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GALACTIC RING NEBULAE ASSOCIATED WITH WOLF-RAYET STARS. IV. THE RING NEBULA S308 AND ITS INTERSTELLAR ENVIRONMENT

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ABSTRACT

We have obtained narrow-band filter photographs, [O III] λ5007 Fabry-Perot line profiles and 21 cm maps of the vicinity of the Sharpless H II region S308 and adjacent nebulae. S308 is a ring nebula surrounding the WN5 star HD 50896. An expansion velocity of 60 km s^{-1} and an age of 7×10^4 years are derived for S308. The total kinetic energy and thermal energy in the shell of S308 can account for only 5% of the total stellar wind energy input. The H II regions S303 and S304 exterior to S308 are also excited by the star HD 50896, showing that S308 is optically thin to UV photons.

Subject headings: nebulae: individual — stars: Wolf-Rayet

I. INTRODUCTION

S308 (Sharpless 1959) is among the first three ring nebulae around Wolf-Rayet (W-R) stars that have been discovered (Johnson and Hogg 1965). However, unlike the other two nebulae—NGC 2359 and NGC 6888 which are bright and well studied (Wendker *et al.* 1975; Kwitter 1981; Schneps *et al.* 1981; and references therein), S308 is fainter and has been a subject of much less observational investigation.

Previous studies of S308 have defined some basic characteristics of the nebula at various wavelengths. It is excited by the WN5 star HD 50896. On the Palomar Sky Atlas red print, S308 appears filamentary and irregular in form with an incomplete ring structure of diameter 35′. In the radio region, Johnson (1971) observed this nebula at 5010 MHz with the NRAO 43 m telescope, deriving an integrated flux of 1.2–1.4 Jy; and Schneps (1979) searched unsuccessfully for CO. Optically, Kwitter (1979) performed a spectroscopic study of the nebula, finding a temperature of $17{,}000\pm5000$ K, an approximate nitrogen abundance of 8.5×10^{-5}, and a helium abundance of about 0.16 by number.

Recent observations have revealed some important new properties of S308, its environment, and its exciting star. In our optical emission line survey of the northern sky (see § II*a* for details), we find that S308 has a bright and complete ring in [O III] λ5007 line emission, as opposed to the appearance on the Palomar Sky Atlas. Moreover, our data show that the H II regions S303 and S304, centered on the W-R star and exterior to S308, have stronger [O III] emission than most other H II regions. Recently, spectroscopic observations (Firmani *et al.* 1979; Firmani *et al.* 1980) and polarimetric observations (McLean *et al.* 1979) indicate that HD 50896 has a compact companion with a mass of $1.3\pm0.4\ M_\odot$; this companion may be the end result of a supernova explosion (Firmani *et al.* 1980).

Motivated by these recent discoveries concerning S308 and its associated W-R star, we have obtained high resolution [O III] line profiles of S303, S304, and S308 and maps of the distribution of the neutral hydrogen in the vicinity of these nebulae. Here we report upon the kinematics of this little studied nebula and its relationship to other nearby nebulae.

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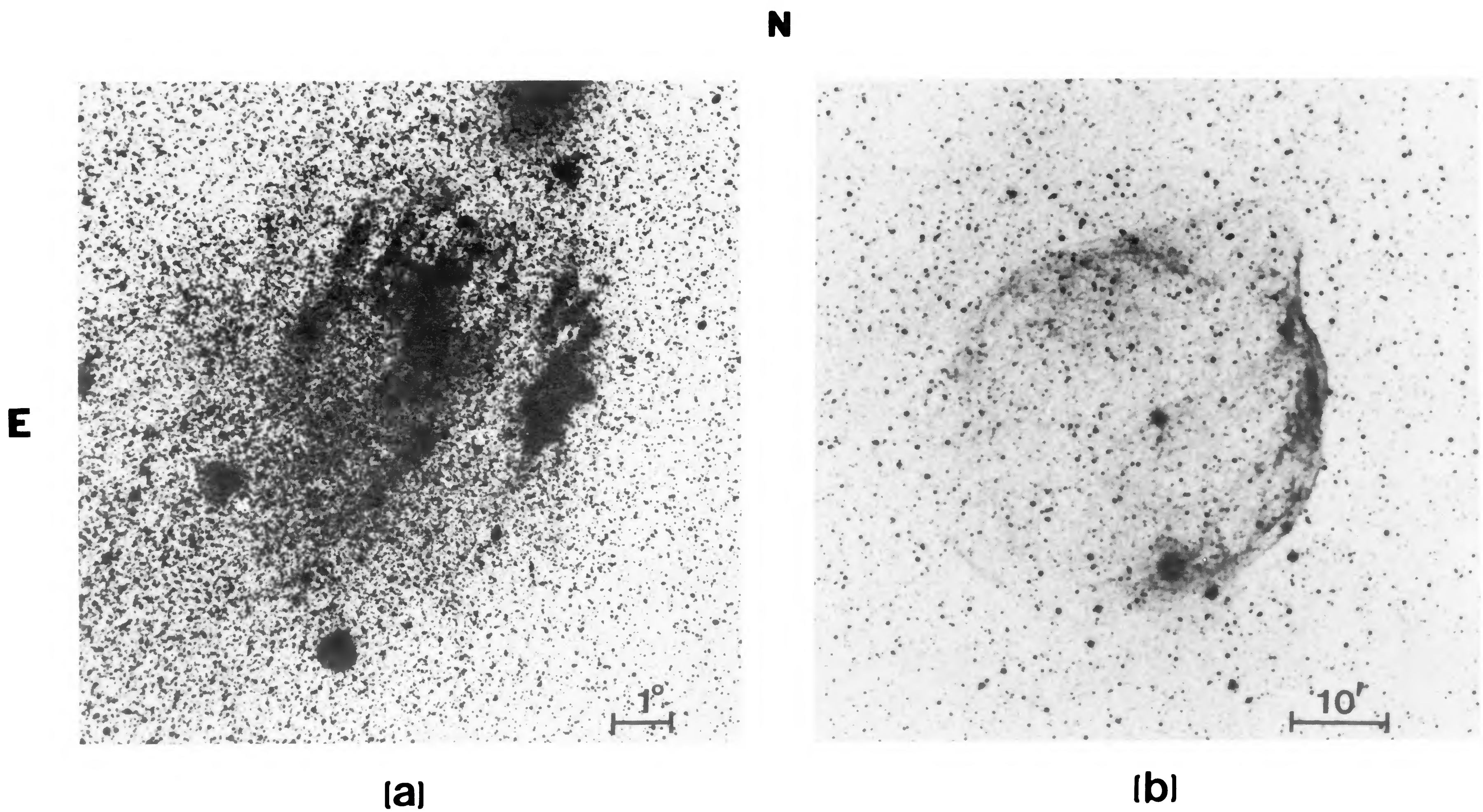

FIG. 1.—(*a*) 135 mm [O III] photograph of the vicinity of S308. S303 and S304 are to the north and the west of S308. The dark patch at the edge of the field and to the north of S304 is caused by the scattered star light from Sirius. (*b*) Curtis Schmidt [O III] photograph of S308.

II. OBSERVATIONS AND RESULTS

a) Narrow-Band–Filter Photographs

Two of us (T. R. G. and Y.-H. C. have recently completed an emission line survey of the northern sky (decl. ≥ −30°) at Kitt Peak National Observatory (KPNO). This work is a continuation of the Milky Way survey by Parker, Gull, and Kirshner (1979). The new survey includes three passbands: "blue continuum" ($\lambda 4224$, $\Delta\lambda = 60$ Å), $H\alpha + [N\ II]$ ($\lambda 6570$, $\Delta\lambda = 75$ Å) and [O III] ($\lambda 5010$, $\Delta\lambda = 50$ Å). For some especially interesting fields we added a fourth passband, [S II] ($\lambda 6736$, $\Delta\lambda = 50$ Å). The camera is identical to the one described by Parker, Gull, and Kirshner (1979), except that a 135 mm focal length f/2 lens is substituted for the 300 mm focal length f/2.8 lens. This affords us more than twice the field of view and one-half the exposure time.

A comparison of our survey plates reveals significant differences between the excitation of S308 and the adjacent nebulae S303, S304, and S310. S308 is best defined on the [O III] plate; it has relatively weaker $H\alpha +$ [N II] emission, and little [S II] emission. S303 and S304 appear on all three plates, while S310 is visible only on the $H\alpha +$[N II] plate. Since the line intensity ratio of [O III]/$H\alpha$ is often used as an indicator for the degree of nebular excitation and the temperature of the exciting stars (Chopinet and Lortet-Zuckerman 1976), apparently S308 has the highest excitation among these four H II regions, and S310 the lowest. The [O III] plate, centered at $l = 235°$ and $b = -10°$, is reproduced in Figure 1*a*.

At Cerro Tololo Inter-American Observatory (CTIO), we have obtained a Curtis Schmidt plate of S308 in [O III], which is reproduced in Figure 1*b*. This plate shows that S308 is a complete ring with a "hernia" in the northwest. The central star is slightly offset to the brighter rim in the west. We have also obtained an image tube plate of the western portion of S308 in [O III] line with the Yale 1 m telescope. This plate reveals filamentary structures in the nebula having scales of as little as 5″. This plate is not reproduced here, because it carries essentially the same information as the Schmidt plate except at slightly higher spatial resolution.

The plate information is listed in Table 1.

b) Neutral Hydrogen 21 cm Line Observations

The region surrounding S308 straddles the boundaries of the Berkeley high- and low-latitude 21 cm H I surveys (Heiles and Habing 1974; Weaver and Williams 1973). In order to have a consistent set of profiles for this study, we mapped the region $l = 232\overset{\circ}{.}5$ to $237\overset{\circ}{.}5$, $b = -5\overset{\circ}{.}5$ to $-14\overset{\circ}{.}5$ over a velocity range of −65 to +145 km s^{-1} with the Hat Creek 26 m telescope. The spatial resolution is about $0\overset{\circ}{.}5$, and the velocity resolution is 2.1 km s^{-1}. From these new 21 cm data, we generated a series of neutral hydrogen maps in successive 4.2 km s^{-1} velocity intervals.

Two features can be seen from these maps: (1) In the direction of S308, most of the neutral hydrogen is between $V_{LSR} = +20$ to $+30$ km s^{-1}. (2) S303 and S304 are projected on the edge of a neutral hydrogen cloud, seen best in the velocity range of +6 to +14 km s^{-1}. This cloud can be traced up to the galactic plane in the Berkeley surveys, and it is also part of a loop structure which extends between $l = 220°$ and 232°, $b = -5°$ and −15°. The H I maps are not reproduced here because better quality PDS playback photographs will be published by Heiles (1982).

c) Fabry-Perot Observations

We used two Fabry-Perot spectrometers (FPS) in this study: the Berkeley piezoelectric-scanned FPS on the 76 cm telescope at Leuschner Observatory, and the pressure-scanned FPS on the 91 cm telescope at CTIO. The properties of these instruments are described by Treffers (1981) and Smith and Weedman (1971), respectively. The [O III] $\lambda 5007$ line is almost 3 times as strong as the $H\alpha$ line in S308 (Kwitter 1979), and it is less contaminated by the galactic background radiation and free of any geocoronal contribution. Moreover, the spectral sensitivity of the S-20 photomultiplier used in the FPS is nearly twice as good at 5007 Å than at 6563 Å. Hence, we confined our observations with both instruments to the [O III] emission. A beam diameter of 2′ was used

TABLE 1

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Plate Number	Filter (Å)	Exp (min)	Date
KPNO 135 mm+CITD			
858	4215	12	1978 Dec 3
957	4215	12	1979 Jan 29
874	5007	15	1978 Dec 2
985	5007	15	1979 Jan 30
1026	5007	10	1979 Feb. 26
1177	5007	10	1979 Mar 29
1178	5007	10	1979 Mar 29
878	6570	12	1978 Dec 4
921	6570	12	1979 Jan 27
1205	6570	12	1979 Mar 30
1206	6570	12	1979 Mar 30
1151	6730	15	1979 Mar 25
1152	6730	15	1979 Mar 25
CTIO 1 m+ITC			
398	5007	50	1980 Apr 17
CTIO Curtis Schmidt			
23821	5007	180	1981 Mar 24

TABLE 2

FABRY-PEROT DATA

Sequence Number (1)	Offset (arcmin) (2)	V_{LSR} (km s^{-1}) (3)	FWHM (km s^{-1}) (4)	Height (counts s^{-1}) (5)	Int. Time (6)	Date (7)
S308C1	N25	+22.9	22	2.9	20.0	1980 Dec 10
S308C2	N18	+25.6	22	9.7	25.0	1980 Dec 10
S308C3	W15, N17	+17.1	24	15.7	82.5	1981 Mar 26
		+45.2	26	12.1		
S308C4	E9, N15.5	+22.1	27	8.3	45.0	1981 Mar 23
		+58.8	22	3.3		
S308C5	N15	+19.6	25	6.1	25.0	1980 Dec 10
S308C6	N10	~+24	?	?	50.0	1980 Dec 15
		~−32	?	?		
S308C7	W16, N3	+20.0	29	16.2	20.0	1980 May 3
		+49.2	23	18.4		
S308C8	W14, N3	+13.6	22	7.8	20.0	1980 May 4
		+69.6	26	6.4		
S308C9	W12, N3	−3.7	28	2.7	25.0	1980 May 4
		+72.4	23	4.1		
S308C10	W16	+27.9	34	16.4	15.0	1980 Dec 10
S308C11	W14	+15.5	25	11.0	22.5	1980 Dec 10
		+54.3	44	5.1		
S308C12	W2	~+85	?	?	100.0	1981 Mar 24
		~+20	?	?		
		~−40	?	?		
S308C13	W10, S8	+10.3	36	3.4	67.5	1981 Mar 23
		+70.1	27	4.2		
S308C14	W12, S10	+16.5	28	4.6	47.5	1981 Mar 23
		+58.5	31	9.5		
S308C15	S10	~+18	?	?	75.0	1980 Dec 15
		~+100 or −60	?	?		
S303C1	E15.5, N77.5	+19.2	21	11.5	12.5	1980 Dec 15
S303B1	E13.8, N78.5	+18.7	25	19.8	25.0	1980 Mar 9
S304B1	W110, N34.7	+20.2	31	11.0	27.5	1980 Mar 9
S308B1	W16, N3	+13.2	37	22.2	17.5	1980 Mar 9
		+45.7	31	27.5		
S308B2	W2	~+20	?	?	40.0	1980 Mar 10
		~−40	?	?		
		~+90	?	?		

throughout the observations. The free spectral range (FSR) of the CTIO FPS (etalon 2) is 154 km s^{-1}; that of the Berkeley FPS can be set at 163 or 480 km s^{-1} by changing the etalon spacing. Observations with the larger FSR on the Berkeley instrument were used only as a check for overlapping orders in the smaller FSR data.

Calibration procedures for these two instruments are different because of available reference lamps. We calibrate the Berkeley FPS using a helium lamp and referencing to He I λ5015. This provides an accurate velocity calibration, but the derived instrumental response may be slightly inaccurate because the reflectivity of the interference coatings on the etalon is wavelength dependent. At CTIO, no lamp with reference lines near 5007 Å is available. Instead, we observe NGC 3199 in Hα and [O III] (Chu 1981). The Hα line from some regions in this object is narrow, and the velocity can be calibrated unambiguously by referencing to an available hydrogen lamp. Since the morphologies and velocity variations of NGC 3199 in the Hα and the [O III] lines are similar, we may assume that these two lines from the narrow-lined regions have the same velocities, to which the S308 oxygen line velocity can then be referenced. The Berkeley and CTIO profiles of [O III] in S303 show good agreement in velocity, allowing for the broader instrumental profile of the Berkeley FPS. In Table 2 we list the offsets from the central star HD 50896 and the Gaussian fits for all the FPS observations, with "B" and "C" in the sequence number (col. [1]) representing Berkeley and CTIO respectively. The velocities are estimated visually if there are question marks in the FWHM and height columns (cols. [5] and [6]). In Figure 2 we present the line profiles. All velocities are referenced to the Local Standard of Rest.

The [O III] line profiles obtained for S308 show two features. One is weak and stationary at the velocity of +20 to +25 km s^{-1}. The origin of this background feature will be discussed in § III*b*. The other feature

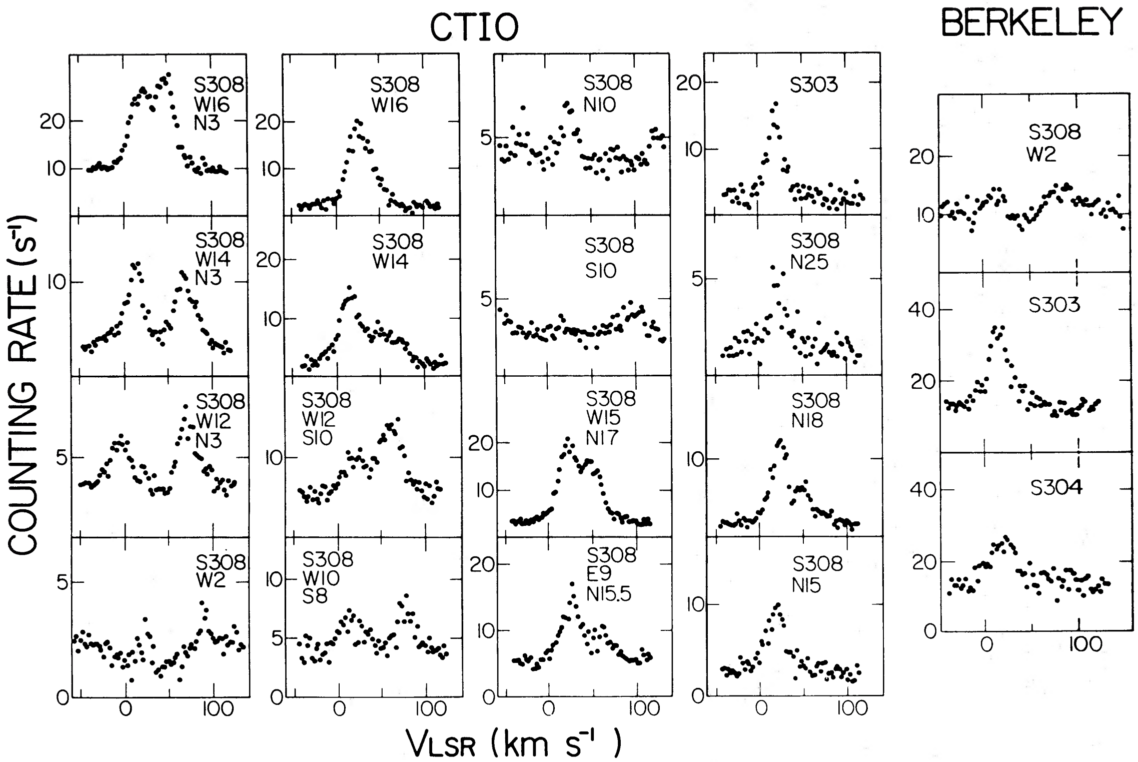

FIG. 2.—The [O III] line profiles for S303, S304, and S308. The offsets (in arcmin) from the star HD 50896 are labeled below the nebula names.

comes from S308 and is our main interest. This S308 feature matches very well the line profiles expected for a thin shell with an expansion velocity of about 60 km s^{-1} and an average systemic velocity of $+33$ km s^{-1}. The spectrum 2′ west of the star has the problem of overlapping orders because the FSR is too small; however, three spectra at this position were taken with three different FSRs (one with CTIO FPS and two with Berkeley FPS), allowing a unique interpretation. The spectra at this position show the front and back sides of the shell at -40 and $+90$ km s^{-1} and the background component at about $+20$ km s^{-1}.

d) *Comparison with UV Data*

Shull (1977) has measured the interstellar Si III absorption from -20 to -38 km s^{-1} in the *Copernicus* UV spectrum of HD 50896. Collisionally ionized gas at 30,000 to 80,000 K behind a strong shock (shock velocity$\approx$50–100 km s^{-1}) is proposed to reproduce this Si III column density and velocity field. Our spectrum taken near the star (W2) shows the front side of the shell at -40 km s^{-1}, which agrees well with the Si III velocity. The expansion velocity of 60 km s^{-1} is also within the shock velocity range proposed. We think this Si III feature arises from the front side of the shell of S308.

Smith, Willis, and Wilson (1980) obtained a high resolution *IUE* spectrum of HD 50896 and found blueshifted interstellar absorption lines of low ionization species. The mean velocity shift is 80 ± 7 km s^{-1}, which is slightly higher than the expansion velocity we derived. This situation is similar to what is found for NGC 6888: the mean velocity shift is 90 ± 9 km s^{-1} (Huber *et al.* 1979), toward the upper end of the expansion velocity range 55 to 110 km s^{-1} (Lozinskaya 1970; Treffers and Chu 1982).

III. DISCUSSION

a) *Kinematics of S308*

The age of a stellar wind-blown bubble can be estimated to be $\eta(r/v)$, where r is the radius, v is the expansion velocity, and η is a constant with values between 0.5 and 0.6, depending upon whether the momentum or the energy of the stellar wind is assumed to be conserved (Steigman, Strittmatter, and Williams 1975; Weaver *et al.* 1977). S308 has a radius of 7.2 pc (distance$\approx$1.5 kpc; see § III*b*) and an expansion velocity of 60 km s^{-1}; its age so derived is about 7×10^4 years. The dynamical age is less than 3% of the lifetime of a W-R phase, a few times 10^5 years (Chiosi, Nasi, and

Sreenivasan 1978). There is little doubt that S308 is a bubble blown by HD 50896.

For a fully ionized and optically thin nebula, the nebular mass (M) can be derived from single-frequency radio data. The equation is given by Smith and Batchelor (1970) as

$$\frac{M}{M_\odot} = 1.24\nu^{0.1} S D^2 T^{0.35} N_e^{-1}(1+3a), \qquad (1)$$

where S is the integrated flux density (Jy) at radio frequency ν (Hz), D is the distance (kpc), T is the nebular temperature, N_e is the nebular electron density (cm^{-3}), and a is the fraction, by numbers of ions, of singly ionized helium. If the nebula is a shell of swept-up ISM, then its mass is

$$\frac{M}{M_\odot} = 650 D^3 \Theta^3 n_0 = 0.12 R^3 n_0, \qquad (2)$$

where Θ is the angular radius of the shell in degrees, R is the linear radius of the shell (pc), and n_0 is the number density of the ambient ISM. The densities are related by

$$N_e \Delta R = 1/3 R n_0, \qquad (3)$$

where ΔR is the shell thickness (pc), and single ionization for all species is assumed. The shell thickness is a function of the shock velocity, given by

$$\Delta R \approx \frac{R}{3\left[1+\left(v^2/C_{\mathrm{II}}^2\right)\right]} \qquad (4)$$

where C_{II} is the isothermal sound speed in the shell (Weaver *et al.* 1977). Adopting the following parameters for S308: $T = 17{,}000$ K (Kwitter 1979), $D = 1.5$ kpc, $S(\nu = 5010\ \mathrm{MHz}) = 1.3$ Jy (Johnson 1971), $a = 0.11$, $\Theta = 0.^\circ 275$, $v = 60\ \mathrm{km\ s^{-1}}$, and $C_{\mathrm{II}} = 10\ \mathrm{km\ s^{-1}}$, we have solved equations (1) to (4) to obtain $M = 40\ M_\odot$, $n_0 = 1\ \mathrm{cm}^{-3}$, $N_e = 30\ \mathrm{cm}^{-3}$, and $\Delta R = 0.06$ pc. The shell electron density of 30 cm^{-3} is consistent with the upper limit of 50 cm^{-3} derived spectroscopically by Kwitter (1979). If we adopt a mass loss rate of $2.6 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ for HD 50896 (Barlow, Smith, and Willis 1981; this value has been adjusted by a factor of 0.78 because of different distances adopted), the total stellar mass input is about 2 $M_\odot$, only 5% of the total nebular mass.

The total kinetic energy resident in the shell of S308 is about 1.4×10^{48} ergs, while the total thermal energy is about 5×10^{48} ergs. The terminal velocity of the stellar wind from HD 50896 is 2700 km s^{-1}, and the wind mechanical luminosity is 5.9×10^{37} ergs s^{-1} (Barlow, Smith, and Willis 1981). In 7×10^4 years the total mechanical energy released by the winds is 1.3×10^{50} ergs. The kinetic energy and the thermal energy can only account for 5% of the total wind energy. The other 95% of the wind energy must have radiated away already. The momentum in the shell is about 50% of the total input from the winds. It is more likely that the shell of S308 is in the momentum conserving phase, instead of energy conserving phase.

b) *Environment of S308*

The southern part of Canis Major, $l = 230°$ to $245°$ and $b = -4°$ to $-12°$, is very rich in Population I objects. There are three H II regions cataloged near S308: S303 and S304 to the north and the west, neither of which has identified exciting stars; and S310, to the east, which is excited by UW CMa and τ CMa (Sharpless 1959). See Sivan's (1974) Hα map of the galactic plane for their locations.

The proximity of S308 to S310 is real, not merely a projection effect, since distances to the exciting stars are comparable. The distance to HD 50896 is 1.5 kpc, based on the modified calibration by Smith (1973). The star τ CMa is a member of the cluster NGC 2362, and its distance can be accurately determined from the cluster's color-magnitude diagram to be 1.5 kpc. The photometric distance to UW CMa is also 1.5 kpc (Lada and Reid 1978). The projected distance between S308 and S310, 160 pc, must be close to the real distance.

Although S303 and S304 are cataloged as two distinct H II regions (Sharpless 1959), their similarities in morphology, line ratio of [O III] λ5007 to Hα+[N II], and radial velocity seem to suggest that they have a common excitation source. The combined shape of S303 and S304 traces a half circle with a center at approximately $l = 235°$, $b = -10.^\circ 5$. The exciting source may have been either a past supernova or existing early-type stars located near the geometrical center. We do not think S303 and S304 are supernova remnants, since they have neither strong [S II] emission nor strong radio emission. We have used the Hat Creek 26 m telescope at 1420 MHz continuum to make 10° long scans centered on S308 in both right ascension and declination; no enhanced emission near these nebulae is detected. There are two stellar candidates for radiative excitation: HD 50896 and the star cluster Cr 121. We rule out Cr 121 as the exciting source for S303 and S304 because the earliest spectral type is only B3, yet the [O III]/Hα+[N II] ratio for these nebulae is higher than that for S310, which is excited by O7f and O9I stars. Higher ratios of [O III]/Hα are associated with excitations by stars of earlier types (Chopinet and Lortet-Zuckerman 1976). HD 50896 is the only possible excitation source. If S303 and S304 are indeed excited by HD 50896, then S308 is optically thin to UV photons from HD 50896. This circumstance explains why the effective temperature determined from the Zanstra method is lower than the value for normal WN5 stars (Morton 1973).

On the [O III] photograph (Fig. 1*a*), there are faint emissions visible over the area enveloped by S303 and

S304. The spectra sampled inside this area often show a weak component at $V_{LSR} = +20$ to $+25$ km s^{-1}, which is not compatible with that of S308 but is close to that of S303 and S304. It is also consistent with that of the H I in this direction. It seems that S303, S304, and the faint nebula between them belong to the same complex structure. The enhanced emission at S303 and S304 is due to their being either on the surface of H I clouds (§ II*b*) and having higher density, or on the tangential part of a curved sheet of gas. It is not clear whether this nebular complex is in front or behind S308.

c) *HD 50896—A Runaway Star?*

Being 260 pc above the galactic plane and having a compact possibly postsupernova companion, HD 50896 has been claimed to be a runaway star (Firmani *et al.* 1979). If so, NGC 2362 (the nearest open cluster) is the most apparent place for HD 50896 to have originated. However, NGC 2362 is less than a million years old (Arp and Van Sant 1958), and a transverse velocity of at least 150 km s^{-1} would be required for the runaway star to account for its present location. At such a velocity the star would have moved more than 10 pc (about 1.3 times the radius of the radius of S308) since the shell was formed. Yet the near-central location of the star in the nebula argues strongly against motion of this magnitude. We conclude that the birthplace of this proposed runaway star, while unknown, must be close to its present position. Indeed, the projected displacement of HD 50896 from the center of the nebula implies the transverse velocity of the star is less than 14 km s^{-1}, in which case it is not a runaway star at all.

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