Supernovae and supernova remnants

Mikako Matsuura (Cardiff University)
Why are SNe & SNRs important?

- Synthase heavy elements
  - dust formation
- Source of kinetic energy into the ISM
  - dust destruction

**Path to the first dust in the Universe**

- Injection of elements
- Condensation to dust

**Formation of the first generation of stars**

- Supernovae – death of massive stars

**Big Bang**
Why are SNe & SNRs important?

- Synthesize heavy elements
  - dust formation
- Source of kinetic energy into the ISM
  - dust destruction

M82 Galactic outflow

Supernova remnant NGC 6960 (Veil Nebula)

100-1000 km s⁻¹ Shocks
Key questions

• Are supernovae & supernova remnants dust producer or destroyer?
  • If dust producer:
    • What is the net dust mass?
    • What types of dust grains are formed?
  • If destroyer:
    • How efficient?
    • How does affect grain size distributions?
It is getting clear that SNe form substantial mass of dust using newly synthesized elements.

<table>
<thead>
<tr>
<th>Cassiopeia A (AD 1681?)</th>
<th>Crab Nebula (AD 1054)</th>
<th>Supernova 1987A</th>
<th>SNe in nearby galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.5 M☉</td>
<td>0.03-0.05 M☉</td>
<td>~0.5 M☉</td>
<td>0.0001–0.02 M☉?</td>
</tr>
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</table>

IR dust observations: only ~10 SNe + SNRs

e.g. Sugerman et al. (2006), Matsuura et al. (2015), De Looze et al. (2017; 2019)
Target opportunity – extra-galactic SNe

SOFIA observations of SN 2014J in M82 – unfortunately no dust
Template for extragalactic SNe – Time evolution of SN 1987A

- The peak of SED shifted to longer wavelength in time
- The inferred mass increases in time?
  - 0.001 $M_\odot$ at day 615

Harvey et al. (1989), Wooden et al. (1993), Bouchet & Danziger (1993), Wesson et al. (2015)
Template for extragalactic SNe – Time evolution of SN 1987A

- The peak of SED shifted to longer wavelength in time
- The inferred mass increases in time?
  - 0.001 $M_\odot$ at day 615
  - 0.002 $M_\odot$ at day 775

Harvey et al. (1989), Wooden et al. (1993), Bouchet & Danziger (1993), Wesson et al. (2015)
Template for extragalactic SNe – Time evolution of SN 1987A

- The peak of SED shifted to longer wavelength in time.
- The inferred mass increases in time?
  - 0.001 $M_\odot$ at day 615
  - 0.003 $M_\odot$ at day 1153

Harvey et al. (1989), Wooden et al. (1993), Bouchet & Danziger (1993), Wesson et al. (2015)
Template for extragalactic SNe – Time evolution of SN 1987A

• The peak of SED shifted to longer wavelength in time
• The inferred mass increases in time?
  • 0.001 $M_{\odot}$ at day 615
  • 0.6 $M_{\odot}$ at day 8515

Harvey et al. (1989), Wooden et al. (1993), Bouchet & Danziger (1993), Wesson et al. (2015)
Template for extragalactic SNe – Time evolution of SN 1987A

- The peak of SED shifted to longer wavelength in time
- The inferred mass increases in time?
  - $0.001 \, M_\odot$ at day 615

Harvey et al. (1989), Wooden et al. (1993), Bouchet & Danziger (1993), Wesson et al. (2015)
But can SN dust survive the impact of reverse shock?

<table>
<thead>
<tr>
<th>Theoretical models</th>
<th>Dust destruction rate %</th>
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<tbody>
<tr>
<td><strong>Reverse shocks</strong></td>
<td></td>
</tr>
<tr>
<td>Nozawa et al (2007)</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>45</td>
</tr>
<tr>
<td>Bianchi and Schneider (2007)</td>
<td>97</td>
</tr>
<tr>
<td>Nath et al (2008)</td>
<td>1</td>
</tr>
<tr>
<td>Silvia et al (2012)</td>
<td>4–56</td>
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<td></td>
<td>5–93</td>
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<td>Micelotta et al (2016)</td>
<td>20</td>
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<td></td>
<td>50</td>
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</table>
Unique opportunity to witness SN dust – reverse shock encounter

SN 1987A
Located at the Large Magellanic Cloud (LMC) – 50 kpc away
Nearest SN explosion in 400 years

Time evolution of SN 1987A ejecta + circumstellar ring (red supergiant material)

Reverse shock (detected in 2003)

France et al. (2010); Fransson et al. (2013)
Unique opportunity to witness SN dust – reverse shock encounter

SN 1987A

ALMA dust

With a speed of $\sim 1000-5000$ km s$^{-1}$ (0.003-0.02 arcsec per year) in projected velocity, the reverse shock should have hit ejecta dust

Cigan et al. (2019)
Only SOIF (±JWST?) can observe this historical event.

Detecting any change in the temperature of FIR ejecta dust requires SOFIA HAWC+ upgrade.
Only SOIFIA (+JWST?) can observe this historical event

Detecting any change in the temperature of FIR ejecta dust requires SOFIA HAWC+ upgrade

FORCAST will retire by that time? JWST?
What types of grains can be formed or survived?

Polarization of SNR Cassiopeia A
850 micron

Dunn et al. (2009)

HAWC+ upgrade enables to study more SNRs than Cassiopeia A (Crab Nebula, Tycho, Kepler)
What is the cooling of SNRs?

Theoretical prediction for SN 1987A -> and other SNRs, such as Cas A?

These important cooling lines fall into the gap between Herschel PACS (>55 µm) and JWST MIRI (<28 µm) -> FIFL-LS extension to 43 µm

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<table>
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<th>Table 4. Dominant cooling transitions for each zone.</th>
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<tr>
<td>Zone</td>
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<tr>
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<tr>
<td>Fe/He</td>
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<td>Si/S</td>
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<td>O/Si/S</td>
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<td>O/Ne/Mg</td>
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<td>O/C</td>
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<td>He (core)</td>
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<td>H (core)</td>
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ISO/SWS spectra of Cassiopeia A (Arendt et al. 1999)  
Jerkstrand et al. (2011)
Near future opportunities of SOFIA

• Dust production and destruction by SNe and SNRs
• Dust compositions
• Cooling lines