Identifying the Origin and Heating Mechanism of Warm Dust in the Supernova Environment

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Poster Based on Fox, O. D., et al. 2010, ApJ, 725, 1768 and Fox, O. D., et al. 2010, ATEL, 2665, 1

Motivation

Infrared emission signifies the presence of warm dust, which can be used as a probe of the supernova's circumstellar environment, explosion mechanism, and even progenitor system. Additionally, dust is the key to confirming supernovae as the primary sources of the large amounts of dust observed in the early (i.e. high redshift) universe.

Still, late-time (>100 days) infrared emission from dust in the supernova environment is rare, with no more than a few dozen published events over the past 30 years (see Table 1). Surprisingly, Type IIn supernovae (SNe), a subclass representing **<10%** of all core-collapse events, make up **>50%** of the list (highlighted by green in Table 1).

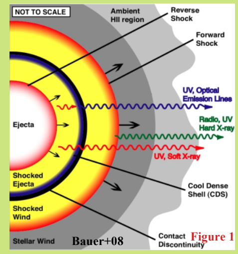
Nonetheless, in many of these cases the observations have served only as a limited tool for probing the origin and heating mechanism of the dust. Insufficient data make constraining the dust properties and geometry difficult. *In fact, not a single mid-infrared spectrum has existed for any Type IIn event before SN 2005ip.* Here, we present a observational study of dust in the supernova environment and methods by which to identify the origin and heating mechanism.

Table 1 novae with Observations of Late-Time Infrared Excess

SN	Type/Subclass	*Spitzer* Observations/Detections?
1979c	II	No/No
1980k	II	No/No
1982e	?	No/No
1982l	II	No/No
1982r	I	No/No
1985l	II	No/No
1986J	IIn	No/No
1987A	II	Yes/Yes
1993J	IIb	No/No
1994Y	?	No/No
1995G	IIn	No/No
1995N	IIn	No/No
1997ab	IIn	No/No
1998S	IIn	No/No
1999Z	IIn	No/No
1999bw	IIn	Yes/Yes
1999el	IIn	Yes/No
1999em	IIP	No/No
2002bu	IIn	Yes/Yes
2002hh	IIP	Yes/Yes
2002ic	Ia/IIn	No/No
2003gd	IIP	Yes/Yes
2004dj	IIP	Yes/Yes
2004et	IIP	Yes/Yes
2005af	IIP	No/No
2005kd	IIn	No/No
2005ip	IIn	No/No
2006gy	IIn	No/No
2006jc	Ib	No/No
2006tf	IIn	No/No
2007od	IIP	No/No
2008S	IIn	No/No
2008iy	IIn	No/No

Origins and Heating Mechanisms

Figure 1 illustrates the core-collapse environment, while Figure 2 highlights the various origins and heating mechanisms of dust in the supernova environment.



Bauer+08 Figure 1

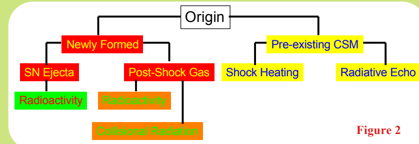


Figure 2

Q: So.....How Can You Distinguish Between All the Possibilities?
A: Infrared Analysis, but it's a tricky art. Proceed with Caution!
We exemplify below with near- and mid-IR observations of SN 05ip.

1. Fit Your Data

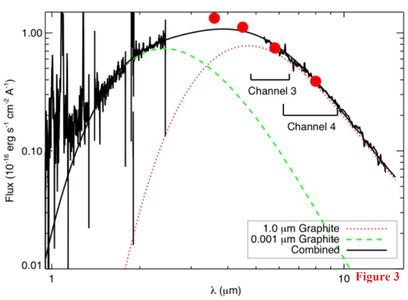


Figure 3

Equation 1 writes the infrared flux as a function of the dust mass, M_d, and temperature, T_d. Figure 3 shows data for SN 2005ip fit by Equation 1. Having mid-IR data, especially spectra, will help constrain your fit. In the case of SN 2005ip, the fit was optimized with 2 components. Table 2 lists the resulting dust parameters. These numbers will prove useful in later analysis.

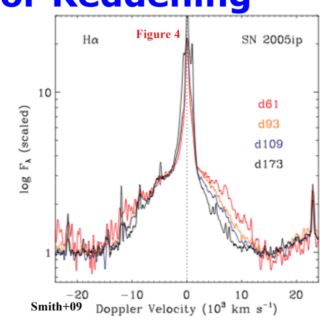
$$F_\nu = \frac{M_d B_\nu(T_d)\kappa_\nu(a)}{d^2}, \quad \text{Equation 1}$$

Table 2

Fit	T_{warm} (K)	T_{hot} (K)	M_{warm} ($M_\odot$)	M_{hot} ($M_\odot$)	L_{warm} ($L_\odot$)	L_{hot} ($L_\odot$)	χ^2
1.0 μm(warm) + 0.1 μm(hot)	540	847	5.9×10^{-3}	5.9×10^{-4}	1.0×10^{8}	5.8×10^{7}	1.17
0.3 μm(warm) + 0.1 μm(hot)	408	838	2.8×10^{-2}	6.7×10^{-4}	1.0×10^{8}	6.2×10^{7}	1.12
0.1 μm(warm) + 0.1 μm(hot)	453	859	4.3×10^{-2}	5.2×10^{-4}	1.1×10^{8}	5.5×10^{7}	1.10
0.01 μm(warm) + 0.1 μm(hot)	472	862	4.5×10^{-2}	5.0×10^{-4}	1.1×10^{8}	5.5×10^{7}	1.10
0.001 μm(warm) + 0.1 μm(hot)	472	862	4.5×10^{-2}	5.0×10^{-4}	1.1×10^{8}	5.5×10^{7}	1.10

2. Check Spectra for Reddening

An easy check for new dust formation is in the fading of the red wing of the spectral lines as a function of time. As new dust forms, it will preferentially absorb light emitted from the far side (i.e. redshifted). The associated line width can distinguish between the fast ejecta (5,000-10,000 km/s) and decelerated post-shocked gas (2,000-5,000 km/s). Figure 4 shows spectra for SN 2005ip, which confirm new dust formation in both regions. Evidence of dust formation, however, does not imply that a majority of the dust is newly formed. Instead, one must consider a variety of factors together, including the spectral, photometric, and temperature evolution. While not discussed in detail here, we show that a majority of the dust in SN 2005ip was ***not*** newly formed.



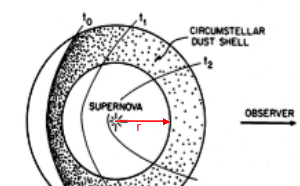
Smith+09 Figure 4

3. Shock Heating

If the dust is ***not*** newly formed, it must have been pre-existing at the time of the supernova. These pre-existing grains may be heated by the forward shock. Two simple geometric arguments can determine the likelihood of this scenario for a particular supernova. 1) For a shock velocity, v_s, the forward shock must have sufficient time ($t = v_s / r_m$) to reach the pre-existing dust grains, which are located at a minimum radius (r_m) defined by the blackbody radius. 2) For an assumed gas-to-dust ratio, the shocked gas mass, M_g, defined by Equation 2, should correspond to the dust mass observed in Figure 3.

$$M_g(M_\odot) \approx 8.3 \times 10^{-5} \left(\frac{v_s}{1000 \text{ km s}^{-1}}\right)^3 \left(\frac{t}{\text{yr}}\right)^2 \left(\frac{a}{\mu m}\right) \quad \text{Equation 2}$$

4. IR Echo: Flash vs. Continuous Heating



Dwek83 Figure 5

Or perhaps the dust is heated by an IR echo (see Figure 5). For a typical IR echo scenario, the supernova peak luminosity ***flash*** heats a shell of dust at a radius, r, to a temperature, T_d. Any dust within a radius r_{evap} will be vaporized. Light travel time effects cause the thermal radiation from the dust grains to reach the observer over an extended period of time, thereby forming an IR echo. Alternatively, the late-time optical luminosity generated by circumstellar interaction could ***continuously*** heat the dust shell.

$$L_{bol} = \frac{64}{3}\rho a r_v^2 \sigma T_{SN}^4 \frac{\int B_\nu(T_d)\kappa(\nu)d\nu}{\int B_\nu(T_{SN})Q_{abs}(\nu)d\nu}. \quad \text{Equation 3}$$

Using Equation 3, the dust temperature can be plotted as a function of the central luminosity for different radii, illustrated by the dotted line in Figure 6 for the observed dust shell radius of SN 2005ip. Solid lines indicate the evaporation temperature, T_{evap}, and observed values, including the dust temperature, T_d, peak luminosity, L_{peak}, and late-time optical plateau luminosity, $L_{plateau}$, which is generated by circumstellar interaction. The dotted line intersects the observed dust temperature at the observed plateau luminosity, which suggests the dust is heated primarily by a circumstellar shock echo.

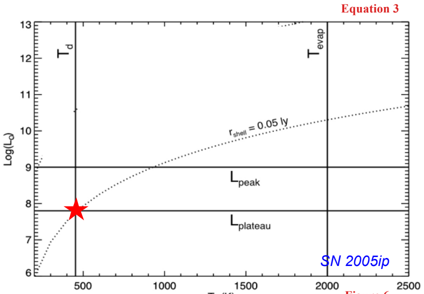


Figure 6

Type IIn Spitzer Survey

Ultimately, the above methods should be implemented on a larger sample. Given the low Type IIn supernova rate, however, we have not been able to build up a substantial database of new Type IIn events. Instead, we have performed a <u>warm</u> *Spitzer* survey of all 68 Type IIn supernovae that have occurred within 250 Mpcs over the past 10 years, with the expectation that a substantial number will still be bright at infrared wavelengths. In fact, 9 supernovae show evidence for late-time infrared emission, in some cases 4 or 5 years post-explosion (see Figure 7). The resulting photometry, along with supporting near-infrared data, are plotted in Figure 8, and the resulting parameter fits are plotted in Figure 9. Interestingly, although independent events, the resulting plateau seemingly represents a single supernova that 'turns off' at about 1500 days. *Is this a common trend?*

We see little evidence of reddening in the spectra (see Figure 10 for several examples), suggesting little new dust formed. We also rule out shock heating from a number of geometric arguments. Instead, like SN 2005ip, the data are consistent with a continuous heating by optical emission generated by circumstellar interactions. Figure 11 plots the observed dust temperatures vs. shell radii. Overplotted is the expected dust temperature as a function of shell radius for optical emission equal to the circumstellar interaction observed in SN 2005ip. This contour is consistent with the observed values.

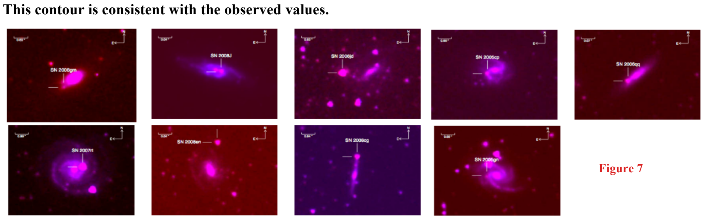


Figure 7

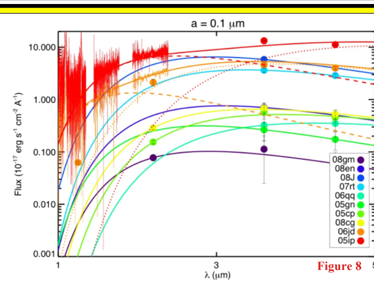


Figure 8

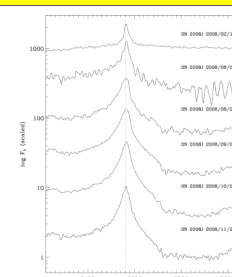


Figure 10

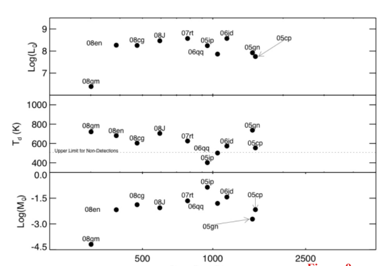


Figure 9

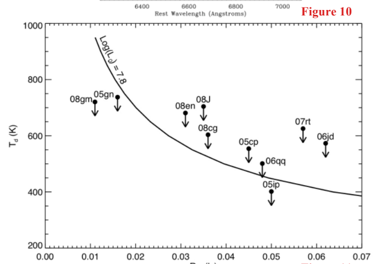


Figure 11

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