IMAGING THE COOL HYPERGIANT NML CYGNI’S DUSTY CIRCUMSTELLAR ENVELOPE WITH ADAPTIVE OPTICS

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ABSTRACT

We present subarcsecond angular resolution, high-Strehl ratio mid-IR adaptive optics images of the powerful OH/IR source and cool hypergiant NML Cyg at 8.8, 9.8, and 11.7 μm. These images reveal once more the complexity in the dusty envelope surrounding this star. We spatially resolve the physical structures (radius ~ 0.14, ~ 240 AU adopting a distance of 1.74 kpc) responsible for NML Cyg’s deep 10 μm silicate dust absorption feature. We also detect an asymmetric excess, at separations of ~0′.3–0′.5 (~520–870 AU), northwest from the star. The colors of this excess are consistent with thermal emission of hot, optically thin dust. This excess is oriented in the direction of the Cyg OB2 stellar association, and is likely due to the disruption of NML Cyg’s dusty wind with the near-UV radiation flux from the massive hot stars within Cyg OB2. This interaction was predicted in our previous paper to explain the geometry of an inverted photodissociation region observed at optical wavelengths.

Key words: circumstellar matter – infrared: stars – open clusters and associations: individual (Cyg OB2) – stars: imaging – stars: individual (NML Cyg) – stars: mass loss

1. INTRODUCTION

The powerful OH/IR source and cool hypergiant NML Cyg is one of the most massive and luminous M stars in the Galaxy (~40M⊙, Mbol ≃ −9.5; Hyland et al. 1972; Humphreys & Davidson 1979, 1994; Morris & Jura 1983; Schuster et al. 2006a; Schuster 2007). Originally discovered by Neugebauer, Martz & Leighton (1965), NML Cyg was easily identified as an extremely bright infrared source (I ∼ 8, K ∼ 1 mag). The star’s relatively close proximity to the Cyg OB2 stellar association confirms its high luminosity (Morris & Jura 1983; Schuster et al. 2006a). Even though NML Cyg is luminous, it is also heavily obscured at visual wavelengths due to high interstellar (IS) and circumstellar (CS) extinction, with V fainter than 16.6 mag. Its visual/near-IR spectrum indicates a M6 spectral type (Wing et al. 1967) and its spectrum peaks in the 2–20 μm range (Gillett et al. 1968; Stein et al. 1969). Thus, the spectrum indicates a substantial, optically thick dusty CS envelope obscuring the central star. NML Cyg’s thick envelope is a result of its strong post-main-sequence (post-MS) wind (with a velocity of 23 km s⁻¹) and high continuous mass-loss rate of 6.4 × 10⁻⁷ M⊙ yr⁻¹ (Hyland et al. 1972; Bowers et al. 1981; Morris & Jura 1983). Habing et al. (1982) mapped an unusual oblong-shaped H II region⁴ at 21 cm nearly 1′ in size around NML Cyg, revealing another unique feature of this enigmatic M supergiant. In addition, more recent high-angular resolution, high-contrast images from the Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) camera reveal an asymmetric CS nebula of dust scattered stellar light (Schuster et al. 2006a). The CS nebula has a shape similar to the H II region, but is about 300 times smaller in radius. It is necessary to consider NML Cyg’s local environment and its effects on the star in order to understand this object’s true nature.

Although NML Cyg is a very luminous post-MS star which is losing mass at a prodigious rate, it does not currently dominate its local IS environment because of its unique location within the Milky Way. It lies in relatively close proximity to Cyg OB2, which is possibly the largest OB stellar association—in size, mass, and number of OB stars—in the Galaxy (see Knödlseder 2003, and references therein for a multiwavelength review). The Cyg OB2 association spans nearly 2° on the sky, or ~30 pc in radius at the distance of 1.74 ± 0.2 kpc (Massey & Thompson 1991), making it one of the closest massive associations to the Sun. Cyg OB2 has ~120 O star members, including five of the 10 most luminous O stars in the Galaxy (Humphreys 1978), and approximately 2500 B stars. The stellar mass within the association is possibly as high as 10⁵ M⊙. The O stars provide the UV radiation responsible for a Strömgren sphere that extends to a radius of at least 2.74° on the sky, or ≥ 80 pc (the projected separation between Cyg OB2 and NML Cyg). The Lyman continuum photon flux of the whole association is estimated to be 10⁵¹ ph s⁻¹, or ≥ 10⁹ ph cm⁻²s⁻¹ at the location of NML Cyg. Mid-IR images from the Midcourse Space Experiment (MSX) satellite show NML Cyg is located in a relative void of gas/dust inside the Cygnus X super bubble (Schuster 2007). This configuration allows the Lyman continuum photons and near-UV radiation from the hot stars within Cyg OB2 to travel the large distance to NML Cyg relatively unimpeded.

Morris & Jura (1983) demonstrated that the Lyman continuum radiation from Cyg OB2 is responsible for the asymmetric H II region observed around NML Cyg. The H II region is the result of a photoionization interaction between the spherically symmetric, expanding hydrogen wind from NML Cyg balanced against an incident plane parallel Lyman continuum photon flux from Cyg OB2 (see Figures 1 and 2 in Morris & Jura 1983). The photoionization is inverted in the sense that usually the nearest massive star is the ionization source and the ionization occurs outward from the central source. Morris & Jura also demonstrated that the strength of the Lyman continuum flux from Cyg OB2 and the density of atomic hydrogen around NML Cyg are sufficient to produce the observed 21 cm emission, thus confirming NML Cyg’s high continuous mass-loss rate. In a similar way,
Figure 1. 8.8, 9.8, and 11.7 μm MMT/AO MIRAC3/BLINC images of NML Cyg's dusty CS nebula. Top row: images of NML Cyg, no postprocessing. Middle row: PSF reference star images (γ Dra, epoch 1). Bottom row: NML Cyg after oversubtracting the PSF images above (scaled to peak brightness to give zero flux). NML Cyg's CS envelope is clearly broader than a point source, extended with a NW/SE orientation. There is also an asymmetric excess on the NW side. The spot in the lower right corner is a PSF ghost. The images are displayed with a square root intensity scale.

Figure 2. NML Cyg SED from photometry in Table 2, as well as ISO Short Wavelength Spectrometer spectra (Justtanont et al. 1996; Kraemer et al. 2002). The 10 μm silicate feature is seen in absorption, and is a result of the optically thick CS envelope enshrouding the star. There is some normalization offset between the ISO spectra and the other observations. At least some of this difference is presumably from the variation in the star's spectrum over its 3 year period. The ground-based observational errors have typical 5%–10% systematic uncertainties (only calibration uncertainties are plotted here). NML Cyg's extreme brightness led to large IRAC PSF fitting errors. The star's high luminosity may have led to saturation in the IRAS observations, resulting in the offset with the ISO spectra.
Schuster et al. (2006a) described how near-UV photons with energies between a few and 13.6 eV photodissociate the molecular gas in NML Cyg’s wind. Schuster et al.’s model explains why the asymmetric shape of the CS nebula resolved in HST WFPC2 images is a consequence of this physical interaction with Cyg OB2. Recent observations of excited-state OH maser emission in NML Cyg’s wind by Sjouwerman et al. (2007) are consistent with an increased OH column density, presumably arising from dissociated H2O molecules at the water photodissociation region (PDR). Since the atomic and molecular gas around NML Cyg is disrupted, the dust facing Cyg OB2 is unprotected from the near-UV photons. It is thus likely that the CS dust grains are heated and destroyed by the radiation from Cyg OB2 and should emit a detectable infrared signature.

In Section 2, we present subarcsecond angular resolution, high Strehl ratio MIRAC3/BLINC mid-IR images of NML Cyg obtained at the 6.5 m MMT observatory with the adaptive optics (AO) system. These observations are among the highest resolution images of this star at mid-IR wavelengths and reveal the complexity in the asymmetric dust envelope surrounding NML Cyg. This photometry from the Spitzer Space Telescope’s Infrared Array Camera (IRAC), the HST WFPC2 camera, and ground-based infrared observations are presented in Section 2. The spectral energy distribution (SED) for NML Cyg’s CS envelope presented in Section 3 shows an optically thick silicate dust absorption feature. In Section 4, we characterize the resolved structures in the dusty CS envelope. In Section 5, we show that the CS dust component facing Cyg OB2 exhibits a silicate feature in emission. We suggest that UV radiation from the hot, massive stars within Cyg OB2 likely causes the inversion in the silicate feature through external heating and dust destruction. We conclude by discussing these results in relation to previous works on NML Cyg and comparing NML Cyg to the extremely luminous M-type hypergiant VY CMa.

2. OBSERVATIONS

2.1. MMT/AO Observations

The inverse PDR model for NML Cyg’s CS envelope described in Schuster et al. (2006a) implies the presence of warm dust near the photodissociation front(s). According to this model, Cyg OB2’s UV radiation is heating/destroying the CS dust on the side facing Cyg OB2. In order to corroborate this model through direct observation, we obtained high-angular resolution, high-contrast mid-IR images of NML Cyg’s dusty CS nebula. The observations were made using the University of Arizona’s AO system (Wildi et al. 2003) and the MIRAC3/BLINC camera (Hoffmann et al. 1998; Hinz et al. 2000) on the 6.5 m MMT telescope. Table 1 summarizes the observations made in 2006 July and Figure 1 shows the NML Cyg images at 8.8, 9.8, and 11.7 μm. The BLINC module was used in ‘chop’ mode with a frequency of ~1 Hz, which is useful for background (sky) subtraction when combined with “nod” dithers. Using natural guide star mode, the MMT/AO system produced stable, high-Strehl ratio (~96%–98%), high signal-to-noise, nearly diffraction limited point-spread functions (PSF) at 10 μm. We have used the source itself as a guide star for the AO system (while extended in the infrared, NML Cyg is a point source at optical wavelengths where the AO system operates). With a magnitude R ~ 14, NML Cyg is at the sensitivity limit for the MMT/AO wavefront sensor, but was successfully used thanks to the excellent sky conditions.

| Table 1 | Observations |
|---------|--------------|
| MMT AO MIRAC3 | λ | Δλ | Airmass | Exposures |
| 2006 Jul 23 UT | (μm) | (μm) | | no. x s |
| NML Cyg | 8.80 | 0.88 | 1.10 | 13 x 20 |
| . | 9.80 | 0.98 | 1.18 | 11 x 20 |
| . | 9.80 | 0.98 | 1.02 | 2 x 20 |
| . | 11.70 | 1.12 | 1.14 | 11 x 20 |
| y Dra (calibrator) | 8.80 | 0.88 | 1.08 | 15 x 30 |
| . | 8.80 | 0.88 | 1.18 | 15 x 30 |
| . | 9.80 | 0.98 | 1.07 | 20 x 30 |
| . | 9.80 | 0.98 | 1.23 | 36 x 30 |
| . | 11.70 | 1.12 | 1.09 | 20 x 30 |
| . | 11.70 | 1.12 | 1.28 | 20 x 30 |
| Spitzer/IRAC | λ | Δλ | Filter | Exposures |
| 2004 Jul 27 UT | (μm) | (μm) | | no. x s |
| NML Cyg | 3.550 | 0.750 | 6588416 | 3 x 10.4 |
| . | 4.493 | 1.015 | | | |
| . | 5.731 | 1.425 | | | |
| . | 7.872 | 2.905 | | | |
| OBO MN Bolometer | λ | Δλ | Filter | Exposures |
| 2000 Aug 10 UT | (μm) | (μm) | | |
| NML Cyg | 1.250 | 0.200 | J | no/a |
| . | 1.653 | 0.297 | H | |
| . | 2.340 | 0.500 | K | |
| . | 3.647 | 1.152 | L | |
| . | 4.900 | 0.700 | M | |
| . | 10.925 | 6.730 | N | |
| . | 7.908 | 0.755 | |
| . | 8.808 | 0.871 | |
| . | 9.803 | 0.953 | |
| . | 10.273 | 1.013 | |
| . | 11.696 | 1.110 | |
| . | 12.492 | 1.157 | |
| HST/WFPC2 | λ | Δλ | Filter | Exposures |
| 1999 Sep 16 UT | (μm) | (μm) | | no. x s |
| NML Cyg | 0.4293 | 0.0473 | F439W (B) | 6 x 500 |
| . | 0.5337 | 0.1228 | F555W (V) | 20, 100, 4 x 400 |
| . | 0.6564 | 0.0022 | F666N (Hα) | 20, 2 x 260 |
| . | 0.6677 | 0.0867 | F675W (R) | 0.5, 10 |

Notes. Exposure time not applicable to UMN bolometer since the instrument measures changes in voltage to obtain instrumental magnitudes and signal-to-noise.

aSaturation.

bNo detection.

eFigure 1 also shows images of the IR standard γ Dra, which was observed at two separate epochs and sky orientations for calibration and PSF characterization (see Table 1, only one epoch is shown in Figure 1). The PSF stability was excellent throughout the night and the sky conditions were especially good, with seeing ≤0.25. In these PSF images the minima/maxima in the diffraction pattern are closely matched to the Airy pattern for a 6.35 m aperture,5 with a FWHM of 0.33 at 8.8 μm, 0.36 at 9.8 μm, and 0.44 at 11.7 μm.

The nearly diffraction limited images have similar benefits in resolution and stability to images from space-based observatories, and at mid-IR wavelengths we can detect and separate the externally heated dust from the rest of NML Cyg’s CS nebula. Relatively long exposure times and a five point dither pattern, repeated multiple times with sub-pixel shifts, provided very high dynamic range (HDR) images of NML Cyg and the calibration/PSF standards, in the range ~2 x 103 to 104 (PSF peak relative

5 The MMT adaptive secondary is undersized to improve IR performance, resulting in a 6.35 m equivalent resolution limit.
to background noise). The images were processed with the Drizzle algorithm to maximize the quality of the data and recover sampling resolution (Hook & Fruchter 1997; Koekemoer et al. 2000; Fruchter & Hook 2002). The processed MIRAC3 images were resampled by $2 \times 2$ from $0.0954$ pixel$^{-1}$ to a scale of $0.0477$ pixel$^{-1}$.

The 8.8, 9.8, and 11.7 $\mu$m filters were chosen to provide good spectral coverage of the 10 $\mu$m silicate dust feature observed for this luminous cool star (Monnier et al. 1997; Blöcker et al. 2001). The photometry of the source in the three MIRAC3 bands is listed in Table 2. The flux in each band was measured in an aperture of 2$''$ radius, with the sky residual background flux (after sky subtraction for each chop/nod sequence) determined outside this aperture. Photometric calibration was obtained using the PSF reference star $\gamma$ Dra as photometric standard.

The photometry has been corrected to a common airmass. The uncertainty in the photometry quoted in Table 2 do not include 5%–10% systematic uncertainties typical for ground based mid-IR observations.

### Table 2

| Instrument | Filter | $\lambda$ (\(\mu\)m) | Flux (Jy) | Error (Jy) |
|------------|--------|------------------------|----------|------------|
| HST/WFPC2  | $V$    | 0.5337                 | 2.377e-04| 0.003e-04  |
|           | $H\alpha$ | 0.6564                | 2.395e-03| 0.014e-03  |
|           | $R$    | 0.6677                 | 6.124e-03| 0.029e-03  |
| OBO MN Bolometer |          |                       |          |            |
| 2000 Aug 10 UT | $J$    | 1.250                  | 21.5     | 1.4        |
|           | $H$    | 1.653                  | 131      | 0.7        |
|           | $K$    | 2.340                  | 333      | 1.0        |
|           | $L$    | 3.647                  | 1287     | 4.2        |
|           | $M$    | 4.900                  | 2121     | 10         |
|           | $N$    | 10.925                 | 4325     | 58         |
|           |        | 7.908                  | 4522     | 90         |
|           |        | 8.808                  | 4124     | 60         |
|           |        | 9.803                  | 3881     | 43         |
|           |        | 10.735                 | 3905     | 71         |
|           |        | 11.696                 | 5020     | 120        |
|           |        | 12.492                 | 5366     | 84         |
| Spitzer/IRAC PSF fitting$^b$ |          |                       |          |            |
| 2004 Jul 27 UT | 3.6    | 3.550                  | 1150     | 160        |
|           | 4.5    | 4.493                  | 1670     | 240        |
|           | 8.0    | 7.872                  | 4160     | 830        |
| MMT AO MIRAC3/BLINCa$^c$ |          |                       |          |            |
| 2006 Jul 23 UT | 8.0    | 8.80                   | 3735     | 63         |
|           | 9.80   | 9.80                   | 3780     | 160        |
|           | 11.70  | 11.70                  | 5280     | 130        |
| IRAS PSC$^c$ |          |                       |          |            |
| 1983      | 12     | 5580                   | 560      |
|           | 25     | 3990                   | 400      |
|           | 60     | 1030                   | 100      |
|           | 100    | 335                    | 34       |

### Notes

$^a$Observational errors exclude typical 5%–10% systematic uncertainties.

$^b$NML Cyg’s mag is near the limit for IRAC PSF fitting (see Schuster et al. 2006b). 5.8 $\mu$m PSF fitting was not reliable.

$^c$Fluxes from the IRAS Point Source Catalog rejects—from the Infrared Science Archive: [http://irsa.ipac.caltech.edu, data tag: ADS/IRSA.Gator#2007/1009/122926_27251.](http://irsa.ipac.caltech.edu) 10% flux uncertainty assumed.

### 2.2. Spitzer/IRAC Observations

Table 1 summarizes our observations of NML Cyg obtained in 2004 July with the IRAC (Fazio et al. 2004) on board the *Spitzer* (Werner et al. 2004; Gehrz et al. 2007). The IRAC images (GTO Program 124, AOR 6588416, pipeline ver. S14.0.0) were processed with IRACproc, a software package that facilitates co-addition and analysis of IRAC data (Schuster et al. 2006b). IRACproc also improves the identification and removal of cosmic rays and other transient signals from the processed images, while simultaneously improving image quality, photometric accuracy and sensitivity (signal-to-noise). Due to the extreme brightness of the source, the core of the IRAC images was saturated, preventing the adoption of standard aperture photometry techniques to measure the flux in the IRAC bands. By fitting a HDR PSF to the diffraction spikes and extended “wings” of the IRAC images, we have however derived the source photometry in the IRAC bands at 3.6, 4.5, and 8.0 $\mu$m (artifacts in the 5.8 $\mu$m image prevented using this technique at that wavelength). The PSFs we used were obtained from the observation of bright stars (Vega, $\epsilon$ Eridani, Fomalhaut, and $\epsilon$ Indi) as part of the *Spitzer* GTO program 90, and are available at the *Spitzer* Science Center Web site. The detailed description of this fitting procedure is available in Marengo et al. (2006) and Schuster et al. (2006b). The photometry is listed in Table 2.

### 2.3. Ground-Based IR Photometry

We obtained ground-based broadband 1–12 $\mu$m photometry in 2000 August at the University of Minnesota’s (UMN) O’Brien Observatory (OBO) with a single element bolometer using a standard chop-nod technique for background sky subtraction (beam diameter $\sim 27''$, Gehrz et al. 1974, 1992; Gehrz 1997). The observations and photometry are summarized in Tables 1 and 2. The absolute calibration of the instrument was determined using $\alpha$ Lyr (Vega) and $\beta$ Peg as primary calibrator, using the procedure described in Gehrz (1997).

### 2.4. HST/WFPC2 PC Photometry

Multiwavelength images of NML Cyg were obtained in September 1999 with the WFPC2 on board the *HST* (Biretta et al. 2000). These observations aimed to investigate the star’s CS nebularity are summarized in Table 1 (images previously published by Schuster et al. 2006a). NML Cyg was observed with broadband Johnson–Cousins $V$ and $R$ filters as well as narrowband $H\alpha$ filter. Prior to co-addition, the images were processed with the Space Telescope Science Institute’s standard calibration reference files. The images were combined with the IRAF/STSDAS software package DITHER, which uses the Drizzle algorithm to recover image resolution from the pixel response of the camera while preserving photometric accuracy (Koekemoer et al. 2000; Fruchter & Hook 2002). Multiple, dithered exposures allowed removal of cosmic rays, bad pixels, and other effects during co-addition. The *HST* photometry is reported in Table 2.

### 3. NML CGY’S BOLOMETRIC LUMINOSITY AND 10 $\mu$m SILICATE DUST ABSORPTION FEATURE

Table 2 summarizes our photometric observations of NML Cyg along with archival IRAS point source fluxes. These observations are plotted on $\lambda F_{\lambda}$ versus $\lambda$ SED in Figure 2.
along with reprocessed archival Infrared Space Observatory (ISO) Short Wavelength Spectrometer spectra (Justtanont et al. 1996; Kraemer et al. 2002). NML Cyg’s spectrum rises rapidly from optical wavelengths through the IR to peak in the 2–20 $\mu$m range, with a broad far-IR tail. Visible light images presented by Schuster et al. (2006a) show that NML Cyg is almost completely obscured by the CS envelope enshrouding the star, thus confirming significant CS extinction. This is evident from the broad 10 $\mu$m silicate dust absorption feature. Due to the optically thick envelope, this feature is a striking characteristic of the NML Cyg spectrum, setting this star apart from other cool hypergiants such as $\mu$ Cep (Gehrz et al. 1970), S Per (Humphreys 1974, and unpublished data), VY CMa (Smith et al. 2001), VX Sgr (Humphreys 1974), HR 5171 A (Humphreys et al. 1971), IRC +10420 (Jones et al. 1993), and M33 Var A (Humphreys et al. 2006), where the 10 $\mu$m silicate feature is seen in emission from optically thin CS nebula shells. NML Cyg is also a semiregular variable with period $\sim$940 days (Monnier et al. 1997, and references therein). The vertical spread between data sets in Figure 2 is well within the $\sim$50% amplitude variation reported by Monnier et al. (1997) from 8 to 13 $\mu$m. Even with this large variability, Monnier et al.’s results show that the 10 $\mu$m silicate feature’s shape is roughly constant over a span of nearly 19 years. In addition, the vertical offsets between observations at other wavelengths in Figure 2 are at least in part due to variability. However, the degree to which NML Cyg’s spectrum varies, in either amplitude or shape, at other wavelengths has not been well established. IS extinction to NML Cyg is also high, with an estimated range of $A_\nu \sim 3.7$–4.6 mag (Lee 1970; Gregory & Seaquist 1976).

We calculate NML Cyg’s minimum bolometric luminosity by integrating the SED in Figure 2, obtaining $L_{bol} = (1.04 \pm 0.05) \times 10^5 \cdot (d/kpc)^2 L_\odot$, or $(3.15 \pm 0.74) \times 10^5 L_\odot$ at 1.74 $\pm 0.2$ kpc (Massey & Thompson 1991, Cyg OB2 distance modulus 11.2). This luminosity does not include a correction for IS extinction, which would add at most a few percent to the total since most of the light is in the mid-IR where extinction is low. The uncertainty in this estimate does not consider the changes in the source brightness due to its variability. This luminosity value is in good agreement with the estimate of $L_{bol} = 1.13 \times 10^5 (d/kpc)^2 L_\odot$ by Blöcker et al. (2001). Thus, NML Cyg’s intrinsic luminosity, a few $\times 10^5 L_\odot$ ($M_{bol} \simeq -9.0$) is similar to that of other extremely luminous M-type hypergiants.

Previously, Morris & Jura (1983) reported a luminosity of $\sim 5 \times 10^5 L_\odot$ for NML Cyg at a distance of 2.0 kpc. This luminosity was equal to the most luminous known M supergiants in the Milky Way and LMC, $M_{bol} \simeq -9.5$, 5$\times 10^5 L_\odot$ (Humphreys 1978; Humphreys & Davidson 1979). Our value is 37% lower, with 24% due to the downwardly revised distance, and 13% from our integration of the SED from 0.5 to 100 $\mu$m (including new photometry). With this revision, NML Cyg appears to be less luminous than the hypergiant VY CMa (M4-5e Ia, $4.3 \times 10^5 L_\odot$ at 1.5 kpc, also without correcting for IS extinction), which has a comparable SED (Smith et al. 2001; Humphreys et al. 2007). The uncertainty in our estimate and the variability of the source makes it difficult to determine unambiguously which of these stars is more luminous. Even with this reduction in luminosity, however, NML Cyg remains the most luminous star with spectral type M6 or later known in the Milky Way.

4. MID-IR IMAGE ANALYSIS

Figure 1 shows that NML Cyg’s CS envelope is clearly extended at mid-IR wavelengths, compared to the point-source (PSF) images of $\gamma$ Dra, as the diffraction pattern appears “filled-in.” As further evidence for the extension and degree of asymmetry, Figure 1 also shows the NML Cyg images after oversubtracting the PSF (epoch 1, scaled to give zero intensity flux at the center pixel in the subtracted images). The asymmetric CS envelope residuals are apparent, having a northwest/southeast elongation axis, and position angle (PA) in the range $\sim 120^\circ$–150$^\circ$. Also visible in the PSF-subtracted images is a lopsided tail extending to the northwest (across the first diffraction ring). The MMT is an elevation/azimuth mount telescope, so the background sky predictably rotates in the image plane while tracking an object. Thus, it was possible to directly confirm the asymmetric extension by observing NML Cyg twice in the same night, at two sky rotation angles separated by $\sim 122^\circ$ (at 9.8 $\mu$m only). The extended components rotated by the same number of degrees (not shown here), eliminating the possibility that the PSF or other instrumental effects are the cause of the observed extension.

NML Cyg’s mid-IR envelope orientation is similar to the 130$^\circ$–150$^\circ$ PAs observed in the OH (Masheder et al. 1974; Benson & M目前已看到的英文文章的文本内容，无法提供图片分析的说明。
Figure 3. MMT/AO MIRAC/BLINC images of NML Cyg after deconvolution with the PSF reference star (γ Dra, epoch 1). The inner contour is set to the source 1/2 maximum flux level and shows that the core of the emission is elongated along the southeast–northwest axis (∼140°, dashed line). The outer contour is set to one-tenth of the source maximum flux level and shows that the external part of the CS emission is lopsided towards the NW quadrant. The images are displayed with a square root intensity scale. The arrow indicates the direction of the Cyg OB2 association.

Table 3

| λ (μm) | Component    | ΔRA (mas) | ΔDec (mas) | Flux (%) | σ (mas) | a/b  | PA (°) |
|--------|--------------|-----------|------------|----------|---------|------|--------|
| 8.8 μm | Core envelope| 0         | 0          | 74.1     | 91.0    | 1.09 | 120    |
|        | Outer envelope| 14       | 87         | 25.9     | 171.7   | 1.00 | ...    |
| 9.8 μm | Core envelope| 0         | 0          | 70.4     | 124.0   | 1.20 | 138    |
|        | Outer envelope| 44       | 105        | 29.6     | 176.5   | 1.00 | ...    |
| 11.7 μm| Core envelope| 0         | 0          | 65.6     | 113.1   | 1.02 | 139    |
|        | Outer envelope| 45       | 98         | 34.4     | 171.7   | 1.00 | ...    |

Notes.
- a Position offsets are relative to core component, +ΔRA. is to the west.
- b The errors, including fit uncertainty and field rotation during the observation, is ∼5 mas.
- c Percentages are relative to total flux. Uncertainties better than 2%.
- d FWHM = 2√ln2×σ.
- e Uncertainty of 10 mas or better.
- f Major axis (a) PA is measured in degrees counterclockwise from north.

∼140° (counterclockwise from north) in the 9.8 and 11.7 μm deconvolved images. This angle is similar to the alignment of the NML Cyg OH, H2O, and SiO masers, also at ∼130°–150°. The PA is slightly smaller (∼120°) in the 8.8 μm image, possibly due to an image artifact in the direction of the MIRAC3/BLINC chop.

To better characterize the shape and spatial scales of the NML Cyg CS envelope, we fit the images in Figure 3 with two two-dimensional Gaussians, one fitting the core emission (which we call the “core envelope” Gaussian) and the other fitting the NW extended low-level structures (the “outer envelope” Gaussian). Note that this fitting process is aimed only to find a practical way of describing the changing colors of the CS envelope at different distances from the center. The fitting process or results do not imply that the individual Gaussians represent individual physical structures in the CS envelope. The core Gaussian has a width and orientation analogous to the core component and is centered on the star. The second Gaussian fits the outer envelope emission and is offset in the NW direction as shown by the 1/10 contour level asymmetry. The best-fit parameters were determined by minimizing the residuals after subtraction of the two Gaussians from the deconvolved images. We start by fitting the first Gaussian to the image core, then the second Gaussian is fit to the core-subtracted image. The process was then iterated to minimize the residuals after subtraction of both Gaussians. Table 3 lists the best-fit parameters for each wavelength, including the size parameter σ and relative flux (in % of the total flux) of each component, the aspect ratio a/b between the major and minor semi-axis and the PA of the core component and the offset of the outer envelope with respect to the core. Figure 4 shows the radial profiles of the deconvolved image and best-fit Gaussians along the cut at PA = 140°. Note how the profiles show the large asymmetry between the southeastern (SE) and NW directions. While the SE profile is fit well by the two Gaussians, some residual flux above the fit is still present in the NW direction.

The agreement in PA and size between the core envelope emission and the NML Cyg maser observations suggests that this emission arises from the NML Cyg’s wind at, or just interior to, the photodissociation front(s) described in Schuster et al. (2006a). The relative flux contribution from the outer envelope component increases from 8.8 to 9.8 to 11.7 μm as we are resolving the optically thin warm dust (T_dust ∼ 200–500 K) farther out in the envelope.
4.2. The Asymmetric NW Excess

To test the accuracy of the deconvolution parametrization in image space, we have subtracted the Gaussian fit, convolved with the PSF reference ($\gamma$ Dra), from the NML Cyg mid-IR images at each wavelength. The residuals are shown in Figure 5. The grid-like pattern is due to the spatial sampling and linear interpolation of the image on the detector grid, and is the limiting factor in the accuracy of the fit. This pattern may be reduced by increasing the number of unique offsets in the dithered observations and by applying higher order interpolation in the reconstruction of the image on a finer pixel grid. The uniform distribution of this residual pattern and the relatively low flux level in the center is indicative of the good quality of the deconvolutions and fits, and also the stability of the MMT/AO PSF.

The figure also shows a clear excess residual in the NW quadrant. The excess peak brightness occurs around $\sim$0$''$3 to 0$''$5 ($\sim$520–870 AU) from the central star, with a broad tail extending toward Cyg OB2. This excess cannot be reduced by adjusting the position and shape of the outer envelope Gaussian, constrained by the fit in the other three quadrants. The shape and orientation of this excess are reminiscent to the lopsided emission seen in the HST images from Schuster et al. (2006a, their Figures 2 and 6). The asymmetric excess is separated from the star in Figure 5 at the spatial resolution limit, i.e., it is resolved according to the Rayleigh criterion. It lies just outside the asymmetric dusty reflection nebula seen in the HST images (Schuster et al. 2006a). We suggest that the excess emission is likely from warm dust that is externally heated/destroyed by UV radiation from Cyg OB2. In the next section, this hypothesis will be tested by directly measuring the flux from this excess.

5. DISCUSSION: CS DUST HEATING AND DESTRUCTION

In Table 4, we list the total flux of the source, the fraction of the total flux in the core and outer envelope, the total flux of all the fit residuals shown in Figure 5, and the excess residual flux in the NW quadrant (residual flux in the NW quadrant minus the residual flux in the opposite SE quadrant). In Figure 6, we plot the [8.8]−[9.8] and [9.8]−[11.7] colors for each CS nebula component. Both the core envelope colors are bluer than the total for the source. This core component likely represents the collective flux from where the silicate absorption is deepest and thus characterizes the geometry of the dust responsible for the
Table 4  
CS Envelope Component Fluxes

| λ (µm) | Components     | Flux (Jy) |
|--------|----------------|-----------|
| 8.8 µm | Total flux     | 3735 ± 63 |
|        | Core envelope  | 2540 ± 67 |
|        | Outer envelope | 888 ± 23  |
|        | Total residual | 307       |
|        | NW−SE excess   | 95 ± 10   |
|        | Vega           | 49.5      |
| 9.8 µm | Total flux     | 3780 ± 160|
|        | Core envelope  | 2422 ± 114|
|        | Outer envelope | 1018 ± 48 |
|        | Total residual | 343       |
|        | NW−SE excess   | 121 ± 4   |
|        | Vega           | 40.2      |
| 11.7 µm| Total flux     | 5280 ± 130|
|        | Core envelope  | 3167 ± 101|
|        | Outer envelope | 1660 ± 53 |
|        | Total residual | 453       |
|        | NW−SE excess   | 170 ± 11  |
|        | Vega           | 28.4      |

Notes. Photometry not color corrected.  
a Observational errors exclude typical 5%–10% systematic uncertainties.  
b Negative error includes uncertainties in subtracting the vertical chop bleeding.

Figure 6.  
Mid-IR color–color plot for NML Cyg and its CS envelope components from MIRAC3 observations. The envelope’s core [8.8]–[9.8] and [9.8]–[11.7] colors are blue as compared to the total for the source, indicative of hotter and optically thick dust. The outer CS envelope component is redder in both colors, indicating cooler dust. In contrast, the colors for the asymmetric excess are blue in [9.8]–[11.7] and red in [8.8]–[9.8], suggesting warm and optically thin (9.8 µm silicate feature in emission) dust. The colors are in the Vega magnitude system. The larger uncertainty in the NW excess colors reflects the possible contribution from MIRAC3 vertical chop bleeding north of the star at 8.8 µm.

optically thick feature seen in the star’s spectrum. NML Cyg’s stellar radius is probably of the order of ~10 AU, typical for the largest red supergiants, and therefore the material comprising the inner CS envelope (σ ~ 0′.12, 200 AU) has a size scale of approximately 20 stellar radii. The outer CS envelope colors are redder than those of the core envelope and the total source. This indicates dust with decreasing temperature and density.

In contrast, the colors for the asymmetric excess are significantly different, being blue in [9.8]–[11.7] and red in [8.8]–[9.8]. These colors can be explained by the presence of optically thin hot dust with the 9.8 µm silicate feature in emission. The fact that the asymmetric dust emission excess appears only on the side facing Cyg OB2 is consistent with an increase in temperature resulting from the external UV radiation. The density is also likely reduced due to dust destruction. Since the asymmetric excess is shielded from the central star by the optically thick inner CS envelope, Cyg OB2’s external energy is required to account for changes in the grain temperature, size, and/or spatial distribution ultimately responsible for the silicate feature’s inversion.

In Schuster et al. (2006a), we showed that the UV flux from the Cyg OB2 association is strong enough to significantly heat the dust grains in the NML Cyg envelope, possibly destroying the smallest grains. The excess mid-IR flux we observe in the NW quadrant may be the direct effect of this heating and destruction. Its presence strongly suggests that the CS envelope of NML Cyg is indeed shaped by the interaction of its wind with the radiation field coming from the Cyg OB2 association.

The direct detection of this physical interaction between NML Cyg and the Cyg OB2 association is further confirmation that the source is indeed in the neighborhood of Cyg OB2. This supports the distance determination of 1.7±0.2 kpc by Massey & Thompson (1991) for this star as one of the most reliable distances for an evolved massive star near the upper luminosity boundary.

6. NML CYG’S COMPLEX CIRCUMSTELLAR ENVIRONMENT

Figure 7 shows the NW excess in our 9.8 µm deconvolved image compared to the scattered light HST/WFPC2 F555W image from Schuster et al. (2006a). As discussed in Section 5, our interpretation for this mid-IR excess is another strong indicator that the UV radiation from the hundreds of massive young OB stars within Cyg OB2 is disrupting NML Cyg’s post-MS wind through photoionization, photodissociation, and grain destruction. The models for these processes explain the inverted HII region’s existence and shape, the asymmetric nebula seen with HST, as well as the externally heated dust visible in our mid-IR images. The inverse photoionization (Morris & Jura 1983) and photodissociation (Schuster et al. 2006a) models for this interaction have assumed a radially symmetric, constant velocity hydrogen gas wind, i.e., density ρ ∝ r⁻². The agreement between theory and observation suggests that this steady-state, uniform outflow is an overall good approximation of NML Cyg’s stellar wind.

However, the asymmetric mid-IR image reveals that NML Cyg’s dusty CS envelope does have a more complex underlying structure. One may speculate that the identified structures may represent the integrated signal from many arcs, loops, bipolar outflows, and other three-dimensional structures below our angular resolution that may be the result of episodic and asymmetric mass-loss, much like VY CMa (see Figure 3, Smith et al. 2001 as well as Humphreys et al. 2007; Jones et al. 2007). Asymmetric structures arising from episodic mass-loss may also modulate the maser and IR emission as they pass through the photodissociation and grain destruction regions. With even better angular resolution and sensitivity (perhaps with James Webb Space Telescope (JWST) and/or the next generation of ground-based nulling interferometers like the Large Binocular Telescope Interferometer and Keck Telescope Interferometer) it should be possible to observe these fainter, compact structures within the larger nebulosity, if they exist.

Previous 11 µm results from Monnier et al. (1997), Danchi et al. (2001), and Blöcker et al. (2001) have suggested the
presence of multiple, concentric density enhancements (shells) surrounding the central star superposed on a $r^{-2}$ wind, characterized by an azimuthally symmetric, but non-steady-state dust outflow, i.e., $\rho_{\text{dust}} \propto r^{-2}$. This, in turn, implied a time-dependent mass-loss, possibly in episodic/periodic events such as a “superwind” phase. The images presented in Section 4 show evidence for a complex distribution in the CS dust, but also reveal an asymmetric excess aligned to the northwest (toward Cyg OB2). The differences with these earlier results are not surprising given the better resolution and Fourier $u, v$ coverage in the MMT/AO images. However, it should be noted that Monnier et al. acknowledged in their conclusions that deviations from spherical symmetry, particularly emission from dense or clumped material in NML Cyg’s CS nebula has been largely dissipated around the star and appears quite different compared to VY CMa’s distance of 1.5 kpc). It is possible that the more distant material in NML Cyg’s CS nebula has been largely dissipated by the winds and radiation pressure inside the Cygnus-X super bubble and is below our detection limits. If NML Cyg were not located in such close proximity to Cyg OB2, it might show a much more extended nebula comparable to VY CMa. However, VY CMa’s mass-loss rate, $(2–4) \times 10^{-4} M_{\odot}$ yr$^{-1}$ (Danchi et al. 1994), is 3–6 times higher than for NML Cyg and this difference may also have significant bearing on the more extensive CS nebulosity.

7. CONCLUSIONS

Our subarcsecond angular resolution AO mid-IR images of NML Cyg provide a new understanding of the complex geometry and physics of the CS environment of this high luminosity cool hypergiant. By spatially resolving the optically thick dusty envelope, we directly image the structures responsible for the creation of a deep 10 $\mu$m silicate absorption feature. This structure, which follows the same orientation of NML Cyg’s maser outflow, is orthogonal to a near-IR equatorial enhancement found by Monnier et al. (2004).

By analyzing the mid-IR colors of structures located at increasing distance from the star, we observe a trend in which the optical depth of the dust decreases in the outer parts of the CS envelope. For the first time we isolate an asymmetric excess, at a distance of $\sim 520–870$ AU, NW from the star, with colors consistent with the emission of hot, optically thin dust. We interpret this emission as the signature of the interaction of the NML Cyg CS envelope with the strong UV flux generated in the nearby Cyg OB2 association. This interaction was predicted in our previous paper (Schuster et al. 2006a) to explain the shape of the inverted PDR we imaged with the HST at optical wavelength. Our new mid-IR observations strongly support the validity of our previous results and the model we proposed for their explanation.

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Facilities: MMT, Spitzer, HST, UMN OBO

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