THE ASTRONOMICAL JOURNAL VOLUME 82, NUMBER 9 SEPTEMBER 1977

The true extent of the γ Cygni supernova remnant

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(Received 23 May 1977)

Aperture-synthesis observations at 1.4 GHz show that the γ Cygni supernova remnant (SNR) has a shell structure of $\sim$62-arcmin diameter, centered at $l = 78\overset{\circ}{.}2$, $b = +2\overset{\circ}{.}1$. Radio emission from the shell is strongest in the southeast quadrant, near the star γ Cygni, where it is concentrated in several tangentially elongated structures. A second region of enhanced nonthermal emission is in the northwest quadrant. Based on a brightness–diameter relation, the observed flux density of 270 ± 40 Jy implies a diameter of $\sim$33 pc and a distance of $\sim$1.8 kpc. Thermal radio emission is observed from the γ Cygni Nebula which lies near γ Cygni and coincidentally near the peak emission of the SNR. The possible significance of the near positional agreement of the thermal and nonthermal radio sources is discussed.

INTRODUCTION

FOR many years, the presence of a strong nonthermal radio source in the vicinity of the F8 Ib star γ Cygni has been known. This source is generally assumed to be a supernova remnant (SNR), although no good optical evidence of such a remnant has been found. A small, bright optical nebulosity, discovered by Drake (1959) very close to γ Cygni, has sometimes been suggested as a visible feature of the SNR (e.g., van den Bergh *et al.* 1973), but detailed optical observations (Johnson 1974, 1976; Lozinskaya 1976) have shown that this nebulosity resembles a normal H II region. It is generally agreed that there is no physical relationship between the star γ Cygni, almost certainly a foreground object, and either the nonthermal radio source (SNR) or the optical nebulosity, but some relationship between the latter two has not been ruled out. In the following, the SNR corresponding to the nonthermal source near γ Cygni will be referred to as the "γ Cygni Supernova Remnant," while the small optical nebulosity will be called the "γ Cygni Nebula."

From a recent 10-GHz survey of the region around γ Cygni, Higgs (1977) confirmed that there are *two* nonthermal radio sources in the vicinity: the one mentioned above plus a second weaker source some 45 arcmin to the northwest. Previously, the angular size of the γ Cygni Supernova Remnant had been quoted as $\sim$10 arcmin, but the 10-GHz observations once again suggested the possibility that the SNR is actually much larger, with the two nonthermal radio sources being brighter regions in an extended shell of emission.

To study this possibility, 1.4-GHz aperture-synthesis observations of the γ Cygni region were undertaken in the summer of 1976.

I. THE OBSERVATIONS

We have used the synthesis radio telescope at the Dominion Radio Astrophysical Observatory (Roger *et al.* 1973) to map a 2-deg square region centered near γ Cygni in both the continuum and H I line at 21-cm wavelength with a resolution of 2×3 arcmin. The left-hand circularly polarized component of the continuum radiation was received in a 15-MHz band from which H I emission was excluded by a notch filter. The line observations, which cover a 1-MHz band with a velocity resolution of 2.6 km sec^{-1}, will be described in detail in a later paper.

Observations, each of 12-h duration, at 68 spacings provided complete sampling of the u,v plane from 61 to 1421 λ E–W. The visibility coefficients were graded with a Gaussian function dropping to 20% at the maximum spacing; the resulting synthesized beamwidth is 2.0 arcmin E–W by 3.1 arcmin N–S. For the continuum observations, the missing lower-order components (spacings $< 61\ \lambda$), corresponding to structure of order 30 arcmin and greater, were extracted as complex visibility coefficients from the single-antenna observations of Wendker (1966) at 1414 MHz. A map synthesized from these low-order coefficients was added to the map derived from the interferometer observations, corrected for the polar diagram of the primary beam.

At each spacing the interferometer observations were calibrated in amplitude and phase by measurements of the point sources 3C 147 and 3C 295, for which flux densities at 1.4 GHz of 22.2 and 22.7 Jy (Kellermann *et*

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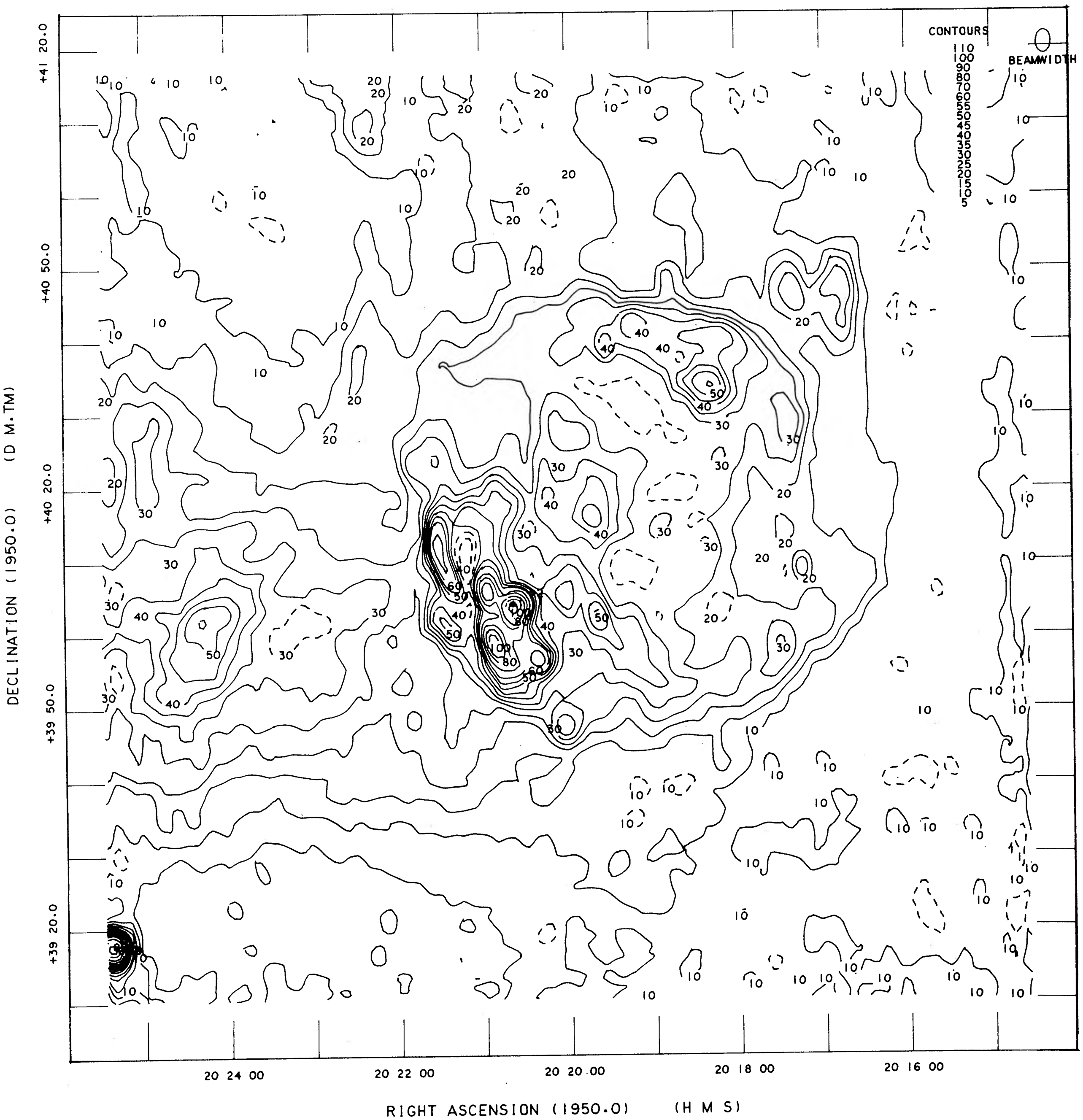

FIG. 1. A map of the 1.4-GHz continuum emission from the γ Cygni region in contours of brightness temperature. Asterisks, almost hidden in the contours of the bright complex in the southeast quadrant, indicate the position of the center of the γ Cygni Nebula (1) and of the star γ Cygni (2). Resolution 2.0 × 3.1 arcmin.

al. 1969) were assumed. The data used for the low-order components were calibrated (Wendker 1966) using flux densities of Cyg A, Tau A, and Vir A taken from Baars, Mezger, and Wendker (1965).

Figure 1 is the map of the continuum emission including data for all spacings. The contours represent brightness temperature, with 1 K equivalent to 30.5 mJy/beam area.

II. RESULTS

A. Structure of Supernova Remnant

The map in Fig. 1 shows a nearly complete shell of emission centered to the northwest of γ Cygni (indicated by the asterisk numbered "2" in the figure), clearly suggestive of a SNR. This shell is centered at $\alpha = 20^h$

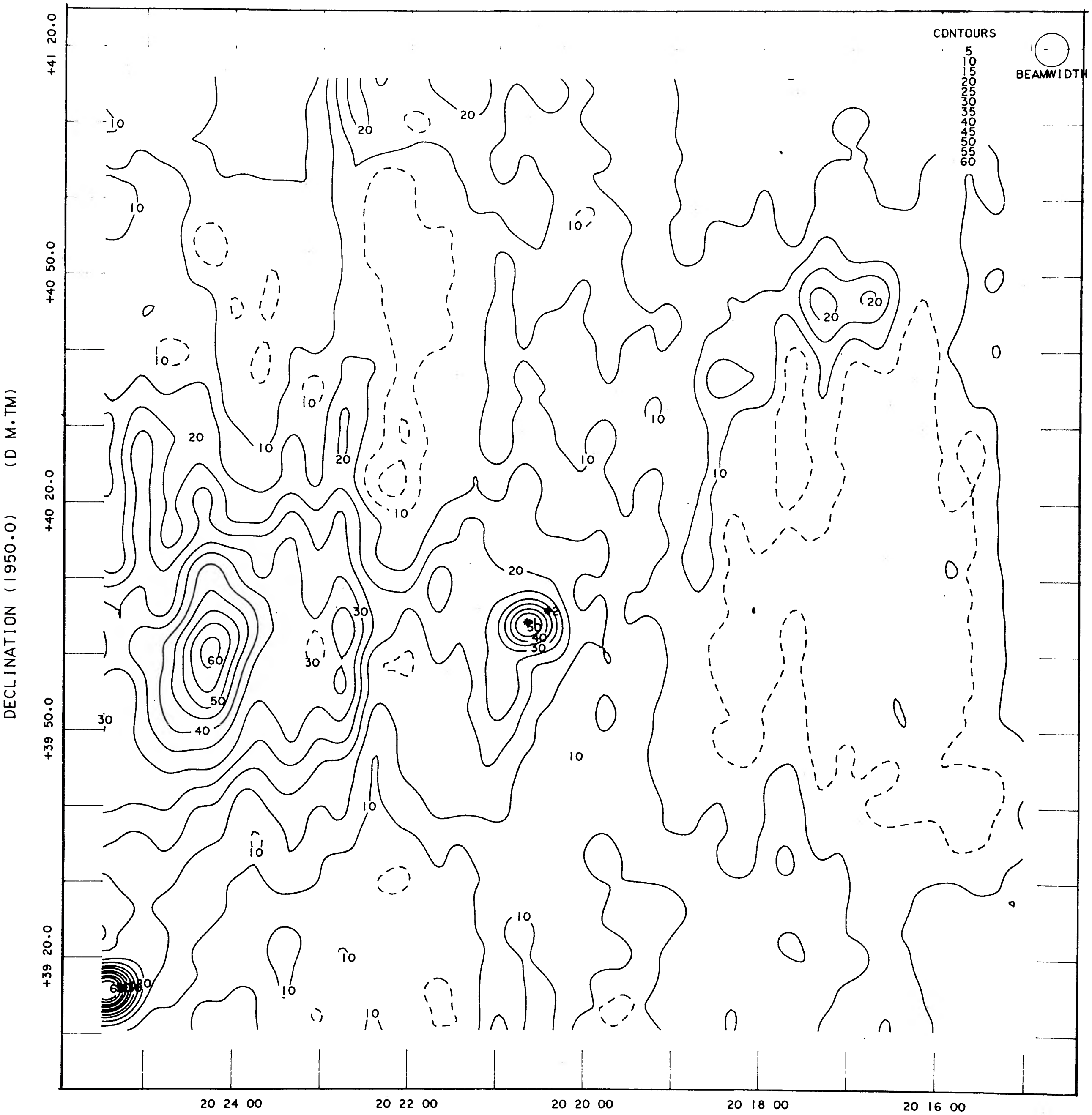

FIG. 2. A map of the thermal component of the continuum emission at 1.4 GHz, computed from the map in Fig. 1 and the 10-GHz map of Higgs (1977). Resolution 4 arcmin.

$19^m\ 25^s$, $\delta = 40°\ 17'$ (1950); $l = 78\overset{\circ}{.}19$, $b = 2\overset{\circ}{.}13$. There appear to be gaps in the shell in the northeast and southwest quadrants. Allowing for our beam size, the shell has a diameter of ~62 arcmin. The position of the γ Cygni Nebula is indicated by the asterisk numbered "1" in the figure and an emission feature is coincident with it. The brightest portion of the supernova shell is near this feature, with the emission being concentrated in structures elongated tangentially with respect to the shell. [This complex corresponds to DR4 in the source list of Downes and Rinehart (1966).] A second region of enhanced emission in the shell lies in the northwest quadrant (DR3). Outside the supernova shell, three emission features are apparent. The large feature near the eastern edge of the map ($\alpha = 20^h\ 24^m$, $\delta = 40°$) is associated with the emission nebula IC 1318b. At the

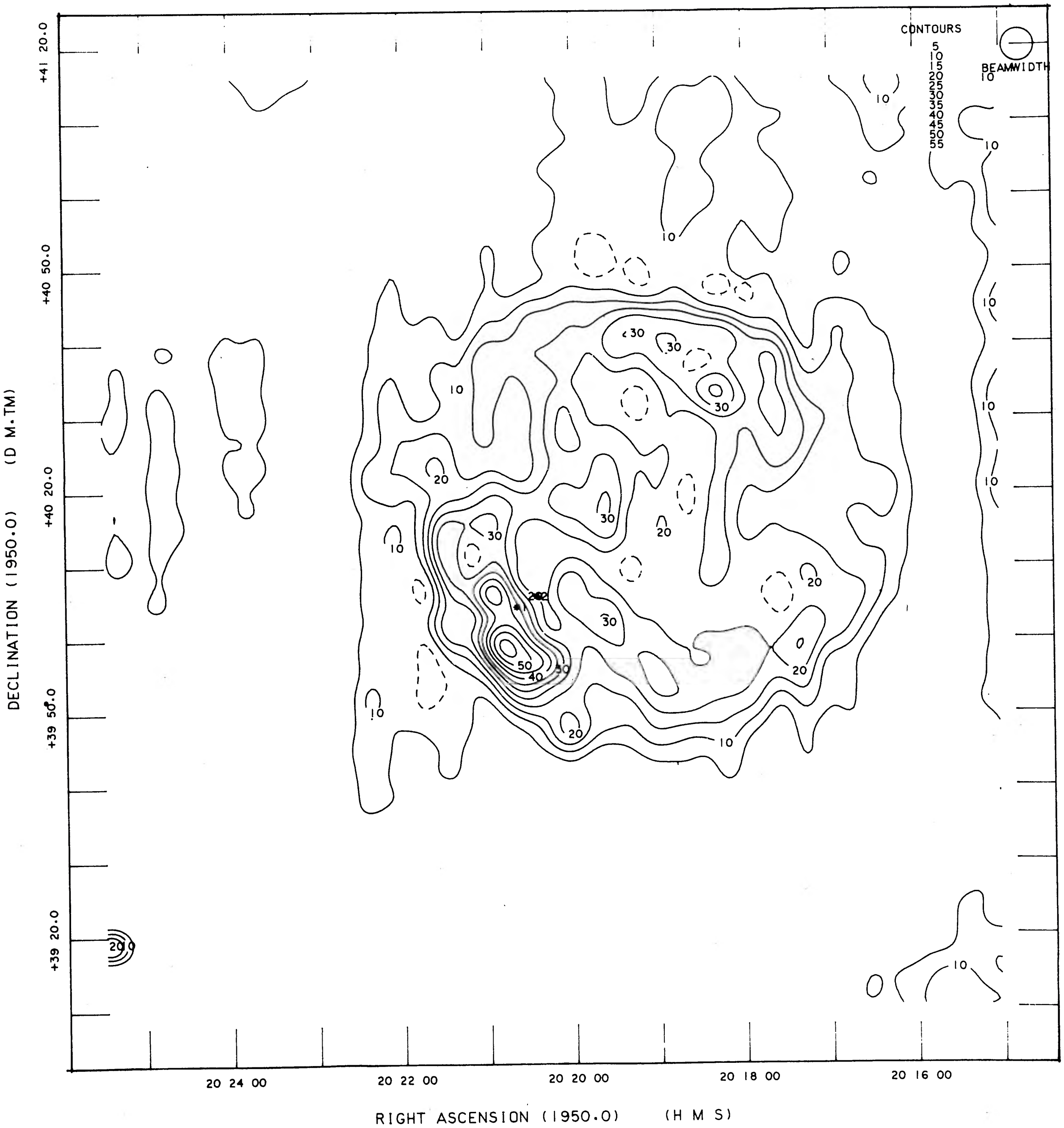

FIG. 3. A map of the nonthermal component of the continuum emission at 1.4 GHz, computed from the map in Fig. 1 and the 10-GHz map of Higgs (1977). Resolution 4 arcmin.

very southeast corner of the map is the compact thermal source G78.1 + 0.6 (DR6). Just outside the shell to the northwest there is a weak complex emission region (α = 20$^{\rm h}$ 17$^{\rm m}$.1, δ = 40° 46′), hereafter referred to as G78.3 + 2.8.

A radio photograph covering the same area as Fig. 1 is presented in Plate IX (p. 772). This gives a better overall impression of the SNR than does the contour map.

B. Separation of Thermal and Nonthermal Emission

If an area of sky contains only two types of radio-emitting regions, each with a distinctive spectral index, it is possible to separate the contributions from the two by using observations made at two different frequencies, but with the same angular resolution. Thus it is theoretically possible to separate the map in Fig. 1 into one map of thermal emission regions and one of nonthermal

TABLE I. Estimated 1.4-GHz flux densities (in janskys).

Thermal flux from γ Cygni Nebula	4.5 ± 1.0
Thermal flux from G78.3 + 2.8	16 ± 5
Nonthermal flux from SNR (within 32-arcmin radius)	270 ± 40
Thermal flux in whole map	980 ± 70
Nonthermal flux in whole map	320 ± 50

emission regions, if data obtained at another frequency are also used. For this purpose we have used the 10-GHz map given by Higgs (1977) with 4-arcmin resolution and a 1.4-GHz map derived by convolving the map in Fig. 1 to the same resolution. If T_n and T_t denote the nonthermal and thermal components of the observed brightness temperature at a given point in the resulting 1.4-GHz map ($T_{1.4} = T_t + T_n$), the corresponding observed brightness temperature in the 10.6-GHz map would be

$$T_{10.6} = (10.6/1.4)^{\beta_t} T_t + (10.6/1.4)^{\beta_n} T_n.$$

Here, β_t and β_n are the spectral indices of the thermal and nonthermal components, respectively. Clearly, if values of β_t and β_n are assumed, T_t and T_n can be calculated at each point from the observed $T_{1.4}$ and $T_{10.6}$. Several sets of β_t, β_n values were used to produce maps of thermal and nonthermal components. The best separation (least "negative" emission) was obtained for $\beta_t = -2.05$ and $\beta_n = -2.65$. The resulting 1.4-GHz maps are presented in Figs. 2 and 3. It must be remembered that this technique assumes constant spectral indices over the map area.

Weak north–south features are apparent in both the thermal and nonthermal maps; these are attributable to residual baseline errors in the 10-GHz map (see Higgs 1977). The thermal map in Fig. 2 shows that the emission peak coinciding with the γ Cygni Nebula is indeed thermal, as is the emission from G78.3 + 2.8. The latter region has been studied by Sabbadin (1976), who found it to be a normal H II region (his No. 9), supporting the above conclusion. The H II regions IC 1318b and G78.1 + 0.6 also appear as thermal sources.

The nonthermal map (Fig. 3) clearly shows the supernova shell. A weak nonthermal region extending to the north of the shell may also be real. On the other hand, a weak nonthermal component at the position of G78.1 + 0.6 is probably not real. It may result from the thermal source having an optically thick component or there may be a slight pointing error in the 10-GHz map. Since G78.1 + 0.6 is at the 14% level of the primary-beam response, this apparent nonthermal component will not be discussed further here.

Since one would have expected β_t to be -2.11, the deviation of 0.06 probably reflects a scale error between the 1.4- and 10.6-GHz data. Therefore we estimate the true spectral index of the SNR to be -0.7 ± 0.1. Variations of this index across the SNR are possible but would not have been detected by the above procedure. Integrated flux densities of sources can be derived from these maps and some are tabulated, with estimated errors, in Table I.

III. DISCUSSION

A. The γ Cygni Supernova Remnant

We have estimated the physical size of the γ Cygni SNR by means of the empirical surface brightness–diameter (Σ–D) relation for 408 MHz derived by Clark and Caswell (1976):

$$\Sigma_{408} = 10^{-15} D^{-3} \quad (\Sigma_{408} > 3 \times 10^{-20}\ \mathrm{W\ m^{-2}\ Hz^{-1}\ sr^{-1}}), \tag{1a}$$

and

$$\Sigma_{408} = 3.6 \times 10^{-5} D^{-10} \quad (\Sigma_{408} < 3 \times 10^{-20}\ \mathrm{W\ m^{-2}\ Hz^{-1}\ sr^{-1}}). \tag{1b}$$

Using the spectral index $\alpha = -0.7$ and the angular diameter of 62 arcmin, we find that the mean surface brightness at 408 MHz is $(2.5 \pm 0.5) \times 10^{-20}$ W m^{-2} Hz^{-1} sr^{-1}. This value is near the transition from Eq. (1a) to (1b) and from either we derive a diameter for the SNR of 33 pc and a distance of 1.8 kpc. Diameters and distances estimated in this way are probably correct to ~30% (Clark and Caswell 1976).

Models for the evolution of SNRs (e.g., Woltjer 1972) indicate that adiabatic expansion will continue until the radial expansion velocity has decreased to ~200 km sec^{-1}. The rate of expansion is dependent on the density of the surrounding interstellar medium. Examination of the H I emission profile in the γ Cygni direction allows a crude estimate of 0.5 atoms cm^{-3} for the neutral-gas density in the first 6 kpc. (An average over this large distance is necessary because of the low velocity dispersion at $l = 78°$, almost tangential to the solar circle.) Since it is quite likely that the gas density in the region of the SNR exceeds the average, we take a density of 1 atom cm^{-3} as a plausible value. A similar estimation of the H I density near 3C 10 (Tycho's SNR) yields a value about an order of magnitude lower. From the known age of 3C 10 and from estimates of its diameter (~14 pc) given by Clark and Caswell (1976), we estimate an age for the γ Cygni SNR of $10^{4.1 \pm 0.3}$ yr and a radial expansion velocity of 600 ± 300 km sec^{-1}. This implies that the expansion may still be largely adiabatic.

It is interesting to note that a possible source of soft x-ray emission has been detected at the 3-σ level in the region of the γ Cygni SNR (Burginyon *et al.* 1973). In addition, γ-ray observations at energies >30 MeV from the COS-B satellite (Caravane Collaboration 1976) have shown an enhancement of emission near the region of maximum intensity of the SNR in the southeast quadrant. Observations with better sensitivity and resolution are required to make any physical association with the SNR definite.

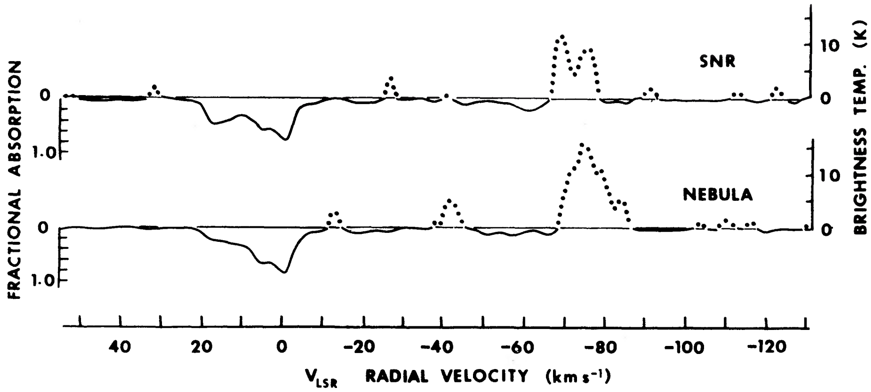

FIG. 4. Spectra of H I emission (positive-going dotted lines) and fractional absorption (negative solid lines) versus radial velocity in the direction of the γ Cygni Nebula and of the nearby peak of emission from the SNR. Computed from synthesis spacings 61–1421 λ.

B. The γ Cygni Nebula

The present observations, and those of Baars *et al.* (1977), show that this nebulosity is a thermal source. It is of interest to derive the type of exciting star required to ionize this region. From the blackbody approximations of Higgs and Ramana (1968) and the flux density in Table I, we find that a single O9.5 V–B0 V star would account for the radio emission if the nebulosity were at a distance of 1.3–2.1 kpc. [This range of distances is typical for most of the nebulae in the Cygnus X region; see, for example, Dickel *et al.* (1969).] Baars *et al.* (1977) present arguments favouring such an exciting star and suggest that star No. 1 of Archipova *et al.* (1974) is the likely candidate. If an approximate angular diameter of 4.5 arcmin is adopted for the radio source, the rms electron density (for d = 1.7 kpc) is 150 $\pm$ 20 cm^{-3} and the total mass of the region is 30 $\pm$ 4 $M_{\odot}$, assuming a uniform-density spherical source ($T_e = 10^4$ K).

Observed LSR radial velocities of the nebulosity (Johnson 1974; Lozinskaya 1976) range from -2 to $+9$ km sec^{-1}, with a value near $+5$ km sec^{-1} appearing most probable. At the galactic longitude of this object no reliable kinematic distances can be derived for $V_r > -5$ km sec^{-1} ($d < 5$ kpc) so that an estimate of the distance to the nebulosity must rest on the identification of the exciting star.

The fact that the position of the γ Cygni Nebula is near the most intense components of the SNR may be more than a coincidence. The brightest portions of the SNR might be expected to be where the expanding supernova shell has encountered a dense interstellar cloud. It is in just such a region that one might also expect star formation to take place. Considering the time scales involved ($\sim 10^6$ yr for the star, $\sim 10^4$ yr for the SNR), it is extremely unlikely, however, that compression of the interstellar medium by the SNR has *caused* the star formation. The near coincidence of the enhanced emission in the northwest quadrant of the shell and the thermal source G78.3 + 2.8 is also suggestive of an interaction between the supernova shell and an interstellar cloud. The electron density of G78.3 + 2.8 is estimated to be $\sim$90 cm^{-3}, much lower than that deduced for the γ Cygni Nebula; thus the cloud to the northwest is possibly less dense than that to the southeast. On the other hand, the form of the SNR is not unusual and may reflect the structure of the interstellar magnetic field more than the density structure of the region.

Preliminary profiles of the 21-cm line emission and absorption in the directions of the γ Cygni Nebula and the brightest SNR component ($\alpha = 20^h 20^m 53^s$, $\delta = 39° 59'$) are presented in Fig. 4. The similarity in the absorption profiles gives no indication of a difference in the distances of the two sources of radio emission, although it does not show that they are at the *same* distance. We feel, therefore, that it is quite likely that the γ Cygni Nebula is physically close to the SNR but not *causally* related to it.

We are grateful to Mr. J. D. Lacey and Mrs. D. I. Stewart for their generous help with the observing. Dr. C. H. Costain and Mr. P. E. Dewdney contributed extensively to the development of computer programs used for the first time in the reduction of these data.

We are indebted to Dr. Baars, Dr. Dickel, and Dr. Wendker for communications of their results prior to publication.

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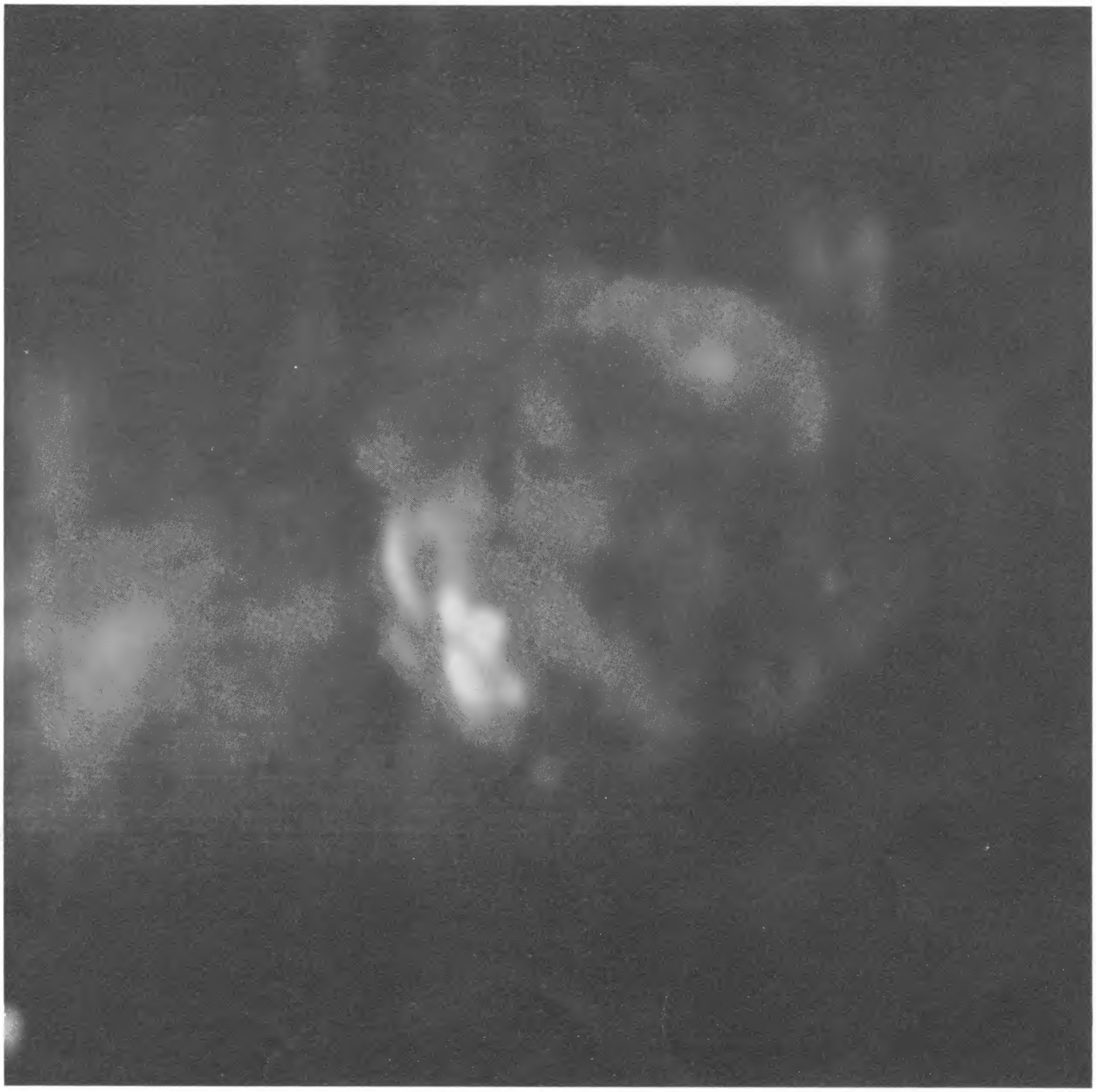

PLATE IX (Higgs, Landecker, and Roger, p. 718). A radio photograph of the γ Cygni supernova remnant. The field of the photograph is approximately 2° on a side, with north at top and east to the left. The nebulous patch at left center is thermal emission from IC 1318b while the point source at lower left is the compact thermal source G78.1 + 0.6.