OBSERVATIONS OF THE OPTICAL TRANSIENT IN NGC 300 WITH AKARI/IRC: POSSIBILITIES OF ASYMMETRIC DUST FORMATION

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ABSTRACT

We present the results of near-infrared (NIR) multi-epoch observations of the optical transient in the nearby galaxy NGC 300 (NGC 300-OT) at 398 and 582 days after the discovery with the Infrared Camera (IRC) on board AKARI. NIR spectra (2–5 μm) of NGC 300-OT were obtained for the first time. They show no prominent emission nor absorption features, but are dominated by continuum thermal emission from the dust around NGC 300-OT. NIR images were taken in the 2.4, 3.2, and 4.1 μm bands. The spectral energy distributions (SEDs) of NGC 300-OT indicate the dust temperature of 810 ± 14 K at 398 days and 670 ± 12 K at 582 days. We attribute the observed NIR emission to the thermal emission from dust grains formed in the ejecta of NGC 300-OT. The multi-epoch observations enable us to estimate the dust optical depth as $\gtrsim 12$ at 398 days and $\gtrsim 6$ at 582 days at 2.4 μm by assuming an isothermal dust cloud. The observed NIR emission must be optically thick, unless the amount of dust grains increases with time. Little extinction at visible wavelengths reported in earlier observations suggests that the dust cloud around NGC 300-OT should be distributed inhomogeneously so as to not screen the radiation from the ejecta gas and the central star. The present results suggest the dust grains are not formed in a spherically symmetric geometry, but rather in a torus, a bipolar outflow, or clumpy cloudlets.

Key words: circumstellar matter – dust, extinction – stars: evolution – stars: variables: general – stars: winds, outflows

Online-only material: color figures

1. INTRODUCTION

Massive stars are expected to play an important role in the interstellar dust budget in young dwarf galaxies as well as in galaxies in the early universe because of their relatively short evolution lifetime (e.g., Dwek et al. 2007; Morgan & Edmunds 2003). Recently, several eruptive objects with intermediate maximum absolute luminosities between classical nova eruptions and supernova (SN) explosions have been discovered. They are termed as SN impostors (Van Dyk et al. 2000) and suggested to be a super-outburst of a luminous blue variable (LBV)-like event rather than a complete disruption of the progenitor. SN impostors provide us with useful opportunities to investigate the effect of an eruptive outburst on the yield of circumstellar dust around the evolved massive stars before core collapse (Sakon et al. 2009; Mattila et al. 2008). Among SN impostors, SN 2008S in NGC 6946 (Arbour & Boles 2008) and the optical transient in NGC 300 (hereafter NGC 300-OT; Monard 2008) are peculiar ones. One of their outstanding characteristics is that their progenitors are deeply embedded in circumstellar dust shells. Khan et al. (2010) carried out a systematic mid-infrared photometric search for candidate objects which are analogous to the progenitors of SN 2008S and NGC 300-OT in four nearby galaxies M33, NGC 300, M81, and NGC 6946 with *Spitzer*/IRAC. They found dozens of extreme asymptotic giant branch (EAGB) objects similar to SN 2008S and NGC 300-OT progenitors, but none of them are brighter than the NGC 300-OT progenitor and redder than the SN 2008S progenitor. They point out that the rarity of such extremely red and luminous progenitors can be interpreted as the short duration of the dust-obscured

phase with rapid mass-loss rates prior to some kind of explosion event in the evolution of massive stars (Thompson et al. 2009; Pumo et al. 2009).

NGC 300-OT was discovered on 2008 May 14 in the nearby spiral galaxy NGC 300 (Monard 2008), the distance of which is 1.9 Mpc. NGC 300-OT has shown an intermediate peak absolute magnitude of $M_{bol} \sim -11.8$ mag with an optical spectrum well reproduced by an F-type supergiant photosphere with emission lines of hydrogen, Ca II, and [Ca II], similar to the typical spectra of low-luminosity SN impostors (Bond et al. 2009; Berger et al. 2009). The progenitor of NGC 300-OT was not detected in *Hubble Space Telescope* (*HST*) archive images (Bond et al. 2009), but was identified in *Spitzer* archival images (Prieto 2008), which suggest the dust-enshrouded nature of the progenitor. Several interpretations have been proposed for the nature of NGC 300-OT: a heavily dust-enshrouded OH/IR star of 10–15 $M_{\odot}$ (Bond et al. 2009), a dust-enshrouded star with a luminosity of about $6 \times 10^4 L_{\odot}$ indicative of a 10–20 $M_{\odot}$ (Berger et al. 2009), or a massive ($M \sim$ 6–10 $M_{\odot}$) carbon-rich asymptotic giant branch (AGB) star or a post-AGB star (Prieto et al. 2009). The validity of those mass ranges is confirmed by Gogarten et al. (2009) based on the method that derives the star formation history of a transient's host stellar population. Prieto et al. (2009) also pointed out the presence of newly formed dust of 1500 K in addition to the pre-existing circumstellar dust of $\sim 3 \times 10^{-4} M_{\odot}$ of 400 K based on the near- to mid-infrared spectral energy distribution (SED) at 93 days after the discovery. Further near-infrared (NIR) observations at later epochs are crucial to investigate the properties of newly formed dust grains at the outburst.
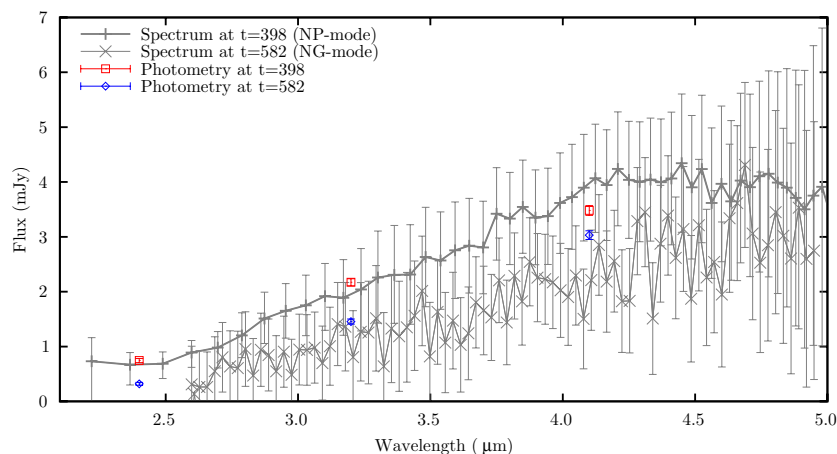
Figure 1. NIR spectrum of NGC 300-OT. The thicker line with the pluses shows the spectrum at 398 days taken with the prism ($\lambda/\Delta\lambda\sim20$), the line with the crosses shows the spectrum at 582 days taken with the grism ($\lambda/\Delta\lambda\sim100$), the squares show the fluxes obtained from the NIR images at 398 days, and the diamonds show the fluxes derived from the NIR images at 582 days.

(A color version of this figure is available in the online journal.)

In this paper, we present our results of NIR observations of NGC 300-OT on the 398th and the 582nd days with the Infrared Camera (IRC) on board AKARI (Onaka et al. 2007). NIR spectroscopy in 2–5 μm and imaging in the three filter bands of $N2$ (2.4 μm), $N3$ (3.2 μm), and $N4$ (4.1 μm) were carried out with the IRC. We focus on the time evolution of the emission from newly formed dust and investigate the dust formation process around NGC 300-OT during its eruptive outburst.

2. OBSERVATIONS AND DATA REDUCTION

The first-epoch data sets were obtained on 2009 June 16, corresponding to the epoch of 398 days after the discovery, as part of the Director's Time (DT). They consist of imaging observations in the three filter bands centered at 2.4 μm ($N2$), 3.2 μm ($N3$), and 4.1 μm ($N4$) (Onaka et al. 2007) of pointing ID 5200806.1 and 5200806.2, and spectroscopic observations with the NIR prism (NP; $\Delta\lambda/\lambda \sim 20$) for 2–5 μm (Ohyama et al. 2007) of pointing ID 5200805.1 and 5200807.1. The second-epoch data sets were obtained on 2009 December 17 corresponding to the epoch of 582 days after the discovery as part of the Mission Program (MP) "Interstellar Medium in Our Galaxy and Nearby Galaxies" (ISMGN; Kaneda et al. 2009). They include imaging observations in the $N2$, $N3$, and $N4$ bands (pointing ID 1422250.1 and 1422250.2) and spectroscopic observations with the NIR grism (NG; $\Delta\lambda/\lambda \sim 100$) for 2.5–5 μm (Ohyama et al. 2007; pointing ID 1422249.1 and 1422249.2).

The imaging data were reduced with the AKARI/IRC Imaging Toolkit for Phase 3 data version 20081015[6] and the flux was measured with `phot` command in the `apphot` package of `IRAF`.[7] The spectroscopic data were reduced with the AKARI/IRC spectroscopy toolkit for phase 3 data version 20090211. The NIR spectra of NGC 300-OT were taken in the slitless spectroscopy mode. Therefore, they are blended with the spectra of diffuse emission from the host galaxy NGC 300. We carefully subtracted the contribution of diffuse emission from NGC 300 by interpolating the signals around NGC 300-OT. The

Table 1
Photometric Data of NGC 300-OT

$\lambda(\mu m)$	$t = 398$ days (mJy)	$t = 582$ days (mJy)
2.4	0.75 ± 0.04	0.33 ± 0.02
3.2	2.22 ± 0.07	1.45 ± 0.05
4.1	3.50 ± 0.09	2.97 ± 0.08

value of a bad pixel was replaced by the median value of the adjoining pixels. The NG spectrum at 582 days was smoothed by a 3 pixel running mean to increase the signal-to-noise ratio without degrading the spectral resolution.

3. RESULTS AND DISCUSSION

3.1. Spectral Data

Figure 1 shows the obtained NIR spectra of NGC 300-OT at 398 and 582 days. No significant contribution is recognized from the polycyclic aromatic hydrocarbon (PAH) features around 3.3 μm, hydrogen recombination lines of Brackett α at 4.05 μm, and Brackett β at 2.63 μm, nor forbidden lines from ionized gas (e.g., [Mg IV] at 4.49 μm, [Ca IV] at 3.21 μm, and [Ca V] at 4.15 μm) in the spectra. Therefore, the NIR spectra of NGC 300-OT at both epochs are dominated by hot dust continuum emission.

3.2. Imaging Data

The results of the photometry are listed in Table 1. Prieto et al. (2010) have reported that the 3.6 μm flux at 587 days is 2.2 mJy, which is in agreement with our results at 582 days. Compared to the fluxes at 398 days, the fluxes at 582 days had declined by 56% in the $N2$, 35% in the $N3$, and 15% in the $N4$ bands.

Since the noise level in the spectroscopic mode at 4.05 μm is about 3 mJy (3σ) and the estimated spectral resolution is 0.2 μm for NP and 0.04 μm for NG, an upper limit of the intensity of Brackett α, which is expected to be the strongest among the hydrogen recombination lines in 2–5 μm, is estimated as 5.1×10^{-17} W m^{-2} and 7.8×10^{-18} W m^{-2} for 398 and 582 days, respectively. Thus, the contribution of Brackett α on the $N4$ band is supposed to be negligible.
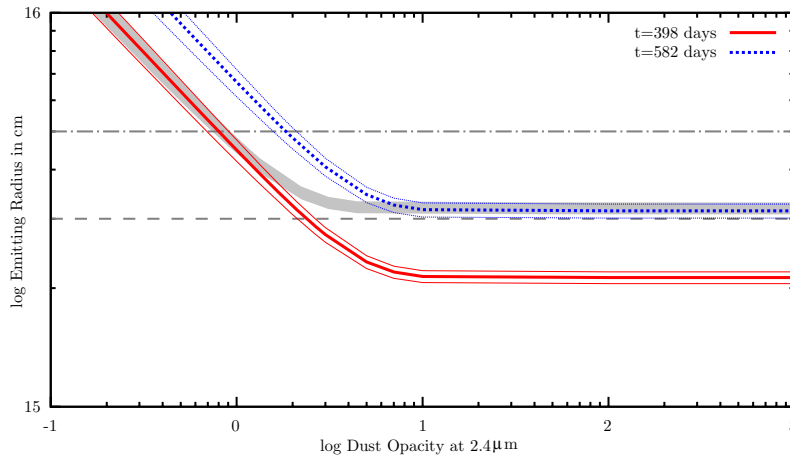
Figure 2. Relation between the dust optical depth at 2.4 μm (τ_ν) and the emitting radius (R). The red solid line shows the relation at $t = 398$ days, while the blue dotted line shows that at $t = 582$ days. The range of uncertainties is indicated by the thin lines. The dashed and dot-dashed lines are upper limits of the emitting radius, respectively, at $t = 398$ days ($R = 3 \times 10^{15}$ cm) and at $t = 582$ days ($R = 5 \times 10^{15}$ cm), corresponding to a shell expansion velocity of 1000 km s^{-1}. Assuming that the dust mass is constant and the dust cloud expands at a constant velocity, the τ_ν–R line at $t = 398$ days is predicted to evolve to the gray shaded region at $t = 582$ days (see the text).

(A color version of this figure is available in the online journal.)

4. DISCUSSION

4.1. Contributions from Two Dust Components

According to Prieto et al. (2009), the SED of NGC 300-OT at 96 days is well explained by three blackbody components of temperatures of $\sim$4000 K, $\sim$1500 K, and $\sim$480 K. The component of $\sim$4000 K is assumed to come from the photosphere. The component of $\sim$480 K (hereafter the warm dust) is attributed to the dust produced in the AGB/post-AGB phase. While the origin of the component of $\sim$1500 K (hereafter the hot dust) remains to be identified, it is most likely to be attributable to the newly formed dust in the outburst ejecta (Prieto et al. 2009, 2010). If these grains are heated by the radiation from the central star and are in radiative equilibrium, the temperature of the dust should follow the relation of $T_d \propto L^{\frac{1}{4}}$, where T_d is the dust temperature and L is the luminosity of the central star. According to the light curve by Bond et al. (2009), the luminosity of NGC 300-OT in the V band had fallen by about 3 mag from 96 to $\sim$200 days. The dust temperatures at $\sim$200 days should be about a half of that at 96 days, or the warm dust temperature at $\sim$200 days should be $\sim$240 K. We estimate that the contribution to the NIR emission from the warm dust decreases from that at 200 days and should be at most 1% of the observed flux at 398 days, which is lower than the uncertainties in the photometry. Thus, we can attribute the observed change of the SED entirely to the hot dust, which comes from dust grains that were formed in the ejecta.

4.2. Optical Depth of the Dust Cloud

To investigate the change in the properties of the dust, we assume a simple model of an isothermal dust cloud and fit the SED derived from the NIR imaging data by $f_\nu \propto \left(1 - e^{-\tau_\nu}\right) B_\nu(T_d)$, where τ_ν is the dust optical depth, and $B_\nu(T_d)$ is the Planck function. We assume that τ_ν is proportional to $1/\lambda$. We derive dust temperatures for both optically thin ($\tau_\nu \ll 1$) and thick ($\tau_\nu \gg 1$) case. The dust temperatures and the total luminosities are listed in Table 2. Based on this simple model, the dust-emitting radius R can be given by

$$R = \left[\frac{D^2 f_\nu}{\pi \left(1 - e^{-\tau_\nu}\right) B_\nu(T_d)} \right]^{\frac{1}{2}}, \quad (1)$$

Table 2
Results of SED Fit

	398 days	582 days
For $\tau \gg 1$		
T_d (K)	813 ± 14	668 ± 12
L_d ($10^5 L_\odot$)	4.0 ± 0.4	3.4 ± 0.3
For $\tau \ll 1$		
T_d (K)	678 ± 10	573 ± 12
L_d ($10^5 L_\odot$)	4.0 ± 0.5	3.3 ± 0.4

where D is the distance to NGC 300-OT from the observer and f_ν is the observed flux. In Figure 2, R is plotted against τ_ν at 2.4 μm. According to Berger et al. (2009), an upper limit of the expansion velocity of the ejecta is about 1000 km s^{-1}. If the ejecta expands with this velocity, R must be smaller than $\sim$3 × 10^{15} cm (the dashed line in Figure 2) at 398 days and then $\sim$5 × 10^{15} cm (the dot-dashed line) at 582 days. Assuming that the dust mass did not change between 398 and 582 days, the dust opacity should be proportional to R^{-2}. If the dust cloud expands at a constant velocity, the ratio of the radius at 582 days to that at 398 days must be equal to $582/398 \sim 1.5$. Therefore, the τ_ν–R line at 398 days is predicted to evolve to the gray shaded region in Figure 2. Only the region where the predicted line overlaps with the observed line at 582 days gives consistent models both at 398 and 582 days. From Figure 2, a lower limit of τ_ν (2.4 μm) is estimated to be $\sim$12 at 398 days and $\sim$6 at 582 days. Therefore, the dust cloud around NGC 300-OT is optically thick at both epochs. It is consistent with the featureless spectra shown in Figure 1. Assuming the constant density, we can estimate a lower limit of the dust mass as $M_d = (4\pi/3)R^2\tau_\nu\kappa_\nu^{-1} \sim 10^{-5} M_\odot$, where κ_ν is the dust mass absorption coefficient at 2.4 μm. The absorption coefficient κ_ν is estimated as $(3/4)2\pi\lambda^{-1}\rho^{-1} \sim 10^4$ cm^2 g^{-1}, where ρ is the mass density of the dust grains, ~ 2 g cm^{-3}, assuming carbon dust (Prieto et al. 2009). In case the density varies as r^{-2}, we need to assume the inner shell radius for the dust mass estimation. If the inner shell radius is within a half or a quarter of R, the estimated dust mass will not change more than ±40 % of that in the constant density case.

If the dust cloud is optically thick, there must be a temperature gradient. Thus, an isothermal model is a crude approximation, particularly for the optically thick case. To examine how secure the conclusion of the optically thick emission is, we consider an optically thin cloud in some more detail. The total dust mass can be estimated for an optically thin case using Equation (4) in Dwek et al. (1983):

$$M_d \simeq 2 \times 10^{-6} \left(\frac{T_d}{1000\,\mathrm{K}} \right)^{-5} \left(\frac{L_d}{10^6 L_\odot} \right) M_\odot, \qquad (2)$$

where L_d is the total dust luminosity in $L_\odot$. Using the temperature and the luminosity in Table 2 for $\tau \ll 1$, we obtain $M_d \sim 5.1 \times 10^{-6}\, M_\odot$ at 398 days and $M_d \sim 1.0 \times 10^{-5}\, M_\odot$ at 582 days. Thus, if the emission is optically thin, the dust mass must be increased by a factor of 2. Theoretical investigations suggest that the nucleation and grain growth will cease in a relatively short time right after the onset of nucleation (Yamamoto & Hasegawa 1977; Draine & Salpeter 1977). Therefore, we conclude that optically thin models cannot account for the observations.

Since the ratio of the opacity at the V band to that at $2.4\,\mu m$ is about 5, the optically thick dust cloud predicts strong extinction at visible wavelengths. Berger et al. (2009) reported $E(B-V) = 0.05 \pm 0.05$ mag at 121 days, which suggests that the extinction by the dust cloud is very small or negligible. Prieto et al. (2010) reported that the R-band magnitude has significantly faded to 23.9 ± 0.2 mag at 585 days, and they surmise that NGC 300-OT is likely becoming self-enshrouded. An upper limit of the extinction at the R band at 585 days can be estimated as 6 mag, if we simply assume the R-band magnitude at 585 days is the same as that at 120 days. Although it may be true that part of the stellar radiation is attenuated, it is too small to account for the extinction caused by the optically thick dust cloud, more than ~ 20 mag, in the preceding discussion. The apparent contradiction suggests that the dust around NGC 300-OT is not uniformly distributed, but rather is distributed in a spherically asymmetrical geometry, such as a torus, bipolar, or clumpy form, so that the dust cloud does not completely screen the radiation from the ejecta gas and the central star. The existence of a significantly asymmetrical dust cloud was also proposed by Patat et al. (2010) and Berger et al. (2009). The present results also support the existence of an asymmetrical dust cloud.

5. SUMMARY

We present the results of the NIR observations on NGC 300-OT at 398 and 582 days after the discovery with the IRC on board AKARI. NIR spectra (2–5 μm) are obtained for the first time. They show no prominent emission or absorption features but are dominated by continuum radiation of the dust around NGC 300-OT. NIR photometric data were taken in $N2$, $N3$, and $N4$ bands. The SED of NGC 300-OT indicates a dust temperature of 810 ± 14 K at 398 days and 670 ± 12 K at 582 days. We estimate the dust optical depth as $\gtrsim 12$ on day 398 and $\gtrsim 6$ on day 582, assuming an isothermal dust cloud. Although the present model is very crude, optically thin models cannot account for the observations at days 398 and 582 consistently. The large optical depths at NIR suggest a large extinction at visible wavelengths, while little extinction is reported based on earlier observations ($E(B-V) = 0.05 \pm 0.05$). Those circumstances suggest that the dust cloud around NGC 300-OT should be distributed asymmetrically so as to not screen the radiation from the ejecta gas and the central star. The present results suggest that the dust formation occurs in NGC 300-OT in the form of a torus, a bipolar outflow, or clumpy cloudlets.

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