Observing the Sites of Dust Formation in Circum-stellar Environments

I. dust formation in WR140
II. dust formation in Nova V1280Sco

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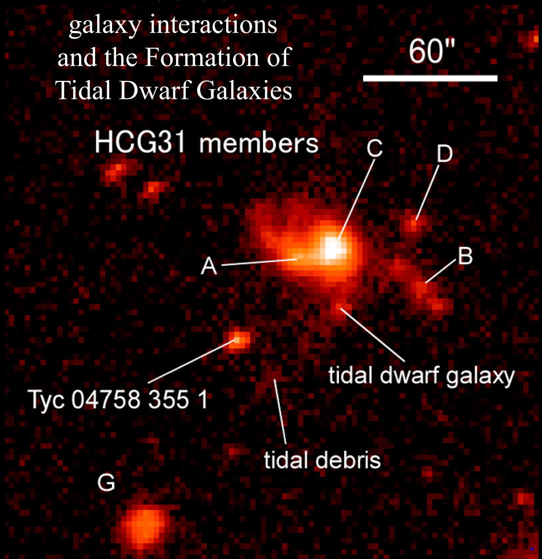
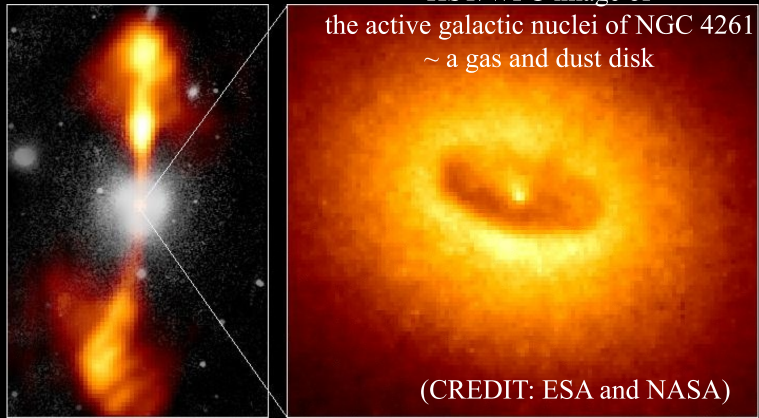
Life Cycle of Dust in Galaxies

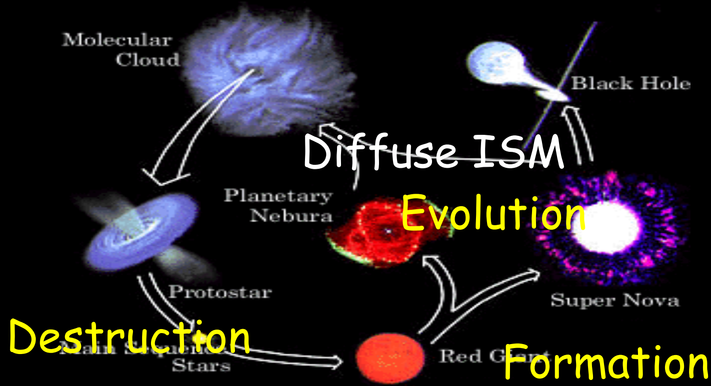
AKARI 9μm image of
Hickson Compact Group 31
~ the site of
galaxy interactions
and the Formation of
Tidal Dwarf Galaxies



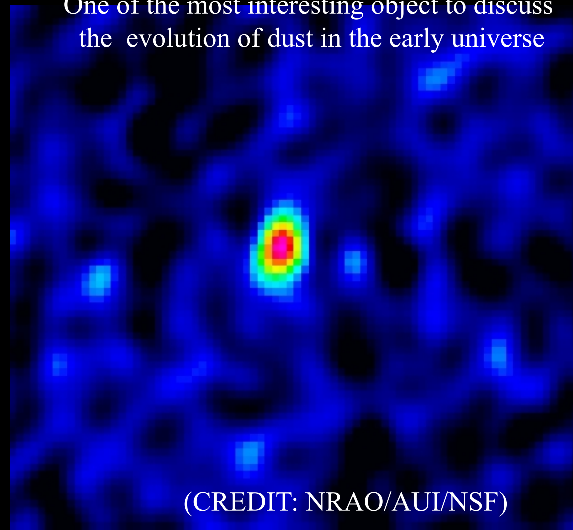
HST/WFC image of
the active galactic nuclei of NGC 4261
~ a gas and dust disk



(CREDIT: ESA and NASA)



VLA image of J1148+5251
~the most distant quasar at z~6.4
One of the most interesting object to discuss
the evolution of dust in the early universe



(CREDIT: NRAO/AUI/NSF)

-- how the dust is synthesized in the stellar wind
-- how they are ejected into the interstellar space
-- how they evolve in various astrophysical environment
-- how they enrich the universe

Infrared spectroscopic observations are useful to examine the composition and the properties of circumstellar and interstellar dust

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

・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).

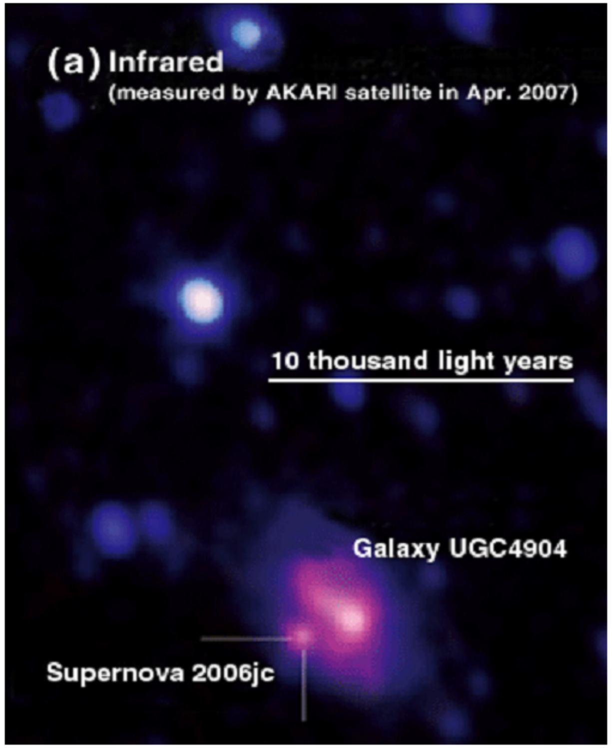
・ Observational Evidence for the dust formation in SN ejecta
- Type II SN2003gd; $0.02M_{solar}$(Sugerman et al. 2006) -> $4\times10^{-5}M_{solar}$(Meikle et al. 2007)
- Type II SN1987A ; $7.5\times10^{-4}M_{solar}$ (Ercolano et al.2007)
- Cas A ; $0.003M_{solar}$ (Hines et al. 2004) or 0.02-$0.054M_{solar}$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

→ much smaller amount of dust formation is suggested observationally

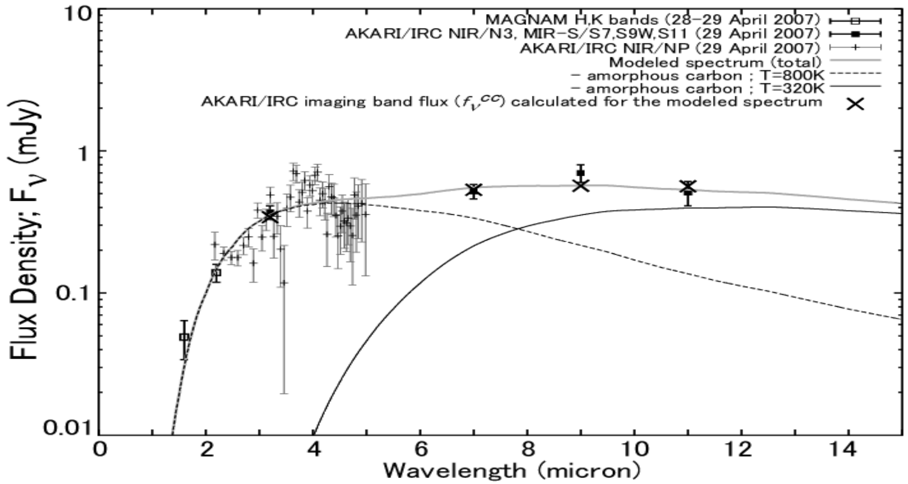
Introduction: Dust formation by SN2006jc

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

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



[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

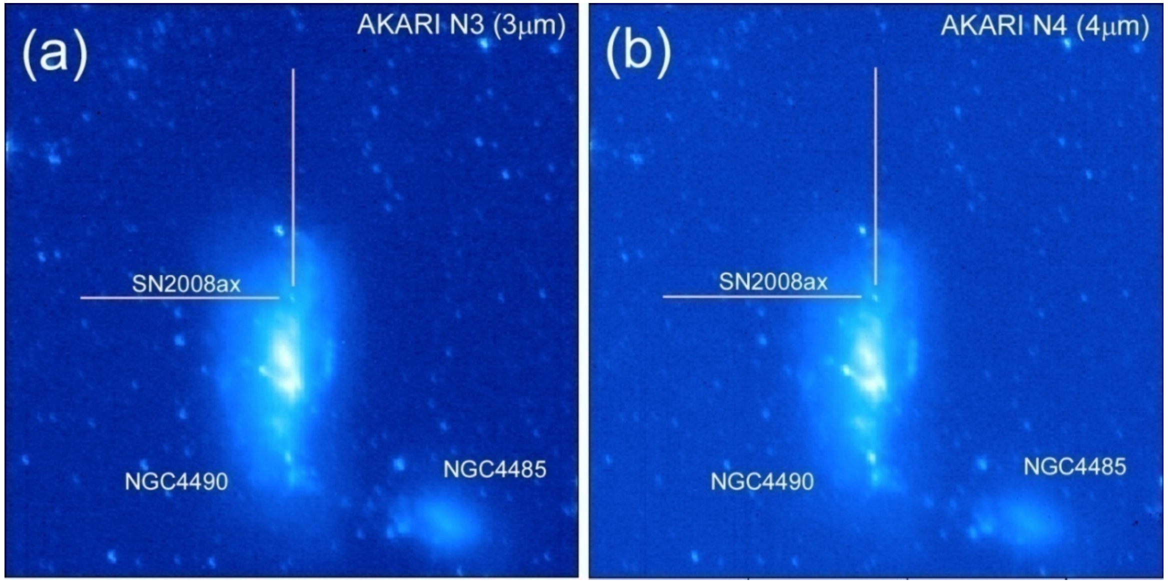
-- the optical light curve similar to that of the He-rich Type IIb SNe 1996cb and 1993J

-- 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

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 Wolf-Rayet Binaries

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

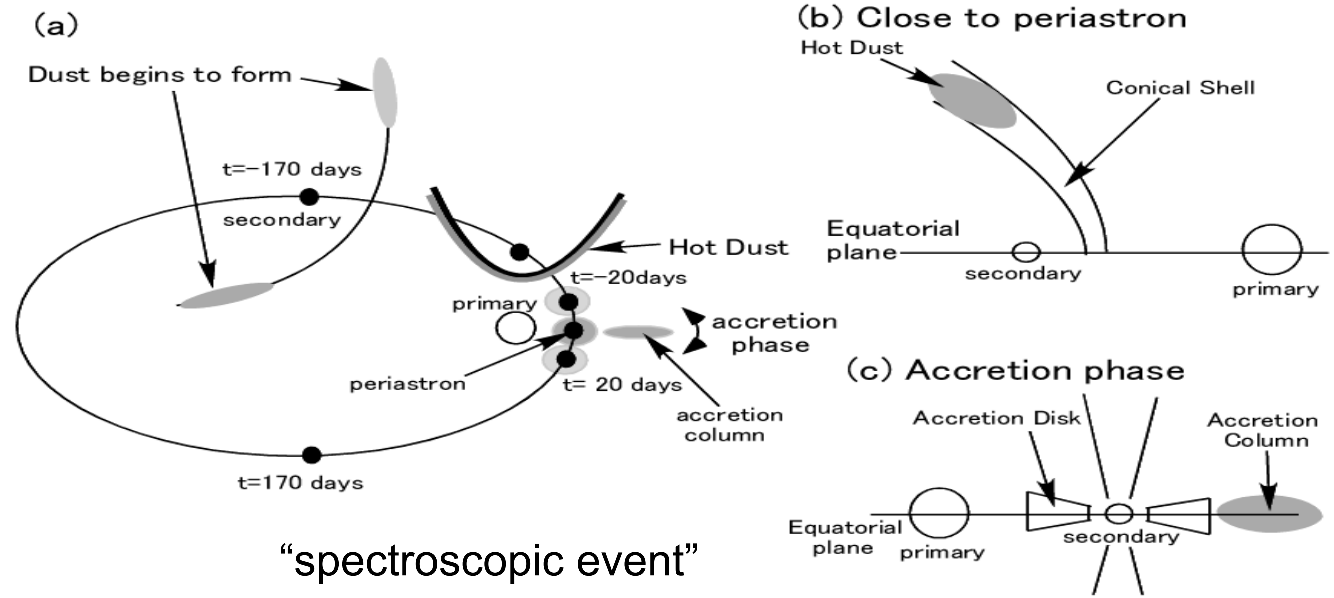
Wolf-Rayet stars; extremely luminous ($L > 10^5 L_\odot$, $T_{eff} \gg 20{,}000K$)

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

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

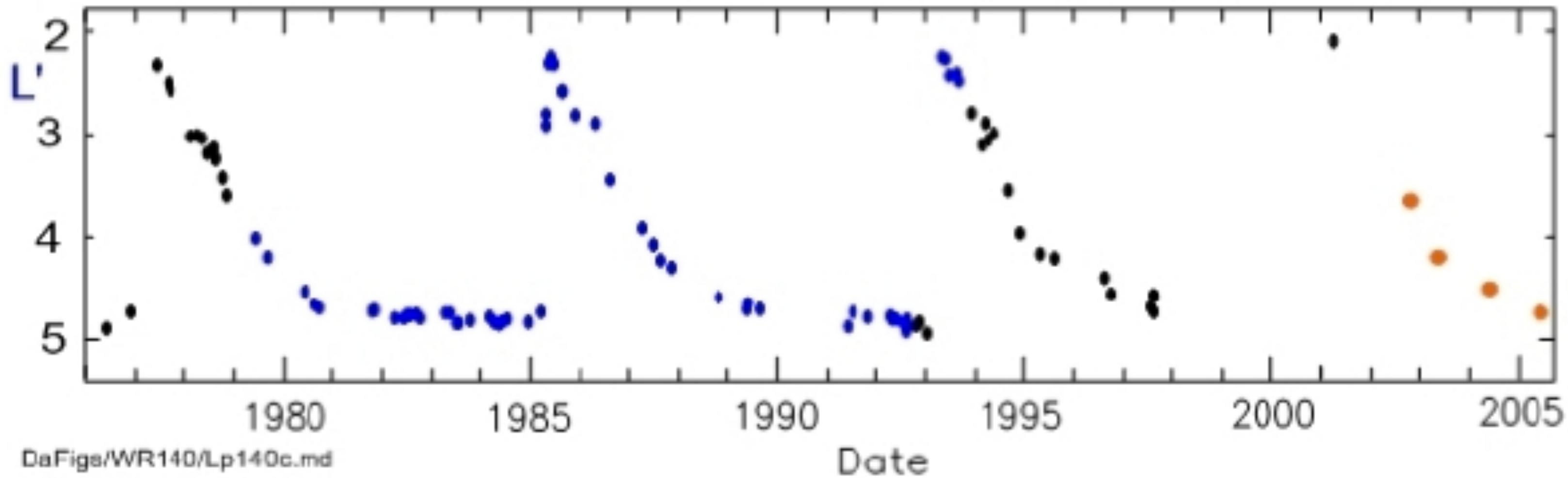


(a) Schematic view of dust formation in the colliding winds.
(b) Formation of hot dust in the colliding winds close to periastron.
(c) The accretion disk during the accretion phase and the formation of hot dust in the accretion column. (Kashi & Soker 2008a)

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; Williams et al.1990) colliding-wind WR binary
(WC7 class Wolf-Rayet star + O4 type star) located at d~1.85kpc
High-eccentricity (e=0.84±0.04)
“spectroscopic events” at 1977, 1985, 1993, 2001 and 2009



Long-term light curve of WR140 in L’ (3.8μm) (P. Williams 2011)

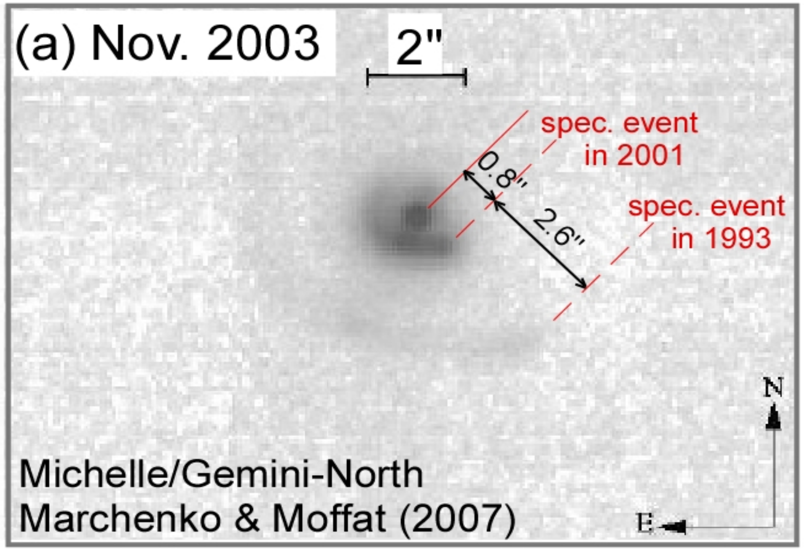
Wind properties; v_{wind}=2860km/s $dM/dt=2\times10^{-5}M_\odot$ for WC7 class Wolf-Rayet star
v_{wind}=3100km/s $dM/dt=2\times10^{-6}M_\odot$ for O4 type star

Interpretations of the “spectroscopic event” in terms of colliding wind theory (Usov 1991)
Dust emission from WR140 (Monnier, Tuthill & Danchi 2002; Williams et al. 2009)

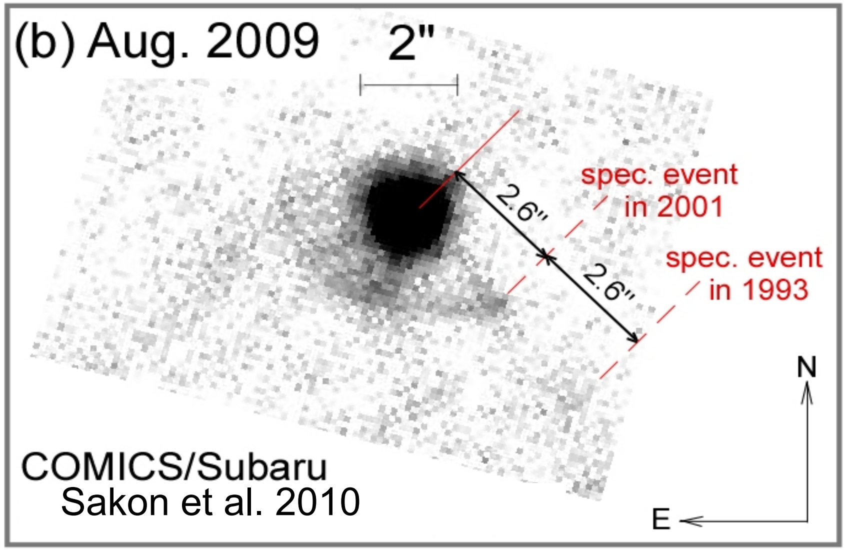
Dust formation by WR140

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

1st epoch; Aug. 2009 (orbital phase ϕ=1.064 from the 2001 periastron)
2nd epoch; Nov. 2009 (orbital phase ϕ=1.097 from the 2001 periastron)
3rd epoch; June 2010 (orbital phase ϕ=1.170 from the 2001 periastron)
4th epoch; June 2011 (orbital phase ϕ=1.300 from the 2001 periastron; scheduled)



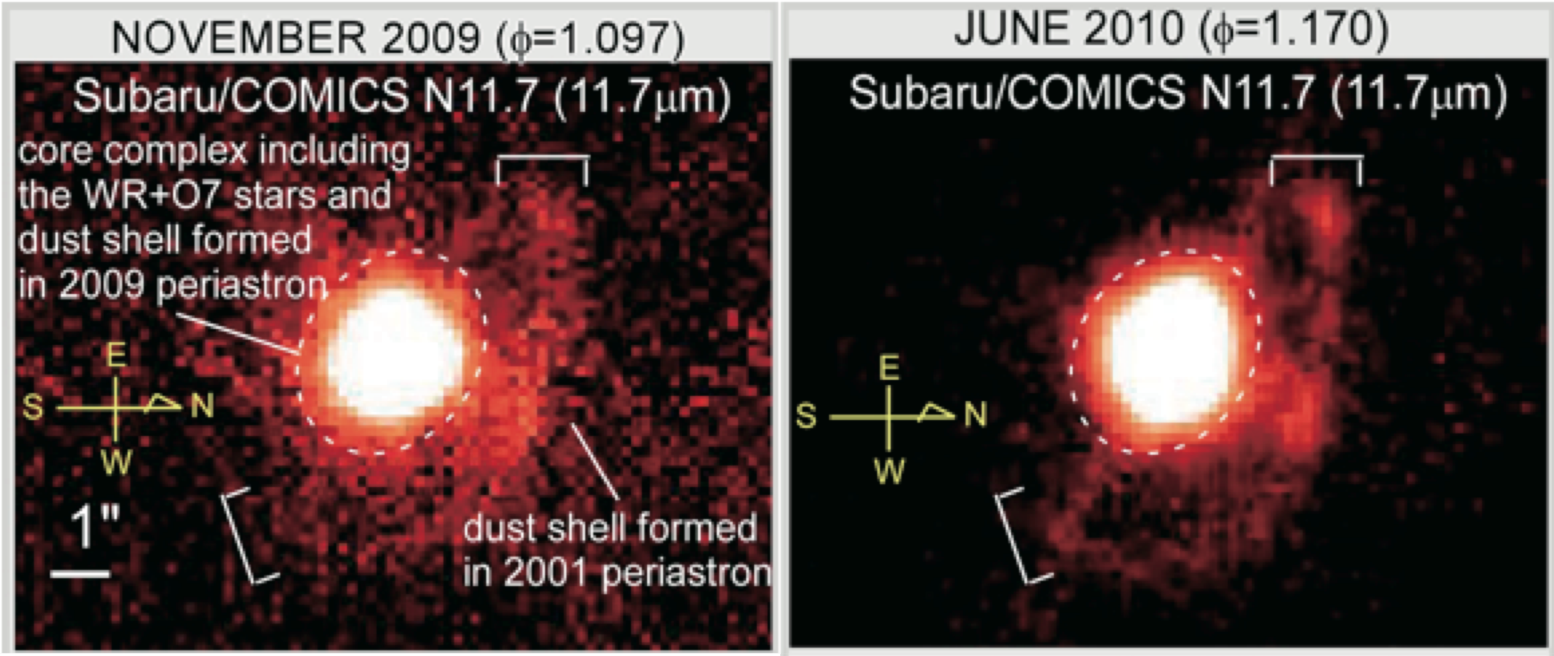
12.5μm image of WR140 taken with Michelle/Gemini-North on Nov. – Dec. in 2003 (Marchenko & Moffat 2007).



11.7μm image of WR140 taken with COMICS/Subaru on 1st Aug. in 2009 (Sakon et al. 2010, Ast.Soc.India Conf.Ser.).

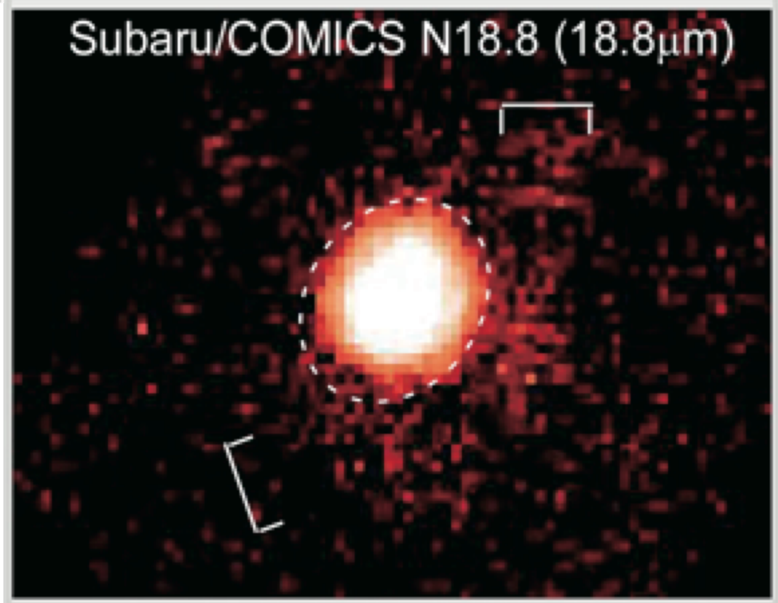
→The expansion velocity of the dust shell; $2.7\pm0.3 \times 10^3$ km s^{-1} , consistent with Williams et al. 2009

Dust Structures around WR140 Revealed by Subaru/COMICS Observations

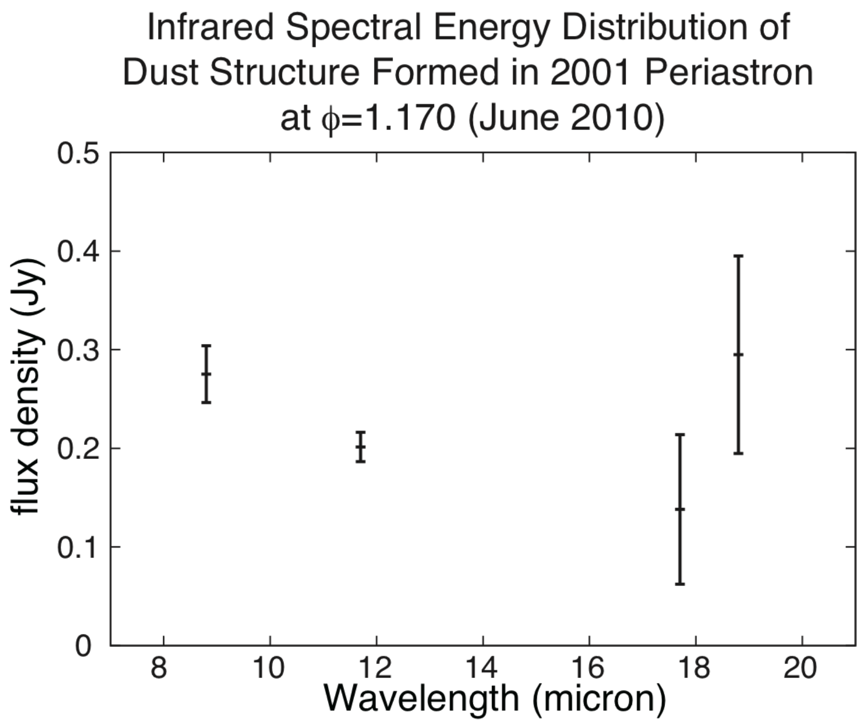


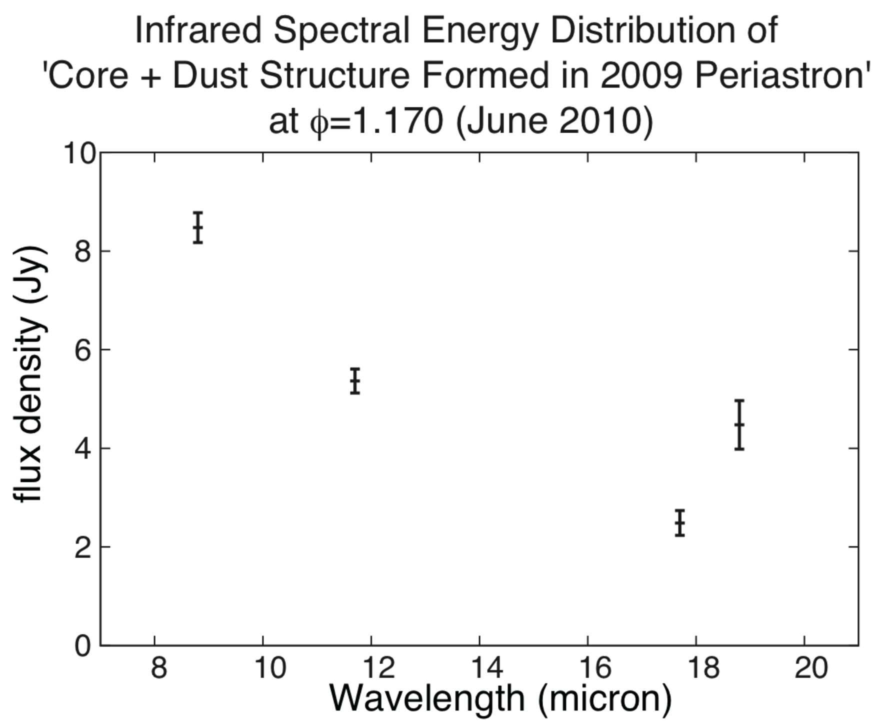
(top left, right) Subaru/COMICS N11.7 band (11.7μm) images of dust structures around WR140 taken at the orbital phases of ϕ=1.097 and 1.170, respectively.

(bottom right) Subaru/COMICS Q18.8 band (18.8μm) image of dust structures around WR140 at the orbital phase of ϕ=1.170



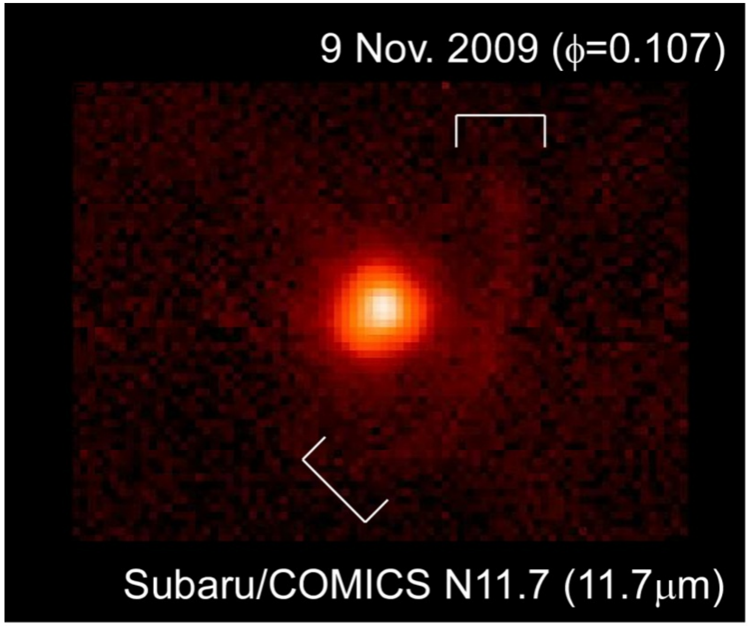
Dust Structures around WR140
Infrared Spectral Energy Distributions (SEDs)

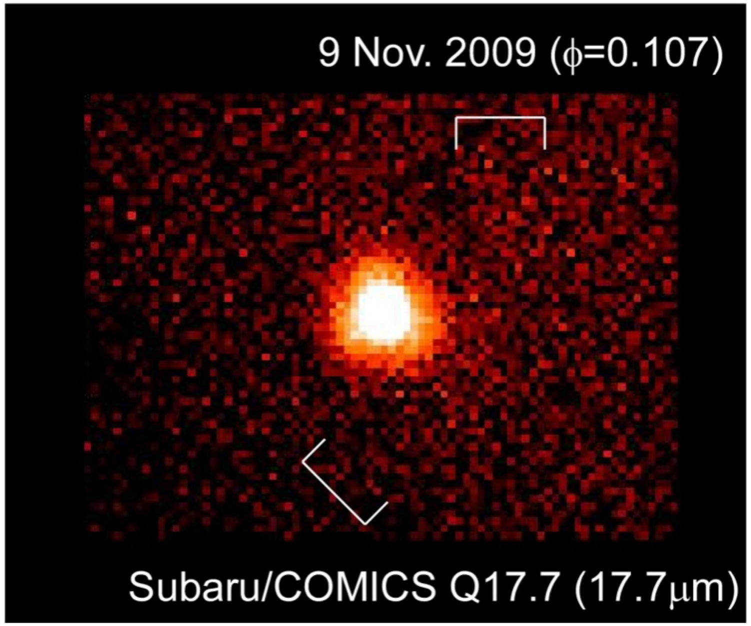




Excess Emission at Q18.8 band;
-- possible contribution of [SIII] at 18.71μm or any contribution of dust band features?

Properties of Dust formed during the 2001 periastron





The results of the photometry of dust shell formed during the 2001 periastron at orbital phases of ϕ=1.097 and ϕ=1.170

orbital phase	ϕ=1.097	ϕ=1.170
N11.7(11.7μm)	0.21±0.02 mJy	0.20±0.02mJy
Q17.7(17.7μm)	0.15±0.04 mJy	0.13±0.06mJy

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

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

orbital phase	ϕ=1.097	ϕ=1.170
T_{acar} (K)	350±50	390±60
M_{acar} (10^{-8} $M_\odot$)	$0.99^{-0.35}_{+0.5}$	$0.68^{-0.4}_{+0.6}$

Properties of Dust formed during the 2001 periastron

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

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

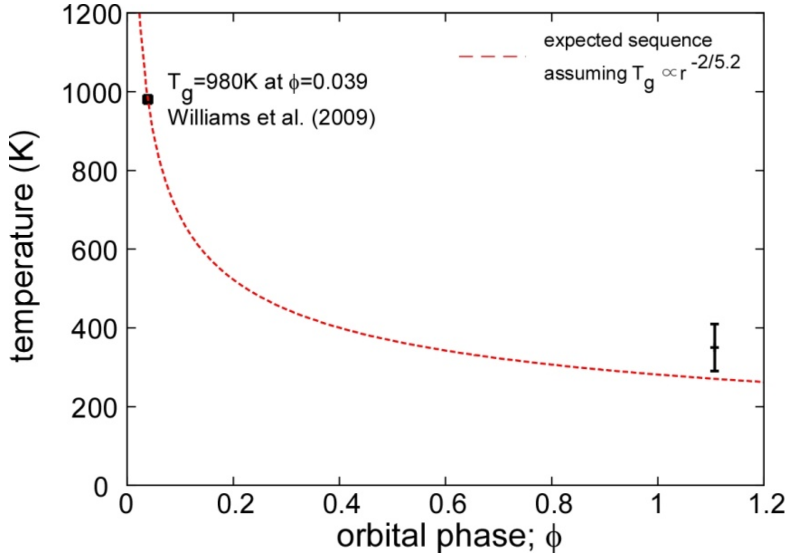
$\bar{Q}_a(a,T)$; the Planck mean absorption cross-section
a; the radius of a dust grain
T_g; the temperature of a dust grain
r; the distance between the dust and either of the two stars (O-type star or WR star)
R_O, R_{WR}; effective radii of the O-type star and the WR star
T_O, T_{WR}; effective temperature 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=1.097 is generally in good agreement with the expected relation of $T_g \propto r^{-2/5.2}$.



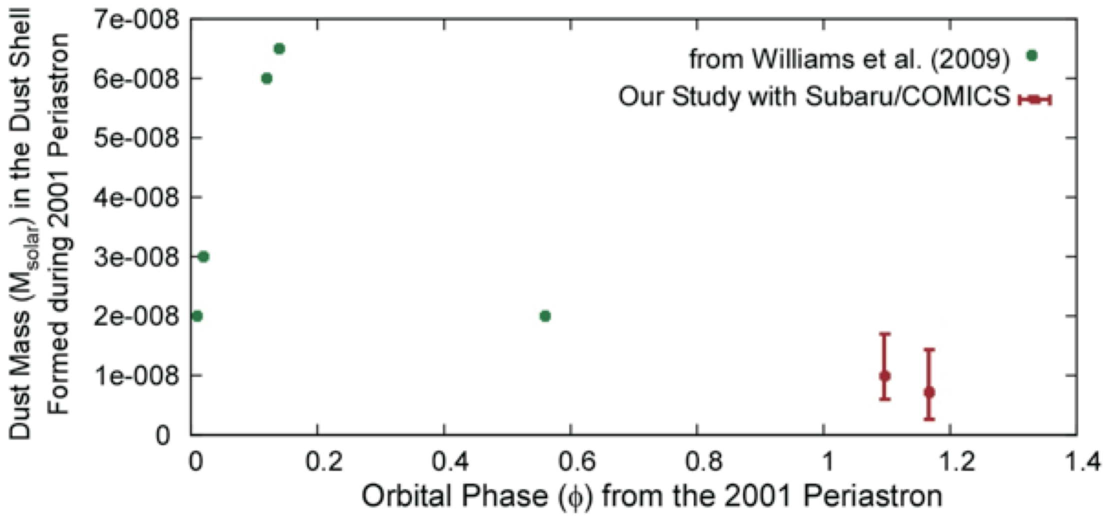
Properties of Dust formed during the 2001 periastron

(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	$0.68^{-0.4}_{+0.6}\times10^{-8}$



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

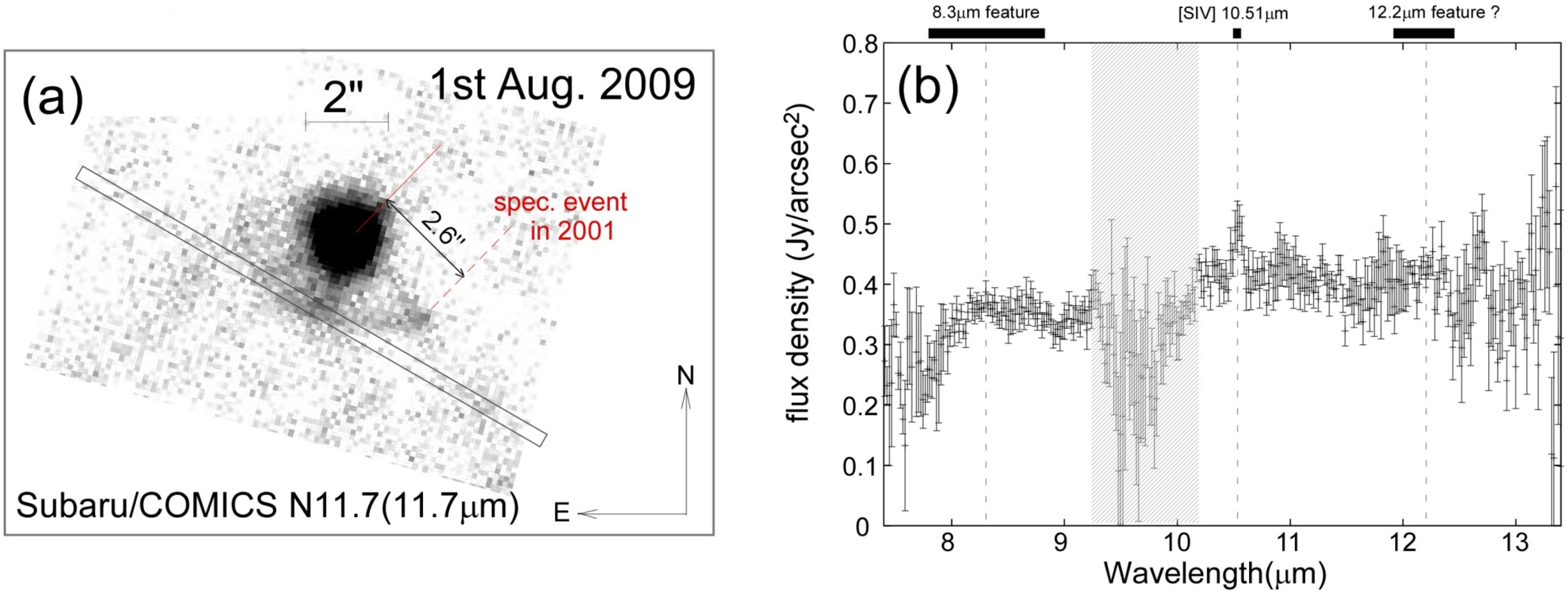
cf. typical size of dust grains in WR140 grow to 0.069μm (Marchenko et al. 2003)

$0.14<\phi$; 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 $\sim1\times10^{-8}M_\odot$ of amorphous carbon dust survives at the orbital phase around ϕ=1.1-1.2.

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

Interpretations; Dust Formation by WR140

Mid-infrared Imaging observations of WR140 at the orbital phases of ϕ=1.064, 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~350-400K with the mass of $1\times10^{-8}M_{\odot}$.

→ In the case of WR140, $1\times10^{-8}M_{\odot}$ of amorphous carbon dust, at most, survives at the orbital phase of ϕ=1.1-1.2

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

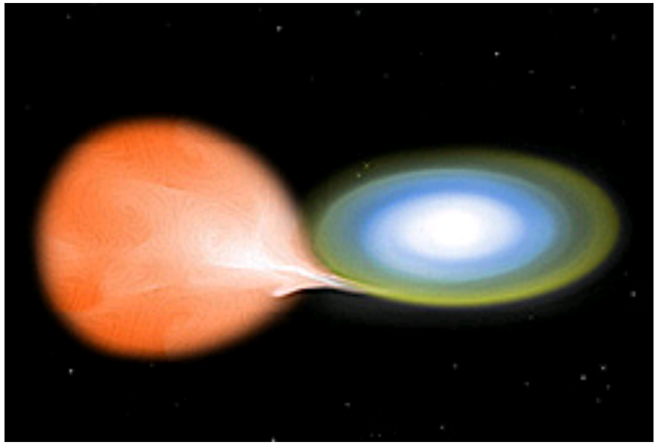
Infrared Observations of Novae with Subaru/COMICS and Gemini/T-ReCS

Sakon, I., Sako, S., Shimonishi, T.,
Onaka, T., Nozawa, T (Univ. of Tokyo)
Takahashi, H. (Gunma Observatory)
Yamashita, T., Fujiyoshi, T. (NAOJ)
Rodomski, J. (Gemini Observatory)
Kanata Telescope Science Team (Hiroshima University)
Nova Science Team

Infrared Observations of Novae

Mid-infrared Imaging and Spectroscopic monitoring observations of Galactic dust forming novae

→ unique laboratories to study the process of dust formation and to understand the mass-loss history of the CO white dwarves from the chemical point of view



Infrared Spectral Evolution of CO Novae and ONeMg Novae

- Hot ejecta gas is initially seen as an expanding photosphere
- When the expanding material becomes optically thin, free-free and line emission dominate

1). CO Novae;

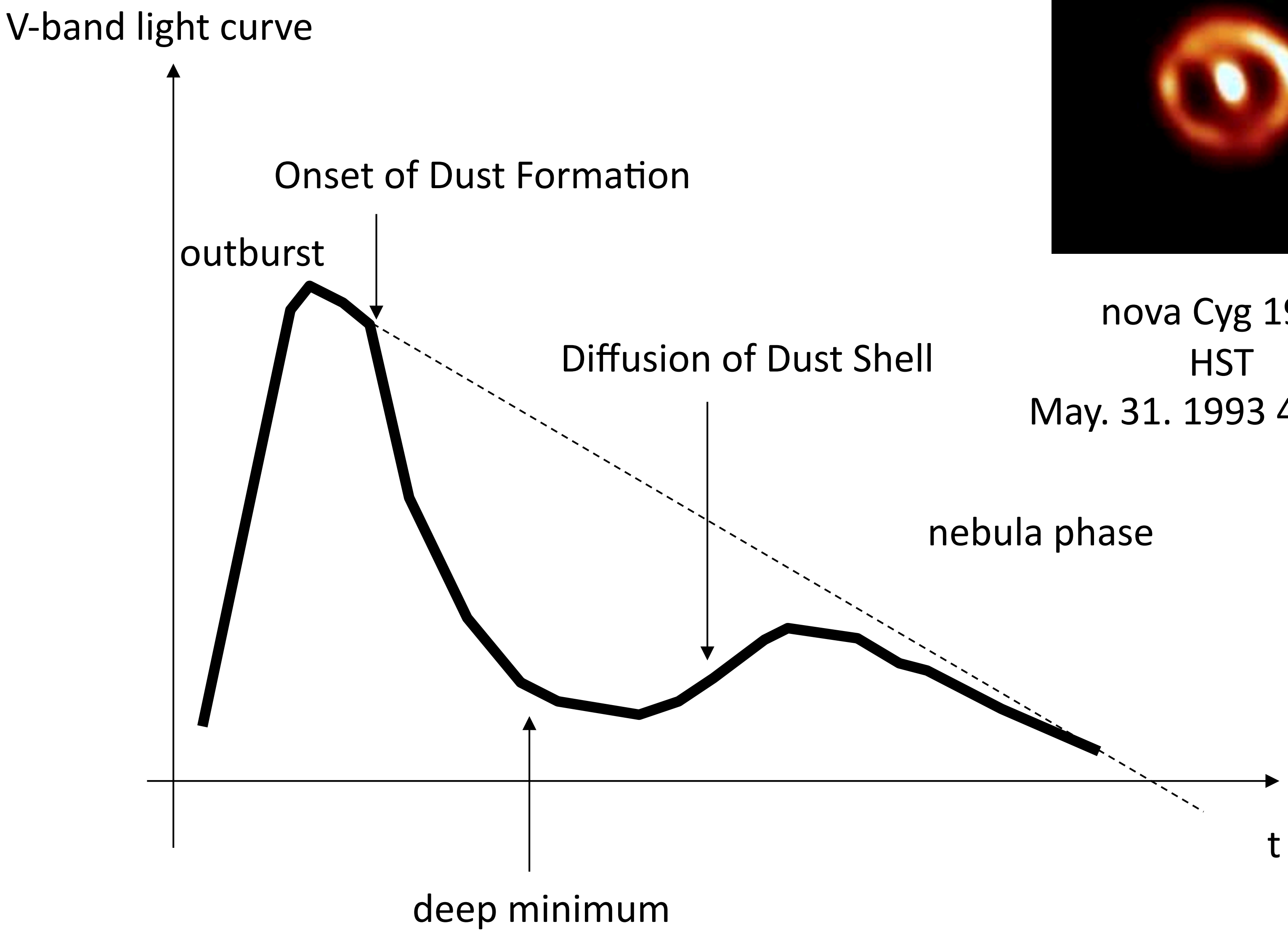
- Thermonuclear runaway (TNR) on the surface of relatively low-mass CO white dwarves (e.g., $M_{WD}<1.1M_{\odot}$)
- Dust formation after the free-free phase is reported for several CO novae [e.g., V2362 CYGNI (Lynch et al. 2008), V705 Cas (Evans et al. 1997), etc.]
- Complicated dust compositions (both Silicates and Carbonaceous dust)

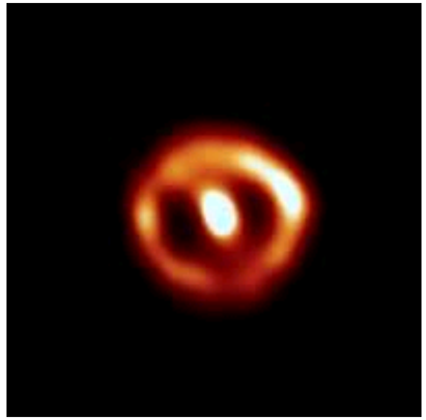
2). ONeMg Novae;

- Thermonuclear runaway (TNR) on the surface of relatively higher-mass ONeMg white dwarves (e.g., $M_{WD}>1.1M_{\odot}$)
- coronal emission-lines phase comes after the free-free phase
- No or little evidence of dust formation (cf., V1974 CYGNI; Woodward et al. 1995)

chemical evolution of the Nova ejecta over various physical phases is not fully understood

Optical Light Curve Evolution of Dusty Novae





nova Cyg 1992
HST
May. 31. 1993 467days

V1280 Scorpii

-Discovered on 2007 Feb 4.86 by Y. Nakamura and Y. Sakurai (Yamaoka et al. 2007)
- d = 1.6±0.4 kpc (Chesneau et al. 2008)
-Dust formation occurred at d~23days after discovery (Das et al. 2007)

VLTI/AMBER and MIDI observations between t=23 d and 145 d (Chesneau et al. 2008)
-An apparent linear expansion rate for the dust shell; 0.35±0.03mas day^{-1}
-Expansion velocity of the nova ejecta; 500±100 km/s
-Dust production rate; 2-8x10^{-9} M_{sun} day^{-1} (a probable peak in production at t=36-46 days)
-The amount of dust in the shell; 2.2x10^{-7} M_{sun}

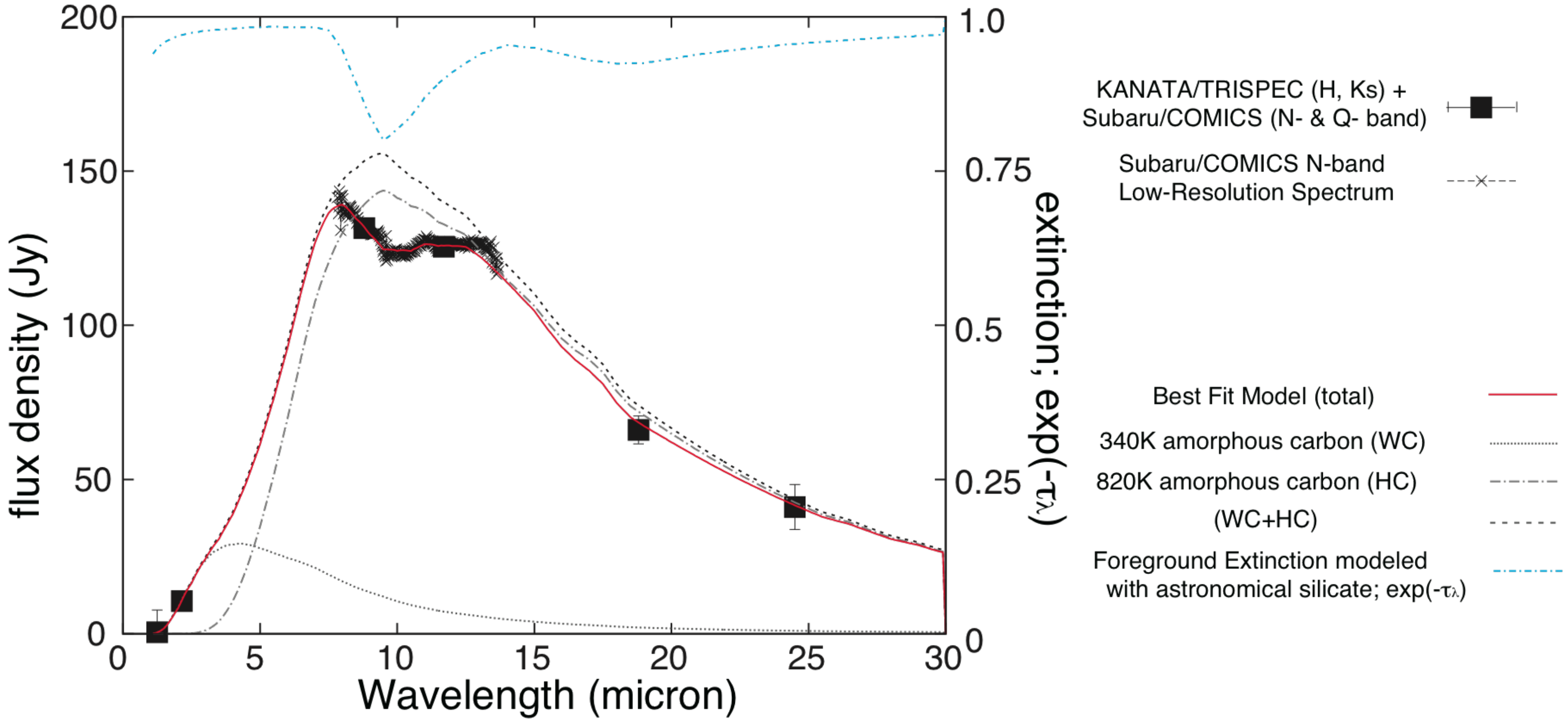
Late-epoch Observations of Dust Forming Nova V1280Sco

- <u>July 7, 2007 (epoch ~150 days)</u>
Subaru/COMICS; N-band spectroscopy (8-13.4μm)
N- & Q-band photometry (8.8μm, 11.7μm, 18.8μm, 24.5μm)
Kanata/TRISPEC (June 26, 2007; epoch ~140 days); Ks-band photometry (2.15μm)

- <u>September 8, 2009 (epoch ~940 days)</u>
AKARI/IRC; near-infrared spectroscopy (2.5-5μm)

- <u>August 1, 2010 (epoch ~1270 days)</u>
Gemini-S/TReCS; N-band spectroscopy (7.7-13.2μm)
N- & Q-band photometry (7.8μm, 9.7μm, 11.7μm,18.8μm, 24.5μm)
Gunma (Aug 26, 2010; epoch ~1300 days);
J, H, Ks-band photometry (1.24, 1.66, 2.15μm)

Spectral Decomposition of model fit to the Infrared Continuum Spectrum of V1280Sco at ~150 days obtained with Subaru/COMICS

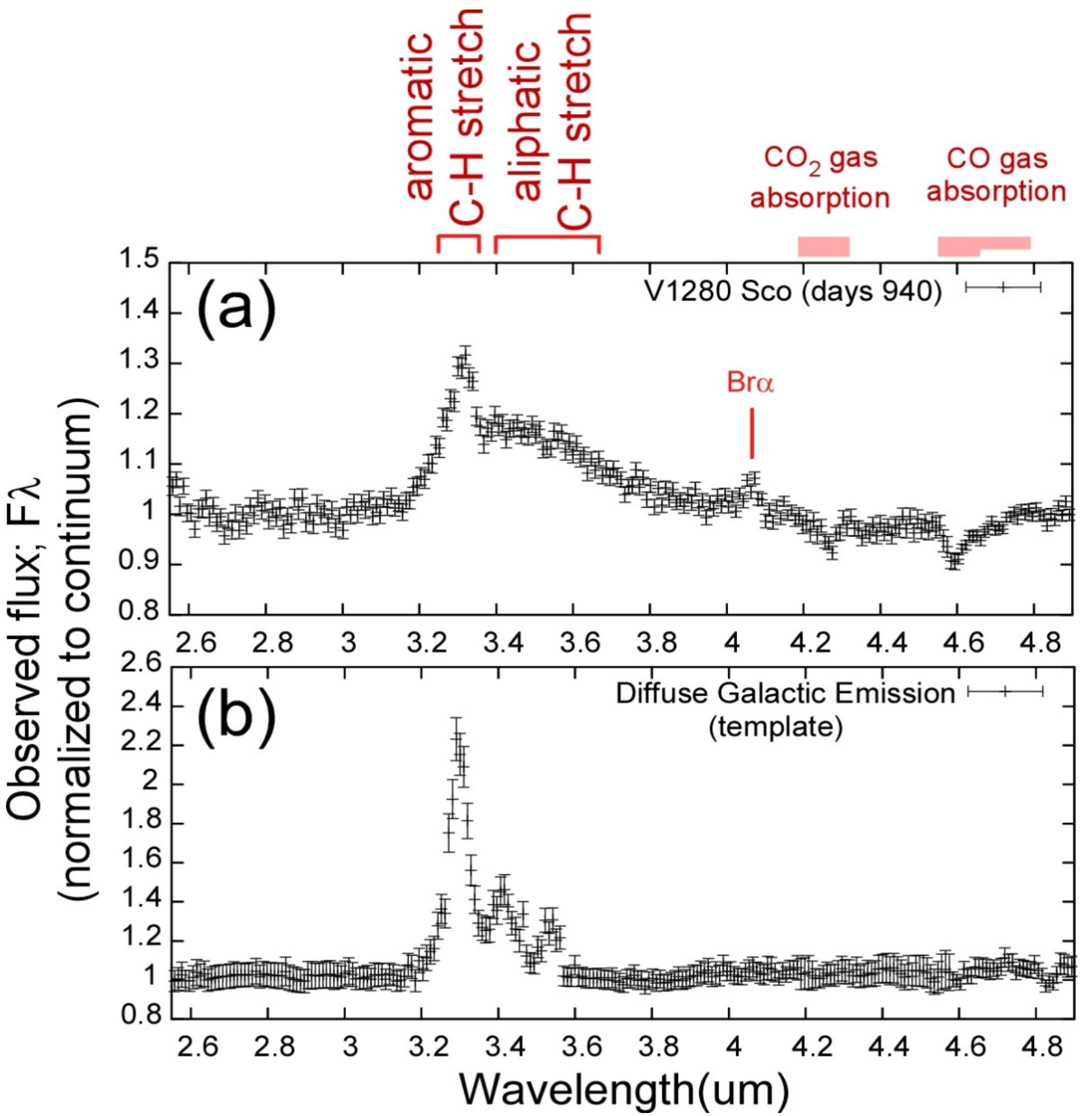


Warm Amorphous Carbon; 340±20 (K), 2.4×10^{-6}Msun

Hot Amorphous Carbon; 820±20 (K), 1.2×10^{-8}Msun

Foreground Extinction; Av ~ 4.0±1.0 mag

Near Infrared Spectrum of V1280Sco at ~940 days with AKARI/IRC

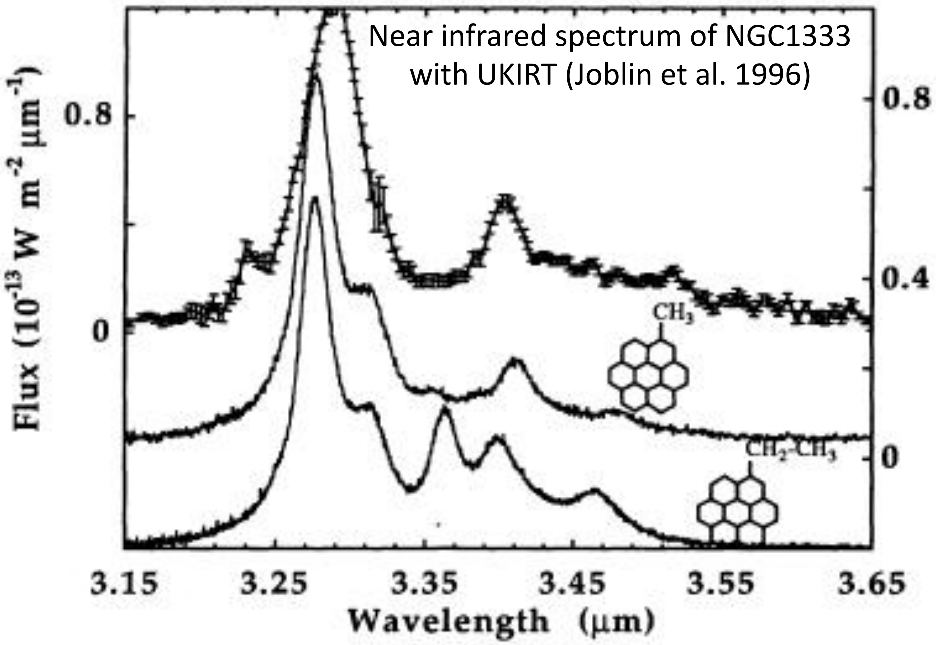


(a) Near-Infrared spectrum of V1280 Sco on the epoch 940 days after the discovery normalized to the continuum obtained with Infrared Camera (IRC) onboard AKARI.
A PAH 3.3μm feature with a strong redwing in 3.4-3.6μm was recognized.

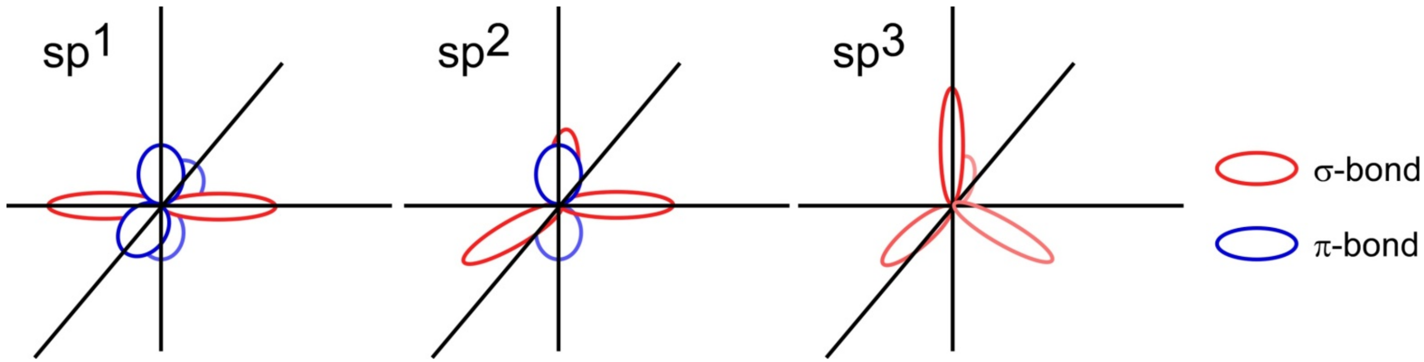
(b) Near-infrared spectrum of Galactic ISM as an example of typical spectrum of PAH features with a normal inter-band ratios among 3.3, 3.4 and 3.5μm features obtained with AKARI/IRC.

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

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



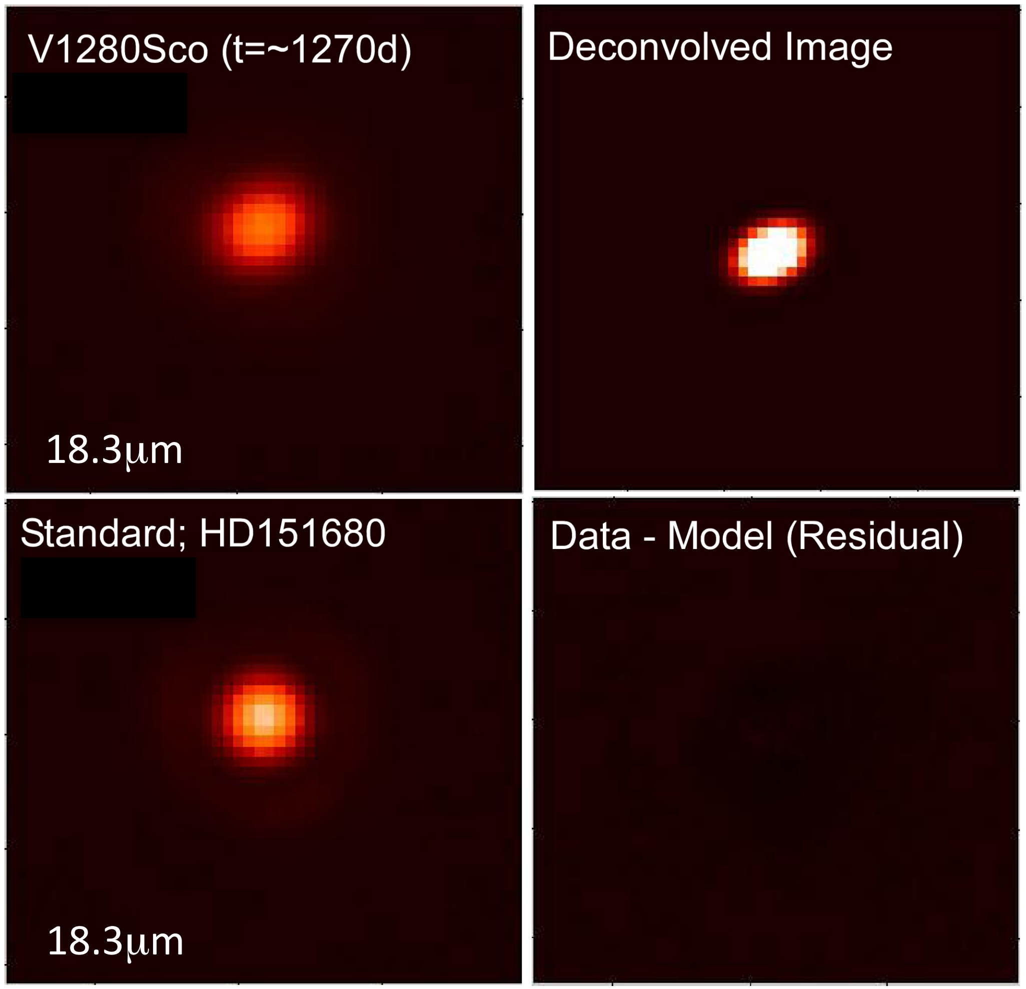
Hydrogenated Amorphous Carbons (HACs) (Duley & Williams et al. 1990)
-contain PAH-like units weakly bounded by van der Waals forces
-consist of a mixture of aromatic hydrocarbons dominated by sp^2 bonds which can produce the polycyclic ring and aliphatic hydrocarbons including sp^1 bonds (like in acetylene) and sp^3 bonds (like in methane).

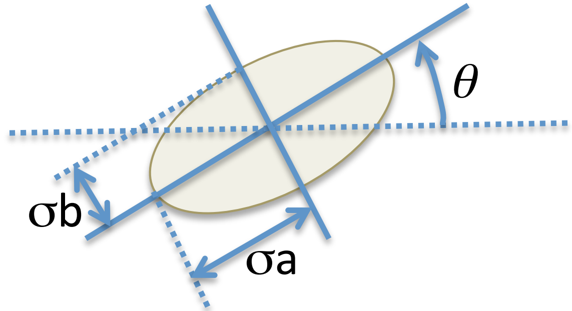


The “aromatic” to “aliphatic” ratio in HACs can be modified by the irradiance of UV fields.

Results of N- & Q-band imaging observations of V1280 Sco at t=~1270 days with Gemini-S/TReCS

Example; Qa band data of V1280Sco and HD151680





Intrinsic profile of the dust emission;
3D-Elliptical Gaussian

θ ; position angle for the major-axis

σa ; semi-major axis radius

σb ; semi-minor axis radius

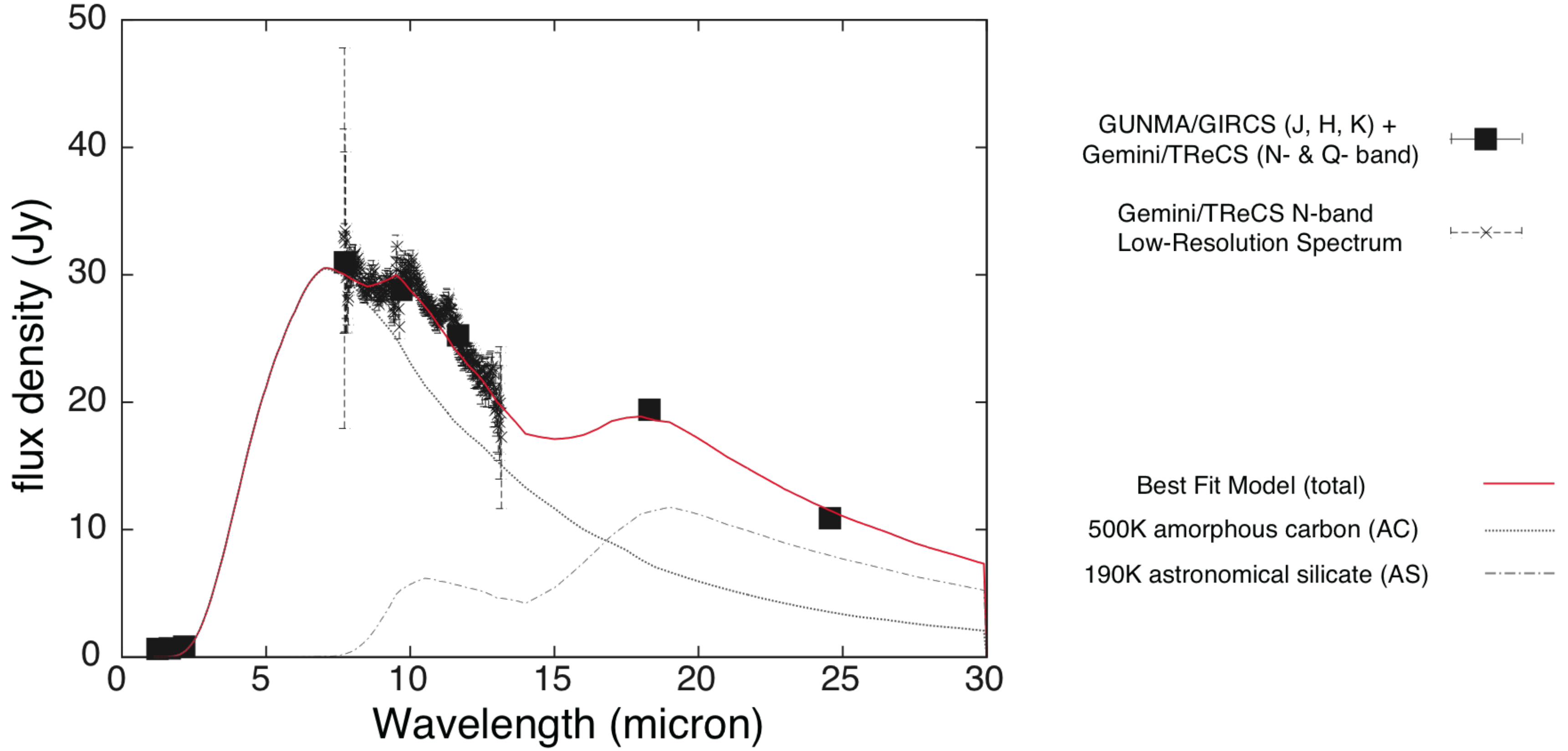
The best-fit 3D-Elliptical Gaussian parameters

Band	λ(μm)	θ (deg)	σa (")	σb (")
Si-1	7.73	25	0.32±0.02	0.19±0.02
Si-3	9.69	25	0.30±0.02	0.18±0.02
Si-5	11.66	25	0.29±0.02	0.15±0.02
Qa	18.30	25	0.29±0.03	0.20±0.03
Qb	24.56	25	0.38±0.03	0.23±0.03

Non-spherical distribution of dust emission

Effective size of the dust shell at 1270d ;
7.2×10^{10} km (~500AU)

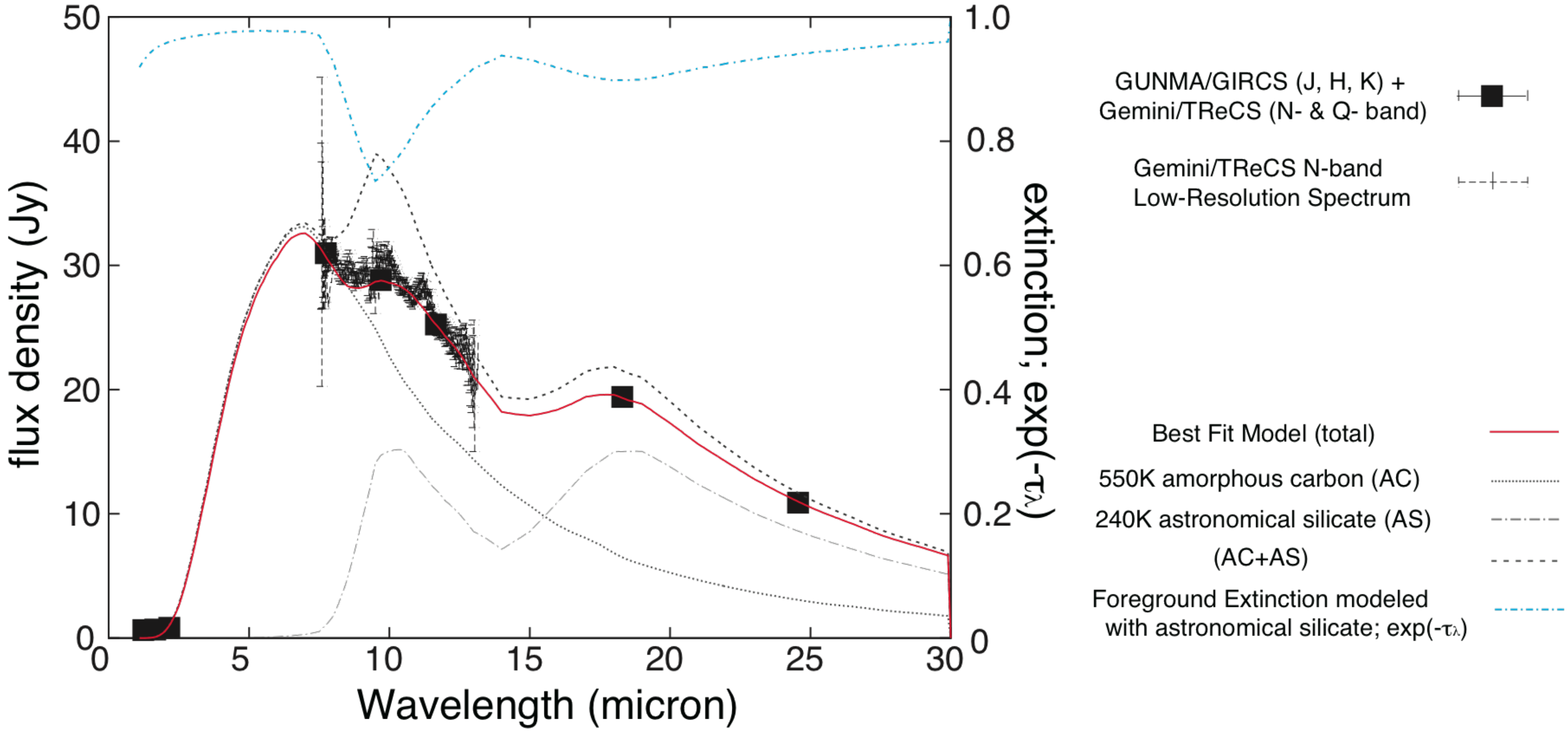
Spectral Decomposition of model fit to the Infrared Continuum Spectrum of V1280Sco at ~1270 days obtained with Gemini-S/TReCS



Amorphous Carbon; 500±5 (K), 9.7x10^{-8}Msun

Astronomical Silicate; 190±5 (K), 1.25x10^{-6}Msun

Alternative Spectral Decomposition of model fit to the Infrared Continuum Spectrum of V1280Sco at ~1270 days obtained with Gemini-S/TReCS

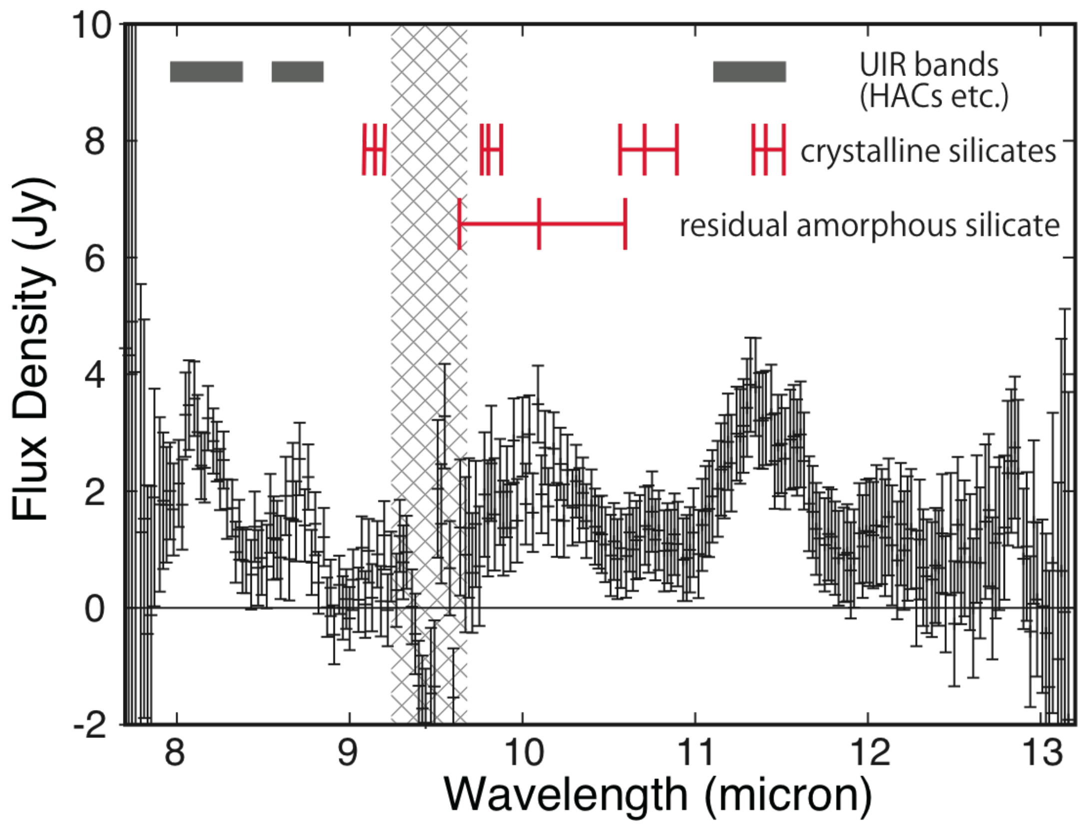


Amorphous Carbon; 550±10 (K), 7.2×10^{-8}Msun

Astronomical Silicate; 240±10 (K), 6.8×10^{-7}Msun

Foreground Extinction; Av ~ 5.5±1.0 mag

Mid-Infrared Spectral Features over the Infrared Continuum modeled with amorphous carbon and astronomical silicate



Features at ~8.1μm, ~8.7μm, ~11.35μm;

Hydrogenated Amorphous Carbons (HACs), NH2-rocks (Grishko & Duley 2002)

→ similar to those found in V704 Cas 1993 (Evans et al. 1997, 2005)

A Broad Feature at ~10.1μm; amorphous silicate

Features at ~9.2μm, ~9.8μm, ~10.7μm, ~11.4μm;

Possible contributions of forsterite, enstatite and diopside (Molster et al. 2002)

Interpretations; IR observations of V1280Sco

-Near- to mid-infrared (1-25μm) spectrum at t = ~1270 days with Gemini-S/TReCS is well reproduced by Emission from warm astronomical silicate and hot amorphous carbon

→ presence of both carbonaceous dust and (pre-existing?) silicate dust (absence of silicate in emission at t=~150 days)

→ the emitting regions of both components are confined within ~500AU (within an expanding dust shell; 0.35mas/day).

-Strong 18-μm /10- μm silicate band ratio

→ presence of lower temperature astronomical silicate dust (T~240K) of $6.8 \times 10^{-7} M_{sun}$?

→Possible annealing effect? (evolution of circumstellar silicate) (Nuth & Hecht 1990) (consistent with the possible detection of crystalline silicate band emission.)

-Detection of 3.3μm feature with strong red-wing in AKARI/IRC NIR spectrum at t = ~940 days

-Detection of 8.1, 8.7 and 11.35μm features in the spectrum of of V1280 Sco at t=~1270 days with Gemini-S/TReCS

→ Formation of Hydrogenated Amorphous Carbons (HACs) in the nova ejecta

-Presence of silicate absorption in the N-band Low-resolution spectrum of V1280Sco at t = ~150 days with Subaru/COMICS

-CO gas absorption in the AKARI/IRC near-infrared spectrum of V1280Sco at t=~940 days

→ presence of rich circumstellar medium around the white dwarf

Mid-infrared Imaging and Spectroscopic monitoring of Galactic dust forming novae

→ unique laboratories to study the process of dust formation and to understand the mass-loss history of the CO white dwarves from the chemical point of view

- Late epoch observations t>1000 days are important to examine the chemical evolution of dust grains formed around novae in harsh UV radiation environment
- High spatial resolution achieved by 8-10m class telescopes in the mid-infrared is indispensable to resolve the dust shell structures at those late epochs

Summary

Whole sky coverage achieved by Subaru/COMICS and Gemini-S/TReCS

- Strong advantages in the chemical understanding of dust formation around evolved stars
- Good collaboration with Space Infrared missions (AKARI, SPICA, etc.)
- Observations of time varying phenomena with a timescale of several years; (novae, Wolf-Rayet +O-type binary stars, nearby supernovae, optical transients etc.)
- Further multi-epoch observations of those targets with Subaru and Gemini are important