

High Resolution 30 μm Imaging of the Homunculus Nebula of Eta Carinae

T. NAKAMURA,¹ T. MIYATA,¹ S. SAKO,¹ T. KAMIZUKA,¹ K. ASANO,¹ M. UCHIYAMA,¹ T. ONAKA,¹ Y. ITA,²
 M. YONEDA,² H. KATAZA,³ K. MOTOHARA,¹ M. KONISHI,¹ T. MOROKUMA,¹ S. KOSHIDA,⁴ K. TATEUCHI,¹
 Y. YOSHII,¹ M. DOI,¹ K. KOHNO,¹ K. KAWARA,¹ M. TANAKA,¹ T. TANABE,¹ T. MINEZAKI,¹ Y. TAMURA,¹ T. AOKI,¹
 T. SOYANO,¹ K. TARUSAWA,¹ H. TAKAHASHI,¹ N. KATO,¹ AND T. HANDA⁵

¹University of Tokyo, Japan

²Tohoku University, Japan

³Institute of Space and Astronautical Science, JAXA, Japan

⁴Pontifical Catholic University of Chile, Chile

⁵Kagoshima University, Japan

ABSTRACT

We present a result of high-resolution 30 μm imaging observations of the Homunculus Nebula of Eta Carinae (η Car). The Homunculus Nebula is known to contain a large amount of cool dust (~ 100 K) at polar lobes and an equatorial torus. While the distribution of the cool dust shows the past dust formation events on η Car such as giant eruptions and binary interactions, no spatially resolved images at long mid-infrared wavelengths (30–50 μm) have been obtained. We observed η Car with a mid-infrared camera MAX38 on the University of Tokyo Atacama 1.0-m telescope, and successfully obtained spatially resolved images of the Homunculus Nebula at 18.7, 31.7 and 37.3 μm . The observations revealed the structure of the massive equatorial torus which contains the dust of $0.09 M_{\odot}$. This amount is equal to approximately 80 % of the total dust mass $0.12 M_{\odot}$ in the Homunculus Nebula. It is also found that the dust of $0.012 M_{\odot}$ exists inside the polar lobes. Assuming that the dust was constantly formed after the giant eruption occurred in 1843, the dust formation rate is estimated as $7 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$. This indicates that the binary interaction plays a significant role in the dust formation on η Car.

1. INTRODUCTION

Eta Carinae (η Car) is one of the best examples for understanding the dust formation in Luminous Blue Variables (LBVs). It has a remarkable circumstellar nebula called the ‘‘Homunculus’’ Nebula. This nebula is one of the most luminous objects in the infrared wavelengths, and the total infrared luminosity integrated from 2–200 μm is $4.3 \times 10^6 L_{\odot}$ at a distance of 2.3 kpc (Davidson & Humphreys 1997). The dust mass in the Homunculus Nebula is estimated to be 0.1–0.15 M_{\odot} (Morris et al. 1999). It corresponds to the gas mass of 10–15 M_{\odot} , assuming that the normal dust-to-mass ratio of ~ 100 .

However, the dust distribution around the Homunculus Nebula has not been well understood yet. Morris et al. (1999) suggested a massive equatorial torus surrounding the η Car binary system which has a period of 5.54 years (Damineli et al. 2008), whereas Smith et al. (2003) proposed that the cool dust component mainly reside in an outer layer of the polar lobes. This is a crucial problem because it would be reflected dust formation history on η Car. The dust production is considered to occur in two modes around η Car, periodic binary interactions and giant eruptions. The bipolar lobes are the products of the giant eruption in 1843 (Morse et al. 2001). On the other hand, the equatorial torus is considered to be an accumulation of dust produced within a few thousand years including the giant eruption(s) and the binary interactions. Its spectral energy distribution indicates that most of the dust has a temperature of ~ 100 K. Observations beyond 30 μm with high spatial resolution are needed to examine these hypothesis.

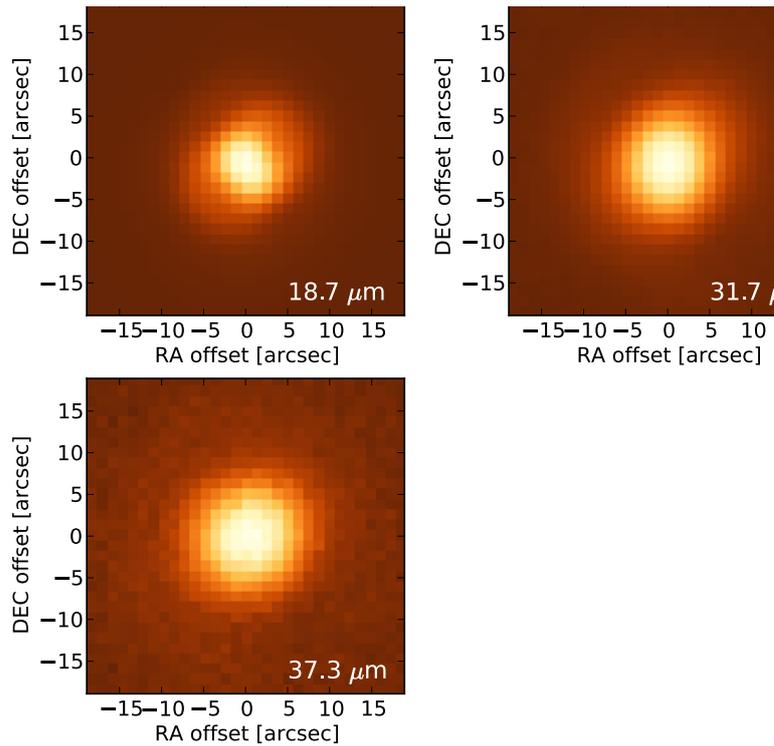
2. OBSERVATIONS

The observations were made with MAX38 on the miniTAO telescope in October 3, 2010. The miniTAO telescope is located at the top of Cerro Chajnantor (Co.) in the Atacama Desert, Chile with an altitude of 5,640 m (Sako et al. 2008). The precipitable water vapor (PWV) is 0.4 to 1.3 mm at Co. Chajnantor. Thanks to the low PWV, we can carry out observations with the 30 μm wavelength region, which had never been observed from the ground-based telescopes (Miyata et al. 2008; Nakamura et al. 2010; Asano et al. 2012). Table 1 summarizes the observational parameters. The PWV values during the observations were between 0.5 to 1.0 mm. All frames were obtained with the chop-nod technique. The images of V1185 Sco were also obtained at 18.7 and 31.7 μm as references of point spread functions (PSFs).

NAKAMURA ET AL.

Table 1. The parameters of the miniTAO/MAX38 observations (October 3, 2010)

λ (μm)	$\Delta\lambda$ (μm)	exp. time ¹ (sec)	FWHM (arcsec)
18.7	0.9	50	4.7
31.7	2.2	100	8.0
37.3	2.4	50	9.3

¹on-source time.**Figure 1.** The 18.7, 31.7 and 37.3 μm images of η Car obtained by miniTAO/MAX38. The 18.7 μm image gives a picture of the bright infrared core and the bipolar lobes. The images of 30 μm bands indicate that most of the cool dust components distributed around the bright infrared core.

3. RESULTS

The images in each filter are shown in Figure 1. The infrared colors of $[31.7]/[18.7]$ and $[37.3]/[18.7]$ give good agreements with the *ISO* results within the margin of the uncertainty. The 18.7 μm image gives a picture of the bright infrared core and the bipolar lobes previously reported in the Q-band imaging (e.g. Smith et al. 2003), while the spatial resolution of our image is lower than those observations. The 31.3 μm and 37.3 μm images have the higher spatial resolution than any observation at these wavelengths. The images of 30 μm bands show that most of the flux comes from the bright infrared core. The spatial profile of 37.3 μm can be fitted with a Gaussian function with a FWHM of 12.0 arcseconds, or 130 % of the PSF size. This result indicates most of the cold dust components distributed around the bright infrared core.

Figure 2 shows a map of color temperature of the dust estimated from the deconvoluted 18.7 μm and 31.7 μm images. The deconvolution was done by the Richardson-Lucy method (Richardson 1972; Lucy 1974) using the reference PSFs. The dust emissivity was assumed to be in proportion to λ^{-1} (e.g. Morris et al. 1999; Smith et al. 2003). A map of optical depth of the dust emission was also derived from the two images. The total flux is scaled to that of the *ISO* observation for each image. The optical depth map of the cool dust clearly shows that most of the cool dust component exists in the equatorial torus. In addition, the temperature map revealed that the cooler dust components exist inside each lobe. These components have temperatures of 120 K, which is considered to be in thermal equilibrium. Since the lobes were formed by the giant eruption in 1843, the dust inside the lobes should have been formed after the eruption.

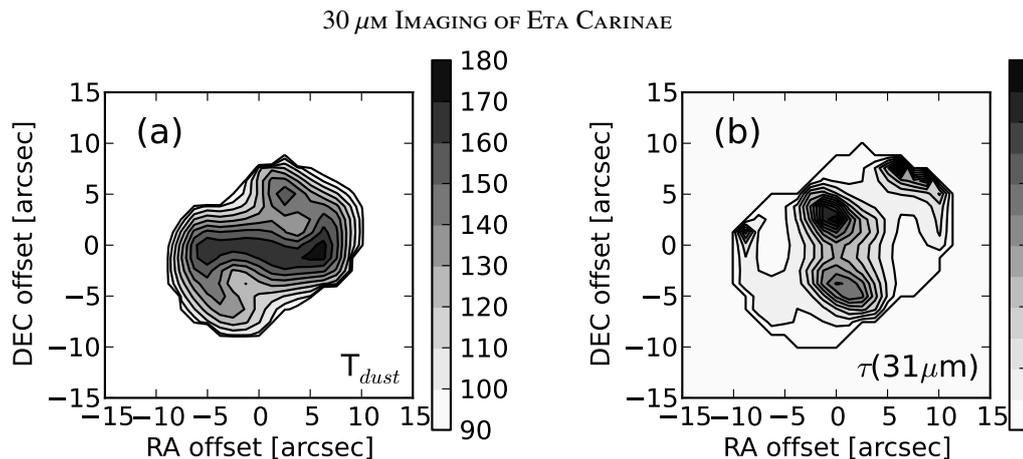


Figure 2. (a) The temperature map of the η Car Homunculus Nebula. The warm components (130–180 K) exist along the edge of the lobes and around the bright infrared core, and cool components (90–130 K) around the equatorial torus and at the center of each lobe. (b) The optical depth map of the Homunculus Nebula. The optically thick regions exist at the equatorial torus and the edge of the lobes.

Table 2. The estimated dust temperature and mass in each region of the Homunculus Nebula.

Region	Dust Temperature	Dust Mass
Equatorial torus	130 K	0.09 M_{\odot}
Polar lobes	170 K	0.015 M_{\odot}
Inside the lobes	120 K	0.012 M_{\odot}
Total		0.12 M_{\odot}

Table 2 summarizes the estimated dust mass of each component based on our mid-infrared images, assuming the grain density $\rho \approx 3 \text{ g cm}^{-3}$ and the dust size $a \approx 1 \mu\text{m}$. The result suggests that both of the giant eruptions and the binary interactions play important roles of dust formation. If the amount of dust inside the lobes was assumed to be constantly formed after the 1843's event, the dust formation rate is estimated as $\sim 7 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$. This rate is much higher than the dust formation rate of WR binaries, an order of 10^{-7} – $10^{-6} M_{\odot} \text{ yr}^{-1}$ (e.g. Marchenko et al. 2002). The efficient dust formation around η Car may be caused by the high eccentricity of the binary system and/or the high mass loss rate of the primary star.

This research is supported by Ministry of Education, Culture, Sports, Science and Technology of Japan, Grant-in-Aid for Scientific Research (21684006) from the JSPS of Japan. T.N. is supported by Grant-in-Aid for JSPS fellow (228881). T.N. is also supported by Hayakawa Sachio foundation.

REFERENCES

- Asano, K., et al. 2012, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 8446, 844634
 Daminieli, A., et al. 2008, MNRAS, 384, 1649
 Davidson, K., & Humphreys, R. M. 1997, Annual Review of A&A, 35, 1
 Lucy, L. B. 1974, AJ, 79, 745
 Marchenko, S. V., et al. 2002, ApJ, 565, L59
 Miyata, T., et al. 2008, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 7014, 701428
 Morris, P., et al. 1999, Nature, 402, 502
 Morse, J. A., et al. 2001, ApJ, 548, L207
 Nakamura, T., et al. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 7735, 773561
 Richardson, W. H. 1972, Journal of the Optical Society of America (1917-1983), 62, 55
 Sako, S., et al. 2008, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 7012, 70122T
 Smith, N., et al. 2003, AJ, 125, 1458