Can supernovae be important source of dust in the interstellar medium of galaxies?

Mikako Matsuura
Cardiff University

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What is the role of SNe on evolution of interstellar medium of galaxies?

1. Providing kinetic energy
2. Source of elements and dust
3. Destroying existing ISM dust
What is the role of SNe on evolution of interstellar medium of galaxies?

1. Providing kinetic energy

- SN explosion energy of $10^{51}$ ergs
What is the role of SNe on evolution of interstellar medium of galaxies?

1. Supernova remnant NGC 6960 (Veil Nebula)
2. Source of elements and dust
3. Destroying existing ISM dust
What is the role of SNe on evolution of interstellar medium of galaxies?

1. Supernova remnant NGC 6960 (Veil nebula)
   - 100-1000 km s\(^{-1}\)

When SN shock waves meet with ISM dust:

- **Grain shuttering**
- **Grain spattering**

2. Source of elements and dust
3. Destroying existing ISM dust

Hirashita
What is the role of SNe on evolution of interstellar medium of galaxies?

SN ejecta – filled with heavy elements (C, Si, O, Mg, Fe)
These refractory elements eventually form dust grains

Supernova 1987A

HST Hα image

SN ejecta

Forward shocks

Ring (progenitor star material)

M33

Herschel dust image

2. Source of elements and dust
3. Destroying existing ISM dust
What is the role of SNe on evolution of interstellar medium of galaxies?

Supernova 1987A

1. Providing kinetic energy
2. Source of elements and dust
3. Destroying existing ISM dust

Context of my talk
Observational studies of
1. Dust formation in SNe
2. Destroying dust
3. Constrains on elements synthesized in SNe
4. SN explosion mechanism
What are the major sources of dust in galaxies?

- Stellar origin (SNe + AGB stars)
  - 0.1-1 $M_\odot$ of dust per SN needed
- ISM grain growth

Submm galaxy
At z~6.4; ~0.4 Giga years
(e.g. Bertoldi et al. 2003)

Dwek & Cherchneff (2011)
Dust history back to $z=8.38$

Lensed galaxy, A2744 YD4 ($z=8.38$)
~200 Myrs old

Laporte et al. (2017)

1.8-10.4x10$^6$ $M_\oplus$ of dust
Evidence of dust formation in stars

Laboratory measurements of isotope-ratios in SiC pre-solar grains

J-type carbon stars?

Novae/supernovae?

AGB stars

Supernovae

Solar

12C/13C

14N/15N

(Zinner et al. 2006)
What are the major sources of dust in galaxies?

- Stellar origin (SNe + AGB stars)
  - 0.1-1 M☉ of dust per SN needed
  - Spitzer observations: $10^{-6} - 10^{-4}$ M☉ of dust per SN
- ISM grain growth

Dwek & Cherchneff (2011)

Submm galaxy
At z~6.4; ~0.4 Giga years
(e.g. Bertoldi et al. 2003)
Role of SNe on galaxy evolution

Questions

• How much elements ejected from SNe?
• How much dust is formed in SNe?
  – How to form dust?

Supernovae enrich the ISM of galaxies with newly synthesised elements and dust
Supernova 1987A

Located in the Large Magellanic Cloud (50 kpc)
Nearest supernova explosion detected in 380 years
Modest ISM extinction
Type II-P SN (progenitor: 18-20 $M_\odot$)
Detection of dust in SN 1987A

- Kuiper Air Borne observatory
- 450-777 days
- $10^{-4} \ M_\odot$ of dust

First detection of dust in SNe

Wooden et al. (1993)
Detection of cold dust

Matsuura et al. (2011)

Herschel Magellanic Clouds survey (HERITAGE; Meixner et al. 2010)

Herschel 250 micron
Spitzer IRAC 8 micron + MIPS 24 micron

d=8500
Herschel detection of SN 1987A

Significantly large mass of dust:
- 0.4-0.7 $M_\odot$ of dust
  - Must be in the ejecta
- C.f. previously reported mass:
  $10^{-6} - 10^{-3} \ M_\odot$

Matsuura et al. (2011;2015)
Our interpretation of large dust mass (0.4-0.7 $M_\odot$) in SN 1987A

- A large mass of dust must have formed in the SN ejecta where rich metals are available
  - 18-20 $M_\odot$ of the progenitor star
  - 2 $M_\odot$ of the metal mass

Questions raised by supernova/dust communities

- C.f. previously reported SN dust mass: $10^{-6} - 10^{-3} M_\odot$
- Did dust grains really form in the ejecta?
  - Alternatives
    - progenitor (red-supergiant) dust
    - ISM swept up dust
ALMA confirmed dust formation in ejecta

Cold dust in ejecta

SN ejecta

Ring: progenitor

Indebetouw et al. (2014)
ALMA photometric points trace cold dust
The ejecta of SN 1987A

- < 25 years after the explosion
- Cold and dense gas in the ejecta
  - ~20 K of dust
- Rich with dust and molecules
- Efficient cooling with adiabatic, lines and dust radiations

Supernova ejecta

Ring: progenitor star
What is the true figure of dust mass? What is the time scale of dust formation?

• Dust mass evolution vs optically thick
  – Dust mass starts with small number and increases in time
  – A large dust mass is present from early days, but hidden by optically thick dust clouds

• SPICA/Origin?

Gall et al. (2014, Nature 511, 326)
Dust chemistry

Higher angular ALMA resolution images

Cigan et al. (in preparation)
Dust chemistry

Higher angular ALMA resolution images

CO and dust emission are spatially anti-correlating
CO dissociation resulted in forming amorphous carbon dust from free C?

Cigan et al. (in preparation)
Context

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How much dust is destroyed by SN forward shocks?

Forward shocks
Reverse shocks

Cassiopeia A (AD 1681?)

Gotthelf et al. (2001)
A big problem in understanding of dust evolution of galaxies

• Theory predicts

Total dust input rate from AGB stars + SNe

\leq

Dust destruction rate by SNe

C.f. ISM grain growth

e.g. Jones & Nuth (2011)
Theoretical prediction of dust destruction by SNRs

<table>
<thead>
<tr>
<th>Destruction rate</th>
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<tbody>
<tr>
<td><strong>Forward shocks</strong> (Destroying existing ISM dust)</td>
<td></td>
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<tr>
<td>Draine and Salpeter (1979)</td>
<td>10–30</td>
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<td>50–70</td>
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<td>McKee et al (1987)</td>
<td>25–38</td>
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<tr>
<td>Jones et al (1994)</td>
<td>12</td>
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<td>22</td>
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<td>Jones et al (1996)</td>
<td>8</td>
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<tr>
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<td>16</td>
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<tr>
<td>Bocchio et al (2014)</td>
<td>91</td>
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<td></td>
<td>29</td>
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| **Reverse shocks** (Destroying newly formed SN ejecta dust) |  |
| Nozawa et al (2007) | 100 | MgSiO$_3$, $M_p=20 \text{ M}_\odot$, $n_H=1 \text{ cm}^{-3}$ |
| | 45 | C, $n_H=1 \text{ cm}^{-3}$ |
| Bianchi and Schneider (2007) | 97 | $M_p=20 \text{ M}_\odot$, $n_H=10^{-24} \text{ g cm}^{-3}$ |
| Nath et al (2008) | 1 | $M_{ej}=2 \times 10^{34} \text{ g}$, $E_{ej}=10^{51} \text{ erg}$ |
| Silvia et al (2012) | 4–56 | C |
| | 5–93 | SiO$_2$ |
| Micelotta et al (2016) | 20 | Amorphous Carbon, $v_s=100 \text{ km s}^{-1}$ |
| | 50 | MgSiO$_3$ |
Shock destructions in future?

- Shocks: largely depending on the geometry of circumstellar matter and the presence of ambient ISM gas

Cassiopeia A (AD 1681?)
- Gotthelf et al. (2001)

Crab Nebula (AD 1054)
- No shock detected

Supernova 1987A
- Reverse shocks in 2011
Cassiopeia A (AD 1681?)

Warm dust: 0.7 $M_\odot$
Cold dust: 0.4 $M_\odot$
(composition dependent)

Reverse shock destruction rate: ~70%

De Looze et al. (2017)
Time evolution of SN 1987A

HST Hα

Forward shocks exited the ring on the East side

Mid infrared (dust)

Matsuura et al. (in preparation)
Spectral energy distribution

Detection of excess at 31 micron

Continuing to Herschel 70 micron

Warm component
$M_d = 0.8 \times 10^{-5}$ Msun $T_d = 191$ K

Excess
$M_d = 3.5 \times 10^{-4}$ Msun $T_d = 85$ K

Matsuura et al. (2019)
Dust reformation in the post shocked region?
Timing – forward shocks are about to pass the ring in the east
Problem: how to overcome available mass of refractory elements, if dust condensation rate was already 100 % at red supergiant phase?
Test the hypothesis with JWST MIRI observations
Reverse shocks: Sgr A East

10^4 years old SNR

SOFIA detection of ejecta dust (survived after reverse shock passage): 0.02 M☉

Not so efficient dust destruction?

Lau et al. (2015)
What will happen to dust in SNRs in long term?

Search for dust in 62 Galactic SNRs
Detection of dust from 40% of SNRs

Majority of SNRs: swept up interstellar or circumstellar dust
5 SNRs: ejecta dust in pulsar wind nebula

G11.2-0.3
(1200-1400 years old)

Chawner et al (2019)
Context

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ALMA detection of molecules

$^{12}\text{CO} \ J=2-1$

$^{12}\text{CO} \ J=1-0$

$^{28}\text{SiO}$

$^{29}\text{SiO}$

FWHM~ 2300 km s$^{-1}$

Cold (20-200 K) ‘molecular gas’ in the ejecta after 25 years

(Kamenetzky et al. 2013)

ALMA cycle-0 program

In 2012 (Day=9173-9300)
Context

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Isotopologues

At millimeter and submillimeter wavelengths, isotope shifts are larger than the SN expansion velocity (~2000 km s\(^{-1}\))
Constraints on SN nucleosynthesis: isotope ratio

\[
\frac{^{28}\text{SiO}}{^{29}\text{SiO}} > 13
\]

Matsuura et al. (2017)
SiO isotopologue ratios

Matsuura et al. (2017)
SiO isotopologue ratios

- SN 1987A could be slightly offset from presolar grains sequence
- Low metallicity effects
  - Neutron-rich isotopes are poor at low metallicity

Matsuura et al. (2017)
SiO isotopologue ratios

Matsuura et al. (2017)

Solar metallicity models

Models require to increase $^{29}\text{Si}$ and $^{30}\text{Si}$ slightly

SN 1987A (~30% of solar $Z_\odot$ ; Woosley)
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Further detections of molecules

Matsuura et al. (2017) First detections of SO and HCO$^+$ from supernovae
How to form HCO⁺?

Explosive nucleosynthesis without mixing

No mixing = no HCO⁺
How does mixing happen?

Historical picture

SN Explosion causes shocks inside the star core

Rayleigh-Taylor instabilities

Map of elements immediately after the explosion

Fryxell et al. (1991)

Wongwathanarat et al. (2015)
Explosive nucleosynthesis with mixing between zones

HCO$^+$ formation

Elemental mass fraction

Interior Mass (M$_\odot$)

Explosive nucleosynthesis for SN 1987A (Woosley)
Clumpy structure found in ejecta

Fossils of clumps formed by shocks at the time of SN explosion

Abellan et al. (2017)
Future

• The number of sample will increase with future space missions – JWST, SPICA & Origin
Summary

• Herschel and ALMA has provided excellent opportunity to understand physical and chemistry of supernovae

• Dust
  – SNe can form significant mass of dust
  – Unresolved problems
    • Dust destruction
    • Dust formation in SNe is common place?
    • Can SN dust be important source of ISM dust?

• Molecules
  – Isotope ratios constraints to explosive nucleosynthesis
  – Clumps traces dynamical motion of gas at the time of the explosion