November 1, 1993

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INTERACTION BETWEEN THE SUPERNOVA REMNANT CTB 80 AND THE AMBIENT INTERSTELLAR MEDIUM: H I AND CO OBSERVATIONS

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Received 1993 January 28; accepted 1993 May 4

ABSTRACT

We performed VLA H I 21 cm line and ^{12}CO $J = 1-0$ line observations of the old supernova remnant (SNR) CTB 80. The clumpy structure of the fast, $v_{\text{exp}} \sim 72 \text{ km s}^{-1}$, expanding SNR shell detected by Koo et al. (1990) is found to be due to fast-moving H I clumps, which have a dense, $n_{\text{H}} \sim 100 \text{ cm}^{-3}$, core surrounded by a relatively diffuse envelope. These clumps are most likely the preexisting “cold clouds” in the ambient interstellar medium (ISM) that had been swept-up and accelerated by the SN blast wave. CO observations show that most of the molecular gas in this region is confined into two large filamentary clouds. There is no certain evidence for the interaction between the SNR and the molecular cloud. By analyzing the Arecibo H I data of Koo et al., we found that the ISM around CTB 80 is far from being uniform and homogeneous. Instead, it seems to be composed of a large cold cloud, a warm neutral medium pervaded by small cold clouds, and a tenuous hot tunnel, which is close to the McKee & Ostriker’s three-phase ISM model. We discuss how the ambient ISM shaped the morphology of CTB 80 in H I, infrared, and radio continuum.

Subject headings: ISM: general — ISM: individual (CTB 80) — radio lines: ISM — supernova remnants

1. INTRODUCTION

Recent detection of a rapidly expanding H I shell by Koo et al. (1990, hereafter KRHFS), together with its associated pulsar PSR 1951+32 (Strom 1987; Kulkarni et al. 1988; Fruchter et al. 1988), makes CTB 80 a “Rosetta stone” for studies of old supernova remnants (SNRs). The H I shell, expanding at 72 km s^{-1} with a radius of $19d_2 \text{ pc}$ where $d_2 \equiv d/(2 \text{ kpc})$ is the distance to CTB 80 in units of 2 kpc, is located around the radio continuum emission of CTB 80 and is most likely a SNR shell associated with CTB 80. The shape of the H I shell is almost circular with its southwestern portion opened and matches that of the infrared shell detected by Fesen, Shull, & Saken (1988), which has a relatively large 60–100 μm ratio. The morphological resemblance strongly suggests that the infrared shell is the outer boundary of the SNR shell which could not be seen in H I 21 cm line because of the Galactic background emission. It is particularly intriguing to have found that the dynamical age inferred from the observed properties of the H I shell, $7.7 \times 10^4 d_2 \text{ yr}$, agrees reasonably well with the characteristic spin-down age, $1.1 \times 10^5 \text{ yr}$, of the pulsar, because this might indicate that our current understanding of the evolution of SNRs at late stages is generally correct.

There are not many old SNRs that have been found to have H I gas moving as fast as in CTB 80, although the study of old SNRs using H I 21 cm line goes back almost 2 decades (Assousa & Erkes 1973). This is partly due to the insufficient sensitivity and insufficient bandwidth in some early observations as can be seen in HB 21, where the sensitive observations by Koo & Heiles (1991) revealed H I gas expanding at 125 km s^{-1} , much faster than the value 20 km s^{-1} of Assousa & Erkes, or in W44, where Koo & Heiles detected H I gas expanding at 150 km s^{-1} , much faster than the value 4 km s^{-1} of Knapp & Kerr (1974). Koo & Heiles detected 15 SNRs with such fast-moving H I gas among 103 known SNRs in the northern sky. Among those SNRs, G78.2+2.1, CTB 80, HB 21, CTB 109, VRO 42.05.01, and IC 443 have been studied in high, $\text{FWHM} \lesssim 3'$, angular resolution (Landecker, Roger, & Higgs 1980; KRHFS; Tatematsu et al. 1990; Braun & Strom 1986; Giovanelli & Haynes 1979). All these observations show that the fast-expanding H I gas *never* forms a complete spherical shell. Instead, they show clumpy, filamentary, and broken shell-like structures, which might indicate that the interstellar medium (ISM) is not only inhomogeneous but also nonuniform over the size of evolved SNRs, i.e., $\gtrsim 20 \text{ pc}$ scale. Therefore, the physical parameters such as dynamical age, explosion energy, etc., derived solely from H I observations, could be very uncertain. For example, in IC 443, the H I shell with a radius of 6.5 pc expanding at $\sim 90 \text{ km s}^{-1}$ (Giovanelli & Haynes) implies an age of $2 \times 10^4 \text{ yr}$ (assuming the SNR is in the pressure-driven snowplow stage; see Cioffi, McKee, & Bertschinger 1989), much older than 3000 yr implied from X-ray observations (Petre et al. 1988). In this regard, CTB 80, which has an associated $\sim 1 \times 10^5 \text{ yr}$ old pulsar and an H I shell with a similar dynamical age, is unique and deserves the title of the “Rosetta stone” for studies of old SNRs.

In this paper, we explore further the interaction of the SNR CTB 80 with the ambient interstellar medium. In KRHFS’s H I 21 cm line maps, which were obtained by using the Arecibo telescope ($\text{FWHM} = 3.3'$), the expanding shell appears clumpy. Also, their results showed that the mass per unit line-of-sight velocity interval decreases rapidly with increasing velocity, which seems to be a common property of old SNRs (Giovanelli & Haynes 1979; Koo & Heiles 1991). Note that, if a shell is expanding with a uniform velocity, we expect an equal mass per unit line-of-sight velocity (Bertout & Magnan 1987). Hence, although the evolutionary model of a SNR in a uniform medium (e.g., Chevalier 1974; Cioffi et al. 1989) seems to yield

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“satisfactory” global physical parameters, a detailed examination of the observed properties suggests that CTB 80 has evolved probably in an *inhomogeneous* medium. Evolution of SNRs in an inhomogeneous medium has been subject to considerable theoretical studies, but still many questions remain to be explored (see review by McKee 1988). In this regard, detailed observational studies of old SNRs can provide very important clues to the theoretical understanding. We performed VLA H I observations, which provided a significantly higher angular resolution ($\text{FWHM} \approx 60''$) than KRHFS’ Arecibo H I observations, and the results are reported here.

We also mapped CTB 80 in $^{12}\text{CO } J = 1-0$ line in order to study the distribution of molecular gas in this region. The molecular gas at $v_{\text{LSR}} = +8$ to $+16 \text{ km s}^{-1}$ has been detected by KRHFS, who made only three cross scans across the SNR. In § 2, we describe the H I and CO observations. In § 3 and 4, we summarize the results of H I and CO observations, respectively. We detected high-velocity dense H I clumps associated with the SNR. We found that the molecular gas detected by KRHFS is distributed along filamentary molecular clouds. In § 5, we discuss the origin of the high-velocity H I clumps and the physical association of molecular gas with the SNR. We also explore the distribution of the ISM around CTB 80 and discuss how it shaped the morphology of CTB 80 seen at other wavelengths. Finally, in § 6, we summarize the results.

2. OBSERVATIONS

H I 21 cm line observations were made using the Very Large Array (VLA) of the National Radio Astronomy Observatory⁶ (NRAO) in D-configuration on 1991 March 2 and 3. The angular diameter $\sim 60'$ of the H I shell around CTB 80 is about twice the VLA field of view, and we mapped this area by making a mosaic of five fields. The central field was centered at $(\alpha_{1950}, \delta_{1950}) = (19^{\text{h}}52^{\text{m}}30^{\text{s}}, +32^{\circ}48')$, and the centers of the other four fields were shifted by $16'$ to east, west, north, and south, respectively.

The flux and bandpass calibrator was 3C 286, which was assumed to have a flux density of 14.85 Jy at 1420 MHz. The phase calibrator, 1922+333, was observed every ~ 50 minutes, and was found to have a flux density of 3.80 ± 0.04 Jy at 1420 MHz. Both left and right circular polarizations were observed simultaneously. With on-line Hanning smoothing, the 128 channel autocorrelators with a bandwidth of 1.5625 MHz provided a velocity resolution of 2.58 km s^{-1} and a velocity coverage of 330 km s^{-1} . The calibrator frequency was shifted $\pm 1.5625 \text{ MHz}$ with respect to the source frequency in order to avoid H I 21 cm line in the band. All calibration was performed inside the AIPS (the Astronomical Image Processing Software) provided by NRAO.

During the observing period, the Sun, which was $\approx 52^\circ$ away from CTB 80, was near solar maximum, and the short spacing data were corrupted. Instead of subtracting the continuum emission from the line channels in the (u, v) plane by finding the CLEAN components of the Sun, which is not an easy task, we subtracted the continuum emission in the map plane. The continuum map was generated by averaging channels with v_{LSR} between $+121 \text{ km s}^{-1}$ and $+149 \text{ km s}^{-1}$. The continuum-subtracted line emission was averaged over four channels, in

order to increase the signal-to-noise ratio. Each field was mapped with natural weighting and CLEANed using the APCLN. The CLEAN components were convolved with a Gaussian beam of $\text{FWHM} = 60''$, which was slightly larger than the main lobe of the dirty beam. For a source larger than the beam, 1 mJy beam^{-1} corresponds to 0.17 K in brightness temperature. The CLEANed five fields were added together using the LTEST, which corrected for the primary beam response. Typical rms noise level is $\sim 1 \text{ mJy beam}^{-1}$. The shortest antenna spacing of the VLA D array is 33 m (or 160λ). The missing short spacing has two effects. First, it limits the largest scale structure which can be reasonably imaged to be $15'$. Second, it generates a negative-bowl around a source. This latter problem causes a major uncertainty in the derived physical parameters of H I structures and should be kept in mind in the following discussions.

CO $J = 1-0$ (115.2712 GHz) line observations were made using the 14 m telescope ($\text{FWHM} = 45''$) at the Five College Radio Astronomical Observatory⁷ (FCRAO) in 1991 June, October, and November. Typical system temperature was $800\text{--}1200 \text{ K}$ in June and was $600\text{--}950 \text{ K}$ in October and November. We used the 15 beam receiver QUARRY. The 32 channel filterbank with 250 kHz frequency resolution and separation provided a velocity resolution of 0.65 km s^{-1} and a velocity coverage of 20.8 km s^{-1} centered at $v_{\text{LSR}} = +10 \text{ km s}^{-1}$. The other filter bank with 1 MHz resolution was used to check any emission between $v_{\text{LSR}} = -32 \text{ km s}^{-1}$ and $+52 \text{ km s}^{-1}$. The $80' \times 65'$ area centered at $(\alpha_{1950}, \delta_{1950}) = (19^{\text{h}}52^{\text{m}}50^{\text{s}}, +32^{\circ}45')$ has been mapped at $50''$ spacing. All observations were made by position switching to a reference position $(\alpha_{1950}, \delta_{1950}) = (19^{\text{h}}50^{\text{m}}00^{\text{s}}, +33^{\circ}20')$.

3. RESULTS OF VLA H I 21 CENTIMETER LINE OBSERVATIONS

3.1. High-Velocity H I Clumps

We show H I channel maps between $v_{\text{LSR}} = +55 \text{ km s}^{-1}$ and $+107 \text{ km s}^{-1}$ in Figure 1. (The SNR shell is centered at $2'$ north of the center of the map and has a radius of $\sim 30'$. See Fig. 9 below.) In Figure 1, the noise increases toward the boundary of each map because of the primary beam correction. Channel maps below $v_{\text{LSR}} = +50 \text{ km s}^{-1}$ are not presented because they are highly confused by the background emission. In Figure 1, some well-isolated H I clumps are clearly seen. They are small and very weak, but we can see that the clumps generally have a dense core and a relatively diffuse envelope. At highest velocities, the clumps appear only near the center of the field, whereas, at lower velocities, they appear to be confined into a shell-like structure of which the southwestern portion is opened.

We identified nine clumps in Figure 1, which are believed to be real because of their relatively large signal-to-noise ratio and their appearance in consecutive channel maps. They are labeled from 1 to 9 in Figure 1. We derived their physical parameters by taking 2 mJy beam^{-1} contour as the boundary of clumps and 2 kpc as the distance to CTB 80 (see § 3.2). The derived physical parameters are listed in Table 1: column (1) contains the running number in the order of decreasing central velocity. Column (2) contains the central velocity which is the flux density-weighted average velocity. Columns (3) and (4)

⁶ The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under co-operative agreement with the National Science Foundation.

⁷ FCRAO is operated with support from the National Science Foundation and with the permission of the Metropolitan District Commission of the Commonwealth of Massachusetts.

FIG. 1.—H I channel maps obtained by making a mosaic of five fields using the VLA. Each channel map has been obtained by averaging over 10.3 km s^{-1} centered at the velocity marked at the right corner of each map. Contour levels increase from -9 mJy beam^{-1} to $+24 \text{ mJy beam}^{-1}$ in 3 mJy beam^{-1} steps. (Negative contours are drawn with dotted lines.) Gray-scale plot distinguishes hill from valley. (The higher flux density is blacker.) The noise increases toward the edge of the map due to the primary beam correction. Some well-isolated emission features are labeled by numbers from 1 to 9. (See text.)

contain the right ascension and declination of the position with peak flux density. Column (5) contains the angular distance of the peak position from the dynamical center of CTB 80, $(\alpha_{1950}, \delta_{1950}) = (19^{\text{h}}52^{\text{m}}30^{\text{s}}, +32^{\circ}46')$ (KRHFS). Column (6) contains the linear size D which is the geometrical mean of the area. Column (7) contains the H I mass M_{HI} . Column (8) contains the average density $\bar{n}_c \equiv M_{\text{HI}}/D^3$. Column (9) contains the density at the position of the peak flux density, $n_{\text{peak}} \equiv N_{\text{peak}}/D$, where N_{peak} is the H I column density at the peak position. Columns (10) and (11) contain the *line-of-sight* momentum, $\int (v - v_0) dm$, and the kinetic energy, $E_K = \frac{1}{2} \int (v - v_0)^2 dm$, of the H I clumps

based on the systematic velocity of $v_0 = +13 \text{ km s}^{-1}$ for CTB 80 (see § 3.2). As we pointed out in § 2, the H I mass and, therefore, the density, momentum, and energy in Table 1 are underestimated because of the negative-bowl effect, which can be as much as $\sim 30\%$. The clumps 7, 8, and 9 extend below $v_{\text{LSR}} = +40 \text{ km s}^{-1}$ which is the velocity limit that we used to derive their masses, and therefore, their masses and the related parameters are the lower limits.

There are several things to be pointed out in Table 1. First, the total H I mass of the clumps is $17 M_{\odot}$, which is only 7% of the total mass of the shell in the same velocity interval

FIG. 1.—continued

(KRHFS). Even if we consider contributions from other features in Figure 1 that have not been cataloged and the uncertainties in our estimation of the clump masses, the result implies that most, $\gtrsim 70\%$, of the H I gas in this velocity interval resides in diffuse extended structures, which we call the “interclump” gas. Second, the total line-of-sight momentum and the total kinetic energy of the clumps are $2.6 \times 10^{41} \text{ g cm s}^{-1}$ and $7.8 \times 10^{47} \text{ ergs}$, respectively. These values are both $\sim 15\%$ of the corresponding momentum and kinetic energy of the shell in the same velocity interval (KRHFS). Together with the first point in the above, then this implies that the average velocity of the clumps is greater than that of the interclump gas, or alternatively, that the interclump gas dominates at lower velocities. Also, since the volume filling factor of the clumps is small, the result suggests that the *momentum per unit volume* of the clumps is significantly greater than that of the entire shell. Third, the average density of the clumps ranges from $\bar{n}_c = 0.7\text{--}1.7 \text{ cm}^{-3}$. This is comparable to the average density of the shell $\sim 2 \text{ cm}^{-3}$ estimated by *extrapolating* the observed mass distribution at high velocities ($v_{\text{LSR}} \gtrsim 40 \text{ km s}^{-1}$) to the lower velocities where the shell could not be identified because of the background emission (KRHFS). Note, however, that most of the mass in the shell resides in relatively slowly moving gas (KRHFS; Koo & Heiles 1991). We were able to detect the high-velocity clumps listed in Table 1 because the column density in narrow velocity interval at their positions is greater than that of the ambient medium. Finally, the *peak* density of the clumps is very large. According to Table 1, it ranges from 17 to 81 cm^{-3} . But the true peak density may be considerably (by a factor of few) greater than these, which are obtained by dividing the peak column density by the *total* size of the cloud, because the dense core occupies only a small fraction of the total area of the clump.

Figure 2 shows the distribution of clumps in the (p, v_{LSR}) diagram, where the negative (positive) projected distance p means a clump located at the west (east) of the dynamical center. Also shown is the locus of a $32'$ radius shell expanding uniformly with $v_{\text{exp}} = 72 \text{ km s}^{-1}$, i.e., a shell with parameters determined by KRHFS. In Figure 2, most clumps are located close to the locus of the shell: six clumps have velocities different from the uniformly expanding shell by less than 10 km s^{-1} , whereas the other three clumps have velocities considerably ($\sim 20 \text{ km s}^{-1}$) different. As shown, in Figure 2, six clumps move faster than the uniformly expanding shell, whereas the other three clumps move slower than the shell. Note that these three slowly moving clumps are among the most massive in Table 1. (Recall that their masses are the lower limits.) This

TABLE 1
PHYSICAL PARAMETERS OF H I CLUMPS

Clump	v_{center} (km s^{-1})	α_{1950}	δ_{1950}	p	D (pc)	M_{HI} ($M_{\odot}$)	$\bar{n}_c$ (cm^{-3})	n_{peak} (cm^{-3})	Momentum ($10^{40} \text{ g cm s}^{-1}$)	E_K (10^{47} ergs)
1	+91	19 ^h 52 ^m 03 ^s	+32°45'8"	5.7	4.4	1.4	0.67	34	3.1	1.2
2	+89	19 52 32	+32 51.0	5.0	4.7	3.0	1.2	68	6.4	2.4
3	+88	19 51 28	+33 01.8	20.4	3.0	0.47	0.71	17	1.1	0.37
4	+83	19 52 16	+32 59.3	13.6	4.2	1.3	0.74	34	2.6	0.92
5	+74	19 51 52	+33 07.0	22.5	3.1	0.58	0.79	20	0.99	0.30
6	+72	19 54 04	+32 52.5	20.8	2.9	0.58	0.96	21	0.95	0.28
7 ^a	+58	19 53 28	+32 42.3	12.8	4.1	2.5	1.5	66	3.2	0.72
8 ^a	+57	19 52 10	+33 07.3	21.7	3.9	2.4	1.7	67	3.0	0.66
9 ^a	+53	19 51 23	+32 55.5	17.0	5.6	4.3	0.99	81	4.8	0.96

^a Clumps 7, 8, and 9 appear at velocities below $v_{\text{LSR}} = +40 \text{ km s}^{-1}$, which is the velocity limit that we used in deriving their physical parameters. Therefore, their velocity centers are overestimated, whereas their masses and the mass-dependent parameters are the lower limits.

FIG. 2.—The distribution of clumps in the (p, v_{LSR}) diagram, where the negative (positive) projected distance p means a clump located on the west (east) of the dynamical center. Error bar in velocity represents the minimum and the maximum velocity that each clump appears, and the error bar in p represents the angular size of each clump. The area of each filled circle is proportional to the mass of the clump. Also shown is the locus of a 32' radius shell expanding uniformly with $v_{\text{exp}} = 72 \text{ km s}^{-1}$.

may suggest that the more massive clumps generally move slower. However, this is not always the case as can be seen by the fastest-moving clump, 2.

3.2. Absorption Spectrum and the Distance to CTB 80

The small beam size of the VLA made it possible for us to obtain an absorption spectrum against the pulsar nebula in CTB 80. (Angerhofer, Wilson, & Mould [1980] also obtained an “absorption” spectrum from the “ON-OFF” measurements using the Arecibo telescope.) In Figure 3, the top picture shows the absorption spectrum, i.e., $1 - \exp(-\tau)$, at $(\alpha_{1950}, \delta_{1950}) = (19^{\text{h}}51^{\text{m}}02^{\text{s}}, +32^{\circ}44'45'')$, whereas the bottom picture shows the emission profile at the same position obtained from the Arecibo telescope. The velocity center of the absorption profile determined by Gaussian fitting is $v_{\text{LSR}} = +8.3 \pm 0.1 \text{ km s}^{-1}$, and the optical depth at the center is $\tau \approx 1.8$. The emission profile between $v_{\text{LSR}} = -40 \text{ km s}^{-1}$ and $+50 \text{ km s}^{-1}$ can be decomposed into three Gaussian components. The component at $v_{\text{LSR}} = +8.2 \pm 0.2 \text{ km s}^{-1}$ has a peak antenna temperature of $T_A \approx 79 \text{ K}$, so that its spin temperature is $T_{\text{ex}} \approx 120 \text{ K}$. (We used a main beam efficiency of 0.84 to convert T_A to the brightness temperature.) Using the optical depth in Figure 3, then its total H I column density is

$$N_{\text{H}} = 1.823 \times 10^{18} \int_{-\infty}^{+\infty} T_b(v) \frac{\tau(v)}{1 - \exp[-\tau(v)]} dv = 4.5 \times 10^{21} \text{ cm}^{-2}. \quad (1)$$

The above H I column density corresponds to the reddening of $E(B-V) = N_{\text{H}}/(5.8 \times 10^{21} \text{ cm}^{-2}) = 0.78 \text{ mag}$ (Bohlin, Savage, & Drake 1978). (Our CO observation shows no molecular gas toward the pulsar nebula in CTB 80 [see § 4], which justifies the use of the previous equation.) This reddening derived from H I observations agrees quite well with $E(B-V) = 0.8$ obtained by Blair et al. (1984) and by Hester & Kulkarni (1989) from optical emission lines associated with the core of the CTB 80.

The absorption peak at $v_{\text{LSR}} = +8.3 \text{ km s}^{-1}$ implies a minimum distance of 1.1 kpc (using $R_{\odot} = 8.5 \text{ kpc}$ and $v_{\odot} =$

FIG. 3.—The absorption spectrum (top), i.e., $1 - \exp(-\tau)$, at $(\alpha_{1950}, \delta_{1950}) = (19^{\text{h}}51^{\text{m}}02^{\text{s}}, +32^{\circ}44'45'')$, obtained from the VLA, and the emission spectrum (bottom) at the same position obtained from the Arecibo telescope (KRHFS).

220 km s^{-1}) to CTB 80. The maximum velocity where the absorption occurs, on the other hand, is $v_{\text{LSR}} = +12.6 \pm 1.3 \text{ km s}^{-1}$, which corresponds to $2.0 \pm 0.4 \text{ kpc}$. If we use the mean H I density of 0.57 cm^{-3} (Dickey & Lockman 1990), then our derived H I column density yields a distance of 2.6 kpc (see also Angerhofer et al. 1980; Blair et al. 1984; Hester & Kulkarni 1988). Kulkarni et al. (1988) and Fruchter et al. (1988) obtained a dispersion measure of 45 pc cm^{-3} toward the pulsar PSR 1951+32, which yields a distance of $\sim 1.5 \text{ kpc}$. Hence, the distance to CTB 80 is probably between 1.5 and 2.5 kpc, and, in this paper, we adopt $d = (2 \text{ kpc})d_2$ as the distance to CTB 80, where $d_2 \approx 1 (\pm 30\%)$ is a scaling factor.

4. RESULTS OF CO $J = 1$ LINE OBSERVATIONS

The distribution of the total integrated CO $J = 1-0$ line intensity in this region is shown in Figure 4, where we can see that most of the molecular gas in this region is confined into two filamentary clouds. The longer one located near the central field of the map, which we call “cloud A,” has a very complicated structure with several dense clumps connected by weak ridges. The dense clump at the eastern end is particularly noticeable because of its steep boundary. (Koo et al. [1993] detected a molecular bipolar outflow associated with an *IRAS* point source in this clump.) The other one, “cloud B,” is located at the southwest and is composed of a large cloud together with a string of small molecular clumps. There are also three small isolated molecular clumps in the northern corners of the map, i.e., one near the NW corner and two at the NE corner. If we use the ratio of H_2 column density to integrated CO $J = 1-0$ line intensity of $N_{\text{H}_2}/I_{\text{CO}} = 2.3 \times 10^{20} \text{ molecules cm}^{-2} (\text{K km s}^{-1})^{-1}$ determined from the analysis of the γ -ray data in the Galactic plane (Strong et al. 1988), the masses of clouds A and B are $(2100 \pm 300)d_2^2 M_{\odot}$ and $(650 \pm 190)d_2^2$

FIG. 4.—The distribution of the total integrated CO $J = 1-0$ line intensity in the CTB 80 region. The cloud with a complicated structure near the central field of the map is called “cloud A,” whereas the cloud located at the southwest is called “cloud B” in the text. Contour levels (in K km s^{-1}) are $\int T_A dv = 1, 2, 4, 6$, and 8 . Gray-scale plot distinguishes hill from valley. (The higher flux density is blacker.) Two thick dashed lines represent the positions where the position-velocity diagram in Fig. 6 is obtained.

$M_\odot$, respectively. The masses of three small clumps are comparable to each other and add up to $(250 \pm 60)d_2^2 M_\odot$.

The velocity structure of the molecular clouds is shown in Figure 5, which shows channel maps integrated over 1.3 km s^{-1} and separated by 1.3 km s^{-1} . In Figure 5, both clouds A and B start to appear in the channel map centered at $v_{\text{LSR}} = +17.1 \text{ km s}^{-1}$. In the case of cloud B, the velocity is maximum at its northern end and decreases roughly systematically along the cloud. Cloud A has the highest velocity at its western end, close to the velocity peak of cloud B and shows a similar velocity structure along its filamentary structure. Therefore the filamentary portions of cloud A and cloud B appear to form an almost complete loop structure. This is better illustrated in Figure 6a which is a position-velocity diagram along the filamentary portions of clouds A and B. The x-axis is the distance (positive toward the east) along the curve from $(\alpha_{1950}, \delta_{1950}) = (19^{\text{h}}50^{\text{m}}34^{\text{s}}, +32^{\circ}59')$, where the line-of-sight velocity is approximately maximum. Figure 6a clearly shows that the velocity structure of clouds A and B is roughly symmetric with respect to the above position. If we take the velocity at $(0, 0)$ to be $+17 \text{ km s}^{-1}$, then the average velocity gradient in either cloud is $\sim 0.1 \text{ km s}^{-1} \text{ arcmin}^{-1}$ (or $0.2d_2^{-1} \text{ km s}^{-1} \text{ pc}^{-1}$).

At $v_{\text{LSR}} = +11.9 \text{ km s}^{-1}$ and below (Fig. 5), we notice several distinct features. First, there appears a relatively strong (peak $T_A^* = 3.5 \text{ K}$) CO emission near $\alpha_{1950} = 19^{\text{h}}51.5^{\text{m}}$. Its location is on the filamentary structure (e.g., see Fig. 4). But its velocity center ($v_{\text{LSR}} \approx +11.5 \text{ km s}^{-1}$) is significantly different from that of the filamentary structure ($v_{\text{LSR}} \approx +15.5$ to $+16.5 \text{ km s}^{-1}$), and there is no indication of the interaction between the two in Figure 5. Second, there appear three small isolated molecular clumps with comparable peak antenna temperatures, $T_A^* \sim 2.3 \text{ K}$, centered at $v_{\text{LSR}} \sim +8 \text{ km s}^{-1}$ in the

northern corners of the field. Again, there is no indication of the interaction with other molecular clouds. Finally, there appears diffuse molecular gas between $\alpha_{1950} = 19^{\text{h}}53^{\text{m}}$ and $19^{\text{h}}54^{\text{m}}$. Its CO intensity initially peaks in the middle of the filamentary structure, and then the peak shifts to the NW direction as the velocity decreases. Note that the entire filamentary structure also shifts to the northwest at the same time. This velocity structure is more clearly shown in Figure 6b, which is similar to Figure 6a, but along a line roughly perpendicular to the filamentary structure. The x-axis is the distance (positive toward the northwest) along the curve from the filamentary structure, i.e., $(\alpha_{1950}, \delta_{1950}) = (19^{\text{h}}53^{\text{m}}49^{\text{s}}, +32^{\circ}48')$. Figure 6b clearly shows that there is a systematic velocity gradient of $\sim 0.25 \text{ km s}^{-1} \text{ arcmin}^{-1}$. The systematic velocity gradient and the positional coincidence strongly suggest that the low-velocity ($v_{\text{LSR}} = +5$ to $+12 \text{ km s}^{-1}$) molecular gas in cloud A is physically associated with the thin filamentary structure which has a considerably higher line-of-sight velocity ($v_{\text{LSR}} = +10$ to $+18 \text{ km s}^{-1}$).

5. DISCUSSION

5.1. High-Velocity H I Clumps

The line-of-sight velocity of the clumps that we detected ranges from $v_{\text{LSR}} = +53$ to $+91 \text{ km s}^{-1}$, which are much greater than the maximum velocity $+15 \text{ km s}^{-1}$ allowed by the Galactic rotation toward this direction. The positional coincidence and the large velocity almost certainly imply that they are the clumps accelerated by the SN blast wave in CTB 80. Therefore, they are very likely the “cold clouds” that were initially in the ambient interstellar medium (ISM) and have been swept-up by the SN blast wave. This seems to be

FIG. 5.—Channel maps integrated over 1.3 km s^{-1} centered at the velocity marked in each map. Contours (in K) are drawn for the average antenna temperature $\bar{T}_A = 0.3, 0.6, 1.0, 1.5, 2.0,$ and 3.0 .

plausible because, in the largely accepted three-phase model of the ISM (McKee & Ostriker 1977), such cold clouds are pervading the ISM. However, there are several factors to consider before we conclude. (Some density enhancements can be also produced from a more or less homogeneous expanding SNR shell through some dynamic instabilities [Chevalier & Imamura 1982; Vishniac 1983; Bertschinger 1986]. The characteristic length scale in this case, $\sim 0.1 \text{ pc}$ [Bertschinger], however, is much smaller than the sizes of clumps in Table 1. Whether there are such small clumps that have not been detected in our observations is not relevant here.)

CTB 80 has an associated pulsar, and, therefore, its progenitor star must have been a massive $\geq 8 M_{\odot}$ star (Wheeler 1981). All stars more massive than $\sim 15 M_{\odot}$ (main-sequence spectral type $\sim \text{B0}$; Allen 1976) are known to possess fast, $v_w = 1500$ to

3000 km s^{-1} , stellar winds, and therefore to produce wind-blown bubbles (Conti 1978; Abbott 1982). KRFHS concluded that the progenitor star of CTB 80 is probably later than B0 because the size of the wind bubble that would have been produced by the progenitor star must be smaller than the current size of the SNR shell. Here we elaborate some of their arguments. We first consider the evolution of wind bubbles in an ideal uniform medium (Castor, McCray, & Weaver 1975; Weaver et al. 1977; Koo & McKee 1992a, b). Initially the wind bubbles are fully adiabatic, i.e., both the shocked wind and the shocked ambient medium are adiabatic. Soon after its formation, the shocked-ambient medium collapses into a thin shell due to the radiative cooling, and a typical wind bubble spends most of its lifetime with a hot adiabatic interior and with a radiative outer shell. If the wind luminosity is not large, the

FIG. 6a

FIG. 6b

FIG. 6.—(a) Position-velocity diagram along the filamentary portions of cloud A and cloud B (see Fig. 4). The x-axis is the distance (positive toward the east) along the curve from $(\alpha_{1950}, \delta_{1950}) = (19^{\text{h}}50^{\text{m}}34^{\text{s}}, +32^{\circ}59')$, where the line-of-sight velocity is approximately maximum. (b) Same as (a), but along the line roughly perpendicular to the filamentary structure (see Fig. 4). The x-axis is the distance (positive toward the northwest) along the curve from $(\alpha_{1950}, \delta_{1950}) = (19^{\text{h}}53^{\text{m}}49^{\text{s}}, +32^{\circ}48')$.

wind bubble is confined by the pressure of the H II region that has been formed by the UV photons from the same exciting star. Using the wind-parameters given by Abbott (1982), we computed the time t_p at which this pressure-confinement occurs for several spectral-type stars (eq. [4.5] of Koo & McKee 1992a). We assumed an ambient hydrogen number density of $n_0 = 1 \text{ cm}^{-3}$ and an ambient sound speed of $c_s = 10 \text{ km s}^{-1}$. In Table 2, $R_s(t_p)$ is the radius at $t = t_p$. Table 2 shows that the wind bubble is confined by external pressure during its main-sequence lifetime for stars later than $\sim \text{O6}$. Although its ram pressure is comparable to the external pressure, the “pressure-confined” bubble continues to expand, $R_s \propto t^{1/3}$, as far as the bubble remains adiabatic because the energy is continuously injected (eq. [4.6] of Koo & McKee 1992a). The size of wind bubbles at the end of the main-sequence lifetime, $R_s(t_{\text{MS}})$, therefore, can be very large even for stars later than O6 as shown in Table 2.

The evolution of bubbles may be different in a cloudy medium. In a cloudy medium, the wind bubbles are not likely to grow to such large sizes because the clouds engulfed by the expanding bubbles can deposit additional mass in the hot interior either through thermal evaporation (Königl 1983; Ostriker & McKee 1988) or through hydrodynamic mixing (Hartquist et al. 1986), which will enhance the cooling. The bubble is likely to become a momentum-driven bubble. The momentum-driven bubble will be stalled when the expansion velocity is comparable to the sound speed in contrast to the adiabatic bubble. According to McKee, Van Buren, & Lazareff

(1984; see also Elmegreen 1976), however, any small clouds in the ambient ISM around the massive stars (main-sequence spectral type earlier than $\sim \text{B0}$) are cleared out during their main-sequence lifetime through the photoevaporation and the rocket effect (Oort & Spitzer 1955). The radius of the region “homogenized” during their main-sequence lifetime, the “homogenization radius” R_h , is independent of the spectral type of the exciting star and is given by $R_h(t_{\text{MS}}) = 56n_m^{-0.3} \text{ pc}$, where n_m is the mean density that the cloud gas would have if it were homogenized. Inside R_h , all clouds but the very massive ones are destroyed. If the ambient medium is homogenized as described by McKee et al. 1984, then the pressure-confined bubbles are expected to remain adiabatic and the final sizes in Table 2 should be roughly correct. Therefore, for stars with main-sequence spectral type earlier than B0, the surrounding volume within $R_s(t_{\text{MS}}) \gtrsim 30 \text{ pc}$ is likely to be devoided of the ISM, and not only the clumps but also a dense SNR shell cannot exist within $R_s(t_{\text{MS}})$. Hence, we conclude that the progenitor star of CTB 80 does *not* have a significant stellar wind, i.e., main-sequence spectral type later than $\sim \text{B0}$, and that the most of the ambient ISM before the SN explosion in CTB 80 has not been processed by the stellar winds, which means the clumps that we have detected are quite possibly the cold clouds initially in the ISM.

There have been considerable theoretical studies on the interaction between a dense “cloud” and a SN blast wave, and the recent progress has been summarized by McKee (1988). Here we discuss our results following McKee. The clumps

TABLE 2
SOME PROPERTIES OF WIND-BLOWN BUBBLES

MS Spectral Type	t_{MS}^a (10^6 yr)	L_w^a ($10^{36} \text{ ergs s}^{-1}$)	t_p (10^6 yr)	$R_s(t_p)$ (pc)	$R_s(t_{\text{MS}})$ (pc)
O4	3.4	21	13	...	101
O6	4.2	5.3	6.7	...	87
O9	10.3	0.11	0.96	16.5	44
B0.5	11.1	0.024	0.45	7.7	27

^a From Abbott 1982.

swept up by a SN blast wave are accelerated in two stages; first they are accelerated by the shock propagating into the cloud with a velocity smaller than the intercloud shock by a factor of $\sim \chi^{1/2}$, where $\chi \equiv \rho_c/\rho_{ic}$ is the cloud-intercloud density ratio, and later they are further accelerated by the ram pressure exerted by the fast intercloud gas. For clouds with a radius a greater than the critical radius

$$a_{cr} \equiv \frac{0.4R_c}{\chi^{1/2}}, \quad (2)$$

where R_c is the initial distance of the cloud from the explosion center, the acceleration is mainly by the cloud shock. (The physical meaning of the critical radius is such that, for clouds with $a < a_{cr}$, the SNR does not evolve significantly during the time for the cloud to be crushed.) The radius of the clumps in Table 1 ranges between 1.5 and 3 pc. As far as the cloud-intercloud density contrast is $\gtrsim 10$, therefore, they are larger than a_{cr} and have likely been accelerated mainly by the cloud shock. McKee et al. (1989) studied the time evolution of the cloud shock including the variation of the driving pressure with SNR expansion. If we assume that a clump is coasting with velocity v_∞ corresponding to the total impulse delivered during the energy conserving phase of the blast wave (eq. [4.14] of McKee et al.), then its velocity is given by

$$\frac{v_\infty}{v_s} = \frac{\alpha_\infty}{\chi^{1/2}} \left(\frac{R_s}{R_c} \right)^{3/2} \frac{a_{cr}}{a}, \quad (3)$$

where R_s and v_s are the current radius and velocity of the blast wave, respectively, and α_∞ is a constant of order unity which depends on the nature of the blast wave, e.g., Sedov-Taylor or evaporative blast wave, and also weakly on the density contrast χ and the geometry of the cloud. If we assume a spherical cloud with a momentum cross section of πa^2 in a Sedov-Taylor blast wave, then $\alpha_\infty \approx 1.1$. Hence, for a clump of $a = 2$ pc and $\chi = 10$ inside of a SNR of $R_s = 20$ pc, it can be accelerated to the velocity equal to that of the blast wave if it were initially at $R_c \approx 0.2R_s = 4$ pc. The clumps that were closer to the explosion center will move faster than the blast wave and will catch up the expanding SNR shell. CTB 80 is the post-Sedov phase. Therefore, the numerical factors will be different from the above. The momentum delivered to the clump might be somewhat smaller than the above because, after the Sedov phase, the driving pressure should be negligible. The basic phenomena, however, should be the same. The relatively large momentum per unit volume of the clumps (§ 3.1) may indicate that they have been swept up at an early stage of the SNR evolution.

Are there any clumps that have possibly caught up the expanding SNR shell in our list? This phenomena was first pointed out by McKee, Cowie, & Ostriker (1978) and was later nicely demonstrated in the numerical simulations of Różyczka & Tenorio-Tagle (1987). In Figure 2, we notice that clump 3 has the line-of-sight velocity considerably greater than other clumps at that projected distance, so that it can be a candidate. This clump is very small and very weak in H I 21 cm line. More sensitive observations are needed in order to address this question.

5.2. Molecular Clouds and the SNR CTB 80

Our CO observations show that the molecular clouds toward CTB 80 have some interesting velocity structures. First, the western portions of the clouds A and B form an almost

closed loop and have a systematic velocity gradient along the filamentary structure (Figs. 4 and 6a). Their spatial and velocity structures could be interpreted as either a collapsing, expanding, or a rotating ring of radius $\sim 17''$ with a systematic velocity of $v_{exp} \sim 2 \text{ km s}^{-1}$. If it is a collapsing or an expanding ring, the ring must be tilted from our line of sight with its line of nodes crossing from northeast to southwest, so that the northwestern portion of the ring is moving away from us. On the other hand, if it is a rotating ring, the line of nodes must cross from northwest to southeast. This motion, which has an associated kinetic energy of $\sim 5 \times 10^{46}$ ergs, however, is very *unlikely* to be associated with the SNR CTB 80 because of the following reasons: (1) If it is an expanding ring, the dynamical time scale $R/v_{exp} \sim 5 \times 10^6 \text{ yr}$ is much longer than the age, $\sim 1 \times 10^5 \text{ yr}$, of CTB 80. (2) If it is either a contracting or a rotating ring, the sense of motion is not consistent with an expanding SNR. (3) Finally, we do not see any indication of perturbed line profiles, e.g., broad line wings ($1 \sigma T_A^* = 0.17 \text{ K}$) along the filamentary structure. Hence, we conclude that the slow $\sim 2 \text{ km s}^{-1}$ systematic motion in clouds A and B is not related to the SNR CTB 80.

Another systematic motion is in the eastern portion of cloud A (Fig. 5). Here the velocity center roughly systematically decreases toward the northwest from $v_{LSR} = +11.5 \text{ km s}^{-1}$ to $+7.5 \text{ km s}^{-1}$ (Fig. 6b). The line width also seems to vary systematically with the velocity center. In Figure 7, we plot the line width (FWHM) as a function of the velocity center. The data have been obtained by fitting Gaussians to each line profile in the area bounded between $(\alpha_{1950}, \delta_{1950}) = (19^h53^m2, +32^\circ44')$ and $(19^h54^m2, +33^\circ02')$. Figure 7 first shows that most emission occurs between $v_{LSR} = +9$ and $+12 \text{ km s}^{-1}$, and that, in this range, the line width is minimum, $\Delta v_{FWHM} = 0.85 \pm 0.01 \text{ km s}^{-1}$ at $v_{LSR} = 11.0 \text{ km s}^{-1}$ and increases to $\Delta v_{FWHM} = 1.48 \pm 0.03 \text{ km s}^{-1}$ at $v_{LSR} = +9 \text{ km s}^{-1}$. (The quoted errors are the uncertainties of the mean. See Bevington 1969.) At velocities greater than roughly $+11.5 \text{ km s}^{-1}$, the width also increases, but the data points are small. At velocities smaller than roughly $+9 \text{ km s}^{-1}$, scatter is large. Therefore, the line width apparently becomes larger as the velocity center moves away from the rest velocity of the filament in this region,

FIG. 7.—Line width (FWHM) as a function of the velocity center in the area bounded between $(\alpha_{1950}, \delta_{1950}) = (19^h53^m2, +32^\circ44')$ and $(19^h54^m2, +33^\circ02')$. The line parameters are determined by fitting Gaussians to each line profile. Some error bars are drawn to show typical errors. Also shown are the average line widths at 0.5 km s^{-1} interval (filled squares).

which is $v_{\text{LSR}} \approx 11.5 \text{ km s}^{-1}$. Could this systematic velocity shift accompanying the increase of the line width have been resulted from the SN shock in CTB 80?

The most clear example of the molecular cloud-SNR interaction is provided in the SNR IC 443, and it might be helpful to compare our results with IC 443. In IC 443, CO observations have shown the presence of very wide lines, $\Delta v_{\text{FWHM}} \sim 20 \text{ km s}^{-1}$, centered at a velocity significantly $\sim 11 \text{ km s}^{-1}$ shifted from the rest velocity of the clouds (DeNoyer 1979; DeNoyer & Frerking 1981). The shock velocity implied from H I observations in IC 443 is $\sim 90 \text{ km s}^{-1}$ (Giovannelli & Haynes 1979; see also Braun & Strom 1986), which is not much different from $\sim 70 \text{ km s}^{-1}$ of CTB 80. But the estimated preshock density in IC 443 is $\sim 400 \text{ cm}^{-3}$, which is much greater than $\sim 2 \text{ cm}^{-3}$ (KRFHS) of CTB 80. The estimated age of IC 443 ranges between 3000 yr and 10,000 yr (Petre et al. 1988; Giovannelli & Haynes 1979). CTB 80 is an old ($\sim 10^5$ yr) SNR, and as such we do not expect to detect CO lines as impressive as in IC 443. If we consider that the density of the molecular cloud is

probably ~ 100 times greater than that of the atomic cloud, then the velocity of the SN shock propagating into the molecular cloud will be ~ 10 times smaller than that of the H I gas. Furthermore, the position of this apparently perturbed region is not at the center of the SNR but away from the dynamical center (see Figs. 8 and 9). The line-of-sight expansion velocity of the H I shell at this position is $\lesssim 40 \text{ km s}^{-1}$. Hence, the shocked molecular gas, if any, will move at $\lesssim 4 \text{ km s}^{-1}$ relative to the rest velocity of the molecular cloud. The multiple velocity components scattered between $v_{\text{LSR}} = +6 \text{ km s}^{-1}$ and $+14 \text{ km s}^{-1}$ and the systematic trend in the velocity width are suggestive for the shocked molecular gas. But at this point, we may safely conclude that there is *no* certain indication of the interaction between the molecular cloud and the SNR CTB 80. CO observations at a higher sensitivity and observations of other molecules such as HCO^+ and SiO , which are found to be enhanced in shocked regions (DeNoyer & Frerking 1981; Ziurys et al. 1987), will be helpful to reach a more concrete conclusion.

FIG. 8a

FIG. 8b

FIG. 8.—H I channel map obtained by integrating between (a) $v_{\text{LSR}} = +8.8 \text{ km s}^{-1}$ and $+11.8 \text{ km s}^{-1}$, and (b) $v_{\text{LSR}} = +11.9 \text{ km s}^{-1}$ and $+14.9 \text{ km s}^{-1}$. The data were obtained by using the Arecibo telescope (KRFHS). Contour levels increase from $\int T_A dv = 20 \text{ K km s}^{-1}$ by 10 K km s^{-1} . Gray-scale plot distinguishes hill from valley. (The higher flux density is blacker.)

FIG. 9.—Radio continuum (49 cm) contour map of Angerhofer et al. (1981) overlaid on the *IRAS* color, S_{60}/S_{100} , map made from the *IRAS Sky Survey Atlas*. The almost circular shell-structure with enhanced color has been detected by Fesen et al. (1988).

5.3. Interaction of CTB 80 with the Ambient Interstellar Medium

Our discussions so far have been based on a roughly uniform, but inhomogeneous, ambient medium. In this section, we present some observational evidence suggesting that the ISM surrounding CTB 80 is *far from* a uniform distribution. Figure 8 shows H I channel maps between $v_{\text{LSR}} = +8.8$ and $+14.9$ km s $^{-1}$ made from the Arecibo H I 21 cm line data, which cover an area barely enough to see the distribution of H I gas in this region. (The data were sampled at 3', i.e., the full beam spacing, along the right ascension axis, and at 6' along the declination axis.) We removed a smooth background emission using a cosecant law. The rest velocity of CTB 80 is probably in this range, most likely between $v_{\text{LSR}} = +12$ and $+15$ km s $^{-1}$ (see § 3.2). In Figure 8, the most noticeable feature is a long “cavity” crossing the map from the NE to the SW direction. The length and the width of the cavity are $\gtrsim 23d_2$ pc and $\sim 7d_2$ pc, respectively. The deficient column density of the cavity between $v_{\text{LSR}} = +8.8$ and $+14.9$ km s $^{-1}$, where the cavity appears most clearly, is $\Delta N_{\text{H}} \simeq 1.5 (\pm 30\%) \times 10^{20}$ cm $^{-2}$. This corresponds to ~ 25 pc along the line of sight, if we use a mean density of ~ 2 cm $^{-3}$. Hence, the cavity appears to be a sheetlike structure along the line of sight. As we discuss later in this section, this cavity, which may be one of the hot “tunnels” in the ISM formed by SN explosions (e.g., Cox & Smith 1974; Smith 1977; McKee & Ostriker 1977), has quite likely been rejuvenated by CTB 80.

Another thing to be noted in Figure 8, particularly in Figure 8b, is the presence of a strong H I emission, which we call the “H I cloud,” in the SW corner of the map. It extends to right below the pulsar which can be identified due to the H I absorption. We think that this H I cloud explains the appearance of the SNR at various wavelengths nicely. First, in KRFHS's H I channel maps, there is no H I gas faster than $v_{\text{LSR}} = +38$ km s $^{-1}$ in this region. The absence of fast-moving H I gas in this region can be attributed to the relatively dense H I cloud. For a density contrast of $\chi \sim 10$, the velocity of the shock propagating into the cloud will be smaller by a factor of ~ 3 . Second, the infrared shell detected by Fesen et al. (1988) also is incomplete in its SW portion. In Figure 9, we show the *IRAS* color, S_{60}/S_{100} , map made from the *IRAS Sky Survey Atlas*. No background emission has been subtracted. In Figure 9, there is a roughly circular region of an enhanced color with its NW limb brightened. The NW limb certainly looks like a portion of an almost circular shell. (If we subtract a smooth background using a cosecant law, we obtain $S_{60}/S_{100} = 0.25$ to 0.30 in the NW limb, which is consistent with $0.30 [\pm 40\%]$ of Fesen et al.) In Figure 9, an important feature to notice is that the SW portion of the infrared shell is not necessarily missing, but instead it can be defined by an enhanced color, $S_{60}/S_{100} \gtrsim 0.24$, well inside of an otherwise roughly “circular” shell. The boundary of the region with enhanced color fits very nicely with the boundary of the H I cloud in Figure 8. Finally, the dense H I cloud probably also played a crucial role in shaping

the peculiar radio morphology of CTB 80. In Figure 9, we have shown the radio continuum map (contour map) of Angerhofer et al. (1981) overlaid on the *IRAS* color map. As Fesen et al. have shown in their paper, the morphology of the NW portion of the radio continuum emission matches very well with the infrared shell, including the peaks and valleys. Fesen et al. and Shull, Fesen, & Saken (1989) explained the radio emission in this region as being due to the relativistic electrons injected from the pulsar PSR 1951+32 streaming along the magnetic field lines in the SNR shell, although it requires a streaming velocity much greater than the Alfvén speed. We propose that the sharp cutoff at the south of the pulsar nebula is due to the relatively dense H I cloud in Figure 8b. Note that the boundary of the radio continuum emission follows the H I cloud boundary reasonably well. We imagine that the swept-up magnetic field that was in the SW portion of the fast expanding shell is now aligned along the surface of the cloud as the shell is blocked by the dense cloud. This aligned magnetic field will prevent the penetration of the relativistic electrons into the cloud.

We now discuss the possible role of the cavity in the evolution of CTB 80. Is there any observational evidence suggesting that the SNR has encountered this cavity? First, the high-velocity H I maps of KRHFS show that there are fast $v_{\text{LSR}} > +38 \text{ km s}^{-1}$ moving H I gas in this region. This fast H I gas could be the walls of the cavity accelerated by the SN blast wave (see next). Second, the SE portion of the infrared shell in Figure 9 does not look like a portion of a spherical shell. Instead it is almost linear along NE-SW direction and is thick $8d_2 \text{ pc}$. This region coincides well with the H I cavity. We

propose that the blast wave destroyed large grains in the walls of the cavity to have a large $S_{60}/S_{100} = 0.3\text{--}0.4$. Finally, the presence of the cavity also explains why the geometrical center of the infrared shell is considerably shifted to the east (by $5'$) from the H I velocity centroid (KRHFS). Hence, various observations seemingly support that the SN blast wave encountered the cavity. When a blast wave experiences a sudden decrease in the density, the shock will accelerate (Kompaneets 1960; Laubach & Probst 1969; Koo & McKee 1990). In contrast to media with finite mass, e.g., an exponential atmosphere, however, the shock will eventually decelerate because the density in the cavity is expected to be uniform. According to the numerical simulation of Tenorio-Tagle, Bodenheimer, & Yorke (1985; see also Falle & Garlick 1982), which did not include the radiative cooling, the ratio of the velocity of the "shell" propagating into the tenuous cavity to that of the shell propagating into the opposite direction approaches a constant value, e.g., for a density contrast of 100, the ratio is ~ 4.2 . This asymptotic value, however, is obtained only after a long time, which is not easily satisfied for a cavity like that shown in Figure 8b. The hydrodynamic evolution of a SNR in an environment such as that envisaged above (see Fig. 10) remains to be explored. It is worthwhile to mention that yet another SNR VRO 42.05.01 is quite possibly in a similar environment (Pinault, Landecker, & Routledge 1987). A systematic study in high-angular resolution H I, infrared, and radio continuum emission might reveal more SNRs in such environment.

Based on the above discussion, we describe the evolutionary history of CTB 80 in a very crude qualitative picture (Fig. 10). A massive star of main-sequence spectral type B0 or later

FIG. 10.—(a–d) A schematic picture showing the evolutionary history of CTB 80. (See text.)

exploded $\sim 1 \times 10^5$ yr ago (Fig. 10a). The ambient ISM had been affected relatively little by the stellar winds and UV photons. When the swept-up mass was comparable to the ejected mass, the SNR entered the Sedov-Taylor stage. As it expanded through the relatively diffuse intercloud medium, which was probably the "warm neutral medium (WNM)," the blast wave also accelerated small dense clumps in the WNM. At $t \sim 2000$ yr (we used $n_0 = 2 \text{ cm}^{-3}$ and the SN explosion energy of 1×10^{51} ergs), when the velocity of the blast wave was $\sim 1000 \text{ km s}^{-1}$, the SNR encountered a cavity which was at ~ 6 pc from the explosion center (Fig. 10b). Because of the large density gradient across the boundary and the negligible mass in the cavity, the shock accelerated to hit the walls of the cavity (Fig. 10c). Hence, the velocity of the shock when it first hit the wall must have been very large. At this stage the pressure in the cavity dropped considerably by adiabatic expansion, so that the blast wave propagating into the walls became a momentum conserving shell and the velocity should have dropped very rapidly. Meanwhile, the blast wave propagating through the WNM became radiative and formed a dense shell. When the shell encounters a large dense H I cloud in the SW, that portion of the shell is slowed down and CTB 80 has its current morphology (Fig. 10d). Note that the pulsar moving transversely at $\sim 300 \text{ km s}^{-1}$ (Fruchter et al. 1988) has caught up the SNR shell which is expanding at $\sim 70 \text{ km s}^{-1}$.

6. SUMMARY

We performed H I 21 cm line observations using the VLA D-array and CO $J = 1-0$ line observations of CTB 80. In the following, we summarize our main results.

1. We detected fast-moving H I clumps associated with CTB 80. The average density of clumps is not large, $\bar{n}_c \sim 1 \text{ cm}^{-3}$, but they have a dense core with a probable density of $n_H \sim 100 \text{ cm}^{-3}$. They are probably the pre-existing cold clouds that have been swept-up and accelerated by the SN blast wave. The

relatively large momentum per unit volume of the clumps suggests that they have been swept-up at an early stage of the SNR evolution. The clump 3 in Table 1 is a possible candidate for having caught up the expanding SNR shell.

2. We obtained a H I absorption spectrum against the pulsar nebula in CTB 80. The H I column density between CTB 80 and us is $N_H \simeq 4.5 \times 10^{21} \text{ cm}^{-2}$, which, with a normal dust-to-gas ratio, yields the reddening consistent with other observations.

3. We found that the molecular gas in this region is confined into two large filamentary clouds. Molecular clouds have a systematic velocity gradient of $\sim 0.1 \text{ km s}^{-1} \text{ arcmin}^{-1}$ along their filamentary structure, which is probably *not* related to the SNR CTB 80. In cloud A we observe multiple velocity components scattered between $v_{\text{LSR}} = +6$ and $+14 \text{ km s}^{-1}$ and also a systematic increase of the velocity width with the variation of the central velocity. It is not clear if this velocity structure is related to CTB 80.

4. We found that the ISM around CTB 80 is far from being uniform and homogeneous. The SNR seems to be expanding mainly into a warm medium pervaded by small cold clouds. These cold clouds appear as high-velocity H I clumps in our data. The SNR apparently encountered and rejuvenated a cavity in the southeast. This cavity has an enhanced $60 \mu\text{m}$ emission compared to its $100 \mu\text{m}$ emission. A large cold H I cloud appears at the southwest of CTB 80. The boundary of the H I cloud matches well with the morphology of CTB 80 in infrared and radio continuum.

We wish to thank C. Heiles, C. F. McKee, W. T. Reach, and S. S. Hong for their helpful comments. We thank the staff of the Joint IRAS Science Working Group and the National Science Data Center for providing the IRAS Sky Survey Atlas Data. This work was supported in part by S.N.U. Posco Research Fund (1992) to B.-C. K.

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