ON ABSORPTION BY CIRCUMSTELLAR DUST, WITH THE PROGENITOR OF SN 2012aw AS A CASE STUDY

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Received 2012 August 20; accepted 2012 September 11; published 2012 October 12

ABSTRACT

We use the progenitor of SN 2012aw to illustrate the consequences of modeling circumstellar dust using Galactic (interstellar) extinction laws that (1) ignore dust emission in the near-IR and beyond, (2) average over dust compositions, and (3) mischaracterize the optical/UV absorption by assuming that scattered photons are lost to the observer. The primary consequences for the progenitor of SN 2012aw are that both the luminosity and the absorption are significantly overestimated. In particular, the stellar luminosity is most likely in the range 10^{4.8} < L_\odot < 10^{5.0} and the star was not extremely massive for a Type IIP progenitor, with M_\star < 15 M_\odot. Given the properties of the circumstellar dust and the early X-ray/radio detections of SN 2012aw, the star was probably obscured by an ongoing wind with M \sim 10^{-5.5} to 10^{-5.0} M_\odot yr^{-1} at the time of the explosion, roughly consistent with the expected mass-loss rates for a star of its temperature (T_\star \simeq 3600^{+500}_{-200} K) and luminosity. In the spirit of Galactic extinction laws, we supply simple interpolation formulae for circumstellar extinction by dusty graphitic and silicate shells as a function of wavelength (\lambda > 0.3 m\mu) and total (absorption plus scattering) V-band optical depth (\tau_V \leq 20). These do not include the contributions of dust emission, but provide a simple, physical alternative to incorrectly using interstellar extinction laws.

Key words: dust, extinction -- stars: evolution -- supergiants -- supernovae: general -- supernovae: individual (SN2012aw)

Online-only material: color figures

1. INTRODUCTION

A key component to understanding supernovae (SNe) is the mapping between the explosions and their progenitor stars. Slow, steady progress is being made, and it is now well established that Type IIP SN are associated with red supergiants (see the review by Smartt 2009). There is a puzzle, however, in that the observed upper limit of \sim 16 M_\odot on the masses Type IIP SN progenitors appears to be significantly lower than the maximum masses of \sim 25 M_\odot for stars expected to explode while still red supergiants (Smartt et al. 2009), part of a more general absence of massive SN progenitors (see Kochanek et al. 2008). Since these “missing” progenitors should be more luminous than those that are being discovered, they must either be hidden, evolve differently than expected, or fail to explode. For example, in the rotating models of Ekström et al. (2012), the upper mass limit for red supergiants is lower, with 20 M_\odot stars being blue rather than red at the onset of carbon burning. Alternatively, O’Connor & Ott (2011) and Ugliano et al. (2012) find that the progenitor masses of 20–25 M_\odot corresponding to the upper mass range for red supergiants are more prone to failed explosions and prompt black hole formation, and such events would have to be found by searching for stars disappearing rather than explosions appearing (Kochanek et al. 2008). Binary evolution can also alter the distribution of final states at the time of explosion given the high probability for mass transfer as stars expand to become red supergiants (e.g., Sana et al. 2012).

If the discrepancy is not explained by the physics of stellar evolution or explosion, then the likely remaining explanation is the effect of circumstellar dust. For example, Walmswell & Eldridge (2012) note that more massive and luminous red supergiants have stronger winds, which can form dust and partly obscure the star. This then biases (in particular) the upper mass limits associated with failed searches for progenitor stars, since the luminosity limits must be corrected for an unknown amount of circumstellar dust extinction. Fraser et al. (2012) and Van Dyk et al. (2012) recently analyzed the progenitor of SN 2012aw, finding that it was both relatively high mass (15–20 M_\odot for Van Dyk et al. 2012 and 14–26 M_\odot for Fraser et al. 2012) and the most heavily obscured of any SN progenitor other than the completely obscured (and debated) SN 2008S class (see Prieto et al. 2008; Thompson et al. 2009; Kochanek 2011). Since most of the extinction vanished after the SN, the dust must have been circumstellar (Fraser et al. 2012; Van Dyk et al. 2012).

Like most studies of circumstellar dust in supernovae or supernovae progenitors, Walmswell & Eldridge (2012), Fraser et al. (2012), and Van Dyk et al. (2012) treat circumstellar dust as if it is a foreground screen that can be quantitatively modeled using Galactic interstellar extinction curve models parameterized by the value of R_V (e.g., Cardelli et al. 1989). Usually, only studies that are self-consistently calculating emission by the dust correctly model the absorption by circumstellar dust (e.g., studies of the SN 2008S class of transients by Wesson et al. 2010; Kochanek 2011; or Szczygiel et al. 2012). But three well-known effects mean that it is never appropriate to make this approximation unless the optical depth is negligible compared with the required precision of the analysis. First, emission from circumstellar dust can be important in the near-IR if the star is presently forming dust at temperatures of 1000–2000 K. This matters most for hotter stars with less intrinsic near-IR emission than the red supergiants we consider here. Second, interstellar dust has the average composition of dust from all sources, while individual stars have the dust associated with their particular chemistry. This is relevant here because \sim 20 M_\odot stars generally produce silicate rather than graphitic dusts (e.g., Verhoelst et al. 2009).
The third, and least appreciated point, is the different role of scattered photons in interstellar and circumstellar extinction. This issue has been discussed in detail by Wang (2005) and Goobar (2008) in the context of anomalously low estimates of $R_V$ for Type Ia SN, but correctly treating the problem has not become a matter of practice. For a foreground screen, scattered light forms a very diffuse, extended halo around the source that is not included in the estimate of the source flux. This halo can sometimes be seen as the extended dust echoes of transient sources (e.g., Sugerman & Crotts 2002). If the circumstellar dust is unresolved, however, the scattered light is simply included in the total flux. Thus, for interstellar extinction you observe only the direct, unabsorbed and unscattered emission, while for circumstellar extinction you observe both the direct unabsorbed and the scattered emission. Most of the observed optical emission from a moderately self-obscured star is scattered light.

Figure 1 shows an example generated by DUSTY (Ivezić & Elitzur 1997; Ivezić et al. 1999; Elitzur & Ivezić 2001) using the spectral energy distribution (SED) of a $10^4$ K blackbody surrounded by $\tau_V = 3$ (scattering plus absorption) of cold silicate dust. The dusty material has a density profile of $\rho \propto 1/r^2$ in a shell with $R_{out}/R_{in} = 2$. Galactic (interstellar) extinction corresponds to putting the dust at such a large radius that we no longer include the scattered light in the observed flux of the star, and the extinction law corresponds to the wavelength dependent difference between the input spectrum and the directly escaping spectrum. Figure 2 shows this ratio converted into an extinction law $R_\lambda$, for pure graphitic, pure silicate, and a 50:50 mix of the two, as compared to Cardelli et al. (1989) Galactic extinction laws with $R_V = 4.0, 3.1$ and 2.0. Galactic dust models typically have a roughly 50:50 mix of graphitic and silicate grains (see the summary in Draine 2011), and using this mix in the DUSTY models roughly reproduces a typical $R_V = 3.1$ Galactic extinction law. The match is not perfect because there are differences in the assumed size distributions. For a star surrounded by an unresolved shell of dust, however, the emission we measure is the sum of the direct and scattered light, which is very different from the direct emission alone. Figure 3 shows this case converted into an effective circumstellar extinction law for the same three dust mixtures. For circumstellar dust, all three examples are now significantly below the $R_V = 3.1$ curve and a given change in color implies a significantly smaller change in luminosity. If we fit the absorption in these DUSTY models with Cardelli et al. (1989) extinction models, the best fits for the graphitic, silicate, and 50:50 dusts are $R_V \simeq 2.4, R_V \simeq 1.6$, and $R_V \simeq 2.1$, respectively. These are the best fits for $\tau_V = 3$ from 0.36 $\mu$m ($U$ band) to 1 $\mu$m. The best fits vary modestly ($\Delta R_V \simeq 0.1$) with $\tau_V$ and the fitted wavelength range, become worse for higher optical depths, and there are no truly good fits. Figure 3 superposes these Cardelli et al. (1989) extinction curves on the DUSTY models. Goobar (2008) found similar estimates for the best Cardelli et al. (1989) extinction curves to model circumstellar dust and also noted that they are not very good approximations. The final point to note in Figures 2 and 3 is that the dust composition is quantitatively important. Interstellar dust is a mixture of graphitic and silicate dusts from many sources. Individual stars, however, typically only produce silicate or graphitic dusts depending on the carbon to oxygen abundance ratio of the stellar atmosphere. To zeroth order, all available carbon and oxygen bond to make CO. Then, a carbon poor (rich) atmosphere has excess oxygen (carbon) to make silicate (graphitic) dusts. The
Figure 3. Effective extinction laws $R_\lambda$ for dust in an unresolved shell around the star where we measure both the direct and scattered light. The solid curves show the results for $\tau_V = 3$ of graphitic dust (top), silicate dust (bottom), and a 50:50 mix (middle). The dashed curves show the best-fit CCM (Cardelli et al. 1989) extinction laws with $R_V = 2.4$ (top, graphitic), $R_V = 2.1$ (middle, 50:50 mix), and $R_V = 1.6$ (bottom, silicate). The fits are never very good, particularly at high optical depth, and the best-fit parameters vary somewhat with the optical depth and wavelength. Goobar (2008) obtained similar results. The peak at long wavelengths (small $\lambda^{-1}$) is a silicate emission feature that DUSTY includes in the scattered light contribution to the emerging spectrum.

Figure 4. Combined 3.6 and 4.5 $\mu$m images of the region surrounding the progenitor of SN 2012aw. The 2$''$ diameter circle marks the estimated position of the progenitor, although the formal uncertainties in the position are far smaller (0$''$.05). The smaller points show the grid of apertures used to estimate the flux limits, where missing points show the locations of dropped apertures (see the text). A few of the grid points lie near fainter sources that are obvious in this co-added image but only marginally detectable (at about 2$\sigma$) in the four individual images combined to make Figure 4. The image is aligned to the world coordinate system with north up and east left.
Table 1

| ObsID          | Date     | $T_{exp}$ (s) | 0.2–10 keV | 0.2–0.5 keV          | 0.5–2 keV   | 2–10 keV | Range     |
|----------------|----------|--------------|------------|----------------------|-------------|----------|-----------|
| 00032319001    | Mar 21.0 | 9151         | 1.78 ± 0.536 | 0.174 ± 0.197        | 1.445 ± 0.458 | 0.162 ± 0.197 | 03/21    |
| 00032319002    | Mar 23.0 | 5856         | 0.449 ± 0.376 | −0.090 ± 0.028       | 0.369 ± 0.306 | 0.171 ± 0.217 | 03/23    |
| 00032319003    | Mar 25.0 | 8843         | 1.528 ± 0.497 | −0.053 ± 0.018       | 1.520 ± 0.475 | 0.061 ± 0.145 | 03/25    |
| 00032319004–006| Mar 30.4 | 22714        | 0.618 ± 0.229 | 0.037 ± 0.112        | 0.523 ± 0.146 | 0.261 ± 0.136 | 03/28–04/01 |
| 00032315015–030| Apr 12.5 | 48188        | 0.258 ± 0.136 | 0.117 ± 0.089        | 0.059 ± 0.058 | 0.184 ± 0.057 | 04/01–02/22 |
| 00032315031–042| Jun 14.9 | 17430        | −0.123 ± 0.198 | −0.302 ± 0.080       | 0.280 ± 0.164 | −0.100 ± 0.076 | 04/26–07/14 |

Notes. (Date) is the exposure time weighted average date, where Range gives the range of dates spanned by the epochs. The counts are in units of counts ks$^{-1}$.

Table 2

| Type | $T_0$ (K) | $T_s$ (K) | $\log_{10} N_{\text{exp}}$ ($L_\odot/L_\odot$) | $\log_{10} \nu_0$ | $\log_{10} M$ ($R_{\odot}/L_{\odot}$) |
|------|-----------|-----------|-----------------------------------------------|-------------------|---------------------------------------|
| sil  | 100       | 3754      | 0.87 (0.72/0.97)                              | 16.97 (16.84/17.10) | −2.85 (−3.14/−2.63)                   |
| sil  | 500       | 3600      | 0.80 (0.48/0.93)                              | 15.31 (15.13/15.46) | −4.91 (−5.09/−4.31)                   |
| sil  | 1000      | 3603      | 0.79 (0.55/0.91)                              | 14.80 (14.67/14.93) | −5.11 (−5.48/−4.86)                   |
| sil  | 1500      | 3823      | 0.85 (0.67/0.94)                              | 14.50 (14.36/14.60) | −5.35 (−5.67/−5.17)                   |
| gra  | 100       | 3897      | 0.64 (0.45/0.74)                              | 17.40 (17.25/17.53) | −2.65 (−3.00/−2.43)                   |
| gra  | 500       | 3528      | 0.44 (0.13/0.60)                              | 15.81 (15.70/15.93) | −4.46 (−4.87/−4.18)                   |
| gra  | 1000      | 3562      | 0.43 (0.17/0.57)                              | 14.97 (14.88/15.07) | −5.30 (−5.65/−5.07)                   |
| gra  | 1500      | 3694      | 0.48 (0.16/0.61)                              | 14.49 (14.37/14.59) | −5.74 (−6.17/−5.50)                   |

Notes. These are the median and 90% confidence intervals of the MCMC results. The implied mass-loss rate $M$ is in units of $\dot{M} = 10^{15} M_\odot$ yr$^{-1}$, and the shock luminosity $L_s$ is in units of $(v_s/(500 \text{ km s}^{-1}))^3 k_{B}^{-1} L_\odot$.

Table 3

| Model Fits |
|------------|
| Type       | $\log_{10} N_{\text{exp}}$ ($L_\odot/L_\odot$) | $\log_{10} \nu_0$ | $\log_{10} M$ ($R_{\odot}/L_{\odot}$) |
| sil         | 0.87 (0.72/0.97)                              | 16.97 (16.84/17.10) | −2.85 (−3.14/−2.63) |
| sil         | 0.80 (0.48/0.93)                              | 15.31 (15.13/15.46) | −4.91 (−5.09/−4.31) |
| sil         | 0.79 (0.55/0.91)                              | 14.80 (14.67/14.93) | −5.11 (−5.48/−4.86) |
| sil         | 0.85 (0.67/0.94)                              | 14.50 (14.36/14.60) | −5.35 (−5.67/−5.17) |
| gra         | 0.64 (0.45/0.74)                              | 17.40 (17.25/17.53) | −2.65 (−3.00/−2.43) |
| gra         | 0.44 (0.13/0.60)                              | 15.81 (15.70/15.93) | −4.46 (−4.87/−4.18) |
| gra         | 0.43 (0.17/0.57)                              | 14.97 (14.88/15.07) | −5.30 (−5.65/−5.07) |
| gra         | 0.48 (0.16/0.61)                              | 14.49 (14.37/14.59) | −5.74 (−6.17/−5.50) |

Notes. These are designed to simply be grabbed with a mouse from the electronic paper and inserted into most numerical environments. The input quantities are $\tau = \tau_0/\nu_0$ and $\lambda = \lambda_0$, and the output quantity is $\lambda_0/\nu_0$. They are valid for $\lambda \geq 0.3$ $\mu m$ and $\tau_0 \leq 20$ and should not be extrapolated outside this range. No emission by the dust is included in the models.

Notes. (Date) is the exposure time weighted average date, where Range gives the range of dates spanned by the epochs. The counts are in units of counts ks$^{-1}$.
Since we are essentially confusion limited, we estimated flux limits using the grid of 36 apertures covering the location of the progenitor and bounded by the nearby brighter stars as shown in Figure 4. The grid spacing was 3′′. We used the IRAF\textsuperscript{4} APPHOT/PHOT to measure aperture magnitudes with a signal radius of 2′′4 and a sky annulus from 2′′4 to 7′′2. The fluxes were calibrated following the procedures given in the Spitzer Data Analysis Cookbook\textsuperscript{5} and aperture corrections of 1.213, 1.234, 1.379, and 1.584 for the 3.6 through 8.0 μm bands. Keeping the sky annulus immediately next to the signal aperture minimizes the effects of background variations created by the galaxy. We used a 2σ outlier rejection procedure in order to exclude sources located in the local sky annulus, and correct for the excluded pixels assuming a Gaussian background flux distribution.

We clipped three of the grid points in the wings of the brighter sources and the two lowest (negative) flux points that lay in an obvious “dark lane,” leaving 31 points. Based on one of the two SINGS epochs, the variances in the four bands are 10.7, 11.4, 12.8, and 14.2 μJy for the 3.6, 4.5, 5.8, and 8.0 μm bands, respectively. This is well above the nominal noise level for the exposure time (0.5, 0.8, 6, and 6 μJy) because there is stellar emission in the region. The variance after co-adding the two SINGS epochs is only slightly smaller, as expected for noise dominated by confusion, so we rather conservatively use the variances derived from the single epoch as 1σ flux limits. Note that some of the grid points clearly lie on sources in the co-added image. These sources are not readily apparent in the four individual sub-images, where their detection significance would be roughly 2σ. A source of similar flux at the supernova position would be equally obvious in Figure 4.

For models of the SED, we combined the V- and I-band estimates from Van Dyk et al. (2012) and Fraser et al. (2012), including the difference in their V-band estimates as an additional systematic error. We used the J and K\textsubscript{s} estimates from Van Dyk et al. (2012), based on their better photometric calibrations. We use a minimum flux uncertainty of 20%, which broadens the V-, I-, and J-band photometric errors, given that the data were obtained over a long time period (1994–2009, with the SINGS IRAC data being obtained on 2004 May 22/23) and Van Dyk et al. (2012) argue for the detection of variability at V and I. We model the star using the MARCS (Gustafsson et al. 2008) stellar atmosphere models, considering only the 15 M\textsubscript{☉}, solar metallicity, 5 km s\textsuperscript{-1} turbulent velocity log\textsubscript{10} g = −0.5 models preferred by Van Dyk et al. (2012) and also considered by Fraser et al. (2012). These are available for effective temperatures of T\textsubscript{e} = 3300–4000 K in steps of 100 K and then 4250 and 4400 K. For intermediate temperatures we linearly interpolate between the available models. We averaged the high resolution MARCS models and the filter transmission functions onto a coarser wavelength grid for use in the DUSTY models and then generated magnitude estimates for each model including the appropriate averages over the filter band passes. We first fit the measurements to normalize the luminosity, and then added a contribution from the upper limits as Δχ\textsuperscript{2} = (F\textsubscript{model}/F\textsubscript{limit})\textsuperscript{2} for each band, where F\textsubscript{model} is the estimate from the normalized model and F\textsubscript{limit} is the 1σ limit on the flux.

Immler & Brown (2012) reported a Swift (Gehrels et al. 2004) X-ray detection of the SN in the first week and Stockdale

\textsuperscript{4} IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

\textsuperscript{5} http://irsa.ipac.caltech.edu/data/SPITZER/docs/dataanalysistools/
Figure 6. Constraints on the visual extinction $A_V$ (top) and stellar luminosity $L_*$ (bottom) as a function of stellar temperature $T_*$. The solid contours show the $1\sigma$ constraints on two parameters ($\Delta \chi^2 = 2.3$) for the graphitic (left) and silicate (right) models and an inner edge dust temperature of $T_d = 1000$ K roughly corresponding to having a dust forming wind at the time of the observations. The points and dashed contours show the results from Van Dyk et al. (2012) and Fraser et al. (2012), respectively. The DUSTY model $\tau_V$ were converted to $A_V = 2.5(1 - w_V)^{1/2} \tau_V / \ln 10$.

(A color version of this figure is available in the online journal.)

Figure 7. Extinction $A_\lambda$ as a function of wavelength for silicate (squares) and graphitic (triangles) circumstellar dust with $R_{\text{out}}/R_{\text{in}} = 10$ and optical depths of $\tau_V = 0.1$ (bottom), 0.3, 1.0, 3.0, 10.0, and 20.0 (top). Note how the shapes of the curves depend on both composition and optical depth. The curves through the points are the model from Table 3.

(A color version of this figure is available in the online journal.)

et al. (2012) and Yadav et al. (2012) report 20 GHz radio detections in the first month. Swift continued to monitor the SN for an extended period, so as an independent probe of the circumstellar medium we obtained all the archival Swift XRT data, binning the observations as summarized in Table 1. We reprocessed the XRT data using the xrtpipeline tool provided by the Swift team. We binned the observations into six roughly logarithmic time intervals and then reprojected each group of observations into a single image. We chose the source region to be a circle centered on the SN with a radius of 10 pixels (23.6′) and a nearby background region without any sources, using aperture corrections based on the analysis of the Swift point-spread function by Moretti et al. (2005). Following Immler & Brown (2012), we assumed a Galactic foreground column density of $2.9 \times 10^{20}$ (Dickey & Lockman 1990). For our epoch best matching Immler & Brown (2012), we reproduce their count rates. While none of the X-ray detections are of very high significance, there appears to be a low level of detectable (3\sigma) and probably time varying X-ray emission for the first 1–2 months. There are no clear detections at low energies (0.2–0.5 keV) and only very marginal detections at high energies (2–10 keV)—the observed counts are completely dominated by the 0.5–2 keV band.

We use the DUSTY (Ivezić & Elitzur 1997; Ivezić et al. 1999a; Elitzur & Ivezić 2001) dust radiation transfer models to correctly include dust emission, absorption, scattering, and composition when modeling the progenitor SED. We use either graphitic or silicate dust models from Draine & Lee (1984) and
curves through the points are the model from Table 4. For an input SED \( \tau_v \) total (absorption plus scattering) optical depth, the observed SED is directly escaping emission and observed light that is direct emission as a function of wavelength for silicate with modulus of \( v \) direct emission and temperature of the star, so we simply considered cases with albedos of \( 0.1 \) for 0, 5, and 20, and 20.0 (top). The curves through the points are the model from Table 4. For an input SED \( S_{\lambda} \), the observed SED is \( S_{\lambda}10^{-0.4A_{\lambda}} \) of which \( S_{\lambda}10^{-0.4A_{\lambda}} F_{\lambda} = S_{\lambda}10^{-0.4A_{\lambda}}F_{\lambda}^{abs} \) is directly escaping emission and \( S_{\lambda}10^{-0.4A_{\lambda}}(1 - F_{\lambda}^{abs}) \) is scattered emission. As in Figure 7, note how the shapes of the curves depend on both composition and optical depth.

(A color version of this figure is available in the online journal.)

While they are not physically correct models, we do recover the results of Van Dyk et al. (2012) and Fraser et al. (2012) if we model our version of the SED including the mid-IR flux limits but no dust emission and using Cardelli et al. (1989) extinction laws. Like Van Dyk et al. (2012), we find that higher \( R_V \) extinction laws provide better fits, but we also find a stellar temperature degeneracy similar to Fraser et al. (2012). Clearly, the models have a “degeneracy” direction which is very sensitive to the exact assumptions of the model and can lead to either tight or loose limits on the effective temperature. The specific rationale for using \( R_V \) \( \leq 4 \) extinction laws in Van Dyk et al. (2012) is not really valid, but allowing freedom in the extinction curve is certainly a more conservative approach. For example, if we fix \( R_V = 4.35 \) and \( T_\ast = 3600 \) K to match Van Dyk et al. (2012), we obtain a luminosity of \( \log_{10} L_{\ast}/L_\odot = 5.15 \pm 0.05 \) compared to 5.21 \( \pm 0.03 \). If we fix \( R_V = 3.1 \) to match Fraser et al. (2012), then we find \( \log_{10} L_{\ast}/L_\odot = 5.10 \pm 0.05 \) for \( T_\ast = 3600 \) K and \( \log_{10} L_{\ast}/L_\odot = 5.43 \pm 0.05 \) for \( T_\ast = 4400 \) K, close the values of \( \log_{10} L_{\ast}/L_\odot = 5.0 \) and 5.6 they find for temperatures of \( T_\ast = 3550 \) K and 4450 K using MARCS models with \( \log_{10} g = 0 \).

Figure 5 shows two representative DUSTY models of the progenitor for circumstellar silicate and graphitic dusts with \( T_\ast = 1000 \) K, roughly corresponding to the expected inner edge dust temperatures if the star was forming dust at the time of the observations. Formally, the graphitic model is a better fit (\( \chi^2 = 5.5 \) versus 8.8), but the models have essentially identical stellar luminosities, \( L_* = 10^{4.9} L_\odot \), and temperatures, \( T_\ast \approx 3550 \) K. Both models marginally satisfy the mid-IR flux limits at this luminosity, with the graphitic models primarily limited by the non-detections at 3.6 and 4.5 \( \mu m \), and the silicate models limited by the contribution of silicate emission peak at 8.0 \( \mu m \).

Figure 5 illustrates all three of the basic points about circumstellar dust as compared with interstellar dust. First, the optical flux is completely dominated by the scattered emission that is not included in interstellar extinction laws. Second, dust emission is quantitatively important to the \( K_\ast \)-band flux. Because the
star is cold, dust emission does not dominate the near-IR flux as it would for a hot star of the same luminosity and degree of obscuration, but it does partly compensate for the absorption. Third, there are quantitative differences between the two dust types in their balance between absorption and scattering and the nature of the mid-IR emission. The total optical depths of the models are quite different, \( \tau_V = 5.9 \) for silicates and \( \tau_V = 2.6 \) for graphite, but the effective absorption optical depths of the two models are very similar, with \( \tau_{SV} = (1 - w_V)^{0.75} \tau_V = 2.2 \) for silicates and 1.9 for graphite.

Figure 6 shows the allowed parameter ranges for the stellar luminosity \( L_* \) and visual extinction \( A_V \) as a function of stellar temperature \( T_* \) as compared to the results from Fraser et al. (2012) and Van Dyk et al. (2012). We again show the results for \( T_d = 1000 \) K. Table 2 gives the results for the other dust temperatures. They are generally similar except for the \( T_d = 100 \) K graphite model. The key issue for the progenitor is that the preferred solutions of both Fraser et al. (2012) and Van Dyk et al. (2012) significantly overestimate the luminosity of the progenitor. Our results agree with Van Dyk et al. (2012) on the temperature, but the luminosity \( L_* \) is a factor of two lower. The mid-IR limits essentially preclude the higher luminosity and temperature solutions of Fraser et al. (2012) unless the dust temperature is made significantly lower than \( T_d = 500 \) K and the dust emission moves out of the IRAC band passes. Even there, only the cold \( T_d = 100 \) K graphite model allows a significantly higher luminosity. As expected, a large part of the difference is that the models based on interstellar extinction are significantly overestimating the overall absorption.

3. DISCUSSION

Fraser et al. (2012) and Van Dyk et al. (2012) argue that the progenitor was probably the most massive yet found for a Type IIP SN, probably at or above the upper limit of \( (16.5 \pm 1.5) M_\odot \) that Smarrt et al. (2009) found in their statistical analysis of the masses of Type IIP progenitors. Given the amount of circumstellar extinction, this seemed to match the suggestion by Walmswell & Eldridge (2012) that the upper mass limit could be biased by increasing levels of dust formation for the more massive red supergiants due to the increase in mass-loss rates with luminosity. Here we argue that many of these inferences are biased by incorrectly modeling circumstellar dust with an interstellar extinction law, thereby overestimating both the amount of extinction and the luminosity of the star. When we model the SED using circumstellar dust models, the luminosity of the star is \( L_* \lesssim 10^3 L_\odot \) and the mass is \( M_* < 15 M_\odot \), where the downward shifts are easily understood from the differing physics of interstellar and circumstellar extinction. The visual extinction is overestimated because interstellar extinction

| Models with \( R_{out} / R_\text{in} = 2 \) |
|-----------------------------|
| \( ggra1 = (0.091091 - 0.013614 s + 5.049922 s + 6.399577 s + 3 + 2.086527 s + 4) \) |
| \( ggra2 = (0.076931 + 3.566326 s - 40.083135 s + 48.029644 s + 3 - 14.815801 s + 4) \) |
| \( ggra3 = (1.604726 - 22.761479 s + 90.223336 s + 88.179577 s + 3 + 25.041643 s + 4) / l + s 2 \) |
| \( ggra4 = (1.240894 + 20.383229 s - 63.820599 s + 57.434801 s + 3 - 15.475733 s + 4) / l + s 3 \) |
| \( ggra5 = (0.392600 - 6.856117 s + 19.106438 s - 16.340312 s + 4.240107 s + 4) / l + s 4 \) |
| \( ggra6 = (0.044443 + 5.800158 s + 2.078890 s + 1.716855 s + 3 - 0.433098 s + 4) / l + s 5 \) |

| Models with \( R_{out} / R_\text{in} = 10 \) |
|-----------------------------|
| \( ggra1 = (0.122211 - 7.859540 s + 1.722856 s + 0.017627 s + 3 + 2.00712 s + 4) \) |
| \( ggra2 = (0.397086 + 6.851399 s + 0.07452 s + 10.503128 s + 3 - 3.22806 s + 4) / l + s 2 \) |
| \( ggra3 = (0.420577 - 7.736732 s + 5.079083 s + 11.868283 s + 3 + 2.016602 s + 4) / l + s 2 \) |
| \( ggra4 = (0.281626 + 3.202032 s + 0.592135 s + 1.043999 s + 3 + 1.25581 s + 4) / l + s 3 \) |
| \( ggra5 = (0.093566 - 0.543338 s - 1.283187 s + 1.231904 s + 3 - 0.913404 s + 4) / l + s 4 \) |
| \( ggra6 = (0.01334 + 0.026020 s + 0.236427 s - 0.256076 s + 3 + 0.140387 s + 4) / l + s 5 \) |
| \( ggrapht10 = (ggra1 + ggra2 + ggra3 + ggra4 + ggra5 + ggra6) / (1 + l + s) (4.399311) \) |
| \( gsil1 = (0.041183 - 10.239763 s + 3.368015 s - 3.994570 s + 3 + 1.668688 s + 4) \) |
| \( gsil2 = (0.127668 + 19.262377 s - 13.077118 s + 19.483457 s + 3 - 8.606155 s + 4) / l + s 2 \) |
| \( gsil3 = (0.141609 + 15.254131 s + 18.619615 s - 32.651846 s + 3 + 14.198402 s + 4) / l + s 2 \) |
| \( gsil4 = (0.089791 + 1.766552 s - 13.867555 s + 28.015047 s + 3 - 12.370802 s + 4) / l + s 3 \) |
| \( gsil5 = (0.042445 + 0.567592 s + 5.721463 s - 10.944883 s + 3 + 4.706386 s + 3) / l + s 4 \) |
| \( gsil6 = (0.006950 - 0.107301 s - 0.821527 s + 1.470719 s + 3 - 0.616414 s + 4) / l + s 5 \) |
| \( gsilicate10 = (gsil1 + gsil2 + gsil3 + gsil4 + gsil5 + gsil6) / (1 + l + s) (4.733179) \) |

Notes: These expressions are designed to simply be grabbed from a mouse with the electronic paper and inserted into most numerical environments. The input quantities are \( s = (\tau_V / 10)^{1/2} \) (Note the change from \( t = \tau_V / 10 \) in Table 3) and \( l = \lambda \) in microns, and the output quantity is \( G^{10}(\lambda_V) \) from Equation (7). They are valid for \( \lambda > 0.3 \mu m \) and \( \tau_V \lesssim 20 \) and should not be extrapolated outside this range. No emission by the dust is included in the models.

Table 4

Direct Emission Fractions for Graphitic and Silicate Circumstellar Extinction Laws
neglects the contributions of scattered light, and, to a lesser extent because of the low stellar temperature, the near-IR ($K_s$) extinction is overestimated by neglecting the emission from hot dust. The absence of a mid-IR source noted by Fraser et al. (2012) is a key point of evidence, since there should have been a detectable source given the proposed, higher luminosities unless the dust is cold and emitting at longer wavelengths than the IRAC bands. In this particular case, the dust composition has little effect on the inferred properties of the star.

Unfortunately, without measuring the mid-IR portion of the SED we cannot determine the dust temperature $T_d$ other than limiting it to be lower than the dust destruction temperature ($T_d \lesssim 1500$ K). However, the wind properties are a strong function of the dust temperature because at fixed optical depth far more mass is required if the material is at larger radii and colder temperatures. Ignoring the minor ($10\%$) corrections from the finite value of $R_{out}/R_{in} = 10$, the mass-loss rate required to support the optical depth is

$$M = 4\pi R_{in}v_w\tau_V\kappa_V^{-1} \approx 10^{-5} R_{in} v_{10}^{15} \tau_{5}\kappa_{5}^{1} M_{\odot} \text{year}^{-1},$$

where $R_{in} = 10^{15} R_{in}\text{cm}$, $v_w = 10 v_{10} \text{km s}^{-1}$, $\tau_V = 5 \tau_{5}^{-1}$, and $\kappa_V = 10^{5} \kappa_{5}^{-1} \text{cm}^{-2} \text{g}^{-1}$ is a typical visual opacity scale for dust. Table 2 gives the values for the individual models. Similarly, the total mass associated with the dusty wind is

$$M = 4\pi \tau_V\kappa_V^{-1} R_{out} \approx 0.0003 \tau_{5}\kappa_{5}^{-1} R_{in}^{2} (R_{out}/R_{in}) M_{\odot}.$$  

Supporting $\tau_V \sim 5$ when $T_d \gtrsim 100$ K and $R_{in} \sim 10^{17}$ cm requires a mass-loss rate $M \sim 10^{-2.5} M_{\odot} \text{yr}^{-1}$ and a minimum total wind mass $M \sim 3 M_{\odot}$ for $R_{out} = R_{in}$, which is implausible for a star with an initial mass of $M_* < 15 M_{\odot}$. For comparison, the empirical approximations of van Loon et al. (2005) for mass loss from oxygen-rich red supergiants predict $\log_10(M/M_{\odot}/\text{year}) \sim -4.8 \pm 0.3$, roughly matching the rates needed if the wind is producing dust with “a standard” opacity at the time of the explosion. Once we assume a reasonable mass-loss rate, opacity, and dust temperature, the total mass of the wind in Equation (2) is principally controlled by the outer radius $R_{out}$, which is unconstrained by the present data. For these typical opacities, the dust mass is then $< 0.5\%$ of the wind mass.

The density of the wind is also tied to the expected phenomenology of the explosion. If we assume the standard $\rho_w \propto v^{-12}$ outer ejecta density profile for red supergiants (Matzner & McKee 1999), then the expected shock velocity is

$$v_s = 8200 E_{51}^{9/20} M_{e10}^{-7/20} M_{5}^{-1/10} v_{w10}^{1/10} t_{1}^{1/10} \text{km s}^{-1}$$

(e.g., Chevalier & Fransson 2003), where the total energy of the supernova is $E = 10^{51} E_{51}$ ergs, the ejected mass is $M_e = 10 M_{e10} M_{5}$, $M \sim 10^{-4} M_{5} M_{\odot} \text{yr}^{-1}$ and $t_1$ is the elapsed time in days. A shock expanding through a dense medium generates a luminosity of $L_{X} = (1/2) M v_{w} E_{51}^{2/7} / v_w$, which we report in Table 2 for $v_{w} = 5000 \text{km s}^{-1}$ and $v_w = 10 \text{km s}^{-1}$. The emission from the forward shock is usually too hard to be easily detected, but assuming that the reverse shock is cooling and that its softer emissions dominate the observable X-ray emissions, the expected X-ray luminosity is

$$L_{X} \approx 9 M v_{w}^{3} / 500$$

$$\approx 1.63 \times 10^{7} E_{51}^{27/20} M_{e10}^{-21/20} M_{5}^{7/10} v_{w10}^{7/10} t_{1}^{3/10} L_{\odot}$$

with a temperature of order 1 keV (e.g., Chevalier & Fransson 2003). If we model the X-ray fluxes in Table 1 using Equation (4) and a range of additional absorption from $N_H = 10^{20}$ to $10^{23} \text{cm}^{-2}$, the mass-loss rates for epochs 1, 3, and 5 (which have the smallest uncertainties) are

$$M \sim (10^{-6.4\pm0.4}, 10^{-5.8\pm0.3}, 10^{-4.7\pm0.3}) \times v_{w10} M_{e10}^{3/2} E_{51}^{-27/14} M_{\odot} \text{yr}^{-1},$$

respectively, with some evidence that the amount of excess absorption needed above Galactic is increasing with time. Such fluctuations and trends are not unusual (e.g., Dwarkadas & Grusko 2012), but the X-ray emission appears to be broadly consistent with the presence of a wind with roughly the right density to explain the extinction of the progenitor. Stockdale et al. (2012) and Yadav et al. (2012) report rising $\sim 20 \text{GHz}$ radio fluxes of 0.160 $\pm$ 0.025 and 0.315 $\pm$ 0.018 mJy roughly 7 and 13 days after discovery that also argue for a significant wind at the time of the SN. If we model the radio emission following Soderberg et al. (2005) assuming the ejecta mass is $M_e = (15-1.4) M_{5} = 13.6 M_{5}$ and $E_{51} = 1$, we obtain estimates of $M \sim 10^{-3.9} v_{w10} M_{5} \text{yr}^{-1}$, although given only two data points at essentially the same frequency, the models are not tightly constrained. The Thompson optical depth of the wind is always negligible, since it is a small ($\lesssim 1\%$) fraction of the dust optical depth, but the cold dust solutions would likely convert the SN into a Type Ibn because the H$\alpha$ luminosity from recombination is of order 3000 $R_{in} L_{\odot}$ and increases linearly with the distance to the circumstellar material. Thus, while the data is fragmentary, the simplest interpretation appears to be that there was a relatively steady $M \sim 10^{-2.5}$ to $10^{-3.0} M_{\odot} \text{yr}^{-1}$ wind creating the obscuration at the time of the SN.

Since the primary reason for inappropriately using Galactic extinction laws for circumstellar dust is almost certainly their ease of use, we supply in Table 3 equivalently easy to use models for absorption by circumstellar dust. The problem is somewhat more complex because the extinction depends on both wavelength and optical depth, but the absorption in the DUSTY models from the UV to mid/near-IR (0.3 $\mu$m–5.0 $\mu$m) can be well modeled by the functional form,

$$A_{\lambda}(\tau_{\lambda}) = \tau_{\lambda} \lambda^{-1} \sum_{i} \sum_{j} a_{ij} \tau_{\lambda}^{i} \lambda^{-j},$$

for optical depths up to $\tau_{\lambda} = 20$. Here, $\lambda$ is the wavelength in microns and $\tau_{\lambda}$ is the total (absorption plus scattering) optical depth in the $V$ band. Table 3 provides these models for $R_{out}/R_{in} = 2$ and 10 in a format where they can simply be extracted from the electronic paper using a mouse and inserted into most numerical environments. The fits reproduce the DUSTY results with rms fractional residuals of 1.4% (1.6%) and 1.8% (2.2%) for the graphic and silicate models and $R_{out}/R_{in} = 10$ (2), although this includes some numerical rounding errors in the DUSTY models at low optical depths and longer wavelengths. They can be extrapolated to longer wavelengths relatively safely, but at these longer wavelengths one would almost always also need to include dust emission. They should not be extrapolated to shorter wavelengths or higher optical depths. Figure 7 shows the circumstellar extinction of the DUSTY models used to build these interpolating functions and the interpolating functions as extracted from Table 3 for $R_{out}/R_{in} = 10$. In some circumstances it will also be useful to separate the direct and scattered light. The fraction of the observed flux that is direct, $F_{\lambda}^{\text{dir}}$, can
be well modeled by

$$G_{\lambda}^{\text{abs}} = -2.5 \log_{10} F_{\lambda}^{\text{abs}}(\tau_V)$$

$$= \tau_V^{1/2}(1 + \lambda^5)^{-1} \sum_i \sum_j a_{ij} \tau_i^{1/2} \lambda^{-j}. \quad (7)$$

These interpolating functions are supplied in Table 4 and the quality of the fits is shown in Figure 8. For a source with intrinsic spectrum $S_\lambda$, the observed spectrum is $S_\lambda 10^{-0.4A_V}$, the directly escaping flux is $S_\lambda 10^{-0.4A_V} F_{\lambda}^{\text{abs}} = S_\lambda 10^{-0.4A_V}(1 - F_{\lambda}^{\text{abs}})$. Obviously, this approach can be generalized to other dust compositions or size distributions. We parameterize the models by $\tau_V$ because $\tau_V$ is closely related to the physical properties of the wind (Equation (1)), while relating it to a color (i.e., $E(B-V)$) would divorce the model from the underlying physics. There is no comparably simple means of treating dust emission because it depends critically on the input spectrum.

These differences are quantitative rather than qualitative—in circumstellar dust models the progenitor of SN 2012aw is still fairly heavily obscured, as found by Fraser et al. (2012) and Van Dyk et al. (2012), and Walmswell & Eldridge (2012) are correct that circumstellar dust introduces a bias that must be modeled when considering the statistics of SN progenitors, particularly when modeling non-detections in analyses like Smartt et al. (2009). However, since changes in extinction physics exponentially modify quantities like luminosities, these differences between the two dust geometries are quantitatively important. We note, however, that SN where circumstellar dust will strongly bias inferences about the progenitor have densities of circumstellar material that will lead to X-ray or radio emission, as observed for SN 2012aw, because the optical depth is proportional to the wind density. For example, combining Equations (1) and (4), we see that the expected X-ray luminosity is $L_X \propto \tau_V$. This means that the properties of the explosion can be used to constrain biases from dust around the progenitor even if the observations of the progenitor are inadequate to constrain the circumstellar extinction.

There are, of course, additional complexities coming from the geometry of the dust around the star that can lead to differences in the effective optical depth along the line of sight for direct emission and averaged over a significant fraction of the shell for the scattered emission. Our simple models provide two means of approximating some of these effects. First, changes in the shell thickness can be used to adjust the balance between scattered and absorbed light. Second, the emergent flux can be modeled as a sum of direct light with one optical depth, and scattered light with another in order to model differences between the mean and line-of-sight optical depths. *Independent of these questions, interstellar and circumstellar extinction are quantitatively different, and in this case ignoring the differences leads to a significant overestimate of the progenitor luminosity and mass.*

We thank J. Beacom, J. Eldridge, S. Smartt, K. Z. Stanek, and T. A. Thompson for discussions and comments, and K. Cross for a quick inspection of the Kingfish Herschel/PACS 70μm images. C.S.K. is supported by NSF grant AST-0908816 and R.K. is supported by NSF grant AST-1108687. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

**Facility:** Spitzer

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