Mid-infrared observations of dust grains in the molecule-forming classical nova V2676 Oph with Subaru/COMICS

T. Ootsubo[1], H. Kawakita[2], A. Arai[2], Y. Shinnaka[2,3], M. Nagashima[2]

[1]Graduate School of Arts and Sciences, The University of Tokyo, Japan

[2]Koyama Astronomical Observatory of Kyoto Sangyo University, Japan, [3] National Astronomical Observatory of Japan

Abstract

A dust-forming nova V2676 Oph (discovered in Mar 2012) is so unique that it was the first nova to provide evidence of both C_2 and CN molecules during its near-maximum phase, and evidence of CO molecules during its early decline phase (Nagashima et al. 2014). The derived carbon- and nitrogen-isotopic ratios in the nova (Kawakita et al. 2015) are consistent with that the nova explosion was hosted by a CO-rich white dwarf (WD) star. In order to confirm a type of the hosting WD (CO-rich or ONe-rich), we performed the mid-infrared photometric and spectroscopic observations of V2676 Oph with COMICS mounted on the Subaru telescope in June 2013 and May 2014. No clear [Ne II] emission line at 12.8 micron was observed, and this fact supports the CO-rich WD hosting V2676 Oph. Furthermore, our observations detected the thermal emission from not only carbon-rich grains but also silicate grains, although this nova is considered as a Carbon-rich (C/O > 1) based on the presence of C_2 observed earlier. Non-equilibrium processes are responsible for the grain formation in the nova. We also detected unidentified-IR feature at 11.4 micron at both epochs.

(A full paper of this work will appear in The Astronomical Journal: Kawakita et al. 2017, AJ, in press)

Background

★ What is classical nova V2676 Oph?

The classical nova V2676 Oph is unique because it was the first nova to provide evidence of C_2 molecules and is only the second example of a nova in which CN molecules have been detected (the first example was DQ Her in 1934) during its near-maximum phase, as reported by Nagashima *et al*. (2014). The nova was discovered by Nishimura (2012) with a UT on 2012 March 25.8 (probably just after the explosion) and was considered an "Fe II-type" classical nova (according to the classification by Williams 1992) based on optical low-resolution spectroscopic observations (Arai & Isogai 2012). Kawakita *et al*. (2016) revealed that the photospheric temperature of V2676 Oph had cooled to ~4500 K around its visual brightness maximum; C_2 and CN molecules form while the estimated typical photospheric temperature of a nova is ~8000 K (Evans *et al*. 2005), corresponding to F-type supergiant stars. During the early decline phase of the nova, strong emission from CO molecules was also detected (Rudy *et al*. 2012). The existence of both C_2 and CN radicals in the photosphere indicates that the nova envelope was C-rich, with C/O>1 (Kawakita *et al*. 2016).

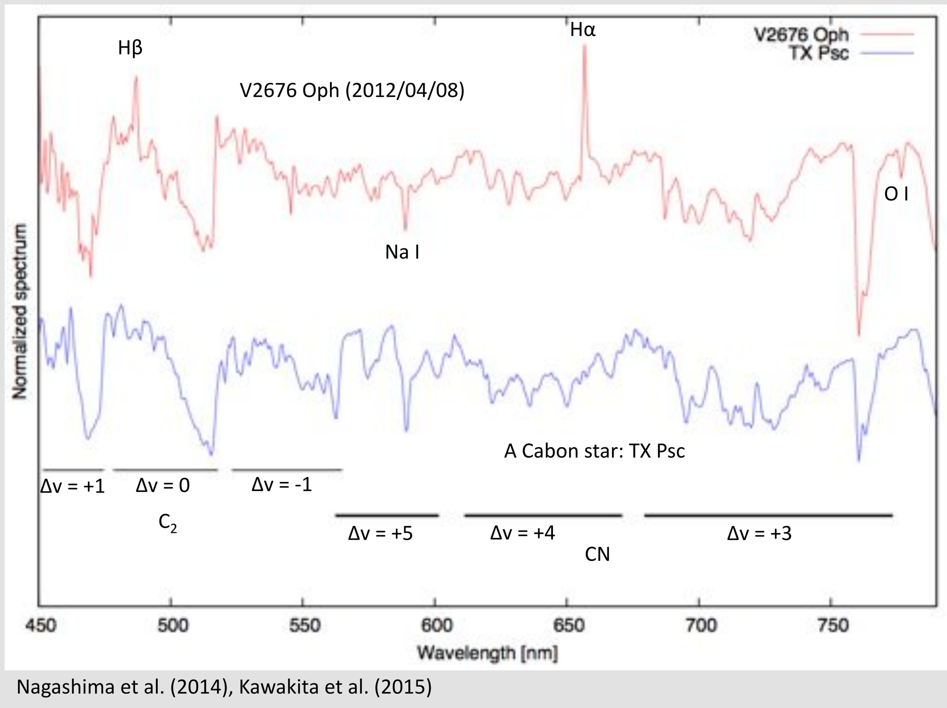

Fig. 1: The first detection of C_2 in classical novae. The upper spectrum is the V2676 Oph (14 days after the discovery). The lower spectrum is a typical carbon-star TX Psc for comparison.

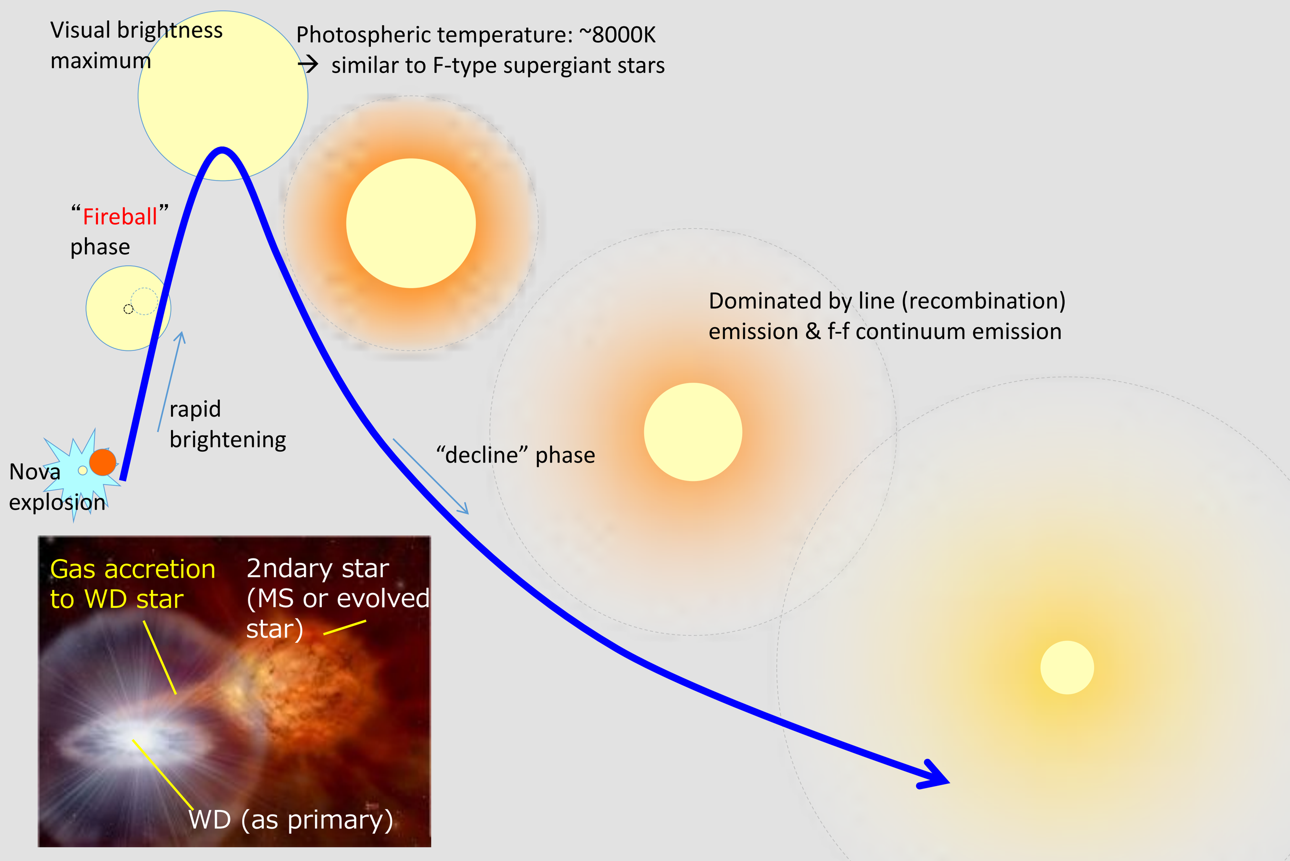

Fig. 2: Evolution of a typical classical nova.

★ Why mid-infrared (MIR) observations are important?

Observational circumstances.

Date
UT 2013 June 20.4 (t =452d)
UT 2014 May 16.5 (t =782d)

Telescope / instrument
Subaru Telescope with COMICS

Observational modes
〈Spectroscopy〉
N-band, low-resolution
λ = 8〜13μm, R〜250
〈Photometry〉
N-band, with filters:
λ_c = 7.8, 8.8, 12.4 μm

Fig. 3: Subaru telescope and COMICS.

To understand the peculiarity of V2676 Oph, we conducted mid-infrared (*N*-band) spectroscopic observations of the nova during its late decline phase. In particular, the [Ne II] emission line at 12.8 μm in the nebular phase of a nova provides a clue to the nature of the WD star hosting V2676 Oph with regard to whether it is CO- or ONe-rich. Usually, novae occurring on ONe-rich WDs exhibit strong [Ne II] emission lines at 12.8 μm in the *N*-band (Evans & Gehrz 2012; Gehrz 2008). Furthermore, V2676 Oph exhibits the signature of dust formation in its light curves (Raj *et al*. 2016). Understanding the nature of dust grains formed in V2676 Oph is also interesting from the point of view of the dust-formation process in novae. Because the envelope of the nova was carbon-rich, C/O>1 (i.e., oxygen atoms were consumed by the formation of CO molecules if the chemical equilibrium for molecular and dust formation is assumed), carbon grains rather than silicate grains in V2676 Oph are, in principle, expected to be enriched.

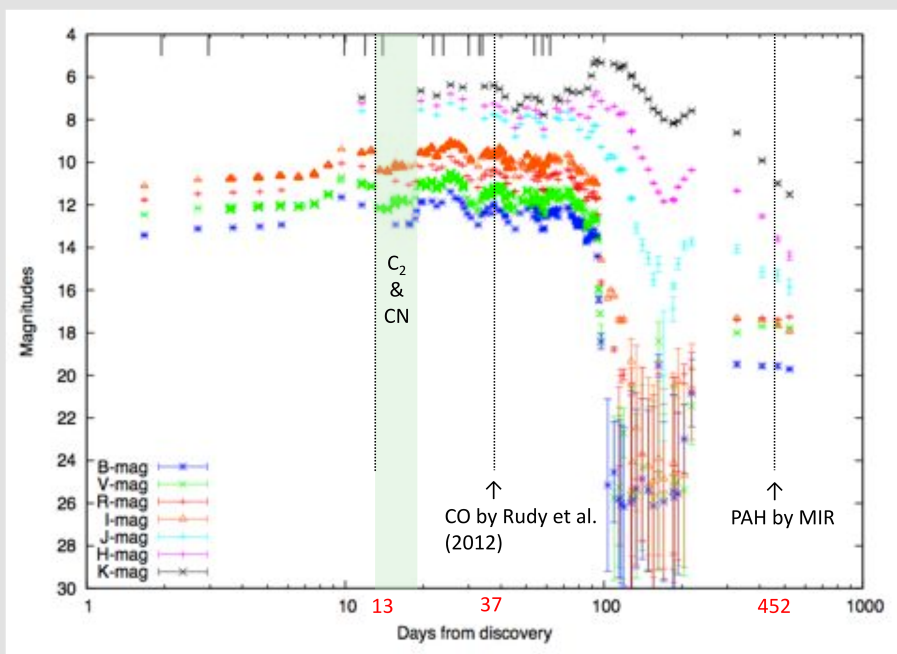

Fig. 4: Multiband lightcurves of V2676 Oph (Nagashima et al. 2014).

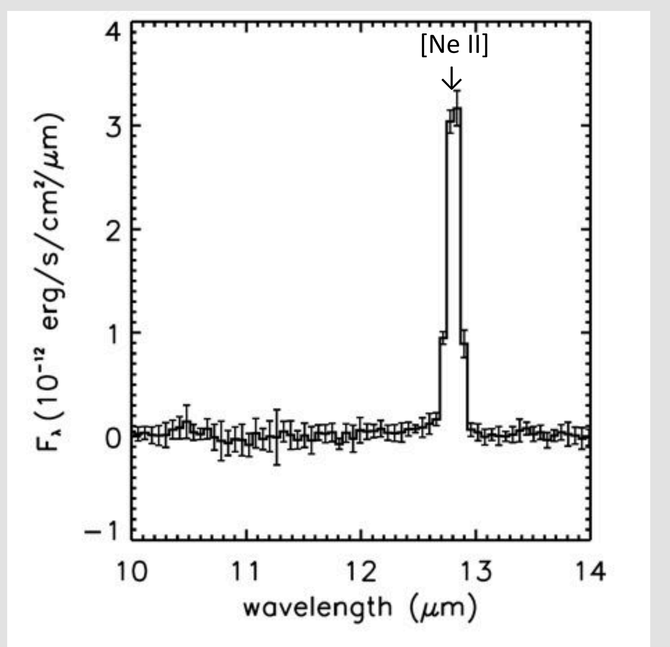

Fig. 5: Typical MIR spectrum for nova hosted by ONe-rich WD, QU Vul (Gehrz et al. 1997).

Results of our MIR observations

Fig. 6 shows the observed low-resolution spectra of V2676 Oph in the *N*-band at t = 452d and 782d (t = 0d is taken to mark the discovery). No clear emission of [Ne II] at 12.8 μm was seen in either the 2013 or 2014 observations, although the [Ne II] emission line is usually recognized in the nebula phase of a nova originating from an ONe-rich WD. To confirm the presence of the [Ne II] emission line, we subtracted the synthesized thermal emission of grains from the observed spectra in the manner described below. In subsequent paragraphs, we will discuss the presence of [Ne II] emission based on the residuals of the spectra. We will also discuss the nature of the dust grains formed in V2676 Oph, as well as the UIR features.

The thermal emission from dust grains at λ (μm) is modeled by the following expression in the case of the optically thin condition:

$$f_{NOVA}(\lambda) = q \times [\,(1-r) \times Q_{abs}[\mathrm{aCar}] \times BB(T_{aCar}) + r \times Q_{abs}[\mathrm{astrSil}] \times BB(T_{astrSil})\,] \times f_{ext}(\lambda)\ .$$

The parameter q denotes the scaling factor for the observed flux density in [W/m²/μm], r is the fraction of astronomical silicate grains, and Q_{abs}[aCar] and Q_{abs}[astrSil] are the absorption efficiencies of amorphous carbon and astronomical silicate grains, respectively. BB(T) is the Planck function at temperature T. Interstellar extinction, $f_{ext}(\lambda)$, is modeled in a similar way to Sakon *et al*. (2016). We assumed astronomical silicate grains of a 0.1 μm radius to reproduce the shape of the extinction curve in the *N*-band. The optical depth at 9.7 μm for interstellar extinction ($\tau_{9.7}$) was calibrated by the estimated value of $\tau_{9.7}$ based on extinction in the *V*-band (A_V) towards the direction of V2676 Oph, A_V = 2.65±0.15 (Kawakita *et al*. 2016). We converted the value of A_V to $\tau_{9.7}$ based on the formula: $A_V/\tau_{9.7}$ = 18.5±1.5 (Roche & Aitken 1984).

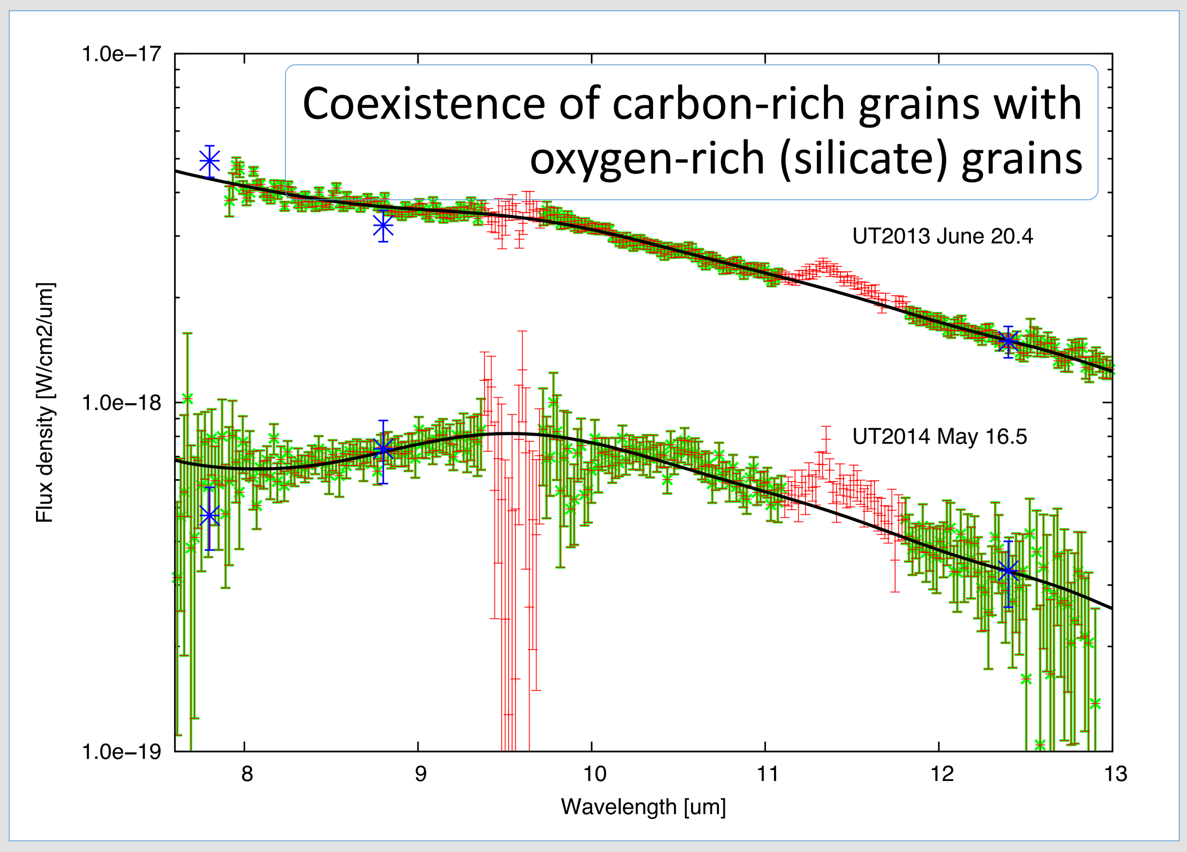

Fig. 6: Low-resolution *N*-band spectra of V2676 Oph taken at t = 452d (UT 2013 June 20.4) and 782d (UT 2014 May 16.5). Photometric data points on both dates are also plotted in the same figure.

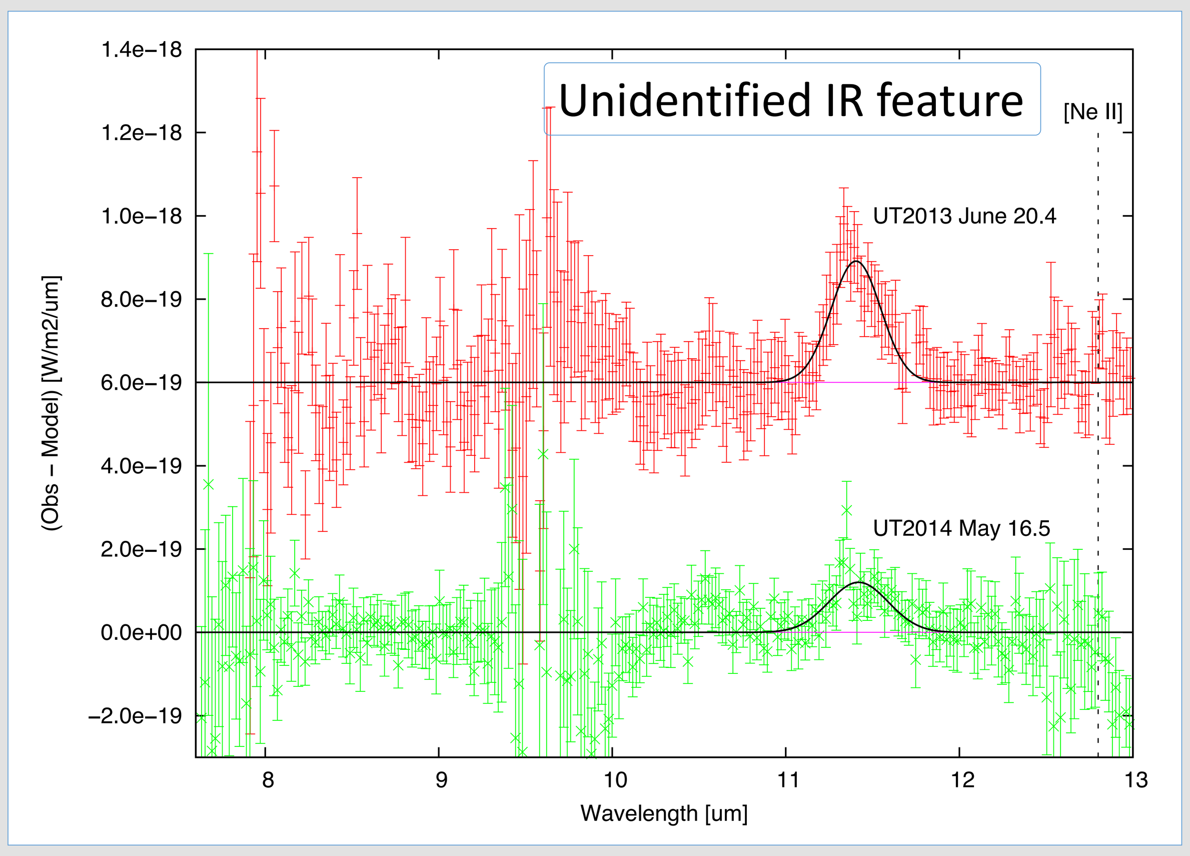

Fig. 7: Residual spectra of V2676 Oph at t = 452d (UT 2013 June 20.4) and 782d (UT 2014 May 16.5). The residual spectrum at t = 452d is shifted by 6×10^{-19} to distinguish these spectra. No prominent [Ne II] emission line at 12.8 μm is recognized in the observed spectra (there is a hint of [Ne II] emission but not significantly so in 2013).

Table 1: Best-fit parameters for V2676 Oph.

Epoch (t = 0d at discovery)	q	r	T_{aCar} [K]	$T_{astrSil}$ / T_{aCar}	reduced-χ^2
t = 452d	5.5±0.7	0.83±0.05	530±30	0.45±0.04	0.71
t = 782d	1.3±0.2	0.98±0.03	840±460	0.30±0.17	0.72

The residual spectra of V2676 Oph after the subtraction of synthesized dust emission spectra from the observed spectra (Fig. 7) showed no evidence of the emission of [Ne II] at 12.8 μm, which is usually observed in the late phase of a nova occurring on an ONe-rich WD (Gehrz *et al*. 1998; Gehrz 2008; Evans & Gehrz 2012). This suggests that V2676 Oph originated on a CO-rich WD. The dust formation in V2676 Oph also supports this hypothesis, because novae on ONe-rich WDs exhibit little dust formation during their decline phase (Gehrz 2008).

CO-rich WD star hosting V2676 Oph → Consistent with (1) lightcurves (Hachisu & Kato 2015; Horne et al. 1993), and (2) isotopic ratios of carbon and nitrogen (Kawakita et al. 2015: Denissenkov et al. 2014)

The UIR emission at 11.4 μm (identified as the aromatic C-H "out-of-plane bending" feature) was clearly detected in both spectra taken at t = 452d and 782d. The coexistence of UIR carriers and carbon-rich grains in V2676 Oph supports the formation of UIR carriers from amorphous carbon grains, as predicted by Mitchell & Evans (1984). If we fit the UIR emission with a Gaussian function, the central wavelength (and full width at half maximum) are 11.40±0.01 μm (0.34±0.02 μm) at t = 452d and 11.42±0.02 μm (0.40±0.05 μm) at t = 782d, and are consistent with those of the UIR emission in V705 Cas (Evans *et al*. 2005). These central wavelengths are slightly longer than the standard wavelength of the UIR feature, 11.25 μm (Evans & Gehrz 2012). No other strong UIR features are seen in V2676 Oph, although a prominent emission complex at around 8.0–9.0 μm was observed in V705 Cas, as reported by Evans *et al*. (2005). The absence of the expected UIR emission at ~8.6 μm (weaker than the emission at ~11.4 μm) might indicate that PAHs in V2676 Oph at t = 452d and 782d were neutral PAHs rather than ionized PAHs (see Fig. 3 in Draine & Lee 2007). However, because free-flying PAH molecules cannot survive against the strong radiation field from the central nova in the later phase, the observed UIR might be explained instead by HAC grains (Evans & Rawlings 1994).

References: Arai & Isogai 2012, CBET, 3072, 2; Denissenkov et al. 2014, MNRAS, 442, 2058; Draine & Li 2007, ApJ, 657, 810; Evans & Rawlings 1994, MNRAS, 269, 427; Evans et al. 2005, MNRAS, 360, 1483; Evans & Gehrz 2012, BASI, 40, 213; Gehrz 2008, Classical Novae; Hachisu & Kato 2015, ApJ, 798, 76; Horne et al. 1993, ApJ, 410, 357; Kawakita et al. 2015, PASJ, 67, 17; Kawakita et al. 2016, PASJ, 68, 87; Mitchell & Evans 1984, MNRAS, 209, 945; Nagashima et al. 2014, ApJL, 780, L26; Nishimura 2012, CBET, 3072, 1; Raj et al. 2016, arXiv-1612.07906; Roche & Aitken 1984, MNRAS, 208, 481; Rudy et al. 2012, CBET, 3103; Sakon et al. 2016, ApJ, 817, 145; Williams 1992, AJ, 104, 725