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SHOCKED INTERSTELLAR GAS IN THE W51 COMPLEX

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ABSTRACT

We report the results of H I 21-cm and molecular line studies of the shocked interstellar gas in the W51 complex. We present convincing evidences suggesting that the shocked gas has been produced by the interaction of the W51C supernova remant (SNR) with a large molecualr cloud. Our results show that W51C is the *second* SNR with direct evidences for the shocked cloud material.

Key Words : ISM: individual (W51) — ISM: molecules — radio lines — supernova remnants

I. INTRODUCTION

The interaction of supernova remnants (SNRs) with dense molecular clouds is of considerable interest because it provides an opportunity to study the complex physical and chemical processes associated with the shocks. But the SNRs with convincing evidences for the interaction are rare, perhaps W28, W44, IC 443, and CTB 109 (see references in Koo & Moon 1996b). In fact, IC 443 has remained as an unique SNR which shows broad molecular emission lines indicating strongly shocked cloud material (DeNoyer 1979a, 1979b).

In this work we present the results of our recent observational studies, which show that W51C is another SNR with clear evidences for the molecular cloud-shock interaction (Koo & Moon 1996a, 1996b).

W51C is a composite SNR which appears as an incomplete shell of $\sim 30'$ diameter in radio continuum (Copetti & Schmidt 1991; Subrahmanyan & Goss 1995). It has a hot ($T_e \simeq 3 \times 10^6$ K), centrally brightened X-ray emitting gas (Seward 1990; Koo, Kim, & Seward 1995). The estimated distance to the SNR is $\sim$ 6 kpc (Koo et al. 1995). Fast moving H I gas in the W51 complex has been detected by Koo & Heiles (1991). Using the Hat Creek 26-m telescope (FWHM=36′), which was destroyed by a windstorm on 1993 January 21, they detected H I gas at velocities between $v_{\rm LSR} = +73$ and $+148$ km s^{-1}. This line-of-sight velocity was much greater than the maximum velocity (~ 60 km s^{-1}) permitted by the Galactic rotation toward this direction and they concluded that the gas must be produced by some local dynamical perturbations. But their low-resolution observations could not reveal the nature of the high-velocity (HV) H I gas.

II. SHOCKED H I

H I 21-cm line observations were made using the 305-m telescope at the Arecibo Observatory and also the Very Large Array (VLA) in D-configuration. High-resolution H I images were made from the VLA data with the missing short-spacing data filled from the Arecibo data.

The HV H I gas is seen between $v_{\rm LSR} \simeq +85$ and $+180$ km s^{-1}. The H I gas is distributed along a loop-like filamentary structure (Fig. 1). The filamentary structure is composed of a central strong arc of $\sim 10' \times 3'$ size and some weak extensions that form an almost closed loop. The total length of the structure is $\sim 20'$ (or 35 pc at a distance of 6 kpc). The line-of-sight velocity decreases systematically along the filamentary structure, from the central region to the ends (Fig. 1).

Table 1. Parameters of the Expanding H I Shell

Parameter	Estimated Value
R_{sc}	~ 6 pc
v_{sc}	~ 100 km s^{-1}
$N(\rm HI)_\perp$	(2–10)$\times 10^{20}$ cm^{-2}
$\Delta M(\rm HI)$	1200 $M_\odot$
Momentum	$> 1.7 \times 10^{10}$ $M_\odot$km s^{-1}
Kinetic energy	$> 1.7 \times 10^{50}$ ergs
Age	$\sim 1.5 \times 10^4$ yr

By comparing with the X-ray and CO distributions (Fig. 2), we have found that the HV H I gas is located at an interface between the X-ray bright central region of the W51C SNR and a large molecular cloud. The correlation between the X-ray, CO, and H I emissions strongly suggests that the HV H I gas has been produced by a shock driven by the SNR into the molecular cloud. The large amount (> 1200 $M_\odot$) of fast-moving H I gas indicates that the shock is a fast, radiative, J-type shock. The VLA line profiles give a maximum *line-of-sight* shock velocity of $\simeq 70$ km s^{-1}. A simple model where a hemispherical H I shell expanding into a cylindrical cloud from the side could explain the observed morphology and velocity structure of the H I gas. The shock velocity corrected for the projection is ~ 100 km s^{-1}. The parameters of the H I shell are summarized in Table 1.

III. SHOCKED CO AND HCO$^+$

We discovered shocked CO and HCO$^+$ associated with the shocked H I using the Kitt Peak 12-m tele-

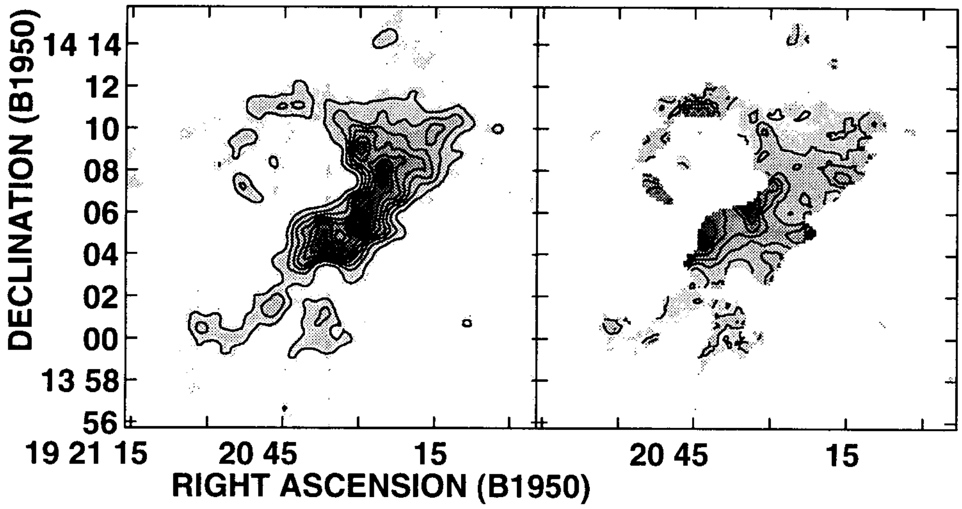

Fig. 1.— (left) Integrated intensity distribution of the HV H I gas. The distribution has been obtained by integrating the intensity over the velocity range between v_{LSR} = +85 and +144 km s^{-1}. The contour levels are evenly spaced, with an interval of 0.026 mJy $beam^{-1}$ km s^{-1}, starting at 0.026 mJy $beam^{-1}$ km s^{-1}. (right) Intensity-weighted mean velocity over the same velocity range. The contour levels are evenly spaced, with an interval of 5 km s^{-1}, starting at 90 km s^{-1}.

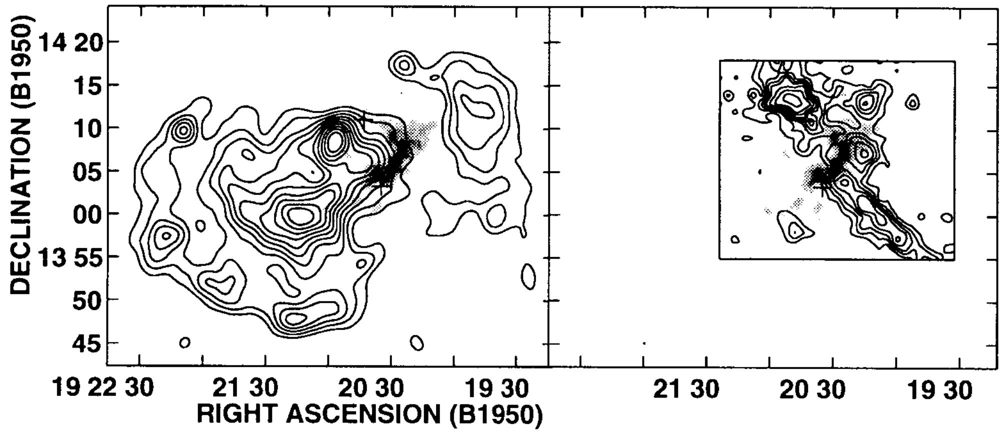

Fig. 2.— Distribution of the HV H I gas (grey map) compared with (left) the ROSAT X-ray image of the W51C SNR (Koo et al. 1995), and (right) the ^{13}CO distribution in this region (Moon 1994). Note that the HV H I emission delineates the western boundary of the X-ray bright central region and the eastern boundary of the ^{13}CO distribution. The contour levels of the X-ray image are evenly spaced, with 0.01 counts s^{-1} $pixel^{-1}$, starting at 0.01 counts s^{-1} $pixel^{-1}$. The ^{13}CO distribution shows the average brightness between v_{LSR} = +55 and +74 km s^{-1}. The contour levels are −0.2, 0.2, 0.4, 0.6, 0.8, 1.0, 1.3, 1.6, and 1.9 K.

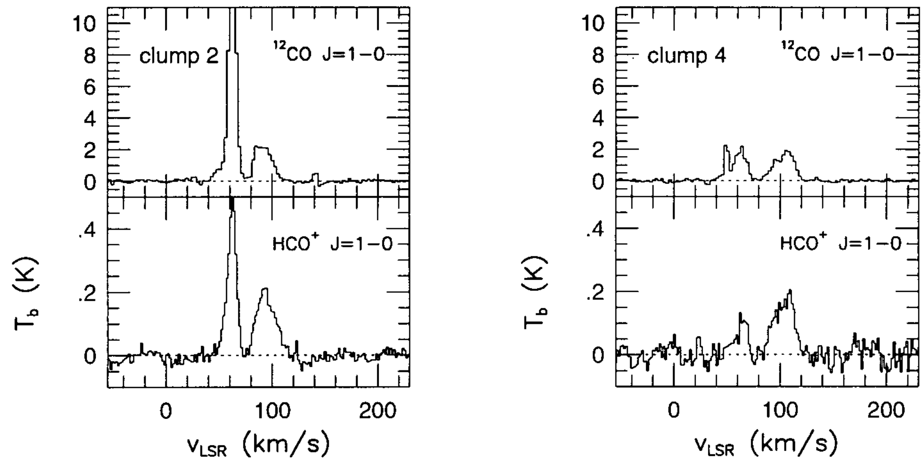

Fig. 3.— ^{12}CO J=1–0 and HCO^{+} J=1–0 spectra at the peak positions called clump 2 and clump 4.

scope. The ^{12}CO J=2–1 and HCO^{+} J=1–0 line profiles at some peak positions are shown in Figure 3. The strong emission between $v_{LSR} \simeq +40$–$+80$ km s^{-1} is from the molecular clouds in the Sagittarius arm including those associated with the W51 complex. The emission at $v_{LSR} \gtrsim +80$ km s^{-1} is from the shocked gas in the SNR. The line-of-sight velocity of the shocked CO is +20–+45 km s^{-1} with respect to the ambient cloud and its emission could be identified easily.

The position and morphology of the shocked CO coincide with the bright portion of the shocked H I (Fig. 4). The coincidence suggests that the fast-moving CO is likely the molecules reformed behind the shock front. Except for the perturbed motions, however, there are no other indications for the shock processing in their emission lines. The excitation temperature is 9–11 K and the HCO^{+}/CO abundance ratio is 1.2–1.3×10^{-4}. These are all typical of cold, quiescent molecular clouds. This seems to be consistent with theoretical results that, at low preshock densities ($\lesssim 10^3$ cm^{-3}), the chemistry behind the shock front proceeds at such low temperatures that one does not expect to distinguish the emission from that of the cold, dense ambient gas (Hollenbach & McKee 1989). It is, however, possible that the molecular species which require longer time for the complete reformation may have relatively *lower* abundances.

The shocked gas generally has the CO/H I abundance ratio less than 4×10^{-5}. The upper limit corresponds to the ratio of CO to hydrogen nuclei in typical molecular clouds. Therefore it implies that almost all of the hydrogen nuclei in the shocked gas are atomic, not molecular. This is consistent with the result that the H I column density perpendicular to the shock front is smaller than 10^{22} cm^{-2}, the column density required for the complete reformation of H_2 molecule. Hence the shock in the W51C SNR appears to be old enough to reform molecules such as CO and HCO^{+}, but not old enough to completely reform H_2.

The CO content of the shocked gas, however, varies a lot, suggesting that the reformation of CO is proceeding at different rates at different locations. There is a tendency such that the shocked H I extends beyond the shocked CO. The shocked gas with very small N(CO)/N(H I) may have not swept up enough column density to reform CO molecules, perhaps because of low preshock density. There are also some weak CO features which appear to be devoid of the associated H I.

IV. CONCLUSIONS

The fast moving H I and molecular gases in the W51 complex are probably produced by the interaction between the SNR W51C and a large molecular cloud. The H I gas is located at the boundary of the cloud and must be the dissociated, ionized, and then recombined preexisting molecules. The fast-moving CO is likely the molecules reformed behind a fast, *dissociative* J-shock. The parameters of the shocked molecular gas are typical of cold, quiescent molecular clouds, which seems to be consistent with theoretical results. The overall morphology of the W51C SNR in X-ray, CO, and H I fits into a SNR produced by a SN explosion near the boundary of a large molecular cloud. Future high-resolution, sensitive observations of H I, H_2, and various molecular species will provide us a great deal of information which can be compared with theoretical models to yield better understanding of the SNR-molecular cloud interaction.

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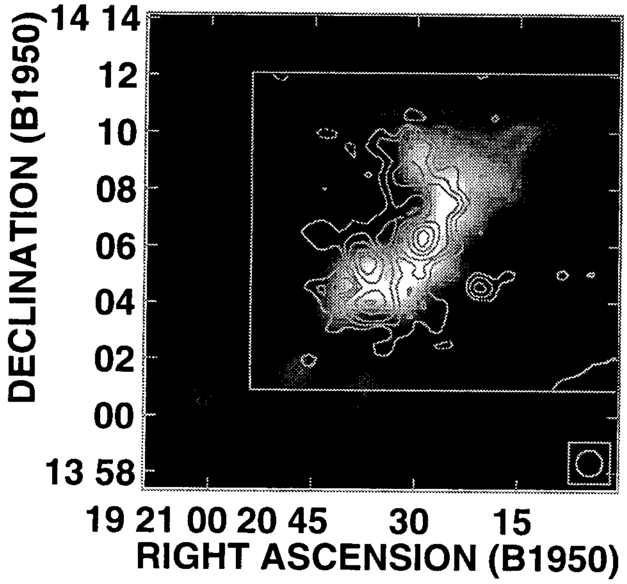

Fig. 4.— Map of the shocked CO (contours) superposed on the map of the shocked H I (gray shades). The CO map is obtained by integrating the ^{12}CO J=1–0 line emission from $v_{\rm LSR}$ = +81 to +120 km s^{-1}. Contour levels are $\int T_b dv$ = −3, 3, 6, 10, 20, 30, and 40 K km s^{-1}. The square box marks the boundary of the area observed in the ^{12}CO J=1–0 line . The beam is shown at the bottom right corner. The H I map has been convolved with a Gaussian beam to have the same angular resolution (55″) as the CO map.

gram, Ministry of Education, 1995, project BSRI-95-5408.

REFERENCES

Copetti, M. V. F., & Schmidt, A. A. 1991, MNRAS, 250, 127

DeNoyer, L. K. 1979a, ApJL, 228, L41

—— 1979b, ApJL, 232, L165

Hollenbach, D., & McKee, C. F. 1989, ApJ, 342, 306

Moon, D.-S. 1994, Master thesis, Seoul National University

Koo, B.-C., & Heiles, C. 1991, ApJ, 382, 204

Koo, B.-C., Kim, K.-T., & Seward, F. D. 1995, ApJ, 447, 211

Koo, B.-C., & Moon, D.-S. 1996a, ApJ in press

—— 1996b, ApJ submitted

Seward, F. D. 1990, ApJS, 73, 781

Subrahmanyan, R., & Goss, W. M. 1995, MNRAS, 275, 755