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CORONOGRAPHIC IMAGING OF THE BIPOLAR NEBULA AROUND THE LUMINOUS BLUE VARIABLE R127

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ABSTRACT

New images of the nebula surrounding the luminous blue variable (LBV) R127 have been obtained with the Johns Hopkins Adaptive Optics Coronograph. These images reveal, for the first time, the detailed morphology of the nebula and show it to be highly asymmetric with large variations in surface brightness. The nebula has linear dimensions of 1.9 × 2.2 pc, assuming a distance to the LMC of 51.2 kpc. The nebular mass, calculated from the integrated Hα flux, is 3.1 $M_\odot$, which is similar to that of the AG Carinae nebula. The coronographic images of the R127 nebula support a recent model of R127 which suggests that an equatorial circumstellar disk is responsible for the observed polarimetric and spectroscopic properties of the star (Schulte-Ladbeck et al. 1993). The images also suggest an evolutionary link between the mechanism responsible for the mass-loss episode which created the nebula and the current mass-loss properties of the system.

Subject headings: stars: circumstellar matter — stars: individual (R127) — stars: mass loss

1. INTRODUCTION

R127 (HDE 269858) in the Large Magellanic Cloud (LMC) was first identified as an emission line star by Henize (1955). Walborn (1977) reported that the spectrum of R127 exhibited features characteristic of both OIafe and WN-type stars, namely high-excitation He II and N III emission, low-excitation N II emission, and narrow S IV and N III absorption. Subsequently, Walborn (1982) classified R127 as an Ofpe/WN 9 star based upon observations which also showed velocity-doubled nebular emission lines indicative of a nonspherical shell expanding with a velocity of ~ 30 km s^{-1}.

R127 was determined to be a luminous blue variable (LBV) as a result of detailed multiwavelength studies by Stahl et al. (1983), which were prompted by an increase in brightness in 1982. R127 continued to brighten throughout the last decade, reaching $V = 8.74$ in 1990 (Wolf 1992). During this time, R127 was reported to have evolved spectrally from an O-type to a B-type star (Stahl et al. 1983; Wolf & Stahl 1986), and then to an A-type star (Wolf 1992). Similar spectral evolution had been noted for other LBVs which had been observed during their brightening phases [e.g., AG Carinae (Caputo & Viotti 1970), S Doradus (Leitherer et al. 1985; Wolf et al. 1989), and R71 (Wolf et al. 1981)]. Despite these brightness and spectral variations, the bolometric luminosity of R127 has remained constant ($M_{\rm bol} \sim -10.3$; Wolf 1989), an unambiguous characteristic of LBVs (Wolf et al. 1981). Recent photometry indicates that R127 has now passed maximum brightness (Wolf 1992; Bateson 1991).

LBVs are believed to be evolved stars lying close to the Humphreys-Davidson instability limit (Humphreys & Davidson 1979) and undergoing rapid and unsteady mass loss. Theoretical evolutionary tracks (Maeder 1989) suggest that massive O stars evolve into LBVs and, subsequently, into W-R stars when they have lost sufficient mass and only their bare helium cores remain. Both R127 and AG Carinae (Stahl 1986) have displayed intermediate Ofpe/WN9 spectral characteristics during their quiescent phases, which considerably strengthen the arguments for such a scenario.

Previous episodes of mass loss from LBVs are often evidenced by circumstellar nebulae, as has been observed around η Carinae (Burgarella & Paresce 1990) and AG Carinae (Nota et al. 1992). Detailed studies of the nebulae provide valuable information on the mass-loss history of the stars and constrain models of the ejection mechanism. In most extragalactic cases, however, evidence for such nebulae is based on the detection of extended emission lines, since direct imaging is made difficult by the extreme brightness of the stars relative to the nebulae. R127, along with some other Ofpe/WN9 stars, exhibits strong, extended nebular emission lines which suggest the presence of an expanding circumstellar shell (Walborn 1982; Stahl & Wolf 1986). Stahl (1987) reported an enhancement of the stellar seeing disk in the region 2″–4″ from the star in his narrow-band [N II] images, thereby supporting the presence of an extended nebula.

In this *Letter*, we describe recent images of the R127 nebula obtained with the Johns Hopkins Adaptive Optics Coronograph (AOC). The combination of a stellar coronograph and adaptive optics achieves both the image contrast necessary to observe the low surface brightness nebula and the angular resolution required to resolve its structure.

2. OBSERVATIONS AND DATA REDUCTION

The observations of R127 were conducted with the AOC on UT 1991 December 27 at the 2.5 m DuPont telescope at Las Campanas Observatory, Chile. The AOC employs an image motion compensation system which improves the angular resolution of the observation (Clampin et al. 1991; Golimowski et al. 1992). In this system, the light from the occulted R127 was reflected by the occulting mask onto a quadrant-CCD (Clampin et al. 1990), which was used to monitor the changes in the image position due to atmospherically induced wavefront tilt and residual telescope guiding errors. A tip/tilt mirror operating at 100 Hz compensated for the measured

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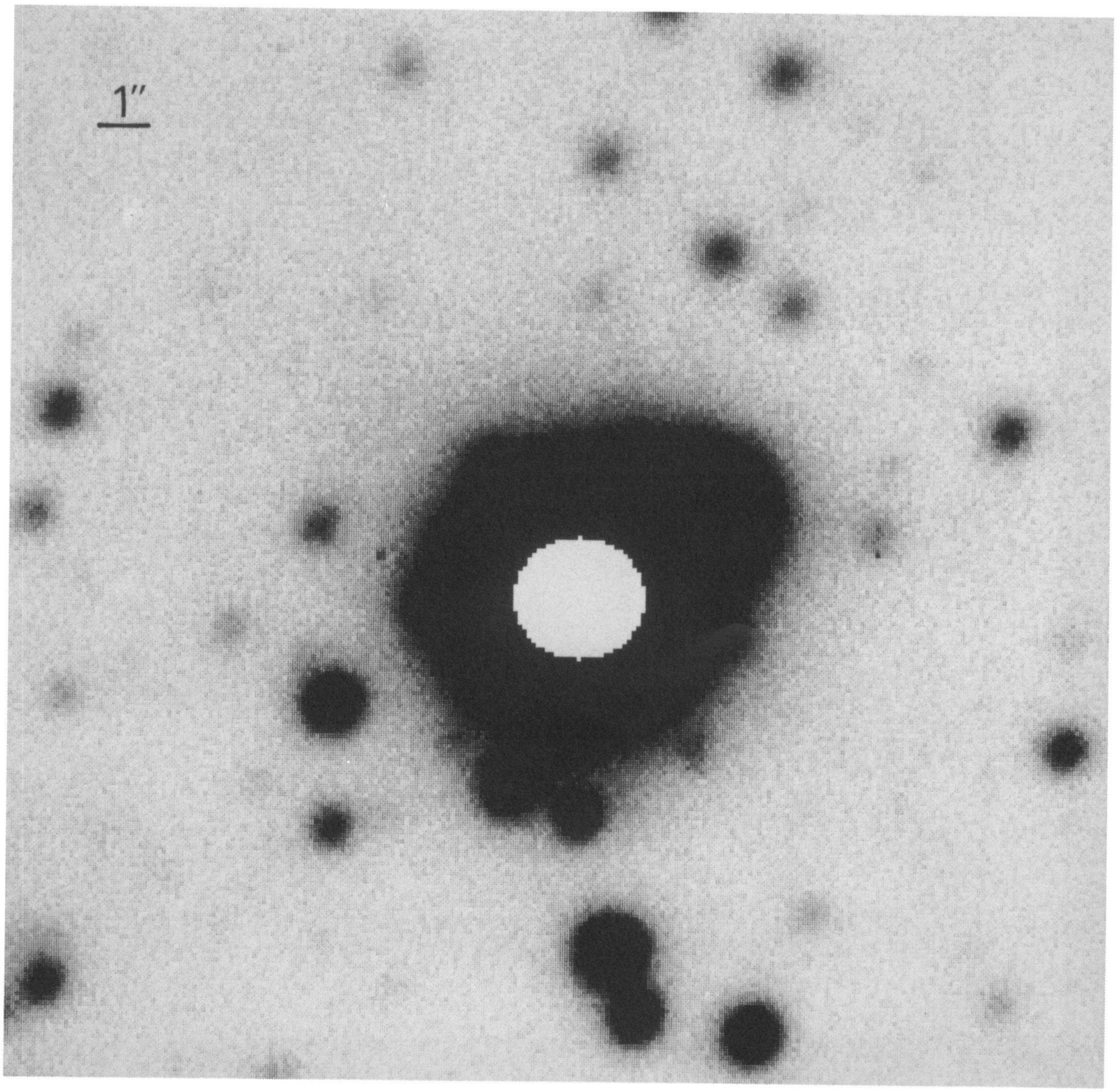

FIG. 1.—100 second *R*-band coronographic image of R127. North is up and east is to the left.

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image motion in real time. The image motion compensation system typically improves the image resolution by a factor of 1.2–2, depending on the telescope aperture and seeing conditions (Golimowski et al. 1992). In the coronograph, a Lyot stop was placed at the location of the reimaged exit pupil beyond the occulting mask to suppress the light diffracted from the telescope's primary mirror and secondary mirror support structure. The telescope's focal plane was reimaged with a magnification of ~ 6 onto a Tektronix CCD with 512×512 27 μm pixels, which were binned 2×2, to provide an effective plate scale of 0.″095 pixel^{-1} and a field of view of $24'' \times 24''$. The CCD had a read noise of $8e^-$ rms and was operated at a gain of $2e^-$/DN.

Two 100 s R-band (OG 570 + KG3; Bessell 1990) images and one 1800 s Hα + [N II] ($\lambda_c = 6560$ Å, $\Delta\lambda = 110$ Å) image were recorded with R127 positioned behind a 2″ diameter occulting mask. An additional 10 s exposure of an unocculted R127 was recorded in order to determine the star's current R-magnitude. The resolution of the coronographic images was 0.″7, determined from the average widths of the three brightest, unblended field stars in the Hα + [N II] image. Images of the unocculted spectrophotometric standard BD + 8°2015 (Stone 1977) were recorded for flux calibration. Reduction of the data was carried out using the standard procedures of bias and dark-current subtraction, division by an average flat-field image, and interpolation over bad pixels and cosmic-ray events.

Figure 1 (Plate L10) shows one 100 s R-band image, which may be directly compared to a similar V-band image obtained under 0.″9 seeing conditions by Nota et al. (1991) using a conventional coronograph. Despite the presence of spillover light from the seeing disk of R127 in the R-band image, many more fainter stars are revealed, several of which lie within 5″ of R127. The Hα + [N II] image is different from the R-band image in the structure of the halo, which appears asymmetric and extended with a faint but clearly resolved substructure.

Enhancement of this underlying emission required the subtraction of the seeing disk of R127 from the image. Since the seeing disk was composed primarily of the continuum and line emission from R127 itself, it could be removed by subtracting a suitably aligned and scaled R-band image. Registration of the R-band image with the Hα + [N II] image was achieved by aligning the centroids of field stars common to both images. The proper scale factor was initially estimated by comparing the exposure times, filter bandpasses, and filter efficiencies for the two images. This estimate was improved through an iterative process of renormalization and subtraction of the two images, with the goal of minimizing the residuals for a given set of field stars. This procedure allowed for differences in spectral types and the presence of line emission in some of the stars. The result of the optimum subtraction is shown in Figure 2 (Plate L11). The residual spillover light at the edge of the occulting mask, not accounted for during the registration and renormalization process, has been artificially masked with a disk of diameter 2.″7. No attempt has been made to correct the residuals in the subtraction of the field stars. The largest subtraction error occurs for the companion star R127B, located $\sim 3''$ to the NW of R127. The ratio of signal to noise in the resultant image ranges from 30 in the faintest regions of the nebula to 70 in the brightest regions.

3. RESULTS

The zoomed Hα + [N II] image shown in Figure 3 (Plate L12) reveals the full extent and morphology of the R127 nebula, and displays clear evidence of deviation from spherical symmetry. The nebula has a diamond shape, with its major axis lying at a position angle (p.a.) of 165°. Its measured dimensions of 8.″0 × 9.″0 translate to a linear size of 1.9 × 2.2 pc, if a distance to the LMC of 51.2 kpc is assumed (Panagia et al. 1992). These dimensions conflict with the values previously published by Stahl (1987), who determines a linear size of 0.8 × 1.1 pc, although the stellar profile depicted in his Figure 4 does suggest that the nebula extends at least 4″ from R127. Our dimensions are also inconsistent with those derived from the spectroscopic observations of Appenzeller, Wolf, & Stahl (1987) obtained with a 6″ long slit. In each case, however, the size of the nebula appears to have been determined from the centers of the brightest regions of the nebula.

There are large variations in the surface brightness of the nebula. Two bright lobes, indicative of strong gas density enhancements, lie along the E-W axis (p.a. = 92°) with an opening angle of $\sim 90°$. The eastern lobe has a surface brightness of 2.54×10^{-15} ergs s^{-1} cm^{-2} arcsec^{-2} at its core. The western lobe, having dimensions similar to those of the eastern lobe, contains a bright knot which lies 2.″2 from R127 at p.a. = 283° and has a surface brightness of 2.86×10^{-15} ergs s^{-1} cm^{-2} arcsec^{-2}. This knot has a much more compact appearance than the eastern lobe's core and could be either a nebular feature or a faint field star. If the knot is a star, it should also appear in the short R-band exposure. To enhance any faint features in the circumstellar region of the R-band image, we have subtracted a profile of the occulted R127 measured along a single radial direction that was uncontaminated by field stars. The resulting image shows no evidence of a star at the location of the knot, thereby supporting the contention that the knot is a gas density enhancement. The nebula is fainter along its major (N-S) axis with the brightest regions lying farther (1″ to $-1.5''$) from the central star than the brighter E-W lobes. In addition, their morphology is different as they appear to be partially resolved extensions of the brighter lobes and detached from R127.

Another interesting feature of the Hα + [N II] image is the presence of faint extended line emission covering a large area to the east. This emission has a typical surface brightness of 4.9×10^{-17} ergs s^{-1} cm^{-2} arcsec^{-2} and is visible in Figure 2, where lower image intensity levels have been selected to enhance the contrast of this faint region. It is essentially featureless except for a low-level fringe pattern, which is due to poor flat fielding at very low signal levels, and some clumps of surface brightness 1.15×10^{-16} ergs s^{-1} cm^{-2} arcsec^{-2} located 7″ from the nebula at p.a. = 94°. This line emission may be directly associated with the nebula or a faint background H II region. The latter was first discussed by Walborn (1982) as a possible source for the nebular emission lines. On the basis of the Hα emission line survey of the Magellanic Clouds by Davies, Elliot, & Meaburn (1976), Walborn concluded that R127 is not located in an H II region. However, there seems to be considerable diffuse Hα emission in its immediate surroundings. Faint, extended Hα emission is evident in long-slit spectra obtained on 1990 February at the European Southern Observatory (ESO) 2.2 m telescope. The observation was made using the Boller and Chivens spectrograph coupled to an RCA CCD, giving a spectral resolution of $R \sim 7000$ over the wavelength range 3630–7250 Å and shows very weak Hα line emission extending east to west across a field of 8′. More recent observations by M. Clampin et al. (1993, in preparation) confirm the existence of this extended material.

The ionized mass of the nebula can be derived from the

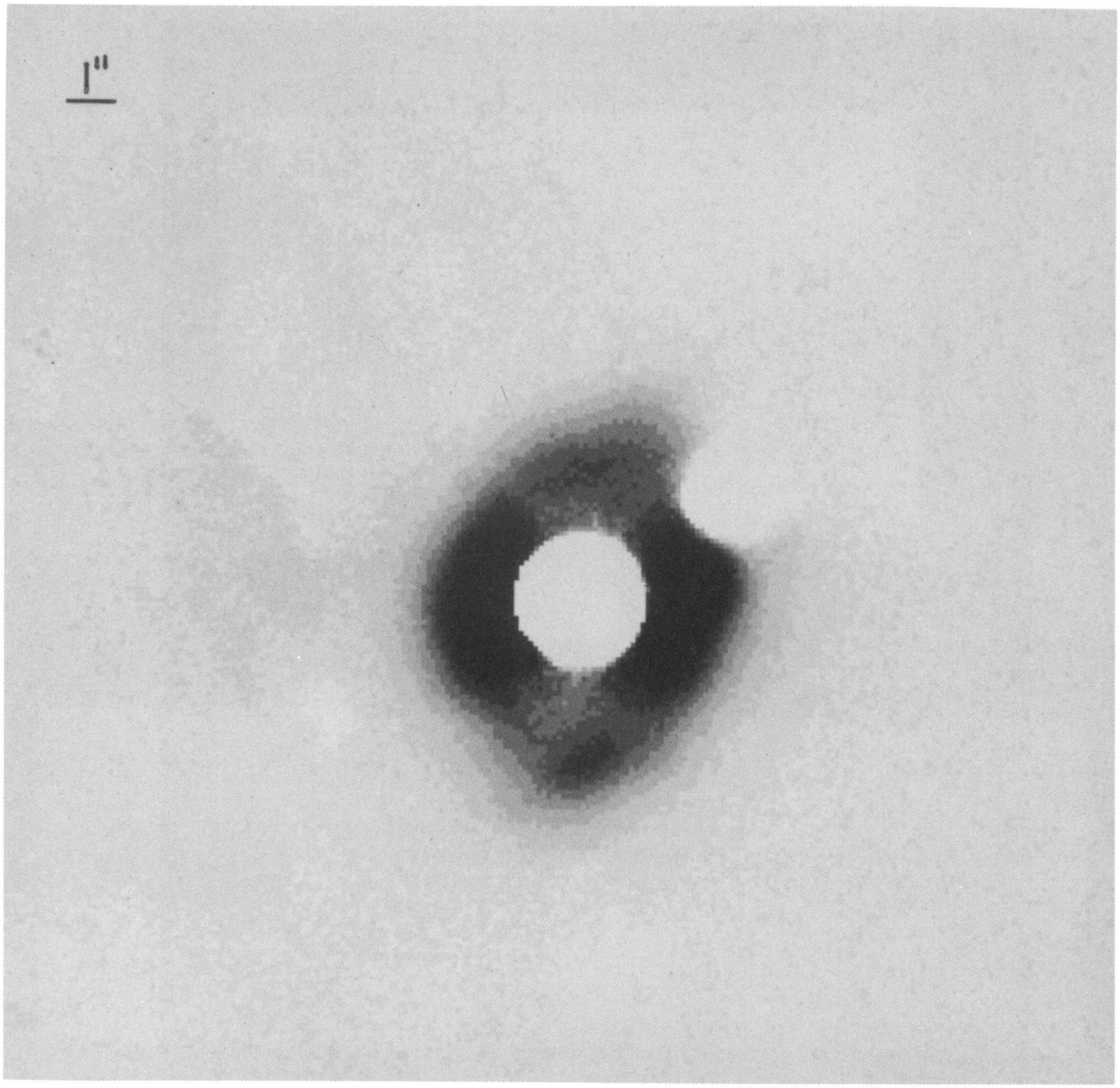

FIG. 2.—1800 Hα + [N II] coronographic image of R127, where we have subtracted the scattered light contribution due to R127, its companion (R127B) and the field stars. North is up and east is to the left. The image is logarithmically scaled to show the faint diffuse material to the east of R127.

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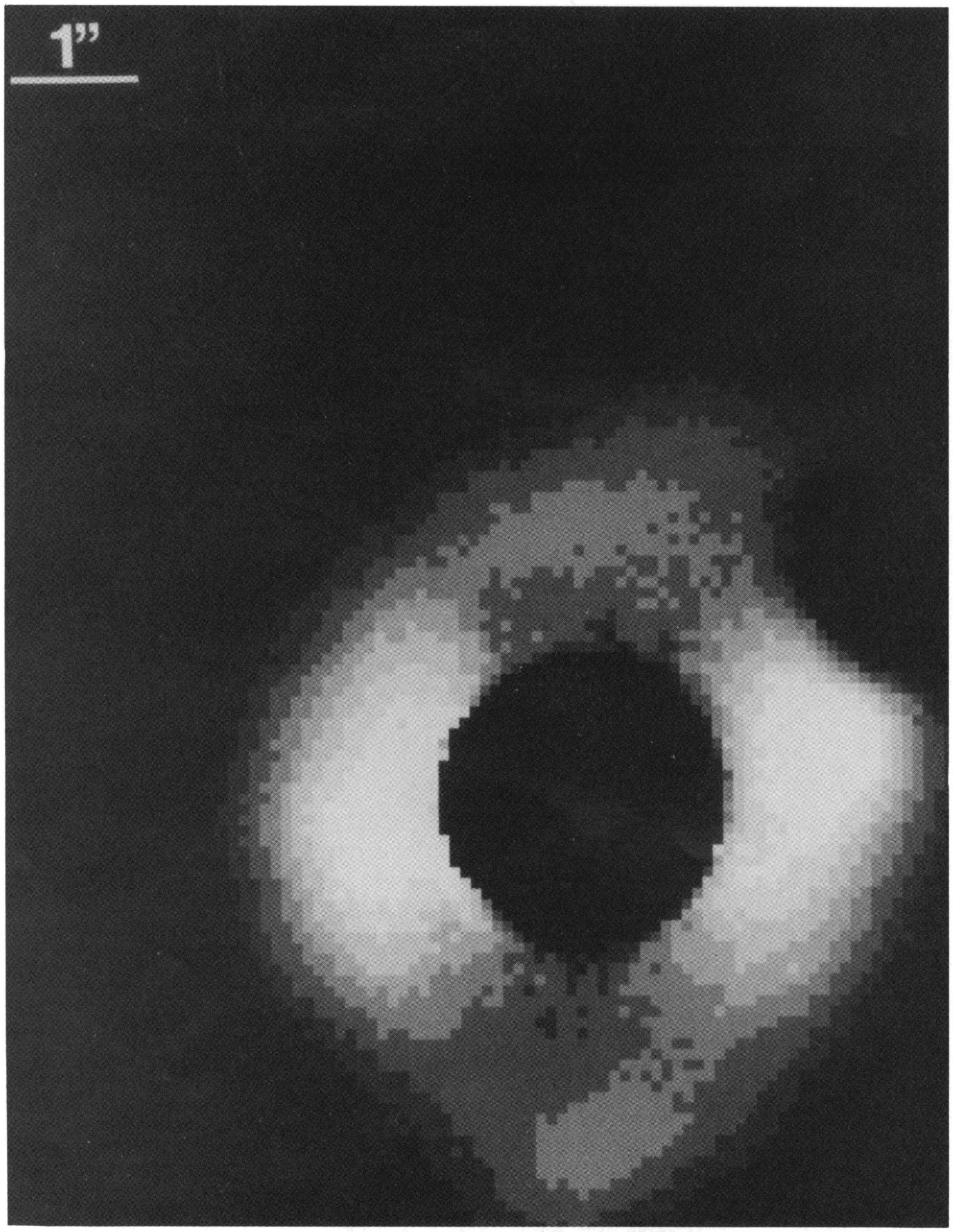

FIG. 3.—Same Hα + [N II] coronographic image of R127, zoomed to show the features within the nebula. North is up and east is to the left.

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integrated, extinction-free emission-line luminosity using the relation $M \propto FD^2T_\epsilon^{0.85}n_\epsilon^{-1}$, where F is the emission line flux, D is the distance, T_ϵ is the electron temperature and n_ϵ the electron density. The integrated Hα flux obtained from the Hα + [N II] image of the nebula is 4.0×10^{-12} ergs s^{-1} cm^{-2}. Since the image has been processed by subtraction of a scaled R-band image, it is necessary to make an allowance for the fraction of Hα flux subtracted with the R-band image. With this correction we obtain a value of 4.4×10^{-12} ergs s^{-1} cm^{-2}. In addition, it is necessary to account for the total integrated contribution due to the [N II] lines 6548 Å and 6584 Å, which we determine from the nebular spectrum of Stahl (1986) to be ~50% of the Hα flux. The Hα + [N II] filter, however, has decreasing transmission at these wavelengths so that the effective contribution of the [N II] lines to the total flux is ~25%. The final calculated Hα flux is then 3.3×10^{-12} ergs s^{-1} cm^{-2}. This figure is in good agreement with Stahl (1987) who derived an Hα flux of 4.1×10^{-12} ergs s^{-1} cm^{-2}, but did not correct for extinction. An extinction-corrected value of 4.0×10^{-12} ergs s^{-1} cm^{-2} follows from Whitford's (1958) extinction law, where $E(B-V)$ has been given by Wolf (1989) as 0.2. We adopt an average electron density for the R127 nebula of 10^3 cm^{-3} which has been derived independently by Stahl & Wolf (1986) and Schulte-Ladbeck et al. (1993) on the basis of the [S II] 6716/6731 Å line ratio. The calculated ionized gas mass is 3.1 $M_\odot$, where $T_e = 7500$ K. This result may be compared to the nebular mass derived from a geometrical model in which we assume a spherical volume of radius 1 pc. This would yield an ionized gas mass of ~125 $M_\odot$ if the spherical volume contains a homogeneous distribution of gas at an electron density of 10^3 cm^{-3}. The order of magnitude discrepancy between the two calculated masses can be understood if the electron density has been measured in high-density regions and represents an upper limit to the gas density in the nebula.

A radius for the Stromgren sphere resulting from the ionizing radiation of R127 may be calculated from the star's basic properties, via Osterbrock's (1989) tabulation. We assume a spectral type of O9 I for R127, based upon the OIafpe/WN9 classification assigned by Walborn (1982) during the star's last observed hottest phase. The total output of ionizing quanta in the Lyman continuum is $N_{\rm L} = 10^{49.83}$ s^{-1} from Leitherer's (1990) calibration of spectral type versus $N_{\rm L}$. The radius of the Strömgren sphere's calculated to be 1.3 pc, where $n_e = n_p = 10^3$ cm^{-3}. This results suggests that the R127 nebula, with linear dimensions of 2.2 × 1.9 pc, just fills the Strömgren sphere. The recombination time scale for the nebula $(-1/\alpha_{\rm B} n_e)$, where $\alpha_{\rm B}$ is the Case B recombination coefficient for hydrogen, is of the order of 10^2 years. Since the period of LBV brightness variations is typically a few tens of years, the nebula will remain ionized as the star evolves into cooler phases.

The diffuse Hα emission observed to the east of R127 cannot be due to gas ionized by R127 itself if the density of the intervening medium is $n_e = n_p = 10^3$ cm^{-3}. However, if we assume that the distribution of matter is nonuniform within the nebula, more distant material could then be ionized by leakage of stellar radiation. (e.g., $n_e = n_p = 100$ cm^{-3} gives a Strömgren radius of 25″.) A physical connection between the nebula and the more extended line emission could be established by spectroscopic investigation of the velocity and chemical composition of the gas.

From the expansion velocity of 28 km s^{-1} (Walborn 1982; Appenzeller et al. 1987), a dynamic time scale of 4×10^4 yr may be inferred. This dynamic time scale is relatively high compared to the currently accepted duration for the LBV phase of ~10^5 yr (Humphreys 1991), but should be considered an upper limit since the shell is likely to have undergone some deceleration. Several other LBVs have nebular shells with similar expansion velocities, including S Doradus (34 km s^{-1}; Stahl & Wolf 1986), R 71 (39 km s^{-1}; Stahl & Wolf 1986), and WRA 751 (26 km s^{-1}; Hutsemekers & Van Drom 1991).

4. DISCUSSION

The general appearance of the R127 nebula is reminiscent of the ring nebula around the Galactic LBV AG Carinae. The AG Carinae nebula has been determined from ground-based imaging and spectroscopy (Thackeray 1950; Smith 1991; Nota et al. 1992) to be a hollow, gaseous shell expanding with an average velocity of 70 km s^{-1}. In apparent analogy to the R127 nebula, two areas of enhanced gas density lie along the minor axis of the AG Carinae ring. Figure 4 (Plate L13) allows a direct comparison of the two nebular morphologies by depicting the Hα + [N II] image of the R127 nebula beside a similar image of the AG Carinae nebula obtained with the same instrumental configuration. The AG Carinae image has been projected to the distance of the LMC and convolved with a Gaussian seeing disk to reproduce the angular resolution and plate scale of the R127 image. A distance of 6 kpc has been assumed for AG Carinae (Humphreys et al. 1989). In addition, the linear dimensions of the AG Carinae nebula have been normalized to those of the R127 nebula, as the AG Carinae nebula is approximately half as large as the R127 nebula. The striking similarity between the AG Carinae and the R127 nebulae indicates that the R127 nebula may also be a detached expanding shell. Close inspection of Figure 3 shows that inner edges of the R127 nebula might be visible to the north and south. Furthermore, there is evidence of a discontinuity in the nebula at p.a. = 160°, so that its western side appears to extend towards the southeast. There is some evidence of a similar discontinuity at the opposing position angle, but the feature is too close to companion star R127B to be confirmed. Both features, however, are near the region of the subtracted seeing disk, and therefore are open to alternative interpretations, such as an unresolved feature within nebula. If it is assumed that an inner edge is indeed resolved along the major axis of the nebula, then the linear distances to the inner edge are 0.46 and 0.53 pc in the north and south, respectively.

Recent polarimetric observations of R127 by Schulte-Ladbeck et al. (1993) show R127 to have high intrinsic continuum polarization (~1%–1.5%, with mean p.a. = 25°), which suggests a large deviation from spherical symmetry close to the star. Schulte-Ladbeck et al. (1993) also find the intrinsic polarization and its position angle to be variable. The mean position angle is approximately perpendicular to that of the two bright lobes (see Fig. 2) which have p.a. = 92° and an opening angle of ~90°. Schulte-Ladbeck et al. (1993) propose a simple model for R127 in which an equatorial circumstellar disk is responsible for the observed polarimetric and spectroscopic properties of the system. In the context of their model, global deviations from spherical symmetry occur within 10 stellar radii of the star. The significance of this result is that an asymmetric outflow already forms in near-photospheric regions. The geometry of the outflow may be closely related to the mechanism responsible for the acceleration of the material. The close agreement of the position angle derived for the unresolved circumstellar disk and for the density enhancements

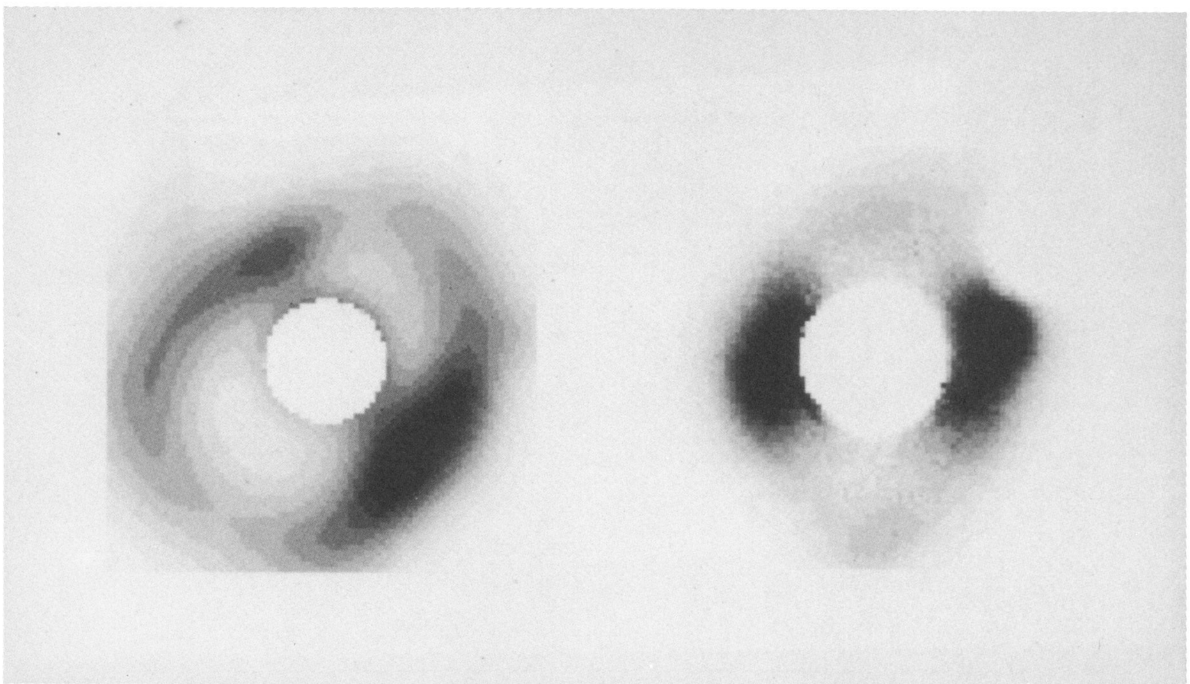

FIG. 4.—Hα + [N II] image of the R127 nebula compared with a Hα + [N II] image of the AG Car nebula obtained with the same instrumental configuration. The AG Car image has been projected to the distance of the LMC and convolved with a Gaussian seeing disk to reproduce the resolution and plate scale of the R127 image. In addition, the linear dimensions of the AG Car nebula have been normalized to those of the R127 nebula.

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detected in the present study may hint at their physical connection. However, it should be noted that the nebula visible in the coronographic images is a relic of a much earlier mass-loss episode. Even accounting for significant deceleration, its age can be expected to be at least 10^3 yr. The nebula was very likely ejected during an earlier outburst, such as the one observed in η Carinae about 150 yr ago (Davidson 1989). In contrast, material observed within 10 stellar radii is characterized by flow time scales on the order of months, i.e., it traces the present mass-loss history of R127. Although, a priori, there is no immediate connection between the inner unresolved material and the outer resolved material, the resemblance of their geometries is striking. This may bear clues for our understanding of the mechanisms operating in LBVs during outburst and in quiescence.

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