Mid-Infrared Imaging and Spectroscopy of Dust Structures Periodically Formed Around WR140 based on Observations with Subaru/COMICS

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Dust formation by massive stars

SCIENTIFIC BACKGROUND

- Dust Formation by massive stars
  important to explore the origin of dust in the early universe
- How much amount of dust is formed in the ejecta of supernovae
- How much fraction of it can survive the circumstellar environment
- Can the dust be formed efficiently before the SN explosions and contribute
  as the budget of interstellar dust

(Dust formation by optical transients → Ohwasan’s talk)

- The amount of \(0.1M_{\text{solar}}/\text{SN}\) dust formation is needed to account for the dust
  content of high red-shift galaxies (Morgan & Edmunds 2003).
- The dust condensation in the ejecta of core-collapse SNe is theoretically
  suggested (Kozasa et al.1991; Todini & Ferrera 2001; Nozawa et al. 2003, 2010).

- Observational Evidence for the dust formation in SN ejecta
  - Type II SN2003gd; \(0.02M_{\text{solar}}\) (Sugerman et al. 2006) → \(4 \times 10^{-5}M_{\text{solar}}\) (Meikle et al. 2007)
  - Type II SN1987A ; \(7.5 \times 10^{-4}M_{\text{solar}}\) (Ercolano et al.2007)
  - Cas A ; \(0.003M_{\text{solar}}\) (Hines et al. 2004) or \(0.02-0.054M_{\text{solar}}\) (Rho et al. 2004)
    → much smaller amount of dust formation is suggested observationally
Introduction: Dust formation by SN2006jc

An Example of the Latest Results on the Dust Formation by Core-collapse SNe

AKARI/Infrared Camera (IRC) observations of SN2006jc in UGC4904

(a) Infrared (measured by AKARI satellite in Apr. 2007)

800K component; Newly formed dust in the ejecta of SN2006jc

\[ T_{\text{hot.car.}} = 800 \pm 10 \text{ (K)} \]
\[ M_{\text{hot.car.}} = 6.9 \pm 0.5 \times 10^{-5} M_{\odot} \]

300K component; pre-existing circumstellar dust

\[ T_{\text{warm.car.}} = 320 \pm 10 \text{ (K)} \]
\[ M_{\text{warm.car.}} = 2.7^{+0.7}_{-0.5} \times 10^{-3} M_{\odot} \]

The amount of newly formed dust is more than 3 orders of magnitudes smaller than the amount needed for a SN to contribute efficiently to the early-Universe dust budget.

Dust condensation in the mass loss wind associated with the prior events to the SN explosion could make a significant contribution to the dust formation by a massive stars.

NIR imaging of SN2008ax with AKARI/IRC on ~100 days

SN2008ax in NGC 4490 (d = 9.6Mpc; Pastorello et al. 2008)
Type IIb (Chornock et al. 2008) discovered by Mostardi et al. (2008) on 2008 Mar 3.45
-- the optical light curve similar to that of the He-rich Type IIb SNe 1996cb and 1993J
-- an OB/WR progenitor star (M_{ms} = 10-14M_{\odot}) in an interacting binary system

\( \rightarrow \) properties of the circumstellar dust shell
\( \rightarrow \) Possible dust formation in the SN ejecta

NIR imaging of SN2008ax with AKARI/IRC on ~100 days

\[ T_{a,\text{car.}} = 767 \pm 45 \text{K}; \quad M_{a,\text{car.}} = 1.2^{+0.4}_{-0.3} \times 10^{-5} M_{\odot} \]
\[ T_{a,\text{sil.}} = 885 \pm 60 \text{K}; \quad M_{a,\text{sil.}} = 6.8^{+2.5}_{-1.7} \times 10^{-5} M_{\odot} \]

Infrared light echo from the dust formed as a result of the WR binary activities
Dust formation by Wolf-Rayet Binaries

Dust Formation in the wind-wind collision of massive Wolf-Rayet binary systems

Wolf-Rayet stars; extremely luminous \((L > 10^5 L_\odot, T_{\text{eff}} \gg 20,000 \text{K})\)

- average mass-loss rate; \(\delta M \sim 10^{-5} M_\odot/\text{yr}\)
- terminal velocity; \(v_\infty \sim 1,000 - 4,500 \text{km/s}\)

Periodic dust formation in binary WC+O system with eccentric orbits

dust production rate; \(\delta M \sim 10^{-6} M_\odot/\text{yr}\) (van der Hucht et al. 1987; Williams 1995)

WR ‘dusters’ --- WR9, WR25, WR48a, WR76, WR80, WR95, WR98a, WR102e, WR106, WR121, WR125, WR137, WR140, etc (Marchenko & Moffat 2007; Wood et al. 2003)
Dust formation by WR140

WR140; long-period (\(P=7.93\text{y}\); Marchenko et al. 2003) colliding-wind WR binary (WC7 class Wolf-Rayet star + O4 type star) located at \(d\sim1.85\text{kpc}\)

“spectroscopic events” in 1993, 2001 and 2009

Observations; Cooled Mid-infrared Camera and Spectrometer (COMICS) / Subaru N- and Q-band imaging and low-resolution spectroscopy of WR140

1\(^{st}\) epoch; Aug. 2009 & 2\(^{nd}\) epoch Nov. 2009 & 3\(^{rd}\) epoch June 2010

12.5\(\mu\text{m}\) image of WR140 taken with Michelle/Gemini-North on Nov. – Dec. in 2003 (Marchenko & Moffat 2007).

11.7\(\mu\text{m}\) image of WR140 taken with COMICS/Subaru on 1\(^{st}\) Aug. in 2009 (Sakon et al. 2009).

→The expansion velocity of the dust shell; \(2.7\pm0.3 \times 10^3 \text{ km s}^{-1}\), consistent with Williams et al. 2009
Dust Structures around WR140
Revealed by Subaru/COMICS Observations

Subaru/COMICS N11.7 band (11.7\,\mu\text{m})

August in 2009
orbital phase $\phi=1.065$
Dust Structures around WR140
Revealed by Subaru/COMICS Observations

Subaru/COMICS  N11.7 band (11.7µm)

November in 2009
orbital phase $\phi=1.097$
Dust Structures around WR140
Revealed by Subaru/COMICS Observations

Subaru/COMICS N11.7 band (11.7µm)

June in 2010
orbital phase φ=1.170
Properties of Dust formed during the 2001 periastron at $\phi=1.097$

The results of the photometry of dust shell formed during the 2001 periastron at the orbital phase of $\phi=1.107$ (9 Nov 2009)

N11.7(11.7\(\mu\)m) 0.21\(\pm\)0.02 mJy  
Q17.7(17.7\(\mu\)m) 0.15\(\pm\)0.04 mJy

\[ f_\nu^X (\lambda) = M_X \left( \frac{4}{3} \pi \rho_X a_X^3 \right)^{-1} \pi B_\nu(\lambda, T_X) Q_{X}^{abs}(\lambda) \left( \frac{a_X}{R} \right)^2 \]

\(X; \) amorphous carbon (\(X=\text{acar}\))  
\(Q_{\text{acar}}^{abs}(\lambda); \) absorption cross section  
(Colangeli et al. 1995)

\(\rho_{\text{acar}} = 1.87 \; (\text{g cm}^{-3})\)  
\(\sigma_{\text{acar}} = 0.01 \mu\text{m}\)  
\(R=1.85 \; \text{kpc}\)

temperature of amorphous carbon  
\(T_{\text{acar}} = 350\pm60 \; \text{K}\)

total mass of amorphous carbon in the dust shell  
\(M_{\text{acar}} = 0.99^{+0.35}_{-0.25} \times 10^{-8} \; \text{M}_\odot\)
The results of the photometry of dust shell formed during the 2001 periastron at the orbital phase of $\phi=1.170$ (June 2009)

- $N_{11.7}(11.7 \mu m) = 0.160 \pm 0.02$ mJy
- $Q_{17.7}(17.7 \mu m) = 0.125 \pm 0.04$ mJy

Temperature of amorphous carbon

$T_{acar} = 330 \pm 60$ K

Total mass of amorphous carbon

$M_{acar} = 0.95^{+0.35}_{-0.35} \times 10^{-8} M_\odot$
Properties of Dust formed during the 2001 periastron

The temperature of amorphous carbon at $\phi=1.097$ (9 Nov 2009); $T_{acar} = 350\pm60$ K

$\phi=1.170$ (4 Jun 2010); $T_{acar} = 330\pm60$ K

• Equations on the radiative equilibrium (Williams et al. 2009)

$$4\pi a^2 \bar{Q}_a(a, T_g) T_g^4 = \pi a^2 \bar{Q}_a(a, T_O) T_O^4 \left(\frac{R_O}{r}\right)^2 + \pi a^2 \bar{Q}_a(a, T_{WR}) T_{WR}^4 \left(\frac{R_{WR}}{r}\right)^2$$

$\bar{Q}_a(a, T)$; the Planck mean absorption cross-section

$a$; the radius of a dust grain

$T_g$; the temperature of a dust grain

$r$; the distance between the dust and either of the two stars (O-type star or WR star)

$R_O$, $R_{WR}$; effective radii of the O-type star and the WR star

$T_O$, $T_{WR}$; effective temperature of the O-type star and the WR star

• $\bar{Q}_a(a, T_g) \propto T_g^{1.2}$ holds for the amorphous carbon grains in the relevant temperature range

→ The radiative equilibrium grain temperature ($T_g$) is expected to decrease with distance from the stars as $T_g \propto r^{-2/5.2}$.

$T_g = 980$K at $\phi=0.039$ (Williams et al. 2009)

The obtained dust temperature of $T_g=350\pm60$K at $\phi=1.107$ is generally in good agreement with the expected relation of $T_g \propto r^{-2/5.2}$. 
Properties of Dust formed during the 2001 periastron

total mass of amorphous carbon in the dust shell at $\phi=1.097$; $M_{\text{acar}} = 0.99^{+0.35}_{-0.35} \times 10^{-8} M_\odot$
$\phi=1.170$; $M_{\text{acar}} = 0.90^{+0.4}_{-0.4} \times 10^{-8} M_\odot$

(Williams et al. 2009; assuming $T_g \propto r^{0.38}$)

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<tr>
<th>Orbital Phase</th>
<th>$M_{\text{acar}}$ ($M_\odot$)</th>
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<tbody>
<tr>
<td>0.01</td>
<td>$2 \times 10^{-8}$</td>
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<tr>
<td>0.02</td>
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<tr>
<td>0.12</td>
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<td>0.14</td>
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<td>0.56</td>
<td>$&lt; 2 \times 10^{-8}$</td>
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(this study)

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<tr>
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Interpretations by Williams et al. (2009)

$0<\phi<0.03$; dust formation begins and new dust condenses

$0.03<\phi<0.12$; growth of recently formed grains at their equilibrium temperature

cf. typical size of dust grains in WR140 grow to 0.069$\mu$m (Marchenko et al. 2003)

$0.14<\phi$; the rate of destruction by thermal sputtering overtakes that of growth by implantation of carbon ions (Zubko 1998) and dust grains are destroyed

At most $1 \times 10^{-8} M_\odot$ of amorphous carbon dust survives at the orbital phase of $\phi=1.097$~1.170.
Summary

Near- to Mid-Infrared observations of SN2006jc and SN2008ax with AKARI/IRC
• The amount of newly formed dust is more than 3 orders of magnitudes smaller than the amount needed for a SN to contribute efficiently to the early-Universe dust budget.
• Dust condensation in the mass loss wind associated with the prior events to the SN explosion could make a significant contribution to the dust formation by a massive stars.

MIR observations of WR140 at the orbital phase of $\phi=1.097$ and 1.170 with Subaru/COMICS
• The expansion velocity of dust clouds is $\sim$2700km/s, consistent with Williams et al. (2009).
• Q-band imaging of dust structures at such later epoch was obtained for the first time.
  • The result of our photometry at 11.7$\mu$m and 17.7$\mu$m of dust structures formed around the WR140 during the previous periaston in 2001 is consistent with the presence of amorphous carbons of $T\sim350\pm60$K with the mass of $1\times10^{-8}M_\odot$ at the epoch of $\phi=1.097$ and $T\sim350\pm60$K with the mass of $0.9\times10^{-8}M_\odot$ at the epoch of $\phi=1.170$
→ In the case of WR140, $1\times10^{-8}M_\odot$ of amorphous carbon dust, at most, survives at the orbital phase of $\phi=1.097$ and 1.170.