

DETECTION OF A MASSIVE DUST SHELL AROUND THE TYPE II SUPERNOVA SN 2002hh

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Received 2005 March 11; accepted 2005 June 1; published 2005 June 20

ABSTRACT

Dust emission from the Type II supernova SN 2002hh in NGC 6946 has been detected at mid-infrared wavelengths by the *Spitzer Space Telescope* from 590 to 758 days after outburst and confirmed by higher angular resolution Gemini North mid-IR observations. The day 600 5.8–24 μm emission can be fit by a 290 K blackbody having a luminosity of $1.6 \times 10^7 L_{\odot}$. The minimum emitting radius of 1.1×10^{17} cm is too large for the emitting dust to have been formed in the supernova ejecta. Using radiative transfer models and realistic dust grain parameters, fits to the observed flux distribution could be obtained with an optically thick dust shell having a mass of 0.10–0.15 M_{\odot} , corresponding to a total dust+gas mass in excess of 10 M_{\odot} , suggesting a massive M supergiant or luminous blue variable precursor to this self-obscured object.

Subject headings: dust, extinction — galaxies: individual (NGC 6946) — supernovae: general —
supernovae: individual (SN 2002hh)

Online material: color figures

1. INTRODUCTION

During their giant phase of evolution, low- and intermediate-mass stars are known to be important contributors to the interstellar dust budget. However, massive stars, in particular their supernovae (SNe), could make the dominant contribution to the dust budget of galaxies (Clayton 1979; Dwek & Scalzo 1980; Todini & Ferrara 2001). Evidence for dust formation by at least some SNe comes from precise isotopic abundance ratio studies of grain inclusions found in meteorites (e.g., Clayton et al. 1997; Travaglio et al. 1999). A determination of the dust contribution from core-collapse SNe (Types II, Ib, and Ic) could have widespread consequences, in particular for our understanding of the origin and evolution of galaxies in the early universe. Many of the earliest formed galaxies are extremely dusty, as evidenced by the detection of their highly redshifted infrared (IR) emission at submillimeter wavelengths (e.g., Ivison et al. 2000). Massive stars in the starbursts that power these young galaxies are the most plausible sources of this dust.

Model studies have shown that the mid-IR spectral region (5–30 μm) is particularly suitable to trace the onset of dust formation in SN ejecta and to determine the amount of dust formed (e.g., Dwek 1988; Kozasa et al. 1989; Todini & Ferrara 2001; Clayton et al. 2001). These dust formation models predict that emission from ejecta condensates should become detect-

able at mid-IR wavelengths within 1–2 yr of outburst. SN 1987A, in the Large Magellanic Cloud, was estimated to have formed a modest amount of dust in its ejecta (Dwek et al. 1992; Wooden et al. 1993), with the dust believed to have first condensed about 530 days after outburst (Danziger et al. 1991). In contrast, the level of submillimeter emission from the 300 yr old SN remnant Cas A has been interpreted as indicating the presence of at least 2 M_{\odot} of cold dust within the remnant (Dunne et al. 2003). However, among the grounds given by Dwek (2004) for disputing this dust mass estimate was that it would exceed the mass of refractory elements in the ejecta of the likely progenitor star, while Krause et al. (2004) argued that the submillimeter emission detected toward Cas A could originate from a foreground molecular cloud complex, leaving still uncertain the observational case for SNe as major dust contributors to galaxies. Here we report the detection by our SEEDS collaboration (Survey for Evolution of Emission from Dust in Supernovae) of thermal dust emission from the Type II SN 2002hh some 600 days after its discovery, based on mid-infrared observations made by the *Spitzer Space Telescope*, together with follow-up mid-IR observations obtained with the 8 m Gemini North telescope.

2. OBSERVATIONS

The Type II supernova SN 2002hh is located in the spiral galaxy NGC 6946, at a distance of 5.9 ± 0.4 Mpc (Karachentsev et al. 2000). NGC 6946 was observed by the *Spitzer* Infrared Nearby Galaxies Survey (SINGS) Legacy program (Kennicutt et al. 2003) with *Spitzer*'s Infrared Array Camera (IRAC) at 3.6, 4.5, 5.8, and 8.0 μm on 2004 June 10 and again on 2004 November 25, 590 and 758 days, respectively, after the 2002 October 27 discovery of SN 2002hh (Li 2002). Both IRAC observation sequences took 35 minutes, yielding the effective exposure times per pixel that are listed in Table 1. The galaxy was also observed at 24, 70, and 160 μm for 55.2 minutes on both 2004 July 9 and 11, with the Multiband Imaging Photometer for *Spitzer* (MIPS). Pipeline-calibrated images of NGC 6946 were obtained from the *Spitzer* public archive. Figures 1a and 1b show IRAC 5.8 and 8.0 μm images of a $30'' \times 29''$ region around SN 2002hh, obtained with a pixel size of $1''.1$ from the

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TABLE 1
FLUXES FROM *SPITZER*

STAR	OBSERVATION DATE	IRAC				MIPS, 24.0 μm
		3.6 μm	4.5 μm	5.8 μm	8.0 μm	
1	2004 Jun/Jul	0.72 \pm 0.14	1.22 \pm 0.12	4.28 \pm 0.50	17.0 \pm 1.6	46.5 \pm 5.1
	2004 Nov 25	0.88 \pm 0.17	1.07 \pm 0.12	3.65 \pm 0.35	12.8 \pm 1.3	...
2	2004 Jun 10	119.6 \pm 18.4	68.9 \pm 4.2	54.9 \pm 2.1	31.4 \pm 1.6	...
	2004 Nov 25	115.6 \pm 15.4	58.8 \pm 4.2	53.5 \pm 2.2	30.4 \pm 1.2	...
3	2004 Jun 10	1.12 \pm 0.35	0.54 \pm 0.10	0.71 \pm 0.21	1.23 \pm 0.28	...
	2004 Nov 25	0.78 \pm 0.19	0.62 \pm 0.21	0.58 \pm 0.16	1.78 \pm 0.82	...
4	2004 Jun/Jul	0.64 \pm 0.17	0.57 \pm 0.11	3.52 \pm 0.46	9.3 \pm 1.2	27.7 \pm 4.5
	2004 Nov 25	0.64 \pm 0.24	0.59 \pm 0.13	3.27 \pm 0.36	10.9 \pm 1.1	...
5	2004 Jun 10	2.11 \pm 0.36	8.6 \pm 1.2	...
	2004 Nov 25	...	0.18 \pm 0.09	1.80 \pm 0.32	6.7 \pm 1.1	...

NOTES.—Flux values are in mJy. Effective exposure time per pixel was 26.8 s for IRAC and 7.34 s for MIPS.

2004 June 10 SINGS observation of NGC 6946. They clearly show the SN (marked as star 1) and a bright adjacent field star (star 2). Using crowded-field point-spread function (PSF) subtraction, we removed these two sources, revealing three additional sources, which we named stars 3, 4, and 5. These sources were identified in all four IRAC bands, with the fluxes listed in Table 1. The error estimates listed there include allowances for flat-field errors, profile errors in fitting the PSF, read noise, and Poisson noise. Astrometry for stars 1–5 from these IRAC images was reported by Barlow et al. (2004). The J2000.0 coordinates measured for SN 2002hh are R.A. = 20^h34^m44^s.23, decl. = +60°07′19″.5 (\pm 0″.3 in each coordinate). These agree well with the J2000.0 radio position of SN 2002hh measured by Stockdale et al. (2002), R.A. = 20^h34^m44^s.25, decl. = +60°07′19″.4 (\pm 0″.2 in each coordinate).

From its 2MASS and IRAC colors, star 2 (=2MASS 20344320+6007234) is likely to be a foreground cool giant in the Milky Way. Stars 4 and 5 were suspected to be a single

extended source, possibly an H II region; for a distance of 6 Mpc to NGC 6946, star 4 has a projected separation of 90 pc from SN 2002hh. Figure 1c shows the MIPS 24 μm image of the same region, obtained with a pixel size of 2″.6. The supernova (star 1) and stars 4 and 5 are clearly detected at 24 μm , with the fluxes listed in Table 1. The IRAC and MIPS fluxes listed in Table 1 have not been corrected to take account of intrinsic source colors; such corrections are estimated to be small. The listed flux uncertainties correspond to the photometric statistical errors; the absolute calibration uncertainties for IRAC and MIPS are estimated to be 5%–6%. It is noteworthy that the 8 μm flux from the supernova (star 1) showed a 25% drop between the IRAC observations of 2004 June and November.

The supernova is only marginally resolved from its neighboring sources in the IRAC and MIPS images, due to the relatively low angular resolution of the 85 cm *Spitzer* (2″.4 at 8 μm). To address the issue of source confusion, we used the Michelle mid-IR imager/spectrometer on the 8 m Gemini North telescope to obtain an 11.2 μm image of 2002hh on 2004 September 26, with an on-source observation time of 900 s. Figure 1d shows the region around SN 2002hh in the Michelle image. With \sim 10 times the spatial resolution of the IRAC observations, the Michelle image completely resolves SN 2002hh from its neighbors and confirms that mid-IR emission originates from the location of the SN. Both the SN and star 2 are easily detected in this image, while star 4/5 is confirmed to be an extended source, which peaks in brightness to the southeast.

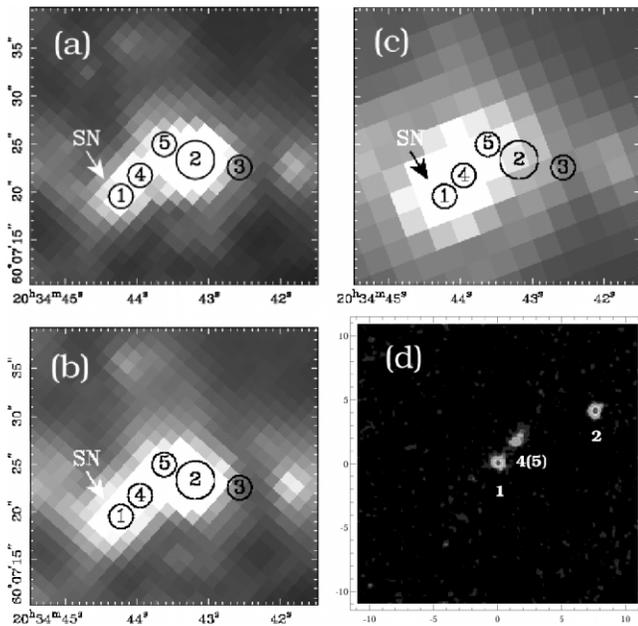


FIG. 1.—(a, b) SINGS IRAC 5.8 and 8.0 μm images of a 30″ \times 29″ region around SN 2002hh (pixel size = 1″.1), obtained on 2004 June 10. (c) SINGS MIPS 24 μm image of the same region (pixel size = 2″.6), obtained on 2004 July 9. (d) Gemini North Michelle 11.2 μm image of a 21″8 \times 21″8 region centred on SN 2002hh (0″.099 pixel⁻¹), obtained on 2004 September 26. Offsets in arcseconds from the position of the SN are marked on the axes. A 3 pixel (0″.3) FWHM Gaussian filter was applied to the cleaned image. [See the electronic edition of the *Journal* for a color version of this figure.]

3. THE INFRARED SPECTRAL ENERGY DISTRIBUTION AND THE MASS OF EMITTING DUST

The observed 2004 June/July MIPS/IRAC spectral energy distribution of SN 2002hh is shown in Figure 2. The longer wavelength *Spitzer* data can be fitted by a 290 K blackbody, which for a distance of 6 Mpc corresponds to a luminosity of $1.6 \times 10^7 L_{\odot}$ and an emitting radius of 1.1×10^{17} cm. More realistic dust particles have $\lambda^{-\alpha}$ emissivities in the IR, with α typically between 1 and 2. For an $\alpha = 1$ emissivity law, a fit to the 2004 June/July 8 and 24 μm fluxes gives a grain temperature of 225 K and a characteristic emitting radius of 5×10^{17} cm, too large for the emitting dust to have been formed in the main SN ejecta, since material traveling at a bulk velocity of 6000 km s⁻¹ would take 25 yr to reach this radius. Light from the supernova would take 6 months to reach the same radius; the light crossing time of 1 yr for a shell of this radius appears consistent with the observed flux decrease at 8 μm of 25% in 5.5 months (Table 1). We infer that the observed

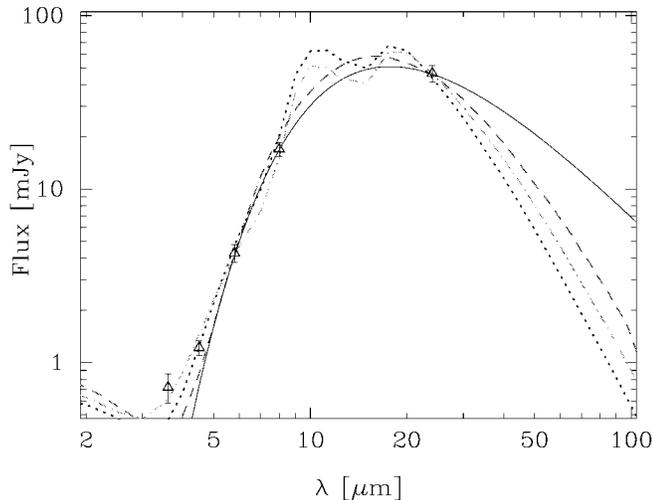


FIG. 2.—Measured IRAC and MIPS fluxes from SN 2002hh in 2004 June/July are shown as open triangles, with vertical bars indicating the flux uncertainties. The solid black line is a 290 K blackbody normalized to the 8.0 μm flux point. The dashed, dotted, and dash-dotted lines correspond to radiative transfer dust models that are discussed in the text. [See the electronic edition of the Journal for a color version of this figure.]

IR emission from SN 2002hh is from preexisting circumstellar (CS) dust ejected by the supernova progenitor star. From day 20 near-IR spectra, an extinction of $A_V = 6.1$ mag has been measured toward the SN by Meikle et al. (2002), of which ~ 1.1 mag were estimated by them to be due to foreground dust in the Milky Way. At SN 2002hh’s angular separation of 129” from the nucleus, an internal extinction of $A_V = 1.2^{+1.3}_{-1.7}$ mag to the midplane of NGC 6946 is predicted (Holwerda et al. 2005). Thus a large fraction of the 5 mag of extinction within NGC 6946 toward SN 2002hh appears to be due to CS dust, which may have condensed within a stellar wind from an earlier M supergiant or luminous blue variable (LBV) phase of evolution of the progenitor star.

We have constructed a number of dust shell models that match the observed 2004 June/July IR flux distribution from SN 2002hh. Fits were obtained for total dust masses of 0.10–0.15 M_\odot , with visual optical depths τ_V in the range 3–4, illuminated by central sources with luminosities of $(2.0\text{--}2.3) \times 10^7 L_\odot$ and effective temperatures in the range 5000–7500 K. The dashed line in Figure 2 corresponds to an amorphous carbon model for a dust shell with an r^{-2} density distribution, an inner shell radius $R_{\text{in}} = 4.0 \times 10^{17}$ cm, a ratio Y of outer to inner shell radii of 3.0, a radial optical depth $\tau_V (=A_V/1.086)$ of 4.0, and a total dust mass of 0.10 M_\odot . The grains had an MRN (Mathis, Rumpl, & Nordsieck 1977) $a^{-3.5}$ size distribution, with minimum and maximum grain radii of $a_{\text{min}} = 0.005 \mu\text{m}$ and $a_{\text{max}} = 0.25 \mu\text{m}$. The model was calculated using Dusty MOCASSIN (Ercolano et al. 2005), a three-dimensional Monte Carlo radiative transfer code, with the amorphous carbon optical constants taken from Hanner (1988). The central source used for the model had a luminosity of $L = 2.3 \times 10^7 L_\odot$ and an effective temperature of $T_{\text{eff}} = 7500$ K. The dotted line in Figure 2 shows an r^{-2} density distribution dust shell model calculated using the two-dimensional radiative transfer code 2-Dust (Ueta & Meixner 2003) for a dust shell containing 25% amorphous carbon and 75% amorphous silicate grains by mass, with MRN $a^{-3.5}$ size distributions and $a_{\text{min}} = 0.005 \mu\text{m}$ and $a_{\text{max}} = 1.0 \mu\text{m}$. The amorphous carbon and amorphous silicate optical constants were taken from Zubko et al. (1996) and Draine & Lee (1984), respectively. The dust shell had $\tau_V = 3$, a mass of 0.15 M_\odot , $R_{\text{in}} = 2.1 \times$

10^{17} cm, and $Y = 1.5$ and was powered by a central source with $L = 2.1 \times 10^7 L_\odot$ and $T_{\text{eff}} = 7000$ K. The best-fitting model (Fig. 2, dash-dotted line; also calculated with 2-Dust) was an amorphous carbon and silicate model having the same central source luminosity and optical depth as above, but with a dust mass of 0.10 M_\odot , $R_{\text{in}} = 1.0 \times 10^{17}$ cm, $Y = 100$, and an embedded constant-density shell or “superwind” located between R_{in} and $10R_{\text{in}}$, followed by a smooth transition to an r^{-2} density distribution having 1/25th of the density of the constant-density shell at the $10R_{\text{in}}$ transition point.

For the best-fitting model (Fig. 2, dash-dotted line), the adopted 25 : 75 ratio by mass for the carbon and silicate dust components is similar to that found necessary to match the light echoes observed from the CS dust closest to SN 1987A (Sugerman et al. 2005). Spectral features attributable to both O-rich and C-rich dust species have been found in the IR spectra of the CS dust shells around the candidate Galactic LBVs AFGL 2298 (Ueta et al. 2001) and HD 168625 (O’Hara et al. 2003). Other grain species that are relatively featureless in the mid-IR could be an alternative to carbon grains, e.g., iron or iron oxide particles, or else “dirty” silicate grains (Jones & Merrill 1976), having larger optical and IR absorptivities outside the mid-IR features than used here, could provide a match to the observed flux distribution without the need for an additional grain species.

4. DISCUSSION

The CS dust mass of 0.10–0.15 M_\odot around SN 2002hh is large, corresponding to an associated gas mass of 10–15 M_\odot if we assume a typical interstellar gas-to-dust mass ratio of 100. From a fit to its *Infrared Space Observatory* IR spectrum, 0.17 M_\odot of dust has been estimated to be around the archetypal LBV η Car (Morris et al. 1999). Another Galactic LBV, AG Car, has a CS dust shell extending from 0.37 to 0.81 pc radius, with a dust mass of 0.25 M_\odot and a gas-to-dust mass ratio of only 32 (Voors et al. 2000). A mass of 0.1 M_\odot has been derived for the dust shell around the Galactic LBV candidate AFGL 2298 (Ueta et al. 2001), while evidence has been found for at least two past superwind events in the dust shell around the self-obscured M supergiant NML Cyg, with total dust masses of 0.02 and $>0.3 M_\odot$ (Bloeker et al. 2001). It seems plausible that the dust shell observed around SN 2002hh may have originated from an episode of enhanced mass loss by the massive star progenitor of this Type II supernova.

The IR luminosity of $2 \times 10^7 L_\odot$ derived for SN 2002hh at \sim day 600 is much higher than the likely luminosity of the supernova ejecta at that epoch. However, given that the light travel timescale across the dust shell is in excess of a year for the models plotted in Figure 2, this could be explainable in terms of the time lags associated with the emission from flash-heated CS dust. A number of Type II SNe have previously been found to exhibit near-IR ($\lambda < 5 \mu\text{m}$) excesses that could be attributed to emission from hot dust, often with post-300 day luminosities comparable to or larger than that observed from SN 2002hh (see, e.g., Gerardy et al. 2002). The high luminosities and the pattern of time evolution of these near-IR excesses has led to them usually being interpreted as arising from flash-heated preexisting CS dust shells (Dwek 1983; Graham & Meikle 1986; Gerardy et al. 2002; Pozzo et al. 2004). The 2.2–3.5 μm emission observed from SN 1979C between days 259 and 440, and from SN 1980K between days 215 and 357, was interpreted by Dwek (1983) as due to preexisting dust, extending in both cases from 3 to 8×10^{17} cm, with visual optical depths of 0.3 and 0.03 and total dust masses of

$(0.6-3) \times 10^{-2}$ and $(0.7-3) \times 10^{-3} M_{\odot}$, respectively. Pozzo et al. (2004) estimated a dust mass of at least $2 \times 10^{-3} M_{\odot}$ around the Type II_n SN 1998S, though they suggested that both preexisting and newly formed dust grains may have played a role in the evolution of its near-IR spectral energy distribution.

Our observations do not rule out the possibility that significant quantities of new dust may have formed in the ejecta of SN 2002hh itself, merely that the observed IR emission is dominated by dust located much farther out than the SN ejecta. At the distance of NGC 6946, the day 615 $8 \mu\text{m}$ emission from the ejecta dust of SN 1987A (Wooden et al. 1993; Bouchet & Danziger 1993) would have been 35 times weaker than that observed from SN 2002hh. SN 1987A's dust visual optical depth at day 600 was estimated to be 0.6 (Lucy et al. 1991), so even if it had been able to condense much more dust than the few $\times 10^{-4} M_{\odot}$ estimated (Dwek et al. 1992; Wooden et al. 1993), its mid-IR emission could only have increased by a further factor of 2, still leaving it a factor of 10 lower than observed from the CS shell surrounding SN 2002hh. One indication of new dust forming in SN ejecta, generally seen in the second year after outburst, is the development of asymmetric blueshifted emission-line profiles, caused by dust preferentially extinguishing redshifted emission from material behind the supernova (Danziger et al. 1991). SN 2002hh has not so far shown any such line-profile evolution. A comparison of visible spectra taken in 2003 July (Mattila et al. 2004) with

those taken in 2004 August and September (Clayton & Welch 2004) indicates that the $H\alpha$ profile shape did not undergo any significant change between ~ 250 and 700 days after outburst.

Our IR observations of SN 2002hh indicate that significant amounts of dust can be produced around the immediate progenitors of some massive-star supernovae. The question of whether such dust can survive the impact of high-velocity ejecta from the subsequent supernova and thereby go on to enrich the dust content of the host galaxy is an interesting one. SN 2002hh is located in a relatively nearby face-on galaxy, which enabled it to be discovered in the optical despite its high dust obscuration. For many galaxies, however, SNe with similar or even greater self-obscuration could easily escape detection by optical supernova searches, suggesting that IR-based supernova searches may be required in order to determine the ratio of dusty to nondusty SNe and the contribution made by the former to the overall dust enrichment rate of galaxies.

We thank the Gemini Observatory for the award of Director's Discretionary Time for observations of SN 2002hh. B. Sugerman has been supported by a *Spitzer* GO-P3333 grant and by internal STScI-DDRF funding. M. Meixner has been supported by NASA grant NAG5-11460. J. Bowey and J. Fabbri were supported by grants from the United Kingdom Particle Physics and Astronomy Research Council.

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