100M_\odot$ is Salpeter, $dN/dM_p \propto M_p^{-x}$ with $x = 2.35$ and that fraction $F$ of the primaries have binary companions distributed in mass $M_s$ as $f(q)$ with $q_{\text{min}} < q = M_s/M_p < q_{\text{max}}$ where $\int dq f(q) = 1$. The joint distribution of the primary and secondary stars in mass is

$$ \frac{dN}{dM_p dM_s} = FM_p^{-x-1} f(q) $$

(16)

with a secondary mass distribution of

$$ \frac{dN}{dM_s} = F f_s q^{-1} f(q) q_{\text{max}} \int_{q_{\text{min}}}^{q_{\text{max}}} q^{-1} f(q) dq. $$

(17)

An observed ccSN can be the collapse of a single star that was never in a binary ($f_{\text{single}} = (1 - F)/(1 + F f_s)$), the primary of a binary ($f_p = F/(1 + F f_s)$), or the secondary of a binary ($f_s = F f_s/(1 + F f_s)$). The fraction of ccSNe with a stellar binary companion is just $f_p$, since when the secondary of a binary explodes the primary is now a compact object (and the binary may have been disrupted).

Here we will just consider the case with $f(q)$ constant over $0.02 < q < 1$. For this uniform model, $f_p = 0.434$ and 70% (41%) of ccSNe have stellar binary companions if $F = 1$ ($F = 1/2$). We show results for $F = 1$ as they can be trivially modified for the addition of stars which are not in binaries. We used the Solar metallicity v1.2S PARSEC (Bressan et al. 2012; Tang et al. 2014) isochrone models to provide estimates of the V band magnitudes for stars of a given age and mass. For these models, the primaries become steadily more (V band) luminous up to $\sim 30M_\odot$ and then rapidly become fainter as mass loss leads to higher temperatures and larger bolometric corrections.

Figure 3 shows the results for all SN with binary companions. Most secondaries are fainter, blue, main sequence stars simply as a consequence of their lower masses, as already noted in [Kochanek 2009]. For this simple model, only $\sim 10\%$ of SNe have observable ($V \gtrsim 26\text{mag}$ at 10 Mpc) secondaries even though most SNe (70% for the $F = 1$ binary fraction used here) occur in systems with a stellar companion. With the addition of dust, companions should almost never be observable until decades after the SN. However, this leads to the interesting observational possibility of searching for slowly reappearing stars at the sites of decades old SNe.

Now, suppose that dust formation is suppressed whenever $Q_s > 10^{50} \text{s}^{-1}$ (Equation 2). This is roughly the flux of silicon ionizing photons from the companion of SN 1993J. As shown in Figure 4 many of the more luminous companions are now easily observed because dust formation has been suppressed. For a threshold of $Q_s > 10^{49.5} \text{s}^{-1}$, dust formation is suppressed in roughly 8% of the binary systems. If the threshold is even modestly higher, the mechanism does not work, since the fraction drops to 3% for a threshold of $Q_s > 10^{49.5} \text{s}^{-1}$ and is negligible for $Q_s > 10^{50} \text{s}^{-1}$. Lowering the threshold rapidly raises the fraction to 15% for $Q_s > 10^{48.5} \text{s}^{-1}$ and 25% for $Q_s > 10^{48} \text{s}^{-1}$. Not all of the visually luminous stars are unobscured, since there are some companions that are luminous but cool. The companion to SN 1993J should have $M_V \sim -5.9\text{mag}$, and it lies in the magnitude range of Figure 3, where the companions can affect dust formation (as expected).

5 DISCUSSION

If SNe form dust as predicted in theoretical models and observed in nearby SNRs, then the binary companions to SNe, particularly ccSNe, should initially be heavily obscured. The decreasing optical depth due to expansion should lead to a steady brightening that should be a nearly unique signature of a binary companion. The inferred optical depths then provide an estimate of the amount of newly formed dust that is independent of the dust temperature. Absorption by dust should be observable (optical depths $\gtrsim 0.01$) for decades to roughly a century after the explosion. The local SNR that might be probed through dust absorption are SN 1987A, Cas A and the Type Ia SN 1885 in M31.

The present day optical depth scale for SN 1987A is $\tau_0 \sim 3\kappa_\text{dust} M_\odot^{-1}$ and current estimates are that $M_\text{dust} \sim 0.5-1.0M_\odot$ [Matsuura et al. 2011; Indebetouw et al. 2011; Matsuura et al. 2015]. Even for these high dust masses, SN 1987A is approaching the point where it is feasible to search for either a surviving companion or a fortuitously obscured background star in the near-IR. Many models for SN 1987A invoke binary interactions, although frequently with a final merger, to explain either the explosion of a blue supergiant or the structure of the surrounding winds (e.g., Podsiadlowski & Joss 1998; Podsiadlowski 1999; Blondin & Lundqvist 1993; Morris & Podsiadlowski 2009).

If there is a surviving companion, the observed mid-IR dust luminosity limits its luminosity to be $\lesssim 10^4 L_\odot$.

While a dwarf (single degenerate) companion to SN 1885A is probably not observable even if present, the remnant of SN 1885A is observed as a spatially extended metal line absorption feature against the stars in the bulge of M 31 [Fesen et al. 1998; Fesen et al. 2013]. These authors comment that there is no obvious continuum absorption by the SNR, implying little dust, but do not present a quantitative limit. The present day optical depth scale for SN 1885A of $\tau_0 \sim 0.02\kappa_\text{dust} M_\odot^{-1}$ is consistent with this comment and we make a quantitative estimate in Auchettl & Kochanek (2017).

The present day optical depth scale for Cas A should be similar to that of SN 1885, with $\tau_0 \sim 0.03\kappa_\text{dust} M_\odot^{-1}$, because the slower expansion of a ccSN compensates for Cas A’s greater age. With dust mass estimates approaching $M_\text{dust} \sim M_\odot$ [Barlow et al. 2010; De Looze et al. 2010], the optical depth of the SNR could be significant. This suggests trying the method of Trimble (1977), comparing the colors of stars superposed on the SNR to those of other nearby stars. This method is probably infeasible because of the limited numbers of stars and because even modest spatial inhomogeneities in the $A_V \sim 5-6\text{mag}$ of extinction towards Cas A [Hurford & Fesen 1996] will confuse the measurements. With some patience, however, it is feasible.
to measure the optical depth through the time variability of the extinction of background stars. Over a decade, the optical depth should drop by $\sim 0.002\kappa d^{-1}M_{0.1}$, which is well within the capabilities of difference imaging methods if $M_d \approx M_0$. This depends on the existence of a (non-variable) background star since Cas A seems to not have had a binary companion (Kochanek 2017), but is otherwise straightforward.

The best cases for the detections of binary companions are the B stars proposed for the Type IIb’s SN 1993J (Maund et al. 2004, Fox et al. 2014) and SN 2011dh (Folatelli et al. 2014, but see Maund et al. 2013). Photometry of both progenitors showed blue excesses (e.g., Albrecht et al. 1994, Arcavi et al. 2011, Bersten et al. 2012) and most models for Type IIb SNe invoke binary mass transfer with predicted secondary properties similar to those of the observed candidates (e.g., Podsiadlowski et al. 1993, Stanchfield & Eldridge 2009, Claey et al. 2011, Benvenuto et al. 2013). However, the colors of the candidate stars require very little extinction, and so imply very stringent limits on the dust mass of $M_d \lesssim 10^{-3}$ and $10^{-1}\kappa^{-1}M^{-1}_{1.0}M_{0.1}$, respectively. Theoretical models by Nozawa et al. (2010) predict the formation of $M_d \approx 0.1M_0$ of dust, and Bevan et al. (2010) infer the presence of $M_d \approx 0.1-0.3M_0$ of dust in SN 1993J in order to model the asymmetries of optical emission lines.

Either these companion identifications are incorrect, or these Type IIb SNe formed negligible amounts of dust. Inhomogeneities can lead to particular lines of sight having more or less extinction, but this should be a matter of degree rather than any light of sight being genuinely transparent. It is also implausible as an argument for rendering both sources visible. Cas A was also a Type IIb SNe (Krause et al. 2008, Rest et al. 2008) and it both lacks a companion (Kochanek 2017), and contains a significant amount of dust ($M_d \sim 0.1-0.8M_0$, Barlow et al. 2014, De Loos et al. 2014). The companion stars invoked for SN 1993J or SN 2011dh would be $R \sim 16$ mag in Cas A and impossible to miss (see Kochanek 2017).

This circle can be squared by the fact that a luminous, hot, stellar companion can suppress dust formation by photoionizing the ejecta sufficiently rapidly. A least in our simple model of the process, the proposed companion to SN 1993J can do so, and this may also be true of the proposed companion to SN 2011dh. Detailed calculations of the full multi-element, time-dependent photoionization process are required to determine the exact threshold for suppressing dust formation. In addition to photoionization, the abundant soft UV photons from a hot companion further inhibit dust formation because they easily destroy very small grains by stochastically heating them much to higher temperatures than predicted by the equilibrium temperature (Kochanek 2014). For SN 1993J in particular, there are also $\sim 10^{39}$ ergs/s of X-rays being generated by the SN shock expanding into the circumstellar medium at the time when dust would form. Some of these X-rays must also contribute to reionizing the interior.

If the secondary has reionized the ejecta, a late time spectrum should show a peculiar, low ionization, heavy element emission line spectrum. At present, spectra of SN 1993J are dominated by emission lines from higher ionization states and with a “boxy” shape that indicates they are largely produced in a shell associated with the shock region (e.g., Fransson et al. 2003). The companion is too cool to contribute to producing these highly ionized states. Where a spherical shell produces exactly a top hat velocity distribution, with $dP/dv$ constant out to the expansion velocity of the shell, recombination lines produced by the companion fully photoionizing the interior ($r < r_0$) would be more “paraboloidal” with a line-of-site velocity distribution $dP/dv \propto 1 - v^2/v_0^2$. Adding the contribution from the exterior ($r > r_0$) would add fainter, broader wings. This contribution to the spectrum of SN 1993J could become more visible as the contribution from circumstellar emission slowly fades.

Since binary companions to SNe should be common and will frequently be hot, main sequence O/B stars (e.g., Kochanek 2009), variability in the binary properties of SNe might help to explain the some of the seeming incoherence of the evidence for dust formation in SNe. In our simple “passively evolving” model, dust formation can be suppressed in 5-25% of ccSNe that are stellar binaries at death. But the effects of the companion are likely more complex. Since the dust forming elements are stratified in radius and have a range of different ionization potentials, less luminous binary companions will still modify which dusts form even if dust formation is not completely suppressed. For example, silicate dust formation is easier to suppress than carbonaceous dust formation because silicon is both closer to the center of the SNR and more easily ionized than carbon.

If many ccSNe form dust, and this still seems inevitable given the physics of dust formation and the observed dust masses in nearby SNR, then almost all limits on the existence of binary companions from post-explosion imaging are invalid unless the companion is sufficiently soft-UV luminous to suppress dust formation. Binary companions must generally be identified by the appearance of a star at the location of the SN decades after the explosion.

Dust formation can also have interesting consequences for interpreting the constraints on the progenitors of the stripped Type Ib/c ccSNe. Because of bolometric corrections, a secondary star to these SNe can be more optically luminous than the primary (see Kochanek 2009). This means that in pre-explosion images, the observed source can be the secondary rather than the primary. Without dust formation, such a mistaken identification is easily rectified because the secondary will still be present in post-explosion images. However, if dust forms, the secondary will also be invisible in the post-explosion images for a long period of time and this may be incorrectly interpreted as confirming that the pre-explosion source was the primary.

This is presently of greatest relevance to the best candidate for a Type Ib progenitor, iPTF13bvn (Cao et al. 2013, Groh et al. 2013, Bersten et al. 2014, Fremling et al. 2014, Eldridge et al. 2013, Eldridge & Maund 2014, Folatelli et al. 2014). Present models for iPTF13bvn prefer scenarios in which the primary was the more visually luminous star, but also predict that the secondary is likely observable as the SN fades (e.g., Eldridge & Maund 2014). Like most other ccSNe, Type Ib SN are predicted to create significant amounts of dust (Nozawa et al. 2008). For the predicted properties of the secondary in the existing models ($T \approx 20000$ K and $L < 10^{47}L_\odot$), dust formation is unlikely to be suppressed. Thus, if no secondary is detected,
nothing can be said about its properties because it may simply be heavily obscured. If a secondary is detected, then iPTF13bvn becomes another example of an SN making negligible amounts of dust ($M_d \lesssim 10^{-3}M_\odot$) and the companion should be at the maximum possible luminosities predicted by Eldridge & Maund (2016).

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