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

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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 ~15% 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.

Q: So.....How Can You Distinguish Between All the Possibilities? At 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

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.

\[
F_\nu = M_d B_\nu(T_d) \alpha = \text{Equation 1}
\]

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.

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 (\( t_s = \frac{r_s}{v_s} \)) to reach the pre-existing dust grains, which are located at a minimum radius (\( r_s \)) 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.

\[
M_g(M_d) = 8.3 \times 10^{-2} \left(\frac{v_s}{1000 \text{ km s}^{-1}}\right)^2 \left(\frac{r_s}{1000 \text{ km}}\right)^3 \text{ Equation 2}
\]

4. IR Echo: Flash vs. Continuous Heating

Or perhaps the dust is heated by an IR echo (see Figure 5). For a typical IR echo scenario, the supernova peak luminosity, \( L_{\text{peak}} \), heats a shell of dust at a radius, \( r_s \), to a temperature, \( T_d \). Any dust within a radius \( r_s \) 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.

\[
L_{\text{bol}} = \frac{64}{3} \rho v_s^2 \sigma T_{\text{peak}}^4 \int B_v(T_{\text{peak}}) \sigma_v \text{ d}v
\]

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 warm Spitzer survey of all 68 Type IIn supernovae that have occurred within 250 Mpc 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 results, the resulting parameter plots seem to corroborate a single supernova that ’burns 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.