AKARI NEAR-INFRARED SPECTRAL OBSERVATIONS OF SHOCKED H$_2$ GAS OF THE SUPERNOVA REMNANT IC 443

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ABSTRACT

We present near-infrared (2.5–5.0 $\mu$m) spectra of shocked H$_2$ gas in the supernova remnant IC 443, obtained with the satellite AKARI. Three shocked clumps—known as B, C, and G—and one background region were observed, and only H$_2$ emission lines were detected. Except in clump B, the extinction-corrected level population shows the ortho-to-para ratio of $\sim$3.0. From the level populations of clumps C and G—both the one obtained with AKARI and the one extended with previous mid-infrared observations—we found that the $\nu = 0$ levels are more populated than the $\nu > 0$ levels at a fixed level energy, which cannot be reproduced by any combination of H$_2$ gas in local thermodynamic equilibrium. The populations are described by the two-density power-law thermal admixture model, revised to include the collisions with H atoms. We attributed the lower ($n$(H$_2$)$_{\nu=0}$)$=10^{2.8}$–$10^{3.8}$ cm$^{-3}$) and higher ($n$(H$_2$)$_{\nu=0}$)$=10^{4.4}$–$10^{5.8}$ cm$^{-3}$) density gases to the shocked H$_2$ gas behind C-type and J-type shocks, respectively, based on several arguments including the obtained high H abundance ($\nu$(H)/$n$(H$_2$) = 0.01. Under the hierarchical picture of molecular clouds, the C-type and J-type shocks likely propagate into “clumps” and “clouds” (interclump media), respectively. The power-law index $b$ of 1.6 and 3.5, mainly determined by the lower density gas, is attributed to the shock-velocity diversity, which may be a natural result during shock–cloud interactions. According to our results, H$_2$, $\nu = 1 \rightarrow 0$, S(1) emission is mainly from J shocks propagating into interclump media. The H$_2$ emission was also detected at the background region, and this diffuse H$_2$ emission may originate from the collisional process in addition to ultraviolet photon pumping.

Key words: infrared: ISM – ISM: individual objects (SNR IC 443) – ISM: supernova remnants – shock waves

1. INTRODUCTION

IC 443 (G189.1+3.0) is an extensively studied supernova remnant (SNR) famous for its interaction with nearby molecular clouds. The interaction has been widely observed over diverse wavelengths: the $\gamma$-ray from hadronic collisions (Esposito et al. 1996; Albert et al. 2007; Acciari et al. 2009; Abdo et al. 2010; Tavani et al. 2010), the X-ray absorption by foreground clouds (Troja et al. 2006), the infrared forbidden lines (Burton et al. 1988, 1990; Inoue et al. 1993; Richter et al. 1995a; Cesarsky et al. 1999; Rho et al. 2001; Rosado et al. 2007), the enhanced CO line ratio (Seta et al. 1998; Xu et al. 2011), the broad molecular emission lines (White et al. 1987; Wang & Scoville 1992; Dickman et al. 1992; van Dishoeck et al. 1993; Snell et al. 2005; Zhang et al. 2010), the bow-like feature in position–velocity diagrams of molecular lines (Tauber et al. 1994), and the OH maser line (Claussen et al. 1997; Hoffman et al. 2003; Hewitt et al. 2006). IC 443 is usually observed when studying the shock–cloud interaction.

Its age ranges from $\sim$3–4 kyr (Petre et al. 1988; Wang et al. 1992; Troja et al. 2008) to $\sim$20–30 kyr (Chevalier 1999; Olbert et al. 2001; Gaensler et al. 2006; Bykov et al. 2008; Lee et al. 2008a). Its distance is thought to be about 1.5 kpc, based on several arguments, such as the contact with Gem OB 1 association (Poveda & Wolff 1968), the empirical $\Sigma$–D relation (Milne 1979; Caswell & Lerche 1979), the total remnant energy (Fesen & Kirshner 1980; Fesen 1984), and the high-velocity absorption lines observed against background stars (Welsh & Sallmen 2003). It extends $\sim$45$'$ (cf. Gaensler et al. 2006) and overlays in the sky with another more extended SNR G189.6+3.3 (Asaoka & Aschenbach 1994). IC 443 consists of two half shells, and another large shell of the SNR G189.6+3.3 overlaps with those half shells; these three shells were named as A, B, and C, respectively, by Braun & Strom (1986).

The overall picture of the remnant region is well outlined in Troja et al. (2006) and Lee et al. (2008a). In the middle of the two shells A and B, there is a W-shaped ridge that shows strong H$_2$ emission lines (cf. Figure 1 and Rho et al. 2001); this ridge is thought to be a torus-type molecular cloud overrun by the SNR shock.

Infrared H$_2$ emission lines are useful in studying shocked molecular clouds, since H$_2$ is the most abundant molecule and its quantum levels cover an energy range wide enough to study shocked gas, whose temperature ranges from a few hundred to a few thousand kelvins. Toward the W-shaped H$_2$ ridge, infrared spectral observations have already been performed from ground (Richter et al. 1995a) and space by Infrared Space Observatory (ISO; Cesarsky et al. 1999) and Spitzer (Neufeld et al. 2007). However, the H$_2$ emission lines which fall within 2.5–5.0 $\mu$m have not been observed completely; the ground observations missed several lines because of the atmospheric absorption, and this wavelength range is not covered by Spitzer spectroscopy and was simply not observed by ISO. Observing this wavelength range is worthwhile because, for instance, we could obtain the population of high-J $\nu = 0$ levels, which is usually assumed to follow that of $\nu > 0$ levels (e.g., Rho et al. 2001; Giannini et al. 2006), but has not yet been thoroughly checked.

Here we present the results of near-infrared spectral observations over 2.5–5.0 $\mu$m for the shocked H$_2$ gas in the SNR IC 443. The observations were performed with the satellite AKARI (Section 2). We detected many H$_2$ emission lines only (Section 3.1) and found that the population of the shocked H$_2$ gas cannot be described by any combination of H$_2$ gas in local thermodynamic equilibrium (LTE), which have been usually
used for (Sections 3.2 and 3.3). Instead, we employed a non-LTE 
Ks gas model (Section 3.4) and interpreted the results in terms 
Figure 1. Observed slit positions. Slit positions are indicated on the 2MASS 
The Astrophysical Journal K image of the SNR IC 443 (Skrutskie et al. 2006). Slit positions are named 
after their representative clump names—“B,” “C,” and “G.” “BG” indicates the 
back-ground. The “W” ridge is dominated by H2 emissions.

2. OBSERVATIONS AND DATA REDUCTION

The spectral observations were performed with the Infrared Camera (IRC; Onaka et al. 2007) on board the Japanese satellite AKARI (Murakami et al. 2007) on 2008 September 26 and 27 during the post-helium phase. During this phase, only near-infrared observations were possible, since the cryogenic cooling with liquid helium had been run out. We used the 5′ × 48′ slit and the grism, whose resolving power and wavelength coverage are Δλ ∼ 0.03 μm and 2.5–5.0 μm, respectively. The observation mode, called the Astronomical Observation Template (AOT), is IRCZ4, which is designed for general spectroscopic observations. It has an imaging observation sandwiched by spectroscopic observations of four frames (cf. Onaka et al. 2009). Comparing this reference image to the Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006), we corrected the default astrometry of the slit given from the satellite attitude information. The obtained accuracy (root-mean-square difference) is less than 0.7.

We observed four regions, three of which are the shocked CO clumps. The rest is the background. Figure 1 shows the four slit positions over the 2MASS Ks image (Skrutskie et al. 2006), which displays a diffuse “W” feature that traces the H2 ν = 1 → 0 S(1) 2.12 μm line emissions (Rho et al. 2001). We name three on-source positions “B,” “C,” and “G” after the names of the shocked CO clumps (Denoyer 1979; Huang et al. 1986), and the background “BG.” Table 1 summarizes our observations—the region name, R.A.–decl. position, observation ID, and AOT.

The data were reduced through the official pipeline, supported by the AKARI team (cf. Onaka et al. 2009). We used the new spectral response curve for the post-helium phase data, which shows a degraded sensitivity, ∼70% of the helium phase sensitivity. Columns of the two-dimensional spectral images are occasionally saturated by the very bright sources in the imaging area of the detector, which cause the column pull-down effect. This effect was corrected by masking out the relevant columns. Hot pixels of the detector were also masked out. During the data reduction, no smoothing and tilt correction were applied to the two-dimensional spectral images.

In order to extract spectra, we chose certain sections along the slit length, then averaged the pixel values within those sections. The extraction sections were carefully chosen so the H2 emission lines were nearly uniform within the sections. The sections extend 10 pixels for clumps B and C, 14 pixels for clump G, and 25 pixels for BG, where one pixel corresponds to 1.46′′ (Onaka et al. 2007); for the data set 1420806-002 of BG, we only chose 5 pixels as an extraction section to avoid abnormal single pixel peak. Figure 2 displays the extracted spectra at each region. For clarity, the error bars were omitted and the spectrum of BG was enlarged by a factor of 20. The statistical error bars can be seen in Figures 3–6.

For the error estimation, we included the systematic error caused by the calibration source type, in addition to the statistical error. Our target is a diffuse source, hence the flux calibration referred to standard point sources is not suitable for our source, since the aperture loss and the slit loss would vary with the source type; the official pipeline uses the calibration from point sources. We considered this type of systematic error and adopted 10% of the signal intensity as the systematic error after private communication with the AKARI helpdesk. It was squarely summed to the statistical error of the line intensity, \( \sqrt{\sigma_st^2 + \sigma_sys^2} \), after measuring the line intensities (cf. Section 3).

3. ANALYSIS AND RESULTS

3.1. Line Identification and Intensity Measurement

Figure 2 shows many emission lines. Since we are concerned with the H2 emission lines, we first compared the wavelengths of the observed emission lines with those of H2. For easier identification of single and blended lines, we made template spectra of H2 gas in LTE at diverse temperature from 1000 K to 4000 K. This temperature range was adopted because the shocked H2 gas usually shows such a range of excitation temperatures at the upper levels of \( E(\nu, J) \sim 5 \times 10^3\)–\(2.5 \times 10^4 \) K (e.g., Rosenthal et al. 2000; Rho et al. 2001; Giannini et al. 2007).

### Table 1

| Region | Pointing Position (R.A., Decl.; J2000) | Observation ID | AOT† |
|--------|--------------------------------------|----------------|------|
| B      | (06:17:16.3, +22:25:41.0)            | 1420803-00[1,2] | IRCZ4 |
| C      | (06:17:44.2, +22:21:49.1)            | 1420804-00[1,2] | IRCZ4 |
| G      | (06:16:41.8, +22:31:41.0)            | 1420805-00[1,2] | IRCZ4 |
| BG     | (06:17:30.0, +22:17:00.0)            | 1420806-00[1,2] | IRCZ4 |

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Figure 2. AKARI IRC near-infrared spectra. Singular and blended lines are indicated with vertical bars and crosses, respectively. These lines are all the H$_2$ emission lines (cf. Table 2). In the case of “BG,” a 20 times enlarged spectrum is plotted for the identification of the $\nu = 0 \rightarrow 0$ S(9) 4.69 $\mu$m line.

2006), which include the upper levels of the H$_2$ emission lines we detected. In this way, we identified all the detected emission lines as H$_2$ emission lines.

Some lines are blended with nearby lines, hence we could not tag them as a single line. The uniquely identified lines and the blended lines are indicated by "|" and "×," respectively, in Figure 2, and their line identifications are listed in Table 2. For a cross-check, this identification was compared with that of the shocked H$_2$ gas observed in the Orion Molecular Cloud-1 (OMC-1; Rosenthal et al. 2000), and our identification turned out to be reliable. Some contribution from Br$\alpha$ blended with the 2.63 $\mu$m line (cf. Figure 2); however, we think it is unlikely since Br$\alpha$ 4.05 $\mu$m, which should be stronger than Br$\beta$, was not detected. The spontaneous transition probabilities of Br$\alpha$ and Br$\beta$ are $A_{22} = 2.7 \times 10^6$ s$^{-1}$ and $A_{01} = 7.7 \times 10^5$ s$^{-1}$, respectively. The features seen at the edge of the band ($<2.6$ and $>4.9$ $\mu$m) were ignored since they are likely to be inadequate to analyze. The 2.56 $\mu$m and 4.95 $\mu$m features seem to be the $\nu = 1 \rightarrow 0$ Q(9) blended with nearby lines and the $\nu = 1 \rightarrow 1$ S(9), respectively.

The line intensities were measured by fitting their line profiles with a continuum plus Gaussian whose full width at half-maximum (FWHM) is fixed to the spectral resolution of the IRC ($\Delta \nu = 0.03$ $\mu$m). Adjacent lines whose profiles are overlapped with each other were fitted simultaneously. As a baseline continuum for the fitting, we used a median-smoothed spectrum of each region; the kernel width ranging from 0.20 to 0.54 $\mu$m was carefully chosen to be wide enough to erase the line emission features. The feature near the edge of the spectrum (e.g., the 2.56 $\mu$m feature in Figure 3) remains unchanged after the median filtering, since the filter only works on those pixels that are away from the edge by more than one-half of the filter width. The fitted profiles are displayed in Figures 3–6, and their measured intensities are listed in Table 2. The intensities of blended lines are shown with the symbol “<,” since we cannot determine the individual contribution of each blended line. The intensities of weak lines, whose signal-to-noise ratio is lower than 3.0, are expressed as 90% confidence upper limits.

3.2. Reddening Correction and H$_2$ Level Population

Over 2.5–5.0 $\mu$m wavelengths, the extinction optical depth becomes greater than one with the hydrogen nuclei column density, $N_H = N$(H$_1$) + 2N(H$_2$), of $\geq 10^{22}$ cm$^{-2}$ (Draine 2003). Since the observed regions are pervaded with dense molecular gas, the measured intensity should be corrected for reddening by the intervening interstellar dust. We exploited the extinction curve of “Milky Way, $R_V = 3.1$” (Weingartner & Draine 2001; Draine 2003) and adopted proper hydrogen nuclei column densities for each region. $A_V = 13.5$ was adopted for the clump C as Neufeld & Yuan (2008) did based on the results of Richter et al. (1995a). We adopted the same $A_V$ for clump B, since its extinction is known to be similar to that of clump C (Burton et al. 1988). No extinction measurement exists toward BG; thus, we assumed it to be the $A_V$ of clump C, the nearest clump from BG. $A_V = 10.8$ was adopted for clump G; this was inferred from $A_{2.12} = 1.3$, obtained by Richter et al. (1995a), employing the “Milky Way, $R_V = 3.1$” extinction curve. The corresponding $N_H$ was calculated with the equation $A_V = N_H/(1.87 \times 10^{21}$ cm$^{-2}$) for $R_V = 3.1$ (Bohlin et al. 1978).

The H$_2$ level population was derived from these reddening-corrected intensities, assuming that the H$_2$ emission lines are optically thin. Since the infrared H$_2$ emission is emanating from...
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Figure 3. Fitting for the H$_2$ emission lines, observed toward clump B. The solid and dashed lines indicate the continuum+line and continuum, respectively. The blended line components are indicated by the dotted lines, if any. The feature around 2.56 $\mu$m is ignored since it is near the end of the band coverage.

electric quadrupole transition, it is optically thin under a typical interstellar medium condition; for instance, the pure-rotational $S(0)$ and $S(1)$ lines become optically thick at the line center when $N$(H$_2$) $>$ $10^{24}$ cm$^{-2}$, adopting the line width of 10 km s$^{-1}$. We derived the reddening-corrected level population of H$_2$ gas from the following equation:

$$N_{rc}(\nu, J) = \frac{4\pi \lambda I_{rc}(\nu, J \rightarrow \nu', J')}{h \nu A(\nu, J \rightarrow \nu', J')} \quad (1)$$

where $I_{rc}(\nu, J \rightarrow \nu', J')$ and $A(\nu, J \rightarrow \nu', J')$ are the reddening-corrected line intensity and the Einstein-A radiative transition probability of the transition from level $(\nu, J)$ to $(\nu', J')$, respectively. The molecular data for H$_2$ were obtained from the database provided by a simulation code, CLOUDY (version C08.00; Ferland et al. 1998). The results are listed in Table 3 and their population diagrams are displayed in Figure 7. $g_J$ is a weight factor that corresponds to $(2J + 1)$ and...
$3(2J + 1)$ for para (even $J$) and ortho (odd $J$) states, respectively; the population of LTE gas appears as a straight line in this diagram.

In Figure 7, clumps B, C, and G show the population of $\nu = 0, 1, 2$, while BG shows that of $(\nu, J) = (0, 1)$ only. In clumps B, C, and G, the $\nu = 0$ population shows a similar shape and little zigzag pattern; when the ortho-to-para ratio approaches 3.0, the zigzag pattern disappears (cf. Neufeld et al. 2006, 2007). The $\nu = 1$ population, however, shows a similar shape and little zigzag pattern only in clumps C and G; clump B shows an evident zigzag pattern over the population of $(\nu, J) = (1, 1), (1, 2),$ and $(1, 3)$. Here we note that the $\nu = 0$ and $\nu = 1$ levels follow different branches. This becomes clearer when plotted with the lower-$J \nu = 0$ population obtained from mid-infrared observations (see the following section). BG shows a much smaller but evident population of the $(\nu, J) = (0, 1)$ level. It is about a factor of 12–38 smaller than clumps B, C, and G (cf. Table 3).
Table 2: Observed H$_2$ Emission Lines Toward Each Region

| Transition | Wavelength ($\mu$m) | Observed Intensity ($10^{-6}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$) |
|------------|---------------------|-------------------------------------------------------------|
|            |                     | B               | C               | G               | BG               |
| $v = 1$–$0$ O(2)$^a$ | 2.63               | <37.9 ± 6.1    | <93.4 ± 10.4    | <58.2 ± 7.1     | ...              |
| $v = 2$–$1$ O(9)$^a$ | 2.72               | ...            | <25.1 ± 5.3     | <13.5 ± 4.2     | ...              |
| $v = 1$–$0$ O(3)    | 2.80               | 89.9 ± 10.0    | 323.1 ± 32.0    | 221.9 ± 22.0    | ...              |
| $v = 2$–$1$ O(3)    | 2.97               | <13.5          | 27.0 ± 4.8      | 18.5 ± 4.1      | ...              |
| $v = 1$–$0$ O(4)    | 3.00               | 39.8 ± 5.2     | 96.7 ± 10.0     | 63.0 ± 6.9      | ...              |
| $v = 1$–$0$ O(5)    | 3.23               | 61.1 ± 7.4     | 196.2 ± 20.0    | 127.0 ± 13.0    | ...              |
| $v = 1$–$0$ O(6)$^a$ | 3.50              | <18.2 ± 4.1    | <46.5 ± 5.8     | <29.2 ± 4.3     | ...              |
| $v = 0$–$0$ S(15)   | 3.63               | ...            | 47.8 ± 5.6      | 24.1 ± 3.4      | ...              |
| $v = 0$–$0$ S(14)$^a$ | 3.72             | ...            | <26.8 ± 3.9     | <10.7 ± 2.6     | ...              |
| $v = 1$–$0$ O(7)    | 3.81               | 18.9 ± 3.4     | 54.1 ± 6.1      | 36.7 ± 4.2      | ...              |
| $v = 0$–$0$ S(13)   | 3.85               | 27.6 ± 3.9     | 96.0 ± 10.0     | 53.1 ± 5.7      | ...              |
| $v = 0$–$0$ S(12)   | 4.00               | ...            | 38.5 ± 4.6      | 21.5 ± 3.1      | ...              |
| $v = 1$–$1$ S(13)$^a$ | 4.07             | ...            | <24.1 ± 3.5     | <14.9 ± 2.7     | ...              |
| $v = 0$–$0$ S(11)   | 4.18               | 60.0 ± 6.8     | 199.3 ± 20.0    | 113.4 ± 11.0    | ...              |
| $v = 0$–$0$ S(10)   | 4.41               | 40.1 ± 5.2     | 122.8 ± 12.0    | 71.2 ± 7.6      | ...              |
| $v = 1$–$1$ O(9)    | 4.58               | ...            | 16.0 ± 3.2      | 9.6 ± 2.6       | ...              |
| $v = 0$–$0$ S(9)    | 4.69               | 134.4 ± 14.0   | 430.8 ± 43.0    | 265.7 ± 27.0    | 14.2 ± 3.5       |

Notes. For those lines whose significance is lower than 3.0, the intensities are expressed with 90% upper confidence limits. The error includes both statistical and systematic components. See the text for detail.

$^a$ These lines may be blended with nearby lines, indicated with the “<” sign.
3.3. Comparison of H$_2$ Populations with Previous Observations: Clumps C and G

As far as we know, the UKIRT CGS4 observation of Richter et al. (1995a) is the only published near-infrared spectroscopic observation that targeted the shocked H$_2$ gas in IC 443; they observed clumps C and G. Toward these two clumps, there are also published results of mid-infrared spectroscopic observations for the shocked H$_2$ gas, performed with ISO (Cesarsky et al. 1999) and Spitzer (Neufeld et al. 2007). For clump B, mid-infrared spectroscopic observations were also performed with Spitzer (Noriega-Crespo et al. 2009); however, they are under analysis and only covered three emission lines, $\nu = 0 - 0$ S(0), S(1), and S(2). Therefore, we concentrated on the data of clumps C and G and compared our AKARI results with those from previous studies.
### Table 3

| State   | Energy Level | \( \log N(\text{H}_2; \nu, J) \) (cm\(^{-2}\)) |
|---------|--------------|---------------------------------|
| \((\nu, J)\) | \((K)\) | \(B\) | \(C\) | \(G\) | \(BG\) |
| (0,11)  | 10261        | 16.06 ± 0.05 | 16.56 ± 0.04 | 16.32 ± 0.04 | 15.08 ± 0.11 |
| (0,12)  | 11940        | 15.36 ± 0.06 | 15.85 ± 0.04 | 15.58 ± 0.05 | ... |
| (0,13)  | 13703        | 15.40 ± 0.05 | 15.92 ± 0.04 | 15.64 ± 0.04 | ... |
| (0,14)  | 15540        | ... | 15.08 ± 0.05 | 14.79 ± 0.06 | ... |
| (0,15)  | 17443        | 14.83 ± 0.06 | 15.37 ± 0.05 | 15.07 ± 0.05 | ... |
| (0,16)\(^a\) | 19403        | ... | <14.72 ± 0.06 | <14.28 ± 0.10 | ... |
| (0,17)  | 21411        | ... | 14.89 ± 0.05 | 14.55 ± 0.06 | ... |
| (1, 0)\(^a\) | 5987         | <15.31 ± 0.07 | <15.70 ± 0.05 | <15.41 ± 0.05 | ... |
| (1, 1)  | 6149         | 15.96 ± 0.05 | 16.52 ± 0.04 | 16.28 ± 0.04 | ... |
| (1, 2)  | 6471         | 15.76 ± 0.06 | 16.14 ± 0.05 | 15.89 ± 0.05 | ... |
| (1, 3)  | 6951         | 16.07 ± 0.05 | 16.58 ± 0.04 | 16.33 ± 0.05 | ... |
| (1, 4)\(^a\) | 7584         | <15.68 ± 0.10 | <16.09 ± 0.05 | <15.84 ± 0.06 | ... |
| (1, 5)  | 8365         | 15.85 ± 0.08 | 16.30 ± 0.05 | 16.09 ± 0.05 | ... |
| (1, 7)  | 10341        | ... | 16.12 ± 0.09 | 15.87 ± 0.12 | ... |
| (1,15)\(^a\) | 22516        | ... | <14.84 ± 0.06 | <14.60 ± 0.08 | ... |
| (2, 1)  | 11789        | <14.94        | 15.25 ± 0.08 | 15.01 ± 0.10 | ... |
| (2, 9)\(^a\) | 18107        | ... | <15.56 ± 0.09 | <15.21 ± 0.14 | ... |

**Notes.** The extinctions are corrected, employing the “Milky Way” extinction curve (\(R_V = 3.1\); Weingartner & Draine 2001), with these parameters: \(A_V = 13.5\) for clump B, clump C, and BG (Burton et al. 1988; Neufeld & Yuan 2008), and \(A_V = 10.8\) for clump G (Richter et al. 1995a).

\(^a\) The population cannot be determined because of the probable line blending with nearby lines (cf. Table 2).
levels show almost constant, vertical gaps in the population diagram, about a factor of 3–4 in the column density. Our AKARI calibration is likely to be correct, because the AKARI $\nu = 0$ level populations are seamlessly merged with those obtained from previous mid-infrared observations (cf. the top panels of Figure 9). However, we cannot rule out that the inconsistency is caused by the difference of observed regions, since the average properties of the shocked H$_2$ gas may change over $\sim 30'' \sim 0.2$ pc scale (see Figure 8).

We note the importance of the space observations, fully covering 2.5–5.0 $\mu$m, for the study of shocked H$_2$ gas. With ground observations, the gap between $\nu = 0$ and 1 levels is hardly inspectable, since only a few $\nu = 0$ levels can be observable at largely separated $E(\nu, J)$ (see the gray plots in the middle panels of Figure 9). Hence, when using the results of ground observations, we are likely to think that a combination of H$_2$ gas in LTE looks viable to reproduce the level populations up to $E(\nu, J) \sim 25,000$ K (see the bottom panels of Figure 9). However, such a gap can be immediately inspectable from the space observations, fully covering 2.5–5.0 $\mu$m, since $\nu = 0, 1$ levels are covered continuously; the AKARI near-infrared observation is a good example.

### 3.4. Power-law Thermal Admixture Model of H$_2$ Gas

As seen in the previous section, the combination of H$_2$ gas in LTE cannot reproduce the observed level population of the shocked H$_2$ gas in clumps C and G, obtained from AKARI and previous mid-infrared observations. Therefore, we applied the power-law thermal admixture model of H$_2$ gas, which had previously successfully reproduced the level population of shocked H$_2$ gas (Neufeld & Yuan 2008; Shinn et al. 2009, 2010; Neufeld et al. 2009, 2010; Lee et al. 2010; Takami et al. 2010; Yuan & Neufeld 2011). The model configuration was the same as that used in the study of the SNR HB 21 (Shinn et al. 2009, 2010) and the young stellar object (YSO) L 1251A (Lee et al. 2010), except for the inclusion of the H atom as an additional collider. Our AKARI spectra include several rovibrational transition lines (e.g., $\nu = 1 \rightarrow 0, 2 \rightarrow 1$), which are sensitive to collision with H atoms (Neufeld & Yuan 2008; Shinn et al. 2009, 2010). Thus, we updated the previous model to reflect the collisions with H atoms.

The H$_2$ column density was calculated with the following equation:

$$dN = aT^{-b}dT,$$

where

$$a = \frac{N(H_2; T > 100 K)(b - 1)}{T_{\text{min}}^{1-b} - T_{\text{max}}^{1-b}}$$

$$T_{\text{min}} = 100 \text{ K}, \quad T_{\text{max}} = 4000 \text{ K},$$

$a$ and $b$ are constants, and $N(H_2; T > 100 \text{ K})$ is the total column density of molecular hydrogen warmer than 100 K. At each temperature, the statistical equilibrium was assumed, and the collisional partners were H$_2$, He, and H. The collisional de-excitation rates were obtained from Le Bourlot et al. (1999) for H$_2$ and He, and from Wrathmall et al. (2007) for H. For the H$_2$ collider, newer rates were calculated by Lee et al. (2008b); however, their results are similar to those of Le Bourlot et al. over 100–6000 K and only include those levels of $J_{\text{up}} \lesssim 8$. Hence, we continued to use those of Le Bourlot et al.’s. The collisional excitation rates were calculated from the detailed balance relation. The H$_2$ density, $n(H_2)$, and the relative abundance of H atom to H$_2$, $X_H = \log(n(H)/n(H_2))$, were set as free

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**Figure 6.** Fitting for the H$_2$ emission lines, observed toward the background (BG). The remaining details are the same as those for Figure 3.
parameters, while $n(\text{He})$ was assumed to be $0.2 \times n(\text{H}_2)$. The ortho-to-para ratio was set to 3.0, since the level populations show little zigzag pattern (cf. the top panels of Figure 9).

First, we tried to fit with a single $n(\text{H}_2)$ value, but we failed. No single $n(\text{H}_2)$ model could successfully reproduce the population of high energy levels. This result reaffirms the previously noted tendency that the single $n(\text{H}_2)$ model does not reproduce the level population over $E(v, J) = 0$–25,000 K (cf. Section 4.1.1). The addition of another $b$ was also unsuccessful. Upon adding an additional $n(\text{H}_2)$ component, we obtained successful results. The fitting results are displayed in Figure 10. For clump G, the fewer data points from mid-infrared observations caused weaker constraints for the fitting parameters than clump C; therefore, we fixed the $X_H$ value as $-1.7$ in view of the fitting results for clump C. Then, we scanned the $\chi^2$ space for fitting parameters. The results are displayed in Figure 11; the step size for the scan was 0.1 for all parameters displayed in Figure 11. The fit parameters with their 90% confidence intervals, together with the reduced chi-square values, are listed in Table 4.

As seen in Figure 10, the reddening-corrected level populations are well reproduced by the power-law thermal admixture model with two different $n(\text{H}_2)$ values; one low $n(\text{H}_2)$ $\sim 10^3$–$10^4 \text{ cm}^{-3}$ and the high $n(\text{H}_2) \sim 10^5$–$10^6 \text{ cm}^{-3}$ (cf. Table 4). The lower and higher density $\text{H}_2$ gases mainly contribute to the lower and higher upper-energy levels, respectively. This indicates that some model parameters may not be uniquely determined, since only a small portion of the modeled population is constrained by the observed population. This point is discussed in detail in Section 4.1.1. The two kinds of $\text{H}_2$ gases share a common power-law index $b$; it is 1.6 and 3.5 for clumps C and G, respectively. The column density ratios of the lower to higher density gas are not much different; they are 40 and 13 for clumps C and G, respectively (see Section 4.1.1 for more notes about the column densities). We obtained $X_H = -1.7$,

Figure 7. Extinction-corrected population diagrams for clumps B (top left), C (top right), and G (bottom left), and the background (bottom right). The extinctions were corrected using $A_V = 13.5$ for clumps B and C and the background (Neufeld & Yuan 2008) and $A_V = 10.8$ for clump G (Richter et al. 1995a). The rotational quantum number ($J$) is printed out near the corresponding point.
Figure 8. Areas of spectra extraction around clumps B (top), C (bottom left), and G (bottom right). The background image is the same as that of Figure 1. The two horizontal rectangles are the extraction areas for AKARI’s data. Each of the two indicates each exposure (cf. Table 1). The vertical rectangles are for the UKIRT CGS4 data (Richter et al. 1995a); we adopted the “position 1” and “position 3” data for clumps C and G, respectively. For clump G, we indicate the whole slit area, since Richter et al. (1995a) did not mention where the extraction area is. The circle is the FWHM (25′′) of the Gaussian taper, used for the spectra extraction of Spitzer data (Neufeld et al. 2007). The square is the extraction area for ISO data (Cesarsky et al. 1999); we adopted the 3 × 3 pixel area around peak B.

Table 4
Fitting Results for the Model Parameters

| Region   | Component 1 | Component 2 | b         | $X_H$ (≡ log[$N(H_2)/T_{\text{min}}$]) | $X^2/\text{dof}$ |
|----------|-------------|-------------|-----------|--------------------------------------|------------------|
|          | log[$N(H_2)$] (cm$^{-2}$) | log[$n(H_2)$] (cm$^{-3}$) | log[$N(H_2)$] (cm$^{-2}$) | log[$n(H_2)$] (cm$^{-3}$) |                           |                  |
| IC 443C  | 21.6$^{+0.2}_{-0.1}$ | 2.8$^{+0.1}_{-0.2}$ | 19.4$^{+0.3}_{-0.2}$ | 5.4$^{+0.3}_{-0.2}$ | 1.6$^{+0.3}_{-0.2}$ | -1.7$^{+0.2}_{-0.2}$ | 5.1 (≡66.1/13.0) |
| IC 443G  | 22.2$^{+0.2}_{-0.4}$ | 3.8$^{+0.2}_{-0.4}$ | 21.1$^{+0.4}_{-0.5}$ | 5.8$^{+0.8}_{-0.4}$ | 3.5$^{+0.3}_{-0.6}$ | -1.7$^{+0.2}_{-0.2}$ | 3.4 (≡40.6/12.0) |

Notes. The confidence limits are given with a 95% significance (cf. Figure 11). $N(H_2)$ means $N(H_2; T > 100$ K). See Section 3.4 for the detailed description about the parameters. $N(H_2)$ of Component 2 is not a firmly determined value, since it sensitively depends on the $T_{\text{min}}$ of the model (see Section 4.1.1).

$^{a}$ In this case, the parameter $X_H$ is fixed as −1.7 to increase the degree of freedom. See Section 3.4 for more details.
which corresponds to \( n(\text{H}_1)/n(\text{H}_2) = 0.02 \); this value is similar to the one where the collision with H atoms starts to dominate the collision with H\(_2\) for the rovibrational transition lines, as mentioned by Neufeld & Yuan (2008) and Shinn et al. (2009, 2010), and smaller than those obtained for protostellar outflows of LDN 1157, \( n(\text{H}_1)/n(\text{H}_2) = 0.1-0.3 \) (Nisini et al. 2010).

The \( \chi^2 \) contour for the column densities shows a rough correlation for both clumps C and G (cf. Figure 11). This seems to be caused by the following fact: If both column densities increase or decrease together, then the \( \chi^2 \) can be decreased by adjusting the power-law index \( b \) shared by the lower and higher density \( \text{H}_2 \) gases. However, if one column density increases and the other decreases, or vice versa, then the \( \chi^2 \) cannot be decreased in the same way as before, since the total \( \text{H}_2 \) population changes its shape, which is related to the power-law index \( b \). The variation of \( n(\text{H}_2) \) and \( N(\text{H}_2) \) is not as effective as \( b \) in adjusting the fitting, as the confidence intervals indicate (Table 4). For clump C, almost no correlation is shown between the densities and between \( b \) and \( X_H \). For clump G, the densities show a complex \( \chi^2 \) surface. It may be caused by the absence of the lowest level data, \( (\nu, J) = (0, 2) \) and \( (0, 3) \), which imposes a weaker constraint for the fitting.

4. DISCUSSION

4.1. Shocked \( \text{H}_2 \) Gas Described by the Power-law Thermal Admixture Model

4.1.1. Comparison Between Model Parameters from Previous and Our Studies

The first attempt to describe the level population of shocked \( \text{H}_2 \) gas with the power-law mixture of thermal \( \text{H}_2 \) gas was by Brand et al. (1988) (see also Burton et al. 1989). They assumed that the \( \text{H}_2 \) gas, shocked by J-type shocks (Draine
density of population of thermally mixed H$_2$ gas at the postshock region, which is equivalent to the power-law thermal admixture of H$_2$ gas in LTE with the power-law index $b = 4.7$ (cf. Section 3.4). They applied this model to the observational data of OMC-1 and found that it is successful in describing the available data at that time. However, the omission of important coolants—such as CO, OH, H$_2$O, and grain—at dense environments such as OMC-1 and of the magnetic field makes the model assumption doubtful (Chang & Martin 1991; Draine & McKee 1993).

Oliva et al. (1990) first tried to use the method of power-law thermal mixing as a phenomenological description tool for the H$_2$ level population, with no background physics; they simply mixed H$_2$ gas in LTE according to the power-law distribution, $dN(T) \sim T^{-b}dT$. In this approach, they found that the H$_2$ population of the SNR RCW 103, obtained from near-infrared observations, can be described with the models whose power-law indices are between $b = 3.8$ and $b = 4.7$. This method was extended to the non-LTE case by Neufeld & Yuan (2008). Applying the method to the Spitzer IRAC data, they found that the shocked H$_2$ gas of the SNR IC 443 can be described with the power-law index $b \sim 3–6$ and the molecular hydrogen density of $n$(H$_2$) $\sim 10^8–10^7$ cm$^{-3}$. Afterward, the same method was applied to the shocked H$_2$ of the SNR HB 21 (Shinn et al. 2009, 2010) and of the outflows from YSOs (Neufeld et al. 2009; Shinn et al. 2010; Lee et al. 2010; Takami et al. 2010; Nisini et al. 2010; Yuan & Neufeld 2011). All of the non-LTE application results are summarized in Table 5; we excluded the work of Nisini et al. (2010) because they varied $T_{\text{min}}$ for the model application.

Table 5 shows that $n$(H$_2$) and $b$ vary with the estimated levels ($\nu = 0$, $J$), $n$(H$_2$) and $b$ both tend to be smaller when the model is applied to lower-$J$ levels; $n$(H$_2$) shows a more drastic variation than $b$. This tendency was already noted in Shinn et al. (2010) through the model application to the data of the SNR HB 21 and OMC-1; now, the tendency is strengthened by additional data from other SNRs and outflows of YSOs. This indicates that the level population of shocked H$_2$ gas is not described by the power-law admixture model with single $n$(H$_2$) and $b$. Moreover, it suggests that we should analyze the level population over as many levels as we can; if we do not, we may have a limited picture of the shocked H$_2$ gas.

To the point of extending the data coverage, our observations are important because we extended the $\nu = 0$ level population obtained from previous mid-infrared studies, from $E(\nu, J) \lesssim 7000$ K up to $\lesssim 22,000$ K (see Figure 9). We were able to reproduce the estimated H$_2$ population with two $n$(H$_2$) and one $b$ after including the H atom as an additional collision partner (Table 4). The two derived $n$(H$_2$)s, $n$(H$_2$) = $10^{2.8}–10^{3.8}$ cm$^{-3}$ and $n$(H$_2$) = $10^{5.4}–10^{5.8}$ cm$^{-3}$, fall into the range previously obtained, $n$(H$_2$) = $10^{2.7}–10^{2.9}$ cm$^{-3}$ (Table 5). Distinct from the previous applications (Table 5), we included in the model H atoms, which efficiently excite high-$J$ $\nu = 0$ levels; hence, we obtained smaller $n$(H$_2$) for the higher density component than we did without H atoms, by a factor of 0.8 dex and 1.7 dex for clumps C and G, respectively.

As mentioned in Section 3.4, the lower and higher density components mainly contribute to the lower and higher energy levels, respectively (Figure 10). This clearly shows why we get different $n$(H$_2$) values depending on which levels are used for the estimation (cf. Table 5). This density property also indicates that the model parameter may not be unique, because the observed population constrains only a small portion of the modeled possibilities by varying $T_{\text{max}}$ and $T_{\text{min}}$ with the obtained fitting parameters (Table 4). In the case of clump C, we found that the $T_{\text{max}}$ of the lower density gas cannot be decreased from the initial model setting 4000 K, while the $T_{\text{min}}$ of the higher density gas can be relaxed up to 1000 K. This result means that a small amount of warm, high density H$_2$ gas can explain the high energy-level population, i.e., $N$(H$_2$; $T > 1000$ K) $\sim 4 \times 10^{18}$ cm$^{-2}$. In a similar sense, the $X_{\text{H}}$ in the lower density gas can be lower, even down to the hydrogen-free case, $n$(H$_{\text{II}}$)/
Figure 10. Two-component model fitting results for the H$_2$ population observed in clumps C (top panels) and G (bottom panels). The line-connected gray points in the left panels are the total H$_2$ population obtained from the model fitting, and their individual components are displayed in the right panels as red (lower density) and blue (higher density) points. (see the text for model description.) The rotational quantum number ($J$) is printed out near the corresponding point.

Table 5

| Target                  | log$[n$(H$_2)]]$ (cm$^{-3}$) | $b$   | Instrument | Estimated Levels | Ref. |
|-------------------------|-------------------------------|-------|------------|------------------|------|
| SNR IC 443              | 5.0–7.0                       | 3.0–6.0 | Spitzer IRAC | $\nu = 0, J = 6$–15 | 1    |
| SNR HB 21-Cloud N       | 2.7–3.3                       | 2.9   | AKARI IRC  | $\nu = 0, J = 3$–8 | 2    |
| SNR HB 21-Cloud S       | 4.6                           | 4.2   | AKARI IRC  | $\nu = 0, J = 4$–13 | 3    |
| OMC-1                   | 3.5                           | 1.9   | AKARI IRC  | $\nu = 0, J = 3$–8 | 3    |
| OMC-1                   | 6.0                           | 3.7   | AKARI IRC  | $\nu = 0, J = 4$–13 | 3    |
| Outflows of YSOs        | $\geq$7.0                     | 2.3–3.3| Spitzer IRS | $\nu = 0, J = 2$–9 | 4    |
| Outflows of YSOs        | $\geq$5.0                     | 3.0–5.5| Spitzer IRS | $\nu = 0, J = 6$–15 | 5*   |
| SNRs and outflows of YSOs| 3.3–3.6                       | 2.3–3.1| Spitzer IRS | $\nu = 0, J = 2$–9 | 7    |

Notes. (1) Neufeld & Yuan 2008; (2) Shinn et al. 2009; (3) Shinn et al. 2010; (4) Neufeld et al. 2009; (5) Lee et al. 2010; (6) Takami et al. 2010; (7) Yuan & Neufeld 2011. The modeled gas consists of H$_2$ and He only, with $n$(H$_2$) = 0.2 $n$(He).

a The central sources (position C and E) are excluded since H$_2$ may not be the only contribution to the IRAC bands.
4.1.2. Nature of the Shocks

There have been many observational studies trying to identify the shock type at clumps C and G at diverse wavelengths—millimeter, submillimeter, and infrared. Much of the observational results were compared with several J- and C-type shocks by Snell et al. (2005), and they concluded that a combination of shocks (dissociative and non-dissociative) is required to explain all the observational results. Later, Spitzer mid-infrared spectral observations showed the emission lines likely from such a combination of dissociative (J-type) and non-dissociative (C-type) shocks at clump C (Neufeld et al. 2007). Previous studies on the shocked H$_2$ gas of protostellar outflows that covered an $E(\nu, J)$ range similar to ours ($\sim$0–25,000 K) showed that a mixture of C- and J-type properties is required to explain the H$_2$ level population (Flower et al. 2003; Giannini et al. 2006; Gusdorf et al. 2008).

Under the shock-combination preference, the immediate question is from which type of shocks the two-component H$_2$ gas originates. We first considered the lower density gas that occupies the most mass of the shocked H$_2$ gas (Figure 10 and Table 4). If the lower density gas originates from J-type shocks, the recombinational lines of H$_1$ are also expected. We checked the relative intensity of the Br$\alpha$ 4.05 $\mu$m line and H$_2$ $\nu_0 = 0$ S(3) line from a theoretical model (Hollenbach & McKee 1989). The ratio of Br$\alpha$/[H$_2$ $\nu_0 = 0$ S(3)] is between $\sim$1 and 10 over the shock velocity 50–100 km s$^{-1}$ and preshock density $10^3$–$10^6$ cm$^{-3}$.

The H$_2$ density obtained from the model fitting likely represents the postshock density, since the H$_2$ emissions are mainly emanating from the reformed H$_2$ gas in J-type shocks (Hollenbach & McKee 1989). The typical J-type shock velocity

$n$(H$_2$) = 0, since the excitation of the low-J $\nu = 0$ levels is predominantly determined by collisions with H$_2$ rather than H$_1$.

Figure 11. Contour of $\chi^2$ in the plane of model parameters for clumps C (left panels) and G (right panels). The 68% and 95% confidence levels are outlined. The tick marks along the contours indicate the directions in which $\chi^2$ values are decreasing. The "⊕" indicates those model parameter values whose $\chi^2$ is minimum, i.e., the best fit. In the right bottom panel, the $\chi^2$ values are plotted about the parameter $b$ only, since the $X_H$ is fixed (cf. Table 4; the bottom figures are displayed on the following page.). The dotted line indicates the best-fit parameter, and the dashed lines indicate the 68% and 95% confidence levels.
is around 100 km s\(^{-1}\) under a general interstellar medium condition (Draine & McKee 1993), hence the density of the molecular reformation regions far down stream would be \(\gtrsim 100\) times higher than the preshock density; this density ratio can be seen from many numerical studies (e.g., Allen et al. 2008; Flower & Pineau Des Forêts 2010). Therefore, the preshock density should be \(n(H_2) \lesssim 10^{13} \text{ cm}^{-3}\) for the lower density gas to be from J-type shocks. This preshock density range is somewhat lower than that considered in the above theoretical model (10\(^2\)–10\(^6\) cm\(^{-3}\)), but the similar ratio \(Br_\alpha/[H_2 \nu = 0 - 0 S(3)]\) would be maintained since the postshock structure is insensitive to the preshock density in J shocks. Therefore, if the lower density gas is from J shocks, then there should be \(Br_\alpha\) of \(~2 \times 10^{-3} - 2 \times 10^{-2}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\), based on the observed intensity of \(H_2 \nu = 0 - 0 S(3)\) (Neufeld et al. 2007). However, no \(Br_\alpha\) line of such a high intensity was detected (Figure 2).

In addition, theoretically, a J shock produces more abundant high-\(T\) (\(\sim 10^4\) K) \(H_2\) gas than a C shock (Wilgenbus et al. 2000; Flower & Pineau Des Forêts 2010). If the lower density gas is from J shocks, the \(H_2\) population diagram must show a much more upturned curvature than we obtained (Figure 10). Overall, the lower density gas is not likely from J-type shocks.

We then checked whether the lower density gas originates from C-type shocks. The postshock gas behind a planar \(C\)-type shock can be approximated as an isothermal gas whose density \(n(H_2)\) and temperature \(T_s\) are as follows (Neufeld et al. 2006):

\[
n(H_2) = 1.5 n_0
\]

\[
T_s = 375 b_B^{-0.36} v_{\nu,6}^{1.35} \text{ K,}
\]

where 10 \(v_{\nu,6}\) km s\(^{-1}\) is the shock velocity and \(b_B(n_0/\text{cm}^{-3})^{1/2}\) \(\mu G\) is the assumed preshock magnetic field for a shock propagating in material of preshock \(H_2\) density \(n_0\). We here note that the above approximation was tested over \(n_0 = 10^3\)–10\(^6\) cm\(^{-3}\) (Neufeld et al. 2006). From this approximation, we can say that the lower density gas is from C shocks propagating into a preshock medium \(n(H_2) \sim 10^{2.6} - 10^{3.6}\) cm\(^{-3}\). Interestingly, this density is similar with the typical density of molecular clouds (\(\gtrsim 10^3\) cm\(^{-3}\)), where the hydrogen dominantly exists in the molecular form \(H_2\) (Snow & McCall 2006). Such a similarity gives a natural way to explain the mass dominance of the lower density gas (Figure 10), since \(H_2\) survives C-type shocks. Therefore, C-type shocks are more suitable to explain the lower density gas than J-type shocks.

If the lower density gas is from C-type shocks, the power-law index \(b\) may reflect the multiple shocks of different velocities. According to the approximation with \(b_B = 1\), it ranges from 3 to 58 km s\(^{-1}\), which corresponds to \(~100-4000\) K gas. This velocity range is theoretically expected for a C-type shock whose preshock density is \(\sim 10^3\) cm\(^{-3}\) and \(b_B = 1\) (Le Bourlot et al. 2002). Also, such diversity in the shock velocity is consistent with the results of Hewitt et al. (2009a), who found that two C shocks are preferred to explain the excitation of shocked \(H_2\) gas around SNRs over the range \(E(\nu, J) \sim 0-8000\) K. However, we here note that this shock velocity range depends on the model parameters we fixed (\(T_{\text{min}}, T_{\text{max}}\)); therefore, the shock velocity range mentioned above (3–58 km s\(^{-1}\)) is not determined observationally. Instead, it should be understood that multiple shocks of a few to a few tens of kilometers per second are required to explain the level population of the lower density gas.

The diversity in the shock velocity may be a natural result during the shock–cloud interaction, since the shock driving pressure would be higher at the head than at the side. This kind of property can be inferred from a numerical simulation for radiative clouds (Nakamura et al. 2006), which showed that the velocity dispersion of the shocked cloud is larger along the shock-normal (the blast wave direction; the \(z\)-axis in Nakamura et al. 2006) than along the shock-tangential (the \(\sigma\)-axis in Nakamura et al. 2006). This velocity dispersion does not exactly correspond to the dispersion of the shock velocity in the cloud; however, it shows in which direction the shock would propagate faster and cause the larger velocity dispersion.

We assigned the same \(H\) abundance for both the lower and higher density gas and obtained \(X_H = -1.7\), equivalent to \(n(H)/n_H = 0.01\) and \(n(H)/n(H_2) = 0.02\) (Table 4). This value is \(\gtrsim 100\) times higher than expected for a typical molecular cloud.
However, as mentioned in Section 4.1.1, we can achieve the population of the lower density gas even with zero H I abundance, since the population is predominantly determined by collisions with H 2 rather than H I. Considering this fact, the C-shock interpretation for the lower density gas has no contradiction with the H I abundance.

Now we move on to discuss from which type of shock the higher density gas originates, first considering the H I abundance. The H I abundance, X_H I, is mainly determined by the vertical gap between ν = 0 and ν > 0 levels in the population diagram, and the gap is dominantly described by the higher density gas (see Figure 10). The obtained X_H I = −1.7, equivalent to n(H I)/n_H I = 0.01 and n(H I)/n(H 2) = 0.02, is expected for a typical diffuse cloud (n_H I ∼ 10^2 cm^{-3}), but is high for a typical molecular cloud (n_H I ∼ 10^4 cm^{-3}), which has X_H I ≲−4.0 (Draine et al. 1983). Therefore, the obtained X_H I must be from one of the following cases: (1) non-dissociative (C-type) shocks propagating into molecular clouds of the high X_H I value, (2) non-dissociative (C-type) shocks propagating into diffuse clouds, or (3) dissociative (J-type) shocks propagating into molecular clouds.

We checked the first case. In view of the calculations of Solomon & Werner (1971), Draine et al. (1983), and Goldsmith & Li (2005), the total ionization rate for H 2 must be ζ ∼ 10^{-13} to 10^{-12} s^{-1} to make the obtained abundance in the higher density H 2 gas of n(H 2) ∼ 10^3 cm^{-3}. However, the measured rate is much smaller than that required: ζ ∼ 5.5 × 10^{-16} s^{-1} (Hewitt et al. 2009b) and ζ ∼ 2.6 × 10^{-15} s^{-1} (Indriolo et al. 2010). The second case is also negative. It was shown that the postshock gas behind a planar C-type shock can be approximated with an isothermal gas whose density is equal to ∼1.5 n_{preshock} (Neufeld et al. 2006). If the shock is C type, the obtained density of n(H 2) = 10^{5.4−10.5} cm^{-3} contradicts the requirement that the preshock medium must be a diffuse cloud (n_H I ∼ 10^2 cm^{-3}). In the third case, however, the high X_H I of −1.7 is expected under appropriate conditions; such an X_H I can be achieved at the T ∼ 1000−4000 K region where the H 2 emission is mainly emanating from reformation (Hollenbach & McKee 1989; Flower & Pineau Des Forêts 2010).

If the higher density gas is from J-type shocks where the H 2 emission predominantly comes from the postshock reformation regions, the obtained model parameters for the higher density gas (Table 4) can be regarded to represent characteristic physical parameters of the reformation regions. Based on this, the preshock density should be a factor of ≤100 smaller than the obtained density of n(H 2) = 10^{5.3−10.8} cm^{-3} since the typical velocity of J shocks is around 100 km s^{-1}. Also, there should exist shocked H I gas, the raw material for the reformation of H 2. The shocked H I gas has already been observed along the “W” ridge (Figure 1) we studied (Braun & Strom 1986; Lee et al. 2008a). Lee (2007) measured the column densities of the shocked H I gas at clumps C and G, which are about ∼3 × 10^{21} cm^{-2}. If we assume that the shocked H I spreads along our line of sight as long as the width of the “W” ridge (∼2’, ∼1 pc), then we obtain the mean H I density of ∼10^4 cm^{-3}, which is smaller than the postshock H I density n(H 2) = 10^{7.4−10.8} cm^{-3}. These n(H I) and n(H 2) values are consistent with the J-shock interpretation, since the H I recombines before the H 2 and the postshock density increases along the distance from the shockfront. We also checked the line profile of H I 21 cm emission (Lee 2007) and H 2 ν = 1 → 0 S(1) emission (Rosado et al. 2007) at clump C and found that they both show the shocked component at the similar velocity ~30 km s^{-1}. Therefore, the J-shock interpretation for the higher density gas seems plausible.

We then considered the meaning of the power-law index b in the higher density gas. As mentioned in Section 4.1.1, T_{min} of the higher density gas can be increased from 100 K to 1000 K without making any difference in the final population of E(ν, J) ≥ 10^4 K levels. This means that the gas in T = 1000–4000 K is necessary to describe the observed population of E(ν, J) ≥ 10^4 K levels. We checked whether the b variation makes any significant change to the level population of E(ν, J) ≥ 10^4 K summed over T = 1000–4000 K; the obtained n(H 2) and X_H I values were fixed while the b value was varied. We found that the b variation makes a negligible effect over b = 1−4.0. This is because the population of E(ν, J) ≥ 10^4 K levels has almost the same slope over the temperature integration range (1000–4000 K) in the power-law thermal model. Therefore, the b value has almost no practical meaning for the higher density gas.

Considering the above discussion, the lower and higher density gases are likely from the C-type and J-type shocks, respectively. This conclusion is consistent with the conclusions from previous studies that claimed a mixture of dissociative and non-dissociative shocks for the description of the observed results (Snell et al. 2005; Neufeld et al. 2007). If we interpret our results based on the hierarchical picture of molecular clouds (Bergin & Tafalla 2007; Williams et al. 2000), the C-type shocks propagate into “clumps,” while the J-type shocks propagate into “clouds” (interclump media); the typical densities of these two constituents (“clouds” and “clumps”) are 50–500 cm^{-3} and 10^3−10^4 cm^{-3}, respectively. This interpretation is consistent with the requirement that the ram pressure (−ρv^2) should be similar between C-type and J-type shocks. In the above discussion, we claimed that C-type shocks propagate into a preshock medium of ∼10^3 cm^{-3} with a shock velocity of a few 10 km s^{-1}, while J-type shocks propagate into a preshock medium of < 10^3 cm^{-3} with a shock velocity of ~100 km s^{-1}.

Before closing this section, we note that the H 2 ν = 1 → 0 S(1) predominantly originates from J-type shocks rather than C-type shocks, according to our results. Interestingly, it was observed that the [Si II] 34.8 μm emission well follows the H 2 ν = 1 → 0 S(1) emission at clump C (Richter et al. 1995a; Neufeld et al. 2007); the [Si II] 34.8 μm emission is an efficient cooling line at T ∼ 1000 K where the H 2 reformation also happens (Hollenbach & McKee 1989). The intensities of [Si II] and H 2 ν = 1 → 0 S(1) are 0.97 and 1.8 in 10^{-4} erg s^{-1} cm^{-2} sr^{-1}, respectively (Neufeld et al. 2007; Table 3). The ratio [Si II]/H 2 ν = 1 → 0 S(1) is 0.54, which is significantly lower than the theoretical expectation of a 100 km s^{-1} J shock into 10^3 cm^{-3} gas, ~5.0 (Hollenbach & McKee 1989). In spite of this difference, the J-shock origin of H 2 ν = 1 → 0 S(1) emission is worth checking further to determine whether it is general in shocked regions, considering that the shocked H 2 gas usually shows a similar shape in the level population over E(ν, J) = 0−25,000 K (cf. Section 4.1.3).

4.1.3. Embedded Coherence in the Obtained Model Parameters

Table 4 shows some coherences of the obtained model parameters for the two-component gases, although clump G has no data for the population of E(ν, J) = (0,2) and (0,3), which are important in the determination of b and density. For example, the density ratio and the column density ratio of the two-component gases are not much different at clumps C and G. This may originate from some common properties of the preshock

\( n_H \geq 10^4 \text{ cm}^{-3}; \text{Draine et al. 1983} \).
medium. One step forward, Richter et al. (1995a, 1995b) already noted the similarity between the H$_2$ level population of SNRs and outflows of YSOs.

We can study such similarities in the two-\(n(H_2)\) power-law thermal admixture models by comparing the model parameters and may lead out the properties of the preshock medium. The power-law index \(b\) would give information about how shock velocity is diverse at the shock–cloud interaction regions, which may be related to the geometrical structure of the clouds. The coming James Webb Space Telescope, which can perform spectral observations over the \(\sim1\text{–}30\ \mu\text{m}\) wavelength range, would provide an excellent opportunity for such studies.

### 4.2. Warm Diffuse Background H$_2$ Gas

At the background region (BG in Figure 1), we detected the H$_2$ \(\nu = 0 - 0\) S(9) line (Figure 6). The extinction-corrected column density gives \(\log[N(H_2; \nu = 0, J = 0, 1)] = 15.08 \pm 0.11\ \text{cm}^{-2}\) (Table 3). This emission may be related to the diffuse background H$_2$ gas previously observed toward SNRs (Neufeld et al. 2007; Hewitt et al. 2009a). In order to check whether the obtained \((\nu, J = 0, 1)\) population is plausible for such a diffuse background H$_2$ gas, the population was compared with those obtained toward other Galactic lines of sight. Since the relative shape of the level population determines the physical condition of the H$_2$ gas, we must compare such a relative shape; thus, we need the population of other levels in addition to the \((\nu, J = 0, 1)\) level.

For this, we employed the \((\nu, J = 0, 2)\) population of the diffuse background H$_2$ gas, previously observed toward clump C of IC 443 (Neufeld et al. 2007), as the \((\nu, J = 0, 2)\) level population of our BG region (Figure 1). We adopted \(I_{\text{diff}} = 1.5 \times 10^{-6}\ \text{erg \ s}^{-1}\ \text{cm}^{-2}\ \text{sr}^{-1}\) as the intensity for the H$_2$ \(\nu = 0 - 0\) S(0) line (cf. Figure 19 of Neufeld et al. 2007) and corrected the extinction with \(A_V = 13.5\), employing the “Milky Way, \(R_V = 3.1\)” extinction curve (Weingartner & Draine 2001; Draine 2003). The population is \(\log[N(H_2; \nu = 0, 2)] = 19.05 \pm 0.07\ \text{cm}^{-2}\). The weighted populations of the \((\nu, J = 0, 2)\) and \((0, 1)\) levels for the BG region are \(\log[N(\nu, J = 0, 2)] = 18.3\) and 13.2, respectively.

We compared the populations of these two levels with those of \((\nu, J = 0, 1)\) obtained toward the “translucent lines of sight” to the Galactic background stars, from the far-ultraviolet observations of H$_2$ absorption lines (Jensen et al. 2010). Since the population of \((\nu, J = 0, 1)\) is absent in the results of Jensen et al. (2010), the relative curvature in the population diagram was compared by scaling up or down the populations of \((\nu, J = 0, 2)\) and \((0, 1)\) levels. From the comparison, we found that our populations make a more upturned curvature than expected from the excitation temperature of \(J \geq 2\) levels, \(\sim200\text{–}550\ \text{K}\) (Jensen et al. 2010). This indicates the existence of H$_2$ gas with a higher temperature than 550 K, which is consistent with the suggestion of Jensen et al. (2010): more than two temperature components are probably necessary to describe the population.

Jensen et al. (2010) tried to fit the population obtained toward two sample targets with a model for photodissociation regions; however, the fits were poor. Such a mismatch was also recognized by Gry et al. (2002) and Falgarone et al. (2005); they suggested that other collisional excitation mechanisms, such as magnetohydrodynamic shocks or intermittent dissipation of turbulence, are required to explain the observed population. The diffuse background H$_2$ gas toward the SNR IC 443 may originate from these mechanisms.

### 5. CONCLUSIONS

We present near-infrared (2.5–5.0 \(\mu\text{m}\)) spectra toward three shocked H$_2$ clumps (B, C, and G) of the SNR IC 443 and one background (BG) region (cf. Figure 1). The observations were performed with the satellite AKARI during its post-helium phase. Only H$_2$ emission lines were detected toward all four directions. We measured the line intensities and, after the reddening correction, obtained the relevant level populations. The level populations were compared with the ones from previous near- and mid-infrared observations. AKARI level populations are well fitted with those from previous mid-infrared space observations, while there is a systematic difference from those from previous near-infrared ground observations. We attributed this difference to the calibration error of previous near-infrared observations, although it may be caused by the different positions of observed regions.

With the AKARI near-infrared observations, we could extend the level population of shocked H$_2$ gas in clumps C and G obtained from mid-infrared observations, from \(\sim7000\ \text{K}\) to \(\sim22,000\ \text{K}\) continuously. From these combined level populations, we found that the \(\nu = 0\) levels are more populated than the \(\nu > 0\) levels at a fixed level energy, which means that the population cannot be reproduced with any combination of H$_2$ gas in LTE, usually used for the description of shocked H$_2$ gas. The populations were well described with a two-\(n(H_2)\) power-law thermal admixture model including the H atom as a collisional partner in addition to H$_2$ and He. The model parameters are two number densities \(n(H_2)\), two column densities \(N(H_2)\), one power-law index \(b\), and the H$_2$ to H$_3$ abundance \(X_H\) (cf. Table 4).

We attributed the lower \((n(H_2) = 10^{2.8}\text{–}10^{3.8}\ \text{cm}^{-3})\) and higher \((n(H_2) = 10^{5.4}\text{–}10^{5.8}\ \text{cm}^{-3})\) density gases to the shocked H$_2$ gas behind C-type and J-type shocks, respectively, based on several arguments such as the preshock density, the amount of shocked gas, the obtained high H$_1$ abundance, the shape of level populations, the line profile, etc. This interpretation is consistent with the hierarchical picture of molecular clouds whose constituents are classified into “clouds,” “clumps,” and “cores” (Bergin & Tafalla 2007; Williams et al. 2000). The C-type shocks are likely propagating into the “clumps” (\(\sim10^{-2}\ \text{cm}^{-3}\)), while the J-type shocks are propagating into the “clouds” (interclump media, \(<10^3\ \text{cm}^{-3}\)). The power-law index \(b\), mainly determined by the lower density gas, is attributed to the diversity in the shock velocity propagating into the clouds. Such a diversity of velocity may be a natural result during the shock–cloud interaction, since the shock driving pressure would be higher at the head than at the side. According to our results, the H$_2$ \(\nu = 1 - 0\) S(1) emission is mainly from J-type shocks propagating into interclump media. In addition, our power-law thermal admixture model would be useful to perform statistical studies on the shocked H$_2$ gas observed around other SNRs and YSOs, which shows coherent excitation characteristics.

H$_2$ emission was also detected at the BG region, and we attributed it to the diffuse H$_2$ gas, pervaded in the Milky Way. This gas may be excited by collisional processes such as shocks or turbulence dissipation, in addition to ultraviolet photon pumping.

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