中間赤外線観測で探る
Eta Carinaeにおける星周ダスト形成

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Dust formation on Massive Stars

- Dust at high-z galaxies
  - z~6 (age: ~1Gyr); $10^8$-$10^9 M_{\text{sun}}$ dust
  - Massive stars will be primary dust suppliers

- When do massive stars form dust?
  - Prior to the SN explosion
  - In the SN ejecta

- SN2006jc
  - $7 \times 10^{-5} M_{\text{sun}} @ 800K + 3 \times 10^{-3} M_{\text{sun}} @ 320K$
  - Pre-existing dust is dominant

QSO SDSS J1148+5251
(Bertoldi et al. 2003)

Pre-existing dust is dominant but little known

(Sakon et al. 2009)
Massive stars’ life

- Varying with changes in initial masses
- mass-losing phase duration: $\sim 10^4$-$10^5$ year

**Wolf-Rayet Stars**

- >75$M_{\text{sun}}$
  - O
  - WN (H-rich)
  - LBV
  - WN (H-poor)
  - WC/WO
  - SN Ic
- 40-75$M_{\text{sun}}$
  - O
  - LBV
  - WN (H-poor)
  - WC/WO
  - SN Ic
- 25-40$M_{\text{sun}}$
  - O
  - LBV/RSG
  - WN (H-poor)
  - SN Ib

(Smartt, 2009)
The LBV phase is considered to be a primary mass loss phase of very massive stars. Observed (H-poor) WR stars have the mass of no more than $25M_{\text{sun}}$.

- Continuum-driven wind (Owocki et al. 2003)
  - Mass-loss rate: $\sim 10^{-3} \text{ Msun/yr}$
  - Exceeding “Eddington-limit”
  - Independent of stellar metallicity
Luminous Blue Variables

- Evolved, massive stars (initial mass: >30M\(_{\text{sun}}\))
- Luminous (~10\(^6\) L\(_{\text{sun}}\)) and high mass-loss rate (~10\(^{-3}\)M\(_{\text{sun}}\)/yr)
- Very rare: 12 LBVs and 23 LBV candidates in our Galaxy (Clark+, 2003)
**LBV variability**

- Giant eruption
  - Variation of > 2 mag
  - Observed two times in the Galaxy (η Carinae, P Cygni)
- Eruption: variation of 1-2 mag
  - Timescale: ~10-40 years
- The origin of variation is still unknown
  - Instability of stars, binary system, etc...

![Graphs and images showing LBV variability](image)
### Dust formation in LBVs

- Many LBVs are associated with circumstellar dust
- The estimated amount of dust mass: \( \sim 0.01--0.1 \text{M}_{\text{sun}} \)
- Much larger than the other types of massive stars (WR, RSG, etc…)

<table>
<thead>
<tr>
<th>Star</th>
<th>( \log(L/L_\odot) )</th>
<th>( R_{\text{net}} ) (pc)</th>
<th>( M_{\text{dust}} ) (M(_\odot))</th>
<th>( M_{\gas} ) (M(_\odot))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta \text{Car}^{a,b} )</td>
<td>6.7</td>
<td>0.1</td>
<td>0.15</td>
<td>3--15</td>
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<tr>
<td>AG Car(^c)</td>
<td>6.25</td>
<td>0.36--0.80</td>
<td>0.22</td>
<td>8.9</td>
</tr>
<tr>
<td>HR Car(^d,e,f)</td>
<td>5.7</td>
<td>0.26</td>
<td>(&lt; 8 \times 10^{-4})</td>
<td>0.8--2.1</td>
</tr>
<tr>
<td>Hen 3-519(^i)</td>
<td>5.7</td>
<td>1.14</td>
<td>0.007</td>
<td>2.0</td>
</tr>
<tr>
<td>Wra 751(^c)</td>
<td>5.7</td>
<td>0.17--0.34</td>
<td>0.017</td>
<td>1.7</td>
</tr>
<tr>
<td>HD 168625(^l,h,i)</td>
<td>5.6</td>
<td>0.21 \times 0.24</td>
<td>0.016</td>
<td>2.1</td>
</tr>
<tr>
<td>P Cyg(^k)</td>
<td>5.8</td>
<td>0.4</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>AFGL 2298(^m)</td>
<td>6.2</td>
<td>0.12--0.72</td>
<td>0.1</td>
<td>10</td>
</tr>
<tr>
<td>R 127(^l)</td>
<td>6.1</td>
<td>1.05 \times 0.8</td>
<td>0</td>
<td>10 \pm 2</td>
</tr>
<tr>
<td>S 119(^l)</td>
<td>6.0</td>
<td>1.0 \times 0.9</td>
<td>0</td>
<td>2.6 \pm 0.7</td>
</tr>
<tr>
<td>R 71(^o)</td>
<td>5.85</td>
<td>0.12--0.18</td>
<td>0.004</td>
<td>11</td>
</tr>
</tbody>
</table>

### (Clark+, 2003) G26.47+0.02 (MSX)
Dust formation in LBVs

- Typical LBV spectrum has a peak around 30µm
  - Cool dust (~100K) emission
- High-resolution >30µm imaging is important to investigate the cool dust components
miniTAO/MAX38

- Tokyo Atacama Observatory: the top of Co. Chajnantor, Atacama, Chile (5640m)
- miniTAO 1m telescope
Thanks to dry environment, atmospheric windows at 30-micron are available

- MAX38 carried out 30-micron observation from the ground for the first time!
### miniTAO/MAX38

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>8-38um</td>
</tr>
<tr>
<td>Detector</td>
<td>Si:Sb BIB 128x128</td>
</tr>
<tr>
<td>FOV</td>
<td>2′.7 x 2′.0</td>
</tr>
<tr>
<td>Pixel scale</td>
<td>1.26″/pix</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>8″.0 @ λ =30um</td>
</tr>
<tr>
<td>Observing mode</td>
<td>- imaging (8 filters)</td>
</tr>
<tr>
<td></td>
<td>- N-band spectroscopy</td>
</tr>
<tr>
<td>Newly developed</td>
<td>- cold chopper</td>
</tr>
<tr>
<td></td>
<td>- metal mesh filter</td>
</tr>
</tbody>
</table>

φ0.9m x 1m height, ~150kg

20cm
The most intensely observed LBV
Remarkable circumstellar nebula called the “Homunculus” Nebula

Giant eruption in 1843
- Formed the Homunculus Nebula

Binary interaction
- LBV+O binary (5.54 years)
- Periodic dust formation occurred

(Kashi+., 2008)
The Homunculus Nebula is considered to be consists of ~100K, 0.1~0.15M$_{\text{sun}}$ dust, but the distribution of the cool dust components is poorly understood.

- Morris+99: in the equatorial torus
- Smith+03: in the polar lobes

30-micron observations can reveal the cold dust distribution of η Carinae.
Observations

- Observed η Carinae Homunculus Nebula
  - Date: 2010/10/3
  - 18.7/31.7/37.3μm imaging
- VY CMa: reference star for the infrared color estimation
  - Infrared colors ([31.7]/[18.7] and [37.3]/[18.7]) are almost same as previous observations with ISO (1996)
- V1185 Sco: PSF standard

<table>
<thead>
<tr>
<th>λ (μm)</th>
<th>Δλ (μm)</th>
<th>Exposurea (sec)</th>
<th>FWHM (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.7</td>
<td>0.9</td>
<td>50</td>
<td>4.7</td>
</tr>
<tr>
<td>31.7</td>
<td>2.2</td>
<td>100</td>
<td>8.0</td>
</tr>
<tr>
<td>37.3</td>
<td>2.4</td>
<td>50</td>
<td>9.3</td>
</tr>
</tbody>
</table>
30-micron imaging

- Obtained the diffraction-limited images at each band
- Resolved the Homunculus Nebula at 31.7μm for the first time
spatial profiles of Homunculus Nebula

- comparing spatial profiles between two directions
- extended structure along both of the directions
- However, most of the infrared source is concentrated in the central core

FWHM: 12.0"  
PSFx1.3

Lobe direction
Torus direction
Deconvolution

- Obtained the deconvoluted image at 18.7/31.7µm
  - IRAF STSDAS/Lucy task
- FWHM of deconvoluted images became approximately 3 arcseconds at each image
The deconvoluted images were compared with previous observations.

The contours are consistent with the image of MIRAC3 whose spatial resolution is 0.6 arcseconds.

Image: MIRAC3/18.0μm
Contour: MAX38/18.7μm (deconvolved)

The deconvoluted images are considered to be reliable.
Calculate the temperature map from 18.7/31.7um
- grain emissivity is proportional to $\lambda^{-1}$ (cf. Morris+, 1999)
- warmer dust (140〜180K): central region, polar lobes
- cooler dust (90〜130K): equatorial torus, inside the lobes
- Calculated the optical depth map from 31μm brightness distribution
- Large optical depth at the edge of the polar lobes and the equatorial torus (up to 1.2)
The distribution of cool dust components has been controversial:
- Morris+99: in the equatorial torus
- Smith+03: in the polar lobes

Our observations clearly showed the cool dust components mainly resides in the equatorial torus

In addition, the cool dust components inside the lobes are found
- this component is in thermal equilibrium
 Estimation of the dust mass at each part

- \( \rho \approx 3 \text{g/cm}^3, \ a \approx 1 \mu\text{m} \)
- A total of 0.12\( M_{\text{sun}} \) dust:
  consistent with Morris+ (1999) and Smith+ (2003)
- 80% of the dust exists in equatorial torus
- > 0.015\( M_{\text{sun}} \) of dust formed at the giant eruption
0.012 $M_{\text{sun}}$ dust in the Polar lobes
- corresponds 10% of the total amount of dust in the Homunculus Nebula

Assuming that this dust formed after the giant eruption, the dust formation ratio is $7 \times 10^{-5} M_{\text{sun}}/\text{yr}$
- Much higher rate than the typical WR binary ($10^{-7} \sim 10^{-6} M_{\text{sun}}/\text{yr}$)

The active dust formation occurred at binary interaction in LBV binaries
30 micron imaging observations of η Carinae carried out with miniTAO/MAX38
Spatially resolved the dust components of the Homunculus Nebula for the first time
Both of the giant eruption and the binary interaction make significant contributions to the dust formation at η Carinae
The active dust formation occurred at binary interaction in LBV binaries