CO Survey toward the Magellanic Supernova Remnants

Hidetoshi Sano[1,2], Yumiko Yamane[2], Takuro Nagaya[2], Kosuke Fujii[3], Satoshi Yoshiike[2], Kengo Tachihara[2], Yasuo Fukui[1,2]

[1]Institute for Advanced Research, Nagoya University (sano@a.phys.nagoya-u.ac.jp); [2]Department of Physics, Nagoya University; [3]Department of Astronomy, School of Science, The University of Tokyo

Abstract: In supernova remnants (SNRs), the interaction between the shock waves and interstellar gas plays an essential role in producing high energy radiation and cosmic rays (CRs). We present new CO observations toward 25 supernova remnants (SNRs) residing with the Large Magellanic Cloud (LMC), including the TeV γ-ray sources N132D and 30 Doradus C. Our observations revealed that ~90% of the SNRs were detected by ^{12}CO(J = 1–0) line emission with a 3σ level or higher. At least ten of them were shown to have CO clouds that have a good spatial correspondence with thermal/non-thermal X-rays; this indicates that shock-cloud interactions may have occurred. The molecular gases associated with N132D showed a high intensity ratio of ^{12}CO J = 3–2 / 1–0 > 0.8, indicates that shock-heating occurred. We also found five molecular clouds and three HI clouds associated with 30 Doradus C, which showed either complimentary or similar distributions to the non-thermal X-ray filaments in a 10 pc scale. The interstellar proton density of 30 Doradus C was estimated to be ~60 cm^{-3}, which corresponded to the total energy of the cosmic-ray protons being at least ~1.2 × 10^{50} erg.

TeV γ-rays in the Large Magellanic Cloud

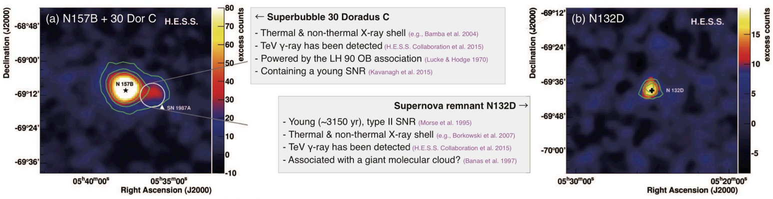

Fig.1: Sky maps of the Large Magellanic Cloud (H.E.S.S. Collaboration et al. 2015). (A) TeV γ-ray emission toward the PWN N157B and the superbubble (SB) 30 Doradus C. (b) TeV γ-ray emission toward the SNR N132D.

- TeV γ-ray SNRs are the most likely candidates for acceleration site of cosmic-ray (CR) below *knee* energy.
- H.E.S.S. discovered the TeV γ-rays in the Magellanic SNR/SB (H.E.S.S. Collaboration et al. 2015).
  → We can demonstrate to study the CR acceleration in the Magellanic sources.
- To reveal the total energy of CRs, we should identify the interstellar gas associated with the SNR/SB.
- Shock-cloud interaction also plays an important role in understanding the CR acceleration (Sano et al. 2015a)
  → Turbulent motion enhances B field and synchrotron X-rays around the clumpy interstellar medium.

We need complete surveys of CO/HI toward the Magellanic SNRs in order to understand the origin of CRs.

Observations & Archival Data

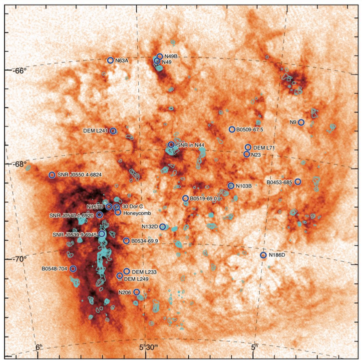

Fig.2: Distribution of the HI emission (Kim et al. 2003) overlaid on the ^{12}CO(J = 1–0) contours taken by the NANTEN radio telescope (Fukui et al. 2008). The superposed circles show the X-ray SNRs, which are the targets of this study.

We observed CO emission lines toward the Magellanic SNRs with X-rays.

^{12}CO(J = 1–0)
Telescope: Mopra 22-m
Angular resolution: ~45 arcsec
Velocity resolution: ~0.53 km s^{-1}
Noise level: ~0.16 K ch^{-1}

^{12}CO(J = 3–2)
Telescope: ASTE 10-m
Angular resolution: ~21 arcsec
Velocity resolution: ~0.1 km s^{-1}
Noise level: ~0.09 K ch^{-1}

HI [archival data]
Telescope: ATCA & Parkes
Angular resolution: ~60 arcsec
Velocity resolution: ~0.82 km s^{-1}
Noise level: ~1.0 K ch^{-1}

X-rays [archival data]
Telescope: *Chandra*
Angular resolution: ~0.5 arcsec

Case 1: Superbubble 30 Doradus C

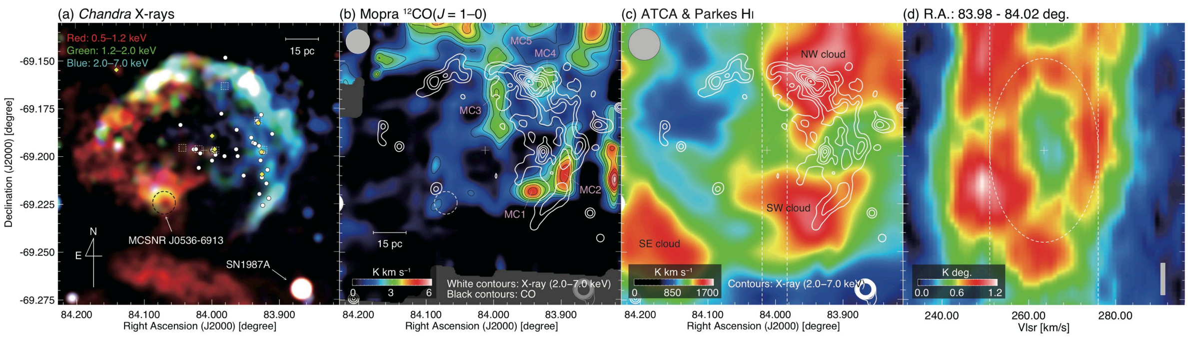

Fig.3: Distributions of X-ray and interstellar gas toward the superbubble 30 Doradus C (Sano et al. 2017a).

(a) RGB image of the superbubble 30 Doradus C observed by *Chandra* (Bamba et al. 2004). The yellow diamonds, white filled circles, dashed squares, and dashed circles show the positions of Wolf–Rayet stars, O-type stars, LH 90, and MCSNR J0536–6913, respectively.

(b) Intensity distribution of ^{12}CO(J = 1–0) obtained with Mopra overlaid with the *Chandra* hard-band X-ray contours (black: 2.0–7.0 keV). The integration velocity range is from V_{LSR} = 251 to 276 km s^{-1}. Black contours represent the CO integrated intensity. Black contours represent the CO integrated intensity. The lowest contour level and the contour interval are 2.80 K km s^{-1} (~5σ) and 0.56 K km s^{-1} (~1σ), respectively.

(c) Intensity distribution of HI line emission obtained with ATCA & Parkes (Kim et al. 2003).The integration velocity range and overlaid contours are the same as in Figure 3b. Superposed contours represent the *Chandra* broad-band X-ray contours (black: 0.5–7.0 keV).

(d) Position–velocity diagram of HI. The integration range in the R.A. is from 83°.98 to 84°.02 shown in Figure 3c. The dashed circle corresponds to the shell radius of 30 Doradus C.

- Five CO clumps, MC1–5, are significantly detected (> 5 σ) along with the non-thermal X-ray shell. It is remarkable that the CO distribution is complimentary to the X-ray peaks in a several pc scale. Especially the most intense clumps MC1 and MC2 are rim-brightened in non-thermal X-rays, suggesting possible evidence for the shock-cloud interaction (e.g., Sano et al. 2010; 2013; 2017b).
- We identified an HI cavity-like structure with a diameter of ~ 0°.1 around V_{LSR} = 264 km s^{-1}, suggesting the expanding motion with ΔV = 12.5 km s^{-1} due to the stellar wind from high-mass stars and/or SNe.
- The interstellar proton density is ~ 60 cm^{-3}, assuming the shell radius ~47 pc and thickness ~10 pc. → If the hadronic process is mainly working, the total energy of CRs W_{pp} at least ~1.2 × 10^{50} erg.

Case 2: SNR N132D

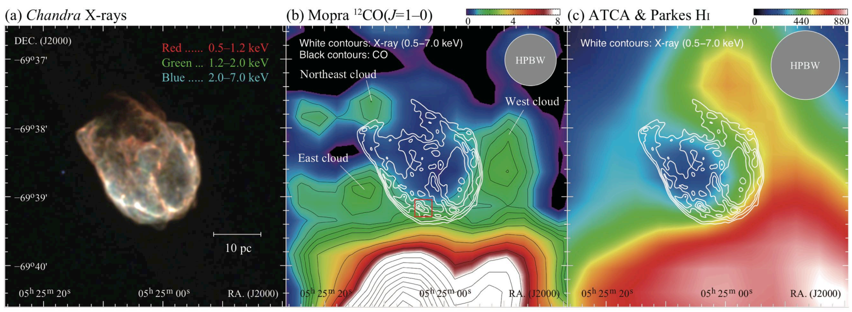

Fig.4: Distributions of the X-ray and interstellar gas toward the SNR N132D (Sano et al. 2015b, 2017c). (a) The *Chandra* three color image of SNR N132D. Red, green, and blue correspond to 0.5–1.2, 1.2–2.0, and 2.0–7.0 keV intensity distributions, respectively. (b) Integrated intensity map of the Mopra ^{12}CO(J = 1–0) data in a velocity range of V_{LSR} = 256.5 to 268.6 km s^{-1} is shown in color. The color scale indicates integrated intensity on a square-root scale in unit of K km s^{-1}. The white contours indicate the X-ray intensity in Fig.4a. The lowest contour level and intervals are 6.50 × 10^{-7} and 2.89 × 10^{-7} counts s^{-1} pixel^{-1}, respectively. (c) Integrated intensity map of ATCA & Parkes HI (Kim et al. 2003). The velocity range and contours are the same as those in Fig.3b. The color scale also indicates integrated intensity on a liner scale and its unit is same as that in Fig.3a. (d) Spatial distribution of the line intensity ratio between ^{12}CO(J = 3–2) and ^{12}CO(J = 1–0) superposed on the X-ray contours as shown in Fig.3b. Data were smoothed with a Gaussian function to an effective beam size of 45′′.

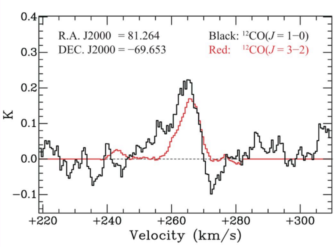

Fig.4: ^{12}CO(J = 3–2) and ^{12}CO(J = 1–0) line profiles toward the southwestern part of N132D that are shown within the red box in Figure 4(b). All the spectra were smoothed so as to have a HPBW of 45′′.

- We newly found three CO clouds and HI gas interacting with the SNR. The two of tem are located in the west and east, which form the cavity-like structures along the X-ray shell.
- We discussed that the CO/HI cavity-like structures were created by the stellar wind / UV photons from the massive star prior to the supernova explosion and are now interacting with the SNR shock. Furthermore, the enhancement of non-thermal X-rays (2.0–7.0 keV) in the southern part can be described as a result of shock interaction with clumpy CO structures.
- We have revealed that a high intensity ratio of ^{12}CO J = 3–2/1–0 > 0.8 toward the southeast region, indicating the shock heating.
- The interstellar proton density is estimated to be ~ 90 cm^{-3}, assuming the shell radius ~ 14 pc and thickness ~ 5 pc.
  → If the hadronic process is mainly working, W_{pp} ~ 1 × 10^{50} erg

Case 3: Other X-ray SNRs

- 90% of the SNRs were detected in CO with 3σ noise level or higher.
- At least ten of them were shown to have CO clouds that have a good spatial correspondence with thermal/non-thermal X-rays

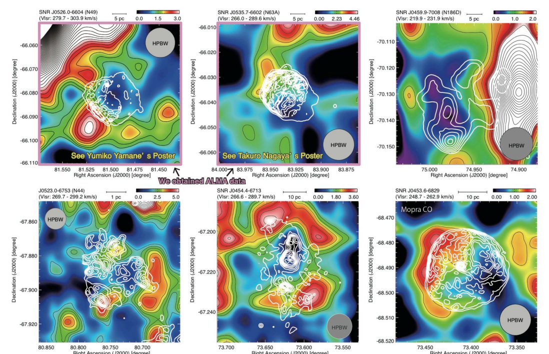

Fig.6: Distributions of the Mopra ^{12}CO(J = 1–0) intensity superposed on the *Chandra* X-ray contours toward (a) N49, (b) N63A, (c) N186D, (d) N44, (e) J0454.4-6713, and (f) J0453.6-6829. The lowest contour levels of CO are 3σ for each SNR.

Conclusions

We revealed the interstellar gas distributions toward the 25 Magellanic SNRs. At least ten of them were shown to have CO clouds that have a good spatial correspondence with X-rays. Some SNRs show a high intensity ratio of ^{12}CO J = 3–2/ 1–0 > 0.8, indicating that shock-heating occurred. Further γ-ray observations using CTA will reveal various TeV γ-ray SNRs in the LMC.

References

- Bamba et al. 2004, ApJ, 602, 257
- Banas et al. 1997, ApJ, 480, 607
- Borkowski et al. 2007, ApJL, 671, 45
- Fukui et al. 2008, 2008, ApJS, 178, 56
- H.E.S.S. Collaboration et al. 2015, Science, 347, 406
- Kavanagh et al. 2015, A&A, 573, 73
- Kim et al. 2003, ApJS, 148, 473
- Lucke & Hodge 1970, AJ, 75, 171
- Morse et al. 1995, AJ, 109, 2104
- Sano et al. 2010, ApJ, 724, 59
- Sano et al. 2013, ApJ, 778, 59
- Sano et al. 2015a, ApJ, 799, 175
- Sano et al. 2015b, ASPC, 499, 25
- Sano et al. 2017a, ApJ, 843, 61
- Sano et al. 2017b, JHEAp, 15, 1
- Sano et al. 2017c, AIP, 1972, 040038