SPECTRAL OBSERVATIONS AND PHYSICAL MODELING OF SHARPLESS 121

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ABSTRACT

The nature of the object Sharpless 121 has been the subject of considerable controversy. Four interpretations have been given of the earlier observations: H II region, planetary nebula, compact source inside a supernova remnant, and nearby object superposed over an extragalactic radio source. New observations were made of this object, using the 46-m telescope of the Algonquin Radio Observatory, to obtain the hydrogen recombination lines and continuum near 3327 MHz and near 10 522 MHz. These observations practically eliminate all but one of the earlier interpretations. The ensuing physical modeling enables the derivation of the basic physical parameters of this shell-type H II region, and an application of stellar-wind theory gives its dynamical parameters.

I. INTRODUCTION

The aims of this investigation are to determine the nature of the object No. 121 in the catalog of Sharpless (1959) and to obtain its physical properties. The object S121 is likely to be located in our Galaxy, as evidenced by its extended optical diameter of about 1.2 arcmin and by its optical shape (irregular—Sharpless 1959; partial ring—Felli and Harten 1981b). The attempts to determine its nature have led to four different interpretations based on continuum observations at radio or optical wavelengths. Thus S121 could be (i) a H II region (Sharpless 1959); (ii) a planetary nebula (a possibility suggested by Felli and Harten 1981b); (iii) a compact radio source inside a supernova remnant (also suggested by Felli and Harten 1981b); or (iv) something in our Galaxy but superposed over an extragalactic radio source (Kazès *et al.* 1975). A line of H2α was detected by Crampton *et al.* (1978) at optical wavelength, but no linewidth or line amplitude is reported. No radio line of hydrogen has been observed so far. In particular, S121 is not included in the survey of hydrogen recombination lines from galactic H II regions (Reifenstein *et al.* 1970). However, a routine search of the molecule CO toward all 313 regions in the Sharpless catalog yielded a line detection in a molecular cloud in the direction of S121 (Blitz *et al.* 1982), but these authors provided no interpretation.

Figure 1 shows a photograph of the visible sky toward S121 (reproduced and adapted from the Palomar Sky Survey). A compendium of past and present radio observations of S121 is given in Table I; many are single-dish observations where the HPBW increases as the observing wavelength increases.

Figure 2 shows a contour map of the area around S121 at radio wavelengths (adapted from the Green Bank survey of Felli and Churchwell 1972). Most of the sources seen are likely to be in our Galaxy (the galactic coordinates of S121 are $l = 90.23°$, $b = +1.72°$).

Section II presents the observing method and instrumentation at the Algonquin Radio Observatory, as well as an outline of the data reduction involved, while Sec. III gives the results of these observations. Section IV presents the interpretation of these Algonquin observations of S121, leading to the determination of its nature. Section V details the physical modeling done to obtain the physical properties of S121. The application of a stellar-wind-driven shell theory to the case of S121 is also included.

II. OBSERVATIONS AND REDUCTION

The 46-m telescope at the Algonquin Radio Observatory* near Lake Traverse, Ontario, was used to observe the object S121 and an adjacent "sky" position. The frequency ranges chosen show the recombination line H125α and the continuum near 3327 MHz, and the recombination line H85α and the continuum near 10 522 MHz.

Observations of the H125α line near the 3327 MHz were made with a receiver operating in the total power mode, using a cooled parametric amplifier with a typical system noise temperature of about 68 K connected to a filter spectrometer (McLeish 1973). Two banks of filters were employed, each composed of 100 channels. The channel width in bank one was 30 kHz (2.70 km/s), and 10 kHz (0.90 km/s) in bank two. The overall sensitivity was 3.2 Jy per degree Kelvin of antenna temperature, and the half-power beamwidth (HPBW) was 8.23 arcmin.

The receiver operating near the H85α line at 10 522 MHz has a cooled parametric amplifier with a typical system noise temperature around 140 K. The H85α line measurements were made with the receiver in the total power mode, and with filter spectrometer bandwidths of 300 kHz (8.55 km/s) in bank one, and of 100 kHz (2.85 km/s) in bank two. The overall sensitivity was 4.2 Jy per

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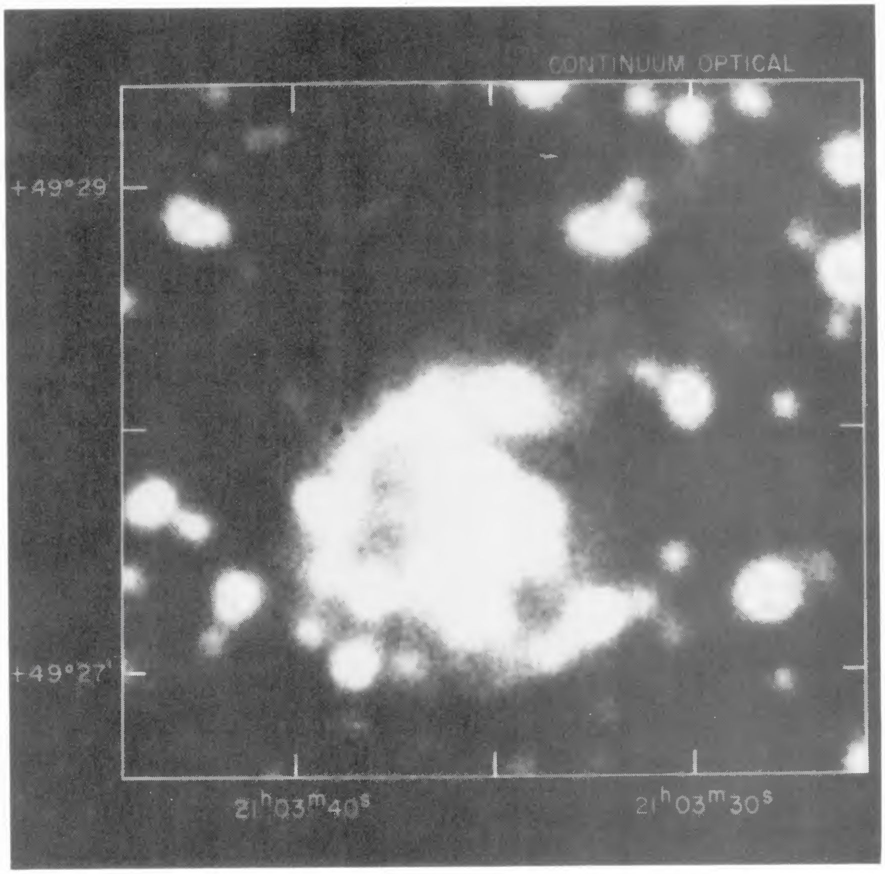

FIG. 1. Reproduction of the red Palomar sky survey photograph of the continuum emission at optical wavelengths in the area of S121. The biggest patch is the object S121 which occupies a roughly circular area with a diameter of about 1.2 arcmin, nominally centered at RA = $21^h03^m35.8^s$ and DEC = $+49°\,27'\,55''$.

degree Kelvin of antenna temperature, and the HPBW was 2.67 arcmin.

The line observations were made with the usual on-source/off-source technique; each spectrum was obtained by observing for 10 minutes on source followed by 10 minutes off source. The off-source position was taken at the same hour angle and declination recorded at the beginning of the on-source observation. White noise was added to the receiver level for the off-source observation to balance it with that for the on-source observation, owing to the continuum flux of the source. On-line processing consisted in taking the difference between the on-source and the off-source observations. During off-line processing, the spectra were averaged together and the effects of the telescope/receiver/spectrometer system (baseline sinusoids, glitches with a 10-

TABLE I. Past and present radio observations of S121.

Frequency (GHz)	Wavelength (cm)	Total continuum flux density (Jy)	Telescope location[a]	Telescope HPBW (arcmin)	Reference
1.4	21.4	$\leqslant 1.0$[b]	Green Bank—91-m	10	Pauliny-Toth *et al.* (1966)
1.4	21.4	$\leqslant 1.4$[b]	Green Bank—91-m	10	Felli & Churchwell (1972)
1.4	21.2	$\leqslant 0.87$[b]	Nançay—300-m	4×22	Kazès *et al.* (1975)
1.4	21.0	0.46	Penticton—0.61-km	0.8×1.5	Higgs and Vallée (1984)
3.3	9.0	$\leqslant 0.70$[b]	Algonquin—46-m	8.23	This paper (1983)
4.8	6.2	0.47	Nançay—300-m	1.5×7	Kazès *et al.* (1975)
5.0	6.0	$\geqslant 0.12$[c]	Westerbork—1.5-km	0.1	Felli & Harten (1981b)
10.5	2.85	0.46	Algonquin—46-m	2.67	This paper (1983)
10.7	2.80	$\leqslant 1.2$	Stanford—0.2-km	0.3×0.4	Felli *et al.* (1974)
115.3	0.26	—	Holmdel—7-m	1.7	Blitz *et al.* (1982)
			Fort Davis—5-m	2.3	

[a] Single dish diameter in meters; longest interferometer baseline in kilometers.
[b] Flux density value may be an overestimate, due to background confusion.
[c] Flux density value may be an underestimate, due to missing short baselines.

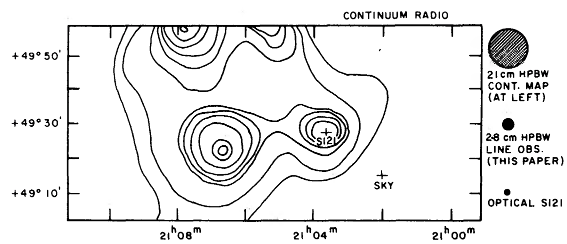

FIG. 2. Sketch of the continuum emission at radio wavelengths, adapted from the contour map of Felli and Churchwell (1972) near λ 21 cm whose HPBW is shown (top right corner). The HPBW used for the hydrogen recombination line H85α near λ 2.8 cm at the Algonquin Radio Observatory is also shown (at right), along with the two positions (+) where such line observations were made (S121, Sky). The size of the object S121 at optical wavelengths is sketched (bottom right corner).

channel period, etc.) were removed.

The beam efficiency was 0.80 at 3327 MHz, and it was 0.65 at 10522 MHz. The total on-source and off-source observing time on S121 was 26 hr at 3327 MHz, and it was 52 hr at 10522 MHz. An additional amount of observing time was spent on the "Sky" position (at RA = $21^h02^m00.00^s$ and Dec = + 49° 15′ 00.00″), equal to the time spent at the S121 position.

III. RESULTS AT ALGONQUIN

Figure 3 shows the H125α recombination line spectra obtained at Algonquin, for each of the two filter banks and for both the object S121 and a "sky" position shown on Fig. 2 (at RA = $21^h02^m00.00^s$, DEC = + 49°15′00.00″). The H125α line is seen toward S121 in both filter banks, but this line is not seen toward the "sky" position.

Figure 4 shows the H85α recombination line spectra obtained at Algonquin, for each of the two filter banks and for both the object S121 and the "sky" position shown on Fig. 2. The H85α line is seen again toward S121 in both filter banks, but is not seen toward the "sky" position.

Table II gives the observational data pertaining to the Algonquin observations of S121. The line amplitude, linewidth, and line displacement were obtained by fitting a Gaussian to the spectra.

Averaging over the four spectra toward S121 [tops of Figs. 3(a), 3(b), 4(a), 4(b)], we obtain a weighted mean Doppler displacement of -54 ± 4 km s^{-1} (as weighted by the inverse square of the signal-to-noise in the antenna line temperature) and a weighted mean linewidth of 18 ± 5 km s^{-1} (as weighted by the uncertainties in the linewidths).

IV. INTERPRETATION AND DETERMINATION OF S121

The mean Doppler displacement $V_{\rm LSR} \approx -54$ km s^{-1} corresponds to the kinematical distance $R_{\rm kin} \approx 6.5$ kpc (from the curves of radial velocity versus distance from the Sun given in Burton 1974). The optical diameter ($\simeq 1.2$ arcmin) corresponds at this distance to a linear diameter of 2.2 parsecs.

At this point, we may consider the four proposed interpretations. (i) Planetary nebula—the linear diameter obtained from the distance and the optical angular size weighs heavily against the planetary nebula interpretation, because the diameter is a factor of 10 too large for a typical planetary nebula (see, e.g., Higgs 1971; Perek and Kohoutek 1967). (ii) Supernova remnant—the very existence of a recombination line from S121 at the typically expected ratio of T_l/T_c is strong evidence against S121 being a nonthermal, compact source inside a supernova remnant. (iii) Extragalactic source—it is unlikely that S121 is superposed over an extragalactic radio source, since such a compact source is not seen in the Westerbork map of Felli and Harten (1981b), and since a thermal spectrum is implied from the continuum flux densities observed at Algonquin, Nançay, and Penticton (Table I). (iv) H II region—we are left with the original interpretation of S121 as a H II region, owing to its recombination line and thermal spectrum and optical

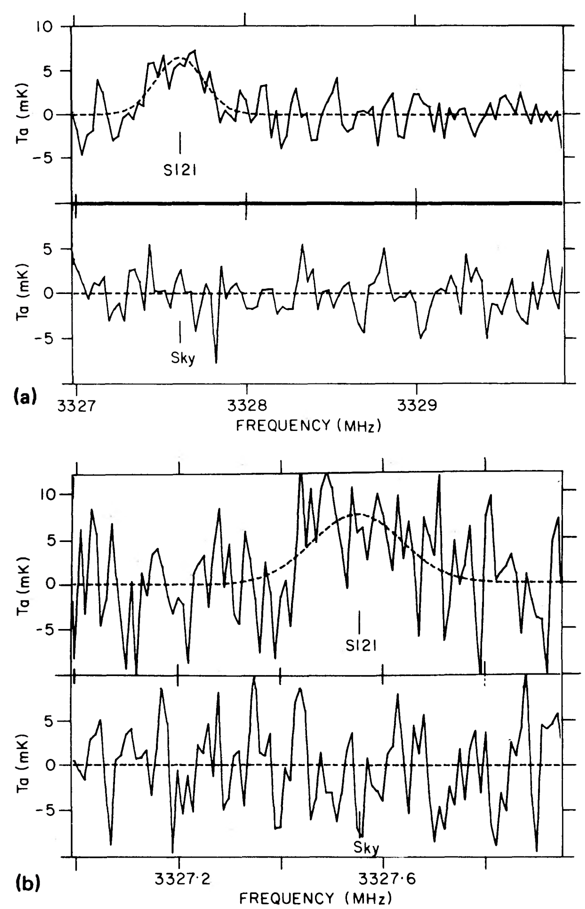

FIG. 3. H125α recombination line spectra at Algonquin, with the telescope pointing at the object S121 (top) and the telescope pointing at a "sky" position (bottom). (a) Filter bank one with 30-kHz spectral resolution. (b) Filter bank two with 10-kHz spectral resolution.

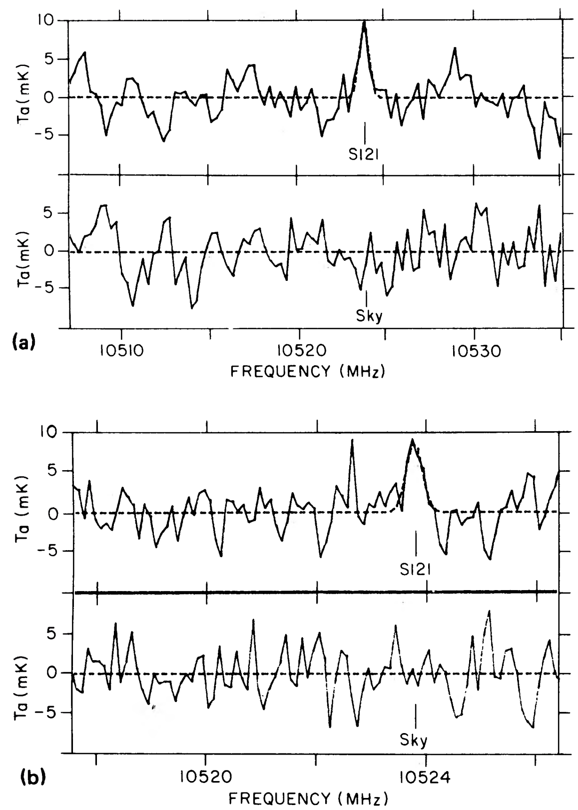

FIG. 4. H85α recombination line spectra at Algonquin, with the telescope pointing at the object S121 (top) and the telescope pointing at a "sky" position (bottom). (a) Filter bank one with 300-kHz spectral resolution. (b) Filter bank two with 100-kHz spectral resolution.

size. In addition, the H2α line of Crampton *et al.* (1978) indicates roughly the same radial velocity, being about -60 km s^{-1} with respect to the standard solar motion (but no linewidth or line amplitude is reported). The CO molecular line seen at the position of S121 (Blitz *et al.* 1982) has a $V_{\rm LSR} \approx -61$ km s^{-1} corresponding to a kinematical distance of $R_{\rm kin} \approx 7.1$ kpc from the Sun (toward $l^{\rm II} \approx 90°$ in the galactic plane). It is known that a small velocity difference (up to 10 km s^{-1}) is generally found between a typical H II region–CO cloud system (e.g., Israel 1978). Blitz *et al.* (1982) stated that the H II region and the CO cloud appear to be "definitely related in spite of the weakness of the [CO] line," especially since the CO cloud "peaks at the position of the H II region." We are most likely dealing with a region of star formation, where the (unseen) star(s) has given rise to the observed radio emission.

V. PHYSICAL MODELING OF S121

In this section, we derive various physical properties of this H II region. (a) Shape of S121—Felli and Harten (1981a) assumed a Gaussian-shaped region, as well as an electron temperature of 10^4 K, and derived a Gaussian electron density of 128 cm^{-3}, using a kinematical distance derived from the H2α line of Crampton *et al.* (1978). In the following, we will use a shell-shaped region, with the inner and outer radii as measured on the optical photograph (Fig. 1), and we will obtain the electron temperature from the Algonquin recombination lines.

(b) Physical parameters—we make use of a FORTRAN program (Vallée *et al.* 1977; Viner *et al.* 1979) whose inputs are the radial variations in electron density (e.g., shell type), temperature, turbulence, and expansion velocity (positive, zero, or negative). Employing the full non-LTE recombination theory with the inclusion of pressure broadening by inelastic electron collisions, this program gives the continuum and recombination line emission to be expected from a spherically symmetric H II region. The choice of the input data to the program is obtained for S121 via an algorithm, shown in Fig. 5. Setting first a low expansion velocity, the program is cycled through successive values of electron temperature (upward arrow at left), each time computing the turbulent velocity (from the observed linewidth) and the electron density (from the mean observed radio continuum flux density). This temperature cycle terminates when the predicted and observed line flux densities match. At this point, the whole scheme is started anew with an increased expansion velocity (upward arrow at right). This expansion velocity cycle terminates soon for S121, because large values of either the expansion velocity and/or the turbulent velocity are ruled out by the observed linewidth. Table III(a) lists the physical properties so derived.

TABLE II. Observational data.

i. Observing wavelength (line)	9.01 cm (H125α)	2.85 cm (H85α)
ii. Rest frequency of H$n\alpha$ line	($n = 125$) 3326.988 MHz	($n = 85$) 10 522.040 MHz
iii. Filter bank channel width	30 kHz; 10 kHz	300 kHz; 100 kHz
iv. Doppler-displacement velocity $V_{\rm LSR}$	-57 ± 2 km/s; -50 ± 2 km/s	-50 ± 2 km/s; -49 ± 2 km/s
v. Full width at half-intensity of line	30 ± 4 km/s; 19 ± 5 km/s	17 ± 6 km/s; 10 ± 3 km/s
vi. Peak line antenna temperature $T_{\rm LA}$	6.5 ± 0.8 mK; 7.5 ± 1.5 mK	10.0 ± 2.7 mK; 8.8 ± 2.0 mK
vii. Peak line brightness temp.	412 mK[a]	72 mK[a]
viii. Line flux density of S121	13 mJy[a]	23 mJy[a]
ix. Continuum flux density of S121	—	0.46 Jy
x. Line-to-continuum ratio	—	0.05

[a] Using the average of $T_{\rm LA}$ from both filter banks, and a source size of 1.2 arcmin.

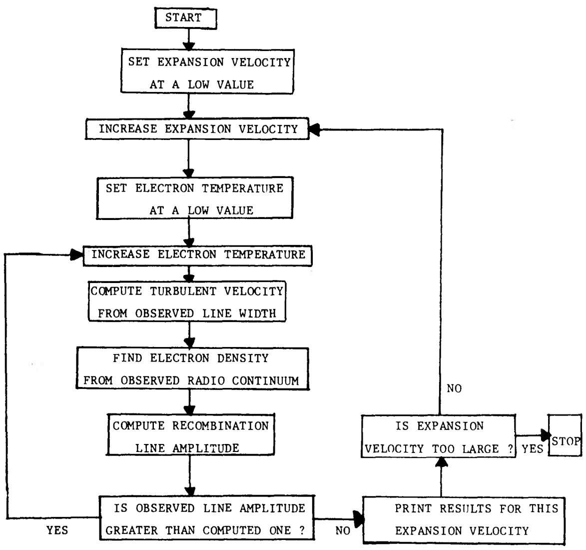

FIG. 5. Algorithm used to obtain the physical parameters in the model of the H II region, as used for S121.

(c) Dynamical parameters—The ring-type optical morphology (Felli and Harten 1981b) is the only clue so far on the dynamics of S121. A suggestive (but not definite) dynamical model could be that of Dyson (1977, 1978) and of Weaver *et al.* (1977) for stellar-wind-driven shells around stars. The algorithm used by Vallée *et al.* (1979) to match the observations of the H II shell IC1805 to the stellar-wind theories of Dyson (1977, 1978) can be used here for the shell of S121. Specifically, the use of Eqs. (4)–(8) of Vallée *et al.* (1979) as prescribed will successively give the shell age, the mechanical luminosity of the stellar wind, the shell velocity, followed by the shell kinetic energy as well as the total energy put in by the stellar wind, and other parameters. Table III(b) lists the properties of S121 derived from the stellar-wind theories. The low value derived here for the shell velocity suggests that the shell may have just left the expanding-shell stage, to enter the stalled-shell stage where the shell has been stalled (e.g., Weaver *et al.* 1977) by the exterior pressure of its surrounding medium [inequality signs in Table III(b) have been introduced to cover this later stage]. More observations are needed to show whether or not the most appropriate dynamical model for S121 is indeed that of a stellar-wind-driven shell.

VI. CONCLUSIONS

Observations of recombination line and continuum emission near 3327 MHz and 10 522 MHz have been made, and they were used to eliminate all but one interpretation of the object S121. These observations were further used to model a shell-type H II region to obtain the basic physical parameters for the object S121. A further analysis, under the assumption that the shell is driven by a stellar wind, was made in conjunction with stellar-wind theories and an appropriate matching algorithm, finally yielding dynamical parameters for S121. Optical observations would be useful to detect the in-

TABLE III. Physical properties of S121.

Property	Value	Primary origin
(a) Derived from basic observations:		
i. Kinematical distance	6.5 kpc	Average V_{LSR} of Hnα line
ii. Central emission measure	8×10^4 pc/cm^6	Radio continuum flux
iii. Monochromatic power, at λ 2.8 cm	2×10^{15} W/Hz	Radio continuum flux
iv. 10 MHz–100 GHz radio luminosity	2×10^{26} W	Radio continuum flux[a]
v. Inner, outer radius of shell	0.85 pc, 1.30 pc	Angular sizes (Palomar S.S.)
vi. Electron temp. in shell, T_s	9000 K	Primarily from Hnα ampl.
vii. Shell electron density, n_s	180 cm^{-3}	Primarily from radio cont.
viii. Turbulent velocity in shell, V_t	6 km/s	Primarily from Hnα width
ix. Mass of ionized gas in shell, M_s	39 $M_\odot$	Shell radii and density
x. Radio excitation parameter, U	38 pc/cm^2	Radio continuum flux
(b) Derived from stellar-wind theory:		
xi. Initial homogeneous electron density, N_0	130 cm^{-3}	Shell radii and density
xii. Age of shell, t_s	$>6.5\times10^4$ yr	N_0, shell density and radii
xiii. Expansion velocity of shell, V_s	<12 km/s[b]	Shell age and radii
xiv. Kinetic energy of shell, E_s	$<5\times10^{46}$ ergs	Shell mass and exp vel.
xv. Mechan. luminosity of wind, L_w	2×10^{35} erg/s	Shell N_0, radii, age
xvi. Wind speed, V_w	2000 km/s	Typical value (Snow & Morton 1976)
xvii. Total energy, E_t	$>3\times10^{47}$ ergs	Age and mech. luminosity
xviii. Stellar mass-loss rate, M_w	1×10^{-7} $M_\odot$/yr	Mechan. lumin. and V_w
xix. Ejected stellar mass, M_e	$>8\times10^{-3}$ $M_\odot$	Age and stellar mass-loss rate
xx. Optical spectral type of star	$<$O8.5 V	Radio excitation parameter

[a] Assuming a thermal spectral index of -0.1 and a turnover frequency of 190 MHz.
[b] Such a low value for V_s suggests that S121 may have left the expanding shell stage, to enter the stage where the shell has been recently stalled by the exterior pressure of its surrounding medium.

ferred 08.5-type star which powers and ionizes the shell, and a detailed CO/molecular map of the region would be useful to clarify the interaction between the H II region and any molecular cloud.

It is of interest to note the existence of yet another object in Sharpless' catalog (S80) that has received multiple interpretations in the literature. There are many similarities between S80 and S121. In particular, S80 has now been shown via line observations (Solf and Carsenty 1982) to be a H II region, with a nearly spherical shell, powered by mass loss from a star, with a shell age of a few times 10^4 years.

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