MULTIWAVELENGTH STUDY OF THE NEBULA ASSOCIATED WITH THE
GALACTIC LBV CANDIDATE HD 168625

A. Pasquali,1,2 A. Nota,3,4 L. J. Smith,5 S. Akiyama,3 M. Messineo,6 and M. Clampin3

Received 2001 December 28; accepted 2002 May 14

ABSTRACT

We present high-resolution HST imaging of the nebula associated with the Galactic luminous blue variable candidate HD 168625, together with ISO imaging and Anglo-Australian Telescope echelle spectroscopy. The overall nebular morphology is elliptical, with the major axis at P.A. ≈ 120°. The dimensions of the nebula are 12'' × 16'' at Hα and 15'' × 23'' at 4 μm. In the HST Hα image the nebula is resolved into a complex structure of filaments and arcs of different brightness. The asymmetry is lost in the HST continuum image, where the nebula appears more diffuse and richer in filaments and clumps with the shape of cometary tails. At 11.3 μm the nebular emission peaks in two diametrically opposite lobes located on the nebula boundaries and along its major axis. A very faint loop is also visible at optical wavelengths north and south of the shell. We suggest that the nebula is an ellipsoid with projected sizes of 14'' and 9'' (0.19 pc × 0.12 pc) along the right ascension and declination directions, respectively. This ellipsoid is expanding at 19 km s^{-1} and is dynamically as old as 4800 yr; it probably interacts with the stellar wind and the loop so that polycyclic aromatic hydrocarbon emission is detected from its caps, i.e., the lobes seen in the ISO images. The chemistry of the loop suggests that it is composed of unprocessed material, probably from the local interstellar medium swept by the stellar wind.

Key words: H ii regions — ISM: bubbles — ISM: individual (HD 168625) — ISM: structure — stars: individual (HD 168625)

On-line material: color figures

1. INTRODUCTION

It is widely recognized that luminous blue variables (LBVs) represent a post–main-sequence phase in which massive stars (M_i ≥ 20 M_{⊙}; Langer et al. 1994) lose a considerable amount of mass via giant eruptions and minor outbursts. The ejected gas and dust build up a circumstellar nebula chemically enriched by the central star nucleosynthesis. From the expansion velocity of known LBV nebulae, a dynamical age of a few 10^4 yr is usually inferred, which points to a very short-lived evolutionary phase. For this reason, LBVs are rare objects; indeed, only 40 are classified as such in the whole Local Group (Humphreys & Davidson 1994). P Cygni and AG Carinae are considered the prototypes of the LBV class.

The LBV nebulae provide us with a wealth of details about their central stars. Their chemical composition is used to determine the evolutionary phase when the LBV instability triggers the nebula ejection (see Smith et al. 1997 and Waters et al. 1999 in the case of AG Car), and their morphology constrains the physics of the central star wind. Except P Cygni, all LBV nebulae display an asymmetric morphology, progressing from elliptical (e.g., AG Car) to bipolar (e.g., η Car and HR Car). Nota et al. (1995) reproduced the observed shapes through an interacting wind model, where a spherical stellar wind interacts with a pre-existing density contrast between the equatorial and polar direction. This density contrast could be, for example, induced by mass transfer in a binary or rotation in a single star (see Bjorkman & Cassinelli 1993; Owocki, Gayley, & Cranmer 1998). From the Hα imaging it is also possible to estimate the ionized gas mass in the LBV nebulae, which is a key parameter in the understanding of the total mass ejected and of crucial importance to constrain the evolutionary models for massive stars.

Unfortunately, the diagnostic power of the nebular morphological details is limited by the spatial resolution accessible from the ground. Coronographic imaging has so far been the observational technique achieving the highest resolution possible from the ground: it has been able to resolve the global symmetry of LBV nebulae out to the LMC (Nota et al. 1995) and the nebular fine structure only for close-by objects such as AG Car. However, the comparison with hydrodynamic models (see Frank 1997; Garcia-Segura, Langer, & Mac Low 1997) obviously requires higher levels of morphological details to properly constrain the shaping mechanism at work in LBV nebulae. Further, a more complete analysis should rely on high-resolution imaging of ionized/neutral gas and dust; this would also assess the total...
(gas + dust) mass of LBV nebulae and hence the total mass lost by the central star during the outburst. For these reasons, we have reobserved a complete sample of LBV nebulae in the Galaxy and in the Large Magellanic Cloud (Schulte-Ladbeck et al. 2002) with the HST/WFPC2 and ISO/ISOCAM, among which is the Galactic LBV candidate HD 168625.

HD 168625 is known to be variable with an amplitude of 0.06 mag (van Genderen et al. 1992), although its variability does not closely follow the typical pattern observed in the case of bona fide LBVs. Nevertheless, its LBV candidacy was proposed when Hutsemékers et al. (1994), for the first time, resolved an associated circumstellar nebula. Nota et al. (1996) imaged the nebula with the STScI coronograph and resolved it into an elliptical shell surrounded by two faint filaments forming a northern and southern loop. A gas mass of \( \sim 0.5 \, M_\odot \) was derived from images in the light of H\( \alpha \). Nota et al. also acquired two sets of spectroscopic data six months apart, where HD 168625 was seen to fade by 0.3 mag and cool from \( T_{\text{eff}} = 15,000 \) to 12,000 K at a constant mass-loss rate of \( \sim 1.1 \times 10^{-6} \, M_\odot \, \text{yr}^{-1} \). In addition, the spectra were used to derive the plasma properties of the nebula: for an assumed \( T_e \) of 7000 K, the average density is 1000 cm\(^{-3}\) and the nitrogen content is \( \log (N/H) + 12 = 8.04 \) indicating that the nebula is composed of stellar ejecta. Unfortunately, the spectra were taken at low resolution, so that the kinematic structure of the nebula was not fully resolved. Nota et al. could measure the brighter, blue-shifted edge of the nebula, which apparently defined an expansion motion of \( \sim 40 \) km s\(^{-1}\) and a dynamical age of \( \sim 10^3 \) yr.

The nebula surrounding HD 168625 was also observed in the mid-infrared by Skinner (1997) and Robberto & Herbst (1998). Their images (taken between 4.7 and 20 \( \mu \text{m} \)) revealed emission by warm dust in the eastern and western edges of the optical nebula. Skinner (1997) derived a dust mass of 9.5 \( \times 10^{-3} \, M_\odot \), for a distance of 2.2 kpc. Robberto & Herbst (1998) revised the distance of HD 168625 from 2.2 to 1.2 kpc and estimated the dust mass of the nebula to be \( \sim 0.003 \, M_\odot \).

We have revisited the nebula associated with HD 168625, employing the high spatial resolution of WFPC2 on board HST and the high spectral resolution of UCLES on the AAT. These new data are complemented with ISO/ISOCAM observations in order to derive a multiwavelength, detailed analysis of the nebular morphology and kinematics, which are then used to trace back the outburst history of HD 168625. The data are presented in § 2. The HST and ISO images are discussed in §§ 4 and 5, respectively; the nebular properties and kinematics are found in §§ 6 and 7, and the stellar spectrum from the echelle data set is presented in § 8. In § 9 we assemble and discuss the overall morphology of the HD 168625 nebula.

2. OBSERVATIONS AND DATA REDUCTION

2.1. The HST Images

HST/WFPC2 observed HD 168625 on 1997 May 29 and August 6. The F547M and F656N filters were used for imaging in the V continuum (200 s) and the H\( \alpha \) line (500 s) to detect stellar emission reflected by dust and H\( \alpha \) emission from the nebular gas, respectively. The images were acquired in CRSPLIT mode to remove cosmic rays and replace saturated pixels. Moreover, since they were taken 4 months apart, the May and August images have a relative rotation of 120°, which allowed us to partially remove the telescope spiders.

The raw data were recalibrated using the pipeline CALWP2 in IRAF/STSDAS, and the most appropriate reference files. No correction for the shutter shading was applied since the adopted exposure times were longer than 10 s. The five images from the same observation date, filter, and orientation were combined with the CRREJ task.

The brightness of the central star saturated the five central columns of each image. To remove them, we fitted the nebula-free portions of each image with a Legendre function of order 1 along the x-axis using the IRAF task FIT1D and subtracted the fit from each image.

As the last step, the August images were rotated and shifted to match the orientation of the May data and then combined using the CRREJ task. We show in Figures 1 and 2b the final H\( \alpha \) and V continuum images of the nebula associated with HD 168625.

During the reduction, we noticed the presence of two small regions of saturated pixels. One of them was at the center of HD 168625 and the other 1°15 from the image center. Assuming a distance to HD 168625 of 2.8 kpc (see § 3), this translates to 0.016 pc or 3200 AU, suggesting that HD 168625 might be a wide binary system.

2.2. The ISO Images

HD 168625 was observed with ISOCAM, on board ISO, on 1997 September 9 and October 23. Images were taken on the star and on an adjacent region of sky with the filters SW5 and LW8. For these observations we used a pixel size of 1°5, which yields an overall field of view of 48° × 48°. The SW array is an InSb 32 × 32 pixels charge injection device, while the LW detector is a 32 × 32 gallium-doped silicon photoconductor array hybridized by indium bumps. The SW5 filter covered the spectral region 3.1–5.2 \( \mu \text{m} \), where a number of hydrogen emission lines from the nebular gas are expected, while LW8 isolated the wavelength region 10.8–11.9 \( \mu \text{m} \) centered on polycyclic aromatic hydrocarbon (PAH) and dust emission. On-source integration times were 271 s for the SW5 observations and 54 s for the LW8. The gain was set to 2.0 for the SW5 images and to 1.0 for the observation with the LW8 filter.

The images were recalibrated using the CAM Interactive Analysis (CIA) software. For each filter several steps were executed: first, we subtracted the dark contribution. An appropriate dark frame was selected from the archive, consistent with the \( T_{\text{int}} \) and gain of our observations. The images were then deslifted, corrected for stabilization effects, and divided by an appropriate flat field. Finally, they were converted into flux units, and the sky was subtracted. They are shown in Figure 3.

2.3. Ground-based Spectroscopy

High spectral resolution observations of the nebula surrounding HD 168625 were obtained with the UCL echelle spectrograph (UCLES) and the MITLL2 2048 × 4096 CCD detector at the coude focus of the 3.9 m Anglo-Australian Telescope on 1999 September 20 and 21 under 1° seeing conditions.

A slit of dimensions 1° × 40° was used with an interference filter to isolate a single order covering H\( \alpha \) and [N II].
The slit was centered on the star, and observations were obtained at position angles of 0° and 90° (20 September) and 120° (21 September), with exposure times of 1800, 1500, and 1800 s. We show in Figure 2a the HST Hα image of the nebula surrounding HD 168625, with these three slit positions superposed.

The data were bias-subtracted, wavelength-calibrated, and sky-subtracted. The spectral resolution is measured to be 6.9 km s⁻¹ and each spatial pixel corresponds to 0.36.

3. THE DISTANCE TO HD 168625

The distance to HD 168625 is not well known. van Genderen et al. (1992) assumed that the star is at the same distance as M17, or 2.2 kpc. This was questioned by Hutsemékers et al. (1994) on the basis that the nebular systemic velocity is greater than that of M17, suggesting that HD 168625 may be more distant. Robberto & Herbst (1998) derived a much closer value of 1.2 kpc from infrared photometric data and the model atmosphere parameters obtained by Nota et al. (1996). Since these parameters were determined assuming a distance of 2.2 kpc, it is not clear that the lower distance of 1.2 kpc is an independent estimate. Moreover, if a distance of 1.2 kpc is assumed, the nebular mass then becomes exceptionally low, at 0.08 M☉, compared with other LBV nebulae (Nota et al. 1995).

From our spectra we have measured a systemic LSR velocity for the star of 25.5 km s⁻¹ (see § 7), which indicates a kinematic distance of 2.8 kpc, assuming the Galactic rotation model of Brand & Blitz (1993). Hutsemékers et al. (1994) noted that the Na i interstellar lines in the spectrum of HD 168625 are at higher positive velocities than those in the spectrum of the nearby bright star HD 168607, assumed to be at the distance of M17.

Further evidence for HD 168625 not being at the same distance as M17 and HD 168607 comes from the proper motions measured by Hipparcos (see Table 1). These clearly indicate opposite motion directions. Indeed, HD 168625 turns out to move toward the northeast, while M17 and HD 168607 transit toward the southeast. Therefore, we agree

| Star       | μλ (mas yr⁻¹) | μµ (mas yr⁻¹) | References        |
|------------|---------------|---------------|-------------------|
| HD 168607  | 1.18 ± 1.24   | −1.16 ± 0.81  | Perryman et al. 1997 |
| HD 168625  | 0.95 ± 1.23   | +0.04 ± 0.84  | Perryman et al. 1997 |
| M17        | 0.14 ± 1.49   | −3.63 ± 0.94  | Baumgardt, Dettbarn, & Wielen 2000 |
with Hutsemékers et al. (1994) that HD 168625 is not associated with either HD 168607 or M17 and probably is at larger distance than M17. Hereafter, we adopt for HD 168625 a distance of 2.8 kpc, which together with $E(B-V) = 1.86$ (Nota et al. 1996) and $V = 8.4$ (van Genderen et al. 1992) gives $M_V = -9.6$.

4. OPTICAL NEBULAR MORPHOLOGY AT HIGH RESOLUTION

The WFPC2 image of HD 168625 in Hα light is shown in Figure 1, where the stellar PSF has not been subtracted. As already observed by Hutsemékers et al. (1994) and subse-
quently Nota et al. (1996), the bulk of the nebular emission originates from an elliptical shell with the major axis oriented at P.A. ~ 120°. A larger, fainter loop is visible in the northern region, as already noted by Nota et al. (1996). A fragment of a southern loop is barely visible at P.A. ~ 250°.

In the new HST images the shell has a size of size of ~12° × 16°7 (0.16 pc × 0.23 pc), in agreement with the previous measurements of Nota et al. (1996). A significant difference with the ground-based coronographic images resides in the texture of the shell, which is not uniform and homogeneous, but rather a superposition of filaments and arcs of different brightnesses, in a way that is very reminiscent of the AG Car nebula (Nota et al. 1995). In the new HST images we also resolve the structure of the brightest region in the shell, the southern rim, which appears fragmented and resembles the shape of a letter W. In correspondence to the vertex of the W the shell shows an inner and an outer layer at different distances from the star [3° (0.04 pc) and 4°3 (0.06 pc), respectively].

Diffuse emission is seen in the northeast quadrant within the shell, between P.A.’s 10° and 60°, and we will refer to this as the “paddle.” The paddle is clumpy and contains knots that are very similar in morphology to the cometary-tail structures observed by HST/WFPC2 in the AG Car nebula (Nota et al. 1995). A second, prominent structure can be identified in the southeast quadrant, which we will label the “arm”; it is a filament that extends from the star toward the edge of the shell and eventually merges with an arc on the shell at ~P.A. = 120°. The arm is at ~30° from the shell major axis.

The image of HD 168625 taken in the V continuum light (F547M) is shown in Figure 2b. The difference between the Hα and V images is striking: in the continuum image the shell disappears almost completely, replaced by a diffuse and filamentary nebula that has the same size of the gaseous shell. Of the gaseous nebula only the outline is barely visible, but it is very different in appearance: the arcs and filaments have disappeared, leaving instead knots and clumps. Many more features similar to the above-mentioned cometary tails emerge in this image. Neither loop is visible, so that the paddle and the arm are left as the dominant structures of the nebula in the V continuum light. To establish whether their higher V brightness (compared with Hα) is intrinsic or due to different filter bandpasses and exposure times, we performed aperture photometry on both the F656N and F547M images, and for the southern edge of the shell, the paddle, and the arm. The aperture radius was set to 5 pixels, for a full aperture diameter of 0′45. The aperture fluxes in units of counts have been summed overall the spatial extension of each feature, normalized by the exposure time of each filter (3000 s for the F656N and 800 s for the F547M filter) and multiplied by the filter inverse sensitivity in order to transform them into units of ergs per square centimeter per second per angstrom (ergs cm⁻² s⁻¹ Å⁻¹). The integrated, dereddened fluxes [E(B–V) = 1.7 from Nota et al. 1996] are reported in Table 2 for the southern edge of the shell, the arm, and the paddle.

### TABLE 2

**DEREDDENED F656N AND F547M PHOTOMETRY OF THE SOUTHERN EDGE OF THE SHELL, THE ARM, AND THE PADDLE**

| Feature (1) | F656N Hα+cont. (2) | F547M Cont. (3) | Continuum in F656N (4) | F656N–F547M (5) | Hα/(Hα+cont.) (%) (6) |
|-------------|---------------------|-----------------|------------------------|-----------------|----------------------|
| Southern edge | 1.6 × 10⁻¹⁶ | 1.1 × 10⁻¹⁶ | 2.9 × 10⁻¹⁷ | 1.3 × 10⁻¹⁶ | 81 |
| Arm | 6.8 × 10⁻¹⁸ | 9.1 × 10⁻¹⁸ | 2.4 × 10⁻¹⁸ | 4.4 × 10⁻¹⁸ | 64 |
| Paddle | 8.2 × 10⁻¹⁷ | 1.4 × 10⁻¹⁶ | 3.7 × 10⁻¹⁷ | 4.5 × 10⁻¹⁷ | 55 |

*E(B–V) = 1.7 is adopted from Nota et al. 1996.*
The dereddened flux in the F547M filter has been scaled by the ratio of the F656N to the F547M bandwidth in order to compute the continuum flux in the F656N filter, under the assumption that the continuum is constant with wavelength. This has been subtracted from the dereddened flux measured in the F656N, and the resulting emission in the Hα line is reported in column (4) of Table 2. Column (5) indicates the percentage contribution of the emission in the Hα line to the Hα + continuum flux detected in the F656N filter. It can be seen that the Hα flux is higher (81%) in the shell southern edge and decreases from the arm (64%) to the paddle (55%). The southern edge of the shell and the paddle are at almost the same distance (~4”, 0.05 pc) from the star so they should be exposed to an equally diluted stellar radiation field. Their difference in the Hα emission should then be due to either a different gas-to-dust ratio or to a different gas density. Indeed, the Hα flux is proportional to the square of the gas density, while the continuum flux is proportional to the dust density, which in turn can be expressed as the product of the gas density and the dust-to-gas ratio. Therefore, the Hα-to-continuum flux ratio is proportional to the product of the gas density with the gas-to-dust ratio. If the gas-to-dust ratio were constant across the nebula, the flux ratio would depend on the gas density alone and hence the continuum flux. But this is not the case for the shell southern edge and the paddle: from the former to the latter the Hα-to-continuum flux ratio decreases and the continuum flux increases. Therefore, we may qualitatively deduce that the gas-to-dust ratio is not constant across HD 168625.

5. MID-IR MORPHOLOGY AND DUST CONTENT

Figure 3 shows the final images of HD 168625 obtained with ISOCAM. The two images are taken with the SW5 and LW8 filters, which cover the spectral ranges 3.1–5.2 μm and 10.8–11.9 μm, respectively. In the images north is up, and east to the left. The two images present a very different view of the nebula. In the SW5 filter the central star appears very bright, while the nebula is faint. A faint diffuse, homogenous emission is discerned against the background, with an overall elliptical shape. The nebular emission originates from a region ≈15”×23” (0.21 pc×0.32 pc) in size, slightly larger than the optical shell. Allowing for the low resolution of the ISOCAM images compared with the HST, the structure observed displays a good overlap with the southern rim of the optical shell.

In the LW8 filter the star appears much fainter and the nebula much brighter, with the same overall elliptical shape. In addition, two bright regions are easily visible in the nebular emission, symmetrically located to the northwest and to the southeast with respect to the central star. In the LW8 filter, the nebula has a larger extension, 31”×35” (0.42 pc×0.48 pc). The two brighter regions are located at the same distance from the central star, ≈7” (0.1 pc). It is interesting to study the relative location of the features detected in Hα and in the mid-IR LW8 filter. In Figure 4 we show the composite final WFPC2 Hα image with the intensity contours from the LW8 filter image superposed. The two bright regions observed in the LW8 image appear located adjacent to the bright boundaries of the optical shell, in correspondence to two dark regions.

What is the origin of the mid-IR emission? The spectral region of the SW5 filter (3.1–5.2 μm) can trace PAHs (3.3 μm), continuum, and gas emission lines, while the LW8 band (10.8–11.9 μm) can indicate presence of SiC (11.4 μm) and PAH (11.3 μm) features (Skinner 1997; Voors et al. 1997).

PAH and silicate emission were first detected in the nebula around HD 168625 by Skinner (1997). Their published image of the HD 168625 nebula taken at 12.5 μm displays a morphology that is identical to the one we observe in the LW8 filter, with two bright regions arranged symmetrically with respect to the star, which the author interprets as a torus or a disk. Skinner (1997) also shows a spectrum of the central condensation in the spectral range 8–24 μm (their Fig. 2). This spectrum shows PAH and silicate emission.

Robberto & Herbst (1998) also observed the HD 168625 nebula at 4.7, 10.1, 11.6, and 19.9 μm. Two of these wavelength regions, namely, the 4.7 and the 11.6 μm are directly comparable to the ISO SW5 and LW8 bandpasses. At 4.7 μm Robberto & Herbst barely detect the nebula, but the central star is well detected. The morphology of their 4.7 μm very faint nebular emission is very similar, allowing for the different spatial resolution, to our SW5 image. At 11.6 μm Robberto & Herbst (1998) find that the bulk of the emission is coming from the nebula. They derive a size at 11.6 μm of 12”×16”, which is consistent with our measurements if we consider the brightness peaks. They also notice that the emission is concentrated in two bright arcs, in the northwest and southeast quadrants, which correspond to the two bright regions we see, at lower resolution, in the LW8 exposure. Robberto & Herbst (1998) argue that the arcs are the outer layer of a thin warm dust shell. A temperature of $T_{dust}=135$ K provides the best fit of their measurements at 11.6, 19.9, combined with the IRAS points at 25 and 60 μm.

It is interesting to note that, in their 11.6 μm image (taken on 1996 August 28), the star appears very bright, while in our LW8 observation (taken in the fall of 1997) the star is barely detected. Robberto & Herbst (1998) extract one-dimensional brightness profiles at various positions in the nebula and clearly show that the peak intensity of the central star is only slightly lower than the peak intensity of the brightest regions in the nebula. Aperture photometry (with a 3” radius) of the brightest regions in the LW8 image gives an average flux a factor of nearly 2 higher than elsewhere. Most likely this discrepancy is due to the already known variability of the central star (Nota et al. 1996).

From our images we have measured an integrated nebular flux of 1.8 Jy in the SW5 filter and 50.4 Jy in the LW8 filter. The measurements have been obtained by subtracting the contribution of the central star. These measured values complement the data obtained by Robberto & Herbst and by IRAS and have been used to estimate the temperature of the dust responsible for the mid-IR emission. We have fitted blackbody curves to all data points at slightly different temperatures, assuming a distance of 2.8 kpc and the nebular sizes as measured in the SW5 and LW8 images, respectively. A best-fit blackbody curve at 113 K is shown in Figure 5. If we give a lower weight to the IRAS 60 μm measurement, which is assessed to be “uncertain or of lower quality,” the data points are well fitted by this blackbody curve, which is a few degrees cooler but not significantly different than the best-fit value of 135 K derived by Robberto & Herbst.

6. NEBULAR MASS AND IONIZATION PROPERTIES

We have used the integrated Hα flux measured in the new HST images to reassess the determination of the ion-
ized gas mass in the nebula made by Nota et al. (1996). The advantage of the high resolution provided by the HST compared with the previous ground based coronographic images, is that the stellar PSF is much smaller, and, therefore, the stellar contamination of the surrounding nebular flux is also much smaller. The integrated Hα flux was measured in the new HST images by masking the residual halo from the central star, and then integrating the Hα flux in the image after sky subtraction. We have not corrected for the Hα flux in the masked region of the image: consequently, the measured Hα flux is a slight underestimate of the true value.

The reddened Hα flux measured from the image is $4 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$. In order to deredden the nebular measured flux, we have used our value of $E(B-V) = 1.86 \pm 0.24$ from Nota et al. (1996). Dereddening the measured Hα flux, we obtain an integrated flux of $9.6 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$, which is slightly higher than the value of $3.7 \times 10^{-10}$ ergs s$^{-1}$ cm$^{-2}$ previously derived by Nota et al. (1996). Adopting values of $T_e = 7000$ K, and $n_e = 1000$ cm$^{-3}$ (Nota et al. 1996), we obtain an ionized gas mass of $2.1 M_\odot$. This ionized gas mass is higher than the value of 0.5 derived by Nota et al. (1996) and considerably higher than the mass of 0.04 $M_\odot$ calculated by Hutsemékers et al. (1994). However, a comparison with other LBV nebulae (Nota et al. 1995) shows the revised ionized gas mass of HD 168625 to be fairly typical.

Nota et al. (1996) concluded that the nebula was ionization bounded. In fact, they estimated a Strömgren sphere radius of $\sim 0.1$ pc. If we compare this value with the physical size of the optical nebula obtained adopting the new distance ($0.16 \times 0.23$ pc), the nebula remains ionization bounded. It is interesting to note that the spatial extent of the dusty nebula, as imaged through the ISO/LW8 filter, is much larger ($0.42 \times 0.48$ pc), providing additional evidence that the optical nebula is ionization bounded.

Fig. 4.—Composite final WFPC2 Hα image with the intensity contours from the LW8 filter image superposed. North is up, and east to the left. [See the electronic edition of the Journal for a color version of this figure.]
7. NEBULAR KINEMATICS

We have extracted spatial profiles from the WFPC2 images of the HD 168625 nebula in correspondence with the slit positions that we used for spectroscopic observations. The tracings are presented in Figure 6: the solid lines refer to the images acquired in the Hα/C11 continuum, while the dashed lines refer to the continuum. We have also associated the more prominent features with the shell southern edge, the paddle, and the arm, described in § 3.

The slits at P.A. = 90° and 120° intercept the shell on both sides of the star; the slit at P.A. = 120° in particular detects both the eastern and western lobes, which dominate the IR emission of the nebula. The slit at P.A. = 90° cuts through the western lobe and marginally samples the northern faint end of the eastern one. The slit at P.A. = 0° is centered on the southern edge of the shell, where the Hα emission of the nebula peaks, but it also detects the northern loop and the fragment of the southern loop.

We have measured the radial velocity of the nebula with a spatial sampling of 2 pixels (0.77) along the cross-dispersion axis with a multi-Gaussian fit of the nebular Hα and [N ii] λ6584 lines in each of the three spectra. Specifically, we have measured the peak wavelength and the intensity of each component in the Hα and [N ii] λ6584 line profiles. Radial velocities have been computed from the peak wavelengths and transformed into heliocentric. We typically detected two to three components per position.

The overall distribution of the nebular [N ii] λ6584/Hα ratio turns out to be bimodal, peaking at 0.51 ± 0.15 and 0.22 ± 0.05. The former is associated with the shell and the latter with the northern and southern loop.

Figure 7 shows the shell velocity distributions in right ascension and declination, where positions are relative to the star. The top panel consists of all the radial velocities measured in the spectra taken at P.A. = 90° and 120°, and the bottom panel collects the radial velocities determined in the spectra at P.A. = 0° and 120°. The filled dots are the observed data, while the open circles represent the velocities obtained by fitting an expanding ellipse. The parameters of the best-fitting ellipses are listed in Table 3 for both the velocity distributions in right ascension and declination. The center of both ellipses is at (0°, 6 km s⁻¹).

According to the above parameters, the shell appears to be an ellipsoid with a full linear size of 14″ (0.19 pc) and 9″ (0.12 pc) projected along the right ascension and declination direction, respectively, and expanding at 19 km s⁻¹. The spatial extensions derived by fitting the velocity distributions agree well with those measured on the HST images. Therefore, we estimate a lower limit to the dynamical age of ≈4800 yr along the right ascension axis and ≈3100 yr in the declination direction.

| TABLE 3 |
| PARAMETERS OF THE BEST-FITTING EXPANDING ELLIPSES |
| Spatial Axis | Semimajor Axis | Semiminor Axis |
| Distribution in R.A. | 19 km s⁻¹ | 7″ |
| P.A. = 90°, 120° | 19 km s⁻¹ | 4′5 |
| Distribution in decl. | 19 km s⁻¹ | 4′5 |
The loop sample is restricted to the declination axis. Its velocity distribution is less well sampled than the shell, and it can be fitted with either an expanding sphere or an expanding ellipse. In Figure 8 we have plotted the observed data (filled dots) and their best fits (open circles). In order to match the loop sample, a circular shell should have a radius of about 9.5' and expand at \(17 \text{ km s}^{-1}\) with its center at \((0', 4 \text{ km s}^{-1})\), while an ellipse should have a semiminor axis of \(9.00\) and expand at \(19 \text{ km s}^{-1}\) (given a center at \(0', 6 \text{ km s}^{-1}\)). The ellipse major axis (i.e., the radial velocity axis) would also be tilted by \(\pm 27^\circ\) toward the south with respect to the shell ellipsoid. The loop dynamical age would thus vary from \(\pm 7300 \text{ yr}\), as in the case of a sphere, to \(\pm 6200 \text{ yr}\) if the loop were represented by a two-dimensional ellipse.

Because of the low spectral resolution of their data Nota et al. (1996) could not distinguish between the shell and the loop, and they could only fit an expanding sphere to their velocity distribution, which in turn defined a radius of about 12" and an expansion velocity of \(\pm 37 \text{ km s}^{-1}\).

8. A NOTE ON THE STELLAR SPECTRUM

We have extracted the stellar spectrum from the data at P.A. = 90°, normalized its continuum to unity, and plotted it in Figure 9, where the top panel shows the full flux scale spectrum, while the bottom panel is a close up of the absorption lines.

Two sets of lines can be identified in the stellar spectrum of HD 168625 based on their FWHM: (1) the Hα P Cygni line and the C II \(\lambda 6584.1, 6582.9\) and Fe II \(\lambda 6614\) characterized by a mean FWHM of \(69 \text{ km s}^{-1}\); and (2) narrow absorption lines with an average FWHM of \(10 \text{ km s}^{-1}\). The latter have been identified with Fe I, Fe II, Ca I, and Ni I features, and possibly Mn and Ti absorptions. These lines were also resolved in the spectrum of P Cygni by Stahl et al. (1993). Israelian et al. (1996) detected D\(\alpha\)Cs in the UV Fe II
and Fe II lines of P Cygni, which vary over a period of nearly 6 months and are believed to be associated with a shell ejection. Therefore, the narrow absorption lines at optical wavelengths may relate to the shell ejection mechanism as well. In the case of HD 168625 it is interesting to compare the stellar spectrum in Figure 8 with those obtained by Nota et al. (1996) in 1995, 5 months apart. The discrete absorptions are present in the October spectrum but not in that of May; moreover, the star modified its Hα profile from flat-topped to P Cygni and underwent a variation of ~0.3 mag in the continuum and ~3000 K in $T_{\text{eff}}$ between May and October. This behavior hints at a shell ejection; the fact that the narrow absorptions are also seen in the 1999 spectrum may indicate that shell ejections are a recurrent episode in the mass-loss history of HD 168625 as for P Cygni.

We have used the C II $\lambda$6578.1, 6582.9 and Fe I $\lambda$6614 lines to derive the radial velocity of the star. The stellar heliocentric radial velocity is 11.7 km s$^{-1}$ and the corresponding LSR value is 25.5 km s$^{-1}$.

### 9. CONCLUSIONS: ASSEMBLING THE PUZZLE

Multicolor imaging of the nebula associated with HD 168625, obtained from space with HST and ISO, shows an elliptical nebula with the major axis oriented at P.A. $\approx 120^\circ$. Its main structure is a shell which HST has resolved into nesting filaments. Both shell morphology and size depend on wavelength:

1. In the Hα light the southern edge is well defined, while the northern part dissolves into diffuse circumstellar matter. The shell surface brightness is higher along the southern edge and peaks between P.A. $\approx 140^\circ$ and P.A. $\approx 210^\circ$.

2. The shell disappears in the V continuum light, where it is replaced by diffuse, filamentary emission within a faint outline that traces the boundaries of the gaseous nebula. At these wavelengths ($\lambda_c \approx 5480$ Å) the bulk of the emission seems to originate from a substructure, the paddle, to the northeast of the central star.

3. The shell lights up again at mid-IR wavelengths, 3.1–5.2 μm and 10.8–11.9 μm, but this time the emission peaks in two lobes that are adjacent to the inner edge of the shell, in correspondence to dark or obscured regions in the optical image. The paddle and the southern portion of the shell, which dominate the continuum and Hα emissions, are far less pronounced here.

4. The size of the nebula is different at optical and mid-IR wavelengths. In the light of Hα the nebula has an extension of $12'' \times 16''$ (0.16 × 0.23 pc) if we exclude the northern loop. At 3.1–5.2 μm the nebula has a larger extension of $15'' \times 23''$ (0.21 × 0.32 pc), and at 10.8–11.9 μm, an even larger size of $31'' \times 35''$ (0.42 × 0.48 pc).

Aperture photometry of the optical images indicates that the paddle and the shell southern edge may differ in the gas-to-dust content, with the paddle more dusty and the southern edge of the shell more gas-rich. Aperture photometry of the infrared images suggests that the eastern and western lobes of the shell are dominated by dust and PAH molecules, in agreement with the findings of Skinner (1997) and Robberto & Herbst (1998) who resolved the lobes up to 20 μm.

We believe that the nebular chemistry and kinematics derived here can explain the observed composite morphology of HD 168625.

Nota et al. (1996) already derived a log (N/H) + 12 of $\approx 8.04$ for the nebula, showing that it is indeed N enriched and hence of stellar origin. They could not resolve the nebula into its components, as we did in this work with the help of echelle data. The higher spectral resolution of our data has allowed us to separate the shell from the loop and measure the [N II] $\lambda$6584/Hα intensity ratio for each component, which we use as a N-abundance indicator. It turns out that the [N II] $\lambda$6584/Hα ratio is on average 0.51 ± 0.15 for the shell and 0.22 ± 0.05 for the loop, which means that the shell is N enriched relative to the loop. In particular, the [N II] $\lambda$6584/Hα ratio measured for the loop is very similar to what is observed for Galactic H II regions. We have indeed selected a number of Galactic H II regions from the sample of Shaver et al. (1983), which are at the same distance of HD 168625 and/or have a plasma temperature $T_{\text{e}}([\text{N II}])$ close to what assumed for HD 168625 ($T_{\text{e}} \approx 7000$ K, Nota et al. 1996). We have computed their relative [N II] $\lambda$6584/Hα intensity ratios and determined the mean value of 0.26 ± 0.08, which compares well with a [N II] $\lambda$6584/Hα $\approx 0.22$ in the loop. This, therefore, implies that the loop is composed of unprocessed material that has been blown by the stellar wind. It is unlikely that the loop is an interstellar bubble such the one detected northwest of HR Car (Nota et al. 1997): its dynamical age is at most $\approx 7300$ yr old, too young for a H II region. The possibility that the loop is a previous stellar ejection also seems improbable: in this scenario, about 3000 yr (i.e., the age difference between the loop and the shell) would have been enough for the star to self-enrich in N by almost a factor of 2. This time interval appears to be quite short with respect to evolutionary models of B stars (Lamers et al. 2001). Therefore, we suggest that the loop consists of local interstellar medium swept by the stellar wind. The fact that we have been able to detect the loop only in the declination direction may imply that the loop lies preferentially on a plane, maybe the equatorial plane of the star.

The radial velocities measured for the shell indicate that it is an ellipsoid expanding at 19 km s$^{-1}$ in both the right ascension and declination directions. Its axes are $14''$ (0.19...
pc) and 9\" (0.12 pc) along the right ascension and declination directions, respectively, in agreement with that estimated from the HST images. Such a morphology is very common among LBV nebulae, the best-known example being AG Car. Nota et al. (1995) explained the elliptical shape of AG Car by invoking a density contrast between the stellar equator and poles, which would restrict the nebula expansion on the stellar equatorial plane and produce a "waist" in the circumstellar nebula. The density contrast would leave the stellar polar axis as the only free direction to the nebular expansion and therefore would shape the nebula into an ellipsoid. There exist several ways to produce a density contrast (Livio 1995), such as stellar rotation and stellar binarity. Although no solid evidence for stellar rotation or binarity is available for HD 168625, one of these mechanisms could be responsible for the overall morphology of the nebula associated with HD 168625, and it also would preferentially direct the present stellar wind along the polar axis of the star, i.e., the right ascension axis of the nebular ellipsoid, so that it would interact with the "caps" of the ellipsoid. The interaction would destroy the CO molecules and give rise to PAH emission, as detected by ISO in the lobes of the nebula. Moreover, the HST images suggest that the shell caps may be interacting with the loop, and this could also produce PAH emission.

We wish to thank the referee for his/her valuable comments and suggestions.

REFERENCES

Baumgardt, H., Dettbarn, C., & Wielen, R. 2000, A&AS, 146, 251
Bjorkman, J. E., & Cassinelli, J. P. 1993, ApJ, 409, 429
Brand, J., & Blitz, L. 1993, A&A, 275, 67
Frank, A. 1997, in ASP Conf. Ser. 120, Luminous Blue Variables: Massive Stars in Transition, ed. A. Nota & H. J. G. L. M. Lamers (San Francisco: ASP), 338
Garcia-Segura, G., Langer, N., & Mac Low, M. M. 1997, in ASP Conf. Ser. 120, Luminous Blue Variables: Massive Stars in Transition, ed. A. Nota & H. J. G. L. M. Lamers (San Francisco: ASP), 332
Humphreys, R. M., & Davidson, K. 1994, PASP, 106, 1025
Hutsemekers, D., Van Drom, E., Gosset, E., & Melnick, J. 1994, A&A, 290, 906
Israelian, G., de Groot, M., Parker, J. W., & Sterken, C. 1996, MNRAS, 283, 119
Lamers, H. J. G. L. M., Nota, A., Panagia, N., Smith, L. J., & Langer, N. 2001, ApJ, 551, 764
Langer, N., Hamann, W.-R., Lennon, M., Najarro, F., Pauldrach, A. W. A., & Puls, J. 1994, A&A, 290, 819
Livio, M. 1995, in Asymmetrical Planetary Nebulae, ed. A. Harpaz & N. Soker (Bristol: IOP), 51
Nota, A., Livio, M., Clampin, M., & Schulte-Ladbeck, R. E. 1995, ApJ, 448, 788
Nota, A., Pasquali, A., Clampin, M., Pollacco, D., Scuderi, S., & Livio, M. 1996, ApJ, 473, 946
Nota, A., Smith, L. J., Pasquali, A., Clampin, M., & Stroud, M. 1997, ApJ, 486, 338
Owocki, S. P., Gayley, K. G., & Cranmer, S. R. 1998, in ASP Conf. Ser. 131, Boulder-Munich II: Properties of Hot, Luminous Stars (San Francisco: ASP), 257
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Robberto, M., & Herbst, T. M. 1998, ApJ, 498, 400
Schulte-Ladbeck, R. E., et al. 2002, in preparation
Shaver, P. A., McGee, R. X., Newton, L. M., Danks, A. C., & Pottasch, S. R. 1983, MNRAS, 204, 53
Skinner, C. J. 1997, in ASP Conf. Ser. 120, Luminous Blue Variables: Massive Stars in Transition, ed. A. Nota & H. J. G. L. M. Lamers (San Francisco: ASP), 322
Smith, L. J., Stroud, M. P., Esteban, C., & Vilchez, J. M. 1997, MNRAS, 290, 265
Stahl, O., Mandel, H., Wolf, B., Gaeng, T., Kaufer, A., Kneer, R., Szeifert, T., & Zhao, F. 1993, A&AS, 99, 167
Waters, L. B. F. M., Voors, R. H. M., Morris, P. W., Trams, N. R., de Koter, A., & Lamers, H. J. G. L. M. 1999, in Lecture Notes in Physics, 523, Variable and Nonspherical Stellar Winds in Luminous Hot Stars, ed. B. Wolf, O. Stahl, & A. W. Fullerton (New York: Springer), 381
van Genderen, A. M., et al. 1992, A&A, 264, 88
Voors, R. H. M., Lamers, H. J. G. L. M., Waters, L. B. F. M., Trams, N. R., & Kaufl, H. U. 1997, in ASP Conf. Ser. 120, Luminous Blue Variables: Massive Stars in Transition, ed. A. Nota & H. Lamers (San Francisco: ASP), 353