The Origin of Outflows in Evolved Stars
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Towards the identification of carriers of the unidentified infrared (UIR) bands in novae

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Abstract. The unidentified infrared (UIR) bands, whose carriers are thought to be organics, have been widely observed in various astrophysical environments. However, our knowledge of the detailed chemical composition and formation process of the carriers is still limited. We have synthesized laboratory organics named Quenched Nitrogen-included Carbonaceous Composite (QNCC) by quenching plasma produced from nitrogen gas and hydrocarbon solids. Infrared and X-ray analyses of QNCC showed that infrared properties of QNCC well reproduce the UIR bands observed in novae and amine structures contained in QNCC play an important role in the origin of the broad 8 μm feature, which characterizes the UIR bands in novae. QNCC is at present the best laboratory analog of organic dust formed around dusty classical novae, which carries the UIR bands in novae via thermal emission process (Endo et al. 2021).

Keywords. (stars:) novae, cataclysmic variables, ISM: lines and bands, infrared: ISM

1. Introduction

The breakthrough brought by the space-based infrared observations, unaffected by atmospheric absorption, made it clear that organics ubiquitously exist throughout the universe from the solar system to distant galaxies. The unidentified infrared (UIR) bands, which consist of a series of emission features arising from aromatic and/or aliphatic C-C and C-H bonds (Allmandola et al. 1989; Tielens 2008), have been widely observed in various astrophysical environments (e.g., Tokunaga 1997). The organics which carry the UIR bands must, therefore, be a major constituent of the circumstellar and interstellar medium of the Galaxy. However, our knowledge of their exact chemical nature is still quite limited.

Polycyclic aromatic hydrocarbons (PAHs; Allmandola et al. 1989) and PAH-like molecular species have been commonly used to interpret the properties of the UIR bands observed in the interstellar medium. However, no individual PAH have successfully reproduced the observed properties of UIR bands. Other than PAHs, bulk carbonaceous grains have also been proposed as possible candidates of the carriers of the UIR bands observed in circumstellar environment. Quenched Carbonaceous Composite (Sakata et al. 1984, 1987) and Hydrogenated Amorphous Carbons (HAC; Jones et al. 1990) are laboratory analogues, while coal (Guillois et al. 1996) and kerogen (Papoular 2001) are examples of organic solids in the terrestrial environments. The mixed aromatic-aliphatic organics nanoparticles (MAON; Kwok & Zhang 2011), which contain heteroatoms including nitrogen in addition to hydrocarbon models have recently been suggested as a more realistic interpretation and the challenges to understand the nature of the carries of the UIR bands are still ongoing.

Classical novae, the final evolutional stage of binary systems harboring a white dwarf, eject heavy elements through outburst events and a part of them exhibit signs of dust formation. Dusty classical novae offer a valuable opportunity to investigate the formation process of dust and organics in space thanks to their higher occurrence. Past studies have shown that the UIR bands observed around novae are characterized by the presence of a broad 8 μm feature (Helton et al. 2011; Sakon et al. 2016).

2. Quenched Nitrogen-included Carbonaceous Composite (QNCC); a laboratory analogue of organics around novae

We have synthesized a laboratory organic, Quenched Nitrogen-included Carbonaceous Composite (QNCC), which can well reproduce the characteristics of the UIR bands observed in dusty classical novae. Figure 1 shows comparison of the infrared absorption spectrum of QNCC with the UIR bands observed in the nova V2361 Cyg on Day 116 after the outburst. The overall spectral properties of the spectrum of QNCC, especially the profiles of the broad 8 μm feature, are in good agreement with the UIR bands observed in V2361 Cyg. QNCC is synthesized by quenching plasma generated from nitrogen gas and hydrocarbon solids, including filmy QCC (Sakata et al. 1990) and PAHs, by a 2.45 GHz microwave discharge. Any QNCCs produced from different hydrocarbon solids (e.g., coronene, anthracene) consistently exhibit a characteristic broad feature at around 8 μm, as well as other major features at 3.3, 6.3, and 11.4 μm. The synthesis method of QNCC qualitatively mimic a possible formation process of organics around novae, where a nitrogen-rich nova wind (e.g., $N/N_{\odot} \sim 201$ for V84s Cen; Gehrz et al. 1998, $N/N_{\odot} \sim 219$ for V2361 Cyg; Munari et al. 2008) interacts with pre-existing carbonaceous dust in the circumstellar medium.

We performed X-ray Absorption Near-edge Structure (XANES) analyses of QNCC with the measurement station for X-ray absorption spectroscopy installed in the beamline BL10 at the NewSUBARU synchrotron radiation facility at the University of Hyogo (Kuki et al. 2015). The result of the XANES analyses show the presence of amine structures, which we conclude to be responsible for the broad 8 μm UIR band observed in novae. The N/C ratio of QNCC is 3-5% based on the measurement using the modified elemental analyzer/isotope ratio mass spectrometer (EA/IRMS; Ogawa et al. 2010). We conclude that QNCC is at present the best laboratory analog of organic dust formed in circumstellar environment of dusty classical novae (Endo et al. 2021).

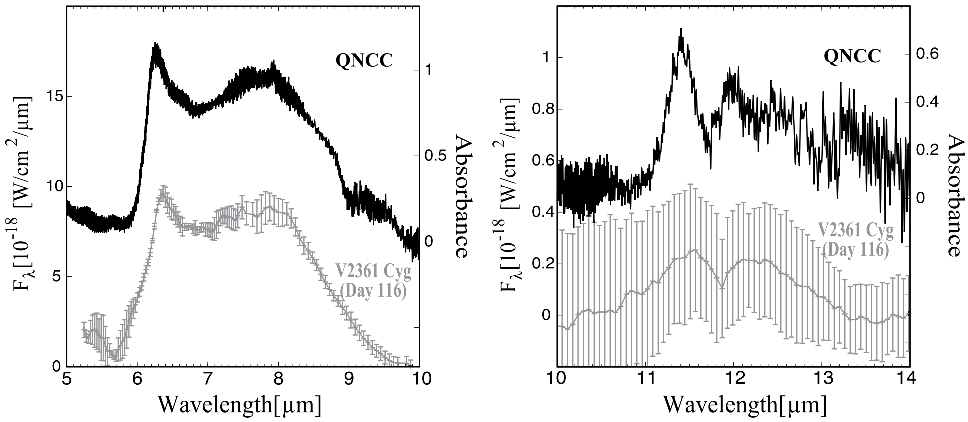

Figure 1. Comparison of the absorption spectrum of QNCC with the UIR bands observed in the classical nova V2361 Cyg on Day 116 after the outburst.

3. Can bulk organic dust carry the UIR bands in novae?

Two major emission mechanisms have been considered to explain the UIR bands and their carriers. Gas-phase PAH molecules emit the UIR bands through the process of UV-pumped IR fluorescence (Leger & Puget 1984; Allmandola et al. 1985). On the other hand, bulk organic dust in the vicinity of a heating source can reach the energy equilibrium and carry the UIR bands via a thermal emission process (Dwek et al. 1980; Duley & Williams 2011).

In the circumstellar environment of novae, bulk organic dust is likely to carry the UIR bands via a thermal emission process because gas-phase PAH molecules are not supposed to survive such harsh conditions around the white dwarf in a nova remnant (Evans & Rawlings 1994). Additionally, Kwok & Zhang (2011) indicated that the carriers of the UIR bands observed in novae V2361 Cyg and V2362 Cyg are expected to be complex organic dust that contains a mixture of miscellaneous aliphatic branches attached to the newly formed ring clusters rather than gas-phase pure PAH molecules.

In order to further clarify whether bulk organic dust can carry the UIR bands in novae, we examined the results of multi-epoch observations of V2361 Cyg with the Infrared Spectrograph (IRS) on Spitzer Space Telescope. The blackbody temperatures (T_d) of the continuum emission of V2361 Cyg are estimated as 660 K on $\tau = 102$ days, 610 K on $\tau = 116$, and 380 K on $\tau = 251$ after the outburst according to Helton et al. (2011). Based on the very simple optically-thin dust emission model, the temporal evolution of the dust temperatures $T_d(\tau)$ is determined by the energy balance between the input energy that the dust particle receives and the output energy that the dust particle radiates:

$$\pi a^2 \bar{Q}(a, T_*) L/4\pi r^2 = 4\pi a^2 \bar{Q}(a, T_d)\sigma T_d^4, \tag{3.4}$$

where a is a grain size of spherical dust, T_* is the effective temperature of the heating source, L is the effective luminosity of the heating sources, σ is the Plank constant, $\bar{Q}(a, T_*)$ and $\bar{Q}(a, T_d)$ are the blackbody mean of absorption coefficient at $T = T_*$ and $T = T_d$, respectively, and r is the distance between the heating source and dust. Assuming the constant expansion velocity of dust as v, r can be given by $r = v\tau$.

In the case of a blackbody, the temporal evolution of the dust temperature as a function of the epoch from the nova outburst, τ, is given by

$$T_d \propto \tau^{-0.5} \tag{3.5}$$

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Table 1. The temporal evolution of the height of 8 μm feature in V2361 Cyg.

τ [days]	T_d [K]	Height of the 8 μm feature [Jy]	Evolution of the 8 μm feature relative to Day 102: Observed	Thermal equilibrium model
102	660	1.8	100 %	100 %
116	610	1.6	88.9 %	78.9 %
251	380	0.19	10.6 %	12.6 %

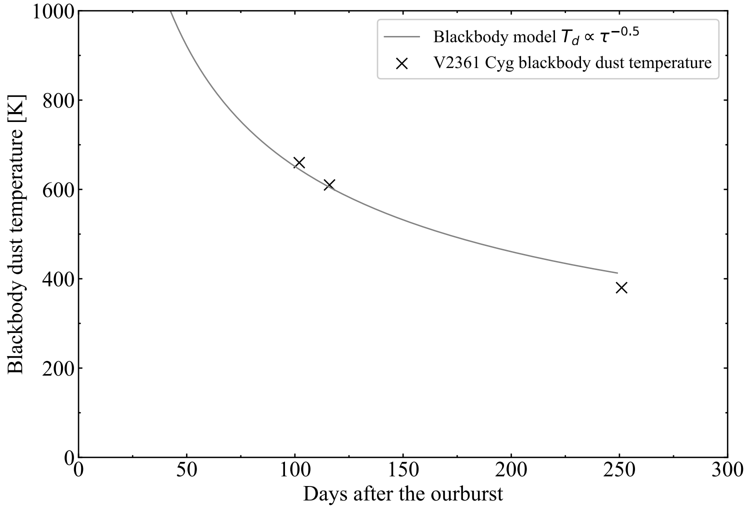

Figure 2. The evolution of the blackbody temperature of the continuum emission in V2361 Cyg as a function of the epoch τ after the outburst.

As shown in Figure 2, the behavior of the blackbody temperatures of continuum emission observed at $\tau = 102$, 116 and 251 days in V2361Cyg (Helton et al. 2011) roughly agree with this very simple model.

The height of the 8μm feature, which characterize the UIR bands in novae, measured at $\tau = 102$, 116 and 251 days are quoted from Helton et al. (2011) and are summarized in Table 1. If the thermal equilibrium model can be applied to the UIR bands in V2361 Cyg, the evolution of the height of the 8 μm feature should be proportional to $[\exp\{hc/\lambda k T_d\} - 1]^{-1}$, where $\lambda = 8$ μm, and h, c, and k are the Plank constant, light speed, and the Boltzman constant, respectively. The observed values of the 8 μm feature height and those of the thermal equilibrium model relative to that at $\tau = 102$ are summarized in Table 1. The observed height of the 8 μm feature at $\tau = 251$ drops to 10.6% of that at $\tau = 102$. The thermal equilibrium model indicates that the value of 8 μm feature height at $\tau = 251$ drops to 12.6% of that at $\tau = 102$. This is roughly consistent with the observed value (i.e., 10.6%).

4. Conclusion

We have synthesized QNCC by the quenched condensation of plasma generated from nitrogen gas and hydrocarbon solids. We conclude that QNCC is at present the best laboratory analog of organic dust formed around dusty classical novae, which carries the UIR bands via a thermal emission process. In the present discussion, we neglect the changing in the luminosity of the heating source (L) as well as the possible destruction of the carriers of the emission. Although long-term monitoring observations are needed to clearly conclude which emission process is dominant, at least, our interpretation that the 8 μm feature is emitted via the thermal emission process consistently explain the observed temporal variations of the 8 μm feature strength well.

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