超新星起源プレソーラーSiC粒子の形成

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1-1. Presolar grains

- discovered in primitive meteorites
- showing peculiar isotopic compositions (different from the solar system’s materials)
- thought to have formed in stars before the Sun was formed

ที่คุณoffering key information on(119,558),(854,937)

- nuclear processes in the parent stars
- physical conditions in which they formed

- abundance (volume fraction): \( \sim 100-500 \text{ ppm} \) \( \sim 0.1-0.5 \% \)

- mineral composition
  graphite, SiC, TiC, Si₃N₄, Al₂O₃, MgAl₂O₄, Mg₂SiO₄, MgSiO₃ ...
1-2. Presolar Type X SiC grains

○ Presolar SiC grains (~10 ppm)

○ Type X SiC grains (~0.1 ppm, size: 0.1-20 µm)
  - 12C/28Si rich, with excesses in 44Ca (44Ti), 49Ti (49V)
    ➔ originated from core-collapse supernovae
1-3. Long-lasting questions

- **Fact**
  A fraction of presolar SiC grains is highly likely SN-origin

- **Question**
  How do these SiC grains form in the ejecta of core-collapse supernovae?
  Any theoretical studies have not yet realized the formation of SiC grains in supernovae
2-1. Elemental abundances in the SN ejecta

Yoshida 2007; 4 $M_{\odot}$ He-core model ($M_{\text{star}} \sim 18$ $M_{\odot}$)

- 44Ti
- 28Si rich
- 12C rich

- O-rich ($O/C > 1$)
- 29, 30Si solar
- 14N rich

Needed unrealistic mixing of the ejecta
2-2. Possible formation site of SiC grains in SNe

○ Moderately energetic SNe

\[ \text{E}_{\text{kin}} = (3-5) \times 10^{51} \text{ erg} \]
(normal SNe: \( \text{E}_{\text{kin}} \approx 1 \times 10^{51} \text{ erg} \))

explosive burning happens at the boundary between O-rich region and He-rich region

\[ ^{3}\text{(4He)} \rightarrow ^{12}\text{C} \]
\[ ^{12}\text{C} + \text{n(4He)} \rightarrow \alpha \text{-elements} \]

Possible formation site of SiC grains in SNe

Pignatari+2013

Umeda & Nomoto 2002
2-3. No formation of SiC in the calculations

☐ Condensation temperature
- C grains: $T_{\text{con}} = 1700$-2200 K
- SiC grains: $T_{\text{con}} = 1300$-1800 K

➔ In C/Si-rich gas, C grains first condense to use up the gas-phase C atoms

☐ Formation path of grains

\[
C_n + C \rightarrow C_{n+1}
\]

\[
(SiC)_n + Si + C \rightarrow (SiC)_{n+1}
\]

More efficient destruction of C grains (clusters)?

UV radiation, high-energy e, chemical reaction, ...

➔ this may not do a good job
2-4. Formation of SiC grains via molecules

○ Previous works

$$C_n + C \rightarrow C_{n+1}$$

$$(SiC)_n + Si + C \rightarrow (SiC)_{n+1}$$

→ accretion of Si/C atoms

○ This work

- accretion of SiC molecules

$$(SiC)_n + SiC \rightarrow (SiC)_{n+1}$$

- coagulation

$$(SiC)_m + (SiC)_n \rightarrow (SiC)_{m+n}$$

rate coefficients of radiative association of molecules $k_{ij}$

$$\frac{dC_k^{mol}}{dt} = k_{ij}(T)c_i c_j$$

Andreazza+2009

Rate coefficients; $k_{ij}$

Temperature; $T$

300 K to $10^4$ K
3-1. Formation of SiC molecules

\[ c(t) = c_{100} \left( \frac{t}{100 \text{ day}} \right)^{-3} \text{ cm}^{-3} \]

\[ T(t) = 10^4 \left( \frac{t}{100 \text{ day}} \right)^{-1} \text{ K} \]

<table>
<thead>
<tr>
<th>Element</th>
<th># abundance</th>
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</thead>
<tbody>
<tr>
<td>He</td>
<td>0.3</td>
</tr>
<tr>
<td>C</td>
<td>0.3</td>
</tr>
<tr>
<td>O</td>
<td>0.001</td>
</tr>
<tr>
<td>Ne</td>
<td>0.001</td>
</tr>
<tr>
<td>Mg</td>
<td>0.002</td>
</tr>
<tr>
<td>Si</td>
<td>0.2</td>
</tr>
<tr>
<td>S</td>
<td>0.19</td>
</tr>
<tr>
<td>Ar</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Pignatari+2013
3-2. Equation of dust formation

**Master equations of dust growth**

\[
\frac{dc_n}{dt} = \frac{1}{2} \sum_{i=1}^{n-1} K_{i,n-i}(T) c_i (c_{n-i} - c_n e^{\gamma_{i,n-1}}) \\
- c_n \sum_{l=1}^{n_{\text{max}}} K_{n,l}(T) (c_l - c_{n+l} e^{\gamma_{n,n}})
\]

\[
K_{i,j}(T) = \alpha_s \pi (a_i + a_j)^2 \left( \frac{8kT}{\pi m_{i,j}} \right)^{\frac{1}{2}}
\]

\[
\gamma_{i,n-i}(T) = \frac{4\pi a_i^2 \sigma}{kT} \left[ (n-1)^{\frac{2}{3}} - (n-i-1)^{\frac{2}{3}} - (i-1)^{\frac{2}{3}} \right] - \ln S_i
\]

taking account of nucleation and grain growth through gas accretion and coagulation between grains simultaneously!
Yes, the formation of SiC grains is possible!
3-4. Formation process of SiC grains

- Formation of SiC grains is possible!!
  - Condensation temperature is higher for higher gas density
  - Dust growth proceeds on a short timescale through rapid accretion of molecules
  - Coagulation makes the average radius by about a factor of 2
3-5. Size distribution of SiC grains formed

- **Timescale of collision**

\[ \tau_{\text{coll}}^{-1} = \pi S_{i,j} \langle v \rangle c_i \]

- **Timescale of gas accretion onto 0.001\(\mu\)m-sized grains**

\[ \tau_{\text{acc}} \simeq 0.028 \text{ day} \left( \frac{a_{ij}}{0.001 \, \mu\text{m}} \right)^{-2} \left( \frac{T}{1500 \, \text{K}} \right)^{-\frac{1}{2}} \left( \frac{m_{ij}}{40m_\text{H}} \right)^{\frac{1}{2}} \left( \frac{c_{\text{tot}}}{3 \times 10^7 \, \text{cm}^{-3}} \right)^{-1} \left( \frac{A_i}{5 \times 10^{-3}} \right)^{-1} \]

- **Timescale of coagulation between 0.001\(\mu\)m-sized grains**

\[ \tau_{\text{coag}} \simeq \tau_{\text{acc}} \left( \frac{1}{4\sqrt{2}} \right) (10^3)^{\frac{1}{2}} 10^3 \simeq 155 \text{ day} \]

- **Timescale of gas expansion**

\[ \tau_{\text{exp}} = \left( \left| \frac{1}{c} \left| \frac{dc}{dt} \right| \right| \right)^{-1} = \frac{t}{3} \simeq 220 \text{ day} \]
3-6. Size distribution of SiC grains formed

- Radius of newly formed grains is larger for higher gas density
- In the density range considered in this study, grain radius is not large enough to reproduce ones observed in presolar SiC grains
4. Summary of this talk

We investigate the formation of SiC grains in the ejecta of supernovae, self-consistently treating

- formation of SiC molecules
- growth of SiC grains via accretion of molecules
- growth of SiC grains via grain-grain coagulation

We have realized, for the first time, the formation of SiC grains (but with small radii of < 0.1 µm...)

## calculations for more dense cases needed to achieve the formation of SiC grains as large as presolar Type-X SiC grains (a > 0.1 µm)