STAR FORMATION ASSOCIATED WITH THE SUPERNOVA REMNANT IC443

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ABSTRACT

We have performed submillimeter and millimeter observations in CO lines toward supernova remnant (SNR) IC443. The CO molecular shell coincides well with the partial shell of the SNR detected in radio continuum observations. Broad emission lines and three 1720 MHz OH masers were detected in the CO molecular shell. The present observations have provided further evidence in support of the interaction between the SNR and the adjoining molecular clouds (MCs). The total mass of the MCs is 9.26 $\times$ 10$^3$ $M_\odot$. The integrated CO line intensity ratio ($R_{CO3-2}/I_{CO2-1}$) for the whole MC is between 0.79 and 3.40. The average value is 1.58, which is much higher than previous measurements of individual Galactic MCs. Higher line ratios imply that shocks have driven into the MCs. We conclude that high $R_{CO3-2}/I_{CO2-1}$ is identified as a good signature of the SNR–MC interacting system.

Key words: ISM: clouds – ISM: individual objects (IC443) – ISM: molecules – ISM: supernova remnants – stars: formation

Online-only material: color figures

1. INTRODUCTION

The progenitor of a core-collapse supernova remnant (SNR) IC443 is a high-mass star (with masses $>8 M_\odot$). High-mass stars can dramatically impact the surrounding environment through stellar winds at their earliest evolutionary stage and supernova (SN) explosions at their last evolutionary stage. When a SNR expands into the surrounding molecular clouds (MCs), the local density of the MCs increases and then some condensed MCs will collapse. The timescale of the collapsed phase is $\sim$10$^5$ yr (Leftflech & Lazareff 1994), while protostellar objects occur in a period on the order of 10$^6$ yr (Reynoso & Mangum 2001). In principle, galactic density waves, the shocks of cloud–cloud collision (e.g., Wang et al. 2004; Xin & Wang 2008), energetic stellar winds (Junkes et al. 1992), and SNR shocks (Frail et al. 1994; Reynoso & Mangum 2000; Melioli et al. 2006) all could induce the collapse of MCs to protostellar objects. Therefore, the interaction between SNRs and MCs is expected to play an essential part in the process of star formation.

SNR IC443, at a distance of 1.5 kpc (Fesen 1984), is located in the Gem OB1 association (Heiles 1984). A pulsar is associated with IC443 (Olbert et al. 2001; Gaensler et al. 2006), suggesting a core-collapse origin. In addition, the age of IC443 is 3000–30,000 yr (Petre et al. 1988; Olbert et al. 2001; Lee et al. 2008). Prior observations suggested that IC443 may be interacting with the surrounding MCs (DeNoyer 1979; Mufson et al. 1986; Dickman et al. 1992; van Dishoeck et al. 1993). Braun & Strom (1986) suggested that IC443 has evolved in a cavity of wind-blown bubble, possibly formed by the pre-SN evolution, and recently started to interact with the cavity shell.
eters have 1501 and 1601 channels, with total bandwidths of 248 MHz and 544 MHz, and equivalent velocity resolutions of 0.21 km s$^{-1}$ and 0.29 km s$^{-1}$, respectively. The beam efficiency $B_{\text{eff}}$ is 0.68 and 0.72 at 230 GHz and 345 GHz, respectively. The forward efficiency $F_{\text{eff}}$ is 0.93. The mapping was done using on-the-fly mode with a 1′ × 1′ grid. The data were reduced using the CLASS (Continuum and Line Analysis Single-Disk Software) and GREG (Grenoble Graphic) software.

The 1.4 GHz radio continuum emission data were obtained from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998).

3. RESULTS

3.1. Molecular Emission

Figure 1(a) presents the integrated intensity maps of CO $J = 2–1$ and CO $J = 3–2$, overlapping the 1.4 GHz radio continuum emission. In Figure 1(a), the CO $J = 2–1$ and CO $J = 3–2$ maps appear as incomplete shells, which may be produced by energetic events near the center, such as strong stellar winds and/or SN explosions. Clouds B–G are clearly identifiable as local integrated intensity peaks around IC443. IC443 also shows an incomplete radio shell morphology on the whole. Each cloud has been designated alphabetically, following the naming convention of DeNoyer (1979) and Huang et al. (1986). Clouds B, C, D, and E are associated with the 1.4 GHz radio continuum emission of IC443. The CO $J = 2–1$ and CO $J = 3–2$ molecular emission is significantly stronger in clouds B, C, and G. However, the molecular emission from clouds A and H is too weak to be detected at the signal-to-noise ratio (S/N) of our survey. Three 1720 MHz OH masers, detected in the radio shell of IC443 (Hewitt et al. 2006), are located close to the peak of clouds C, D, and G, respectively. Figure 1(b) shows CO $J = 3–2$ spectra at the peak position of clouds B–G, respectively. The line profile of clouds B and C is greatly broadened in the blue wing, while the line profile of cloud F is greatly broadened in the red wing. For cloud C, CO emission in velocity intervals $-60$ to $2$ km s$^{-1}$ is well associated with a broad component of molecular hydrogen gas at $-30$ km s$^{-1}$ (Rosado et al. 2007). The fitted and derived parameters for clouds B–G are summarized in Table 1.

The different transitions of CO trace different molecular environments. In order to obtain the integrated intensity ratio of CO $J = 3–2$ to CO $J = 2–1$ ($R_{\text{CO}(3-2)/\text{CO}(2-1)}$), we convolved the 80′ resolution of CO $J = 3–2$ data with an effective beam size of $\sqrt{130''^2 - 80''^2} = 102''$. The integrated intensities were calculated for the CO $J = 3–2$ line in the same velocity range as the CO $J = 2–1$ line. The integrated range is from $-60$ to $28$ km s$^{-1}$. Figure 2 shows the distribution of $R_{\text{CO}(3-2)/\text{CO}(2-1)}$ (color scale) overlaid with the distribution of the CO $J = 3–2$ line integrated intensity (contours). The maximum ratio of cloud C is 3.40, which is located at R.A. = 06$^h$17m42s (J2000), decl. = +22°22'34" (J2000). For cloud G, the maximum ratio (3.18) is located at R.A. = 06$^h$16m35s (J2000), decl. = +22°32'34" (J2000). The ratio value for the entire MC is between 0.79 and 3.40. The average value is 1.58, which is much higher than the typical value (0.55) for MCs in the Galactic disk (Sanders et al. 1993) and the value (0.69) for the normal MCs in M33 (Wilson et al. 1997), and even higher than the value (0.8) in the starburst galaxies M82 (Guesten et al. 1993).

We assume local thermodynamical equilibrium for the gas and an optically thick condition for the CO $J = 3–2$ line to use
the relation \( \nu_{\mathrm{H}_2} \approx 10^4 \nu_{\mathrm{CO}} \) (Dickman 1978). The optical depth of \( \tau = 3.1 \) is given by Braun & Strom (1986). The column density is estimated as (Garden et al. 1991)

\[
N_{\mathrm{CO}} = 1.89 \times 10^{15} \frac{T_{\text{ex}} + 0.92}{T_{\text{ex}}} \exp(16.6/T_{\text{ex}}) \int T_{\text{mb}} d\nu \text{ cm}^{-2}.
\]

The excitation temperature of the CO \( J = 3-2 \) line, \( T_{\text{ex}} \), is estimated following the equation \( T_{\text{ex}} = 16.6/\ln[1 + (T_{\text{mb}}/16.6 + 0.0024)] \), where \( T_{\text{mb}} \) is the corrected main-beam temperature. If cloud cores are approximately spherical in shape, the mean \( \mathrm{H}_2 \) number density is \( N(\mathrm{H}_2) = 1.62 \times 10^{-19} \nu_{\mathrm{H}_2}/L \), where \( L \) is the cloud core diameter in parsecs (pc). The mean diameter is 1.75 pc for all the MCs. Furthermore, their mass is given by \( M_{\mathrm{H}_2} = \frac{1}{2} \pi L^2 \mu_{\mathrm{H}_2} m(\mathrm{H}_2) \) (Garden et al. 1991), where \( \mu_{\mathrm{H}_2} = 1.36 \) is the mean atomic weight of the gas and \( m(\mathrm{H}_2) \) is the mass of a hydrogen molecule.

### 3.2. Infrared Emission

IRAS (IR) point sources are good signposts of recent star formation. In order to explore a causal relationship between IC443 and star formation, we have searched for protostellar candidates in the IRAS Point Source Catalog that fulfill the following selection criteria (Junkes et al. 1992): (1) \( F_{100} \geq 20 \text{ Jy} \), (2) \( 1.2 \leq F_{100}/F_{60} \leq 6.0 \), (3) \( F_{25} \leq F_{60} \), and (4) \( R_{\text{IRAS}} \leq 2 \cdot R_{\text{radio}} \), where \( F_{25}, F_{60}, \) and \( F_{100} \) are the infrared fluxes at three IR bands (25 \( \mu \text{m}, 60 \mu\text{m}, \) and 100 \( \mu\text{m} \)) bands, respectively. The first criterion selects only strong sources. The second and third discriminate against cold IR point sources probably associated with cool stars, planetary nebulae, and cirrus clumps, while the fourth guarantees that the search diameter includes the complete surface of IC443. However, these selection criteria may include not only protostars but also dust heated by shocks. A dozen IR point sources were found in a search circle around IC443 within a 25′ radius centered at R.A. = 06h17m13s (J2000), decl. = +22°37′10″ (J2000). The coordinates are adopted as the explosion center (Lee et al. 2008). The names and coordinates of these IR point sources are listed in Table 2. Figure 3 shows that the IR sources are associated quite well with the CO molecular shell. IR 4 and IR 10 are located on the peak position of the CO molecular shell. Infrared luminosity (Casoli et al. 1986) and dust temperature (Henning et al. 1990) are respectively expressed as

\[
L_{\text{IR}} = (20.653 \times F_{12} + 7.538 \times F_{25} + 4.578 \times F_{60} + 1.762 \times F_{100}) \times D^2 \times 0.30,
\]

\[
T_d = \frac{96}{(3 + \beta) \ln(100/60) - \ln(F_{60}/F_{100})},
\]

where \( D \) is the distance from the Sun in kpc. The emissivity index of dust particles (\( \beta \)) is assumed to be 2. The calculated results are presented in Table 2.

To further look for primary tracers of star formation activity in the vicinity of IC443, we used the 2MASS All-Sky Point source database in the near-infrared \( J(1.25 \mu\text{m}), H(1.65 \mu\text{m}), \) and \( K_s(2.17 \mu\text{m}) \) bands, with an S/N greater than 10. The 2MASS database provides a good opportunity to select YSO candidates associated with or even embedded in MCs. From the database, we selected 10,272 near-infrared sources in a search circle around IC443 within a 25′ radius. Figure 4 shows the \( (H - K_s) \) versus \( (J - H) \) color–color (CC) diagram. The two solid curves represent the location of the main sequence (MS) and the giant stars, respectively (Bessel & Brett 1988). The parallel black dashed lines are reddening vectors. The blue dashed line is \( (J - H) = 1.7(H - K_s) + 0.450 \), the blue solid line is \( (J - H) = 0.493(H - K_s) - 0.439 \), the red dashed line is \( (J - H) = 1.7(H - K_s) + 1.400 \), and the red solid line is \( (J - H) = 0.2 \). 2MASS sources are classified into three regions: cool giants, normally reddened stars, and infrared excess sources. Because YSOs have near-infrared excess (Lada & Adams 1992), YSO candidates are located at the rightmost of the reddened vectors (Weintraub & Kastner 1996; Hanson et al. 1997; Paron et al. 2009). Based on this criterion, we find 1666 YSO candidates in the mentioned region. Figure 5(a) presents the spatial distribution of these selected YSO candidates. It is clear that the YSO candidates are not symmetrically distributed.

**Figure 2.** CO \( J = 3-2 \) intensity map is superimposed on the line intensity ratio map (color scale); the line intensity ratios \( (R_{\mathrm{CO}(3-2)/\mathrm{CO}(2-1)}) \) range from 0.79 to 3.40 by 0.34. The wedge indicates the line intensity ratio scale. A, B, C, D, E, F, G, and H indicate the different MCs (Denoyer 1979; Huang et al. 1986).

(A color version of this figure is available in the online journal.)

**Figure 3.** Positions of IR point sources relative to the CO \( J = 3-2 \) shell around IC443. The filled squares are the IR sources.

(A color version of this figure is available in the online journal.)
in the entire selected regions and are mostly concentrated in clouds C and G. Regarding the geometric distribution of the YSO candidates, we plot the map of the star surface density, which was obtained by counting all the YSO candidates with a detection in the J, H, and Ks bands in squares of 4' x 4', as shown in Figure 5(b). From Figure 5(b), we can see that there are clear signs of clustering toward the interacting regions. The number of the YSO candidates increases when going from the border of clouds to the center. The existence of YSO candidates may indicate star formation activity.

Because the selected YSO candidates exhibit different near-IR excess, we then separated these YSO candidates into three classes based on criteria developed by Lee & Chen (2007), including low-mass CTTSs and intermediate-mass HAeBe stars and other YSO candidates. Generally, CTTSs are in an earlier evolutionary stage, while HAeBe stars exhibit a stronger near-IR excess than CTTSs. In Figure 4, CTTS candidates lie between the rightmost black dashed line and the blue dashed line, and above the blue solid line; HAeBe star candidates lie between the blue dashed line and the red dashed line, and above the red solid line. In this way, we found a total of 154 CTTS candidates and 419 HAeBe star candidates. Figure 6 shows the spatial distribution of selected CTTS and HAeBe star candidates. From Figure 6, we clearly see that the CTTS and HAeBe star candidates are concentrated around the CO molecular shell. Because these CTTS and HAeBe star candidates are grouped together, they are likely to be CTTSs and HAeBe stars.

4. DISCUSSIONS

4.1. IC443 and MCs

The morphology of IC443 in the 1.4 GHz radio continuum emission coincides very well with the surrounding MCs except for the northern region where there are no MCs detected. We suggest that the shocks interacting with the MCs in the northern region are strong enough to blow away the MCs. On the other hand, it may be that the CO emission of MCs in the northern region is too weak to be detected at the S/N of our survey. CO molecular emission from the MCs shows a shell morphology on the whole. The broadened line wings were detected in the molecular shell. The radio continuum emission also presents a shell morphology, which may arise from the SNR shocks that are blocked by surrounding condensed MCs (Frail & Mitchell 1998). Three 1720 MHz OH masers were detected around the radio shell of IC443 (Hewitt et al. 2006). Theoretical studies suggest that 1720 MHz OH masers are more efficiently pumped in hot, condensed shocks clouds. The masers may be excited when a nondissociative shock, produced by the interaction of IC443 with the surrounding MCs, propagates into the sufficiently condensed MCs. Together these observations strongly indicate that the MCs are interacting with IC443. The maximum value of $R_{CO(3-2)/CO(2-1)}$ in clouds C and G is higher than that in clouds B, D, E, and F. We consider that the positions of clouds C and G are the strongly interacting regions. Comparison with previously published observations reveals that $R_{CO(3-2)/CO(2-1)}$ for the MCs associated with IC443 are systematically larger than those for the MCs in the Galactic disk (Sanders et al. 1993), the M33 (Wilson et al. 1997), and the starburst galaxies M82 (Guesten et al. 1993). High $R_{CO(3-2)/CO(2-1)}$ in starburst galaxies may be due to unusual conditions in these dense, hot regions (Aalto et al. 1997), while for normal MCs the most likely explanation is a significant contribution to the CO emission by low column density material (Wilson & Walker 1994). When an SN expands into the surrounding parental MCs,
the shocks resulting from the interaction of the SNR with the MCs can heat gases. As the temperature of gases increases, the line opacities decrease as the upper $J$ levels become more populated. Depopulating the $J = 2$ and $J = 3$ levels leads to the $R_{\text{CO}}(3-2)/R_{\text{CO}}(2-1)$ increase. High $R_{\text{CO}}(3-2)/R_{\text{CO}}(2-1)$ ($\sim 1.58$) in the interacting region may imply that shocks have driven into MCs and have impacted the temperature and chemistry of MCs. We consider that high $R_{\text{CO}}(3-2)/R_{\text{CO}}(2-1)$ is also identified as a good signature of the SNR–MC interaction system. From Table 1, the total mass of the MCs is $9.26 \times 10^3 M_\odot$. The value indicates that all MCs associated with IC443 may be a giant molecular cloud (GMC; $\geq 10^4 M_\odot$ for GMC).

4.2. Recent Star Formation in the MCs

The superposition of IR 4 and IR 10 with cloud peaks and the association of other IR sources with the CO molecular shell are very unlikely to be by chance. If IR sources simply mark intensity peaks in the CO molecular shell, it will be difficult to explain why we did not see IR sources at the other unshocked regions. We suggest that the selected IR sources represent the signatures of protostars. The protostar formation may be triggered by shocks. In Table 2, all the IR sources have $L_{\text{IR}} < 10^3 L_\odot$, thus all the selected IR sources are considered to be low-mass protostars. We suggest that the shocks interacting with the MCs may be strong enough to tear up the condensed GMC.

From the distribution of YSO candidates in the interacting regions, we identified two young star clusters, C and G. Since these redder NIR sources are clustered, it is unlikely that they are all just reddened foreground and background stars. It is more likely that most of the YSO candidates are YSOs physically associated with the interacting regions between IC443 and MCs. Because the distribution of the YSO candidates is grouped and elongated around the CO molecular shell, it strongly supports triggering star formation. In addition, low-mass CTTS candidates and intermediate-mass HAeBe star candidates are grouped together in the strongly interacting regions, indicating that these stars are more likely to be formed by triggering.

Lefloch & Lazareff (1994) mentioned that star formation may undergo a collapse phase of a timescale of $\sim 10^5$ yr. Condensed molecular matter can form a protostar after the matter has cooled, which occurs in a period on the order of $10^6$ yr, while the age of CTTS is $10^5$–$10^7$ yr. Such periods are far longer than the age of IC443, which is 3000–30,000 yr (Petre et al. 1988; Olbert et al. 2001; Lee et al. 2008). Hence, the formation of the protostars and YSO candidates (including CTTSs and HAeBe stars) may not be triggered by the shocks of SNR IC443. Braun & Strom (1986) suggested that the SN explosion of IC443 had occurred in a pre-existing cavity blown by the stellar wind of the high-mass progenitor. The spectral type of the IC443 progenitor is O or B (Heiles 1984), applying the
measurements of individual Galactic MCs, implying that shocks of lifetime of such stars (2 × 10^6 yr) form protostars and YSO candidates. We further conclude that the formation of the protostars and YSO candidates may be triggered by the stellar winds from the high-mass progenitor of IC443. The distribution of YSO candidates may show a shell morphology (see Figure 5(b)), which requires further confirmation. Moreover, the newly forming stars triggered by the shocks of IC443 may be in the phase of deeply embedded protostars. In the future, we need to perform much higher angle resolution submillimeter observations to detect them.

5. SUMMARY

We have presented a large-area map of MCs in the vicinity of SNR IC443 in CO J = 2–1 and CO J = 3–2 lines. The shell-shaped morphology, the broadened emission lines, and the associated three OH masers further suggest that these MCs interact with IC443. The integrated CO line intensity ratio (R_CO(2-1)/CO(3-2)) (~1.58) for the entire MC exceeds previous measurements of individual Galactic MCs, implying that shocks have driven into MCs. We suggest that high R_CO(2-1)/CO(3-2) is also identified as a good signature of the SNR–MCs interacting system. All of the MCs associated with IC443 are most probably a GMC, with a total mass of 9.26 × 10^3 M⊙. The selected protostellar objects and YSO candidates (including CTTSs and HAeBe stars) are grouped around the interacting regions. This provides a strong signpost of ongoing star formation. Comparing the age of IC443 and the timescales for the stellar winds of the IC443 progenitor with the characteristic timescales for star formation, we conclude that the protostellar objects and YSO candidates may not be triggered by SNR IC443, but triggered by the stellar winds of the IC443 progenitor. Moreover, the newly forming stars triggered by the shocks of IC443 may be in the phase of deeply embedded protostars.

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