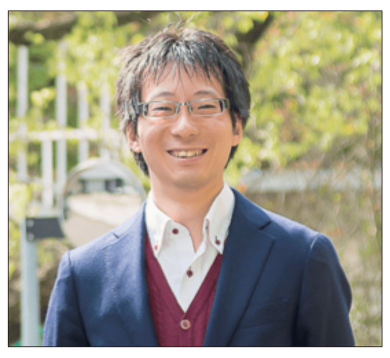

NAGOYA UNIVERSITY

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ALMA view of the molecular clouds associated with the Magellanic SNRs

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Abstract: The Large Magellanic Cloud (LMC) is among the best laboratories for studying various astronomical objects and their physics because of its almost face-on inclination to us, and a well-known distance (~50 kpc). Supernova remnants (SNRs) in the LMC were well studied by radio continuum, optical, and X-ray observations (e.g., Bozzetto et al. 2017 and references therein). By contrast, very few attempts have been made to observe molecular clouds associated with the LMC SNRs (Banas et al. 1998). Sano et al. (2017a,b) observed 25 X-ray bright LMC SNRs using the Mopra 22-m and ASTE 10-m radio telescopes with a spatial resolution of ~6–11 pc. At least twelve of them were shown to have giant molecular clouds that have a good spatial correspondence with X-ray shells; this indicates that shock-cloud interactions may have occurred. Subsequently, we observed four SNRs using the Atacama Large Millimeter/ submillimeter Array (ALMA) with a spatial resolution of ~0.4–0.7 pc. We spatially resolved clumpy molecular clouds associated with the LMC SNRs for the first time (N49, Yamane et al. 2018; N103B, Sano et al. 2018; N63A, Sano et al. 2019; and in the superbubble 30 Doradus C, Yamane et al. 2019 in preparation; N132D, Sano et al. 2019b in preparation). We are therefore entering a new age in studying the Magellanic SNRs yielding a spatial resolution comparable to what had been possible only for Milky Way SNRs. In this poster, we report our latest results of CO studies in the X-ray bright LMC SNRs using the Mopra, ASTE, and ALMA.

SNRs in the MW and the LMC

- In our Milky Way, molecular clouds associated with supernova remnants (SNRs) play an essential role in understanding not only the shock heating/compression of the interstellar medium (ISM), but also the origins of thermal/non-thermal X-rays, γ-rays, and cosmic rays.
  1) The shock-cloud interaction excites turbulence that enhances the magnetic field up to ~1 mG [e.g., 1,2,3], which can be observed as shocked gas clumps with limb brightening in the synchrotron X-rays [e.g., 4,5,6].
  2) For the ionized plasma in the Galactic SNR RCW 86, We found a positive correlation between the thermal X-ray flux and gas density around the shocked region, indicating that shock ionization occurred [7].
  3) The interstellar protons also act as a target for cosmic-ray protons producing GeV/TeV γ-rays via neutral pion decay. The good spatial correspondence between the interstellar protons and γ-rays provides evidence for cosmic-ray acceleration in the Galactic SNRs [e.g.,8–15]

In order to better understand the origins of γ-/X-rays, and cosmic-rays, we need to have a large sample of SNRs.

- The Large Magellanic Cloud (LMC) is the best laboratory for studying because of its almost face-on inclination to us and a well-known distance (50 ± 1.3 kpc) [16]; **this suggests that we can be easily observe it and suffer very little contamination to identify the interstellar gas associated with the SNRs.** The previous studies discovered 59 confirmed and an additional 15 candidate SNRs in the LMC (Fig. 1, [17] and references therein). Therefore, we can perform a complete statistical study on a type of object that is crucial not only in galaxy evolution but also in origins of the γ-rays, X-rays, and cosmic-rays. Banas et al. (1997) carried out CO studies toward the three LMC SNRs N23, N49, and N132D (Fig. 2, [18]). They presented clear evidence for the cloud association in the LMC SNRs for the first time.

Despite the advantage and uniqueness, a large CO survey of the Magellanic SNRs has not been attempted...!!!

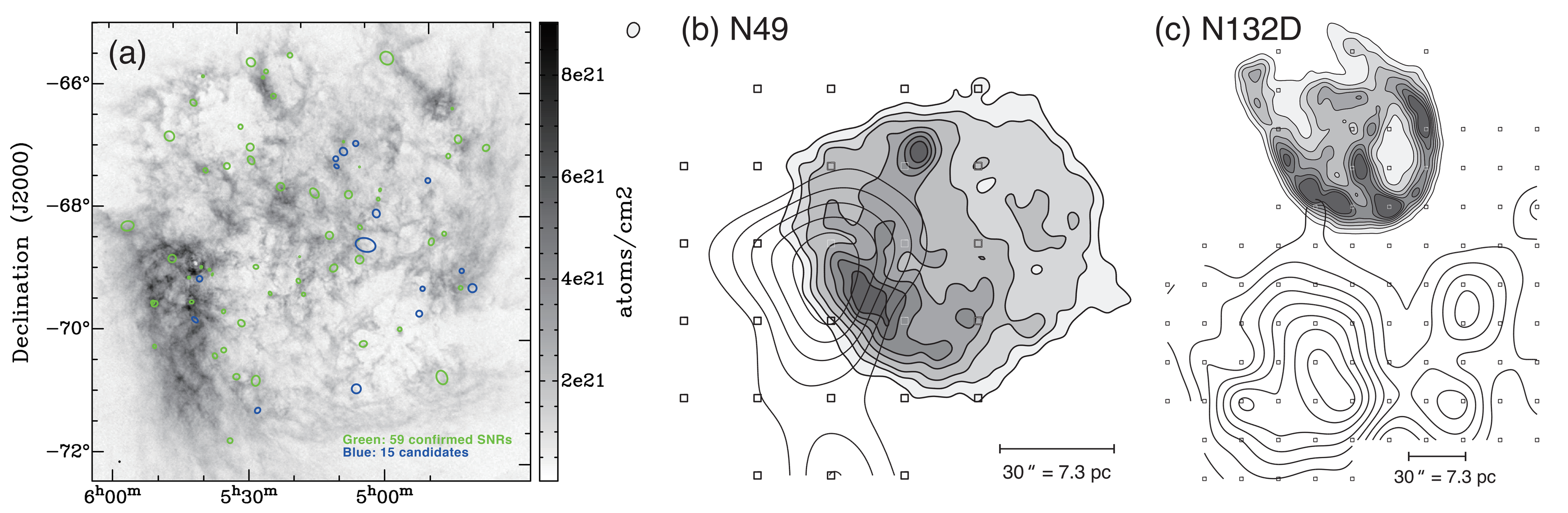

Fig. 1 (a) Spatial distribution of the 59 confirmed and 15 candidate SNRs in the LMC [17]. Image is HI peak temperature map (Kim et al. 1998). (b-c) ROSAT X-ray maps of (b) N49 and (c) N132D overlaid with CO contours [18].

CO Survey of the LMC SNRs (Sano+17bc)

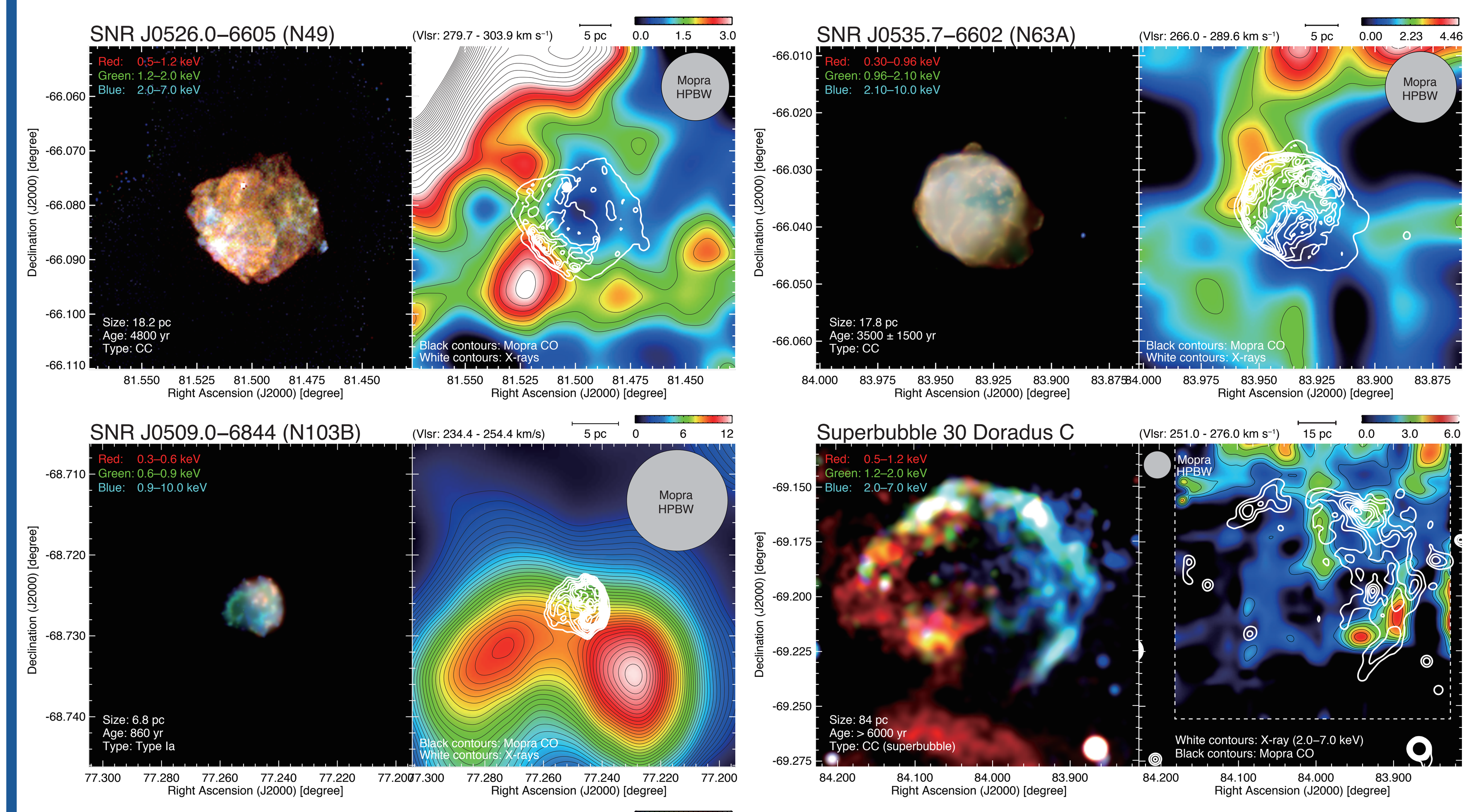

Fig. 2 (left panels) RGB images of *Chandra* X-rays toward the LMC SNRs N49, N103B, N132D, N63A, and superbubble 30 Doradus C. The size, age, and type are also shown in left bottom corner for each panel. (right panels) CO maps obtained with Mopra or ASTE overlaid with *Chandra* X-rays (white contours). All SNRs are located near the giant molecular clouds [19].

The SNRs in our CO survey were selected from the *Chandra* SNR catalog. We surveyed the 25 SNRs with $^{12}CO(J = 1–0)$ and $^{12}CO(J = 3–2)$ line emission with the Mopra 22-m radio telescope and the Atacama Submillimeter Telescope Experiment (ASTE) [19,20]. The angular resolution is 45" for Mopra and 26" for ASTE, corresponding to the spatial resolution of ~6-11 pc. At least ten of them were shown to have CO clouds that have good spatial correspondence with X-rays indicating that shock-cloud interactions may have occurred.

ALMA CO Results toward the LMC SNRs and Superbubble (Sano+18,19bc; Yamane+18,19)

LMC SNR N49 (Yamane, Sano et al. 2018, ApJ, 863, 55)

LMC SNR N63A (Sano et al. 2019, ApJ, 873, 40)

Superbubble 30 Dor C (Yamane, Sano et al. 2019, in preparation)

LMC SNR N132D (Sano et al. 2019, in preparation)

LMC SNR N103B (Sano et al. 2018, ApJ, 867, 7)

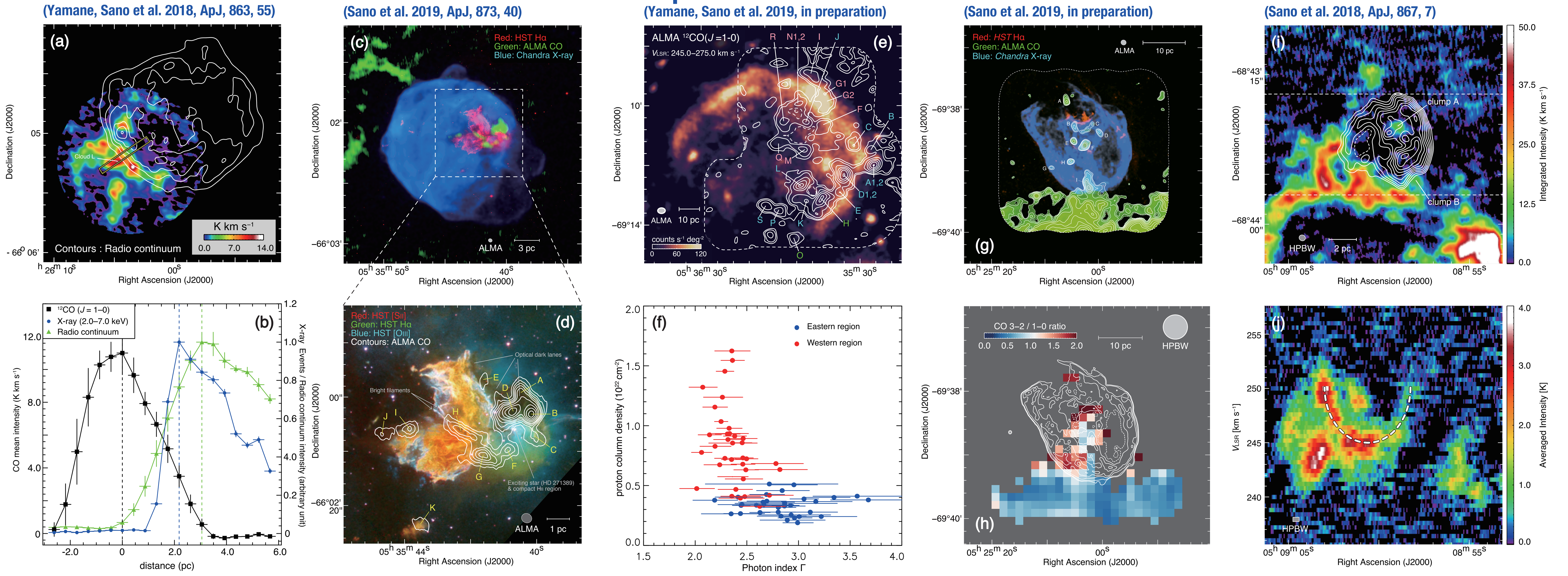

Fig. 3 (a) ALMA CO map superposed on the synchrotron radio continuum toward the LMC SNR N49 [18]. (b) Radial profiles of CO, X-rays, and radio continuum for the rectangular region as shown in Figure 3a [18]. (c) Three-color image of SNR N63A. The red, green, and blue colors represent the HST Hα (Chu 2001), ALMA $^{12}CO(J=1–0)$, and Chandra X-rays (E: 0.3–6.0 keV, Warren et al. 2003), respectively [23]. (d) Three-color images of SNR N63A observed by HST [Image credit: NASA, ESA, HEIC, and The Hubble Heritage Team (STScI/AURA)]. The red, green, and blue colors represent the [SII], Hα, and [OIII]. The superposed contours indicate the ALMA CO integrated intensities [23]. (d) Integrated intensity map of ALMA $^{12}CO(J=1–0)$ superposed on the hard X-ray image (E: 2.0-7.0 keV) toward the LMC superbubble 30 Doradus C [24]. (f) Correlation plots between the photon index and total ISM proton column density toward 30 Dor C [24]. (g) Three-color image of N132D obtained with the Hubble Space Telescope (HST) Hα (red), ALMA $^{12}CO(J=1–0)$ (green), and Chandra X-rays in the energy band of 0.5–7.0 keV (blue) [25]. (h) Intensity ratio map of $^{12}CO(J=3–2)$ / $^{12}CO(J=1–0)$ using ASTE and ALMA. Both the data were smoothed with a Gaussian kernel to an effective beam size of 23" [25]. White dashed contours represent the X-ray intensity. The gray areas represent that the $^{12}CO(J=1–0)$ and/or $^{12}(J=3–2)$ data show the low significance of ~8 sigma or lower. (i) Integrated intensity map of ALMA $^{12}CO(J=1–0)$ of N103B superposed on the Chandra X-ray contours. (j) Position–velocity diagram of the ALMA $^{12}CO(J=1–0)$ [26]. The integration range in decl. is from −68° 43'51" to −68° 43'21", corresponding to the dashed lines in Fig.3i. The dashed curve represents an expanding gas motion [26].

N49

N49 is the LMC SNR which is thought to be associated with the giant molecular cloud [18]. We have resolved 21 CO clumps with radii of 1–2 pc with an angular resolution of ~3" using ALMA (Fig.3a) [21]. The total virial mass is ~5.3 × 10³ solar mass, although the CO-derived mass is only ~1.9 × 10³ solar mass, indicating that the shock wave may be perturbing the molecular clumps. We have found that some of the CO peaks are rim brightened in both hard X-rays and the radio continuum on a 0.7–2 pc scale (Fig.3b). We have argued that the enhancement of the synchrotron radio continuum around the clumps can be interpreted as a result of magnetic field amplification via a shock–cloud interaction [e.g., 1–6]. On the other hand, recombining plasma that dominates in hard X-rays–was possibly formed via thermal conduction between the SNR shock wave and the cold/dense molecular clumps (e.g., [22]).

N63A

N63A is a unique SNR associated with the shock-ionized and photoionized optical nebulae. We spatially resolved molecular clouds embedded within the optical nebulae (Fig.3cd, [23]). X-ray spectroscopy reveals that the absorbing column densities toward the clouds are ~(1.5–6.0) × 10^{21} cm^{-2}, which are ~1.5–15 times less than the averaged ISM column densities. This means that the X-rays are produced not only behind the molecular clouds, but also in front of them. We conclude that the molecular clouds have been completely engulfed by the shock waves, but have still survived erosion owing to their high density and short interacting time. The X-ray spectrum is well explained by an absorbed power-law model or a high-temperature plasma model, in addition to thermal plasma components, implying that the shock interaction is efficiently working for both cases through shock ionization and *B* field amplification.

30 Dor C

30 Dor C is the synchrotron and TeV gamma-ray bright superbubble, which is a candidate for the efficient cosmic-ray accelerator. We spatially resolved CO clumps associated with the western shell of 30 Dor C which comprises synchrotron X-rays (Fig.3e, [24]). The synchrotron X-rays are clearly enhanced around the molecular clumps. The total ISM column density clearly shows a negative correlation with the photon index of synchrotron X-rays (Fig.3f), indicating that the maximum energy of accelerated cosmic-ray electrons are possibly energized via the shock-cloud interactions.

N132D

N132D is the brightest X-ray SNR in the LMC. We spatially resolved nine CO clouds toward the SNR (Fig.3g, [25]). The CO clouds spatially coincide not only with the Hα emission, but also with O-rich ejecta traced by optical and X-ray wavelength. We found high-intensity ratios of CO 3-2/1-0 > 1.2 toward the CO clouds without extra heating source such as massive stars and infrared sources (Fig.3h). This indicates that the molecular clouds are heated by the shockwaves of N132D.

N103B

N103B is a young (~860 yr) Type Ia SNR in the LMC. We have spatially resolved CO clouds along the southeastern edge of the SNR with an angular resolution of ~1.8" (~0.4 pc in the LMC, Fig.3i, [26]). The molecular clouds show an expanding gas motion in the position–velocity diagram with an expansion velocity of ~5 km s^{-1} (Fig.3j). The spatial extent of the expanding shell is roughly similar to that of the SNR. We present a possible scenario that N103B exploded in the wind-bubble formed by the accretion winds from the progenitor system, and is now interacting with the dense gas wall. This is consistent with a single-degenerate scenario.

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