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 in the ejecta of core-collapse supernovae (SNe)

  -> Important to explore the origin of dust in the early universe

  e.g., The amount of $0.1M_{solar}$/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).

- Observational Evidence for the dust formation in SN ejecta

  - Type II SN2003gd; $0.02M_{solar}$ (Sugerman et al. 2006)
    -> $4x10^{-5}M_{solar}$ (Meikle et al. 2007)
  - Type II SN1987A ; $7.5x10^{-4}M_{solar}$ (Ercolano et al.2007)
  - Cas A ; $0.003M_{solar}$ (Hines et al. 2004) or $0.02\text{-}0.054M_{solar}$ (Rho et al. 2004)

  → much smaller amount of dust formation is suggested observationally

  A gap still remains in produced dust mass in core-collapse SN ejecta between those observational results and theoretical prediction of $0.1 - 1M_{solar}$ (Nozawa et al. 2003)

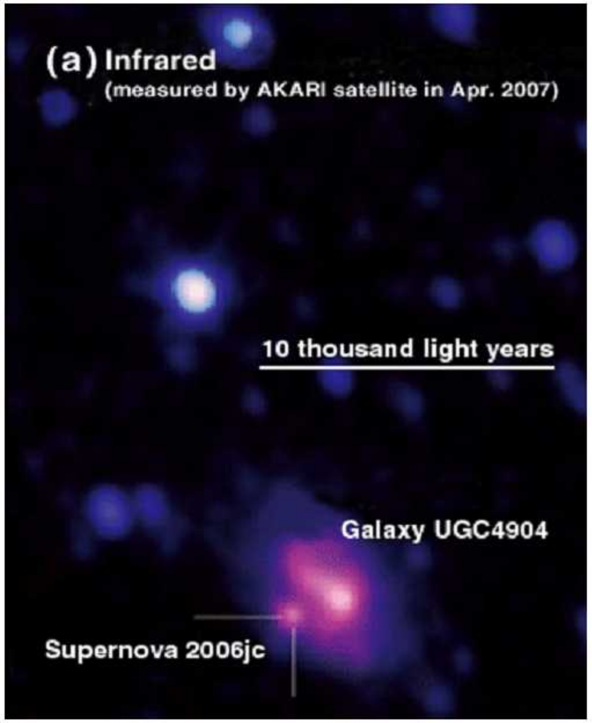
ISSUES TO BE SOLVED

-- How much amount of dust is formed in the SN ejecta and what fraction of it can survive to become the interstellar dust.

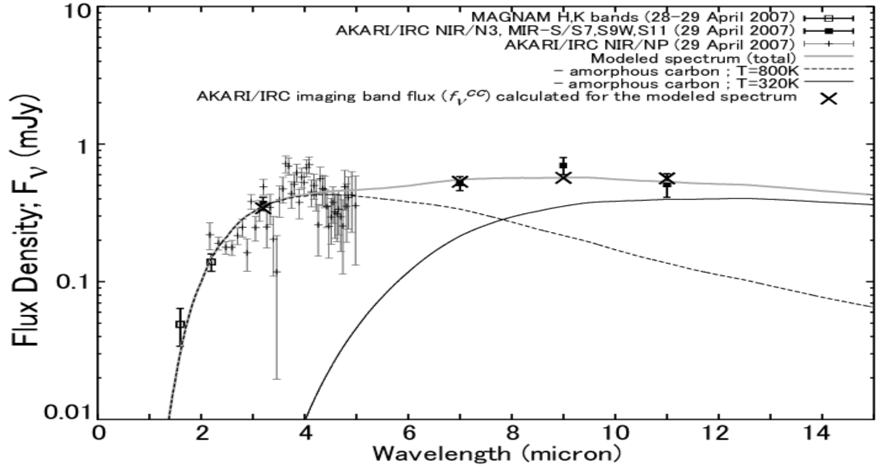
1. Dust formation by SN2006jc

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

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



[3μm(blue), 7μm(green), 11μm(red)]



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

$T_{hot.car.}$ = 800±10 (K)

$M_{hot.car.}$ = 6.9±0.5 x 10^{-5} M_{solar}

300K component; pre-existing circumstellar dust

$T_{warm.car.}$ = 320±10 (K)

$M_{warm.car.}$ = $2.7^{+0.7}_{-0.5}$ x 10^{-3} M_{solar}

→ 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.

(Sakon et al. 2009, ApJ, 692, 546)

2. Dust Emission around SN2008ax

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

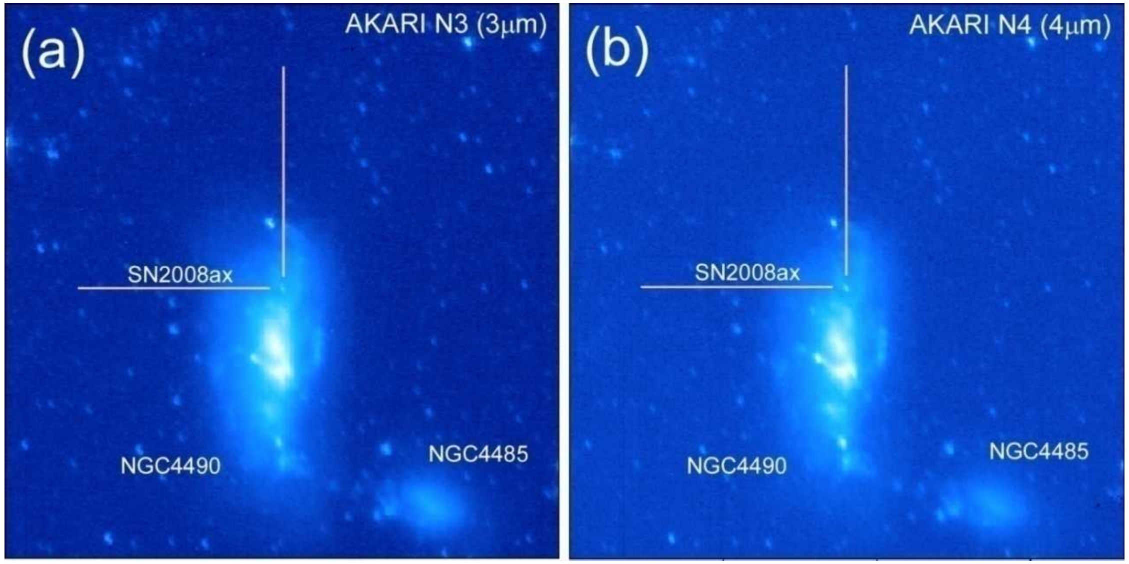
-- the optical light curve similar to that of the He-rich Type IIb SNe 1996cb and 1993J

-- an OB/WR progenitorstar (M_{ms} = 10-14$M_{\odot}$) in an interacting binary system

→ properties of the circumstellar dust shell

→ Possible dust formation in the SN ejecta

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



0.33±0.03 mJy at N3(3μm) and 0.41±0.03 mJy at N4(4μm) bands

→ $T_{a.car.}$=767±45K; $M_{a.car.}=1.2^{+0.4}_{-0.3}\ 10^{-5}\ M_{\odot}$

→ $T_{a.sil.}$=885±60K; $M_{a.sil.}=6.8^{+2.5}_{-1.7}\ 10^{-5}\ M_{\odot}$

Infrared light echo from the dust formed as a result of the WR binary activities

3. Dust formation by Wolf-Rayet Binaries

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

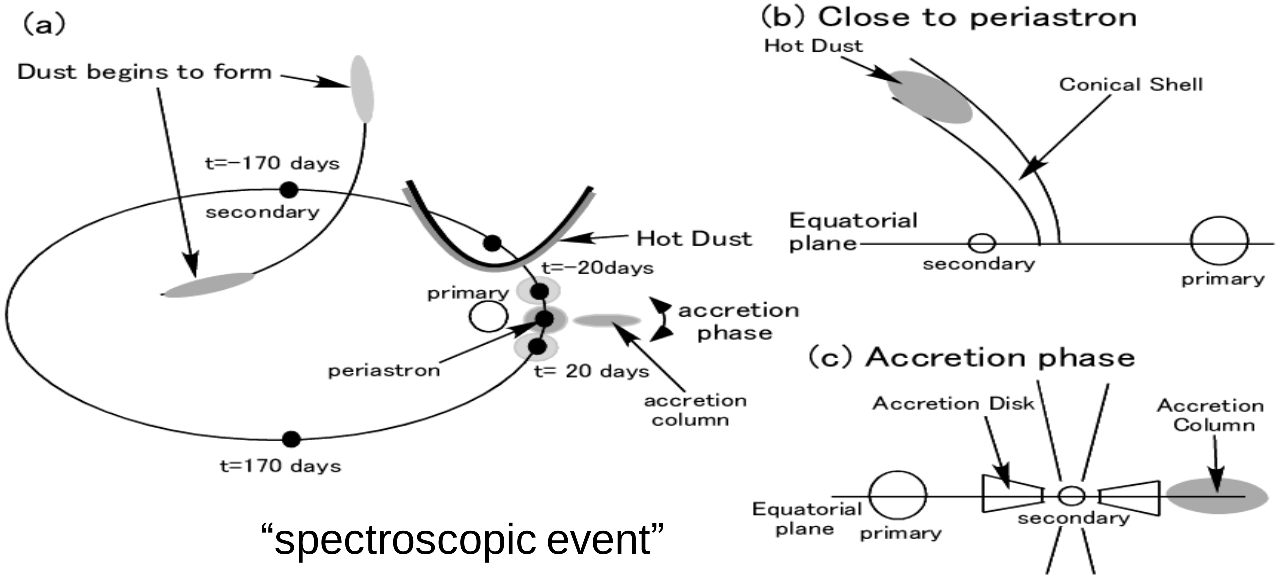
Wolf-Rayet stars; extremely luminous ($L > 10^5 L_\odot$, $T_{eff} \gg 20{,}000K$)

average mass-loss rate ; $\delta M \sim 10^{-5} M_\odot/yr$

terminal velocity ; $v_\infty \sim 1{,}000 - 4{,}500 km/s$

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

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



"spectroscopic event"

(a) Schematic view of dust formation in the colliding winds.
(b) Formation of hot dust in the colliding winds close to periastron.
(c) The accretion disk during the accretion phase and the formation of hot dust in the accretion column. (Kashi & Soker 2008a)

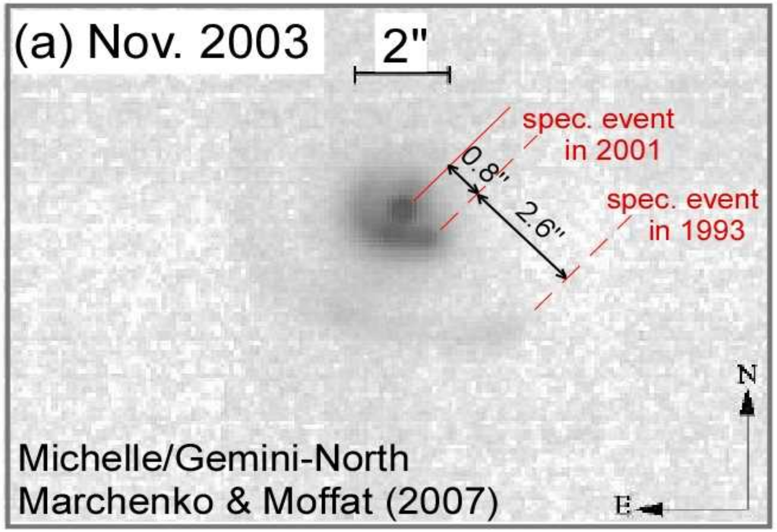
WR 'dusters' --- WR9, WR25, WR48a, WR76, WR80, WR95, WR98a, WR102e, WR106, WR121, WR125, WR137, WR140, etc (Marchenko & Moffat 2007; Wood et al. 2003)

Dust formation by WR140

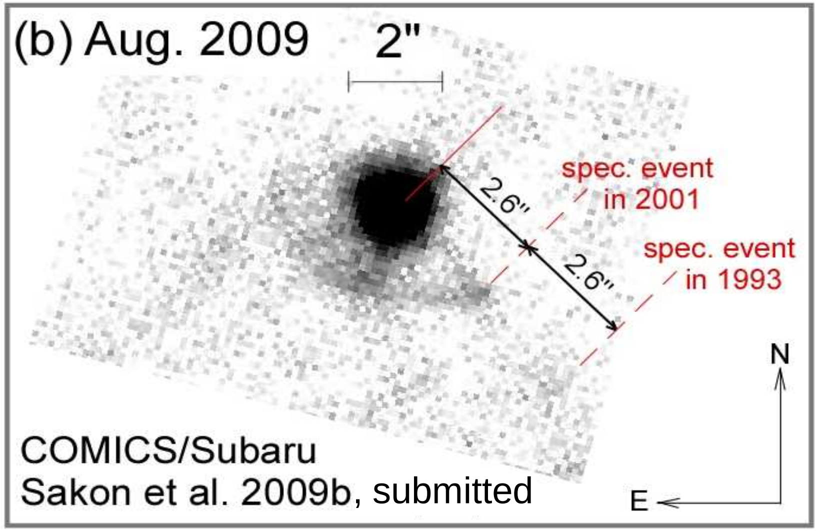
WR140; long-period (P=7.93y; Marchenko et al. 2003) colliding-wind WR binary (WC7 class Wolf-Rayet star + O4 type star) located at d~1.85kpc

"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
1st epoch; Aug. 2009 & 2nd epoch Nov. 2009 & 3rd epoch June 2010 (scheduled)



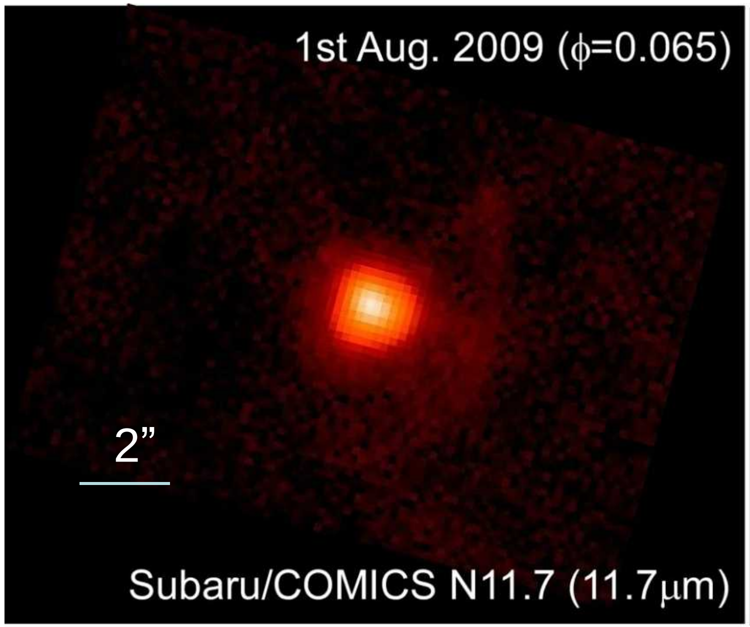
12.5μm image of WR140 taken with Michelle/Gemini-North on Nov. – Dec. in 2003 (Marchenko & Moffat 2007).

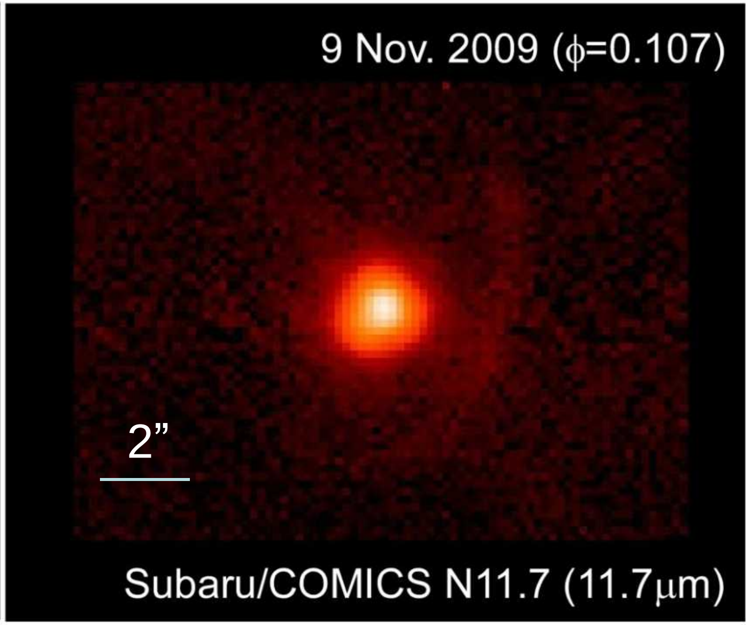


11.7μm image of WR140 taken with COMICS/Subaru on 1st Aug. in 2009 (Sakon et al. 2009b, submitted).

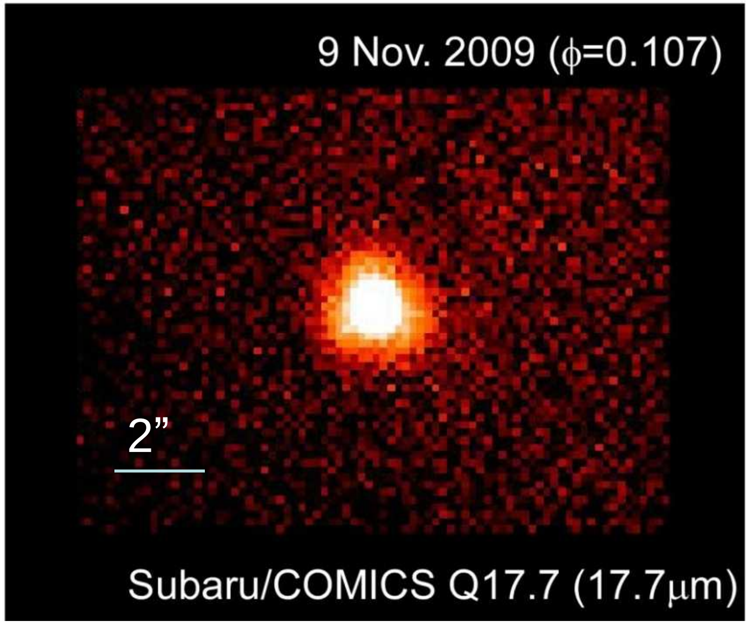
→The expansion velocity of the dust shell; $2.7 \pm 0.3 \times 10^3$ km s^{-1} , consistent with Williams et al. 2009

Dust Structures around WR140 Revealed by Subaru/COMICS Observations



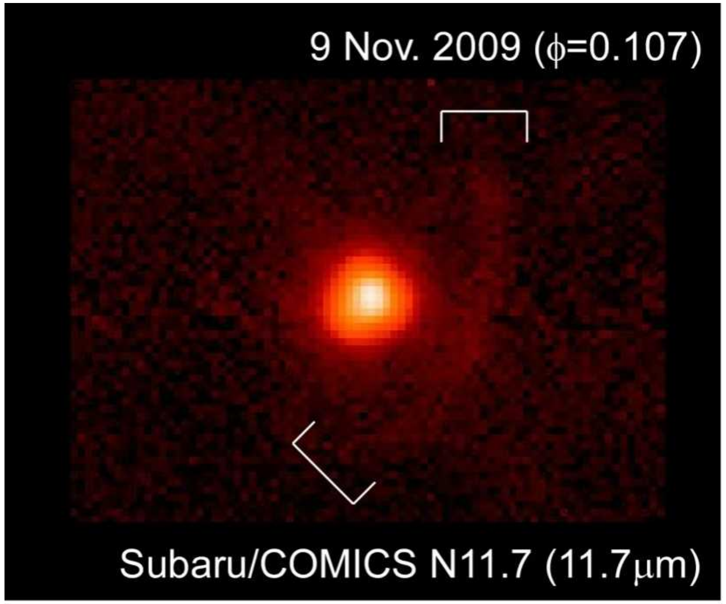


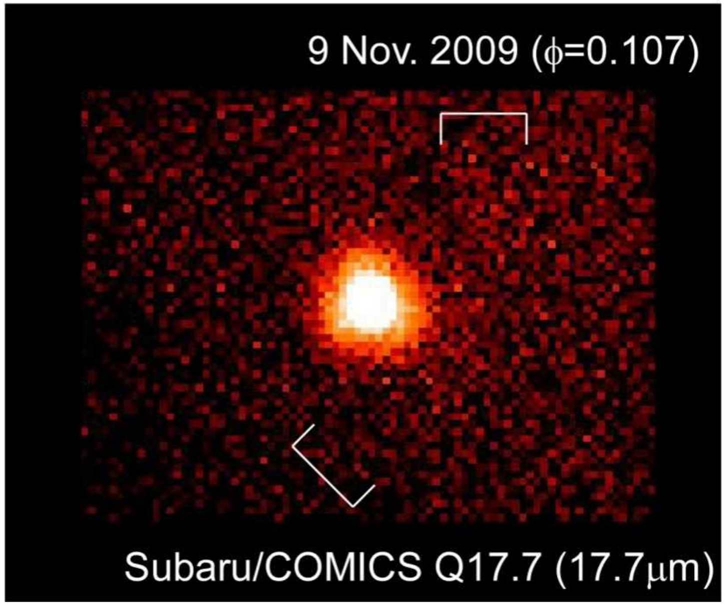
(top left, right) Subaru/COMICS N11.7 band (11.7μm) images of dust structures around WR140 taken at the orbital phases of ϕ=1.065 and 1.107, respectively.



(bottom right) Subaru/COMICS Q17.7 band (17.7μm) image of dust structures around WR140 at the orbital phase of ϕ=1.107

Properties of Dust formed during the 2001 periastron





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

N11.7(11.7μm) 0.21±0.02 mJy
Q17.7(17.7μm) 0.15±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=acar)
$Q^{abs}_{acar}(\lambda)$; absorption cross section (Colangeli et al. 1995)
ρ_{acar} =1.87 (g cm^{-3})
a_{acar}= 0.01μm
R=1.85 kpc

temperature of amorphous carbon
T_{acar} = 350±60 K
total mass of amorphous carbon in the dust shell
$M_{acar} = 0.99^{-0.35}_{+0.5} \times 10^{-8}\ M_\odot$

Properties of Dust formed during the 2001 periastron

The temperature of amorphous carbon at ϕ=1.107 (9 Nov 2009)； T_{acar} = 350±60 K

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

$$\underbrace{4\pi a^2 \bar{Q}_a(a,T_g)T_g^4}_{\text{Energy output via thermal emission}} = \underbrace{\pi a^2 \bar{Q}_a(a,T_O)T_O^4\left(\frac{R_O}{r}\right)^2}_{\text{energy input from the O5 star}} + \underbrace{\pi a^2 \bar{Q}_a(a,T_{WR})T_{WR}^4\left(\frac{R_{WR}}{r}\right)^2}_{\text{energy input from the WC7 star}}$$

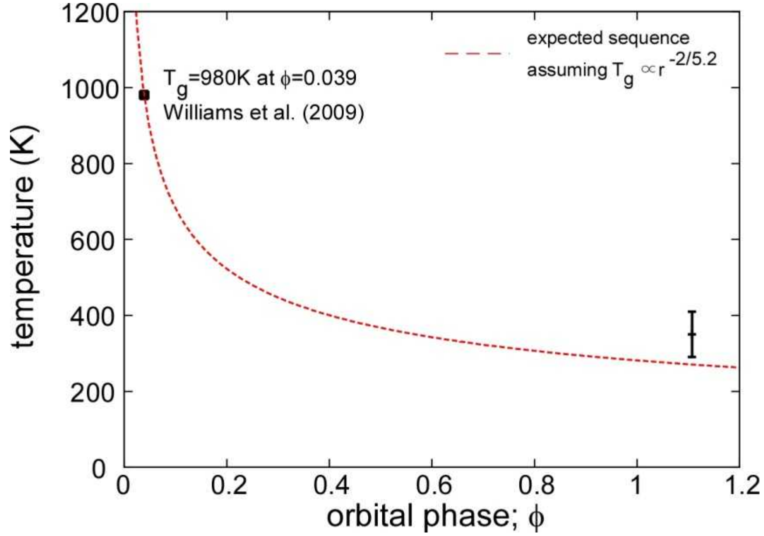
$\bar{Q}_a(a,T)$; the Planck mean absorption cross-section
a; the radius of a dust grain
T_g; the temperature of a dust grain
r; the distance between the dust and either of the two stars (O-type star or WR star)
R_O, R_{WR}; effective radii of the O-type star and the WR star
T_O, T_{WR}; effective temperature 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 (Tg) is expected to decrease with distance from the stars as $T_g \propto r^{-2/5.2}$.

T_g = 980K at ϕ=0.039 (Williams et al. 2009)

The obtained dust temperature of T_g=350±60K at ϕ=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

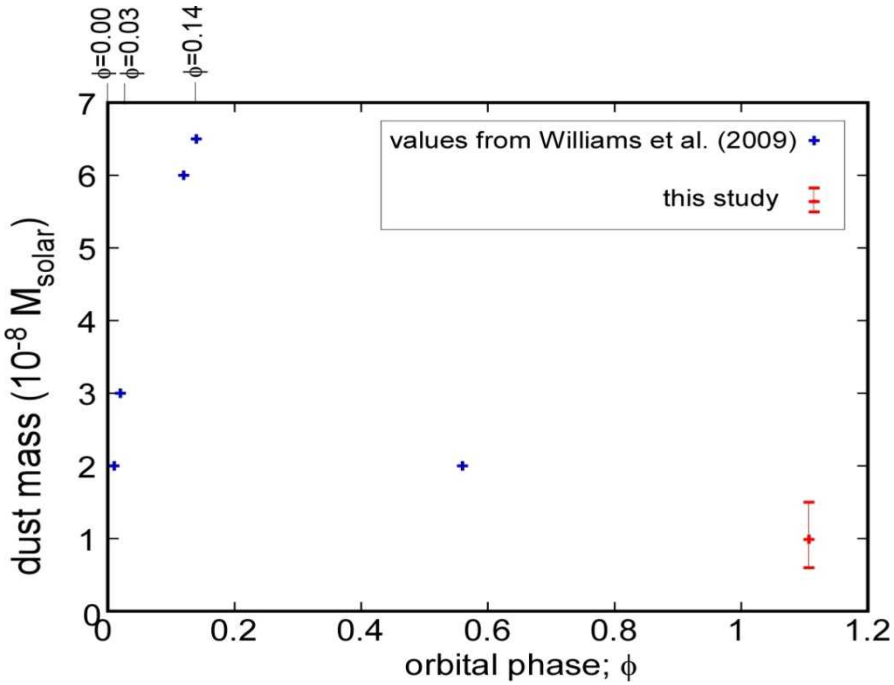
total mass of amorphous carbon in the dust shell at ϕ=1.107 ; $M_{acar} = 0.99^{-0.35}_{+0.5} \times 10^{-8}\ M_{\odot}$

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

orbital phase; ϕ	M_{acar} ($M_{\odot}$)
0.01	2×10^{-8}
0.02	3×10^{-8}
0.12	6×10^{-8}
0.14	6.5×10^{-8}
0.56	$<2\times10^{-8}$

(this study)

orbital phase; ϕ	M_{acar} ($M_{\odot}$)
1.107	$0.99^{-0.35}_{+0.5}\ \times10^{-8}$



Interpretations by Williams et al. (2009)

0<ϕ<0.03 ; dust formation begins and new dust condenses

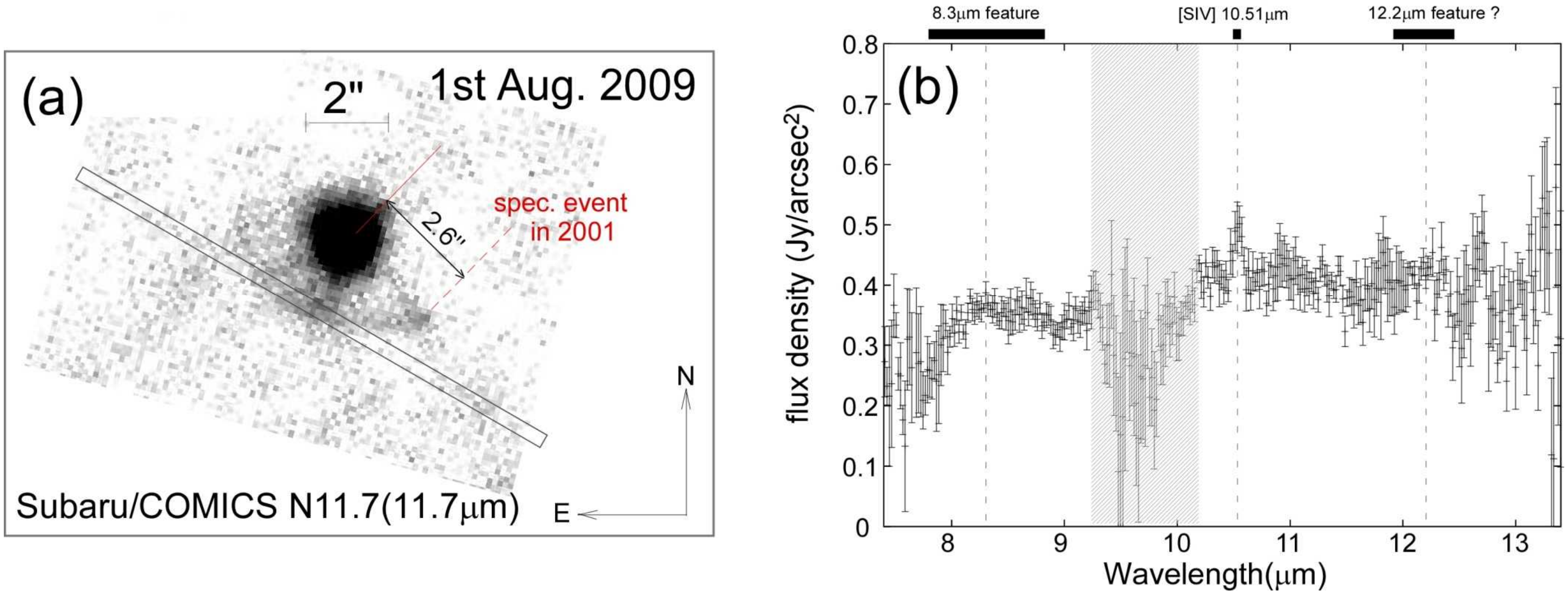
0.03<ϕ<0.12 ; growth of recently formed grains at their equilibrium temperature
cf. typical size of dust grains in WR140 grow to 0.069μm (Marchenko et al. 2003)

0.14<ϕ ; 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 $1\times10^{-8} M_{\odot}$ of amorphous carbon dust survives at the orbital phase of ϕ=1.107.

Properties of Dust formed during the 2001 periastron

A Result of the N-band Low-resolution Spectroscopic Observations of dust structures formed as a result of the previous spectroscopic events



-- broad dust band features at ~8.3μm and ~12.2μm

･･･ similar broad band features are found in NGC300-OT(Prieto et al. 2009)

･･･ Hydrogenated amorphous carbons (HACs) seen in C-rich proto PNe

Continuous mid-infrared spectroscopic observations of periodically dust-making WR binaries with Subaru/COMICS is essential to understand the chemical evolution of dust formed around the massive stars during its evolutional history

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

Mid-infrared Imaging observations of WR140 at the orbital phase of ϕ=1.107 with Subaru/COMICS

・The expansion velocity of dust clouds is ~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 11.7μm and 17.7μm of dust structures formed around the WR140 during the previous periaston in 2001 is consistent with the presence of amorphous carbons of $T \sim 350 \pm 60$K with the mass of $1 \times 10^{-8} M_{\odot}$.

$\rightarrow$ In the case of WR140, $1 \times 10^{-8} M_{\odot}$ of amorphous carbon dust, at most, survives at the orbital phase of ϕ=1.107.

Mid-infrared spectroscopy of dust structures formed in the 2001 periastron

・The N-band spectrum of dust clouds formed during the 2001 periastron event exhibits broad bands at 8.2μm and 12.2μm together with fainter features at 8.6μm etc, which may be attributed to hydrogenated amorphous carbons.

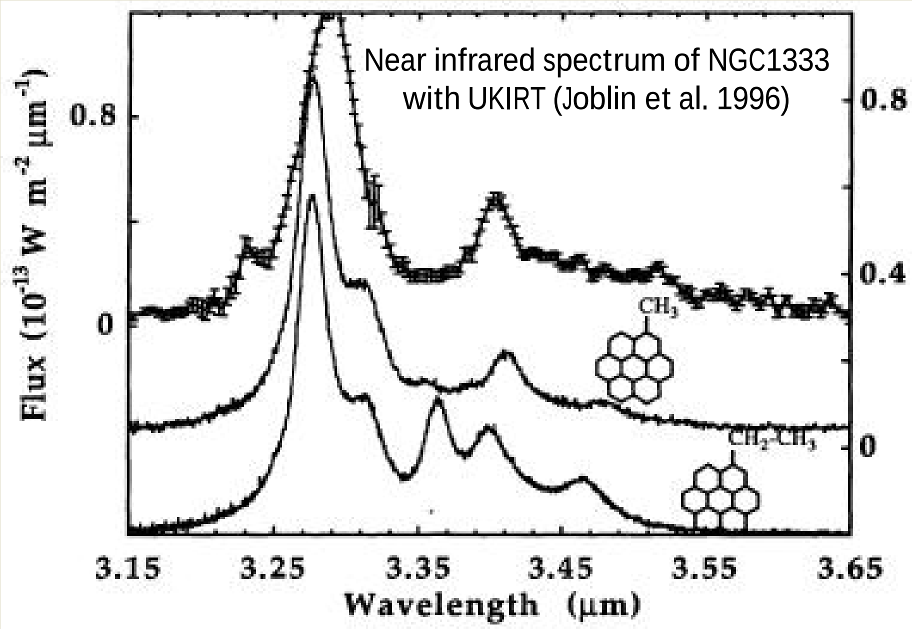
・Continuous mid-infrared spectroscopic observations of periodically dust-making WR binaries with Subaru/COMICS is essential to understand the chemical evolution of dust formed around the massive stars during its evolutional history

Near-Infrared Spectroscopy of Dust formed around Nova V1280 Sco

Itsuki Sakon, Takashi Onaka(University of Tokyo), Fumihiko Usui, Hideo Matsuhara,
Hiroshi Murakami (ISAS/JAXA), Masuo Tanaka(University of Tokyo),
Akira Aarai, Makoto Uemura, Koji Kawabata(Hiroshima University)、
Takuya Yamashita(NAOJ)、AKARI IRC team

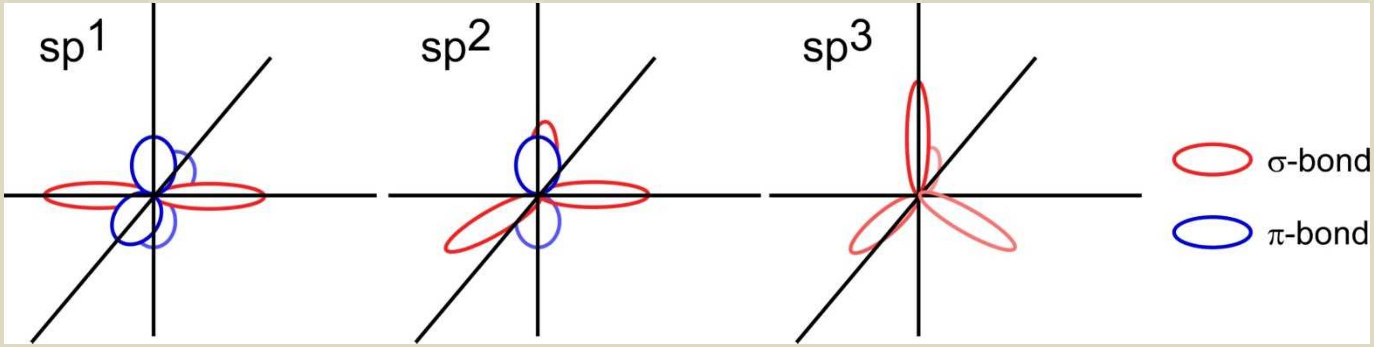
Polycyclic Aromatic hydrocarbons (PAHs) (Allamandola et al. 1989)

3.3μm feature; aromatic C-H stretch mode
3.4μm feature; aliphatic C-H stretch mode



Hydrogenated Amorphous Carbons (HACs) (Duley & Williams et al. 1990)

-contain PAH-like units weakly bounded by van der Waals forces
-consist of a mixture of aromatic hydrocarbons dominated by sp^2 bonds which can produce the polycyclic ring and aliphatic hydrocarbons including sp^1 bonds (like in acetylene) and sp^3 bonds (like in methane).

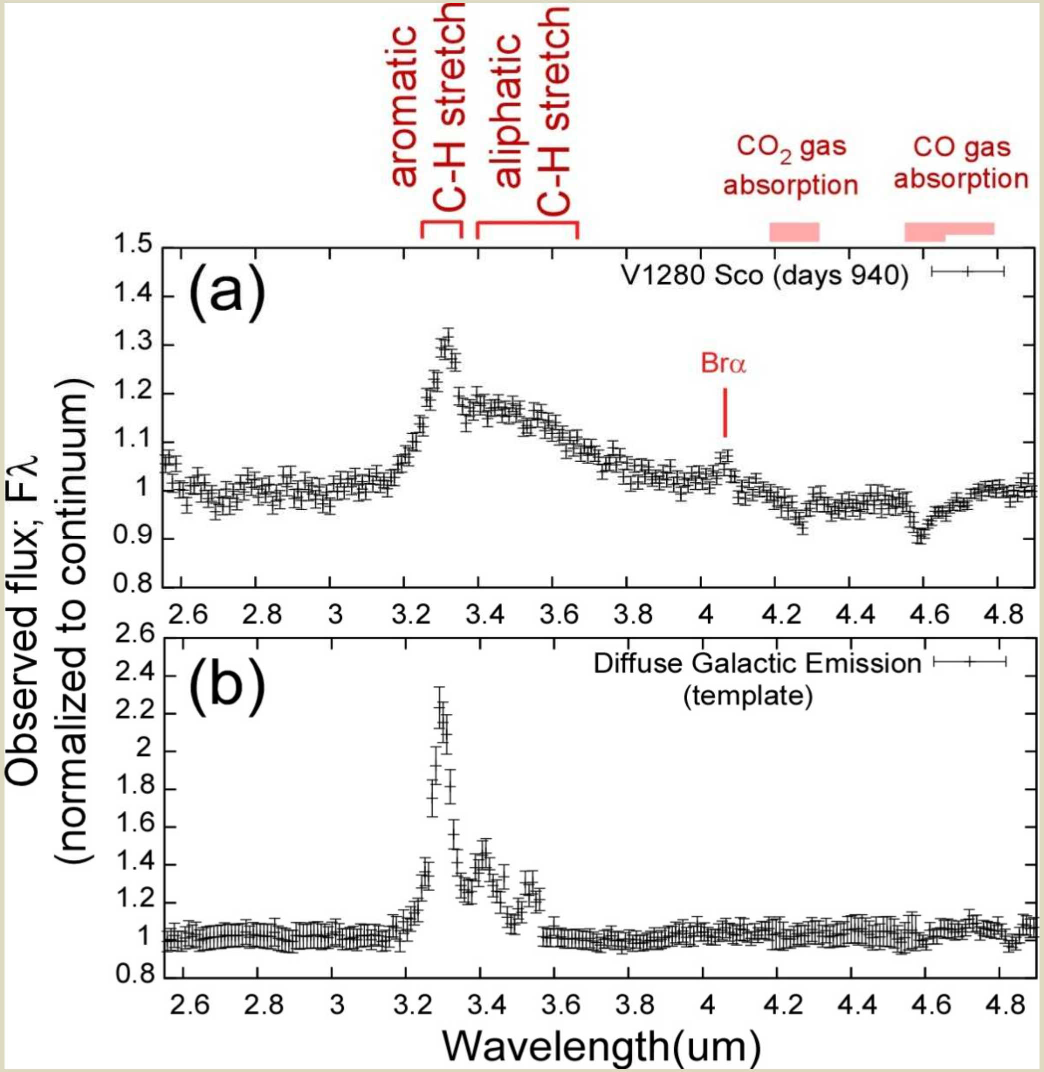


The "aromatic" to "aliphatic" ratio in HACs can be modified by the irradiance of UV fields.

Near-Infrared Spectroscopy of Dust Forming Novae

V1280 Scorpii;

-Discovered on 2007 Feb 4.86 by Y. Nakamura and Y. Sakurai (Yamaoka et al. 2007)
-Dust formation occurred after d~23days (Das et al. 2007)



(a) Near-Infrared spectrum of V1280 Sco on the epoch 940 days after the discovery normalized to the continuum obtained with Infrared Camera (IRC) onboard AKARI. PAH 3.3μm feature with a strong red-tail in 3.4-3.6μm was recognized (Sakon et al. 2010, in prep.).

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(b) Near-infrared spectrum of Galactic ISM as an example of typical spectrum of PAH features with a normal inter-band ratios among 3.3, 3.4 and 3.5μm features obtained with AKARI/IRC.