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Dust formation by massive stars studied by infrared observations with AKARI/IRC and Subaru/COMICS

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Abstract. Recent AKARI/IRC observations of SN2008ax in NGC4490 on the day 98 has revealed the presence of near-infrared excess emission. This emission can be interpreted as the re-radiation from the pre-existing circumstellar amorphous carbon dust of a color temperature of 767±45 K and the mass of $1.2^{+0.4}_{-0.3} \times 10^{-5}$ $M_\odot$ or silicate dust of 885±60 K and $6.8^{+2.5}_{-1.7} \times 10^{-5}$ $M_\odot$, which may have been formed in the mass loss wind from the OB/WR progenitor in an interacting binary system. In order to investigate the on-going dust formation by WR binary systems, the mid-infrared observations of the Galactic WR binary WR140 were carried out with Subaru/COMICS on 1st August 2009. 11.7μm image of WR140 has shown that the dust cloud formed during the previous periastron passage in 2001

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has expanded up to 2.6″ away from the stellar core with an expansion velocity of 2.7±0.3 $\times 10^3$ km s^{-1}. The high-spatial resolution N-band spectrum of dust structures around WR140 was obtained for the first time and broad band features at ∼8.3 μm and ∼12.2 μm were detected. The possible carriers of these emission bands are discussed.

Keywords : circumstellar matter – dust, extinction – supernovae: individual(SN2008ax) – stars: Wolf-Rayet – infrared: stars

1. Introduction

Since the presence of significant amount of dust in the high redshift quasars, where low- to intermediate- mass stars cannot contribute as dust budgets, is reported (Bertoldi et al. 2003), dust formation by massive stars has become the object of attention to explore the origin of dust in the early universe. One of the major processes of dust formation by massive stars is the dust condensation in the ejecta of core-collapse supernovae (SNe) (Kozasa, Hasegawa & Nomoto 1991; Todini & Ferrara 2001). 0.1–1 $M_\odot$ of dust formation per typical SN is needed to explain the amount of dust in the early universe (Moran & Edmunds 2003) and theoretical calculations also predict a similar amount of dust formation (Nozawa et al. 2003). However, the typical amount of newly formed dust in the ejecta of a supernova obtained from recent observations, is only in the range 10^{-3}–10^{-5} $M_\odot$ (Ercolano, Barlow & Sugerman 2007; Meikle et al. 2007; Mattila et al. 2008; Sakon et al. 2009) except for a few cases, e.g., 0.02$M_\odot$ for SN2003gd (Sugerman et al. 2006) and 0.02$M_\odot$ for the Galactic supernova remnant Cas A (Rho et al. 2008).

Sakon et al. (2009) have recently presented the near- to mid-infrared spectral energy distribution (SED) of type Ib SN2006jc at the epoch of 220days after explosion obtained with AKARI satellite. They explained that the near-infrared emission is carried by hot amorphous carbon of 800K with a mass of 7×10^{-5} $M_\odot$, which is supposed to be the newly formed dust in the SN ejecta. They also found excess emission over the 800K component in the mid-infrared, which is reasonably explained by thermal emission from pre-existing warm amorphous carbon of 300K with a mass of 3×10^{-3} $M_\odot$ possibly formed in the mass loss wind associated with the Wolf-Rayet activities. In addition, Spitzer IRAC photometric data of SN2006jc at a similar epoch is presented by Mattila et al. (2008), in which the contribution of pre-existing circumstellar dust has also been pointed out. These results suggest that dust condensation not only in the SN ejecta but also in the mass loss wind associated with events prior to the SN explosion, may contribute efficiently to the dust formation by a massive star during its whole evolutionary history. However, it is suggested that a single metal-free massive star in the early universe may die without losing a large fraction of its mass (Baraffe et al. 2001) and therefore, the dust formation process in the early universe still remains puzzling. On the other hand, binary systems can play an important role in the mass-loss activity by evolved massive stars even in low-metallicity environments. In addition, more abundant massive binary systems are expected to exist in the early universe (Machida 2008). In this sense, Wolf-Rayet binary systems can be proposed as an important dust source in the early universe.

In Section 2, we present the latest result on the near-infrared observation of SN 2008ax at the epoch 98 days with AKARI/IRC and examine the properties of pre-existing circumstellar dust that may have been formed around the progenitor WR star in an interacting binary system. In Section 3, in order to further examine the dust formation process in the colliding winds of Wolf-Rayet binary system, we present the latest result on the mid-infrared observation of WR140 with Subaru/COMICS and examine the composition and the properties of dust formed during a previous periastron passage in 2001.

2. Pre-existing circumstellar dust around SN2008ax

Supernova (SN) 2008ax is a Type IIb supernova (Chornock et al. 2008) at a distance of 9.8Mpc (Pastorello et al. 2008) and was discovered on 2008 March 3.45 (UT) (Mostardi et al. 2008) in the host galaxy NGC4490. Recent observational studies have shown that the overall shape of the optical light curve of SN2008ax resembles that of the He-rich Type IIb SNe 1996cb and 1993J (Pastorello et al. 2008) and that the progenitor was likely to be an OB/WR star of main sequence mass of 10–14$M_\odot$ in an interacting binary system (Crockett et al. 2008). Therefore, near- to mid-infrared observations of SN2008ax in its early epoch are useful to examine the properties of circumstellar dust that might have been formed in colliding winds of the WR binary system prior to the final core-collapse.

The near-infrared observations of SN2008ax at the epoch of 98 days after the discovery were carried out with AKARI/IRC as part of the Director's time observations of AKARI. Figure 1 shows the near-infrared images of SN2008ax and the hot galaxy NGC4490 taken with AKARI/IRC *N3* (3.2μm) and *N4* (4.1μm) bands. As a result of the PSF photometry, we obtain 0.33$\pm$0.03 mJy and 0.41$\pm$0.03 mJy for *N3* and *N4* band flux densities, respectively. The red spectral energy distribution in the near-infrared band indicates the detection of infrared emission from the circumstellar dust shell, which might have been formed in the colliding winds of the WR binary activities, and have survived the shock breakout in the initial phase of the SN explosion. Assuming an optically thin clump of spherical amorphous carbon dust grains with a uniform particle radius of 0.01μm, the near-infrared emission is explained by the presence of

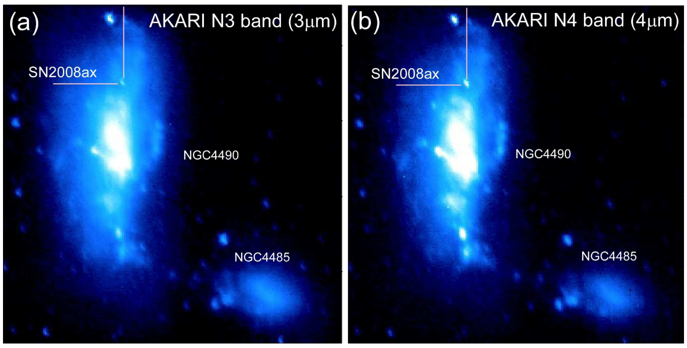

Figure 1. (a), (b) Near-infrared images of SN2008ax in the host galaxy NGC4490 on the epoch of 98 days after the discovery, taken with AKARI/IRC *N3* (3.2μm) and *N4* (4.1μm) bands, respectively. The size of each image is $330'' \times 330''$.

amorphous carbon dust of $T_{a.car.} = 767 \pm 45$ K and $M_{a.car.} = 1.2^{+0.4}_{-0.3} \times 10^{-5} M_{\odot}$, in which the absorption efficiency of amorphous carbon dust grains is calculated from the optical constants of Edo (1983) and $\rho_{a.car.} = 2.26$ g cm^{-3}. Assuming an optically thin clump of spherical astronomical silicate dust grains with a uniform particle radius of 0.01μm, on the other hand, the near-infrared emission is explained by the presence of astronomical silicate dust of $T_{a.sil.} = 885 \pm 60$ K and $M_{a.sil.} = 6.8^{+2.5}_{-1.7} \times 10^{-5} M_{\odot}$, where the absorption efficiency of astronomical silicate is taken from the values tabulated in Draine (1985) and $\rho_{a.car.} = 3.3$g cm^{-3}. We note that these values are just rough estimates derived by employing a single-temperature approximation. Longer wavelength information beyond 5μm is crucial to accurately estimate the dust mass.

3. Properties of dust formed by WR140

WR140 is one of the best studied Galactic long-period, colliding-wind Wolf-Rayet binary (WC7 class Wolf-Rayet star O4 type star, $P = 7.93$y, $e = 0.881$; Marchenko et al. 2003) located at a distance of 1.85kpc (Dougherty et al. 2005). Interesting periodic features in the light curves of multi-wavelengths have been reported whenever the O-type star companion passes through the densest region of the carbon-rich WR wind. During the event, the WR outflow is compressed in the wind-wind collision zone and the shocked gas is expected to cool rather quickly to the dust condensation temperature. Actually, Marchenko et al. (2007) have presented the high-quality 12.5μm image of WR140 taken with Gemini-North/Michelle in 2003 and have detected concentric dust arcs around WR140 which can be linked with the 1993 and 2001 dust formation episodes. Recently, Williams et al. (2009) have presented the mid-infrared images of WR140 taken between 2001 and 2005 and have investigated the dynamic evolution of dust structures formed around the time of a previous periastron passage in 2001. High spatial resolution mid-infrared spectroscopic observations are quite useful to understand the dust synthesis in WR140 from the chemical point of view, but few mid-infrared spectroscopic analyses of dust structures in WR140 have so far been published.

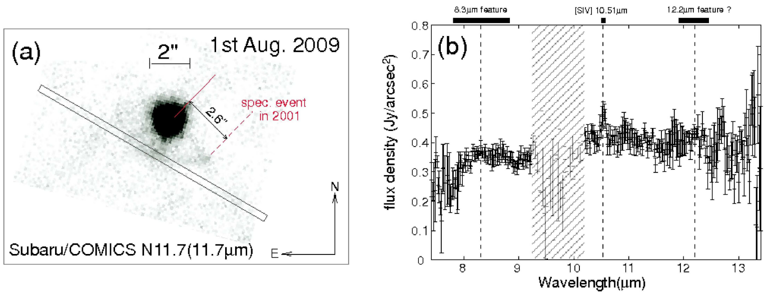

Figure 2. (a) N11.7 band image of WR140 taken with Subaru/COMICS on 1st August 2009. The slit for N-band low-resolution (NL) spectroscopy is settled so that it passes through the dust shell formed during the previous periastron in 2001. (b) NL spectrum of dust shell associated with the previous periastron in 2001 is obtained by averaging data within 1" from the densest part of the dust shell. We used HD197989 as the standard star for absolute flux calibration and atmospheric absorption correction. The total on-source integration time was 1440 sec. The 9–10μm data, where atmospheric ozone absorption lowers the signal-to-noise ratio, is masked with shadows.

We have carried out mid-infrared imaging and spectroscopic observations of WR140 in August 2009 with Subaru/COMICS. Figure 2a shows the 11.7μm image of WR140 together with the slit position for N-band low-resolution spectroscopy. The dust shell formed during the spectroscopic event of 2001 is found to have expanded by the projected distance of $2''.6$ further from the infrared core. We obtain $2.7{\pm}0.3{\times}10^3$km s^{-1} as the projected expansion velocity of the dust shell. Figure 2b shows the N-band spectrum of the dust shell formed during a periastron passage in 2001. Broad dust band features peaking at 8.3μm (hereafter 8.3μm band) and a possible broad feature near 12.2μm (hereafter 12.2μm band) are detected as well as the ionic line of [SIV] at 10.51μm. The presence of broad band features similar to the $\sim$8.3μm band has been reported for several other objects and several possible carriers have been proposed for them. Molecular SiO is proposed as the carrier of the broad emission band at $\sim$8–9μm observed in the mid-infrared spectra of several type IIP supernovae (e.g., Kotak et al. 2006, 2009). Hydrogenated amorphous carbons (HACs) can also be proposed as the carrier of the broad emission band centered at 8.2μm observed in several objects with a relatively low excitation temperature including Galactic carbon-rich proto-planetary nebulae (Sloan et al. 2007). Taking account of the atmospheric composition of the WC7 class WR star, the primary of WR140, the efficient formation of SiO molecules, which is sometimes expected as the precursor of silicate dust, in the Wolf-Rayet wind seems less likely. Quite recently, Prieto et al. (2009) have presented the Spitzer mid-infrared spectrum of the luminous transient in the nearby galaxy NGC300 (NGC300-OT) at the epoch of 93 days after its discovery. They reported the presence of two prominent broad emission features at $\sim$8.3μm and $\sim$12.2μm in the mid-infrared spectrum of NGC300-OT and discussed the similarity in the spectral characteristics to the carbon-rich proto-planetary nebulae in the Galaxy. The 8.3μm and 12.2μm bands in the mid-infrared spectrum of dust cloud around WR140 closely resemble those reported by Prieto et al. (2009) in the mid-infrared spectrum of NGC300-OT in terms of their band widths and their peak positions, although the 12.2μm band in our spectrum is marginal at the 3σ noise detection limit. If this is the case, HAC can be a possible candidate for the carriers of the 8.3μm and 12.2μm bands in the spectrum of WR140. We also recognize possible faint features at 8.6, 11, 11.8, and 12.7μm, which are roughly consistent with the features associated with the lattice vibration mode of aromatic C-H bonds in terms of their peak wavelengths, although they are marginal at only 2σ noise detection limit. Additional continual mid-infrared spectroscopic observations with better signal-to-noise ratio are needed to identify the carrier of these features and to further investigate the evolution process of dust formed around WR140 during the periastron passage not just in 2001 but also in 2009.

4. Summary

Recent near-infrared observations of SN2008ax in NGC4490 with AKARI/IRC on the day 98 have detected a re-radiation from the pre-existing circumstellar dust which has been formed around the OB/WR progenitor in an interacting binary system. We also have carried out the mid-infrared imaging and spectroscopic observations of the Galactic WR binary WR140 with Subaru/COMICS to directly investigate the on-going dust formation by the WR binary system. The high-spatial resolution N-band spectrum of the dust structures around WR140 was obtained for the first time and broad dust band features at $\sim$8.3μm and 12.2μm have been detected. They are quite similar to those found in the Spitzer mid-infrared spectrum of NGC300-OT presented by Prieto et al. (2009).

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