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DISCOVERY OF A NEARBY TWIN OF SN 1987A'S NEBULA AROUND THE LUMINOUS BLUE VARIABLE HD 168625: WAS SK −69 202 AN LBV?[1]

Nathan Smith
Astronomy Department, University of California, Berkeley, CA, USA; nathans@astro.berkeley.edu
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ABSTRACT

Spitzer Space Telescope images of the luminous blue variable (LBV) candidate HD 168625 reveal the existence of a bipolar nebula several times larger than its previously known equatorial dust torus. The outer nebula of HD 168625 has a full extent of $\sim 80''$ or 0.85 pc, and one of the lobes has a well-defined polar ring. The nebula is a near twin of the triple-ring system around SN 1987A. Because of these polar rings, and accounting for stellar/progenitor luminosity, HD 168625 is an even closer twin of SN 1987A than the B supergiant Sher 25 in NGC 3603. HD 168625's nebula was probably ejected during a giant LBV eruption and not during a red supergiant phase, so its similarity to the nebula around SN 1987A may open new possibilities for the creation of SN 1987A's rings. Namely, the hypothesis that Sk −69 202 suffered an LBV-like eruption would avert the complete surrender of single-star models for its bipolar nebula by offering an alternative to an unlikely binary merger scenario. It also hints that LBVs are the likely progenitors of some Type II supernovae, and that HD 168625's nebula is a good example of a pre-explosion environment.

Key words: circumstellar matter — stars: evolution — stars: individual (HD 168625) — stars: mass loss — stars: winds, outflows — supernovae: individual (SN 1987A)

1. INTRODUCTION

Massive stars expel most of their initial mass on their journey from the beginning of the main sequence to the Wolf-Rayet phase. While steady line-driven winds may contribute some of the envelope shedding, much of the mass loss probably occurs near the end of core-H burning in a series of continuum-driven eruptions or explosions (Smith & Owocki 2006). These rarely observed events (see Humphreys et al. 1999) occur during a brief hot supergiant phase when the star is seen as a luminous blue variable (LBV; Humphreys & Davidson 1994). Observations of expanding circumstellar nebulae around LBVs indicate that masses of a few tenths to a few tens of solar masses can be ejected in a single giant eruption that lasts only a few years (Smith & Owocki 2006; Clark et al. 2005; Smith et al. 2003). The trigger and energy supply for these blasts still evade understanding, but it is expected that they may recur on timescales of several hundred years.

The potential recurring nature of these outbursts provides a fairly obvious observational prediction: some LBVs should be surrounded by multiple nested ejecta shells from a sequence of previous outbursts. LBVs are extremely rare, and the detection of faint filamentary shells is hampered by the bright central stars. However, there are a few well-documented cases in which ancient filamentary shells with ages of a few thousand years have been detected outside of the younger LBV nebulae, such as η Carinae (Walborn 1976; Smith et al. 2005; Bohigas et al. 2000), P Cygni (Meaburn 2001; Meaburn et al. 1996, 1999, 2004), and HR Carinae (Nota et al. 1997; Weis et al. 1997). This paper reports the new discovery of another example in an outer shell around HD 168625.

HD 168625 (Hen 3-1681) is an 8 mag mid-B supergiant found at the outskirts of M17, only $\sim 1'$ away from the LBV star HD 168607 (Chentsov & Luud 1989). It is probably located at a distance of ~ 2.2 kpc (van Genderen et al. 1992), although distances of 1.2–2.8 kpc have been proposed (Robberto & Herbst 1998; Pasquali et al. 2002). Chentsov & Gorda (2004) have argued convincingly that HD 168625 and HD 168607 are close to one another in space, and that both are part of Sgr OB1 (Humphreys 1978) at 2.2 kpc.[2] Its bright, dusty shell nebula was discovered by Hutsemékers et al. (1994), and has since been studied further by Nota et al. (1996), Robberto & Herbst (1998), Pasquali et al. (2002), and O'Hara et al. (2003). The $12'' \times 16''$ ring nebula is expanding at about 20 km s^{-1}, has a dynamical age of a few thousand years, is nitrogen-enriched, and has an estimated total mass of 0.2–2 $M_{\odot}$ (the lower estimates come from dust mass times 100, while the higher estimates come from direct estimates of the gas mass). The atmosphere of the central star also has nitrogen-enhanced composition (Garcia-Lario et al. 2001). Like other LBVs, HD 168625's nebula has bright infrared [Fe II] emission, indicating a high-density, low-ionization shell (Smith 2002). The newly discovered nebula reported here is far outside this shell.

Strictly speaking, the blue supergiant HD 168625 is still a "candidate" LBV because it has not yet been observed to exhibit the classical LBV or S Doradus–type photometric variability (Sterken et al. 1999; van Genderen 2001; Humphreys & Davidson 1994). However, it is widely suspected that the presence of a dense shell nebula like that around HD 168625 points toward a previous giant LBV eruption; van Genderen (2001) classifies HD 168625 as an ex/dormant LBV for this reason.

The discovery of the ancient outer nebula around HD 168625 reported here is more significant than just one more example added to the three nested LBV nebulae mentioned above, due to the relatively low luminosity of this LBV. On the H-R diagram, it sits at the bottom of the range of luminosities for currently known LBVs (see Smith et al. 2004). This low luminosity means that it may have already passed through a red supergiant (RSG) phase,

[1] Based on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract 1407.

[2] If true, the pair HD 168625 and HD 168607 is just one example of many pairs of eerily similar massive stars that are closely spaced on the sky (e.g., Walborn & Fitzpatrick 2000).

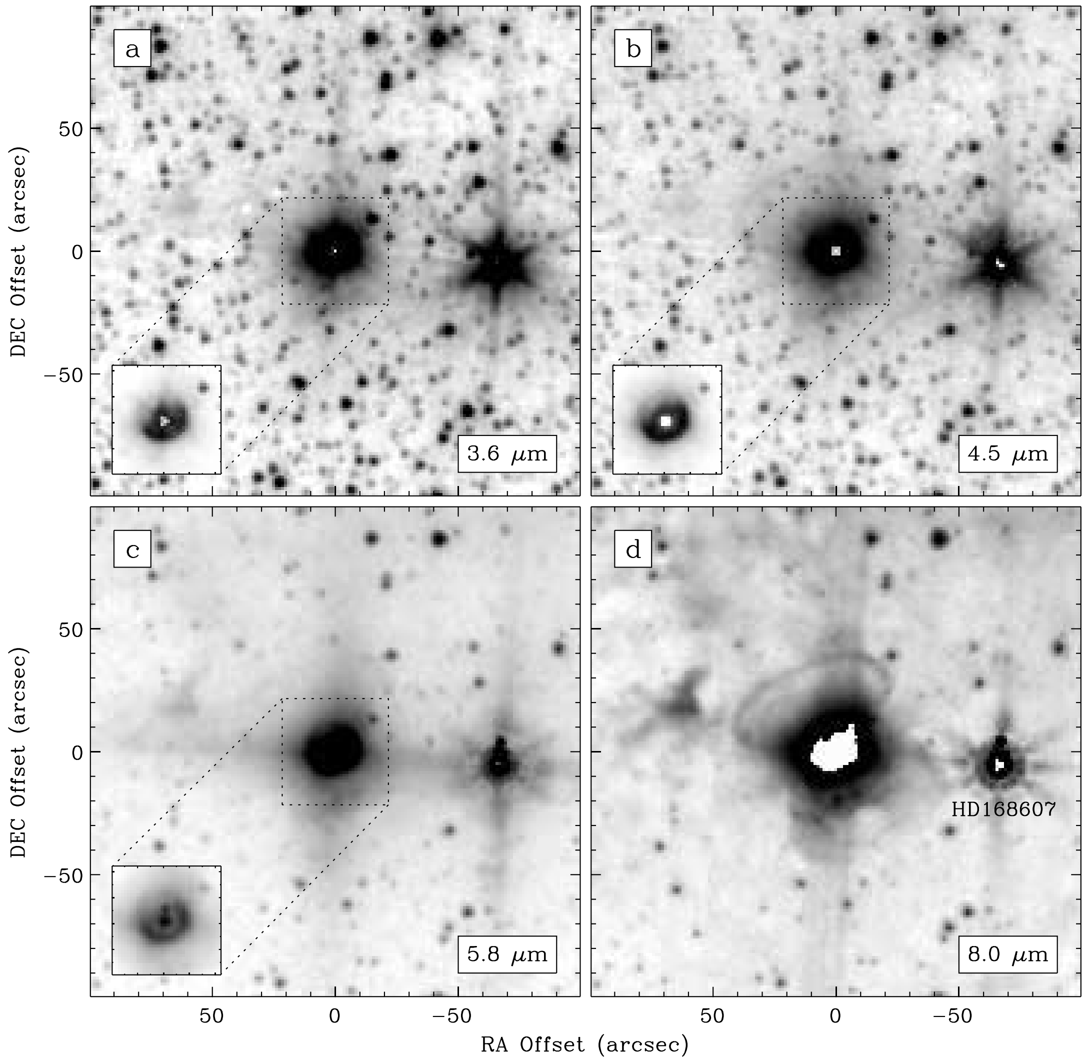

Fig. 1.—*Spitzer* images of the nebula around HD 168625 in the four IRAC bands, taken as part of the GLIMPSE project. The faint outer bipolar nebula (especially the northeast polar ring) is best seen at 8.0 μm. The blob located at offset +60″, +20″ may or may not be associated with the circumstellar ejecta. HD 168607 is located ∼65″ west of center.

and makes it of great interest for examining the full parameter space for mass loss through violent LBV outbursts. As discussed in more detail below, its similar morphology to the nebula around SN 1987A makes it particularly interesting.

2. OBSERVATIONS

Spitzer Space Telescope images of HD 168625 were obtained with the Infrared Array Camera (IRAC; Fazio et al. 2004) as part of the GLIMPSE survey (Benjamin et al. 2003) of the inner Milky Way. The reader is referred to the GLIMPSE team Web site for details about the data acquisition and processing.[3] IRAC data for the region around the target were retrieved from the archive through the GLIMPSE team Web site, where the full image set was released on 2006 September 1. The resulting *Spitzer* images in the four IRAC bands at 3.6, 4.5, 5.8, and 8.0 μm are displayed in Figure 1. The insets in Figures 1*a*, 1*b*, and 1*c* show a different intensity scale in the central region including the circumstellar dust ring that has already been studied at mid-IR wavelengths using ground-based data with higher spatial resolution (Robberto & Herbst 1998; Meixner et al. 1999; O'Hara et al. 2003). The central star saturated the IRAC detector in the 3.6 and 4.5 μm images, while warm circumstellar dust within ∼10″ of the star badly saturated the detector at 8.0 μm. The nearly vertical streaks in Figure 1 at position angle P.A. $= -5°$ from both HD 168625 and 168607, as well as what appear to be nearby companion stars along this same position angle, are both detector artifacts caused by the bright central stars.

The previously known $12'' \times 16''$ ring nebula around HD 168625 is clearly detected in all four IRAC bands in Figure 1; in fact, the whole ring is saturated in the 8.0 μm image. The 8.0 μm image in Figure 1*d* also shows more extended nebulosity out to ∼40″ from the star. The nebula is apparently bipolar, with a thin loop or ring to the northeast and some emission with similar extent to the southwest. The presence of this extended emission is dubious at 3.6 and 5.8 μm but is clearly seen at 4.5 μm. This extended structure is real, since IRAC images reveal no comparable extended features around the neighboring star HD 168607. This is the case at visual wavelengths as well (Hutsemékers et al. 1994). In hindsight, some Hα emission can be seen coming from outer regions of the nebula in Figure 1 of Hutsemékers et al. (1994). However, there is no indication that this diffuse Hα emission is related to HD 168625, so Hutsemékers et al. attributed it to the background H ii region M17.

3 See http://www.astro.wisc.edu/sirtf/.

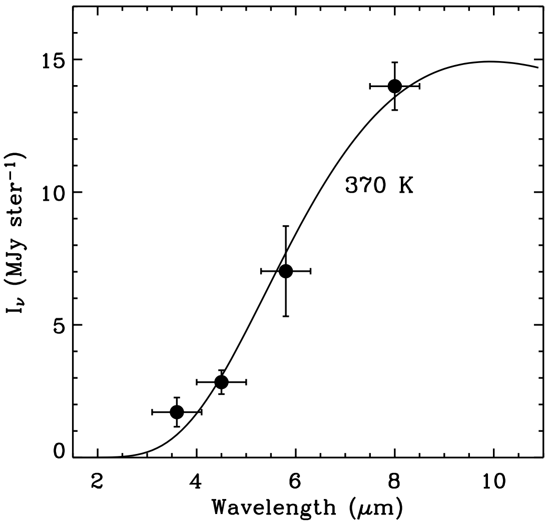

FIG. 2.—SED of the surface brightness in the northeast polar ring. The surface brightness was measured in a 2.4″ square aperture located 29″ east and 28″ north of HD 168625, and the surface brightness of the nearby background sky was subtracted.

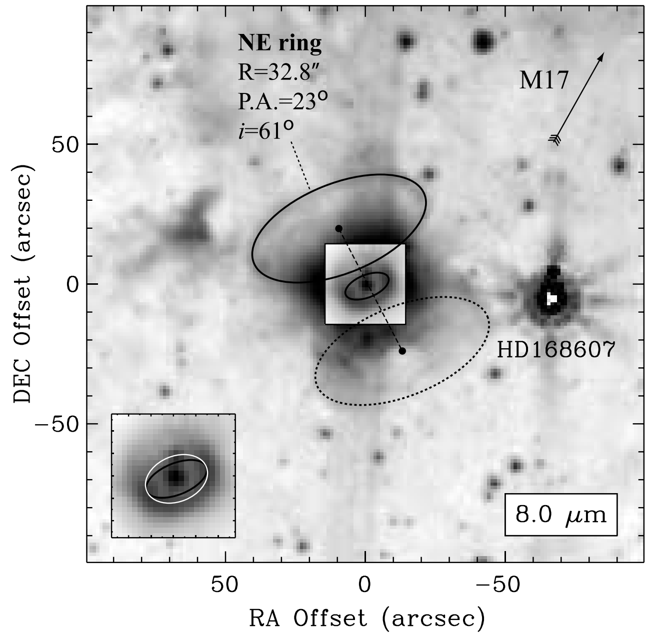

FIG. 3.—The 8.0 μm image of HD 168625 from Fig. 1*d* with representative rings superposed (for the saturated area around the central star, the 5.8 μm image is substituted). The northeast ring that is drawn here matches the size and shape of the observed emission from the nebular ring. The emission from the southeast polar lobe is not as well defined as the northeast ring, so drawn here is an ellipse of the same size, aspect ratio, and position angle that is matched to the extent of the polar lobe emission. A dashed line connects the centers of these two ellipses, representing a projection of the polar axis. The smaller ellipse in black superposed on the inner equatorial ring has 25% of the size of the polar rings, with the same position angle and inclination. The inset in the lower left shows that an ellipse of the same radius but with a slightly smaller inclination angle (*white*) fits the inner ring better. The arrow in the upper right indicates the direction toward the center of the nearby H II region M17.

Figure 2 shows the sky-subtracted spectral energy distribution (SED) of the surface brightness at a position in the northeast polar ring. A 370 K Planck function with λ^{-1} emissivity is shown for comparison with the data. However, this is of limited use for inferring physical properties of the nebulosity, since scattered light or emission features such as Brα, polycyclic aromatic hydrocarbons, or silicate emission may contribute to the emission seen in the IRAC filters. Although dust at $\sim$370 K seems to fit the data fairly well, it would be surprising to find dust at that high a temperature so far from the central star. At the likely separation of the northeast ring from the central star ($\sim$40″ or 88,000 AU), dust heating by the central engine is negligible, and the dust should be at a temperature similar to that of cool grains in the surrounding interstellar medium. Thus, it is likely that the IRAC SED is dominated by a combination of scattered light, thermal dust continuum, and emission features at these wavelengths, so deriving a reliable dust mass is not possible here. IR spectroscopy of the nebula would be useful, but it was not observed with the SWS or LWS on the *Infrared Space Observatory*, and HD 168625 has not yet been observed with the IR spectrograph on *Spitzer*. There is an interesting discrepancy in mid- to far-IR photometry, however, in that fluxes from the *Infrared Astronomical Satellite* (*IRAS*) are all systematically larger than fluxes obtained with ISOPHOT, the *Midcourse Space Experiment*, or ground-based mid-IR imaging, all of which have smaller beam sizes than *IRAS*. This hints that cool dust in the more extended outer nebula discovered here may have substantial flux at longer wavelengths, so submillimeter data would be beneficial for measuring or placing limits on its mass. Unfortunately, the 100 μm *IRAS* flux density of $\sim$580 Jy listed in the *IRAS* point-source catalog is flagged as unreliable.

3. RESULTS: MORPHOLOGY AND GEOMETRY

3.1. *The Outer Rings and Bipolar Nebula*

Spitzer IRAC images reveal a previously unknown large bipolar nebula around HD 168625, extended 40″ toward the northeast and toward the southwest. The most interesting feature is a well-defined ellipse or ring in the northeast polar lobe. The discovery of such a ring around an evolved hot supergiant star is of great interest with regard to its implications for the nebula around SN 1987A. This is discussed further in §§ 4.3 and 4.4.

Figure 3 shows that the entire visible part of the northeast ring matches a smooth ellipse, corresponding to a circle inclined 61° from the plane of the sky, and rotated with its semiminor axis (the polar axis) at a position angle of 23°. The parameters of this ellipse in Figure 3 are accurate to within $\lesssim$5%. The ring's FWHM thickness is about 2 pixels (2.4″), which matches the diffraction limit of the *Spitzer* telescope at 8.0 μm, so the ring's thickness is unresolved in IRAC images.

The southeast polar lobe does not have such a clearly defined ring in IRAC images. The dashed ellipse drawn in Figure 3 is meant to illustrate that a ring identical to that in the northeast polar lobe can match the extent of the diffuse 8.0 μm emission in the southwest polar lobe. Thus, it is plausible that such a ring defines the outer extremity of a conical lobe. A line connecting the centers of the northeast and southwest rings is drawn in Figure 3 (representing the polar axis), and it passes within 1″ of the central star. Figure 3 also shows a smaller ellipse drawn in black over the inner equatorial ring. This ellipse has the same inclination, position angle, and polar axis, but the radius is one-quarter of the northeast polar ring.

Thus, the bipolar lobes appear to be axisymmetric in basic shape and extent, but asymmetric in their detailed morphology. Potential sources of this asymmetry are (1) stronger ionization of the northern lobe by UV radiation from stars in the nearby H II region M17, (2) influence of the LBV wind from the nearby

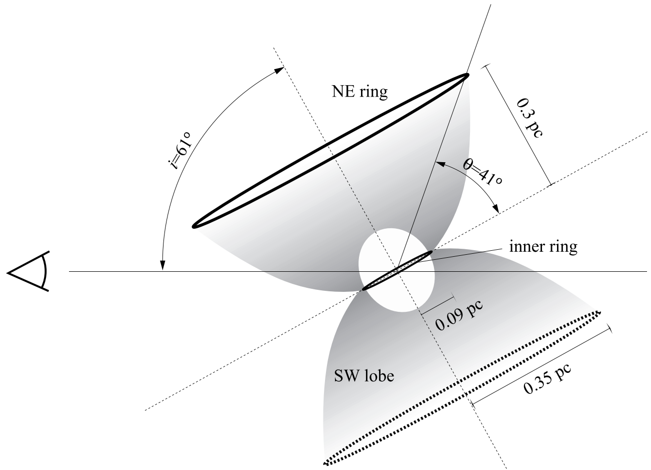

Fig. 4.—Sketch of the proposed three-dimensional geometry in the nebula around HD 168625, as viewed from the side, at a latitude near the equator. An Earth-based observer is at the left. See Table 1 for details.

star HD 168607 that may have disturbed a hypothetical southwest polar ring, or (3) intrinsic asymmetry in the star's mass ejection toward each of its poles. Whatever the cause, it is interesting that only the northern half of the inner ellipsoidal shell is seen in Hα images (Hutsemékers et al. 1994).

The first option of preferential external UV illumination of HD 168625's nebula by M17 is quantitatively plausible if they are located at the same distance. HD 168625 is projected on the sky about 11′ from the ionizing star cluster at the center of M17, indicating a probable separation of ~15 pc (including a factor of $\sqrt{2}$). If they really are at the same distance, HD 168625 would seem to have a suspiciously clear shot to these O stars, as the large-scale horseshoe or Ω-shape of M17 opens directly toward HD 168625. Hanson et al. (1997) estimated a total Lyman continuum luminosity of 1.2×10^{50} s^{-1} for the O stars that power M17, indicating a Lyman continuum flux of $\Phi_{\rm H} \simeq 5 \times 10^9$ s^{-1} cm^{-2} in the vicinity of HD 168625 for a separation of 15 pc. With ionization balance given roughly by $\Phi_{\rm H} \simeq \alpha_B l n_e^2$, this external ionizing flux could support electron densities of 500–1000 cm^{-3} if the typical path length l is ~1″ or 3.3×10^{16} cm ($\alpha_B = 2.3 \times 10^{-13}$ cm^3 s^{-1} is the case B recombination coefficient). This is comparable to typical densities estimated in similar LBV nebulae, and is comparable to the expected ionizing flux from a mid-B supergiant at the radius of the ring. The second option of external influence from the stellar wind ram pressure of the neighboring LBV HD 168607 is plausible simply because the two stars have similar mass-loss rates, and the projected separations between the gas in the southwest polar lobe and each of the stars are comparable. In the two cases in which external effects cause the asymmetry, special geometric orientations are necessary so that only one lobe feels the external influence. The third alternative, in which the star's mass-loss geometry is intrinsically asymmetric toward its two polar hemispheres, is not easily accomplished either and would be rare among known bipolar nebulae.

3.2. *The Inner Equatorial Ring*

Previous optical/IR imaging of the inner dust ring found it to be a flattened toroid or ring, with a radius of ~8″ (0.085 pc) and an inclination angle[4] of $i \simeq 60° \pm 15°$ (O'Hara et al. 2003; Pasquali et al. 2002; Robberto & Herbst 1998; Nota et al. 1996; Hutsemékers et al. 1994). Observed kinematics showed that it had a radial expansion speed of 19–20 km s^{-1} (Hutsemékers et al. 1994; Pasquali et al. 2002), and consequently, a dynamical age of a few thousand years. This inner ring is taken to define the equatorial plane. Imaging also revealed a fainter ellipsoidal shell that met the equatorial ring but was more elongated along the polar axis (e.g., Hutsemékers et al. 1994; O'Hara et al. 2003; Nota et al. 1996). Emission from this ellipsoidal shell, which is brightest in the northeast polar lobe at radii up to about 12″ from the star, can be seen in the insets of Figure 3.

The structure of the inner ring in the IRAC images seems to suggest a slightly lower inclination (Fig. 3, *white ellipse in the inset*) than 61° (*black ellipse*). However, detailed study of IR and optical images with higher spatial resolution found a best-fit inclination of 60° ± 15°, as noted above. This is within 1° of the inclination derived here for the outer northeast polar ring. Therefore, the outer polar rings and the inner equatorial ring are plane-parallel. There is a slight tilt in the nebula, in the sense that the line connecting the centers of the two polar rings is not perpendicular to the major axes of the rings.

3.3. *Geometric Interpretation*

Figure 4 shows a sketch of the proposed three-dimensional geometry of the ring system and bipolar nebula around HD 168625 as viewed from the western side, near the equatorial plane (an Earth-based observer is to the left). The northeast ring is a well-defined ellipse, providing an accurate measure of several geometric parameters in the system under the assumption that the object is a circular ring inclined to our line of sight. The parameters in Figure 4 and Table 1 are based on the observed dimensions of the northeast ring, and all assume a distance of 2.2 kpc.

The northeast ring is at a latitude of 41° from the equator, so half the opening angle of the conical bipolar lobes would be 49°. The polar ring resides at a height above the equatorial plane of 0.3 pc, and a radial distance from the star of 0.46 pc. The kinematics of the outer polar rings have not yet been measured, but this is an important observational goal. If they have the same ~4000 yr dynamical age as the inner ring, they would be

TABLE 1
Geometric Parameters of the Circumstellar Rings

Parameter	HD 168625	SN 1987A
Inner ring inclination (deg)	61 ± 2	43 ± 3
Outer ring inclination (deg)	60 ± 15	47–51
Outer ring thickness (pc)	<0.026	<0.08
Outer ring spherical radius (pc)	0.46	0.5–0.64
Outer ring cylindrical radius R (pc)	0.35	0.43–0.45
R(pole)/R(eq)	4	2.2
Ring height (pc)	0.3	0.3–0.43
Ring latitude (deg)	41 ± 2	32–45
Cone opening angle (deg)	98 ± 2	90–116
Position angle of polar axis (deg)	23	−9
$V_{\rm exp}$(pole) (km s^{-1})	(110)	26
$V_{\rm exp}$(eq) (km s^{-1})	19	8.3
Dynamical age (10^4 yr)	0.4	2.2
N/O [(N/O)$_\odot$]	>3	≳10

Notes.—All values for HD 168625 assume a distance of $D = 2.2$ kpc. The parameter $V_{\rm exp}$(pole) is in parentheses because it has not been measured but was calculated assuming that it has the same age as the inner ring. Values are taken from Burrows et al. (1995), Plait et al. (1995), Crotts & Heathcote (1991), Meaburn et al. (1995), Fransson et al. (1989), Sonneborn et al. (1997), and Hutsemékers et al. (1994).

[4] Here inclination is defined as the tilt of the equatorial plane from the plane of the sky, as in binary systems.

expanding at roughly 110 km s^{-1}. This is still slower than the central star's observed terminal wind velocity of $v_\infty = 183$ km s^{-1} (Nota et al. 1996), so it is at least plausible that the inner and outer rings are coeval.

The polar axis is tilted out of the plane of the sky by $90° - i = 29°$, but it is not certain from images alone which way the polar axis is pointing. Figure 4 is drawn with the northeast polar axis tilted toward us and the southwest polar axis tilted away, such that the expansion center of the northeast ring would be blueshifted. This is based primarily on the observed morphology and kinematics of the well-studied inner ring; the inner equatorial ring is brighter on its southern rim in scattered light (Pasquali et al. 2002), and predominantly forward scattering of dust grains at visual wavelengths would imply that this is the near side. If the south/southwest part of the equatorial ring is closer to us, then the northeast polar axis would need to be tilted toward us. This orientation is also favored by the observed expansion velocities in the inner ring (Hutsemékers et al. 1994; Pasquali et al. 2002). Further study with deep high-resolution spectra of the outer nebula could provide a more certain answer.

Spitzer images also reveal extended diffuse emission just outside the inner ring that was not revealed in previous IR imaging. This may represent warm dust in the side walls of the biconical surface of the polar lobes, which may connect the inner ring to the outer rings, as depicted by the shaded regions in Figure 4. These side walls of the biconical lobes are drawn as slightly curved surfaces in Figure 4, but this detail of the geometry remains to be determined spectroscopically. These thin walls have counterparts in the "sheets" of material that seem to connect the inner and outer rings of SN 1987A (Burrows et al. 1995).

4. DISCUSSION

4.1. *Swept-up RSG Wind or LBV Eruption?*

Although it may be plausible that HD 168625 has already passed through an RSG evolutionary phase before becoming an LBV, it is highly unlikely that most of the mass in the outer nebula reported here was ejected in that previous RSG phase and shaped afterward. Doppler shifts or proper motions of the outer nebula have not yet been measured, so its dynamical age is unknown. However, there are essentially two possibilities worth considering: the outer bipolar nebula could have been ejected at the same time as the inner ring, with a dynamical age of ~4000 yr (Table 1), or it could have been ejected much earlier. (A scenario in which the outer bipolar lobes are significantly younger than the inner ring can be rejected because their required expansion speed would be faster than the stellar wind's terminal velocity.) Both these two possibilities are inconsistent with a nebular origin during the RSG phase, for the following reasons:

1. If the inner and outer rings are coeval, then the required expansion speed of the outer rings is $V_{\rm exp} \simeq 110$ km s^{-1} (Table 1). This high speed rules out an RSG origin for the nebula. On the other hand, such speeds are typical in giant LBV eruptions.

2. If the inner and outer rings are *not* coeval, and the outer rings were ejected much earlier, then an RSG origin is probably ruled out as well. This is because the creation of *multiple* shells in an interacting RSG/LBV winds scenario would require the star to transit from the RSG to the LBV phase twice in a few thousand years. Two blue loops in the H-R diagram are not predicted by current evolutionary models (e.g., Arnett 1991; Maeder & Meynet 2000; Fitzpatrick & Garmany 1990). While the nebula's dynamical timescale is in marginal agreement with a single transition episode from RSG to blue supergiant, it is an order of magnitude shorter than the time that would be needed for two full blue loops, set by the thermal timescale of the He core.

Of course, the expectation that the nebula was most likely ejected in one or more LBV eruptions does not preclude the possibility that HD 168625 has already passed through an RSG phase. In fact, low-luminosity LBVs probably *are* post-RSGs, in order to raise their *L*/*M* ratio enough that they are subject to the LBV instability (see Smith et al. 2004; Humphreys & Davidson 1994). In any case, it would be desirable to obtain high-resolution spectra of the outer nebula around HD 168625 in order to measure its apparent Doppler velocities and chemical abundances. Observed line-of-sight motion can be deprojected with the geometry in Figure 4 to independently derive the dynamical age of the outer nebulosity.

What causes the bipolar shape of the outer nebula? No evidence for a close companion star has been reported, even though this star has been studied spectroscopically and photometrically in the interest of testing its LBV nature (e.g., Chentsov & Luud 1989; Sterken et al. 1999; Nota et al. 1996; Pasquali et al. 2002). At the high inclination of the ring system ($i \simeq 61°$), we might expect orbital reflex motion or even periodic eclipses to be detectable if the central star is a close binary, so renewed monitoring of this star may be interesting. Evidence of orbital reflex motion would go a long way toward demonstrating that tidal spin-up by a close companion may be related to bipolar geometry. Whether spun up by a companion or not, however, a star in near-critical rotation is probably the culprit (see § 4.2). LBV eruptions from rotating stars should produce bipolar mass loss (e.g., Owocki 2003), as demonstrated in the case of η Car (Smith 2006).

4.2. *Implications for Mass Loss through LBV Eruptions*

The dynamical age for the new outer bipolar nebula around HD 168625 has not yet been measured, but it is at least ~4000 yr. It is the fourth Galactic LBV or LBV candidate to exhibit such a large outer filamentary shell, following η Car (Walborn 1976; Smith et al. 2005; Bohigas et al. 2000), P Cyg (Meaburn 2001; Meaburn et al. 1996, 1999, 2004), and HR Car (Nota et al. 1997; Weis et al. 1997).

The chief reason that the new discovery of this ancient nebula around HD 168625 is interesting for research on LBVs is because of the star's relatively low luminosity compared to other LBVs. HD 168625 is at the bottom of the range of luminosities for LBVs and LBV candidates on the H-R diagram (see Smith et al. 2004). It has not been observed to suffer the same photometric variability as more luminous bona fide LBVs. Its nebula, however, indicates that violent mass loss through repeated giant LBV eruptions may be important across the full range of LBV luminosity. Furthermore, its bipolar morphology with a tightly pinched waist and no evidence for binarity in the central star is consistent with the idea that rotation can drive bipolar mass loss (Owocki 2003; Dwarkadas & Owocki 2002; Owocki et al. 1996; Cranmer & Owocki 1995), even at relatively low LBV luminosities. Presumably this can occur because the stars approach or violate the classical Eddington limit during their giant eruptions when the mass is ejected, allowing the star's rotation to be more influential at the resulting lower effective gravity (e.g., Langer 1998; Glatzel 1998; Maeder & Meynet 2000).

4.3. *A Galactic Analog of the Nebula around SN 1987A*

The multiringed geometry of HD 168625's nebula depicted in Figure 4 makes it the Milky Way's closest analog to the famous triple-ring nebula around SN 1987A. The two nebulae are compared in Table 1, in which we see that all of HD 168625's parameters are very close to those of SN 1987A. When a range of parameters is given, they often overlap. Both have nitrogen-enriched nebulae, although the level of nitrogen enrichment in HD 168625 is not as well constrained (see Table 1). The only substantive physical differences between the two nebulae (more than $\pm 30\%$) are that HD 168625's inner equatorial ring is smaller and its dynamical age is less. Given more time, the stellar wind of HD 168625 ($\sim$183 km s^{-1}) will continue to sweep up its equatorial ring to have a larger radius more akin to that of SN 1987A, Rayleigh-Taylor instabilities will lead to protrusions like the "fingers" that cause the hot spots in SN 1987A's ring (e.g., Michael et al. 2000), and the ring's expansion speed may decrease as the wind sweeps up more mass. At present, the outer nebula around HD 168625 is very difficult to see at visual wavelengths because it is overwhelmed by light from the bright central star, and the nebula may be mostly neutral with only weak intrinsic Hα emission. However, it is easy to imagine that in the not too distant future, an event may occur that will flash-ionize HD 168625's nebula and remove the bright central star, making the nebula appear identical to SN 1987A's.

A comparison to SN 1987A has also been made for the blue supergiant Sher 25 in NGC 3603 (Brandner et al. 1997a, 1997b), which harbors an equatorial ring. However, unlike HD 168625, Sher 25 shows no sign of polar rings, but instead shows irregular structure in the bipolar lobes. A few objects do show pairs of plane-parallel rings, like the planetary nebula Abell 14 and the massive eclipsing binary RY Scuti (Smith et al. 2002), but in these systems the ring pairs are at low latitudes near the equator, and they lack a third inner ring. Many planetary nebulae have an equatorial torus or ring at the waist of their bipolar lobes (e.g., Balick & Frank 2002), and with limb brightening, some of these polar lobes may appear ringlike. However, HD 168625 is the only one around a massive star, so among objects known to date, its nebula may be the best analog of the pre-supernova (pre-SN) environment around SN 1987A.

Stellar properties further justify the close comparison between the nebulae around HD 168625 and SN 1987A. SN 1987A's progenitor was identified as the blue supergiant Sk −69 202 (Walborn et al. 1987). Its B3 I spectral type would correspond to $T_{\rm eff} \simeq 16{,}000$ K (Crowther et al. 2006), and its luminosity of $\lesssim 10^5\ L_\odot$ would indicate an initial mass of roughly 20 $M_\odot$ (Arnett 1991; Woosley et al. 1987). HD 168625 is almost identical by comparison; it has $T_{\rm eff} \simeq 15{,}000$ K and a luminosity of 10^5–$10^{5.4}\ L_\odot$ (Nota et al. 1996), corresponding to a likely initial mass of 20–25 $M_\odot$. Both stars have probably passed through the RSG phase in the recent past (see Smith et al. 2004). On the other hand, Sher 25's parameters are significantly different. Its spectral type of B1.5 Ia indicates that it is hotter than Sk −69 202, and its luminosity of $10^{5.9}\ L_\odot$ (Smartt et al. 2002) is much higher. In fact, this luminosity is so high that it precludes Sher 25 from having been an RSG (Humphreys & Davidson 1994), so its evolution on the H-R diagram has been very different from that of Sk −69 202. Chemical abundances reinforce this conjecture; Smartt et al. (2002) find that Sher 25's N/O ratio is incompatible with a previous RSG phase.

4.4. *Potential Implications for the Progenitor of SN 1987A*

The profound similarities discussed above beg the question: *Was SN 1987A's progenitor an unrecognized or quiescent LBV*? If the nebula had been discovered prior to 1987, then Sk −69 202 would likely have been classified as a low-luminosity LBV candidate by today's criteria. In a sense, an LBV hypothesis for the SN 1987A progenitor is a small modification from the established fact that it was a blue supergiant, since the duration of the LBV phase one infers from observed statistics is identical to the expected timescale for a post-RSG blue loop at this stellar mass (e.g., Martin & Arnett 1995). The LBV hypothesis is also consistent with the nitrogen enrichment in SN 1987A's circumstellar ejecta (Fransson et al. 1989; Sonneborn et al. 1997), since LBV nebulae are commonly N-rich (e.g., Smith & Morse 2004; Davidson et al. 1986; Lamers et al. 2001). Furthermore, there are growing hints that some small fraction of Type II SN progenitors are LBVs (e.g., Gal-Yam et al. 2007; Kotak & Vink 2006; Smith & Owocki 2006; Smith 2007).

So then, *was the bipolar circumstellar nebula around SN 1987A ejected in an episodic eruption like those seen in LBVs, rather than arising from a swept-up asymmetric RSG wind*? There is evidence for much larger scale bipolar nebulosity well outside the triple rings around SN 1987A, seen in continuum emission from light echoes (e.g., Sugerman et al. 2005; Crotts et al. 1995; Wampler et al. 1990). Formation of these outer bipolar lobes by interacting winds would require more than one blue loop, but multiple blue loops are not expected. On the other hand, multiple nested nebulae with the same geometry are expected from repeated LBV-like ejection events. Here we have seen that SN 1987A's two closest Galactic analogs, HD 168625 and Sher 25, both ejected their ringed bipolar nebulae as blue supergiants, most likely in LBV outbursts (see § 4.1). Detailed studies of η Car (e.g., Smith 2006) have established a clear precedent that near-critically rotating LBVs can eject bipolar nebulae without resorting to a pre-existing equatorial density enhancement, and that they can do so repeatedly with the same geometry. In η Car it was even found that the mass concentration peaked at mid-latitudes of around 50°–60° (Smith 2006), similar to the latitudes of the polar rings around HD 168625 and SN 1987A. Thus, the bipolar shapes of LBV nebulae in general—and the ringed structure of HD 168625's nebula in particular—argue that a past LBV-like episode may be an alternative mechanism to explain the formation of SN 1987A's rings. The LBV hypothesis for SN 1987A is appealing because it may avert the complete surrender of rotating single-star models as an alternative to an improbable binary merger event.

Perhaps the strongest objection to this LBV progenitor scenario for SN 1987A would seem to be the low expansion speed of SN 1987A's equatorial ring, which is slow even compared to wind speeds of RSGs. However, this is not much of a showstopper for the LBV hypothesis. LBV nebulae exhibit a wide range of expansion speeds, sometimes in the same object. For example, η Car's ejecta move at speeds from as high as 600 km s^{-1} or more down to speeds as low as 40 km s^{-1} (Smith 2006). We might expect some very low speeds, since the escape speed formally tends toward zero when a star violates the classical Eddington limit during an LBV eruption (e.g., Zethson et al. 1999). Indeed, $V_{\rm exp}$ for HD 168625's equatorial ring is only 19 km s^{-1}, which is even slower than the 26 km s^{-1} expansion speed of SN 1987A's polar rings (recall that the fast polar ring speed of 110 km s^{-1} listed in Table 1 *assumes* that the rings are all coeval). Incidentally, HD 168625's equatorial and (assumed) polar ring expansion speeds are nearly identical to Sher 25's equatorial and polar speeds (Brandner et al. 1997a, 1997b). Another potential objection is the relatively low luminosity of Sk −60 202 compared to LBVs, but the low end of the luminosity range for LBVs is not well characterized. While it seems unlikely Sk −69 202 could have been a bona fide LBV exhibiting classical S Doradus variability at its relatively low luminosity, it may nevertheless have suffered episodic mass loss analogous to a giant LBV-type eruption.

The recognition that SN 1987A's progenitor was a blue supergiant (Walborn et al. 1987) instead of an RSG was surprising at the time, and led to drastic revisions in our understanding of stellar evolution for massive stars (e.g., Arnett 1991). Furthermore, the high degree of axial symmetry in the bipolar circumstellar nebula, thought to have been ejected during the RSG phase, challenged our understanding of the formation of bipolar nebulae (Blondin & Lundqvist 1993; Martin & Arnett 1995). It required an external source of angular momentum, ultimately strengthening the case for a binary merger before the SN event (Podsiadlowski 1992; Morris & Podsiadlowski 2006; Collins et al. 1999). It is amusing to ponder how the debate about SN 1987A's pre-SN evolution might have unfolded somewhat differently had it been postulated at the time that the progenitor could have been a low-luminosity quiescent LBV, or that the bipolar geometry originated in an LBV-like eruption instead of in the RSG phase.

With the close comparison to SN 1987A, an even more amusing notion is the possibility that HD 168625 will suffer a core collapse in the near future. Given its relatively small distance of 2.2 kpc, its low interstellar extinction, and its declination of only -16°, the SN would be seen from the northern hemisphere and would likely be one of the most spectacular celestial events in recorded history.

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