Infrared property of nitrogen-included carbonaceous dust produced via microwave discharge and its comparison with the observed unidentified infrared (UIR) bands

Izumi Endo,[1] Itsuki Sakon,[1] Takashi Onaka,[1] Seiji Kimura,[2] Setsuko Wada,[2] Nanako Ogawa,[3] Naohiko Ohkouchi,[3] and Hikaru Yabuta[4]

[1]*Department of Astronomy, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*

[2]*Coordinated Center for UEC Research Facilities, The University of Electro- Communication, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan*

[3]*Japan Agency for Marine-Earth Science and Technology, 2-15, Natsushima-cho, Yokosuka-city, Kanagawa, 237-0061, Japan*

[4]*Department of Earth and Planetary Systems Science, Hiroshima University, Kagamiyama 1-3-1, Hiroshima 739-8526 Japan*

ABSTRACT

We have experimentally synthesized nitrogen-included carbonaceous compounds (NCC) by exposing quenched carbonaceous composite (QCC) to nitrogen plasma via 2.45 GHz microwave discharge. QCC synthesized by quenching the plasma of methane gas exhibits infrared features arising from aromatic/aliphatic C – H and aromatic C – C bonds. Our experiments indicate that the absorption spectrum of NCC shows infrared features at 3.29, 6.25, 8 and 11.4 μm. These features are remarkably similar to those of the unidentified infrared (UIR) features observed around Galactic dust forming novae. In this report, we discuss comparison of infrared spectrum of NCC with the observed UIR bands seen in spectra taken with *AKARI* and other facilities.

Keywords: Unidentified infrared (UIR) band, Quenched carbonaceous composite (QCC), Dust synthesis

1. INTRODUCTION

1.1. Unidentified Infrared (UIR) bands

The unidentified Infrared (UIR) bands (e.g., Gillett et al. 1973) consist of a series of emission features arising from aromatic/aliphatic C – C and C – H bonds (Allamandola et al. 1989) and have been ubiquitously observed in the interstellar and circumstellar environment (Tokunaga 1997). Based on theoretical calculations and laboratory experiments, many studies have been conducted to search for the carriers of UIR bands. The polycyclic Aromatic Hydrocarbon (PAH) hypothesis (Léger & Puget 1984; Allamandola et al. 1985) has been commonly accepted by the community and has been used to interpret the observed characteristics of the UIR bands. However, the true nature of the carriers of the UIR bands has not been fully understood so far. Hudgins et al. (2005) claim that the nitrogen inclusion should naturally occur in circumstellar birth places of PAHs and that most of the species responsible for the UIR bands contain nitrogen. Recently, Kwok & Zhang (2011) claim that the most likely carriers of the UIR bands are amorphous organic solids with a mixed aromatic-aliphatic structure. Therefore, further experimental approaches to examine the infrared properties of aromatic and aliphatic hydrocarbons with hetero-atom inclusions are crucial for the better understanding of the nature of the carriers of the UIR bands.

1.2. Quenched Carbonaceous Composite (QCC)

Quenched Carbonaceous Composite (QCC) is synthesized by quenching the plasma produced from methane gas via 2.45 GHz microwave discharge (Sakata et al. 1983). This experimental method well simulates the process of dust condensation in stellar winds. Sakata et al. (1984) have shown that the conjugated double bonds in QCC can reproduce the interstellar 220 nm extinction bump. Moreover, in particular, the infrared absorption spectrum of filmy QCC exhibits a series of infrared features arising from aromatic/aliphatic C – H and C – C bonds and some of the features are in good agreement with the observed characteristics of the UIR bands (see Table 1). Therefore, QCCs are useful laboratory synthesized dust to examine the nature of the carrier of the UIR bands.

Corresponding author: Izumi Endo
endo@g.ecc.u-tokyo.ac.jp

Table 1. UIR bands and infrared features of filmy QCC (Allamandola et al. 1989; Sakata et al. 1987)

the UIR bands (μm)	QCC (μm)	Interpretation
3.29	3.29	Aromatic C–H stretch
3.4	3.42	Aliphatic C–H stretch
3.46	3.49	C–H stretch
5.25	5.25	Combination of C–H out-of-plane and in-plane bend
6.2	6.2	Aromatic C–C strech
	6.95	Asymmetric deformation of C–H
	7.28	Symmetric deformation of C–H
7.6-8.0	7.65	Aromatic C–C stretch
11.2	11.4	Aromatic C–H out-of-plane deformation of one adjacent hydrogen atoms on a ring
	11.9	Aromatic C–H out-of-plane deformation of two adjacent hydrogen atoms on a ring
	13.24	Aromatic C–H out-of-plane deformation of three, four, or five adjacent hydrogen atoms on a ring

2. EXPERIMENT

Nitrogen-included carbonaceous compounds (NCC) is synthesized in the plasma reaction room via 2.45 GHz microwave discharge (see Figure 1). The outline of the experimental procedures are the followings;

1. Synthesize about 5 mg of filmy QCC on the Si substrate
2. Put QCC on Si substrates in the plasma reaction room
3. Evacuate the reaction room to 10^{-4} Torr
4. Introduce (flow rate: ~4 Torr) N_2 gas to the reaction room
5. Generate N_2 plasma via 2.45 GHz microwave discharge (300 W; $I = 0.2$ A, $V = 1.5$ kV)
6. Irradiate N_2 plasma to QCC for 10–30 seconds
7. Collect NCC on the Si substrates placed in the plasma reaction room

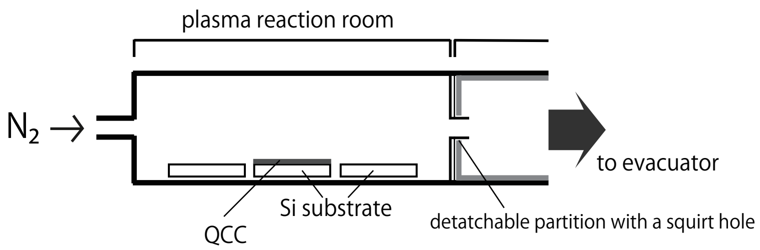

Figure 1. The figure of experimental facility

Sample	Raw material	gas	Reaction time
NCC(30s)	QCC 5 mg	N_2 4 Torr	30 s
NCC(10s)	QCC 5 mg	N_2 4 Torr	10 s

Table 2. A summary of experiment conditions

3. RESULT

We have synthesized NCC under two different experiment conditions (see Table 2). The first configuration employs 10 seconds as the plasma reaction time while the second configuration employs 30 seconds. In the following analyses, NCC synthesized with the former configuration is named as NCC(10s) and that with the latter as NCC(30s)

3.1. NCC(10s)

The left panel of Figure 2 shows comparison of the absorption spectrum of NCC(10s) and that of filmy QCC. An outstanding caracteristic of infrared spectrum of NCC(10s) is the presence of a broad 6–9 μm band feature. Band features at 3.29, 3.42, 3.49, 5.25, 6.2, 6.95, 7.28, 11.4 μm of filmy QCC are still recognized in that of NCC(10s). The 11.9 μm feature is slightly shifted to 11.96 μm in the case of NCC(10s). The 3.42 μm feature of the filmy QCC arising from aliphatic C–H bonds has become weakened, and the 7.65 and 13.24 μm features of filmy QCC disappear. Instead, two new band features appear in the spectrum of NCC(10s). One is at 2.95 μm arising from N–H_2 or N–H stretch, and the other is at 4.5 μm arising from N≡H stretch.

3.2. NCC(30s)

The right panel of Figure 2 shows comparison of the absorption spectrum of NCC(30s) and that of filmy QCC. Band features at 3.29 and 11.4 μm of filmy QCC are still recognized in that of NCC(30s). The 6.2 μm feature is slightly shifted to 6.25 μm in the case of NCC(30s). The 3.42 μm feature of filmy QCC arising from aliphatic C – H bonds almost disappears. The other band features including those at 2.95 and 4.5 μm also disappear. A new broad band feature appears at around 8 μm.

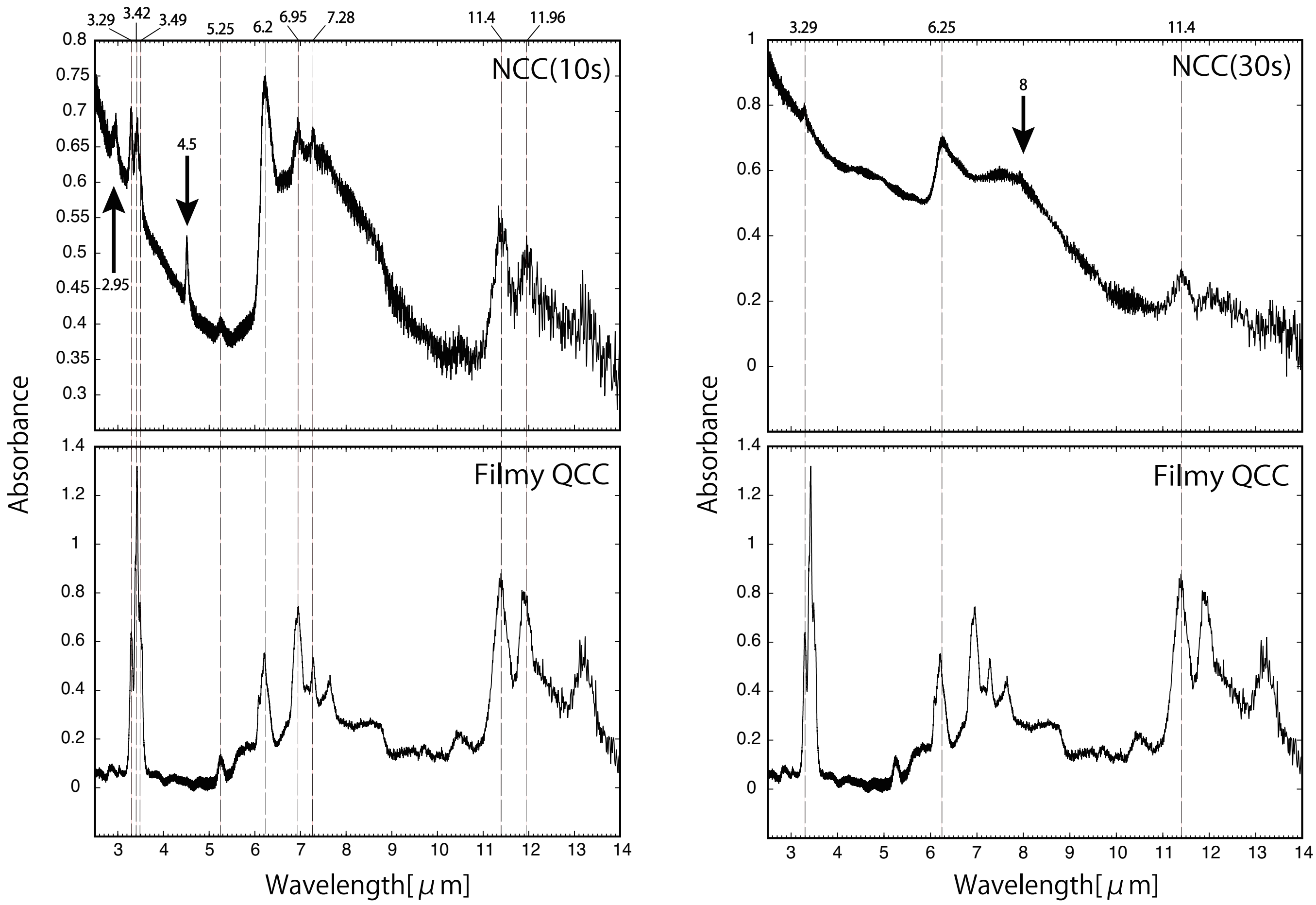

Figure 2. (*Left panel*) Absorption spectra of NCC(10s) and filmy QCC. (*Right panel*) Absorption spectra of NCC(30s) and filmy QCC.

4. COMPARISON WITH OBSERVATIONS

Figure 3 shows comparison of the absorption spectra of QCC, NCC(10s) and NCC(30s) with the observed UIR bands. The infrared features at 3.29 μm, 6.25 μm, 8 μm and 11.4 μm seen in the spectrum of NCC(30s) are more similar to the characteristics of the observed UIR bands in novae compared with any other known materials including QCC and individual PAHs. We note that the peak positions of these features in NCC(30s) appear at a somewhat longward side of the *Class A* UIR band features (e.g., see Figure 3(e)) and are more similar to those of the *Class C* UIR band features (Peeters et al. 2002; van Diedenhoven 2004). Helton et al. (2011) claim that the *Class C* UIR bands are seen in spectra of classical nova V2361 Cyg. The UIR bands seen in the near- and mid-infrared spectrum of classical nova V1280 Sco (see Figure 3(d)) are also roughly consistent with the characteristics of the *Class C* UIR bands (Sakon et al. 2016). Kwok & Zhang (2011) propose a mixed aromatic-aliphatic organic nanoparticles as the carriers of the UIR bands seen in the classical novae V2361 Cyg and V2362 Cyg. In the process of dust condensation in the nova outburst ejecta, nitrogen inclusion into carbonaceous dust can naturally occur (e.g., Hudgins et al. 2005). The similarities between the infrared features of NCC(30s) and the observed *Class C* UIR bands may suggest that hetero-atom, in particular, nitrogen inclusion in the carrier of the UIR bands should be taken into account for the better understanding of 'astronomical PAHs'. Further study on NCC can contribute to identify the carriers of the UIR bands.

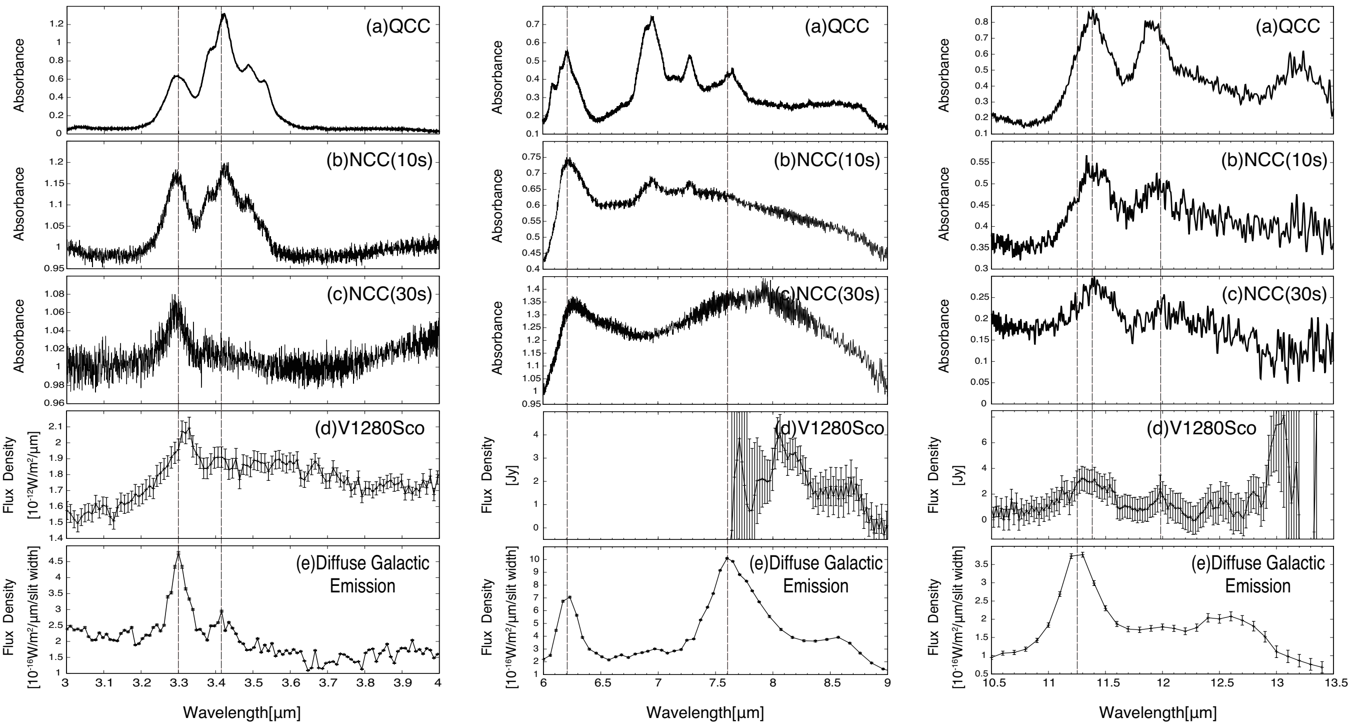

Figure 3.
(a) Absorption spectrum of Filmy QCC produced from methane gas plasma via 2.45 GHz microwave discharge
(b) Absorption spectrum of NCC(10s) synthesized by exposing Filmy QCC to nitrogen plasma for 10 seconds
(c) Absorption spectrum of NCC(30s) synthesized by exposing Filmy QCC to nitrogen plasma for 30 seconds
(d) Infrared spectrum of V1280Sco at 940 days from the nova outburst obtained by *AKARI*/IRC (left: 3–4 μm), and that at 1280 days obtained by Gemini-S/TReCS (middle: 6–9 μm, right: 10.5–13.5 μm) (Sakon et al. 2016)
(e) Infrared spectrum of Diffuse Galactic Emission obtained by *AKARI*/IRC (pointing 1400261.1, $l = -48°$, $b = 0°$)

ACKNOWLEDGMENTS

AKARI is a JAXA project with the participation of ESA. We thank all the members of the *AKARI* project, particularly those who have engaged in the observation planning and the satellite operation for their continuous help and support. This work is supported in part by a Grant-in-Aid for Young Scientists (A) (Grant Number 16H05997).

REFERENCES

Allamandola, L. J., Tielens, A. G. G. M., & Barker, J. R. 1985, ApJ, 290, L25
Allamandola, L. J., Tielens, A. G. G. M., & Barker, J. R. 1989, ApJS, 71, 733
Gillett, F. C., Forest, W. J., & Merrill, K. M. 1973, ApJ, 183, 87
Helton, L. A., Evans, A., Woodward, C. E., & Gehrz, R. D. 2011, in PAHs and the Universe, eds C. Joblin, A. G. G. M. Tielens, EAS Publications Series, vol. 46, 407
Hudgins. D. M., Bauschlicher, C. W., & Allamandola, L. J. 2005, ApJ, 632, 36
Kwok, S., & Zhang, Y. 2011, Nature, 479, 80
Leger, A., & Puget, J. L. 1984, A&A, 137, L5
Peeters, E., Hony, S., Van Kerckhoven, C., et al. 2002, A&A, 390, 1089
Sakata, A., Wada, S., Okutsu, Y., Shintani, H., & Nakada, Y. 1983, Nature, 301, 493
Sakata, A., Wada, S., Onaka, T., & Tokunaga, A. T. 1987, ApJL, 320, L63
Sakata, A., Wada, S., Tanabe, T., & Onaka, T. 1984, ApJL, 287, L51
Sakon, I., Sako, S., Onaka, T., et al. 2016, ApJ, 817, 145
Tokunaga, A. T. 1997, Diffuse Infrared Radiation and the IRTS, ASP Conf. Ser., 124, 149
van Diedenhoven, B., Peeters, E., Van Kerckhoven, C., et al. 2004, ApJ, 611, 928