SHOCKED MOLECULAR GAS IN THE SUPERNova REMNANT HB 21

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ABSTRACT

We have carried out $^{12}$CO $J = 2$–1 line observations of the supernova remnant (SNR) HB 21 in order to search for evidence of interaction with molecular clouds. We mapped the eastern half (80' × 110') of the SNR almost completely. Molecular gas appears to be distributed mainly along the boundary of the SNR, but the overall distribution has little correlation either with the distortion of the SNR boundary or with the distribution of radio brightness. Along the eastern boundary, where the SNR was considered to be interacting with molecular clouds in previous studies, we have not found any strong evidence for the interaction. Instead, we detected broad (20–40 km s$^{-1}$) CO emission lines in the northern and southern parts of the SNR. In the northern area, the broad-line emitting cloud is composed of a small (~2' or 0.5 pc), very bright, U-shaped part and several clumps scattered around it. There is a significant enhancement of radio emission with a flat (~0.28 ± 0.17) spectral index possibly associated with this cloud. In the southern area, the broad-line emitting cloud is filamentary and appears to form an elongated loop of ~30' in extent. Small (~1.2 or 0.3 pc), bright clumps are seen along the filamentary structure. We have obtained sensitive $J = 1$–0 and $J = 2$–1 spectra of $^{12}$CO and $^{13}$CO molecules toward several peak positions. The intensity of $^{12}$CO $J = 2$–1 emission is low ($T_{mb} < 7$ K) and the ratio of $^{12}$CO $J = 2$–1 to $J = 1$–0 intensities is high (1.6–2.3), which suggests that the emission is from warm, dense, and clumpy gas. We have applied a large velocity gradient analysis to derive their physical parameters. The detected broad CO lines are believed to be emitted from the fast-moving molecular gas swept up by the SNR shock. The small (~20 km s$^{-1}$) shock velocity suggests that the shock is a nondissociating C- shock. We discuss the correlation of the shocked molecular gas with the previously detected, shocked atomic gas and the associated infrared emission.

Subject headings: ISM: individual (HB 21) — ISM: kinematics and dynamics — ISM: molecules — radio lines: ISM — supernova remnants

1. INTRODUCTION

The number of supernova remnants (SNRs) with convincing evidence for interaction with ambient molecular clouds has increased considerably in recent years. The evidence ranges from a simple morphological relation to the detection of broad and/or shock-excited emission lines from various molecules. Although circumstantial evidence could be very suggestive, it is the molecular lines from the shocked gas that are essential for understanding the physical and chemical processes associated with the molecular shock. In this regard, there are still only a few SNRs adequate for the study of molecular cloud-shock interaction; perhaps W28 (Arikawa et al. 1999), W44 (Seta et al. 1998), W51C (Koo & Moon 1997), 3C 391 (Reach & Rho 1996, 1999), and the classical source IC 443 (DeNoyer 1979; Tauber et al. 1994 and references therein).

This paper reports the discovery of broad emission lines from the shocked CO gas in HB 21. HB 21 (G89.0+4.7) is one of those SNRs with mixed morphology, e.g., shell-like in radio and center-filled in the X-ray (Rho & Petre 1998), where the center-filled, thermal X-ray emission is suggested to be caused by interaction with molecular clouds. It has a nearly complete radio-continuum shell with an angular extent of ~120' × 90' (Hill 1974; Tatematsu et al. 1990, hereafter T90). The shell is elongated along the northwest-southeast direction. The brightness distribution of the shell is not uniform but enhanced in scattered areas. Particularly noticeable features are the V-shaped northern boundary, a ~30' sized loop structure in the south central area, and the one in the central region of the eastern boundary (see Fig. 1). Optical nebulosity associated with HB 21 has not been detected in Hα or [S II] plates (van den Bergh 1978). X-ray emission from HB 21 was detected by Leahy (1987) and studied in detail by Leahy & Aschenbach (1996). The distance to the SNR is uncertain. We adopt 0.8 kpc following T90, which is the distance to the Cyg OB 7 complex (Humphreys 1978).

HB 21 has been a suspect for interaction with molecular clouds based on its radio appearance and the ambient molecular clouds (Erkes & Dickel 1969; Huang & Thaddeus 1986; T90). Erkes & Dickel (1969) suggested that the distorted boundaries with enhanced radio brightness might be the places where the SNR is interacting with dense ambient gas. Huang & Thaddeus (1986) found that the giant molecular cloud associated with Cyg OB 7 appears to be partially surrounding HB 21 (see also Dobashi et al.)
ated Universities, Inc., under contract with the National Science Foundation. T90 obtained a higher resolution (2:7) CO map of the eastern part of the SNR and found that the eastern boundary of the SNR appeared to be in contact with molecular and atomic clouds. They also made a coarsely sampled map of the regions with enhanced radio emission and detected molecular and atomic clouds. They also made a coarsely sampled map of the SNR appeared to be in contact with molecular clouds. The interaction between an SNR and a molecular cloud, gave OH masers, which are known to be an indicator for the direction of the shock. For CO observations, which provided high resolution (0.25 km s⁻¹) of the SNR. (We observed the central area in Figure 1, which had not been covered in our CO J = 2–1 observations, in CO J = 1–0 line emission and detected only several small (~1') clumps other than some faint extension associated with the clouds in southern and eastern parts of the remnant.) But the overall distribution has little correlation either with the distortion of SNR boundaries or with the distribution of radio brightness (cf. § 3.2). For the purpose of discussion, we divide the remnant into three areas (Fig. 2): (1) the eastern area (R.A. > 20°47'), where three relatively large (~15') clouds and several filamentary clouds are present; (2) the northern area, centered at (20°46', +51°00'), where a small (~2'), very bright U-shaped cloud is noticeable; and (3) the southern area, centered at (20°44', +49°50'), where clumpy and filamentary clouds with complicated structures are present. We detected broad (20–40 km s⁻¹) emission lines from the clouds in the northern and southern areas, which will be discussed in detail in the next sections. In the following, we summarize the results regarding the eastern area.

In the eastern area, there are three clouds centered at declinations Δ ≈ +50°49', +50°15', and Δ ≈ +49°50'. We call these three clouds A, B, and C following T90 (see Fig. 2 for the location of these clouds). Figure 3 shows the channel maps of the eastern area. The velocity ranges of the channel maps were chosen to show the essential features clearly. Cloud A appears at vLSR = +9 to −6 km s⁻¹ and is composed of two velocity components centered at +6 and −2 km s⁻¹, respectively. The former component (6 km s⁻¹), which is seen in Figure 3a, is extended and the emission peaks at the southern part (Δ ≈ +50°45') of the cloud, while the latter component (−2 km s⁻¹), which is seen in Figures 3b and 3c, is spatially confined and comprises the northern part of the cloud. Their maximum brightnesses are Tmb,max = 11 and 7 K, respectively. Cloud B appears at vLSR = +1 to −9 km s⁻¹ and is seen in Figures 3c and 3d. The south central part of the cloud, e.g., the region between Δ = +50°10' and 17', is bright and appears to be connected

3. CO RESULTS

3.1. Overall Distribution and Clouds in the Eastern Area

Figure 1 shows the distribution of the integrated intensity of CO J = 2–1 emission. The velocity range is between vLSR = +3.9 and −17.5 km s⁻¹, which covers most of the emission. The overlaid contour map shows the 1420 MHz brightness distribution of HB 21 (T90). The overall distribution of CO gas in Figure 1 is not very different from the low-resolution map of T90. But Figure 1 shows much more detail in the next sections. In the following, we summarize the main results of our paper.

2. OBSERVATIONS

12CO J = 2–1 line observations were carried out using the 12 m telescope of the National Radio Astronomy Observatory at Kitt Peak in 1999 June and 2000 January. The FWHM of the telescope at 230 GHz was 27". We mapped the eastern half (80° × 110°) of the SNR almost completely using the on-the-fly observing technique. We used 256 channel filter banks: one with 500 kHz and the other with 1 MHz resolution. We split each filter bank into two sections and observed two linear polarizations simultaneously. The velocity resolution and coverage of the 500 kHz filter bank were 0.65 km s⁻¹ and 83 km s⁻¹, while those of the 1 MHz filter bank were two times greater. Typical system temperatures were 350–450 K. During the observing run in January 2000, we had some trouble because of telluric CO J = 2–1 emission, which appeared at vLSR = 4–5 km s⁻¹. The emission was not cancelled out completely by usual position-switching observation and produced a hill-and-valley feature in the spectra, the strength of which depends on elevation. We were able to avoid the contamination from telluric CO emission by averaging out the contaminated velocity channels because the telluric CO emission line is narrow (0.8 km s⁻¹) and the absolute strength of the "hill" and "valley" features are equal.

We also obtained sensitive spectra of 13CO J = 2–1, 12CO J = 1–0, and J = 2–1 lines toward several peak positions. For CO J = 1–0 observations, we used 1 and 2 MHz filter banks, so that they have the same velocity resolution and coverage with those of CO J = 2–1 line observations. We also used the millimeter autocorrelator for the 12CO observations, which provided high resolution (0.25 km s⁻¹ after smoothing) spectra. We have converted the observed temperatures (Tmb) to the main-beam brightness temperature (Tmb) using the corrected main-beam efficiency provided by the NRAO.

Additional observations of 12CO and 13CO J = 1–0 lines were performed using the Taeduk Radio Astronomy Observatory (TRAO) 13.7 m telescope (half-power beamwidth = 49' at 115 GHz) in 2000 January and March. A SIS receiver equipped with a quasi-optical sideband filter was used along with a 250 kHz, 256 channel filter bank. The main beam efficiency was 0.41 at 115 GHz (Roh & Jung 1999), and the pointing accuracy was better than 10°. Typical system temperatures were about 750 K at 115 GHz and 450 K at 110 GHz.

1 The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.
Fig. 1—$^{13}$CO $J = 2-1$ integrated intensity map of HB 21. The velocity range is from $v_{LSR} = +3.9$ to $-17.5$ km s$^{-1}$, and the integrated intensity varies from 0 to 64 K km s$^{-1}$. Overlaid contour map shows the 1420 MHz brightness distribution of HB 21 obtained by T90 using the TRAO synthesis telescope.

to cloud C. Cloud C has two components at very different velocities, e.g., one at +2 to $-11$ km s$^{-1}$, which is seen in Figures 3c and 3d, and the other at +17 to +10 km s$^{-1}$, which is not shown in Figure 3 but has a distribution similar to the other velocity component. According to the result of T90, cloud C extends to $\delta \approx +49'40'$.

An interesting feature in Figure 3 is the semicircular loop that appears above cloud B in Figure 3b. The ratio of the minor, which is along the north-south direction, to the major axis is 0.8. If it is at 0.8 kpc, the linear size of the semimajor axis would be $R_a = 3$ pc. The velocity increases systematically from both ends to the northern top of the loop, which is consistent with an expanding loop. The top portion is redshifted with respect to both ends by $\approx 3$ km s$^{-1}$. If we assume that the ellipticity is caused by projection, then the expansion velocity would be $v_{exp} \approx 5$ km s$^{-1}$, so that the dynamical age of the ring is probably shorter than $R_a/v_{exp} \approx 6 \times 10^5$ yr. This is much greater than the age ($3 \times 10^4$ yr, Koo & Heiles 1991, scaled to 0.8 kpc adopted in this paper) of HB 21 and, therefore, the loop might not be associated with HB 21. We suspect that the loop is originated from some energetic phenomena in cloud B. A faint
“V-shaped” structure that connects cloud B and the ends of the loop in Figure 3b seems to indicate the association of the two.

3.2. Northern U-Shaped Cloud

The cloud in the northern area is composed of a small (~2), very bright, U-shaped cloud and several clumps scattered around it (Fig. 1; see also Fig. 9 for enlarged view). Figure 4 shows its velocity structure. There are several points to be made from Figure 4: First the U-shaped cloud is composed of several clumps, the central velocities of which shift systematically from +3 to −6 km s⁻¹ as we move from the northeast to the northwest along the structure. The integrated intensity attains a maximum at (20°46′03″, +51°00′00″), which we call HB 21:BML-N1 (broad molecular line—northern position 1), or simply N1. Second, there are several other clumps in the field. These clumps, except the one near the southeastern corner at \( v_{\text{LSR}} = -13 \) km s⁻¹, appear over a wide (>10 km s⁻¹) velocity range. Among them, the one at (20°45′55″0, +51°03′30″), which we call HB 21:BML-N2 (or N2), appears over the widest (~30 km s⁻¹) velocity interval. Third, there is a diffuse emission at +2 km s⁻¹ to the northeast of the cloud. Its line is narrow (2–3 km s⁻¹), and it is part of a large (~20) cloud that appears to be connected to cloud A. We consider that the clumps aligned along the northeast-southwest direction in Figure 4 are associated and call them cloud N, i.e., cloud N does not include the diffuse emission in the northeastern area and the clump in the southeastern corner (cf. T90, who detected only the diffuse molecular gas at \( v_{\text{LSR}} = 1 \) to 6 km s⁻¹ in this area and called it cloud D).

As can be expected from Figure 4, most clumps in cloud N have broad emission lines. As an example, we show the spectra of N1 and N2 in the top frames in Figure 5, where we see that the spectrum of N1 is box-shaped and its full width (at zero intensity) is 30 km s⁻¹, while that of N2 is asymmetric and extends from −21 to +11 km s⁻¹. For comparison, the spectrum of the diffuse, extended structure in the northeastern part of this area has narrow (2–3 km s⁻¹) emission lines centered at +2 km s⁻¹, a sample of which is shown in the lower right frame in Figure 5.

We have obtained sensitive \( J = 1–0 \) and \( J = 2–1 \) spectra of \(^{12}\)CO and \(^{13}\)CO molecules at the two peak positions, N1 and N2, and Figure 5 shows the spectra. The molecule and transition are marked in each spectrum. The second spectrum from the top is \(^{12}\)CO \( J = 2–1 \) emission convolved to the \( J = 1–0 \) beam size (55″) to be compared with the \( J = 1–0 \) spectra. The difference between the top and convolved spectra indicates that some velocity components,
e.g., the narrow component centered at +4 km s\(^{-1}\) of N1 and the broad component at -8 km s\(^{-1}\) of N2, are confined to small areas. By comparing the \(J = 1-0\) and the convolved \(J = 2-1\) spectra, we notice that the ratio of \(J = 2-1\) to \(J = 1-0\) intensities is high and that it varies over the profile: For N1, the ratio is between 1.2 and 2.0 in the central parts of the spectrum, while it increases at the wings, e.g., \(\sim 5\) at +5 km s\(^{-1}\) and -13 km s\(^{-1}\). For N2, the ratio varies between 0.8 and 2.8, and it is higher between -11 km s\(^{-1}\) and 0 km s\(^{-1}\). The ratios of the \(^{12}\)CO \(J = 2-1\) and \(J = 1-0\) integrated intensities \(^{12}\)R\(_{2-1/1-0}\) are 1.6 and 1.7 for N1 and N2, respectively. The \(^{13}\)CO \(J = 2-1\) line is clearly detected toward N1, while it is marginally detected toward N2. For N1, the line has double peaks centered at +1 and -9 km s\(^{-1}\), while the \(^{12}\)CO \(J = 2-1\) line profile toward N1 is composed of several narrow peaks. The narrow peaks might indicate that the emission is from several, unresolved subclumps. Presumably, the \(^{13}\)CO emission might be from these subclumps too, which is not apparent in the profile in Figure 5 because of low signal-to-noise ratio and low velocity resolution. (Note that the velocity resolutions of the \(^{12}\)CO \(J = 2-1\) and \(^{13}\)CO \(J = 2-1\) lines are 0.25 and 0.68 km s\(^{-1}\), respectively.) The ratios of \(^{12}\)CO \(J = 2-1\) to \(^{13}\)CO \(J = 2-1\) integrated line intensities \(^{12/13}\)R\(_{2-1}\) are 20 \(\pm\) 3 and 40 \(\pm\) 14 for N1 and N2, respectively. (The errors are statistical errors.) Table 1 summarizes the line parameters of the peak positions, i.e., their coordinate, velocity range \((v_{\text{min}}, v_{\text{max}})\), \(^{12}\)CO \(J = 2-1\) peak brightness temperature \(T_{\text{mb,max}}\), \(^{12}\)R\(_{2-1/1-1}\), \(^{12}\)R\(_{2-1}\), and the ratio of \(^{12}\)CO \(J = 1-0\) to \(^{13}\)CO \(J = 1-0\) integrated line intensities \(^{12/13}\)R\(_{1-0}\). The detailed line diagnostics based on the observed line parameters in Table 1 are discussed in § 3.4.

**TABLE 1**

| Name        | \(\alpha_{1950}, \delta_{1950}\) | \(v_{\text{min}}, v_{\text{max}}\) (km s\(^{-1}\)) | \(T_{\text{mb,max}}\) (K) | \(^{12}\)R\(_{2-1/1-1}\) | \(^{12}\)R\(_{2-1}\) | \(^{12/13}\)R\(_{1-0}\) |
|-------------|---------------------------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| HB 21:BML-N1... | 20 46 03.2, +51 00 00         | -20, +10                      | 3.6             | 1.6             | 20 \(\pm\) 3    | 20 \(\pm\) 1 |
| HB 21:BML-N2... | 20 45 55.0, +51 03 30         | -21, +11                      | 3.1             | 1.7             | 40 \(\pm\) 14   | ...             |
| HB 21:BML-S1... | 20 44 37.2, +49 47 10         | -22, +20                      | 2.7             | 1.9             | 28 \(\pm\) 4    | 96 \(\pm\) 50  |
| HB 21:BML-S2... | 20 44 31.0, +49 55 20         | -27, +0                       | 2.9             | 1.7             | ...            | 104 \(\pm\) 43  |
| HB 21:BML-S3... | 20 42 45.2, +49 56 50         | -35, +9                       | 6.9             | 2.3             | ...            | 103 \(\pm\) 43  |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
3.3. Southern Filamentary Cloud

In the southern part of the SNR, the emission is detected at $v_{\text{LSR}} = -35$ to $+20$ km s$^{-1}$. The velocity structure is shown in Figure 6. At positive velocities, we see several clouds with narrow lines come and go, e.g., a diffuse cloud that extends $\sim 10'$ along the north-south direction centered at $(20^h 44.5', +50'00')$ between $v_{\text{LSR}} = 0$ and $+5$ km s$^{-1}$. The CO distribution at negative velocities is fairly complicated: the distribution is filamentary, and small ($\approx 1.2$ or 0.3 pc), bright clumps are seen along the filamentary structure. The filamentary structure, which we call cloud S, appears to form a loop of $\sim 30' \times 10'$ in extent, elongated along the north-south direction. The eastern part of the loop is particularly clumpy and has a semicircular shape (see the channel map centered at $-10.1$ km s$^{-1}$).

The clumps generally have broad ($\gtrsim 10$ km s$^{-1}$) lines. Among them, three clumps marked by crosses in Figure 6 have the broadest (30–40 km s$^{-1}$) lines, and we show the $^{12}$CO $J = 2$–1 and $J = 1$–0 spectra at their peak positions, which we call S1, S2, and S3 from east to west (see Fig. 2), in Figure 7. Again we show the convolved $J = 2$–1 spectra together, although the line shapes do not change significantly by convolution toward these peak positions. We have obtained some sensitive $J = 1$–0 and $J = 2$–1 spectra of $^{12}$CO and $^{13}$CO molecules at these peak positions, and the line parameters are listed in Table 1. Note that $^{12}R_{2-1/1-0} = (1.7–2.3)$ and $^{12}R_{2-1} = (28 \pm 4$ toward S1) are similar to those of the northern positions, while $^{12}R_{1-0}$’s, although they have large uncertainties, appear to be much greater than that of N1.

3.4. Excitation Parameters of Broad Emission Lines

The broad CO lines are presumably emitted from the shocked gas, where physical parameters vary greatly over a short distance scale. But still it would be worthwhile to estimate their excitation parameters based on elementary considerations. First, the observed $^{12}R_{2-1} = 20$–40 are significantly less than either the average ratio (67.3 $\pm$ 1.5; Langer 1997) of $^{12}C^{13}C$ in the solar neighborhood or the terrestrial value (89), implying that the $^{12}$CO $J = 2$–1 lines are not optically thin. If we adopt $^{12}C^{13}C = 67$ and assume that the emission is thermalized, then the optical depth for the $^{12}$CO $J = 2$–1 line is $\tau = 1.1–3.4$. On the other hand, the $^{12}R_{1-0} = (100 \pm 50)$ close to or greater than the terrestrial value implies that $^{12}$CO $J = 1$–0 lines are optically thin, except at N1 where $J = 1$–0 and $J = 2$–1 lines appear to have comparable optical depths. This, however, is not conclusive because of large uncertainties associated with $^{12}R_{1-0}$. Second, the large values of $^{12}R_{2-1/1-0} = 1.6–2.3$ imply that the broad-line emitting region is warm and dense. For typical molecular clouds, where the $J = 2$ level is subthermally excited, the ratio is usually less than unity. For example, molecular clouds in the local arm exhibit ratios ranging from 0.53 (Taurus) to 0.75 (Orion A) (Sakamoto et al. 1994, 1997). Our spectra of ambient gas also show this, e.g., see the spectra toward S2 in Figure 7 where the narrow component at $+2$ km s$^{-1}$ has $^{12}R_{2-1/1-0} = 0.72$. But the large ratio is common for the shocked molecular gas in SNRs (see § 4.1). Third, the low (<7 K) brightness temperature of $J = 2$–1 lines, regardless of their moderate optical depths, implies that the emitting region must be clumpy, i.e., composed of subclumps, and the emission is beam-diluted. From the above considerations, we may conclude that the broad emission lines are from warm, dense clumps with significant column densities so that the $2$–1 lines are optically thick.

We have applied the large velocity gradient (LVG) model (Scoville & Solomon 1974; Goldreich & Kwan 1974) to our broad CO lines in order to derive their excitation parameters. The model assumes a uniform, spherical cloud with a constant velocity gradient ($\delta v \propto r$). If the lines are emitted from the shocked region where temperature and density vary greatly, the resulting parameters may be considered as “average” values. Since we have found that the emission is beam-diluted, we have used the line ratios, $^{12}R_{2-1/1-0}$ and $^{12}R_{2-1}$, instead of brightness temperatures to determine the excitation parameters. According to our LVG analysis, the observed ratios are possible for $T_e \geq 50$ K. Figure 8a shows the result of our model computations when $T_e = 100$ K, where curves of constant $^{12}R_{2-1/1-0}$ and constant $^{12}R_{2-1}$ are drawn in the $[X(1^{12}CO)/(dv/dr), n(H_2)]$ plane. $X(1^{12}CO)/(dv/dr)$ is the fractional abundance of $^{12}$CO relative to $H_2$ $[X(1^{12}CO)]$ per unit velocity gradient interval. Asterisks mark the observed ratios toward the peak positions where both ratios are obtained, i.e., N1, N2, and S1. According to Figure 8a, $n(H_2) = (3–7) \times 10^3$ cm$^{-3}$ and $X(1^{12}CO)/(dv/dr) \approx (1–4) \times 10^{-6}$ pc (km s$^{-1}$)$^{-1}$ at the three peak positions. There are multiple choices for N1, e.g., the same ratios are obtainable when $n(H_2) = 3 \times 10^3$ cm$^{-3}$ and $X(1^{12}CO)/(dv/dr) = 4 \times 10^{-7}$ pc (km s$^{-1}$)$^{-1}$. We adopt the lower density because it is comparable to the densities in the
other peak positions and because the density of greater than $10^5$ cm$^{-3}$ appears to be too high for the CO emission to explore. If the temperature becomes higher, both $n(H_2)$ and $X^{12\text{CO}}/(dv/dr)$ need to be greater.

In Figure 8b, we plot the expected CO $J = 2 - 1$ radiation temperature $J (T_b) \equiv (hv/k_b)/[\exp (hv/k_b T_b) - 1]$, which is just the brightness temperature when $hv \ll k_b T_b$ and the expected $^{12/13}R_{1-0}$ are from the same LVG model. Note that the expected radiation temperatures are much greater than the observed main-beam brightness temperature. We have estimated beam filling factors of $(7.7-8.8) \times 10^{-2}$ from the ratio of these two brightnesses. We have estimated the CO column densities $\approx (2.4-11) \times 10^{17}$ cm$^{-2}$ at these peak positions by $n(H_2)[X^{12\text{CO}}/(dv/dr)]\Delta v$, where $\Delta v = 14-18$ km s$^{-1}$ is the velocity width. The excitation parameters derived from the LVG analysis are listed in Table 2. Note

**TABLE 2**

**PHYSICAL PARAMETERS DERIVED FROM LVG ANALYSIS**

| Name | $n(H_2)$ (10$^3$ cm$^{-3}$) | $X^{12\text{CO}}/(dv/dr)$ (10$^{-6}$ pc km$^{-1}$ s) | $N$(CO) (10$^{17}$ cm$^{-2}$) | Beam Filling Factor | $^{12/13}R_{1-0}$ |
|------|-------------------|-----------------|------------------|------------------|-----------------|
| N1... | 6.1 | 4.3 | 11 | 0.077 | 40 |
| N2... | 3.1 | 1.4 | 2.4 | 0.088 | 57 |
| S1... | 7.0 | 2.1 | 6.4 | 0.079 | 50 |
that the $^{12}/^{13}$R$_{1-0}$ expected from the LVG model differ from the observed ones. At N1, the observed value is small by a factor of 2, while, at S1, it is large by a factor of 2 ± 1. Considering the weakness of $^{13}$CO $J = 1-0$ lines and various uncertainties associated with different telescopes, however, it is not obvious if this difference is critical.

We have made a crude estimate of the mass of the broad-line clouds as follows. If the CO $J = 1-0$ line emission is optically thin, then $M$(H$_2$) can be obtained from the CO $J = 1-0$ luminosity $L_{10}$(CO) by $M$(H$_2$) = $L_{10}$(CO)$_{mb}$/[$h\nu_{10} A_{10} f_{J=1}$ $X$(CO)], where $f_{J=1}$ is the fraction of CO molecules at the $J = 1$ level and the other coefficients have their usual meanings. In our case, CO $J = 1-0$ emission has less optical depth than the $J = 2-1$ emission, but is not very optically thin, so that the above formula might yield an underestimate. What we have is the
luminosity of CO $J = 2-1$ emission $L_{21}^{12}\text{CO}$, which has moderate optical depth. But, since $12^R_{2-1/1-0} = 1.6-2.3$ at the peak positions, we may obtain $L_{19}^{12}\text{CO}$ by assuming that $L_{10}^{12}\text{CO} = (1/2)(v_{10}/v_{12})^2L_{21}^{12}\text{CO}$, where $v_{10}$ and $v_{21}$ are CO $J = 1-0$ and $J = 2-1$ line frequencies, respectively. Finally, we assume $f_{2-1} = 0.2$, which is a mean value of those (0.15–0.26) at the three peak positions obtained from the LAG analysis. We have found that the $H_2$ masses of clouds N and S are $\sim 8$ and $\sim 55 M_\odot$, respectively. The mass of the central U-shaped part of cloud N is $\sim 3 M_\odot$, while the masses of the small clumps in cloud S are $\sim 1 M_\odot$.

4. INTERACTION BETWEEN HB 21 AND MOLECULAR CLOUDS

4.1. Evidence for the Interaction

Broad CO emission lines with large $12^R_{2-1/1-0}$ in clouds N and S strongly suggest that they are being shocked. The observed velocity width is as large as $\sim 40$ km s$^{-1}$. Note that, toward this direction ($\ell = 89^\circ$), the LSR velocity permitted by the Galactic rotation is $\lesssim 0$ km s$^{-1}$, so that it is not impossible for broad lines to be produced by molecular clouds accidentally aligned along the line of sight. But it is highly improbable that such alignment (over a few kiloparsecs) occurs in very small (1–2) areas on the sky. We also searched for protostellar candidates around the broad-line emitting regions using the Infrared Astronomical Satellite (IRAS) Point Source Catalog, because broad lines can be emitted from the high-velocity gas associated with protostellar object too. We did not find any suspicious sources, except one, IRAS 20444+4954, which is located close to the S2 clump, i.e., at $(29'' + 14'', 68'' + 11'')$ from the peak position in Table 1. The source has been detected in two IRAS wave bands, i.e., 60 and 100 $\mu$m, with flux densities of $F_{60\mu m} = 0.99$ Jy and $F_{100\mu m} = 12.97$ Jy. We have found that the source is located within a small ($\sim 1' \times 2'$), bright ($T_{mb} \approx 6$ K) CO $J = 2-1$ core at $v_{LSR} \approx 1$ km s$^{-1}$, so that it might be a young stellar object associated with the $\sim 10'$ sized, diffuse cloud in the northern part of the +2.9 km s$^{-1}$ map in Figure 6 rather than with the S2 clump. Also the velocity of the S2 clump is similar to those of the other fast-moving clumps in this area, which suggests that they have the common origin. Therefore, the broad lines we detected are almost certainly from the fast-moving molecular gas swept up by the SNR shock in HB 21.

Another indication that the broad CO lines are from the shocked gas is their high $12^R_{2-1/1-0} = 1.6-2.3$. As we have shown in §3.4, the high ratio implies that the emitting gas is warm and dense, which might be manifestation of shock. Indeed high $12^R_{2-1/1-0}$ is a common property of the broad lines from the shocked molecular gas in SNRs. All six SNRs known to have broad molecular emission lines, i.e., W28 (Arikawa et al. 1999), 3C 391 (Reach & Rho 1999), W44 (Seta et al. 1998), W51C (Koo & Moon 1997), HB 21 (this paper), and IC 443 (e.g., van Dishoeck et al. 1993), have ratios greater than 1, which implies that the broad CO lines in these SNRs are all emitted from warm and dense, shocked gas. Meanwhile, the maximum brightness temperature ($\lesssim 7$ K) of the CO $J = 2-1$ line in HB 21 is significantly less than those of other SNRs, even if it was obtained with a higher spatial resolution (0.1 pc), e.g., it is 33 K for W28 (W. T. Reach & J. Rho 2000, in preparation) and IC 443 (van Dishoeck et al. 1993) when observed with a resolution of 0.2 pc. The much smaller CO $J = 2-1$ brightness temperature with comparable $12^R_{2-1/1-0}$ implies that either the shocked gas in HB 21 is composed of much smaller clumps or is less dense.

On a large scale, HB 21 appears to be in contact with a giant molecular cloud (GMC) along its eastern boundary (Huang & Thaddeus 1986; Tatematsu et al. 1990). The GMC is $130 \times 70$ pc in extent (Dobashi et al. 1994), and the structure that we distinguish as clouds A, B, and C defines the western boundary of the GMC. T90 inspected the correlation between these clouds and the SNR in detail and concluded that cloud A might be interacting with the SNR because it is located where the radio continuum boundary of the SNR is distorted. On the other hand, they concluded that clouds B and C might not, because there is no indication of the interaction in the distribution of radio brightness. According to our high-resolution observations, however, there is little relationship between the boundaries of cloud A and the SNR. Instead, since the velocity of the ambient molecular gas around HB 21 might be negative (see §4.3), we consider that clouds B and C have a better chance of interaction. But we have detected broad CO lines toward none of these eastern clouds. Even if an SNR is interacting with a molecular cloud, however, the broad lines may be absent. 3C 391 (G31.9+0.0), which appears to be located at the edge of a large molecular cloud, for example, has no broad CO lines along the interface (Wilner, Reynolds, & Moffett 1998; Reach & Rho 1999). But strong [O I] 63 $\mu$m emission has been detected near the interface, which indicates that the SNR is interacting with the molecular cloud (Reach & Rho 1996). This would happen if the shock is dissociative and molecules have not reformed.

4.2. Enhanced Radio Emission Possibly Associated with Northern U-Shaped Cloud

Figure 9 shows an enlarged view of the northern area overlaid with a 325 MHz radio continuum map of the SNR. Note that there is an enhanced radio continuum emission elongated along the northeast-southwest direction in the

![Fig. 9](image-url)
central area. Its peak position falls exactly inside the U-shaped part of cloud N. The positional coincidence suggests that the enhancement is possibly associated with cloud N. We have derived a spectral index ($\alpha$) of $-0.28 \pm 0.17$ for the radio emission associated with the U-shaped central part using the 325 and 1420 MHz maps. The derived index has a large uncertainty because of the confusing "background" level, but it appears to be flatter than the mean spectral index $-0.4 \pm 0.03$ of HB 21 (Willis 1973). For cloud S, there is no obvious correlation between the CO emission and radio continuum brightness, although the radio continuum appears to be bright around the cloud in general.

It is not obvious, observationally or theoretically, what determines whether or not radio synchrotron emission becomes enhanced when SN shock hits a dense cloud. Observationally, we see very limited correlation between radio continuum brightness and shocked molecular gas in some SNRs, i.e., the shocked molecular gas is not usually associated with radio continuum enhancement and vice versa (see also Chevalier 1999). In IC 443, for example, shocked molecular gas is distributed in a fragmentary, flattened, ring, which partly overlaps with the radio continuum shell (e.g., see Dickman et al. 1992 for the shocked molecular gas and Green 1986 for the radio continuum). But the radio continuum is brightest in the northeastern part of the shell where there is no shocked molecular gas, and the radio continuum is not particularly bright toward the shocked molecular gas, perhaps except around the southern part of the molecular ring (see next paragraph). In 3C 391, there is a shocked molecular clump in the southern part of the SNR, but there is only a faint, local radio continuum peak at $\sim1.5$ pc apart from the shocked clump, the association of which cannot be confirmed (Reach & Rho 1999). In W28, on the other hand, there is a ridge of radio continuum emission associated with the shocked molecular gas (Arikawa et al. 1999). Theoretically, it could be either the dense cloud or the surrounding intercloud medium where synchrotron emission becomes enhanced. If the shock propagating through the dense cloud is radiative, there will be a large compression of cosmic rays and magnetic field, which would increase the synchrotron emissivity (van der Lann 1962; Blandford & Cowie 1982). But this mechanism may not work because the molecular shocks in old SNRs are not ionizing shocks and, therefore, high-energy particles may escape from the shocked region (Draine & McKee 1993; Chevalier 1999). On the other hand, the shocked intercloud medium surrounding the cloud, particularly the medium behind the cloud, could have enhanced synchrotron emissivity because of the increased magnetic field strength there (e.g., Jones & Kang 1993; Mac Low et al. 1994). In HB 21, the peak of the enhanced radio emission is located behind the shocked cloud (Fig. 8). It is also noteworthy that the cloud has a U shape, which is similar to what we would expect when a small cloud is swept up by a strong shock (e.g., Klein, McKee, & Colella 1994; Mac Low et al. 1994). These morphological characteristics seem to suggest that the enhanced emission is not physically associated with the shocked cloud but with the shocked surrounding intercloud medium.

In some respects, the region around cloud N in HB 21 is similar to the flat ($x \sim -0.2$) spectral region in IC 443, which is also located behind a shocked molecular cloud (Green 1986; Keohane et al. 1997). In IC 443, Keohane et al. (1997) found that the flat spectral region is particularly bright in hard X-rays, which are most likely caused by synchrotron radiation. They concluded that the enhanced hard X-ray emission and the flat spectral index is because of shock acceleration of cosmic rays behind dense clouds. More observational study is certainly needed for HB 21 in order to reveal the relationship between the northern U-shaped cloud and the enhanced radio emission.

4.3. Nature of the Shock and Shock Parameters

Cold molecular gas around HB 21 in general has central velocities between $v_{LSR} \approx -8$ and $+6$ km s$^{-1}$, which must be the velocity range of the preshock gas. In the areas where broad lines have been detected, there is diffuse molecular gas at positive ($0$ to $+5$ km s$^{-1}$) velocities (see Figs. 4 and 6). If this gas represents the preshock gas, then, since the broad lines are centered and spread out mostly at negative velocities, the gas should have been shocked and accelerated toward us systematically. If we take $+3$ km s$^{-1}$ as the velocity of the preshock gas, and if we take either the central or peak positions of the broad lines as the systematic velocities of the shocked gas, then the line-of-sight velocities of the shock would be $\lesssim 10$ and $\lesssim 20$ km s$^{-1}$ for clouds N and S, respectively. And, if we take 0.9 and 0.75 $R_e$ ($R_e =$ the radius of the SNR) as their projected distances from the center of the SNR, then their deprojected velocities are $\lesssim 23$ and $\lesssim 30$ km s$^{-1}$, respectively. Such coasting clumps are indeed theoretically expected for the old SNRs such as HB 21. Molecular clumps swept up by a SNR blast wave are accelerated by the shock propagating into the clumps and also by the ram pressure of interclump gas (e.g., McKee 1988). The characteristic timescale for acceleration is $R_e/v_p$, where $R_e$ is the radius of the clump, which becomes $\sim 1 \times 10^4$ yr ($< 10^4$ yr) for the clumps in HB 21 using $R_e \approx 0.25$ pc and $v_p \approx 25$ km s$^{-1}$. The wings of the broad lines may be attributed to the gas accelerated by shocks propagating from sides. But one difficulty in this scenario would be that there is no clear correlation in the distributions of the broad lines between the preshock and postshock gases. In the southern area, for example, the preshock gas ($2-3$ km s$^{-1}$ component) is distributed in a filamentary cloud extended along the north-south direction, while the broad-line emitting clumps are distributed over a much wider area to the southwest of this cloud. Also, it is rather awkward that there are no broad lines centered near the velocity of the preshock gas. Alternatively, it could be the molecular gas at negative velocities that is associated with the SNR, and, in the northern and southern areas, most, if not all, of the ambient gas may have been shocked. In this picture, the shocked gas may be coasting too, but not necessarily at high speeds because the velocity of the preshock gas is somewhere within the velocity range of the broad lines, e.g., near the velocity of the peak. The shock velocity determined from the line width is $\lesssim 20$ km s$^{-1}$. Of the two possible interpretations, we prefer the latter because of the difficulty with the former mentioned above. But, since the difference in the shock velocities between the two interpretations is $\lesssim 10$ km s$^{-1}$, the following discussion remains basically valid even if the velocity of the preshock gas is 0 to $+5$ km s$^{-1}$. (The derived properties of the shocked gas in § 3.4 should remain valid, too, in either case because the emission from the preshock gas might be in narrow lines and its contribution to the integrated intensity of broad lines is expected to be small.)
The observed shock velocity is $\leq 20$ km s$^{-1}$. This is less than the critical velocity for the dissociation of molecules, which is $25$–$50$ km s$^{-1}$ depending on preshock density and magnetic field strength (Hollenbach & McKee 1980; Draine, Roberge, & Dalgarno 1983). Hence, the shock might be a nondissociating C-shock. The observed integrated intensity of the CO $J = 2$–$1$ emission is $(3$–$9) \times 10^{-7}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at the peak positions. If we consider the beam dilution ($\theta = 3.4\arcsec$), the actual surface brightness may be greater by an order of magnitude, e.g., $(4$–$10) \times 10^{-6}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This is much larger than the angle-averaged surface brightness predicted from shock model computations. Draine & Roberge (1984), for example, computed surface brightnesses expected for steady state C-shocks propagating through molecular gas with different preshock conditions. According to their result, the angle-averaged surface brightness of CO $J = 2$–$1$ emission varies from $1 \times 10^{-7}$ to $2 \times 10^{-6}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for a 10–20 km s$^{-1}$ shock propagating through a molecular cloud with $n(H_2) = 5 \times 10^2$ to $5 \times 10^3$ cm$^{-3}$. Larger shock velocity does not raise the surface brightness, while higher preshock density may yield $\leq 3 \times 10^{-6}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The much higher surface brightness toward the peak positions would be possible if these are directions where we are observing the shock tangentially.

We want to discuss briefly the nondetection of OH 1720 MHz masers in HB 21 because such masers are known to indicate interaction of SNRs with molecular clouds (Frail et al. 1996). First, the OH masers may require a very specific set of physical conditions that might not be realized in HB 21. According to Lockett, Gauthier, & Elitzer (1999), the 1720 MHz masers arise only in C-shocks when $T \approx 50$–$125$ K, $n(H_2) \sim 10^5$ cm$^{-3}$, and with OH column density $10^{16}$–$10^{17}$ cm$^{-2}$. According to our result in § 3.4, the density of the shocked molecular gas in HB 21 appears to be much lower than required. Second, it is not impossible that the OH maser emission, even if present, had been missed in the survey by Frail et al. (1996), who mapped the SNRs in rectangular grids with full-beam (or 2 × full-beam) grid spacing. It would be worthwhile to search for OH masers toward the shocked CO gas in HB 21.

Koo & Heiles (1991) detected shocked H I gas associated with HB 21. The shocked H I gas moves at $v_{LSR} = 42$–$123$ km s$^{-1}$ and is confined to the southern part ($\delta = +50^00'$–$50^030'$) of the SNR. The highest velocity component coincides with cloud S, although the angular resolution (36') of the H I observation is too large for a detailed comparison. Koo & Heiles (1991) assumed that the shocked H I gas represents a cap portion of a large expanding H I shell and derived a mean ambient H I density of $3.7$ cm$^{-3}$ (when

![Fig. 10.—The 60 $\mu$m image of HB 21. CO distribution is shown in solid contours.](image-url)
squared to 0.8 kpc adopted in this paper). If the molecular shock has been driven by this H I shell, then we can roughly estimate the density of the shell as follows: We assume that the shocked molecular gas is confined to a thin slab and that the radiative H I shell has an uniform density of $\rho_0$. Then it is straightforward to show that $\rho_0$ is related to the density of the molecular cloud $\rho_c$ by $\rho_0 \approx \rho_c (v/\nu_{rs})^3$ (for $v_{rs} \gg v$) where $v_{rs}$ and $v$ are the velocities of radiative shell and shocked molecular slab, respectively (e.g., see Chevalier 1999). For HB 21, $v_{rs} \sim 130$ km s$^{-1}$ and $v \sim 20$ km s$^{-1}$. If we take the $H_2$ density of the cloud to be $n(H_2) \sim 1 \times 10^3$ cm$^{-3}$, the density of the H I shell would be $n_0(H) \sim 47$ cm$^{-3}$. By comparing with the mean ambient density (3.7 cm$^{-3}$), this implies a compression factor $\beta \sim 13$ for the H I shell. Such moderate compression would be obtained if the ambient magnetic field is uniform and magnetic pressure dominates the pressure in the shell. (The equation is obtained by assuming that ambient magnetic field is uniform and magnetic pressure dominates the pressure in the shell. See Chevalier [1974] for a discussion.) Alternatively, the fast-moving H I gas could be the gas originally associated with the molecular clouds, i.e., the atomic and molecular shocks may be produced when the SNR shock hits a large molecular cloud. In this case, the fast-moving H I gas represents the swept-up interclump medium or H I envelope of the molecular cloud. High-resolution H I observation is needed to reveal the relation between the shocked atomic and molecular gases.

4.4. Infrared Emission from HB 21

We used archival data from IRAS to search for infrared emission associated with the remnant. In his catalog of infrared emission from supernova remnants, Arendt (1989) called HB 21 a “probable” infrared source at 12 and 60 $\mu$m, with total fluxes of 180 ± 60 and 800 ± 350 Jy, respectively. The main source of uncertainty is confusion with unrelated emission in the Galactic plane, which cannot be easily separated in infrared images. Using the IRAS Sky Survey Atlas (I SSA; Wheelock et al. 1994), we created an image covering the region around HB 21 at 60 and 100 $\mu$m. There is extensive emission to the south, east, and west of the remnant, but with no clear correlation with the radio or CO image. The region toward the center of the remnant is relatively fainter than these edges, but the northern part of the remnant is also faint. It is not possible to tell whether the emission is related to a partial shell around the remnant or just fluctuations in the background emission.

To search for infrared emission associated with the remnant in more detail, we obtained a dedicated IRAS HIRES image at all four wavelengths (12, 25, 60, and 100 $\mu$m). The 60 $\mu$m image, where HB 21 is most prominent, is shown in Figure 10. Comparing the IRAS and CO images, it is evident that the southern filamentary cloud, cloud S, is detected as a long arc, with very similar location, shape, and width. The 60 $\mu$m surface brightness of the filament is typically 7 MJy sr$^{-1}$, and its structure is clumpy, like that of the CO emission. But the peaks of CO and infrared emission do not match in detail, suggesting that the 60 $\mu$m emission does not arise from the exact same regions as the CO. In the northern area, there is also a good correspondence between the infrared and CO emission. The general correspondence in the south and north, and partial overlap in the east, show that many of the infrared features around the edge of HB 21 are related to the remnant, although the infrared emitting regions differ in detail from the CO emitting regions.

The nature of the infrared emission from HB 21 could be either dust grains surviving the shock or from spectral lines from shock-excited gas or both. We have estimated the mean surface brightness and color of the CO clouds by using several faint regions in the field as background. The results are summarized in Table 3. The far-infrared color ratio, $I_{60}/I_{100} \approx 0.20$, for clouds A, B, and C is almost identical to that of diffuse cirrus clouds in the solar neighborhood (Boulanger & Pérault 1988). This suggests that the infrared emission from clouds A, B, and C is most likely caused by dust heated at the surface of the molecular clouds by the interstellar radiation field; specifically, it suggests that the infrared emission is not related to shock fronts into the clouds. On the other hand, clouds N and S have a significantly higher color ratio $I_{60}/I_{100} \approx 0.27$. This enhanced color, and the morphological correspondence with the broad molecular line emitting regions, suggests that the infrared emission from clouds N and S is caused by shocks in propagating into the clouds. Conversely, the normal infrared color of clouds A, B, and C is consistent with their being caused by ambient molecular clouds.

If the infrared emission from clouds N and S is caused by dust, then the relatively higher $I_{60}/I_{100}$ could be caused by smaller or warmer dust grains. For dust heated by the average interstellar radiation field in the solar neighborhood, about half of the emission at 60 $\mu$m is thought to be due to small, transiently heated grains (Draine & Anderson 1985; Desert, Boulanger, & Puget 1990). Thus, if the enhanced 60 $\mu$m emission is caused by dust grains, then clouds N and S may contain a larger fraction of small grains. An enhanced abundance of small grains would be expected if a significant fraction of larger grains were shattered behind the shock front. Observations of local cirrus clouds with significant velocities revealed that $I_{60}/I_{100} \approx 0.29$ is typical for clouds with $V_{LSR} > 30$ km s$^{-1}$, suggesting that grain shattering was significant in the shocks that

| Cloud Name | $I_{12}$ (MJy sr$^{-1}$) | $I_{25}$ (MJy sr$^{-1}$) | $I_{60}$ (MJy sr$^{-1}$) | $I_{100}$ (MJy sr$^{-1}$) | $I_{60}/I_{100}$ |
|------------|-------------------------|-------------------------|-------------------------|-------------------------|------------------|
| A………       | 1.1 (0.2)               | 1.1 (0.1)              | 4.2 (0.2)              | 20.8 (2.3)             | 0.20 (0.03)      |
| B……………  | 1.7 (0.1)               | 1.8 (0.1)              | 5.9 (1.1)              | 29.5 (2.4)             | 0.20 (0.04)      |
| C……………  | 1.7 (0.1)               | 1.7 (0.1)              | 8.0 (1.1)              | 38.0 (2.4)             | 0.21 (0.03)      |
| N……………  | 1.0 (0.2)               | 0.8 (0.1)              | 4.8 (0.2)              | 17.0 (2.3)             | 0.28 (0.04)      |
| S……………  | 1.2 (0.1)               | 1.2 (0.1)              | 6.8 (1.1)              | 26.3 (2.4)             | 0.26 (0.05)      |

Note.—Numbers in parentheses are estimated (1σ) errors.
accelerated local clouds to intermediate velocities (Heiles, Reach, & Koo 1988). Theoretically, significant shattering is not predicted for slow shocks, such as is inferred from the widths of the CO lines, but faster shocks through somewhat lower density interclump gas, with $v'_i > 100 \text{ km s}^{-1}$, could produce the enhanced 60 $\mu$m emission (Jones, Tielens, & Hollenbach 1996).

Spectral lines could contribute significantly to the infrared emission from clouds N and S. The most important lines in the IRAS passbands, based on infrared spectra of similar supernova remnants (Oliva et al. 1999; Cesarsky et al. 1999; Reach & Rho 2000), are [O III] 88 $\mu$m in IRAS band 4, [O I] 63 $\mu$m in band 3, [Fe II] 26 $\mu$m in band 2, and [Ne II] 12.8 $\mu$m and H$_2$ lines in band 1. If we were to interpret all of the IRAS emission from cloud S as caused by the ionic lines listed above, then, using the system response and bandwidths (Beichman et al. 1988), we find that the brightest line would be [O III] 88 $\mu$m, with intensity $I = 1.3 \times 10^{-2}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$. Relative to this line, the other bright lines would have ratios $\lambda 63/88 = 0.27$, $\lambda 26/88 = 0.13$, and $\lambda 12.8/88 = 0.26$. The implied brightness of the [O I] 63 $\mu$m line can be easily produced by shocks with velocities $\sim 100$ km s$^{-1}$ into moderate-density ($10^3$ cm$^{-3}$) gas (Hollenbach & McKee 1989); however, such shocks do not produce as much [O III] emission as observed because the column density of highly ionized gas is insufficient. Slower shocks into denser gas can also produce [O I] 63 $\mu$m lines this bright (Draine, Roberge, & Dalgarno 1983). However, slower (C-type) shocks produce essentially no ionic line emission—especially not an ion such as O III. Nor would the slow shocks destroy grains adequately to produce significant gas-phase Fe II. Therefore, if the infrared emission is from slow shocks, the IRAS 100 $\mu$m band emission is from dust, and the IRAS 60 $\mu$m band emission is from a mix of dust and the [O I] 63 $\mu$m line. The nature of the IRAS 12 and 25 $\mu$m band emission is more difficult to constrain. If the infrared emission is from slower shocks, such as that inferred from the CO observations, then there is likely a contribution from H$_2$ lines. H$_2$ rotational lines are the dominant coolant for a range of molecular shocks (Rho et al. 2001; Reach & Rho 2000). For now, it is not possible to tell clearly what fraction of the infrared emission is from gas or dust. The nature of the infrared emission from HB 21 (and other supernova remnants) can be determined in the future using spectroscopy or narrowband imaging.

5. SUMMARY

We have mapped the eastern half (80’ × 110’) of the SNR HB 21 in $^{12}$CO J = 2–1 line emission almost completely. Our map, which has been sampled completely with 27’’ resolution, shows the detailed structure of molecular clouds in this area. We have detected broad CO lines with large $^{12}$R$_{2-1/1-0}$ in the northern and southern parts of HB 21, which is direct evidence for the interaction between molecular clouds and the SNR. We summarize the main results of this paper as follows.

1. We detected shocked molecular clouds, clouds N and S, with broad (20–40 km s$^{-1}$) CO lines in the northern and southern parts of the SNR. Cloud N is composed of a small (~2’ or 0.5 pc), very bright, U-shaped, clumpy part and several clumps scattered around it. Cloud S is filamentary and appears to form an elongated loop of ~30’ in extent. Small (~1.2 or 0.3 pc), bright clumps are seen along the filamentary structure. The H$_2$ masses of clouds N and S are ~8 and ~55 $M_\odot$, respectively.

2. We have obtained sensitive J = 1–0 and J = 2–1 spectra of $^{12}$CO and $^{13}$CO molecules toward several peak positions of clouds N and S. They have $^{12}$R$_{2-1/1-0}$ = 1.6±2.3 and $^{12}$R$_{2-1/10}$ = 20–40 with CO J = 2–1 main-beam brightness temperature less than 7 K. According to our LVG analysis, $T_2 \geq 50$ K, and, for $T_2$ = 100 K, $n(H_2) = (3.7) \times 10^3$ cm$^{-3}$ and N(CO) $\simeq (2.4–11) \times 10^{17}$ cm$^{-2}$. The emitting region appears to fill a small (0.077–0.088) fraction of the beam.

3. There is an enhanced radio emission that attains a maximum exactly inside the central U-shaped part of cloud N. The emission has a spectral index (~0.28 ± 0.17) flatter than that of the whole remnant. The association of this emission with cloud N needs to be explored.

4. Clouds N and S are visible in the IRAS H IRES images at all four wavelengths (12, 25, 60, and 100 $\mu$m). They have the far-infrared color ratio $I_{120}/I_{100} \simeq 0.27$, which is significantly greater than that (0.20) of the other clouds in this area. This enhanced color, and the morphological correspondence with the broad molecular line emitting regions, suggests that the infrared emission from clouds N and S is caused by shocks in propagating into the clouds.

5. Along the eastern boundary of the SNR, three relatively large (≥15’ or 3.5 pc) clouds and several filamentary clouds are present. No broad CO emission or enhanced 60/100 $\mu$m color were detected in any of these clouds, and there is little relationship between the boundaries of the clouds and the SNR. Therefore, there is no strong evidence for the interaction of the SNR with molecular clouds along the eastern boundary.

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