SOFIA OBSERVATIONS OF SN 2010jl: ANOTHER NON-DETECTION OF THE 9.7 μm SILICATE DUST FEATURE

BRIAN J. WILLIAMS1 AND ORI D. FOX2

1 CRESST and X-ray Astrophysics Laboratory, NASA/GSFC, Code 662, 8800 Greenbelt Road, Greenbelt, MD, USA; brian.j.williams@nasa.gov
2 Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA

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ABSTRACT

We present photometric observations from the Stratospheric Observatory for Infrared Astronomy (SOFIA) at 11.1 μm of the Type IIn supernova (SN IIn) 2010jl. The SN is undetected by SOFIA, but the upper limits obtained, combined with new and archival detections from Spitzer at 3.6 and 4.5 μm, allow us to characterize the composition of the dust present. Dust in other SN IIn has been shown in previous works to reside in a circumstellar shell of material ejected by the progenitor system in the few millennia prior to explosion. Our model fits show that the dust in the system shows no evidence for the strong, ubiquitous 9.7 μm feature from silicate dust, suggesting the presence of carbonaceous grains. The observations are best fit with 0.01–0.05 M⊙ of carbonaceous dust radiating at a temperature of ~550–620 K. The dust composition may reveal clues concerning the nature of the progenitor system, which remains ambiguous for this subclass. Most of the single star progenitor systems proposed for SNe IIn, such as luminous blue variables, red supergiants, yellow hypergiants, and B[e] stars, all clearly show silicate dust in their pre-SN outflows. However, this post-SN result is consistent with the small sample of SNe IIn with mid-IR observations, none of which show signs of emission from silicate dust in their IR spectra.

Key words: dust, extinction – supernovae: general – supernovae: individual (SN 2010jl)

1. INTRODUCTION

Type IIn supernovae (SNe IIn) are named for the narrow hydrogen emission lines produced in a dense, slowly moving, pre-existing circumstellar medium (CSM). Typically attributed to the progenitor winds, the CSM has densities and velocities that suggest extremely high mass-loss rates, in some cases up to ~0.1 M⊙ yr⁻¹ (Fox et al. 2011, hereafter F11; Kiewe et al. 2012). The progenitors of SNe IIn are unknown. The implied mass-loss rates are often compared to the episodic dense winds observed in some massive stars, such as Luminous Blue Variables (LBVs; e.g., Smith et al. 2011 and references therein).

SNe IIn account for more than half of all known SNe with late-time (>100 days) infrared (IR) emission (F11), implying the presence of warm dust. F11 showed, via a warm mission (3.6 and 4.5 μm only) Spitzer survey of 10 SNe IIn, that the observed emission is consistent with pre-existing CSM dust, heated by the optical emission generated by the forward shock interaction with the dense CSM. This is in contrast to most core-collapse SNe with IR emission, where observations are consistent with a small amount of newly formed ejecta dust (e.g., Kotak et al. 2005; Sugerman et al. 2006; Williams et al. 2008). Since the dust is produced in the outflow of the progenitor system, characterizing this dust may offer a clue about the pre-SN system. However, as F11 showed, Spitzer observations at 3.6 and 4.5 μm are sufficient only to establish the presence of a warm dust component, and not to determine the composition of the dust.

It is well-known that massive stars make dust in their stellar winds, but what type of dust depends on the star’s mass and evolutionary state. In general, stars make either silicate or carbon dust in their outflows, where the determining factor is the C/O ratio in the stellar atmosphere. The presence or absence of a broad, strong emission feature at 9.7 μm that only arises from silicate dust provides a method by which to distinguish the two grain populations, provided images or spectra exist in the 8–13 μm range.

1.1. Potential SNe IIn Progenitors and Their Dust Signatures

The LBV scenario is a promising candidate for the progenitor systems of SNe IIn. Gal-Yam & Leonard (2009) identify a hypergiant progenitor undergoing LBV-like mass loss in pre-explosion images of SN 2005gl. However, it has several complications. Most LBVs achieve observed rates of only M < 10⁻⁴ M⊙ yr⁻¹ in their S Doradus state (Humphreys & Davidson 1994). Standard radiation and line-driven wind models similarly have difficulty reproducing such substantial rates (e.g., Smith & Woosley 2006). Classical stellar evolution models suggest these massive stars should evolve into the Wolf–Rayet (WR) phase before exploding (Heger et al. 2003). More recently, proposed solutions include swept up WR winds (Dwarkadas 2011), binary accretion (Kashi 2010), and gravity-wave driven winds (Quataert & Shiode 2012), but these all have limitations of their own.

While often variable and unpredictable in brightness, LBVs are typically very luminous in the IR due to the significant amounts of dust formed in their outflows. Though hardly a homogeneous bunch, most LBVs are consistent with some sort of silicate dust in their spectra. Some, such as HR Car (Umana et al. 2009), show strong features from amorphous silicate grains, while others, like the LMC LBV R71, exhibit features of crystalline silicates (Morris & the Spitzer WIRING team 2008). Additionally, a few LBVs like HD 316285 and HD 168625 (Morris & the Spitzer WIRING team 2008; Umana et al. 2009) show emission features from polycyclic aromatic hydrocarbons (PAHs), though whether these PAHs are formed in the stellar outflow or are pre-existing in the interstellar medium (ISM) is unknown. In η Carinae, Smith (2010) reports that the IR spectra may be best fit with corundum dust (Al₂O₃), which also shows a strong ~10 μm feature. We are unable to identify any examples in the literature of IR spectra from CSM...
surrounding an LBV that unambiguously shows signs of graphite or amorphous carbon dust.

Red supergiants (RSGs), typically very bright in the IR, also show signs of silicate dust in the spectra of their CSM. In a sample of 19 RSGs in the LMC, Woods et al. (2011) report that among the 14 that show emission from warm dust, most show the 9.7 μm silicate feature, or other features of non-carbonaceous dust. They note that a few show weak PAH emission features, but that at least some of these may arise from the ISM.

Other possibilities include any massive star that loses a significant amount of mass to stellar winds after evolving off the main-sequence. Yellow hypergiants are believed to be intermediate stages of stellar evolution with strong winds, between the RSG and LBV phases (Lagardec et al. 2011). Again, though, the dusty shells seen around some of these stars, like IRC+10420, show strong silicate features in their spectra (Humphreys et al. 1997). B[e] supergiants, massive (~15–70 M☉), luminous, poorly understood early-type stars with slow stellar winds that form dusty circumstellar material may also be precursors to LBVs and/or WR stars. A Spitzer spectroscopic study of B[e] supergiants in the LMC shows that the dusty disks around these stars contain strong features of both crystalline and amorphous silicates, along with PAH features, but no carbonaceous dust (Kastner et al. 2006).

An intriguing potential progenitor is suggested by Wesson et al. (2010) and Kochanek (2011) based on archival Spitzer observations of the possible SN IIn 2008S. They rule out silicate grains and state that this absence of silicates may be evidence against a supergiant progenitor, favoring instead an “extreme” asymptotic giant branch (AGB) star. However, this result should be interpreted with caution, as other authors report that SN 2008S is in fact a supernova impostor, and was more likely an LBV eruption (Smith et al. 2009). SN impostors and/or LBV eruptions may be relevant if, ultimately, they explode as SNe IIn (see Mauerhan et al. 2013).

Some authors have proposed a binary scenario for the progenitors of SNe IIn. Among binary systems, observations of carbon-rich stars AGB stars are consistent with mass transfer from an evolved binary companion (Aoki et al. 2002). In order to explain the apparent close timing between the mass loss and SN events, Chevalier (2012) explored the possibility of mass loss driven by a common envelope involving a compact object and a massive star, finding that at least some SNe IIn could be explained this way.

η Car itself is a binary system. Iping et al. (2005) report the likely detection of the companion star, η Car B, and note that while a detailed stellar classification for this secondary is inconclusive, η Car B could potentially be a WR star. Neither the formation site nor the composition of the dust in η Car is well-understood (Smith 2010). Even the origin of the CSM is uncertain, as winds from either or both of the two stars could contribute.

1.2. SNe IIn in the IR

Only a few SNe IIn have been observed and detected at mid-IR (>4.5 μm) wavelengths. Fox et al. (2010) show 5–14 μm Spitzer IRAC and IRS observations of SN 2005ip, whose spectrum is clearly fit with a carbonaceous grain model with no contribution from silicate dust required. van Dyk (2013) detected SN 1995N in archival data at 12 μm with the Wide-Field Infrared Survey Explorer (WISE) and 24 μm with Spitzer and showed that both silicate and graphite dust models have problems fitting the IR spectral energy distribution (SED). Silicate grains were also ruled out for SN 2008S, which was detected at 24 μm by Spitzer, though its status as a supernova is questionable (see Section 1.1). SN 2006jd was seen at 12 μm by the WISE (Stritzinger et al. 2012) without the silicate feature.

SN 2010jl was observed from the ground in the optical/near-IR by Maeda et al. (2013). Their data are sensitive to the hottest component of the dust, and they find dust temperatures of >1000 K. While they find equally good fits to this portion of the spectrum with carbonaceous and silicate grains, the temperatures required for the silicate grains are higher than the condensation temperature for those grains, and thus they favor carbonaceous grains. In this Letter, we report direct observations of the all-important mid-IR band using the Stratospheric Observatory for Far-Infrared Astronomy (SOFIA), where we can detect the presence or lack of a silicate bump. We do not detect SN 2010jl, but the upper limits we derive rule out the presence of a silicate feature, and are well-fit by models of carbon dust, confirming the conclusions of Maeda et al. (2013).

2. OBSERVATIONS

SN 2010jl was discovered in UGC 5189A (distance 49 Mpc) on 2010 November 3.5 by Newton & Buckett (2010), at a position of α = 09h42m53.3s, δ = +09°29′42.1″ (J2000.0). It was identified as a Type IIn by Benetti et al. (2010) and Yamanaka et al. (2010). Multi-wavelength observations all point to a strongly interacting SN with a dense CSM (Fransson et al. 2014; Ofek et al. 2014). Pre-SN Hubble Space Telescope images show a luminous, blue point source at the position of the SN (Smith et al. 2011), but the data are insufficient to determine whether this source is a young cluster, a single luminous star, or a star caught during outburst. SN 2010jl shows significant evidence for late-time IR emission. Some interpret this as evidence for newly formed dust (e.g., Smith 2012; Maeda et al. 2013; Gall et al. 2014; Jencson et al. 2015), while others suggest the presence of a pre-existing, unshocked dust shell (e.g., Andrews et al. 2011; Fox et al. 2013; Fransson et al. 2014; Borish et al. 2015).

As part of an ongoing monitoring project of several SNe IIn at late times (PI: O. Fox), SN 2010jl has been observed in the mid-IR roughly 10 times with the Spitzer Space Telescope, all at the near-IR wavelengths of 3.6 and 4.5 μm (the SN occurred after the end of Spitzer’s cryogenic mission). The SN is clearly detected in the Spitzer images, as we show in Figure 1, and has a flux of several mJy at both wavelengths. We also observed the SN with the FORCAST instrument on SOFIA using the 11.1 μm filter on 2014 May 5–6 at an altitude of 38,000 feet, with a total integration time of 6400 s. The images are taken in chop/nod mode with a 60″ throw, and several hundred 30 s frames were coadded for a final data mosaic. The final mosaic has pixels 0.″75 on a side with a resolution of approximately 2.″7.

Neither SN 2010jl nor the host galaxy were detected in our mosaicked image. The lack of detection of the host galaxy makes setting an upper limit on any point source easier, since we are background-limited and not confusion-limited. To obtain a 1σ upper limit, we computed the standard deviation of the pixels in a 20″ × 20″ box centered on the source coordinates and converted this via the CALFCTR header parameter to get an rms value in Jy pix⁻¹. We then multiplied
this by the square root of the extraction area (4 pixel radius, 50 total pixels) centered on SN 2010jl. The upper limit obtained in this method is 4.2 mJy, in good agreement with the 4.7 mJy value that we extrapolate from the SOFIA Observer’s Handbook (Section 7.1.4) based on our exposure time.

Since SNe are time-variable objects, we must compare our SOFIA observations with those most contemporaneous from Spitzer. We extract fluxes for four of the Spitzer observations, taken on 2013 January 30, 2013 June 29, 2013 July 3, and 2014 July 9. We find no clear trend of systematic brightening or fading, so we average these four fluxes for each wavelength and use this average flux for our modeling, below. The average fluxes are 5.0 (1.4) and 5.69 (1.3) mJy for 3.6 and 4.5 μm, respectively. The values in parentheses represent the standard deviation of the four measurements, which are significantly larger than Spitzer’s photometric uncertainties, and thus a very conservative estimate of the uncertainties.

3. DUST MODELING WITH THE NEW SOFIA UPPER LIMIT

F11 modeled the Spitzer 3.6 and 4.5 μm emission from multiple SNe IIn, considering a variety of origins and heating mechanisms for the dust. They rule out newly formed ejecta dust, as well as collisional heating of CSM dust by hot electrons behind the forward shock. They find that the most likely physical scenario is that a pre-existing dust shell is heated by UV and optical radiation from circumstellar interaction of the forward shock with dense material. The two short wavelength data points are insufficient to determine the type of dust present, and F11 considered both silicate and graphite grains. With the addition of the SOFIA upper limit at 11.1 μm, we can compare models of silicate and graphite dust over a much broader wavelength range that includes the 9.7 μm silicate feature.

The spectrum of a warm dust grain is simply the wavelength-dependent absorption cross-section of the grain multiplied by the Planck blackbody function. We consider several different types of grains. In addition to graphite and ‘‘astronomical’’ silicate grains, with absorption cross-sections derived from bulk optical constants given in Draine & Lee (1984), we also consider amorphous carbon grains (Rouleau & Martin 1991), as well as other silicate grains, such as glassy and amorphous forms of both enstatite and forsterite (Dorschner et al. 1995; Jäger et al. 2003). For all grains, we assume a single grain size of 0.1 μm. This model is simplistic, but a more detailed model cannot be constrained by only three data points, and the overall shape of the spectrum is not significantly changed by the addition of more grain sizes. More importantly, Temim & Dwek (2013) have recently shown that more physically realistic dust models, which take into account a range of grain-size distributions, will lower the amount of mass inferred. Thus, our models represent an upper limit to the amount of dust formed in the pre-existing CSM shell.

We use a least-squares algorithm to fit the data for each grain composition. Since the flux values are of the same order of magnitude, we fit in linear space, and use only two free parameters: dust temperature and total mass. We obtain good fits to the SED with models of both graphite (T = 553 K) and amorphous carbon (T = 616 K) grains, as we show in Figure 2. While we cannot further distinguish between these two models, the difference is not particularly relevant to the goals of this paper. The only significant difference between the graphite and amorphous carbon models is the amount of dust needed to fit the spectrum. Since amorphous carbon has a higher emissivity than graphite over the range of 1−20 μm, it requires less dust to achieve the same luminosity. Our graphite model requires 0.057 M⊙ of dust, while only 0.012 M⊙ of amorphous carbon is necessary (assuming 49 Mpc distance).

Most importantly, we find that no silicate grain model can adequately reproduce the data for all three points. We show the best-fit model for ‘‘astronomical silicates’’ in Figure 2, as fit to the two Spitzer points alone. This model requires a dust temperature of 863 K with a radiating dust mass of 0.024 M⊙. The 11.1 μm model prediction from this model is roughly an order of magnitude higher than the upper limit of the flux.

Figure 1. Left: SOFIA 11.1 μm image of the field of SN 2010jl. Neither the SN nor the host galaxy are detected. Right: Spitzer 3.6 (blue) and 4.5 (red) μm image of the same region, clearly showing the SN, indicated by the tick marks, and host galaxy UGC 5189A.
density from the SOFIA data. Even fitting a silicic model to the extreme uncertainty values of the Spitzer fluxes yields completely nonphysical results. Other silicate models, such as “glassy” silicates, lead to even poorer fits. While we cannot rule out a small contribution from silicate grains (having only three data points makes this difficult to constrain), silicate dust does not dominate the SED, and it is not required at all to obtain a good fit to the data. If the dust we see comes from a pre-existing shell of material, then this conclusion is at odds with the pre-SN dust observed in most proposed progenitor systems for SNe IIn.

WR stars are one type of massive star that is known to produce significant amounts of carbon dust (Woods et al. 2011). However, since WR stars have blown off their hydrogen (and in some cases, helium) envelopes, it is generally accepted that WR stars would explode as Type Ib/c SNe. An interesting suggestion is made by Dwarkadas (2011), who argues that at least some SNe IIn may explode after brief (<10^4 years) WR phases for their progenitors. This is quantitatively consistent with the model of F11, who report that the progenitor system of SN 2006jd experienced a significant period of mass loss a few hundred years prior to explosion. Work by Anderson et al. (2012) found, by investigating the correlation of SNe IIn with the recent star formation history of the explosion site, that SNe IIn trace recent, but not ongoing star formation, implying that most of these SNe do not arise from the most massive stars.

There are other possibilities as well. The dust observed may be from newly formed ejecta dust, and thus not indicative of the pre-SN outflow. A high optical depth or significantly larger grains than are found in the ISM might suppress the silicate feature (Lucy et al. 1991). While we cannot say for certain that the lack of a silicate feature definitively means a carbon rich environment, the results here and in other SNe IIn are interesting and merit further study.

4. SUMMARY

The SN IIn 2010jl, easily seen in Spitzer 3.6 and 4.5 μm, is undetected in 11.1 μm images from SOFIA. With the flux at the two Spitzer wavelengths and an upper limit at 11.1 μm, we can characterize the dust composition. Only carbonaceous grains (either graphite or amorphous carbon) can fit the spectrum; silicate grain models overpredict the 11.1 μm upper limit by an order of magnitude or more. Our model fits suggest on the order of 0.01–0.05 M⊙ of dust radiating at a temperature of ∼550–620 K. SN 2010jl joins a growing list of SNe IIn whose dust signatures do not show the 9.7 μm silicate feature. As F11 argue, the dust in these SNe is contained in a pre-existing circumstellar shell, blown off by the progenitor system before the explosion. Thus, the dust that we observe can reveal something about the unknown nature of the progenitor.

Most of the potential progenitor classes for SNe IIn are toward the massive end of the stellar spectrum: LBVs, RSGs, yellow hypergiants, and B[e] stars, all of which eject significant quantities of material. However, they are all observed to produce silicate dust during their pre-SN lifetimes, not carbonaceous. It is possible some stars may have a mixed chemistry in their outflows, producing some amount of both silicate and carbon grains. This has been observed in some AGB stars, and Williams et al. (2012) inferred the presence of dust grains of both types in Spitzer observations of Kepler’s supernova remnant. Although Kepler is the remnant of a Type Ia, it is known to be interacting with a dense CSM from the progenitor system, and could be a low mass analog of SNe IIn. An intriguing possibility is that of a binary system where one of the stars is a carbon-rich WR star.

While we advise caution against drawing broad conclusions about the nature of SNe IIn from an indirect method and such a small sample size, we urge further study of these systems from the standpoint of both stellar evolution and dust nucleation in the atmospheres and outflows of massive stars. The James Webb Space Telescope will enable spectroscopic detection of many SNe IIn in the mid-IR, allowing detailed studies of individual SN spectra, as well as the ability to do statistical studies on large samples of SNe IIn in the mid-IR.

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Facilities: SOFIA, Spitzer

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