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 → Ohwasa-san's talk)

- 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, 2010).

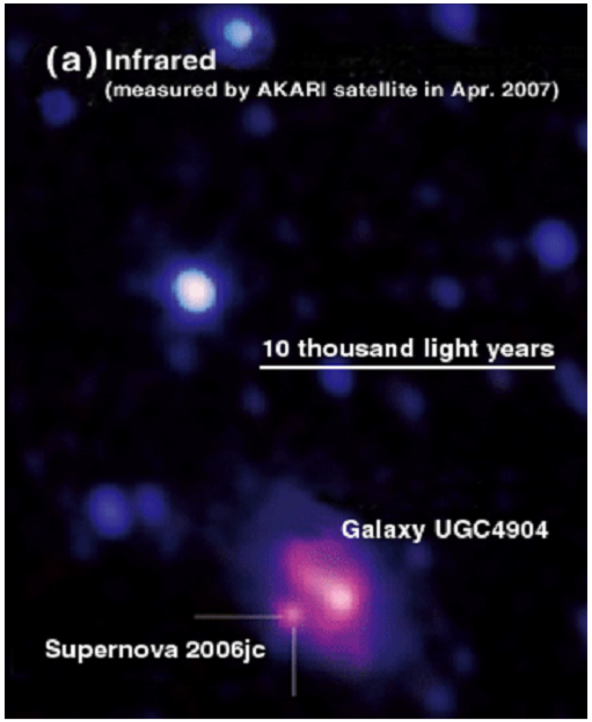
- Observational Evidence for the dust formation in SN ejecta
  - Type II SN2003gd; $0.02M_{solar}$(Sugerman et al. 2006) -> $4\times10^{-5}M_{solar}$(Meikle et al. 2007)
  - Type II SN1987A ; $7.5\times10^{-4}M_{solar}$ (Ercolano et al.2007)
  - Cas A ; $0.003M_{solar}$ (Hines et al. 2004) or 0.02-$0.054M_{solar}$ (Rho et al. 2004)

    → much smaller amount of dust formation is suggested observationally

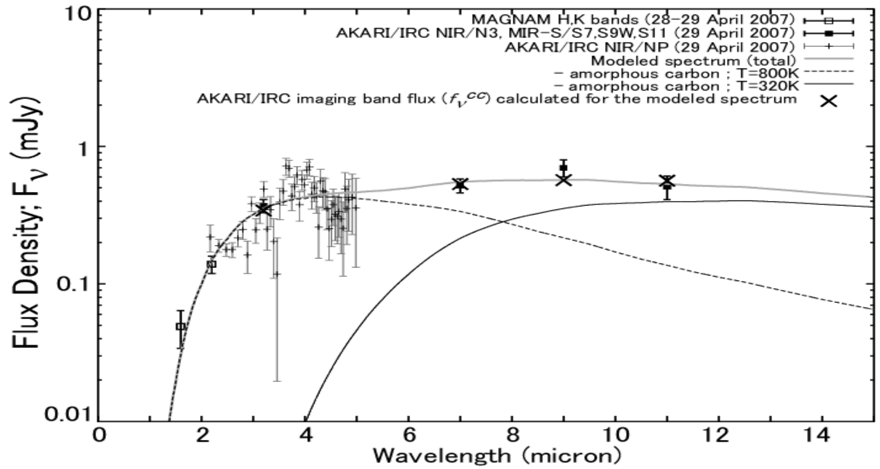
Introduction: Dust formation by SN2006jc

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

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



[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)

Introduction: 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

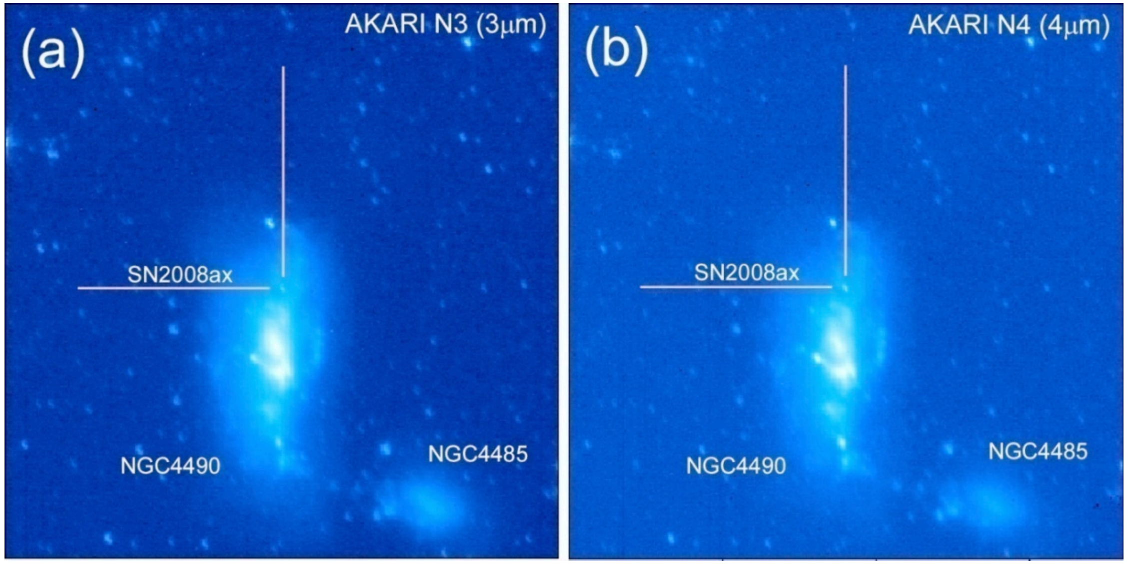
-- the optical light curve similar to that of the He-rich Type IIb SNe 1996cb and 1993J

-- 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

Dust formation by Wolf-Rayet Binaries

<u>Dust Formation in the wind-wind collision of massive Wolf-Rayet binary systems</u>

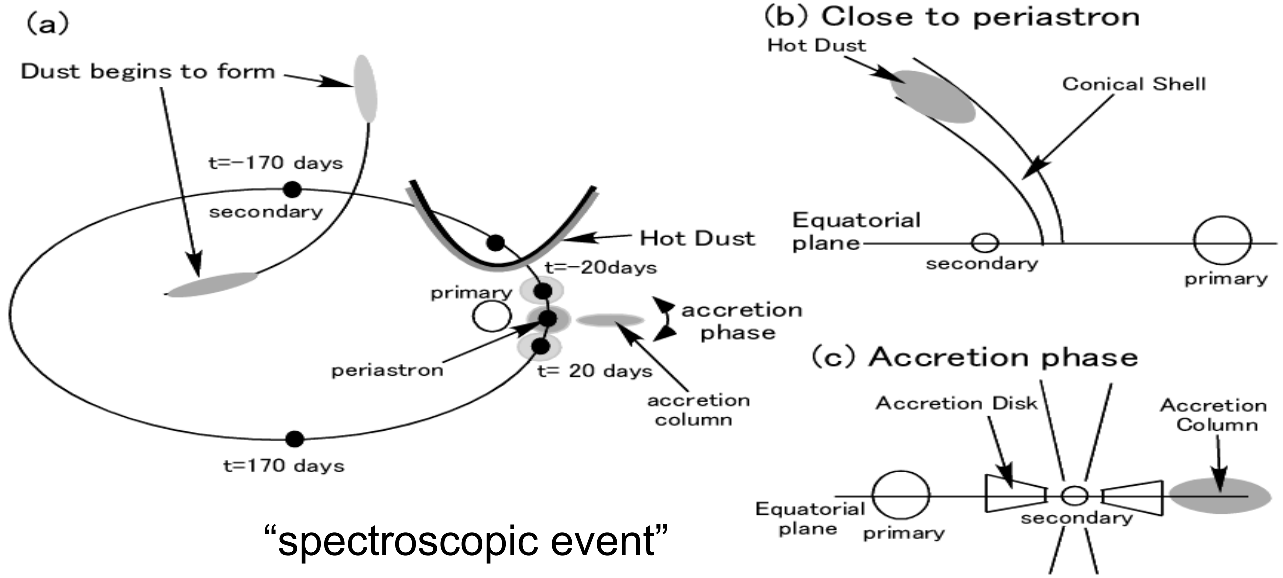
Wolf-Rayet stars; extremely luminous ($L > 10^5 L_\odot$, $T_{eff} \gg 20{,}000$K)

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)

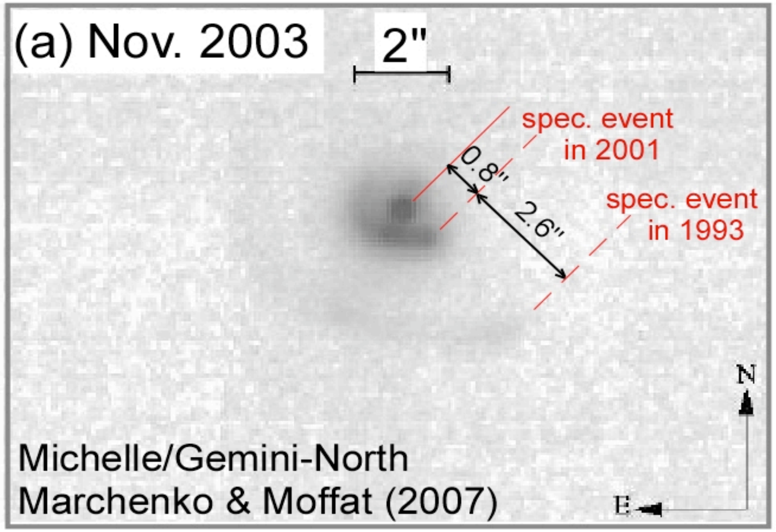
WR 'dusters' --- WR9, WR25, WR48a, WR76, WR80, WR95, WR98a, WR102e, WR106, WR121, WR125, WR137, WR140, etc (Marchenko & Moffat 2007; Wood et al. 2003)

Dust formation by WR140

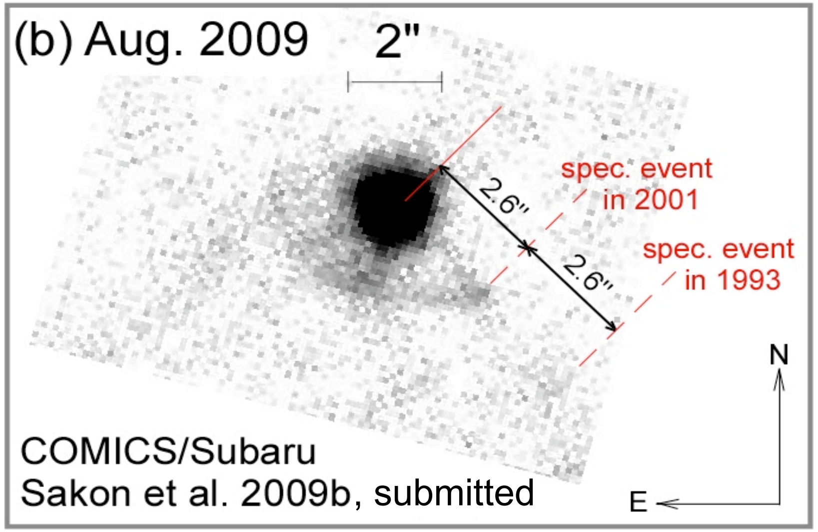
WR140; long-period (P=7.93y; Marchenko et al. 2003) colliding-wind WR binary (WC7 class Wolf-Rayet star + O4 type star) located at d~1.85kpc

"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



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

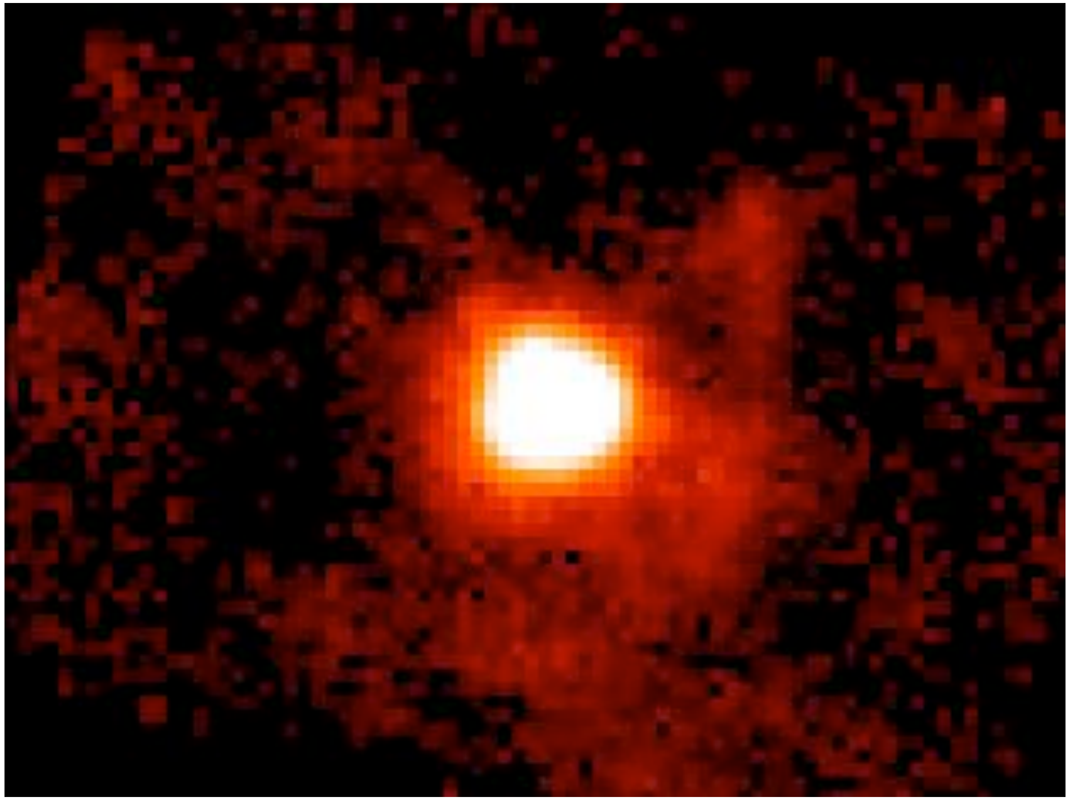


11.7μm image of WR140 taken with COMICS/Subaru on 1st Aug. in 2009 (Sakon et al. 2009).

→The expansion velocity of the dust shell; $2.7\pm0.3 \times 10^3$ km s^{-1} , consistent with Williams et al. 2009

Dust Structures around WR140 Revealed by Subaru/COMICS Observations

Subaru/COMICS N11.7 band (11.7μm)

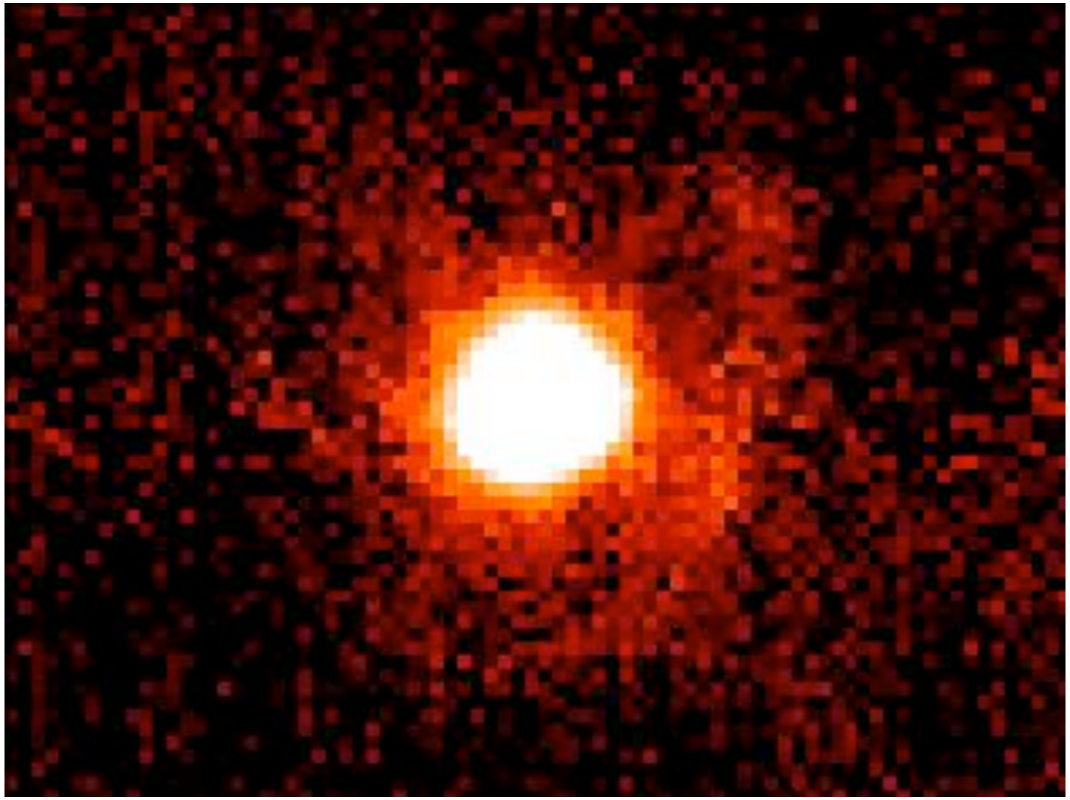


August in 2009

orbital phase ϕ=1.065

Dust Structures around WR140
Revealed by Subaru/COMICS Observations

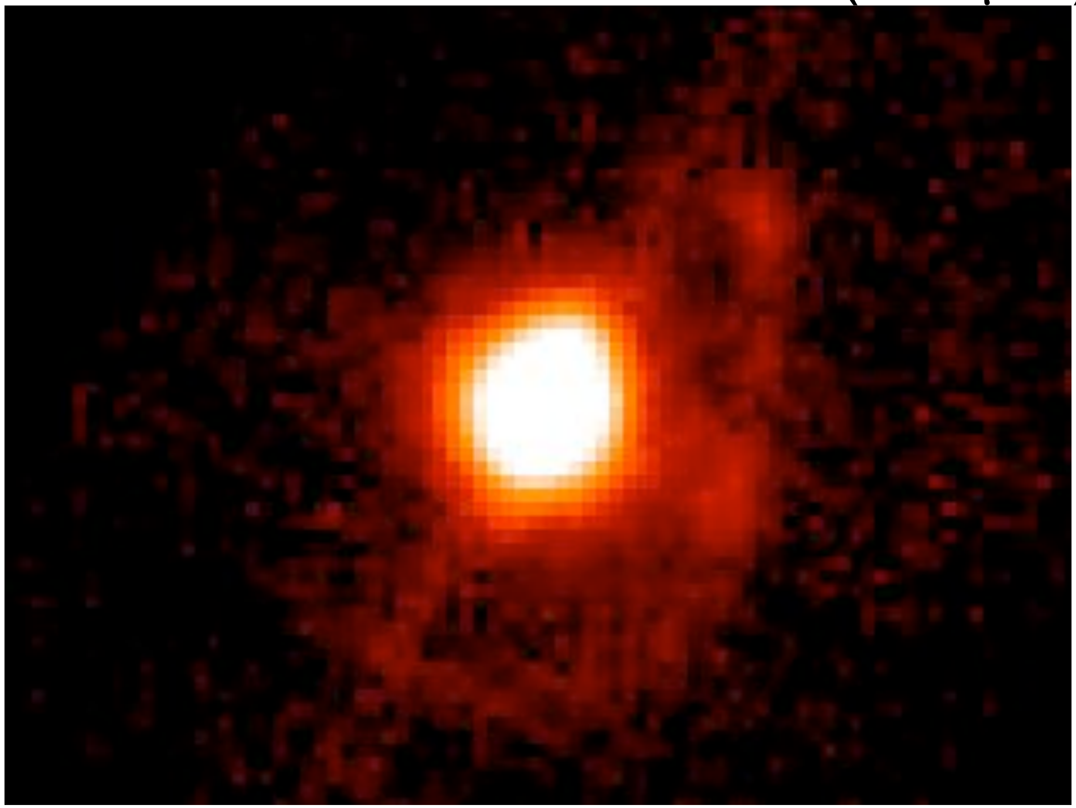
Subaru/COMICS N11.7 band (11.7μm)



November in 2009
orbital phase ϕ=1.097

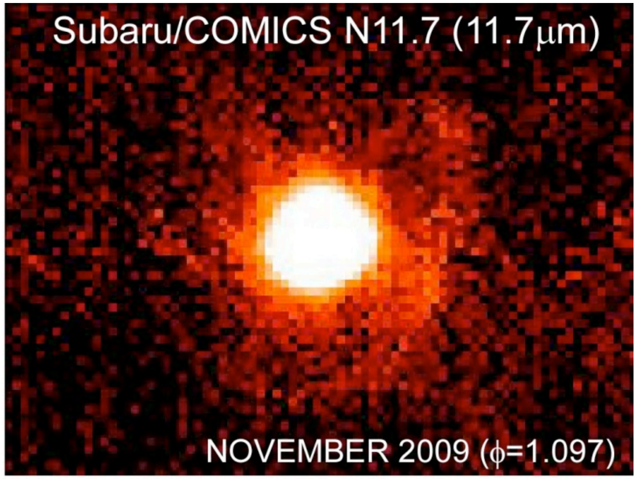
Dust Structures around WR140
Revealed by Subaru/COMICS Observations

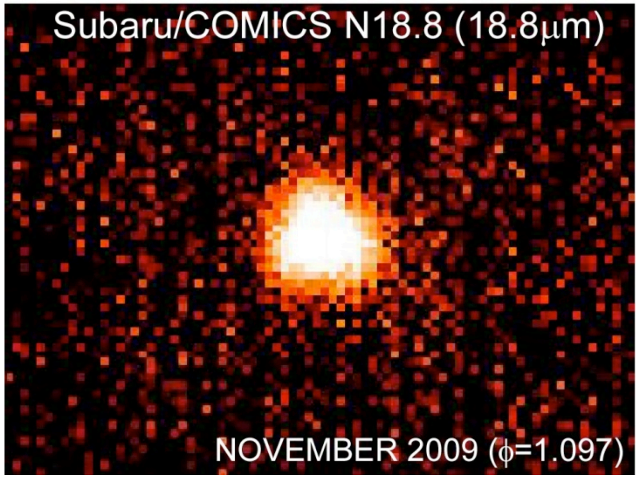
Subaru/COMICS N11.7 band (11.7μm)



June in 2010
orbital phase ϕ=1.170

Properties of Dust formed during the 2001 periastron at ϕ=1.097





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

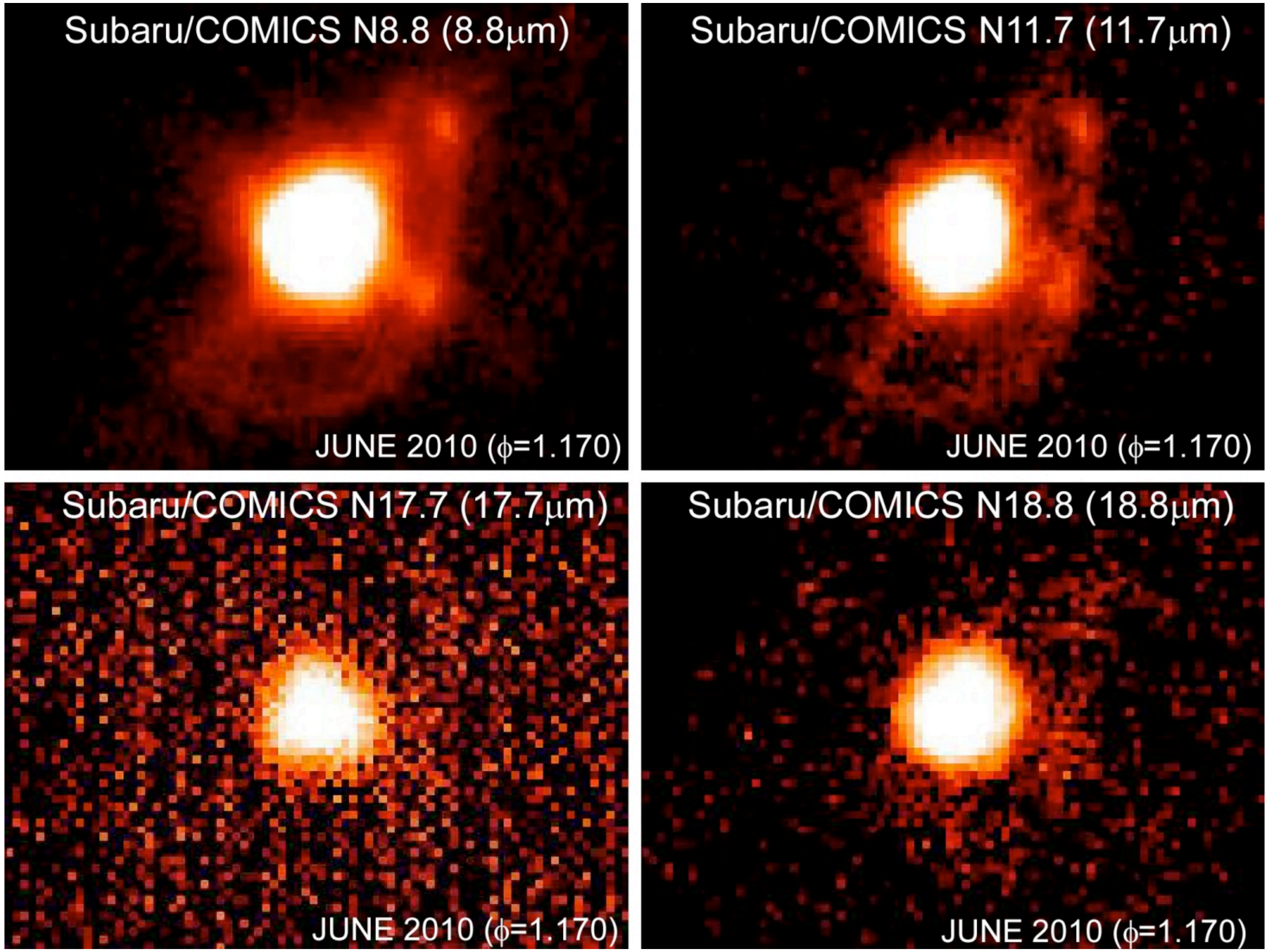
N11.7(11.7μm)   0.21±0.02 mJy
Q17.7(17.7μm)   0.15±0.04 mJy

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

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 at ϕ=1.170



The results of the photometry of dust shell formed during the 2001 periastron at the orbital phase of ϕ=1.170 (June 2009)

N11.7(11.7μm) 0.160±0.02 mJy

Q17.7(17.7μm) 0.125±0.04 mJy

temperature of amorphous carbon

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

total mass of amorphous carbon

$M_{acar} = 0.95^{-0.35} \times 10^{-8} M_{\odot}$

Properties of Dust formed during the 2001 periastron

The temperature of amorphous carbon at ϕ=1.097 (9 Nov 2009); T_{acar} = 350±60 K
ϕ=1.170 (4 Jun 2010); T_{acar} = 330±60 K

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

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

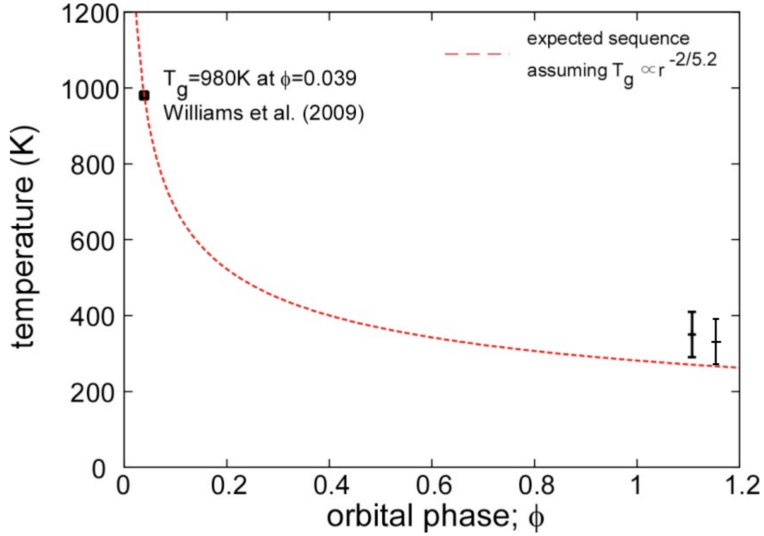
$\bar{Q}_a(a,T)$; the Planck mean absorption cross-section
a; the radius of a dust grain
T_g; the temperature of a dust grain
r; the distance between the dust and either of the two stars (O-type star or WR star)
R_O, R_{WR}; effective radii of the O-type star and the WR star
T_O, T_{WR}; effective temperature 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=1.097 ; $M_{acar} = 0.99^{-0.35}_{+0.5} \times 10^{-8}\ M_{\odot}$

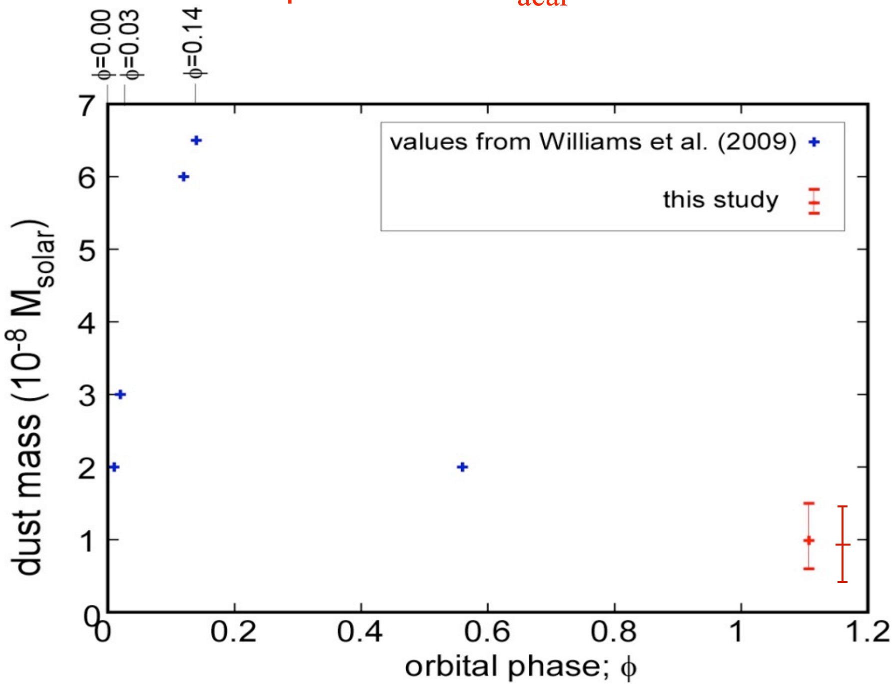
ϕ=1.170 ; $M_{acar} = 0.90^{-0.4}_{+0.5} \times 10^{-8}\ M_{\odot}$

(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} ($M_{\odot}$)
1.097	$0.99^{-0.35}_{+0.5} \times10^{-8}$
1.170	$0.90^{-0.4}_{+0.6} \times10^{-8}$



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=1.097~1.170.

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 ϕ=1.097 and 1.170 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~350±60K with the mass of $1\times10^{-8}M_{\odot}$ at the epoch of ϕ=1.097 and T~350±60K with the mass of $0.9\times10^{-8}M_{\odot}$ at the epoch of ϕ=1.170

→ In the case of WR140, $1\times10^{-8}M_{\odot}$ of amorphous carbon dust, at most, survives at the orbital phase of ϕ=1.097 and 1.170