

The evolution of mid-infrared spectral energy  
distribution of dust forming Nova V1280SCo  
based on infrared observations  
with Subaru/COMICS, Gemini/T-ReCS and AKARI/IRC

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

# Ground-based Mid-Infrared Observation

Mid-Infrared Instruments onboard 8m class telescope

- Subaru Telescope/Cooled Mid-Infrared Camera and Spectrometer (COMICS)

- Gemini-South Telescope/ TReCS

N-band ( $7.6\text{-}13.0\mu\text{m}$ ), Q-band ( $16\mu\text{m}\text{-}25\mu\text{m}$ )



[http://www.gemini.edu/images/pio/telescope\\_images/20060131\\_GSSnow.jpg](http://www.gemini.edu/images/pio/telescope_images/20060131_GSSnow.jpg)



# AKARI Mission



JAXA/ISAS mission  
for infrared astronomy  
with ESA participation

Telescope with 685mm SiC Mirror  
cooled by 179l LHe  
& mechanical coolers

2 instruments: IRC & FIS

Launched on Feb. 22, 2006  
Successfully performed near-  
to far-infrared observation

LHe: 2006 May - 2007 Aug  
(phases I&II)

Warm mission: 2008 June - 2010  
(phase III; 2-5 $\mu$ m imag. & spec.)



# 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

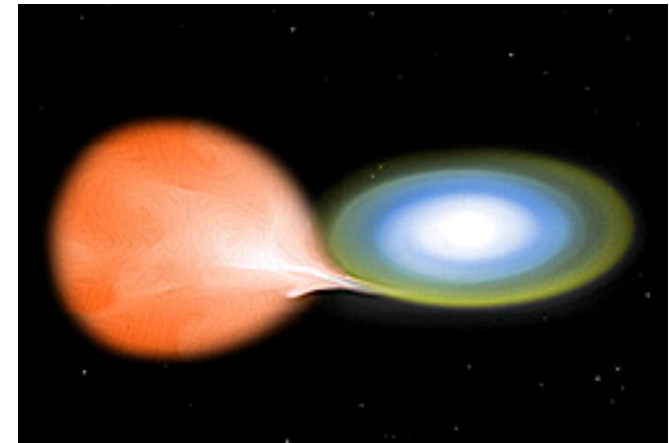
- Hot ejecta gas is initially seen as an expanding photosphere
- When the expanding material becomes optically thin, free-free and line emission dominate

### 1). CO Novae;

- Thermonuclear runaway (TNR) on the surface of relatively low-mass CO white dwarves (e.g.,  $M_{\text{WD}} < 1.1 M_{\odot}$ )
- 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.,  $M_{\text{WD}} > 1.1 M_{\odot}$ )
- 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

# V1280 Scorpii

- Discovered on Feb 4.86, 2007 by Y. Nakamura and Y. Sakurai (Yamaoka et al. 2007)
- $d = 1.6 \pm 0.4$  kpc (Chesneau et al. 2008)
- Dust formation occurred at  $d \sim 23$  days 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;  $0.35 \pm 0.03$  mas day<sup>-1</sup>
- Expansion velocity of the nova ejecta;  $500 \pm 100$  km/s
- Dust production rate;  $2 - 8 \times 10^{-9} M_{\text{sun}} \text{ day}^{-1}$  (a probable peak in production at  $t = 36 - 46$  days)
- The amount of dust in the shell;  $2.2 \times 10^{-7} M_{\text{sun}}$

## Late-epoch Observations of Dust Forming Nova V1280Sco

- July 7, 2007 (epoch ~150 days)

Subaru/COMICS; N-band spectroscopy (8-13.4 $\mu\text{m}$ ), N- & Q-band photometry (8.8, 11.7, 18.8, 24.5 $\mu\text{m}$ )

Kanata/TRISPEC (June 26, 2007; epoch ~140 days); Ks-band photometry (2.15 $\mu\text{m}$ )

- Aug. 1, 2010 (epoch ~1272 days) [GS-2010B-C-7, PI; Sakon, I.]

Gemini-S/TReCS; N-band spectroscopy (7.7-13.2 $\mu\text{m}$ ), N- & Q-band photometry (7.8, 9.7, 11.7, 18.8, 24.5 $\mu\text{m}$ )

Gunma (Aug 26, 2010; epoch ~1300 days); J, H, Ks-band photometry (1.24, 1.66, 2.15 $\mu\text{m}$ )

- July 10, 2011 (epoch ~1616 days) [GS-2011B-C-4, PI; Sakon, I.]

Gemini-S/TReCS; N-band spectroscopy (7.7-13.2 $\mu\text{m}$ ), N- & Q-band photometry (7.8, 9.7, 11.7, 18.8, 24.5 $\mu\text{m}$ )

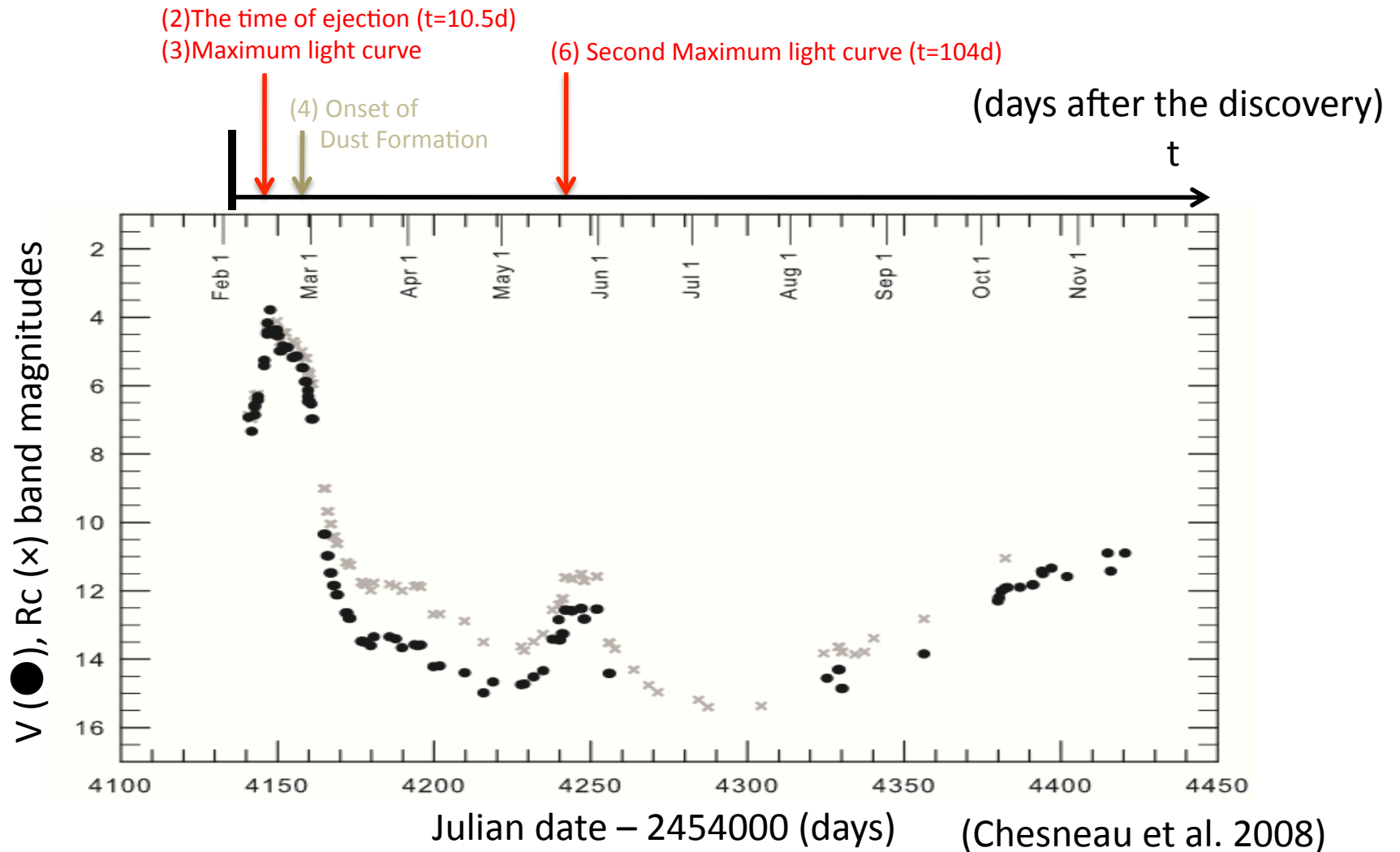
Gunma (Sep 8, 2010; epoch ~1670 days); J, H, Ks-band photometry (1.24, 1.66, 2.15 $\mu\text{m}$ )

- Sep. 8, 2009 (epoch ~940 days) [AKARI phase 3-II Open Time program "SENN", PI: Sakon I.]

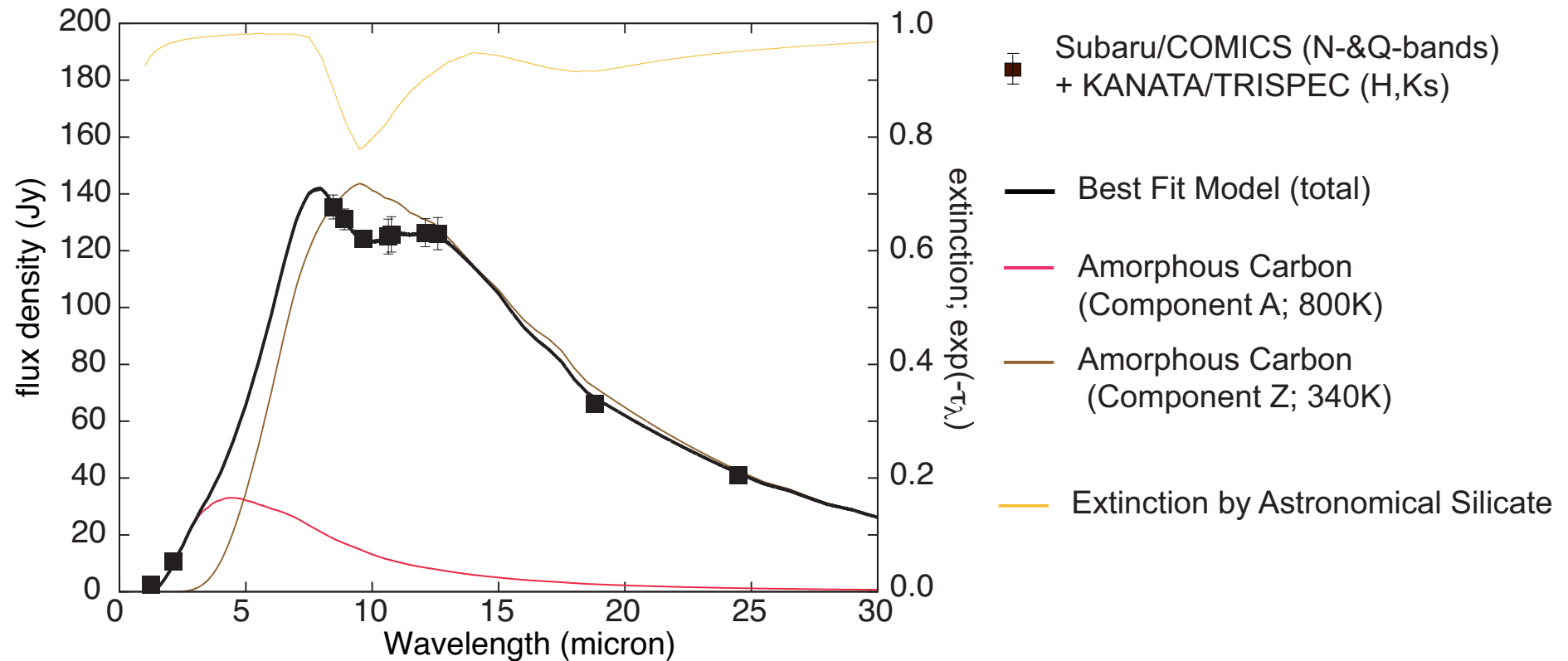
AKARI/IRC; near-infrared spectroscopy (2.5-5 $\mu\text{m}$ )

# Mass loss and Dust Formation History of V1280Sco

- (1) DISCOVERY ; 2007, Feb., 4.85 [JD=2454136.85] (t=0 days; Yamaoka et al. 2007)
- (2) THE TIME OF EJECTION ; 2007, Feb., 15 (t~10.5±7 days; Das et al. 2008; Chesneau et al. 2008)
- (3) MAXIMUM LIGHT CURVE ; 2007, FEB., 16 (t=12 days after the discovery)
- (4) ONSET OF DUST FORMATION ; 2007, FEB, 28 (t=23 days after the discovery)
- (5) HIGHEST DUST FORMATION ; t=36-45 days  $7.4 \times 10^{-9} M_{\text{sun}}/\text{day}$  (Chesneau et al. 2008)
- (6) SECOND MAXIMUM ; 2007, MAY, 20 (t=104 days after the discovery)



# Spectral Decomposition of model fit to the Infrared Continuum Spectrum of V1280Sco at $\sim 150$ days obtained with Subaru/COMICS



Component A; Amorphous Carbon;  $800 \pm 20$  (K),  $1.7 \times 10^{-8} M_{\text{sun}}$   
Component Z; Amorphous Carbon;  $340 \pm 20$  (K),  $2.4 \times 10^{-6} M_{\text{sun}}$   
Foreground Extinction;  $A_v \sim 4.5 \pm 0.5$  mag

# Temperature Evolution of Dust Formed in the Nova Wind

Assuming the radiative equilibrium

$$4\pi a^2 \langle Q_{\text{abs}}(a, T_d) \rangle T_d^4 = \pi a^2 \langle Q_{\text{abs}}(a, T_{\text{WD}}) \rangle T_{\text{WD}}^4 (R_{\text{WD}}/r)^2$$

$$L_{\text{WD}} = 4\pi\sigma R_{\text{WD}}^2 T_{\text{WD}}^4$$

$\langle Q_{\text{abs}}(a, T) \rangle$  ; the Planck mean absorption cross-section for amorphous carbon

$a$ ; the radius of a dust grain [m]

$T_d$ ; the temperature of a dust grain

$r$ ; the distance between the dust and the white dwarf [m]

$R_{\text{WD}}$ ; effective radii of the White dwarf star [m]

$T_{\text{WR}}$ ; effective temperature of the white dwarf star [K] ( $\sim 10000\text{K}$ ; Chesneau et al. 2008)

$L_{\text{WR}}$ ; total luminosity of the white dwarf star [W] ( $\sim 8400L_{\odot}$ ; Chesneau et al. 2008 )

$\sigma$  ; Stephan-Boltzmann constant [ $\text{W K}^{-4} \text{m}^{-2}$ ]

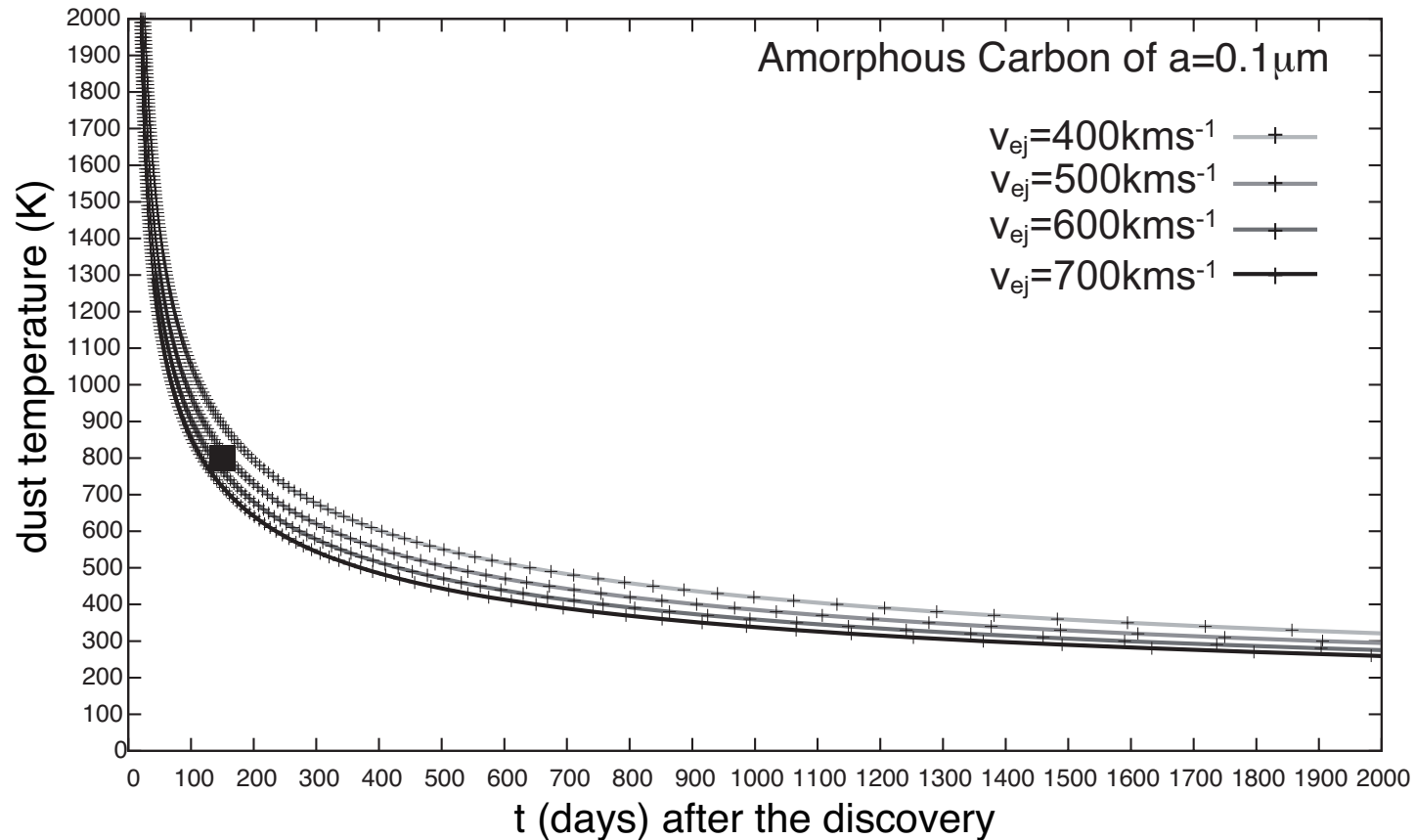
$$r = (L_{\text{WD}}/16\pi\sigma)^{1/2} (\langle Q_{\text{abs}}(a, T_{\text{WD}}) \rangle / \langle Q_{\text{abs}}(a, T_d) \rangle)^{1/2} T_d^{-2}$$

If the dust particles formed in the nova wind ejected at  $t=t_{\text{ej}}$  are assumed to expand with a constant velocity  $v_{\text{ej}}$  [ $\text{km s}^{-1}$ ], they reach at  $r = 8.64 \times 10^7 v_{\text{ej}} (t - t_{\text{ej}})$  [m]

$$(L_{\text{WD}}/16\pi\sigma)^{1/2} (\langle Q_{\text{abs}}(a, T_{\text{WD}}) \rangle / \langle Q_{\text{abs}}(a, T_d) \rangle)^{1/2} T_d^{-2} = 8.64 \times 10^7 v_{\text{ej}} (t - t_{\text{ej}})$$

# Origin of 800K Amorphous Carbon at 150 days

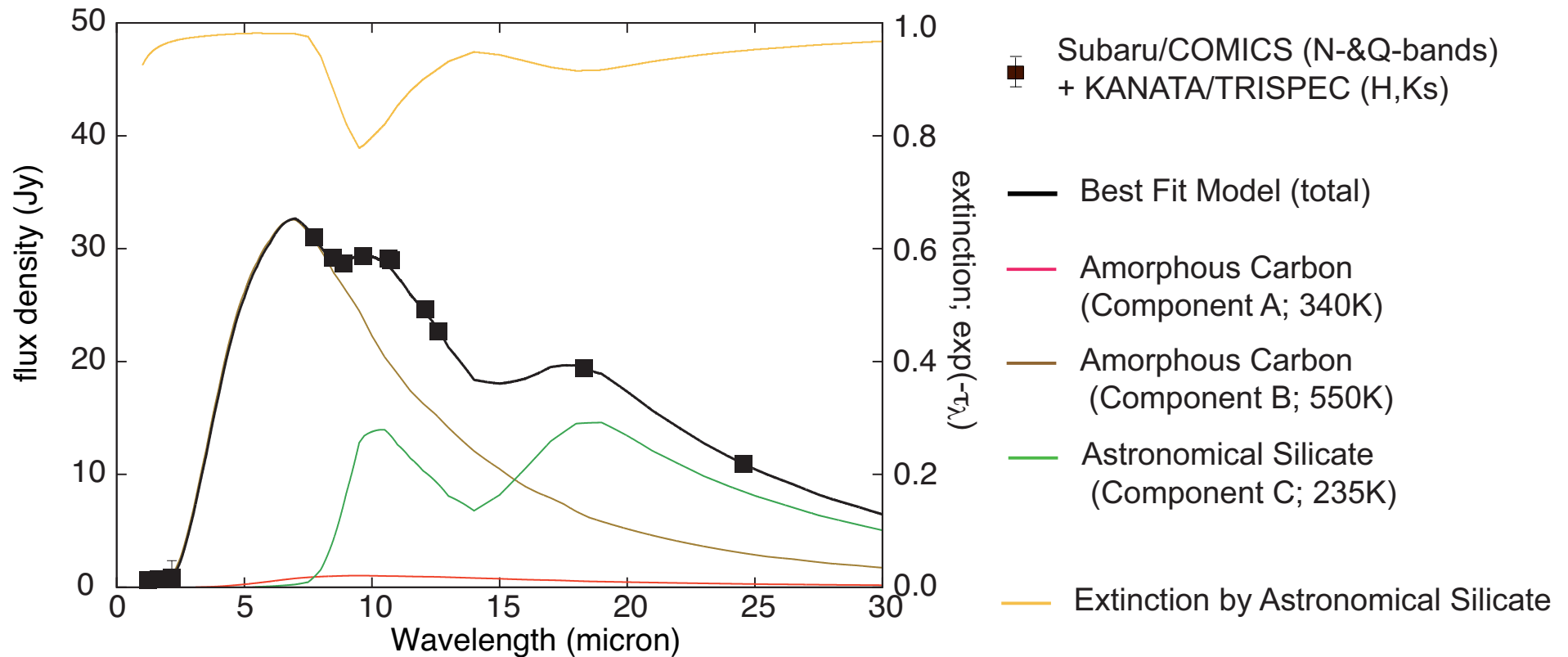
Temperature evolution of amorphous carbons formed in the nova wind ejected at  $t=10.5$  days



The temperature of amorphous carbons formed in the nova wind ejected at 10.5 days expanding with a velocity of 500km/s (Chesneau et al. 2008) should become 800K at  $t=150$ days.

The temperature of those amorphous carbons at  $t\sim 40$  days, which corresponds to the epoch of highest dust formation, is consistent with the condensation temperature of amorphous carbons ( $\sim 1500\text{K}$ ).

# Spectral Decomposition of model fit to the Infrared Continuum Spectrum of V1280Sco at $\sim 1272$ days obtained with Gemini-S/TReCS



Component A; Amorphous Carbon;  $340 \pm 10$  (K),  $1.7 \times 10^{-8} M_{\text{sun}}$

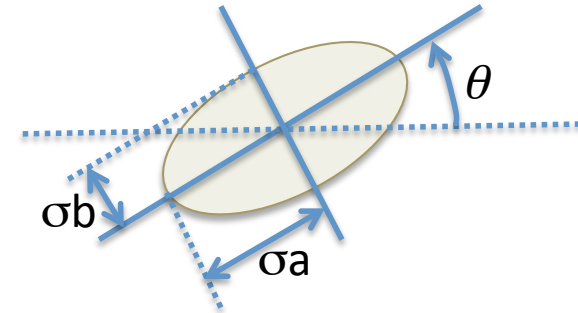
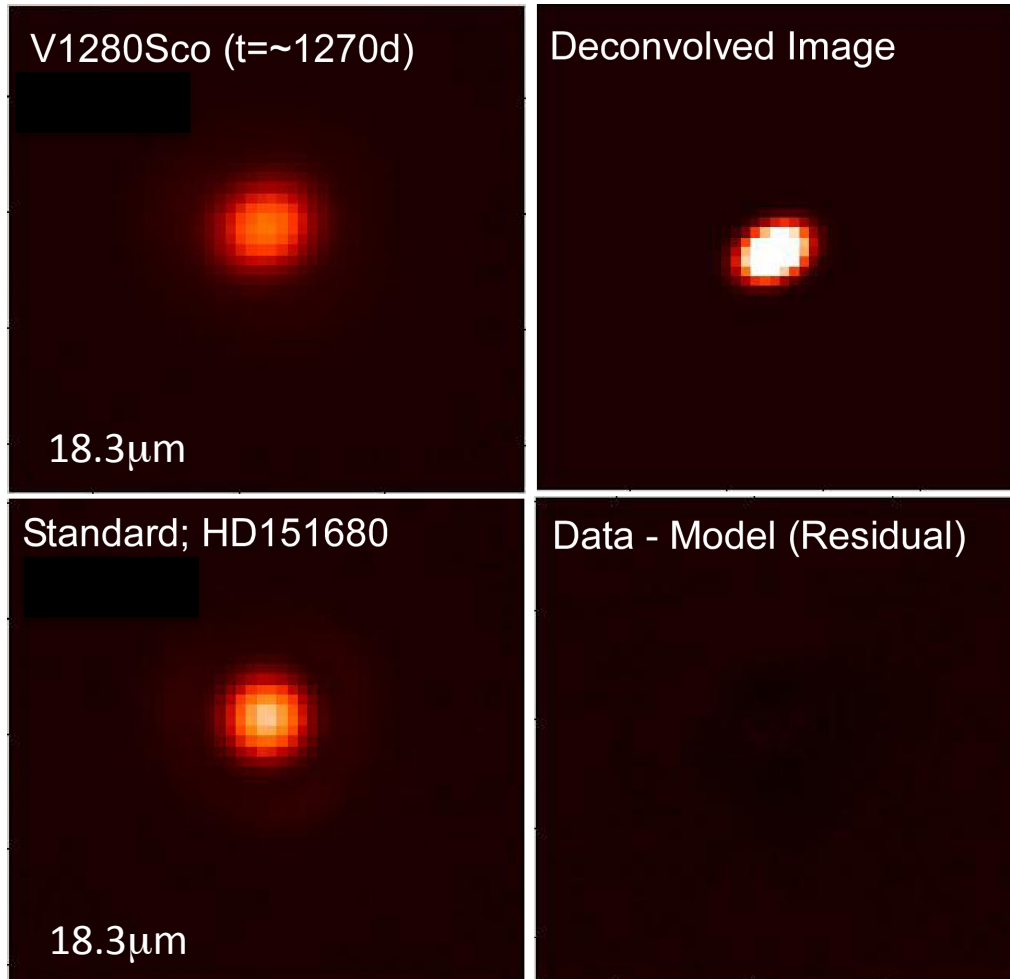
Component B; Amorphous Carbon;  $550 \pm 20$  (K),  $7.1 \times 10^{-8} M_{\text{sun}}$

Component C; Astronomical Silicate;  $235 \pm 10$  (K),  $7.1 \times 10^{-7} M_{\text{sun}}$

Foreground Extinction;  $A_v \sim 4.5 \pm 0.5$  mag

# Results of N- & Q-band imaging observations of V1280 Sco at $t \sim 1270$ days with Gemini-S/TReCS

Example; Qa band data of V1280Sco and HD151680



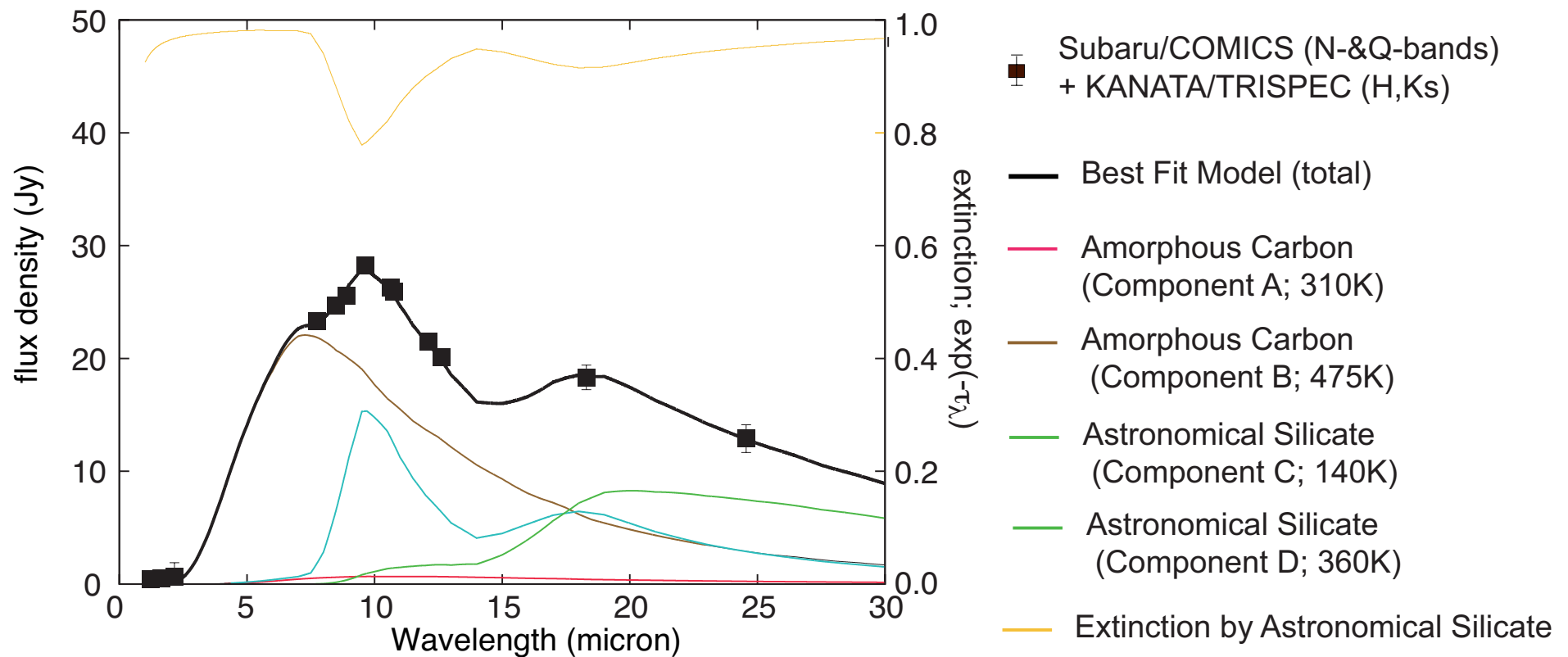
Intrinsic profile of the dust emission;  
3D-Elliptical Gaussian  
 $\theta$  ; position angle for the major-axis  
 $\sigma_a$  ; semi-major axis radius  
 $\sigma_b$  ; semi-minor axis radius

The best-fit 3D-Elliptical Gaussian parameters

Band	$\lambda(\mu\text{m})$	$\theta$ (deg)	$\sigma_a$ (")	$\sigma_b$ (")
Si-1	7.73	25	$0.32 \pm 0.02$	$0.19 \pm 0.02$
Si-3	9.69	25	$0.30 \pm 0.02$	$0.18 \pm 0.02$
Si-5	11.66	25	$0.29 \pm 0.02$	$0.15 \pm 0.02$
Qa	18.30	25	$0.29 \pm 0.03$	$0.20 \pm 0.03$
Qb	24.56	25	$0.38 \pm 0.03$	$0.23 \pm 0.03$

Non-spherical distribution of dust emission  
Effective size of the dust shell at 1270d;  $7.2 \times 10^{10}$  km  
→ consistent with the expansion velocity of 500 km/s

# Spectral Decomposition of model fit to the Infrared Continuum Spectrum of V1280Sco at $\sim 1616$ days obtained with Gemini-S/TReCS



Component A; Amorphous Carbon;  $310 \pm 10$  (K),  $1.7 \times 10^{-8} M_{\text{sun}}$

Component B; Amorphous Carbon;  $475 \pm 25$  (K),  $8.7 \times 10^{-8} M_{\text{sun}}$

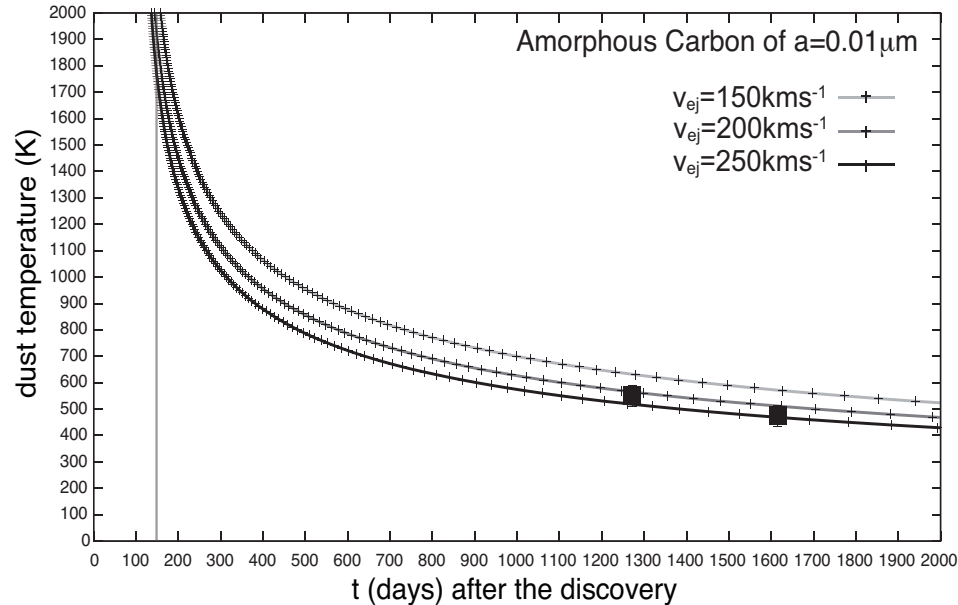
Component C; Astronomical Silicate;  $140 \pm 25$  (K),  $3.6 \times 10^{-6} M_{\text{sun}}$

Component D; Astronomical Silicate;  $360 \pm 25$  (K),  $8.9 \times 10^{-8} M_{\text{sun}}$

Foreground Extinction;  $A_v \sim 4.5 \pm 0.5$  mag

# Origin of 550K Amorphous Carbon at 1272 days

Temperature evolution of amorphous carbons formed in the nova wind ejected at  $t=104$  days

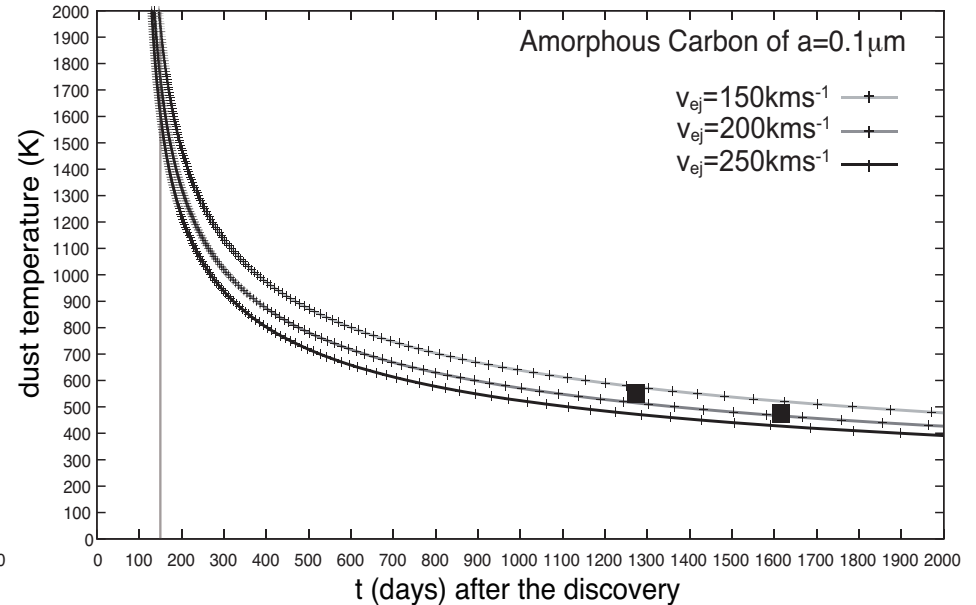


(left)

The temperature of amorphous carbon with a size of  $a=0.01\mu\text{m}$  formed in the wind of nova ejected at 104 days expanding with 200-250 km/s should be  $\sim 550\text{K}$  at  $t=1272\text{d}$  and  $\sim 480\text{K}$  at  $t=1616\text{d}$ .

(right)

The temperature of amorphous carbon with a size of  $a=0.1\mu\text{m}$  formed in the wind of nova ejected at 104 days expanding with  $\sim 200\text{ km/s}$  should be  $\sim 500\text{K}$  at  $t=1272\text{d}$  and  $\sim 480\text{K}$  at  $t=1616\text{d}$ .



The condensation of this component had not yet begun on  $t\sim 150$  days

→ The nova wind ejected at  $t=104$  days might be corresponding to the blue shifted ( $\sim -255\text{km/s}$ ) absorption component of permitted FeII lines found in the optical spectrum obtained on  $t=824\text{d}$  (Sadakane et al. 2010)

## Origin of 235K Astronomical Silicate at 1272 days

Assumptions; the 240K astronomical silicate dust grains are in radiative equilibrium  
and  $\langle Q_a(a, T_d) \rangle \propto T_d^\beta$  holds for the astronomical silicate ( $1 < \beta < 2$ )

→ The temperature of astronomical silicate in radiative equilibrium follows  $T_d \propto r^{-2/(4+\beta)}$

If the  $235 \pm 10$  K *astronomical silicate dust at 1272 days* and  $140 \pm 25$  K *astronomical silicate dust at 1616 days* have the same origin and are newly formed dust in the nova wind, the epoch of the ejection of the resource materials should become  $t = 1120 - 1220$  days

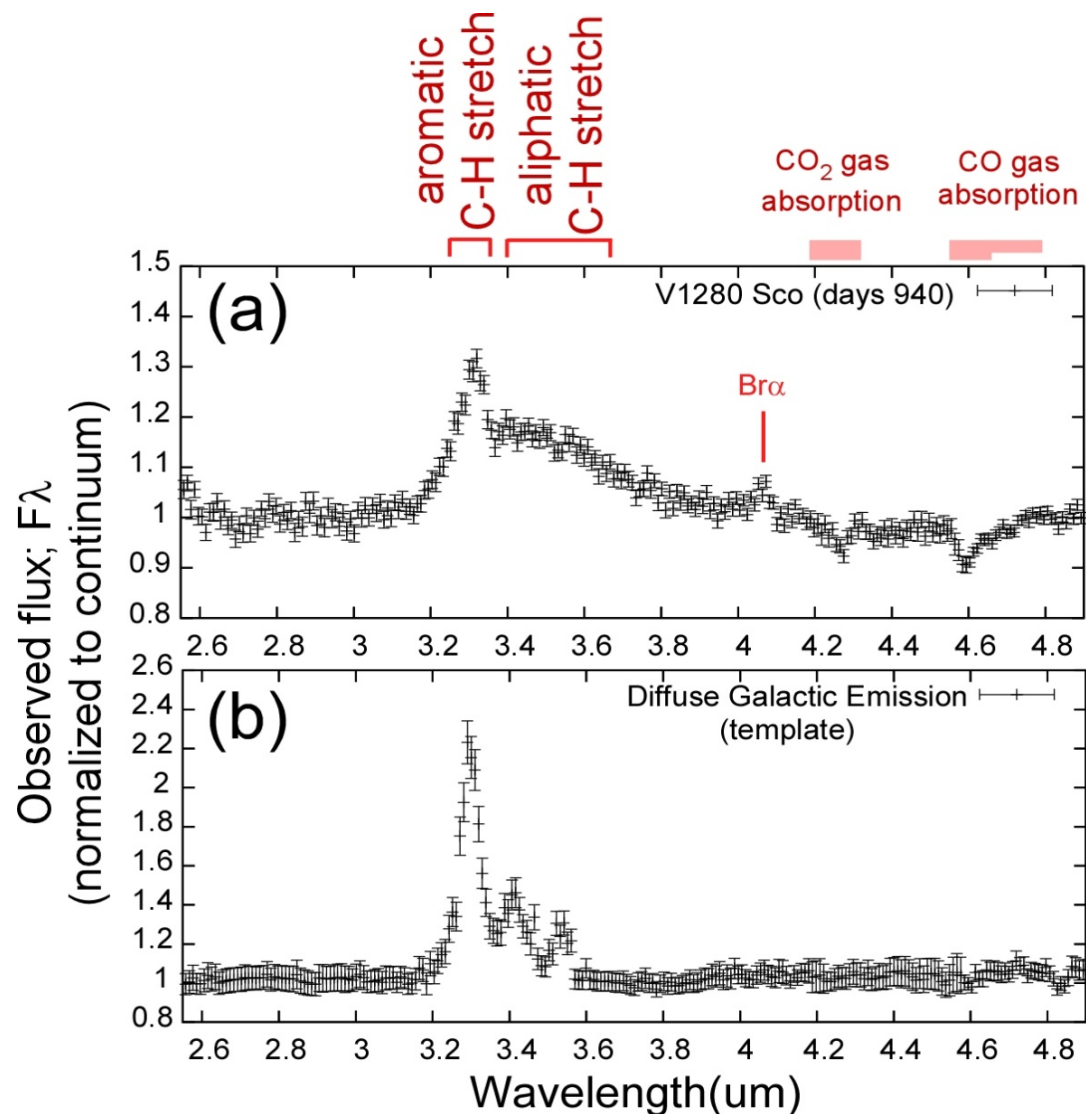
Rapid cooling of silicate dust grains requires their high expansion velocity;

→ Related to the  $2000 \text{ km s}^{-1}$  high velocity component reported in Naito et al. (2009) [?]

## Presence of new 360K Astronomical Silicate at 1616 days

If the 300K astronomical silicate at 1616 days should also be the newly formed dust in the nova wind, intermittent nature of nova wind is suggested.

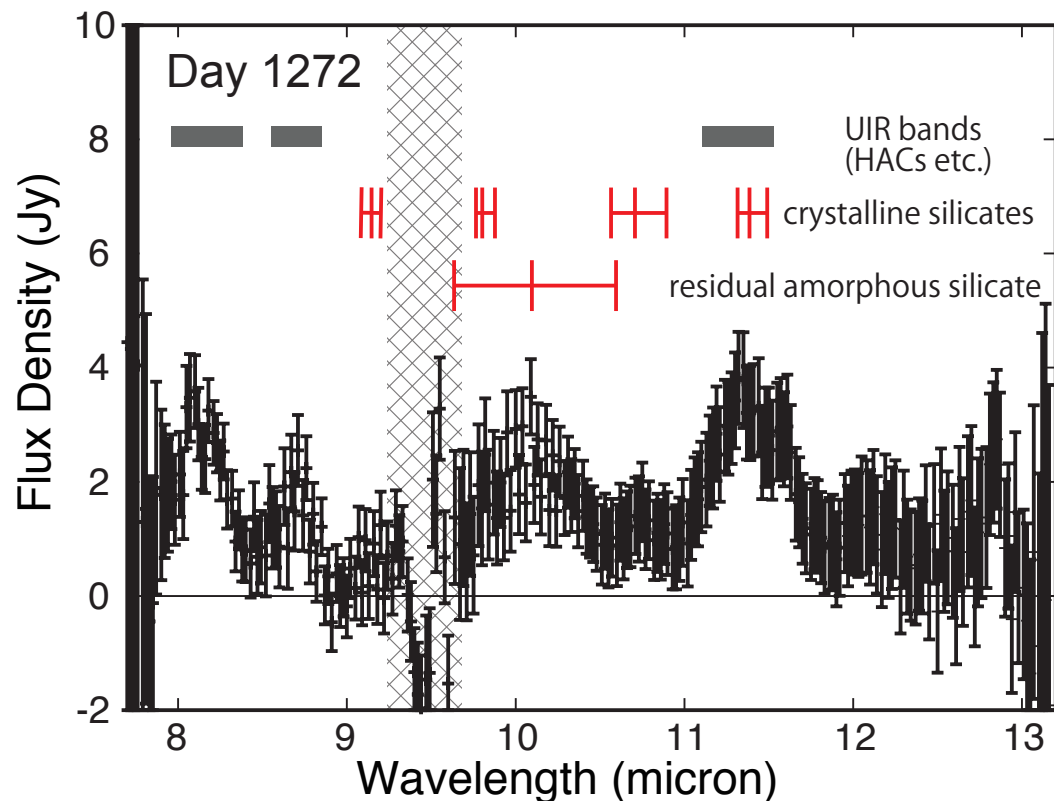
# Near Infrared Spectrum of V1280Sco at ~940 days with AKARI/IRC



(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 3.3 $\mu\text{m}$  feature with a strong redwing in 3.4-3.6 $\mu\text{m}$  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 3.5 $\mu\text{m}$  features obtained with AKARI/IRC.

# Mid-Infrared Spectral Features over the Infrared Continuum modeled with amorphous carbon and astronomical silicate at 1272 days



Features at  $\sim 8.1\mu\text{m}$ ,  $\sim 8.7\mu\text{m}$ ,  $\sim 11.35\mu\text{m}$ ;

Hydrogenated Amorphous Carbons (HACs), NH<sub>2</sub>-rocks (Grishko & Duley 2002)

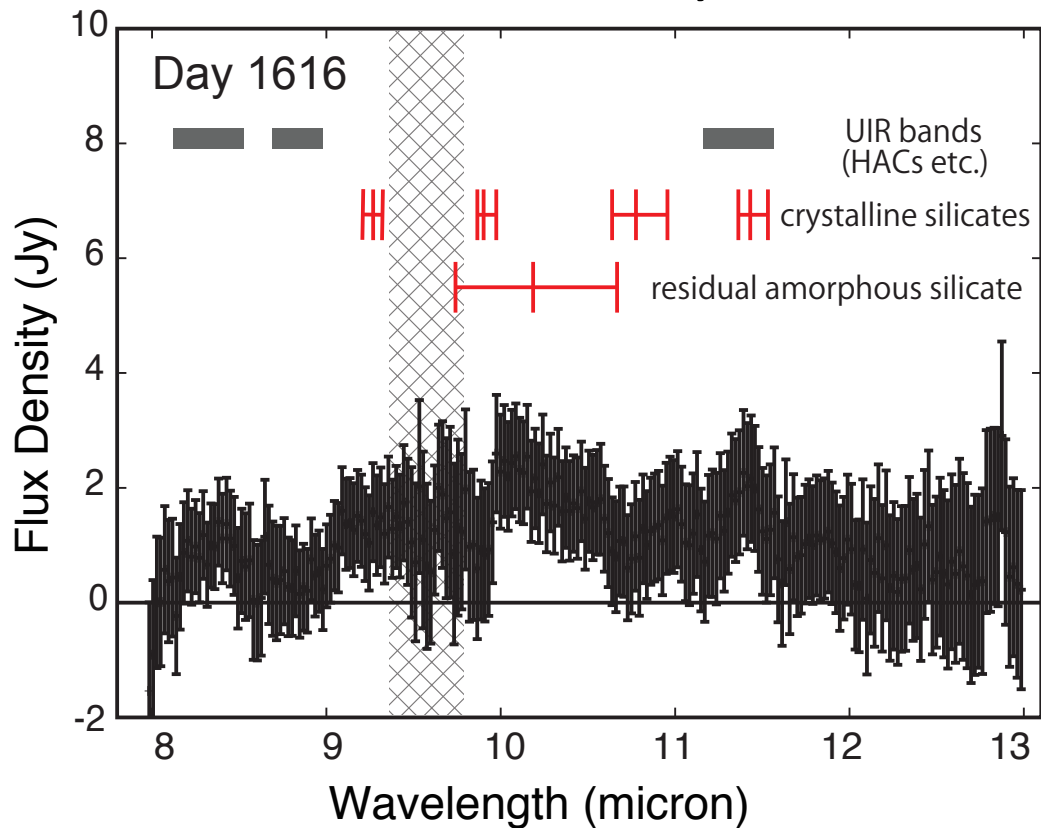
→ similar to those found in V704 Cas 1993 (Evans et al. 1997, 2005)

A Broad Feature at  $\sim 10.1\mu\text{m}$ ; amorphous silicate

Features at  $\sim 9.2\mu\text{m}$ ,  $\sim 9.8\mu\text{m}$ ,  $\sim 10.7\mu\text{m}$ ,  $\sim 11.4\mu\text{m}$ ;

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

# Mid-Infrared Spectral Features over the Infrared Continuum modeled with amorphous carbon and astronomical silicate at 1616 days



Possible HAC features at  $\sim 8.1\mu\text{m}$ ,  $\sim 8.7\mu\text{m}$ ,  $\sim 11.35\mu\text{m}$  have diminished at  $t=1616$  days

## Summary; IR observations of V1280Sco

800K amorphous carbon dust observed at  $t \sim 150$  days is expected to be the newly formed dust in the nova wind ejected around at the maximum of the light curve ( $t \sim 10.5$  days) expanding with a velocity of 500 km/s.

550K amorphous carbon dust observed at  $t \sim 1272$  days is expected to be the newly formed dust in the nova wind ejected at the second maximum light curve ( $t \sim 140$  days) expanding with a velocity of 200-250 km/s.

New presence of 235K astronomical silicate dust at  $t \sim 1272$  and 140K astronomical silicate dust at  $t \sim 1616$  days may indicate the late-epoch formation of astronomical silicate in the nova wind

New presence of 360K astronomical silicate dust at  $t \sim 1616$  days may indicate the intermittent natures of nova wind activities and of the dust formation histories of V1280Sco

Detection of  $3.3 \mu\text{m}$  feature with strong red-wing in AKARI/IRC NIR spectrum at  $t = \sim 940$  days and of  $8.1$ ,  $8.7$  and  $11.35 \mu\text{m}$  features in the spectrum of V1280 Sco at  $t \sim 1270$  days in the N-Band low resolution spectra obtained with Gemini-South/TReCS indicate the presence of Hydrogenated Amorphous Carbons (HACs) in V1280Sco

Multi epoch mid-infrared observation of dust forming novae with higher time-resolution ( $\sim$  a week) are important to investigate the condensation process of dust and molecular species.