AND IN THE DARKNESS BIND THEM: EQUATORIAL RINGS, B[e] SUPERGIANTS, AND THE WAISTS OF BIPOLAR NEBULAE

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Received 2007 February 13; accepted 2007 March 30

ABSTRACT

We report the discovery of two new circumstellar ring nebulae in the western Carina Nebula, and we discuss their significance in stellar evolution. The brighter of the two new objects, SBW 1, resembles a lidless staring eye and encircles a B1.5 Iab supergiant. Although seen in Carina, its luminosity class and radial velocity imply a larger distance of ~7 kpc in the far Carina arm. At that distance its size and shape are nearly identical to the equatorial ring around SN 1987A, but SBW 1's low N abundance indicates that the ring was excreted without its star passing through a red supergiant phase. The fainter object, SBW 2, is a more distorted ring, is N-rich, and is peculiar in that its central star seems to be invisible. We discuss the implications of these two new nebulae in context with other circumstellar rings such as those around SN 1987A, Sher 25, HD 168625, RY Scuti, WeBo 1, SuWt 2, and others. The ring bearers fall into two groups: Five rings surround hot supergiants, and it is striking that all except for the one known binary are carbon copies of the ring around SN 1987A. We propose a link between these B supergiant rings and B[e] supergiants, where the large spatially resolved rings derive from the same material that would have given rise to emission lines during the earlier B[e] phase, when it was much closer to the star. The remaining four rings surround evolved intermediate-mass stars; all members of this ring fellowship are close binaries, hinting that binary interactions govern the forging of such rings. Two-thirds of our sample are found in or near giant H II regions. We estimate that there may be several thousand more dark rings in the Galaxy, but we are scarcely aware of their existence—either because they are only illuminated in precious few circumstances or because of selection effects. For intermediate-mass stars, these rings might be the preexisting equatorial density enhancements invoked to bind the waists of bipolar nebulae.

Key words: circumstellar matter — H II regions — stars: mass loss — stars: winds, outflows

1. INTRODUCTION

Nonspherical mass loss is a key ingredient for understanding the roles of rotation, magnetic fields, and close binary interactions in various stages of stellar evolution. Bipolar structure is common in nebulae surrounding evolved stars across the H-R diagram, most notably in planetary nebulae (Balick & Frank 2002) and in more massive hot stars like luminous blue variables (LBVs). Many bipolar nebulae have a dense torus or ring at their pinched waist where the polar lobes meet at the equator, as seen in prototypical objects like η Carinae (Smith et al. 2002a) and in dramatic Hubble Space Telescope (HST) images of planetary nebulae like MyCn 18 (Sahai et al. 1999), NGC 2346, and NGC 7027 (Latter et al. 2000).

Perhaps the most outstanding and familiar example of such equatorial structure is the inner ring around SN 1987A (Plait et al. 1995; Burrows et al. 1995; Crotts & Heathcote 1991; Crotts et al. 1989). In SN 1987A, as well as planetary nebulae, the prevailing interpretation for the formation of these equatorial rings and bipolar nebulae has been that a fast, low-density wind expands into an asymmetric, slow, dense wind from a previous red giant or supergiant phase (e.g., Blondin & Lundqvist 1993; Martin & Arnett 1995; Collins et al. 1999; Frank & Mellema 1994; Frank 1999). This requires that the slow wind have a strong equatorial density enhancement (i.e., a disk) that can be swept-up to form a ring, but the origin of this putative preexisting disk is unclear, and evidence of them around red supergiants (RSGs) is nonexistent.

The formation of equatorial disks by single stars has been of continued interest to the Be star community, since these stars are rapid rotators. B[e] supergiants are suspected to be their high-luminosity analogs (e.g., Zickgraf et al. 1986). The wind-compressed disk model (Bjorkman & Cassinelli 1993) suggests that rapidly rotating stars will form disks as material ejected at midlatitudes is directed toward the equator. While such disks are inhibited in hot stars with line-driven winds because of the effects of gravity darkening and velocity-dependent forces (Owocki et al. 1996; Cramer & Owocki 1995), wind compression may still operate in other circumstances. Ignace et al. (1996) suggested that cool stars may experience moderate compression, while Smith & Townsend (2007) propose that thin disks can form in continuum-driven LBV eruptions. Changes in ionization with latitude on a gravity-darkened rotating star has been suggested to play a role in disk formation as well (e.g., Lamers & Pauldrach 1991; Cure et al. 2005). However, any disk formation around cool stars requires rapid rotation much in excess of rotation rates expected for the distended envelopes of red giants and supergiants. Indeed, Collins et al. (1999) estimated that while in the RSG phase, the progenitor of SN 1987A must have been rotating at ≥0.3 of its critical breakup speed to produce the observed nebular morphology—which is impossible for normal single-star evolution—so they conclude that the RSG...
was most likely spun-up by swallowing a companion. Thus, close binary interactions and mergers are often taken as potential sources of angular momentum to focus material toward the equator. Magnetic fields may provide yet another avenue for the formation of equatorial disks or rings (ud-Doula & Owocki 2002; Washimi et al. 1996; Townsend & Owocki 2005; Matt & Balick 2004).

The equatorial ring around SN 1987A is quite unusual in that it really is a hollow ring and not just a limb-brightened shell or pinched waist of an hourglass. A virtual twin of SN 1987A’s equatorial ring has been discovered in the Milky Way: the ring around the blue supergiant Sher 25 in NGC 3603 (Brandner et al. 1997). More recently, Smith (2007) has suggested another twin of SN 1987A’s nebula around the Galactic LBV candidate HD 168625. Two other notable examples are the ringed planetary nebulae WeBo 1 (Bond et al. 2003) and SuWt 2 (Schuster & West 1976). Regardless of the nature of their central stars, these objects are similar in the unusually distinct ring morphology of their ejecta. To this class we add two more examples, both discovered in the Carina Nebula (NGC 3372; see Fig. 1).

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**2. OBSERVATIONS**

2.1. CTIO Mosaic Images

The discovery of the two ring nebulae described in this paper was made serendipitously during a narrowband imaging survey of the Carina Nebula, although these images are not shown here as they are of lesser quality than the Magellan images described below. We surveyed the entire 2.5° × 4° area of the giant Carina Nebula on 2003 March 10 using several pointings with the 8192 × 8192 pixel imager MOSAIC2 mounted at the prime focus of the Cerro Tololo Inter-American Observatory (CTIO) 4 m Blanco telescope. This camera has a large 35.4′ field of view, which allowed us to efficiently survey the whole nebula using the [O iii] λ5007, Hα+[N ii], and [S ii] λ6717,6731 narrowband filters, plus the i′ broadband filter. Further details of the observations and data reduction can be found in previous papers from the same project (e.g., Smith et al. 2004, 2005a). Because we were trying to maximize efficient spatial coverage of the nebula in multiple filters, we did not do a full set of MOSDITHER exposures to correct for the ~3″ interchip gaps. One of the objects of interest here (SBW 2) ended up straddling a gap, motivating the subsequent imaging with the 6.5 m Magellan telescope described below. Both nebulae were easily recognized as circumstellar rings in the Hα+[N ii] filter images, but no circumstellar emission was seen in images in the other filters taken with similar 5–10 minute exposure times.

The positions of these two ring nebulae are listed in Table 1, and their approximate locations are marked on the wide-field image in Figure 1. These absolute sky coordinates from the MOSAIC2 images were determined with reference to USNO catalog stars.

2.2. Magellan Images

Following the initial discovery in CTIO images, we obtained narrowband Hα images of the two Carina ring nebulae on 2005 February 21 using the CCD imager MagIC mounted on the 6.5 m Clay telescope of the Magellan Observatory. MagIC has a 2048 × 2048 pixel SITe detector, with a spatial pixel scale of 0.069″ and a 142″ × 142″ field of view on the 6.5 m Clay telescope. The night was decidedly nonphotometric with patchy and highly variable seeing, but the seeing was still quite good at ~0.6″. SBW 1 was bright enough to observe easily with a 6.5 m telescope looking through clouds, and we took a set of three exposures of 120 s each. SBW 2 is much fainter, and while we observed it the cloud cover became more crippling, but with periodic thin patches. Therefore, we took a long series of about 30 consecutive 300 s exposures as the clouds rolled by, and we selected only the highest quality images (the ones with the largest number of counts and best seeing) to shift and add together. The small 0.069″ pixels were rebinned.

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**TABLE 1**

| Name               | α(J2000.0) | δ(J2000.0) | Apparent Size (arcsec) | Comments |
|--------------------|------------|------------|------------------------|----------|
| SBW 1.................. | 10 40 19 4 | −59 49 09 7 | 11.1 × 7.1 | V = 12.7, R = 12.14 |
| SBW 2.................. | 10 36 09 2 | −59 09 19 2 | 37 × 23    | (R = 18.5, 20.5, 20.7) |

Notes.—For SBW 1 these coordinates correspond to the bright central star, while the position for SBW 2 corresponds to the approximate center of the ring, since no obvious bright star can be associated with it. The V and R magnitudes of the stars are from the GSC 2.2 catalog. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
by a factor of 3 to larger pixels of 0.207". The final Hα+[N II] images of the two rings are shown in Figure 2, while intensity tracings through the middle of each ring are shown in Figure 3.

2.3. NTT/EMMI Echelle Spectra

We used the ESO Multi-Mode Instrument (EMMI) on the New Technology Telescope to obtain high-resolution spectra of SBW 1 and SBW 2 on the nights of 2003 March 11 and 12, respectively (one and two nights after their discovery in CTIO images). For both targets we used the number 10 echelle grating and EMMI’s red CCD with a 4096×4096 pixel MIT/LL detector, a pixel scale of 0.166"×0.058", and \( R = \frac{\lambda}{\Delta \lambda} = 28,000 \) (10 km s\(^{-1}\)) at wavelengths near Hα. We calibrated the wavelengths using an internal emission lamp.

For SBW 1, we used EMMI in cross-dispersed mode, with a 15"×1" slit aperture, oriented at P.A. = 45° across the minor axis of the nebula (see Fig. 4a). SBW 1 is in a region of bright nebular emission in the western Carina Nebula, so we also obtained

Fig. 2.—Magellan/MagIC Hα+[N II] images of (a) SBW 1 and (b) SBW 2. Note that the two images are not reproduced here at exactly the same size scale.

Fig. 3.—Intensity tracings across the images in Fig. 2. (a) Tracing along the minor axis of SBW 1, taken from two 0.5" wide segments on either side of the EMMI slit aperture shown in Fig. 4a, in order to avoid bright light from the star. (b) Tracing through the middle of SBW 2, immediately to the northwest of the EMMI slit shown in Fig. 4b. In each panel, the dashed line is a model for the expected emission from a cross section through a limb-brightened thin shell with the inner and outer radii listed in each panel. In panel b, especially, it is clear that the observed emission is not consistent with the limb-brightened shell.
similar exposures of an adjacent position offset by 30" southeast to subtract emission from the nebula and sky. The red [S ii] \( \lambda \lambda 6717,6731 \) doublet was faintly visible in the resulting spectra, but the signal-to-noise ratio in the 30 minute exposure was too low to provide a meaningful measure of the electron density. This is consistent with the fact that we detected no extended structure in narrowband [S ii] images. Aside from \( \text{H}_\alpha \) and [N ii], no other emission lines were detected in the nebula. The order including \( \text{H}_\alpha + \text{[N ii]} \) emission is shown in Figure 5a, while tracings of the spectrum through the northeastern and southwestern portions of the ring are shown in Figure 5b, and an extracted spectrum of the central star is shown in Figure 5c. Detailed views of the long-slit kinematics for \( \text{H}_\alpha \) and [N ii] \( \lambda 6583 \) are shown in Figures 6a and 6b, respectively.

For SBW 2, which has a larger size on the sky, we used a longer 6' × 1" aperture, with a flat mirror in the beam instead of a cross-disperser, and we used a narrowband order-sorting filter to isolate \( \text{H}_\alpha + \text{[N ii]} \). This long slit was also oriented at P.A. = 45° through the minor axis of the ellipse (Fig. 4b). Unfortunately, SBW 2 was observed at the end of the night and had less than half as much time as we would have liked, an the resulting signal-to-noise ratio of the spectrum was much less than half of what this object deserved. The resulting spectrum is noisy and is not displayed here (dominated by read noise, since it is in a region of very faint nebular background emission; see Fig. 1). These spectra are useful, however, because although we detected the \( \text{H}_\alpha + \text{[N ii]} \) lines, we detected no Doppler shifts from one side of the ring to the next. The limiting resolution of 10 km s\(^{-1}\) for these data then imply a limiting intrinsic radial expansion speed of ±8 km s\(^{-1}\) (±16 km s\(^{-1}\) across the diameter of the ring) when corrected for the disk inclination angle (see below).

### 2.4. CTIO 4 m/RC Spec Spectra

We used RC Spec on the CTIO 4 m to obtain medium-resolution (\( R \approx 6000 \)) red spectra of SBW 1, SBW 2, and SuWt 2 on 2006 March 15. RC Spec\(^{10}\) is the Cassegrain gratingspectrograph on the V. M. Blanco 4 m telescope, equipped with a Loral 1K × 3K CCD detector. We used grating G380 and filter GG495 to sample wavelengths \( \Delta \lambda = 5480–7153 \) Å, with a pixel scale of 0.5" × 0.55 Å, and an effective 2 pixel spectral resolution of roughly 50 km s\(^{-1}\). The slit width was set at 0.8", matched approximately to the seeing, with the long slit oriented as in Figure 4 for SBW 1 and SBW 2, and along the major axis of the ring at P.A. = −45° for SuWt 2. We used total integration times of 9 minutes for SBW 1, and 40 minutes for SBW 2 and SuWt 2. The conditions were photometric, and the data were flux calibrated using observations of the spectrophotometric standards LTT 3218

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\(^{10}\) See http://www.ctio.noao.edu/spectrographs/4m_R-C/4m_R-C.html.
and LTT 4816. Wavelength calibration was performed with reference to an internal HeNeAr lamp. Emission from the background sky and H\textsc{ii} region was subtracted by sampling nebular emission along the slit adjacent to each object.

The extracted flux-calibrated spectra are shown in Figure 7, and line intensities for several emission lines relative to H\textsc{i}/C\textsc{ii} = 100 are listed in Table 2. The relative line intensities in Table 2 have been dereddened.

A reddening of $E(B - V) = 0.5$ for SBW 2 is a standard value for relatively unobscured regions in Carina (e.g., Smith et al. 2005b), while we chose a higher value of $E(B - V) = 1.0$ for SBW 1, even though it too appears in Carina, for reasons justified later in § 3.1.2. The value of $E(B - V) = 0.25$ for SuWt 2 was determined by matching the continuum shape of the central star in our spectra to an early A-type photosphere (however, this value is very uncertain due to the small overall wavelength range of our red spectra). Uncertainties are a few percent for the brightest lines, and several to 10\% for the faintest lines. For SBW 1 and SBW 2 we give upper limits to the intensity of \[\text{N}\text{ii}] k 5755, since it is important for constraining the electron temperature and chemical abundances.

On 2006 March 16 we also obtained a blue spectrum of the central star of SBW 1 with RC Spec on the CTIO 4 m telescope in order to determine the spectral type of the central star. Two 150 s exposures covering roughly 3000–6000 \AA\ were obtained with the 0.67\" slit along a position angle of about 10\°. The data were reduced in the standard way, and emission from the sky and background H\text{ii} region was subtracted by fitting background

Diffuse emission along the slit. Figure 8 shows a normalized spectrum extracted from a \(\sim 1.5\") segment of the slit.

### 2.5. New Observations of SuWt 2 and WeBo 1

Using the MOSAIC2 camera on the CTIO 4 m telescope (during the same survey of star-forming regions in which we discovered SBW 1 and SBW 2, as noted earlier in § 2.1), we also obtained an H\text{a}+[\text{N}\text{ii}] image of another ring nebula called SuWt 2 on the same night of 2003 March 10. SuWt 2 was originally discovered on red photographic plates by Schuster & West

![Fig. 6.—Long-slit nebular kinematics of SBW 1 in (a) H\text{a} and (b) [N\text{ii}] \(\lambda 6583\). The velocity scale is heliocentric, and the dashed line marks the presumed systemic velocity at +22 km s\(^{-1}\), which is offset by +30 km s\(^{-1}\) from the average emission velocity of gas in the Carina Nebula at \(-8.1\) km s\(^{-1}\) (Smith 2004). These two panels are sections of the data in Fig. 5a.](image)

![Fig. 7.—Extracted CTIO/4 m RC Spec spectra of (a) SBW 1, (b) SBW 2, and (c) SuWt 2. Aperture sizes and their approximate locations are noted in each panel.](image)

### Table 2

| \(\lambda\) (\AA) | L.D. | SBW 1 | SBW 2 | SuWt 2 | WeBo 1 |
|-----------------|-----|------|------|--------|--------|
| 5755\ldots\ldots | [N\text{ii}] | <0.99 | <17.1 | 11.3 | \(\leq 2.4\) |
| 5876\ldots\ldots | He i | \ldots | \ldots | \ldots | 5.7 |
| 6300\ldots\ldots | [O i] | 30.4 | 20.7 | 14.6 |
| 6312\ldots\ldots | [S\text{ii}] | \ldots | 10.5 | \ldots |
| 6364\ldots\ldots | [O i] | \ldots | \ldots | 11.9 |
| 6548\ldots\ldots | [N\text{ii}] | 14.1 | 174 | 201 | 62.2 |
| 6563\ldots\ldots | H\text{a} | 100 | 100 | 100 | 100 |
| 6583\ldots\ldots | [N\text{ii}] | 46.2 | 568 | 620 | 201 |
| 6717\ldots\ldots | [S\text{ii}] | 6.82 | 31.1 | 46.3 | 4.7 |
| 6731\ldots\ldots | [S\text{ii}] | 6.56 | 26.9 | 34.8 | 4.1 |

**Notes.**—Intensities are given relative to H\text{a} = 100, and have been dereddened using \(R = 3.1\) and the \(E(B - V)\) values listed in Table 3. Uncertainties in fainter lines are typically 10\%, but more for the faint lines in WeBo 1. Upper limits are given for [N\text{ii}] \(\lambda 5755\) in SBW 1 and SBW 2, while the value for WeBo 1 is a marginal \(\sim 2\sigma\) detection, which we regard as an approximate upper limit.
(1976), but the new CCD image presented here (Fig. 9) has greater sensitivity and was obtained in better seeing conditions with a narrow filter. The new image of SuWt 2 is discussed in § 5.

The ring nebula WeBo 1 was first reported by Bond et al. (2003), who discussed its morphology in images and the properties of the central star. It was discovered independently on 1999 October 6 during our narrowband imaging survey of nearby star-forming molecular clouds, seen on a wide-field narrowband Hα image obtained with the 1° field of view MOSAIC CCD camera mounted on the Kitt Peak 0.9 m telescope. This prompted us to obtain additional imaging and spectroscopy of WeBo 1.

A deep Hα image was obtained at the f/10 Nasmyth focus of the Apache Point Observatory near Sunspot, New Mexico, on 2001 September 25 using a 2048 × 2048 pixel CCD (SPICam) with a 40 Å passband Hα filter and a total exposure time of 1160 s. The CCD was binned 2 × 2 to provide a pixel scale of 0.22″.

This image is shown in Figure 10a. Low-dispersion (R = 500) spectra were then obtained on 2001 September 26 with the Dual-channel Imaging Spectrometer (DIS) at the 3.5 m telescope, using a 0.9″ slit width. The slit was oriented along the major axis of the ring as indicated in Figure 10a, and included the light of the two brightest stars located in the ring interior. The resulting spectrum of the northern portion of the ring is shown in Figure 10b. In addition, a high-resolution (R = 20,000) spectrum, shown in Figure 10c, was obtained on 2000 December 18 with the HIRES spectrometer on the Keck I telescope. The aperture traced the northern edge of the nebula with the slit aligned along the major axis of the ring.

Finally, we searched for J = 1–0 CO emission in a 10′ diameter box using the 16 beam SEQUOIA array at the 14 m diameter radio telescope at the Five College Radio Astronomy Observatory near Amherst, Massachusetts, on 2001 January 6. No emission was found at any velocity above an rms brightness temperature level of 0.3 K in 92 kHz wide channels.

3. RESULTS

3.1. Imaging and Spectroscopy of SBW1

3.1.1. Basic Morphology and Kinematics

SBW 1 appears as a distinct, almost perfectly smooth elliptical nebula with a well-defined outer edge in Figure 2a. With its bright central star it resembles a wide-open staring eye, lidless and wreathed in flame, probably deserving a nickname like the “Eye of Sauron” nebula; later in this paper we discuss its relation to the other rings. This ring is brightest at its southeastern and northwestern apaxes, due to limb-brightening, and the interior of the ring is partially filled-in with diffuse emission. Figure 3a shows an intensity tracing through the minor axis of the nebula, along with a model of the expected emission for a slice through a limb-brightened shell where the inner and outer radii listed in the figure give the best fit to the intensity of the edges of the nebula. Clearly it is plausible that additional emission fills its center—however, the kinematics of this nebula are unusual, as discussed below.

The outer limb-brightened edge of the equatorial ring allows us to measure its geometric parameters accurately. The major axis of the ring is 11.1′′ ± 0.1′′, while the minor axis is 7.1′′ ± 0.1′′. This yields an inclination of i = 50.2° ± 1° if the ring is circular. The polar axis (corresponding to the direction of the minor axis on the sky) lies at P.A. = 32.4° ± 1°. The intrinsic physical dimensions of the ring depend on the distance, which turns out to be somewhat surprising, as discussed in § 3.1.2.

Faint but visible in Figure 2a are a set of outer rings, another few arcseconds to the northeast and southwest. These remind one of the fainter outer rings around SN 1987A, although they do not have the same special magnificence, appearing very thin, like butter scraped over too much bread. They give the impression of limb-brightened edges of faint bipolar lobes above and below the equatorial plane defined by the brighter inclined ring. In fact, the image of SBW 1 in Figure 2a resembles the SN 1987A model image of Martin & Arnett (1995) more closely than SN 1987A itself does. This might lead one to suspect that the true geometry of SBW 1 is akin to that of the bipolar model of Martin & Arnett. An even more extended, and fainter third set of rings or polar lobes may be present as well—these are hard to see on the printed page because of the gray-scale levels in Figure 2a, but their emission can be seen at ±9′′ from the star in the intensity tracing along the polar axis of the nebula in Figure 3a. Deeper images may help reveal these putative outer rings, although they are nearly as faint as the fluctuations in the background nebula.

High-resolution spectra of SBW 1 in Figures 5 and 6 clearly show extended nebular Hα and [N II] emission lines. The detailed kinematic structure of the emission along the slit shown in Figure 6 is rather bizarre. The strongest emission at the position of the main ring is redshifted to the northeast, and blueshifted to the southwest. The faint emission that fills the ring’s interior in

![Figure 8](https://example.com/f8.png)
images follows the same general trend, but the detailed kinematic structure shows a triangular shape above and below the star in Figure 6. The emission does not converge on the star at the central position, as would be expected for a Hubble flow (homologous expansion), but instead meets the position of the star at ±12 km s\(^{-1}\). We offer no obvious explanation for this strange kinematic structure, except that it is marginally consistent with the interior of the ring being filled with a steadily outflowing flared disk. The cause of the triangular kinematic shape may be geometric, such that the motion of material was initially ejected or subsequently diverted out of the equatorial plane to form a flaring ring. In that case, the centroid of this emission at ±12 km s\(^{-1}\) implies a radial expansion speed for the ring and disk of roughly 19 ± 2 km s\(^{-1}\) when it is corrected for the inclination angle of 50.2°. This expansion speed is identical to the radial expansion speeds of the rings around the blue supergiants Sher 25 and HD 168625.

### 3.1.2. The Central Star and its Distance

Figure 8 shows the spectrum of the central star of SBW 1, which exhibits a spectral type of B1.5 lab. The luminosity class is not entirely clear, because higher dispersion (Fig. 5) shows that the Balmer absorption lines are partially filled-in with nebular emission. The extracted spectrum of the bright central star in Figure 5 shows some nebular emission rising above the continuum level in H\(_\alpha\) and double-peaked in the [N\(_{\text{ii}}\) ]\(\lambda6583\) line, superposed on a smooth continuum spectrum with prominent broad Balmer absorption. Despite the nebular contamination, a spectral type of B1.5 lab seems likely. The luminosity class has two important ramifications concerning implications for stellar evolution, as well as the distance to SBW 1.

First, it means that the central star is a massive star with an initial mass of roughly 18–25 \(M_\odot\), and the ring is therefore an example of a presupernova environment much like that around SN 1987A. The spectral type of B1.5 lab justifies a close companion to both Sher 25 (B1.5 Ia; Moffat 1983) and the progenitor of SN 1987A (B3 I; Walborn et al. 1989), as well as permitting a link to the B[e] supergiants because of the emission-line spectrum (see § 4.2).

Second, the high luminosity suggests a distance much larger than 2.3 kpc, meaning that it is seen through the Carina Nebula and is projected within its boundaries only by chance, as if it wants to be found there. The absolute visual magnitude of a B1.5 lab supergiant should be about -7.0 (Crowther et al. 2006), and the observed visual magnitude is roughly \(m_V\) = 12.7 (Table 1). If SBW 1 were located at 2.3 kpc in the Carina Nebula, the required total line-of-sight extinction would be very large at \(A_V\) ~ 7.9 mag. Such high extinction is plausible, at least in principle, since SBW 1 is seen along the same sight line as dense molecular gas and dust associated with the Carina Nebula (Zhang et al. 2001; Grabelsky et al. 1988; Smith et al. 2000). However, the 2MASS colors (\(J = 10.55, \ H = 10.18, \text{and} \ K = 9.95\)) suggest that the visual extinction is more like 3–5 mag, depending on the extinction law. This implies that the star appears faint for its luminosity class because it is actually at a much farther distance.

In fact, the observed radial velocity of SBW 1 also implies a much larger kinematic distance that places it in the far Carina arm. The systemic velocity in Figure 6 is redshifted from the centroid of nebular emission in Carina by roughly +30 km s\(^{-1}\). The heliocentric radial velocity of \(\eta\) Car and the Carina Nebula is \(-8.1\ \text{km s}\(^{-1}\) (Smith 2004), but that of SBW 1 is +22 ± 4 km s\(^{-1}\), or an LSR velocity of roughly 10 ± 4 km s\(^{-1}\). The Carina Nebula is seen near the tangent of the Sagittarius-Carina spiral arm (e.g., Bok 1959), and a positive radial velocity at its position places SBW 1 outside the solar circle on the far side of the Milky Way.

The corresponding distance at a longitude of \(l = 287°\) for a flat rotation curve is ~7 kpc.\(^{11}\)

This larger distance joins SBW 1 to a string of other famous hot supergiants with circumstellar nebulae in the far Carina arm, seen on either side of the Carina Nebula, such as Sher 25 in NGC 3603, AG Car, Hen 3-519, and HR Car. The massive cluster Westerlund 1 is also thought to be at a similar distance in part of the Galactic plane. SBW 1 is less conspicuous than these stars and its ring has not been discovered until now because of its much higher extinction column along its line of sight through dust and gas in the Carina Nebula, or perhaps simply because it is overshadowed by other spectacular objects in the brighter inner parts of the nebula. At 7 kpc, the required extinction for its apparent magnitude is roughly 5 mag. This is in much better agreement with the extinction implied by near-IR photometry as noted above. Also, the larger distance of 7 kpc means that the ring’s radius is about 0.19 pc—almost identical to the rings around SN 1987A and Sher 25. With a radial expansion speed of 19 km s\(^{-1}\), its dynamical age is ~10^4 yr. This age, too, is comparable to the rings around SN 1987A and Sher 25.

Its high luminosity and circumstellar ring make SBW 1 an object of considerable interest, and its similarity to the equatorial ring around SN 1987A hints at some things which have not yet come to pass. The central star deserves further observations and analysis, such as monitoring for photometric and spectroscopic variability (i.e., is it an eclipsing or spectroscopic binary?), as well as detailed atmospheric spectral analysis to accurately determine its physical parameters. This is important if SBW 1 is a potential supernova progenitor.

### 3.1.3. Size, Mass, and Chemical Abundances

Table 2 lists line intensities for SBW 1, corrected for a reddening value of \(E(B-V)\) = 1 that would correspond to our estimate of \(A_V\) ~ 5, adopting the value of \(R = 4.8\) that is appropriate for extinction in the direction of Carina (e.g., Smith 2002). From the red [S\(_{\text{ii}}\) ]\(\lambda6717,6731\) doublet, we measure an electron density of \(n_e\) = 513 cm\(^{-3}\), and from the ratio [N\(_{\text{ii}}\) ]\(\lambda6548+\lambda6583\)/5755 we find an upper limit to the electron temperature of \(T_e\) < 12,350 K. In the extracted EMMI spectrum of the nebula (Fig. 5b) we measure a [N\(_{\text{ii}}\) ]\(\lambda6583/\lambda5755\) intensity ratio of 0.483, which is within a few percent of the value we measure from RC Spec data. This would yield a N\(^+\)/H\(^+\) abundance of \(\geq 1.6 \times 10^{-5}\) for an upper limit of \(T_e\) < 12,350 K, or N\(^+\)/H\(^+\) ~ 2.7 \times 10^{-5} for a more likely temperature of \(T_e\) = 10,000 K. This is still lower than the solar abundance level; the nitrogen abundance would be roughly solar if the electron temperature were as low as 7000 K (note, however, that this is only the abundance of N\(^+\)). The electron temperature would need to be roughly 5000 K or less, or there would need to be a large neutral N fraction compared to hydrogen in order for this ratio to suggest a considerable N over-abundance in the ring. Therefore, our data are consistent with no significant N enrichment in the ring of SBW 1. This lack of distinct nitrogen enrichment implies that SBW 1 has not yet passed through an RSG phase, much like its twin Sher 25 (Smartt et al. 2002). Thus, in both these cases the equatorial rings must have

\(^{11}\) But we may yet be deceived. There is some hint in our [O\(_{\text{ii}}\)] images and long-slit spectra that the ring may be seen in silhouette against the background nebular emission. If true, this would mean that SBW 1 must be located within the Carina Nebula after all and that its radial velocity is anomalous, unless there is another H region projected behind Carina. Higher signal-to-noise ratio data of the same type or possibly UV spectroscopy of absorption-line profiles to the star may resolve this ambiguity. If SBW 1 is far beyond Carina, the far (receding) side of the H region should be seen in absorption. Thus, there are still questions that need answering.
been ejected when the stars were blue supergiants. This has important implications for the rings around SN 1987A (Smith 2007; Smith & Townsend 2007).

If the ring is fully ionized, we can estimate its mass from the electron density and its apparent geometry in images. If we approximate the geometry of the ring as a torus, then at a distance of 7 kpc, the ring’s radius is \( R \approx 0.19 \) pc or \( 5.9 \times 10^{17} \) cm, and the radius of its cross-sectional area is \( r \approx 5.3 \times 10^{16} \) cm (\( \sim 0.5^\circ \)). Then, assuming pure H gas, the ring’s mass would be

\[
M \approx 2\pi^2 r^2 M_{\odot} \frac{n_e}{c}. \tag{1}
\]

With \( n_e = 513 \text{ cm}^{-3} \) (Table 3), we find \( M \approx 0.014 M_{\odot} \). This is probably a lower limit to the total mass, however, because we have neglected any neutral fraction or dense clumps, and we have ignored the mass of the disk interior to the ring, which may be comparable to the ring itself. This mass is comparable to the range of masses inferred for the few hundred AU disks around B[e] supergiants (Zickgraf et al. 1986). The largest mass known in a B[e] star disk is about 0.3 \( M_{\odot} \) around R126 (Kastner et al. 2006). It is also comparable to the mass for the rings around RY Scuti (Smith et al. 2002b).

It would be interesting to measure the thermal-infrared flux from SBW 1, in order to measure its dust mass. Our long-slit spectra obtained with RC Spec hint that significant dust may be blocking light from the background nebula in some emission lines (the low signal-to-noise ratio and foreground emission preclude an accurate estimate of the dust mass, however).

### 3.2. Imaging and Spectroscopy of SBW 2

The structure of SBW 2 is far less orderly than SBW 1. It is much fainter, more diffuse and ratty-looking, less symmetric, and it lacks a clear outer edge. The most unnatural and curious property, however, is that there is no obvious bright star near its center. There are three faint stars inside the ring (with \( R \approx 18.5, 20.5, \) and 20.7 mag), as well as a few extremely faint stars that are scarcely detected in our Magellan image with \( R \) of about 26 to 27. However, none of these stars is at the ring’s center, and none stands out as an obvious candidate for a central star that may have ejected it. The sound crossing time of the ring is only a few tens of thousands of years. Any white dwarf at that young age should be several magnitudes brighter at visual wavelengths than these stars (e.g., Bergeron et al. 1995) if SBW 2 is within the Carina Nebula at 2.3 kpc. Thus, the central star in SBW 2 might avoid being seen if it were older, but to disappear entirely, that is a rare gift. Is the central object completely obscured by its own dust? Probably not, as we should see the outside of such an envelope ionized by whatever ionizes the rest of the ring. Perhaps the most likely—if unsatisfying—explanation is that a tight binary system was disrupted when one of the stars shed a large fraction of the system’s mass. The origin of the ring and its invisible star system has since passed out of all knowledge, but proper motions of stars in the surrounding field may be quite illuminating.

The purpose of the intensity tracing in Figure 3b is to illustrate that SBW 2 is not a limb-brightened spheroidal shell, but an actual flattened ring with a cleared interior. The intensity tracing through the minor axis of the nebula shows that the brightness in the middle of the ring drops to roughly zero. On the other hand, the dotted line in Figure 3b shows a model of the brightness distribution we would expect for a limb-brightened shell with a thickness corresponding to the apparent ring thickness in images. It is clear that the central region of the nebula would be more filled-in if it were a limb-brightened shell, unless the ring were much thinner than observed. Thus, the morphology of SBW 2 is that of a flattened equatorial ring with a hollow center, titled at an inclination angle of about 52°. The average radius of the ring is 19.8°, or 0.22 pc if it is in the Carina Nebula at 2.3 kpc. This makes its average radius only 10% larger than the equatorial ring around SN 1987A (the inner and outer radii of SBW 2 are roughly 0.16 and 0.25 pc, respectively).

Another unusual or unexpected property of SBW2 is that the brightest parts of the ring are not at the southeastern and northwestern tangent points along the major axis, as would be expected from limb-brightening in an optically thin ring like SBW 1. In fact, the brightness distribution is the opposite—the brightest parts of SBW 2 are the near and far sides along the minor axis. This points to a high degree of azimuthal asymmetry in the system, perhaps implying that an eccentric binary system played a role in shaping the ejecta.

Although SBW 2 is projected within the boundaries of the star-forming Carina Nebula, it is unlikely that this is a normal pre-main-sequence circumstellar envelope. In our experience, no pre-main-sequence stars or protostars are surrounded by circumstellar disks that look anything like SBW 2. They either have a bright central star with a bipolar reflection nebula or jets, or if the central star is obscured, it is because it is seen behind a dark, edge-on obscuring lane like in HH 30 (Burrows et al. 1996; Stapelfeldt et al. 1999), HK Tau (Stapelfeldt et al. 1998), HV Tau C (Stapelfeldt et al. 2003), and several other reflection nebulae in Taurus and Orion (Padgett et al. 1999). This is clearly not the case here. In some situations such as debris disks around Vega-like stars, images of the circumstellar disks may resemble SBW 2, but they all have bright central stars that overwhelm the nebula in optical images (e.g., Schneider et al. 1999; Fukagawa et al. 2004; Greaves et al. 1998).

This speculation is borne out when we consider the spectrum of SBW 2, and the chemical abundances it implies. The spectrum is shown in Figure 7b, with line intensities listed in Table 2. The strong [N ii]\, lines relative to H\,\alpha immediately raise suspicion that the gas is nitrogen rich. (It also means that our H\,\alpha image in Fig. 2b is actually a [N ii] image.) With \( n_e \approx 280 \text{ cm}^{-3} \) and an upper limit of \( T_e < 14,900 \text{ K} \) (Table 3), we find a lower limit of \( n(\text{N}^+)/n(\text{H}^+) > 1.3 \times 10^{-4} \), or about 1.5 times the solar abundance of N. For a more likely temperature of \( T_e \approx 10,000 \text{ K} \), the nitrogen abundance would be \( \sim 4 \) times solar, and this is only for N\,\text{ii}. Thus, the gas in SBW 2 is clearly nitrogen-rich, and it is therefore the result of post-main-sequence mass loss, probably from an intermediate-mass progenitor star. Since the Carina Nebula H\,\alpha region is only about 3 Myr old, this object must be an interloper, passing through the nebula instead of having been born there. The lack of any ionizing source within the ring argues strongly that it is within the Carina Nebula, and not just projected along the same sight line, like SBW 1.

The emitting layer thickness of the ring seems to be roughly \( l \approx 2 \times 10^{17} \) cm (corresponding to a projected width of \( \sim 5^\circ \); see Fig. 2b). With a density of \( n_e = 280 \text{ cm}^{-3} \) indicated by the [S ii] lines (Table 3), it requires an incident flux of ionizing photons of \( \phi_0 \approx 10^4 \text{ s}^{-1} \text{ cm}^{-2} \) in order to be fully ionized (\( \chi = 2.6 \times 10^{-13} \text{ cm}^{-2} \) is the case B recombination coefficient). At a projected radius of 70° or \( \sim 45 \) pc from the central ionizing clusters of the Carina Nebula, the ambient Lyman continuum flux near SBW 2 would be roughly \( \phi_0 / (4\pi d^2) \approx 10^4 \text{ s}^{-1} \text{ cm}^{-2} \) as well (Smith 2006). Thus, the star clusters of the Carina Nebula supply sufficient radiation to keep SBW 2 fully ionized. This argues that SBW 2 is, in fact, located within the Carina Nebula itself and not just projected along the same sight line by chance. If our assumption that SBW 2 is fully ionized is incorrect, and that only its...
outer surface is ionized, then the required ionizing flux goes down. While the nebula is ionized, it lacks detectable \([\text{O III}]\) emission in our images (not shown).

Assuming that SBW 2 is fully ionized, we can provide a lower limit to its mass using the same technique as we did for SBW 1. Using equation (1), but with \(r = 1.7 \times 10^{17} \text{ cm} \) (4.9") and \(R = 6.6 \times 10^{17} \text{ cm} \) (0.22 pc) from Figure 2b, and \(n_e = 280 \text{ cm}^{-3}\) from Table 3, we find a total mass of \(\sim 0.1 \, M_\odot\) of ionized gas.

3.3. Imaging and Spectroscopy of SuWt 2

This exotic ring nebula is shown in Figure 9a, which is an \(H\alpha+[\text{N II}]\) image obtained with the MOSAIC2 camera on the CTIO 4 m telescope. This image shows considerably more detail than the discovery plates (Schuster & West 1976). From the image in Figure 9a we measure an inclination angle of 64" (±2"), and from Figure 9b we find an average radius of 40.5" or about 0.2 pc at a distance of 1 kpc, making it yet another ring with roughly the same radius as that of SN 1987A’s ring. As was the case for SBW 2, an intensity tracing across SuWt 2 (Fig. 9b) shows that it is not a limb-brightened ellipsoidal shell, but instead is an actual flattened equatorial ring. A shell model would require substantially more flux in the center of the nebula than is seen in this image. Rather than being partially filled-in, SuWt 2 has faint excess flux outside the ring, suggesting that the ring may be the inner edge of a swept-up disk. The central star of SuWt 2 has been found to be a 4.91 day eclipsing binary composed of two A-type stars of roughly 2.5 \(M_\odot\) each (Bond 2000; Bond et al. 2002), where the inclination is in rough agreement with our estimate of the inclination of the ring nebula.

Figure 7c shows the red spectrum of the ring nebula, and Table 2 lists measured line intensities corrected for \(E(B-V) = 0.25\). We do not have a reliable estimate of \(E(B-V)\) for SuWt 2, but this reddening value is roughly what is needed to make the observed stellar colors consistent with an A-type photosphere. The strong nitrogen lines indicate that the \(H\alpha+[\text{N II}]\) image is dominated by \([\text{N II}]\) \(\lambda 6583\) emission, and hint at an enhanced N abundance. With \(n_e \approx 100 \text{ cm}^{-3}\) (the observed \([\text{S II}]\) lines are close to the low-density limit) and \(T_e = 11,400 \text{ K}\) from the \([\text{N II}]\) line ratio, the observed \([\text{N II}]\) \(\lambda 6583/H\alpha\) ratio indicates \(n(N^+)/n(H^+) \approx 2.5 \times 10^{-4}\), or almost 3 times the solar abundance of N. Again, this is only for \(N^+\), so the true N abundance could be higher. The presence of nitrogen-rich ejecta confirms that SuWt 2 is a post-main-sequence object, and suggests that it had an intermediate-mass progenitor star. This is curious, given that the central star system of SuWt 2 is observed to be an eclipsing binary of two A-type main-sequence stars.

Except for their central stars, SuWt 2 and SBW 2 are near twins. Again, we find that the ionization of this ring is rather suspicious. Ionized gas in the ring nebula requires a stronger flux of ionizing photons than can be supplied by two A-type stars. Bond et al. (2002) hypothesized that there may be a third star in the system—probably an unseen white dwarf—to account for the necessary UV flux. However, this white dwarf would need to be in a wide orbit, detached from the A+A eclipsing binary, and would therefore not be able to strongly affect the shape of the ring.

However, here we note a speculative alternative. Figure 9 also shows a bright star about 1’ east-northeast of SuWt 2. This is the B2 star SAO 241302. It could supply the required ionizing photons if the two are at the same distance, following the same reasoning as above for SBW 2 in Carina. This may seem at first to be rather fortuitous. However, we note that the \(H\alpha\) image of SuWt 2’s ring in Figure 9 shows an asymmetric brightness distribution. In particular, the ring is brighter on the east-northeast side—exactly on the side facing the bright B star. Thus, much like SBW 2 in Carina and possibly also Sher 25, the nebula may be \textit{externally illuminated} by a nearby hotter star. This possibility requires further investigation.

3.4. Imaging and Spectroscopy of WeBo 1

This ring-shaped planetary nebula is located near the star-forming region W4 in the Perseus arm of our Galaxy, about 5’ southwest of the X-ray binary LS I +61 303 (WeBo 1 was discovered serendipitously while studying this source; Bond et al. 2003). It surrounds a barium star and suspected white dwarf that may be the source of ionizing photons for the nebula. Bond et al. (2003) proposed that the equatorial ring was ejected during the tidally locked asymptotic giant branch (AGB) phase of the more massive star in the binary before it became a white dwarf.
and that some of the AGB wind was accreted onto the companion star that is seen today as a rapidly-rotating barium star. Thus, while the star shows no eclipses or orbital reflex motion that have been detected yet, the atmospheric chemical abundances give a strong indication that close binary evolution played a role in the axisymmetric mass loss.

3.4.1. New Results

Figure 10a shows an Hα image of the ring obtained with the ARC 3.5 m reflector. The ring has a sharp inner edge with a radius of about 25". As noted already by Bond et al. (2003), the lack of emission in the ring’s interior means that it is a toroid and not a limb-brightened ellipsoidal shell. The major to minor axis ratio of 3.85 implies that the ring is close to edge-on with an axis of symmetry inclined by 75° ± 3° with respect to the line of sight. In contrast to the sharp inner boundary, the outer edge of the ring is diffuse, much like SBW 2 and SuWt 2.

The line intensities in Table 2 are measured from the spectra in Figures 10b and 10c. The higher resolution Keck spectrum was used for the relative intensities of [N II] λ6548 and λ6583 because they were better separated from Hα than in the lower resolution DIS spectrum. The observed line intensities have been corrected for $E(B - V) = 0.57$ (Bond et al. 2003). Table 3 lists the electron density, electron temperature, and N$^+$/H abundance calculated from these ratios. The red [S II] lines are unusually weak in the spectrum, and unfortunately, the corresponding larger uncertainty in their intensities introduces a factor of $\sim 2$ uncertainty in the electron density. The critical [N II] λ5755 line is also very weak, with a marginal 2 $\sigma$ detection that we regard as an upper limit. This indicates an upper limit to the electron temperature of $\lesssim 10^4$ K, which seems reasonable enough. From these values and the strength of [N II] λ6583, we find a N$^+$/H$^+$ $\lesssim 10^{-4}$, indicating that the nebular gas is strongly enhanced in nitrogen, well above the solar value. This points toward an intermediate-mass AGB progenitor star, just as in the case of SBW 2 and SuWt 2.

Interestingly, we see weak emission from He i λ5876 and [Ar III] λ7136 in the spectrum. These high-ionization lines cannot be caused by radiation from the cool central star that dominates the visual spectrum, requiring either a hot white dwarf or an external source of ionization. We note that WeBo 1 is found in the outskirts of the giant H ii region W4, and is near the famous microquasar and radio-emitting X-ray binary LS I +61 303. This proximity is intriguing, although the morphology in the [O III] image presented by Bond et al. (2003) seems to suggest a centrally located ionizing source.

4. DISCUSSION

4.1. Comparison with Other Rings

**SN 1987A:** Probably the most famous equatorial ring associated with post-main-sequence evolution is the remarkable equatorial ring around SN 1987A. It was discovered shortly after being flash-ionized by the supernova, and eventually became the subject of intense study with *HST* (Crotts et al. 1989; Lundqvist & Fransson 1991; Jakobsen et al. 1991; Plait et al. 1995; Burrows et al. 1995; and others). Now is a particularly interesting time for study of SN 1987A, as the supernova blast wave is overtaking the circumstellar ring and causing a host of phenomena that are of great interest to shock evolution (Luo & McCray 1991; Chevalier & Dwarkadas 1995; Borkowski et al. 1997; Michael et al. 2000; Pun et al. 2002; Smith et al. 2005b). The appearance of a number of hot spots around the ring (Sonneborn et al. 1998; Michael et al. 2000; Pun et al. 2002; Sugerman et al. 2002) make it look like a pearl necklace. These spots show that while the ring appeared fairly smooth in images before it was struck by the shock, it had actually been shaped by Rayleigh-Taylor instabilities (Michael et al. 2000). The nebula around SN 1987A is usually assumed to have been ejected during a previous RSG phase and then swept-up by a blue supergiant wind. The ring itself is thought to be a swept-up thin disk that formed in the RSG wind as a consequence of close binary activity—possibly even a merger (Blondin & Lundqvist 1993; Martin & Arnett 1995; Morris & Podsadlowski 2006; Collins et al. 1999). However, the larger outer rings that compose the triple-ring system around SN 1987A still seem to defy explanation. Soker (2002) hypothesizes that these rings formed from precessing jets, while Morris & Podsadlowski...
(2006) suggest that they are a natural consequence of a binary merger event. In any case, they are bona fide rings and not just limb-brightened edges of an hourglass (Burrows et al. 1995). Interestingly, our image of SBW 1 in Carina looks more like one of these hourglass nebula simulations intended for SN 1987A (see, e.g., Fig. 5 in Martin & Arnett 1995).

**Sher 25:** The nebula around this B1.5 supergiant in NGC 3603 (Sher 1965; Moffat 1983) is often held up as the Milky Way’s “twin” of SN 1987A’s progenitor. Sher 25 has an equatorial ring that is reminiscent of the one around SN 1987A (Brandner et al. 1997). However, Sher 25 is more luminous than Sk 69 202. With log \( (L/L_\odot) = 5.9 \) (Smartt et al. 2002), Sher 25 is probably too luminous to have gone through an RSG phase. In fact, Smartt et al. find that the observed N/O abundance is incompatible with Sher 25 having been an RSG, and that the nebula was probably ejected as a blue supergiant. Furthermore, the spectrum of Sher 25 does not show the broad lines we would expect from an extremely rapid rotator that should be the product of a merger event (e.g., Morris & Podsiadlowski 2006). Thus, the similarity of its nebula to that around SN 1987A may pose some difficulties for the RSG/merger scenario for the shaping of SN 1987A’s nebula. Our new discovery of SBW 1 provides yet another twin of Sher 25 and SN 1987A. SBW 1 has the same radius as the rings around Sher 25 and SN 1987A, and the central star is also a B1.5 supergiant (although it is less luminous than Sher 25, with a luminosity class of Iab instead of Ia). It also lacks the strong N-enrichment required for post-RSG evolution.

**HD 168625:** The equatorial ring around this LBV candidate was discovered by Hutsemékers et al. (1994), and has been studied by several authors since then. In a recent study (Smith 2007) we discovered rings in a larger bipolar nebula seen in Spitzer images, making the nebula the nearest Galactic analog of the triple-ring system around SN 1987A. The detection of an analog to SN 1987A’s nebula around an LBV is significant, because it provides a precedent that massive stars can eject rings+bipolar nebulae in LBV outbursts as blue supergiants rather than as RSGs. Elsewhere (Smith 2007) we have discussed this object in more detail, along with strong implications for the progenitor of SN 1987A.

**RY Sct:** This is a massive 11 day eclipsing binary system in a state of overcontact (Milano et al. 1981), probably a WR+OB progenitor. Its unusual circumstellar nebula was first spatially resolved as a limb-brightened dust torus in the thermal-IR, where the compact torus had an apparent radius of only 1" (Gehrz et al. 1995, 2001). The inner wall of this dust torus is ionized by the hot central stars, giving rise to strong radio continuum emission (Hjellming et al. 1973) and a peculiar, high-excitation emission-line spectrum (Merrill 1928; Smith et al. 2002b). The morphology of this ionized component of the nebula is remarkable—in high-resolution HST images it appears to be a pair of plane-parallel thin rings on either side of the equatorial plane (Smith et al. 1999). Proper motions indicate that the rings were ejected recently during an event sometime in the 19th century (Smith et al. 2001). The rings have radial expansion speeds of a little more than 40 km s\(^{-1}\) (Smith et al. 2002b). These ionized double rings have half the radius of the larger dust torus, only 0.5" or 900 AU at that distance. The inclination angle of the rings agrees to within a few degrees with the inclination angle of the orbit derived from the eclipsing light curve (Smith et al. 2002b; Milano et al. 1981), providing strong empirical evidence that the nebula and binary system share the same equatorial plane, and that close binary evolution plays an important role in shaping the nebula. RY Sct is one of our best cases of a massive star caught in the act of shedding mass and angular momentum through its outer Lagrange point, probably an important step on its way toward becoming a colliding-wind WR+OB binary system. It argues strongly that equatorial rings can be the consequence of close binary evolution.

**He 2-147:** This equatorial ring nebula surrounds a binary system that is a symbiotic Mira. It was probably ejected in a symbiotic nova event about 300 yr ago, and currently shows a planetary nebula-like spectrum in the blue, and a cool supergiant spectrum in the red (Corradi et al. 1999, 2000). It is a close relative of bipolar symbiotic planetary nebulae like He 2-104.

Other clear examples of equatorial rings that are not as well studied as the above are SuWt 3, Abe 14, M1-41, Abe 47, and Lo 18 (see Schwarz et al. 1992). SuWt 3 (Schuster & West 1976) is a remarkably clean, thin ring nebula that looks like a perfect ellipse, with \( i \approx 58\degree \) and \( R = 28\arcsec \). The distance to SuWt 3 is not known, but \( R = 0.14 \, \text{pc} \times D_{\text{kpc}} \) makes it comparable to the other rings if the distance is around 1 kpc. Another intriguing object that deserves further study is the planetary nebula Abe 14 (Schwarz et al. 1992). It shows what seems to be a pair of plane-parallel rings above and below the equatorial plane, plus an outer torus component to the nebula (see Manchado et al. 1996). The appearance of the nebula is very similar to the unusual double-ring nebula around RY Sct (see above). Finally, there are still many more bipolar nebulae with less well-defined equatorial tori or rings at their waists, like \( \eta \) Car, He 2-104, NGC 2346, NGC 7027, MyCn 18, and Abel 55.

### 4.2. Rings around B Supergiants and a Link to the B[e] Supergiants

B[e] supergiants are luminous post-main-sequence stars that are characterized by IR-excess emission from dust and prominent emission-line spectra, including the Balmer emission lines plus numerous lines of permitted and forbidden Fe\(^+\) and other species (Zickgraf et al. 2003; Miroshnichenko et al. 2002). This emission is thought to arise in an outflowing circumstellar disk within a few hundred AU of the star (e.g., Zickgraf et al. 1986). Like the lower luminosity Be stars, B[e] supergiants are thought to be rapid rotators.

B[e] supergiants have high luminosities, and occupy a similar area in the H-R diagram as some of the less massive LBVs. However, unlike the LBVs, B[e] supergiants typically do not exhibit marked photometric or spectroscopic variability. Perhaps they are an earlier phase immediately before the LBVs, where the star still has sufficient mass to insulate it from the near-Eddington LBV instability. There are some deviations from this trend, however, hinting that B[e] supergiants and LBVs may be related after all: R4 in the SMC is a B[e] supergiant that exhibits variability characteristic of the LBVs (Zickgraf et al. 1996). Interestingly, R4 is very close to HD 168625, SBW 1, and the progenitor of SN 1987A on the H-R diagram, with a presumed initial mass of \( \sim 20 \, M_\odot \) (Zickgraf et al. 1996). These similarities taken together with the equatorial ring geometry suggest a plausible connection between B[e] stars and more extended rings. Also, R4 demonstrates that even relatively low luminosity blue supergiants (low luminosity, at least, compared to extreme LBVs like \( \eta \) Car) can be susceptible to instabilities that cause sporadic outbursts. If a significant IR excess from dust were detected in SBW 1, it would support this connection because the B[e] star disks also contain dust.

We therefore propose a direct link between B[e] supergiants and the class of massive, early B supergiants surrounded by spatially resolved ring nebulae (including SN 1987A, SBW 1, Sher 25, and HD 168625). Specifically, we suspect that the outflowing disks in B[e] stars that emit their IR excess and bright-line spectra will continue to expand, and after a few thousand years will form spatially resolvable equatorial rings at \( \sim 10^3 \) AU from the stars. This
would be analogous to the disk clearing that is thought to occur in lower luminosity Be stars (e.g., Meilland et al. 2006). This link, in turn, would suggest that in the massive rings in our sample, rapid rotation rather than close binary evolution may shape their ejecta. Both Sher 25 and HD 168625 have been studied, and no evidence for binarity has yet been reported, although renewed efforts would be of great interest. SBW 1 should also be monitored to search for eclipses or radial velocity variations. Both Sher 25 and SBW 1 are luminous hot supergiants that probably have not gone through a RSG phase, as noted earlier, while HD 168625 is an LBV candidate. Thus, the most plausible scenario for the formation of their rings is ejection by a rapidly rotating star in an LBV eruption or some related episodic mass loss as blue supergiants (see Smith 2007; Smith & Townsend 2007). In this context, the fact that their nebulae are near twins of SN 1987A is quite suggestive.

It is worth pointing out that the presence of discrete rings—as opposed to smooth thin disks—is evidence for recent temporal variability of the central star in each object, regardless of the specific interpretation for their formation. The presence of a ring requires either (1) a brief ejection episode as a blue supergiant, \( B[e] \) star, or LBV, where \( M^{\prime} \) increased drastically for a short time, or (2) the initial formation of a thin disk over a long timescale, which is then swept up into a ring following a sharp increase in the speed of the stellar wind. Both these mechanisms would require that the ejection of rings is a consequence of late stages of stellar evolution, rather than normal main-sequence evolution.

In the context of linking spatially resolved rings to \( B[e] \) supergiants, \( RY \) Sct (Smith et al. 2002b) is perhaps one of the most interesting objects available for detailed study. It has a toroidal nebula, it shares many spectroscopic properties in common with the \( B[e] \) supergiants (Men’shchikov & Miroshnichenko 2005; Allen & Swings 1976; Smith et al. 1999), and it is an eclipsing binary in a state of overcontact that is known to be shedding mass and angular momentum. Its rings have a radius of 1000–2000 AU—between the expected radii of emitting circumstellar material around \( B[e] \) stars (a few to several hundred AU) and most of the spatially resolved rings discussed here at radii of a few \( \times 10^4 \) AU. The dust mass and IR excess of \( RY \) Sct are similar to the \( B[e] \) supergiants, although the grains are at a lower temperature around \( RY \) Sct because they are farther from the star. The \( \sim 40 \) km s\(^{-1}\) expansion speed of its rings (Smith et al. 2002b) is typical of the narrow-line regions around \( B[e] \) stars (Zickgraf et al. 1986), but faster than the speeds of the more extended rings discussed in this paper, which have presumably decelerated. Thus, \( RY \) Sct may represent a very short-lived “missing link” between the \( B[e] \) supergiants and the early \( B \) supergiants surrounded by rings.

### 4.3. The Role of Binarity

The sample of objects in Table 4 may yield interesting clues to the role of close binary interactions in the formation mechanism of circumstellar rings. Six of the nine objects are known to be or suspected to be close interacting binaries. \( RY \) Sct, SuWt 2, and He 2-147 are definite eclipsing binaries, while the central star of \( SBW \) 1 is a barium star that probably resulted from mass transfer in a Roche lobe overflow (RLOF) phase (Bond et al. 2003). The remaining two suspected binaries are somewhat unusual cases: SN 1987A is thought to have undergone a binary merger event when the ring was ejected, as noted in § 1 (although there may be problems with the merger interpretation; Smith 2007; Smith & Townsend 2007). The invisible central star in the \( SBW \) 2 ring probably requires that a central binary system was disrupted and that the stars were ejected from the system, as discussed earlier in § 3.2. Taken together, this collection of objects strongly suggests that mass loss through the outer Lagrangian point in a common-envelope/RLOF phase of close binary evolution is a preferred avenue for the forging of rings, at least for intermediate-mass systems. There are good reasons why more luminous massive stars can produce rings without close binary influence (Smith & Townsend 2007). \( RY \) Sct is a key object in this regard, as it is currently caught in this brief but important RLOF phase, and it is the only confirmed binary among the supergiants with rings. In a scenario in which a massive star has a companion close enough and massive enough to shape its ejecta, it would be difficult for that companion to escape detection.

Forging of such rings through close binary interaction may be relevant for the formation of bipolar planetary nebulae if a fast wind expands into such an environment with a strong equatorial density enhancement. Some of the most tightly pinched waists among bipolar planetary nebulae are seen in so-called symbiotic PNe, and several of these are strongly suspected to be binaries (e.g., M2–9 [Doyle et al. 2000], Mz 3 [Smith 2003], and Hb 12 [Hsia et al. 2006]). However, several of the objects we discuss here are equatorial rings that are suspected to be present before the planetary nebula phase, and are only seen in rare circumstances as discussed next.

### 4.4. A Secret That Only Fire Can Tell: Are Equatorial Rings Commonplace?

Two-thirds of the objects in Table 4 (the two new objects discovered here, plus SN 1987A, Sher 25, HD 168625, and \( SBW \) 1) are seen projected in or near giant \( H \) regions—environments that may provide a copious external source of UV photons (admittedly,
the nebula of SN 1987A was flash ionized by the supernova event itself. RY Sct has a sufficiently hot and luminous star to provide its own UV illumination. SBW 2 in Carina has no bright central star, but we have shown earlier that the hot stars that power the Carina Nebula can supply sufficient ionizing photons. SuWt 2, with two A-type stars, may have a similar problem, with a nearby early B star providing a similar solution. WeBo 1 is near W4 and the X-ray binary LS I +61 303. This raises the question of whether such rings around post-main-sequence stars might be fairly common, but go unseen where there is a lack of favorable external illumination. Such precious rings may be the long-sought-after donuts (e.g., Frank et al. 1998) needed for the interacting winds scenario of bipolar planetary nebula formation. Even if external ionization is not critical in making these rings visible, the fact that most of them are seen in close proximity to H II regions certainly increases their chances for serendipitous discovery.

This suggests that there may be many more rings of similar size and morphology surrounding post-main-sequence intermediate-mass stars throughout the Galaxy, but they go undetected either because they are not illuminated or because most of the Galactic plane has not been surveyed with deep narrowband imaging as intensively as star-forming regions have been. Excluding the more massive stars in our sample, which may supply their own ionization and are probably found preferentially near H II regions anyway, we can make an order of magnitude extrapolation. H II regions occupy only 0.1%–1% of the volume of the galactic disk, so there may be several hundred to a few thousand more dark rings in the Galaxy, comparable to the known number of planetary nebulae. This estimate is probably conservative, since not all galactic H II regions have been surveyed in detail. Thus, it is at least plausible that such a population of undetected rings could exist, and that these could play a role in binding the waists of bipolar planetary nebulae. Thus, such rings may partly answer the question “where’s the donut” posed by Frank et al. (1998).

5. SUMMARY

5.1. SBW 1 in Context

The discovery of the ring in SBW 1 is the most interesting result of this study, because it adds to the small number of such rings known around blue supergiants that are likely supernova progenitors. In particular, the radius and morphology of the ring in SBW 1 make it nearly identical to the equatorial ring around SN 1987A, and the luminosity and spectral type of the central star are almost identical to the RSG. SBW 2 is near W4 and the X-ray binary LS I +61 303. This raises the question of whether such rings around post-main-sequence stars might be fairly common, but go unseen where there is a lack of favorable external illumination. Such precious rings may be the long-sought-after donuts (e.g., Frank et al. 1998) needed for the interacting winds scenario of bipolar planetary nebula formation. Even if external ionization is not critical in making these rings visible, the fact that most of them are seen in close proximity to H II regions certainly increases their chances for serendipitous discovery.

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We thank Steve Lawrence for kindly obtaining the blue spectrum of SBW 1 for us, and Nolan Walborn for advice on its spectral type. We also thank Jon Morse for assistance on the Magellan observing run and Bo Reipurth for assistance with the Keck run. Partial support for N. S. was provided by NASA through grant HF-01166.01A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Additional support was provided by NSF grant AST-98-19820 and NASA grants NCC2-1052 and NAG-12279 to the University of Colorado.

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5.2. SBW 2 in Context

In all respects, except for the troublesome fact that its central star is missing, SBW 2 is a carbon copy of SuWt 2 and WeBo 1. These rings are associated with intermediate-mass (2–8 $M_\odot$) close binary stars. Their rings appear thicker and more diffuse, with inner edges that are sharper than their outer limits, as compared to the more elegant equatorial rings around the blue supergiant stars. Their radii around 0.2 pc are oddly similar to those surrounding the more massive stars. They all seem to be nitrogen-rich, with [N II] /6583 much brighter than Hα. All seem to lack a suitable source of ionizing photons, unless a hot white dwarf has gone undetected in each system. We have suggested that the lack of any bright central star in SBW 2 may indicate that a binary system has been disrupted, which would be quite extraordinary, while the remaining rings in the intermediate-mass class all seem to be close binaries. Thus, in contrast to the massive stars with rings, at low/intermediate mass it seems more likely that close binary evolution rather than rapid rotation of single stars governs the forging of these rings. If they are detected only in these few cases because of selection effects or favorable ionization, such rings may be numerous in the Galaxy. As such, they could provide the preexisting equatorial density enhancements needed to form bipolar nebulae through the interacting winds scenario.
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Note added in proof.—After making a preprint of this article publicly available, we were informed that our object SBW 2 also appeared previously in a catalog of planetary nebulae as PHR 1036–5909 (Q. A. Parker et al., MNRAS, 373, 79 [2006]).