Type IIIn's and the Final Stages

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SN 2006jd
Type IIln’s in the Mid-IR

Late-time Spitzer mid-IR Evolution

Log\((L_d/L_\odot)\)

Days Post-Discovery

05ip (NIR)
08gm
08ip

Epoch 1

08en
08cg
08J
07rt
06id
05ip
06qq
05ip
05gn
05N.(NIR)
LBV Progenitor Eruptions?

\[
\dot{M} = \frac{M_d}{Z_d \Delta r} v_w 
= \frac{3}{4} \left( \frac{M_d}{M_{\odot}} \right) \left( \frac{v_w}{120 \text{ km s}^{-1}} \right) \left( \frac{0.05 \text{ ly}}{r} \right) \left( \frac{r}{\Delta r} \right) M_{\odot} \text{ yr}^{-1}
\]

Mass Loss Associated with Radiatively Heated Graphite Dust Shell

<table>
<thead>
<tr>
<th>SN</th>
<th>(\dot{M} \times (10\Delta r)/r) ((M_{\odot} \text{ yr}^{-1}))</th>
<th>(t_{\text{eruption}}) (yr)</th>
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<td>30</td>
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Blackbody, Shock, Echo Plateau, and Vaporization Radii

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<th>(r_{bb}^a) (ly)</th>
<th>(r_{s2}^b) (ly)</th>
<th>(r_{sl}^c) (ly)</th>
<th>(r_{ech}^d) (ly)</th>
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<td>0.033</td>
<td>0.20</td>
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<td>1479</td>
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<td>0.013</td>
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<td>0.007</td>
<td>0.039</td>
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<td>0.010</td>
<td>0.057</td>
<td>0.60</td>
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</table>

ODF+11
Expected High Energy Emission

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

Minimum Radii

\[ \text{Log}(L_{\text{opt}}/L_0) = 9.0 \]
\[ \text{Log}(L_{\text{opt}}/L_0) = 8.0 \]
\[ \text{Log}(L_{\text{opt}}/L_0) = 7.0 \]

ODF+11
Type IIn’s at late-times

Late-time Type IIn Evolution

Log($L_d/L_0$)

Days Post-Discovery

Spitzer 1

05ip (NIR)

05gn (NIR)
Type IIIn’s at late-times
Type IIln’s at late-times
Type IIn’s at late-times
Type II\textsubscript{N}’s at late-times
Type IIin’s at late-times

Late-time Type IIin Evolution

Log($L_d/L_0$)

Days Post-Discovery

05ip (NIR)

06jd

95N (NIR)
Type IIln’s at late-times

Late-time Type IIln Evolution

Log($L_d/L_0$)

Days Post-Discovery

05ip (NIR) 07rt 07rt 07rt 95N (NIR)
Type IIn's at late-times

Late-time Type IIn Evolution

Log($L_d/L_0$)

Days Post-Discovery

05ip (NIR) 08en

Spitzer 1 Spitzer 2 WISE Keck

95N (NIR)
Type II In's at late-times

Late-time Type II In Evolution

Log($L_d/L_0$)

Days Post-Discovery

Spitzer 1
Spitzer 2
WISE
Keck

05ip (NIR)
10II
10III
95N (NIR)
X-Rays as a Discriminator

1. Time ($r/v_s$) [day]
2. Flux [erg cm$^{-2}$ s$^{-1}$]
3. Luminosity [erg s$^{-1}$]

- Radial velocity of wind ($r/v_w$)
- Mass in R
- Shock breakout in a wind profile
- Mass in R
- Shock breakout inside a star
- Sun

SN 2010jl

- Swift
- Chandra
- Optical/100

Ofek+12
SN 2010jl - H/alpha
Techniques Apply to All Varieties

- Type II: 05ip
- Type Ib/c: 06jc, 01em
- Impostors: 02bu, 08S, NGC 300-OT1
- SLSNe: 06gy, 06tf, 10jl
- Type Ia: 00cx, 02ic, 05gl, 08J (?), 08cg (?)

- Are All Type IIn Supernovae?
- What are the progenitors to SLSNe?
- Why Do All the SNe in my sample look the same? Or do they?
What traits distinguish subclasses?

- Peak Luminosity
- Expansion Speed
- Rise/Fall Time
- Infrared?
- X-rays?
- Radio?
- Rates?
- Environments?
Implications and Future Work

• In general, the Type IIln subclass seems to have a warm dust component that likely is due to an `IR echo' that forms from the heating of a large, pre-existing dust shell. The heating mechanism is likely the optical luminosity generated from the forward shock interaction with the circumstellar medium.

• Mass-loss rates and progenitor wind speeds suggest LBV progenitors that have undergone eruptive events tens to hundreds of years before going SN.

• Will be able to observe the echo turn off? What is the mechanism?

• And more…
  – Can these techniques be used for other supernova/transient types?
  – If LBVs can go supernova, than their cores are significantly more evolved than stellar evolution models predict?
  – If LBVs yield large amounts of dust in their progenitor winds, then perhaps there is a connection to the large mass stars associated with Pop. III stars in the early universe?
X-Rays From LBV Eruptions?

Smith+08
2) Dust In Other Transients

Kochanek+11
What About the Non-Detections?
# Likely Heating Mechanisms

## Evidence for Dust Origin and Heating Mechanism

<table>
<thead>
<tr>
<th>SN</th>
<th>Newly Formed?</th>
<th>Shock Heating?</th>
<th>IR Echo?</th>
<th>Shock Echo?</th>
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<td>no</td>
<td>yes</td>
</tr>
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<td>maybe</td>
<td>no</td>
<td>maybe</td>
</tr>
<tr>
<td>2005ip</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>2006jd</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>maybe</td>
</tr>
<tr>
<td>2006qq</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>2007rt</td>
<td>yes (^a)</td>
<td>no</td>
<td>no</td>
<td>maybe</td>
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<td>2008J</td>
<td>maybe</td>
<td>maybe</td>
<td>no</td>
<td>maybe</td>
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<td>no</td>
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<td>yes</td>
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</table>

\(^a\)Trundle et al. (2009)
Origin and Heating of Warm Dust

**Origin**
- **Newly Formed**
  - SN Ejecta
  - Post-Shock Gas
    - Radioactivity
    - Collisional Radiation
- **Pre-existing CSM**
  - Shock Heating
  - Radiative Echo

**Must Consider:**
1) Energetic Constraints
2) Dust Temperature Constraints

**Quick Definition:**
1) Blackbody Radius
2) Shock Radius
3) Evaporation Radius
4) Echo Radius

\[
\begin{align*}
  r_{bb} &= \left( \frac{L_{bb}}{4\pi \sigma T_{bb}^4} \right)^{\frac{1}{2}} \\
  r_s &= v_s t \\
  r_{evap} &= t_{ech} \\
  r_{ech} &= \frac{ct_{ech}}{2}
\end{align*}
\]
Physical Mechanism

Red Supergiant
Blue Supergiant
LBV (η Car)
Late W-R (WN)
Early W-R (WC/WO)
Massive Binaries


SN 1987A (faint, slow)

SN II-P

SN II-L/IIb (little H)
SN Ib (no H)
Type Ic (no H, He) GRB/XRF

SN 1993J

SN 2005gl

Gal-Yam+07
Why do we care about dust?

- The presence of dust yields various clues about the supernova explosion and the progenitor system, including:
  - *Geometry of circumstellar medium and progenitor evolution*
  - Peak supernova luminosity & explosion mechanics
  - Shock velocity & circumstellar interaction

- The presence of dust also allows us to probe the possibility that supernovae are significant sources of dust in the early universe
  - Observations reveal large amounts of reddening (i.e. dust) in the early universe (Maiolino+04)
  - But at less than 1 Gyr (Z>6), the universe was not populated by low-mass AGB stars, which are the dominant sources of dust in our local universe

![Graph showing observed and modeled dust extinction ratios](image)
New Dust Contribution

<table>
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<tr>
<th>Fit</th>
<th>$T_{\text{warm}}$ (K)</th>
<th>$T_{\text{hot}}$ (K)</th>
<th>$M_{\text{warm}}$ ($M_\odot$)</th>
<th>$M_{\text{hot}}$ ($M_\odot$)</th>
<th>$L_{\text{warm}}$ ($L_\odot$)</th>
<th>$L_{\text{hot}}$ ($L_\odot$)</th>
<th>$\chi^2$</th>
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<td>$1.0 \mu m$(warm) + $0.1 \mu m$(hot)</td>
<td>540</td>
<td>847</td>
<td>$5.9 \times 10^{-3}$</td>
<td>$5.9 \times 10^{-4}$</td>
<td>$1.0 \times 10^8$</td>
<td>$5.8 \times 10^7$</td>
<td>1.17</td>
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<tr>
<td>$0.3 \mu m$(warm) + $0.1 \mu m$(hot)</td>
<td>408</td>
<td>838</td>
<td>$2.8 \times 10^{-2}$</td>
<td>$6.7 \times 10^{-4}$</td>
<td>$1.0 \times 10^8$</td>
<td>$6.2 \times 10^7$</td>
<td>1.12</td>
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<tr>
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<td>453</td>
<td>859</td>
<td>$4.3 \times 10^{-2}$</td>
<td>$5.2 \times 10^{-4}$</td>
<td>$1.1 \times 10^8$</td>
<td>$5.5 \times 10^7$</td>
<td>1.10</td>
</tr>
<tr>
<td>$0.01 \mu m$(warm) + $0.1 \mu m$(hot)</td>
<td>472</td>
<td>862</td>
<td>$4.5 \times 10^{-2}$</td>
<td>$5.0 \times 10^{-4}$</td>
<td>$1.1 \times 10^8$</td>
<td>$5.5 \times 10^7$</td>
<td>1.10</td>
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<tr>
<td>$0.001 \mu m$(warm) + $0.1 \mu m$(hot)</td>
<td>472</td>
<td>862</td>
<td>$4.5 \times 10^{-2}$</td>
<td>$5.0 \times 10^{-4}$</td>
<td>$1.1 \times 10^8$</td>
<td>$5.5 \times 10^7$</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Ejecta Dust

Post-Shock Dust
Physical Mechanism

Type II-P SNe dominate the observed explosions.

Direct observations of progenitors (SNe 2003gd, 2005cs, 2008bk, 2004dj, and 2004am) identify red-supergiant (RSG) progenitors. But all have masses from 8.5-17 $M_\odot$.

If true, where are the higher mass RSG progenitors?
- New IMF?
- New theory of stellar evolution and explosions?
- Need to account for dust extinction?
• **Type Ib/c progenitors never observed directly.**

• Lack of H -> progenitor wind -> Wolf-Rayet (WR) stars. But with known galactic WR characteristics, little chance we haven’t directly detected a progenitor yet. Also, Type Ib/c rate would require WR stars to form as low as $16 \, M_\odot$.

• These results suggest 2 progenitor systems:
  - Interacting binaries
  - WR stars (But what happens to the WR stars that don’t form SNe?)
• What is the fate of the most massive stars (i.e., LBVs) w/ masses 80-120 \( M_\odot \)? Evolution theory suggests they lose their H/He envelopes and end up WR stars. And any eventual core-collapse should result in a black hole.

• Direct detection of a single LBV progenitor (SN2005gl). An additional event (SN2006jc) was observed coincident w/ a prior LBV-like outburst. Furthermore, ultra-bright (10^{51} \text{ erg}), H-rich events (e.g., SNe 2006gy, 2005ap, 2008es, 2006tf) require massive progenitors, consistent with LBVs.

• But physical mechanism that produces the ultra-bright Type IIn (and II-L) SNe remains controversial and unresolved. If LBVs, this would imply the cores are significantly more evolved than predicted by stellar evolution models.
  – Perhaps the core-collapse model doesn’t even work in this case (e.g., pair-instability)?
Late-time IR Emission From SNe IIn

Type IIn Undefined before 1990

Late-time Spitzer mid-IR Evolution

Log\((L_{\nu}/L_{\odot})\)

Days Post-Discovery

Epoch 1 \black\bullet\ Epoch 2

<table>
<thead>
<tr>
<th>SN</th>
<th>Subclass</th>
<th>Spitzer Observations?/Detections?</th>
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<td>IIn</td>
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X-Rays

Graphs showing luminosity ($L_{\text{erg/s}}$) and temperature ($T_{\text{obs}}$) over time ($t$) for different conditions with specified parameters $t_{\text{bo}}$ and $v_{\text{bo}}$. Data points for SN1998S and SN2005gl with various observational magnitudes and error bars.
2) Dust From Impostors?

Kochanek+11