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SRAO CO Observation of Supernova Remnants in $l = 70°$ to $190°$

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Abstract. We present the results of ^{12}CO $J = 1$–0 line observations of eleven Galactic supernova remnants (SNRs) between $l = 70°$ and 190° obtained using the Seoul Radio Astronomy Observatory (SRAO) 6-m radio telescope. We detected CO emission towards most of the remnants. In seven SNRs, molecular clouds show a good spatial relation with their radio morphology: G73.9+0.9, G84.2−0.8, G85.4+0.7, G85.9−0.6, G93.3+6.9 (DA530), 94.0+1.0 (3C 434.1), and G182.4+4.3. Two SNRs are particularly interesting. In G85.4+0.7, there is a filamentary molecular cloud aligned along the south-east boundary of the remnant. This cloud extends to the nearby HII region G84.9+0.5. If the molecular cloud is associated with both the HII region and the SNR, the distance to the SNR would be 5–7 kpc. In 3C 434.1, there is a large molecular cloud blocking the western half of the remnant where the radio continuum emission is faint. The cloud shows a very good spatial correlation with radio continuum features, which strongly suggests the physical association of the cloud with the SNR. This gives a distance of 3 kpc to the SNR. We performed ^{12}CO $J = 2$–1 line observations of this cloud using Kölner Observatorium für Sub-Millimeter Astronomie (KOSMA) 3-m telescope and found a region where the ^{12}CO $J =$ 2–1/1–0 line ratio is high. We present a hydrodynamic model showing that 3C434.1 could have resulted from a SN explosion occurred just outside the boundary of a thin, molecular cloud.

Keywords. supernova remnants, ISM: molecules, ISM: clouds

1. Introduction

SN explosions strongly affect the environment, while, at the same time, the evolution of a supernova remnant (SNR) is strongly affected by the environment itself. Among the environmental impacts of SN explosions, the interaction with molecular clouds (MCs) is of particular interest where we can study the microphysics of molecular shocks and the hydrodynamics of SNR blast waves. There have been many studies of individual SNRs, and about 70 out of the 274 Galactic SNRs (Green 2009) are known to be interacting with molecular clouds (Jiang *et al.* 2010). Systematic studies, however, are limited. As far as we are aware of, the only systematic study of the molecular environment of SNRs is by Huang and Thaddeus (1986), who surveyed ^{12}CO $J = 1$–0 emission lines toward Galactic SNRs from $l = 70°$ to 210°. Their results were useful for studying the distributions of large molecular cloud complexes near SNRs, but have a limitation because of the low spatial resolution ($\sim 8'.7$) of the telescope.

We have carried out a systematic CO observation of eleven SNRs in $l = 70°$ to 190°. In this paper, we present a summary of observations and main results, with some details on the SNR 3C 434.1. For the details of the survey results, see Jeong *et al.* (2012).

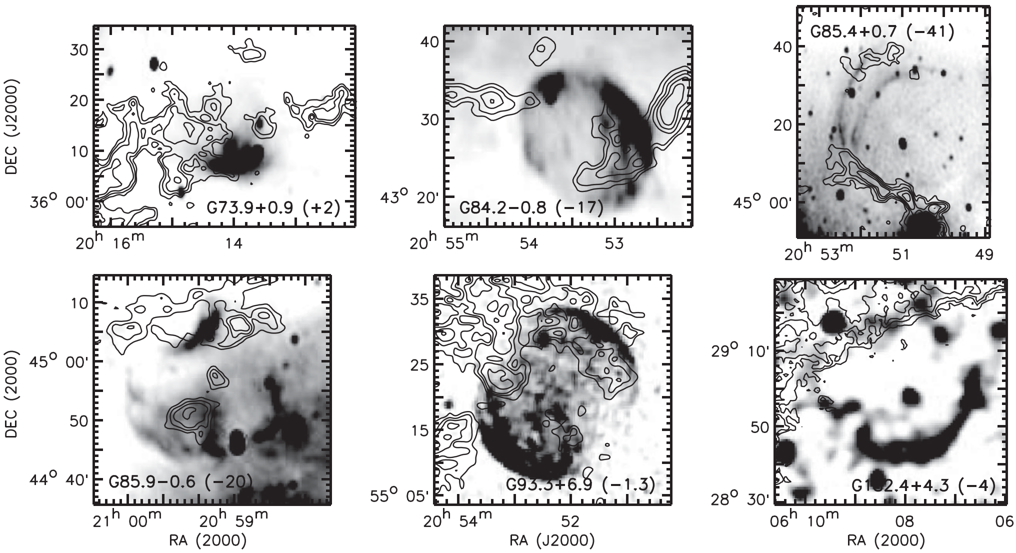

Figure 1. ^{12}CO $J = 1$–0 average intensity maps of the selected targets which show spatially-correlated features with CO molecular clouds (Jeong *et al.* 2012). The numbers in the parentheses are the central velocities of the CO maps.

2. Observation

Our target SNRs are selected among the 35 SNRs in $l = 70°$ to $190°$ (Green 2004): G73.9+0.9, G76.9+1.0, G84.2−0.8, G85.4+0.7, G85.9−0.6, G93.3+6.9 (DA530), 94.0+1.0 (3C 434.1), 166.2+2.5 (OA184), 179.0+2.6, 180.0−1.7 (S147), and G182.4+4.3. They have angular sizes between 10′ and 180′ and located outside the area of the Outer Galaxy Survey or the Galactic Ring Survey (Jackson *et al.* 2006) of the Five College Radio Astronomy Observatory (FCRAO).

The ^{12}CO $J = 1$–0 observations using SRAO 6-m telescope Seoul Radio Astronomy Observatory (SRAO) were carried out from October 2003 to May 2005. The half-power beam size of the telescope is 120″ and a main beam efficiency is 70% at 115 GHz (Koo *et al.* 2003). The telescope has a 100 GHz SIS mixer receiver with a single-side band filter and a 1024-channel auto-correlator with 50 MHz bandwidth. The typical system temperature ranged from 500 to 800 K, and the typical *rms* noise level was 0.3 K on T_{mb} scale at 1 km s^{-1} velocity resolution. To check the system performance and the pointing accuracy, we observed the bright standard source near the target every one or two hours. We mapped areas fully covering the radio morphology of individual SNRs with either half-beam (60″) or full-beam (120″) samplings.

3. Results of the Survey

We detected CO emission toward most SNRs. In seven SNRs, the CO emission showed spatially-correlated features with radio continuum emission: G73.9+0.9, G84.2−0.8, G85.4 +0.7, G85.9−0.6, G93.3+6.9 (DA530), 94.0+1.0 (3C 434.1), and G182.4+4.3. Fig. 1 shows the CO intensity maps of the 6 SNRs and a brief summary is given below for each of them. The result on 3C434.1 is presented separately in the following section.

G73.9+0.9 This is a diffuse SNR located in the complex Cygnus region. It has a partial shell-feature in south and a pulsar-wind nebula candidate inside (Kothes *et al.* 2006). We have detected a large MC at +2 km s^{-1} that appears to be blocking the eastern boundary

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of the SNR. But there is no obvious morphological relation between the CO and radio continuum brightnesses.

G84.2-0.8 This is a shell-type SNR of an elliptical shape. The boundary of the SNR, in particular the western boundary, shows features of enhanced radio continuum brightness. There is a MC at -17 km s^{-1} that matches very well with the bright portion of the western SNR shell. This cloud was first noted by Feldt & Green (1993), but our high-resolution map reveals its morphological correlation with the SNR clearly. If this cloud is associated with the SNR, which is likely, the distance to the SNR will be 4.9 kpc. There is also a filamentary cloud protruding the northwestern SNR shell, near another radio-continuum enhanced region, but its association is not clear.

G85.4+0.7 This is a shell-type SNR with two distinct, partial shells. According to Kothes *et al.* (2001), the inner shell is non-thermal and the outer thermal. They noted that the SNR is inside an Hi bubble at -12 km s^{-1} and proposed a distance of 3.8 kpc to them. In our observation, however, there is a filamentary MC at -41 km s^{-1} which appears to have a similar curvature with the radio continuum shells and connects to their southern ends. This spatial correlation suggests that their association is likely. We mapped a larger area surrounding the SNR in ^{12}CO J = 1–0 line and found that this cloud extends to the compact Hii region G84.9+0.5 in the south. If the MC is associated with both the HII region and the SNR, the kinematic distance to the SNR becomes 7.2 kpc according to the rotation curve of Brand and Blitz (1993) (cf. Foster *et al.* 2007 proposed a distance of 4.9 kpc to the HII region).

G85.9−0.6 This is a shell-type SNR with a kinked arc in the north. We note that there is a MC at -20 km s^{-1} superposed on this arc structure, but they do now show apparent spatial correlation. If they are associated, the distance to the SNR would be 5 kpc.

G93.3+6.9 (DA530) This is a bilateral type SNR located at high galactic latitude (Gaensler 1998). Landecker *et al.* (1999) found an Hi bubble at -12 km s^{-1} which spatially coincides with the SNR, and proposed a distance of 3.5 kpc. We have detected a diffuse CO emission at the velocity of -1.3 km s^{-1} in the northern area of the remnant, but the morphology of the CO emission is not clearly correlated with the radio continuum.

G182.4+4.3 This is well-defined shell-type SNR with a bright, half shell structure in the southwest (Kothes *et al.* 1998). There is a diffuse CO emission at ~ -4 km s^{-1} that match well with the radio-faint, northwestern boundary of the SNR. There is, however, no evidence of the interaction.

4. Molecular-Blocked SNR G94.0+1.0 (3C434.1)

3C434.1 is a shell-type SNR with an asymmetric radio morphology; a bright semi-circular shell with complex filaments in the east with no distinct feature in western area (Willis 1973; Landecker *et al.* 1985). We have found that the MC at -13 km s^{-1} overlaps with the western part of the remnant. The spatial correlation between the two is clearly seen in Fig. 2 which is a channel map at -13 km s^{-1}. Note the thin filamentary structure tracing the western boundary of the SNR including a "bar-like" structure within the remnant. The above morphological correlation between the CO and radio continuum strongly suggests that the MC is interacting with the SNR. We performed ^{12}CO J = 2–1 follow-up line observations of the cloud using KOSMA 3-m telescope, and found that ^{12}CO J = 2–1/1–0 line ratio is high in the southern molecular cloud, which supports the above conclusion. The systemic velocity of the MC yields a kinematic distance of 3.0 kpc to the SNR, which is less than the previous estimates, e.g., 4.5 kpc of Foster (2005).

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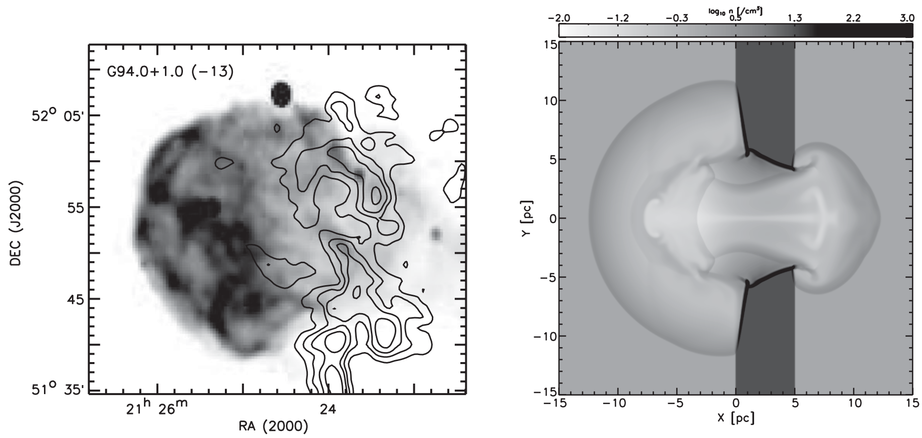

Figure 2. (left) SRAO ^{12}CO J = 1−0 channel map of SNR 3C 434.1 at −13 km s^{-1}. (right) Density structure of hydrodynamic model at t = 7,950 yrs (see text for details).

We have developed a hydrodynamic model to understand the radio morphology of the SNR (Jeong *et al.* in preparation). We assume that the SN exploded at 1 pc from the boundary of a sheet-like cloud with a thickness of 5 pc. The H-nuclei number density of the cloud is assumed to be 20 cm^{-3}, whereas the density of the diffuse medium is set to be 1 cm^{-3}. We assume that the cloud had a cylindrical hole at the center to match the radio continuum structure. The radius of the hole is assumed to be 3 pc. For the calculation, we adopt 3-dimensional hydrodynamic code developed by Harten, Lax and van Leer (HLL) with modified cooling effect (Harten *et al.* 1983). The simulation box consists of 512 × 256 × 256 grids with a spatial resolution of 1/16 pc. The result of the numerical simulations is shown in Fig. 2, which shows the density structure at 7,950 yrs. The simulation result recovers well the basic radio morphology of the SNR, except the long straight filaments that extends far out from the western part of the remnant. More details on the study of this SNR will be published elsewhere.

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Discussion

Jiang B.: Among those SNRs which you showed spatial coincidence with CO emission may not be really associated with the molecular clouds. For example, DA 530, the asymetric radio shell and the distance ($\sim$ 2kpc), makes it not consistent with the molecular cloud you showed. So are you going to look for other evidence for the association?

Jeong: Yes, we will use more data to do it.

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