Chandra and ALMA studies of Supernova Remnants

Hidetoshi SANO (Gifu University; sano.hidetoshi.w4@f.gifu-u.ac.jp)

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ABSTRACT We present our recent studies of X-rays and shocked molecular clouds traced by radio-line emission (CO) in supernova remnants (SNRs). Multiwavelength studies using Chandra and ALMA allow us to reveal the efficient acceleration mechanism of cosmic rays and the shock-ionization processes in Galactic/Magellanic SNRs at a good resolution of ~1-6 arcseconds for the first time. The shock-cloud interaction enhances turbulent magnetic up to mG, which causes synchrotron X-ray limb-brightening on the surface of the shocked cloud, as well as short-time flux variation of the X-rays. The reflected shocks will efficiently produce the hard X-rays from high-temperature plasma. The spatially resolved X-ray spectroscopy following the CO cloud distribution is critical to understanding the spatial variation of thermal plasma conditions. Moreover, an expanding shell of neutral gas in Type Ia SNRs provides alternative evidence for the single-degenerate origin of the Type supernovae. In this poster, we also discuss future perspectives for combining studies of Chandra and ALMA.

Shock Interaction with the Inhomogeneous and Clumpy ISM

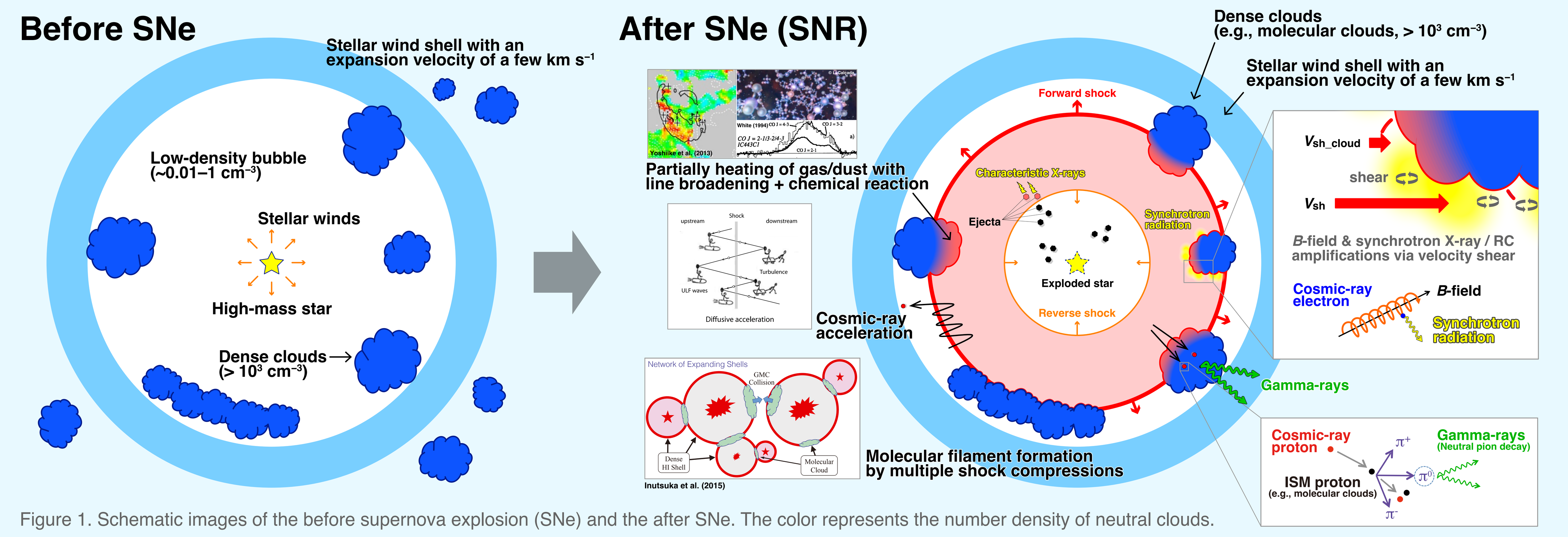


Figure 1. Schematic images of the before supernova explosion (SNe) and the after SNe. The color represents the number density of neutral clouds.

1. Before the SNe, the high-mass progenitor star evacuated the atomic hydrogen gas (traced by HI) through its strong stellar wind.
2. The evacuated gas creates a stellar wind bubble whose inside density is ~0.01 cm^{-3}, and an expanding gaseous shell.
3. On the other hand, molecular clouds can survive wind erosion owing to their high densities (> 1000 cm^{-3}).
4. The shock interaction with the inhomogeneous and clumpy gas causes various physical phenomena (see left panel).

➡ **Shock-cloud interaction plays an essential role in understanding the low- and high-energy physical processes in the ISM.**

Chandra–ALMA Synergy

- *Both telescopes can achieve a high-angular resolution of ~0.5 arcseconds.*
- *Chandra can unveil the thermal plasma as well as synchrotron X-rays, which were likely enhanced through shock-cloud interactions in SNRs...!!*
- *ALMA can observe CO emission lines tracing shocked neutral molecular clouds. (cloud mass, size, density, kinetic temperature, radial velocity with a resolution of ~0.1 km s⁻¹)*

SNR RX J1713.7–3946 (Sano et al. 2020a, ApJL, 904, 24) ➡

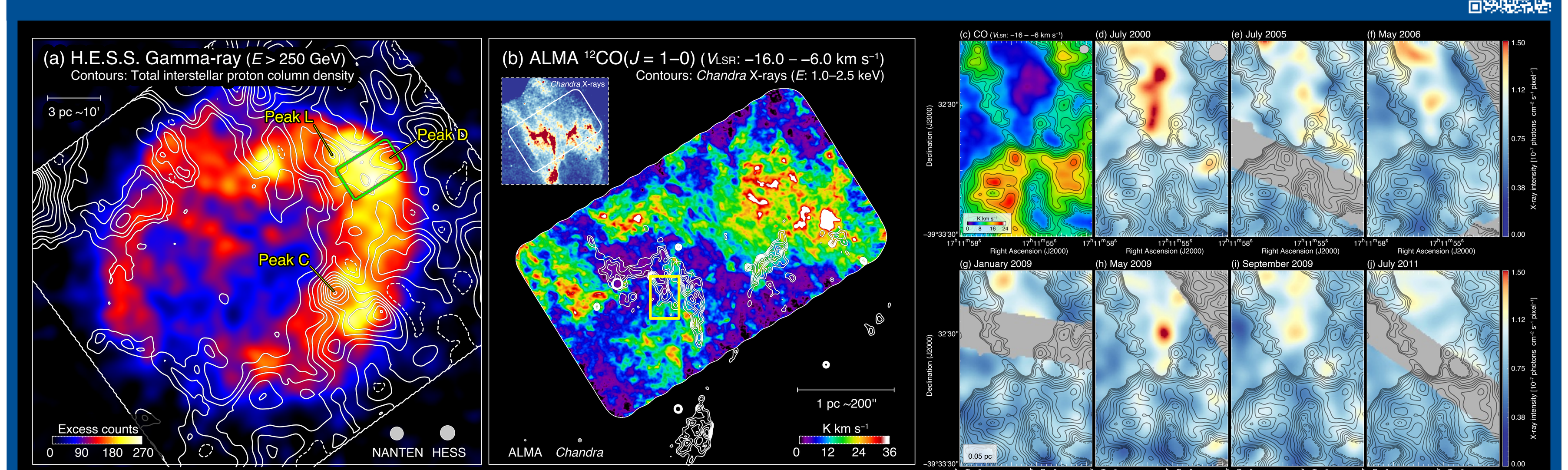
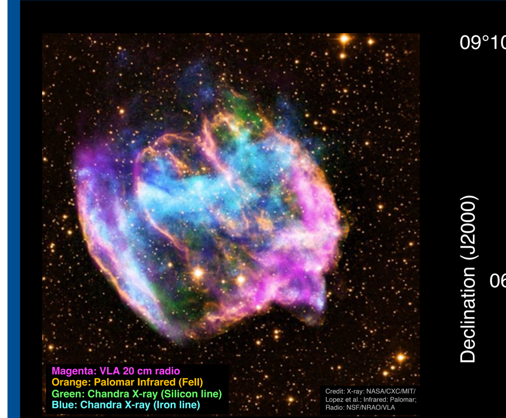


Figure 2. (a) TeV gamma-ray excess map of RX J1713.7–3946 (H.E.S.S. Col. 2018). Superposed contours indicate the ISM proton column density (Fukui et al. 2012). The green box represents the ALMA observed area. (b) ALMA CO map superposed on the Chandra X-rays. The yellow box indicates the presented area in Fig. 2(c–j). (c–j) Enlarged views of (c) CO and (d–j) Chandra X-rays in multiple observing epochs.

We found clumpy CO cloudlets (0.01 pc scales) associated with synchrotron X-ray hot spots with month- or year-scale time variations, suggesting shock-cloud interactions enhance the turbulent magnetic fields up to ~ 3 mG.

SNR W49B (Sano et al. 2021, ApJ, 919, 123) ➡



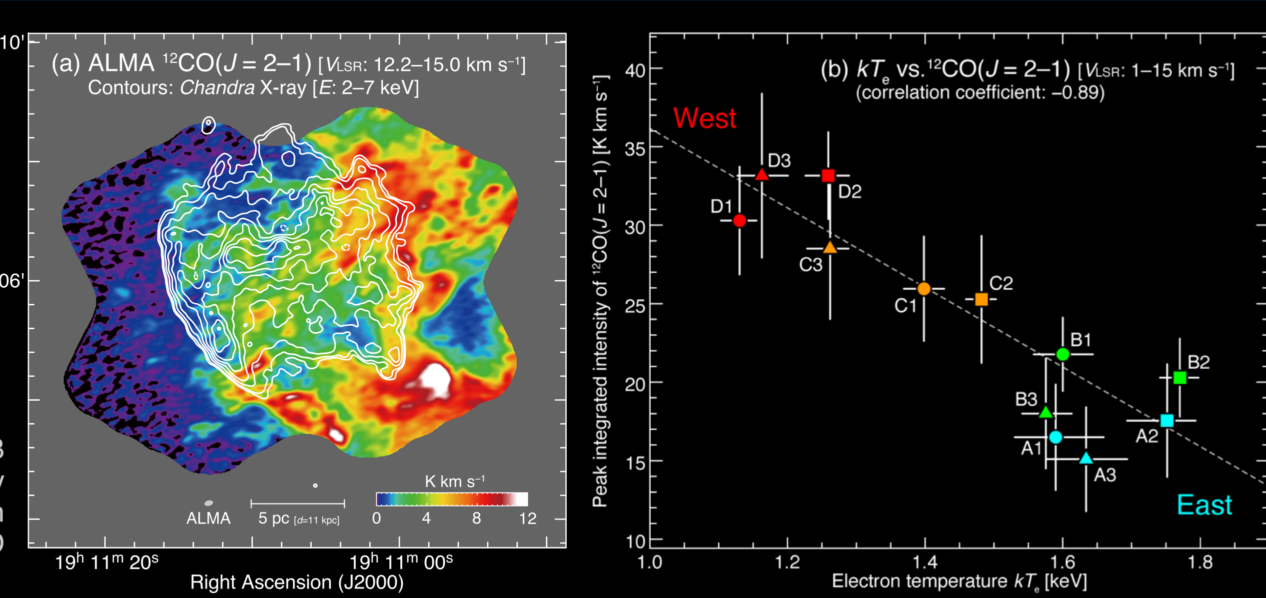


Figure 3. (a) ALMA CO map of W49B superposed on the Chandra X-ray contours. (b) Correlation plot between the electron temperature kT_e and CO integrated intensity.

The CO clouds at ~10 km s^{-1} show a good spatial correspondence to the X-ray deformed shell. We also found a negative correlation between the CO intensity and the electron temperature of recombining plasma, implying that the originof the high-temperature recombining plasma in W49B can be understood to be the thermal conduction.

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

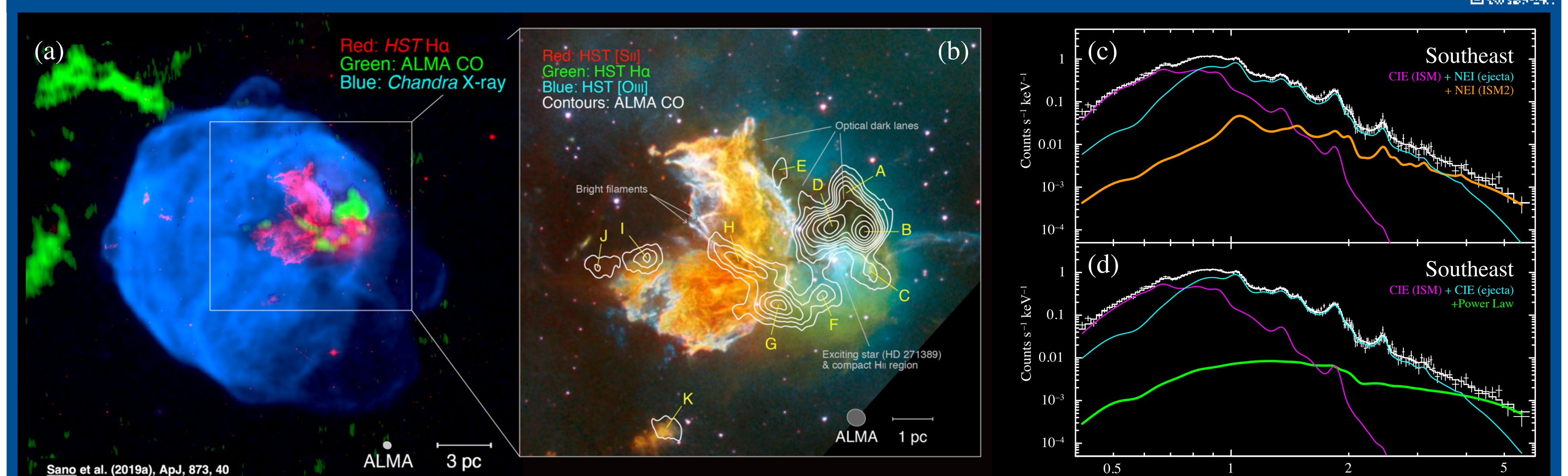


Figure 4. (a) RGB image of N63A. The red, green, and blue represent the HST Hα, ALMA CO, and Chandra X-rays, respectively. (b) Enlarged view of optical lobes superposed on the CO contours. (c–d) Background-subtracted ACIS-S spectra of the SEregion with the best-fit models.

We spatially resolved shock-survived molecular clouds embedded within the optical nebulae. The hard X-rays are well reproduced by an absorbed power-law model or a high-temperature plasma model, implying that the shock-cloud interaction works efficiently.

LMC SNR N132D (Sano et al. 2020b, ApJ, 902, 53) ➡

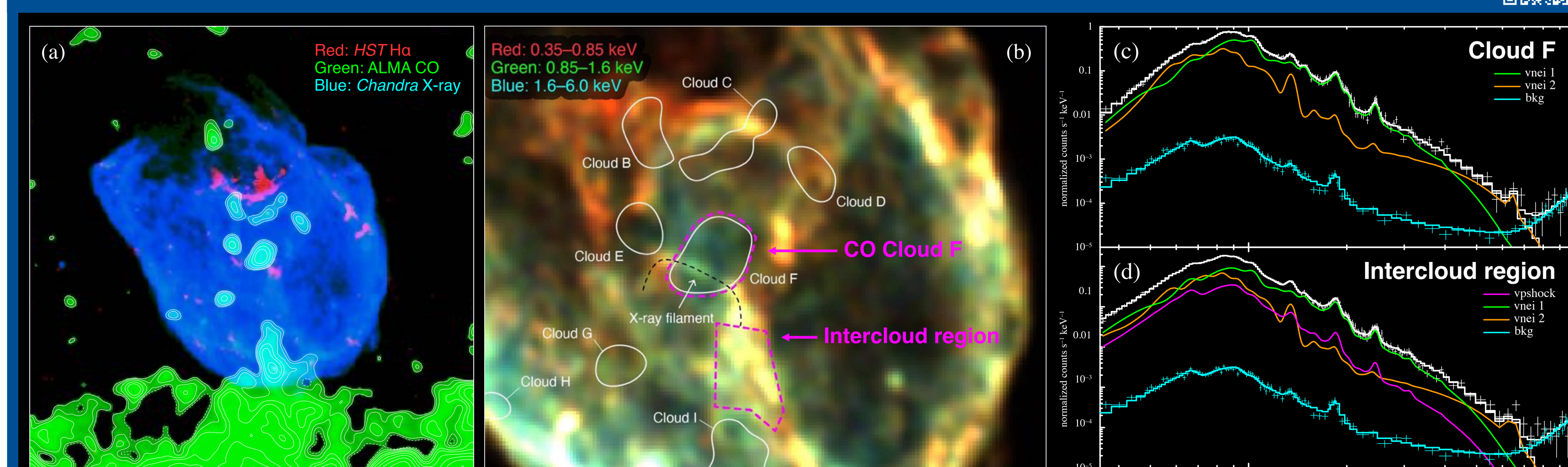


Figure 5. (a) RGB image of N132D. The red, green, and blue represent the HST Hα, ALMA CO, and Chandra X-rays, respectively. (b) X-ray RGB image superposed on the cloud boundaries. (c–d) ACIS spectra of cloud F, intercloud region, and background region.

We spatially resolved shock-survived molecular clouds embedded within the SNR. Through the spatially resolved X-ray spectroscopic analysis, we note that the forward shock has been terminated toward Cloud F, suggesting that ISM-based X-ray spectroscopy is needed.

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

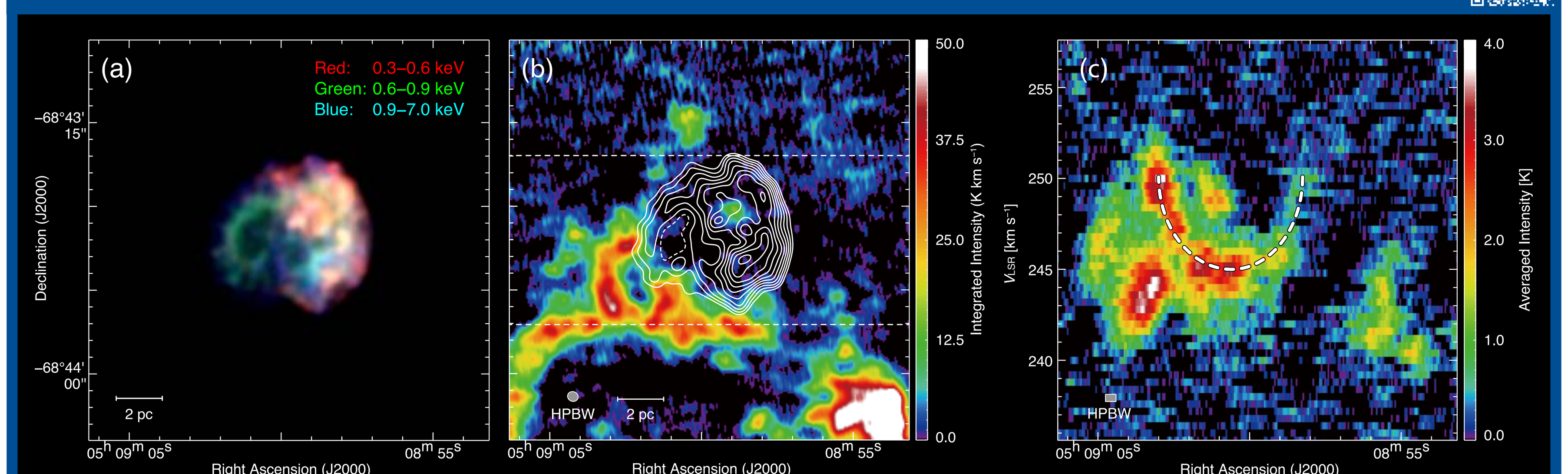


Figure 6. (a) Chandra X-ray image of N103B (R: 0.3-0.6 keV, G: 0.6–0.9 keV, B: 0.9–7.0 keV). (b) ALMA CO intensity superposed on the Chandra X-ray contours. (c) Position-velocity diagram of CO. The dashed curve represents the expanding gas motion.

We found that ALMA-resolved CO clumps perfectly delineate the southeastern X-ray shell boundary. The CO clump inside the shell spatially coincides with the optical and X-ray blobs. Strong accretion winds from the binary progenitor system possibly formed the expanding gas motion, supporting the single-degenerate scenario.

LMC SNR N49 (Sano et al. 2023, ApJ, 958, 53) ➡

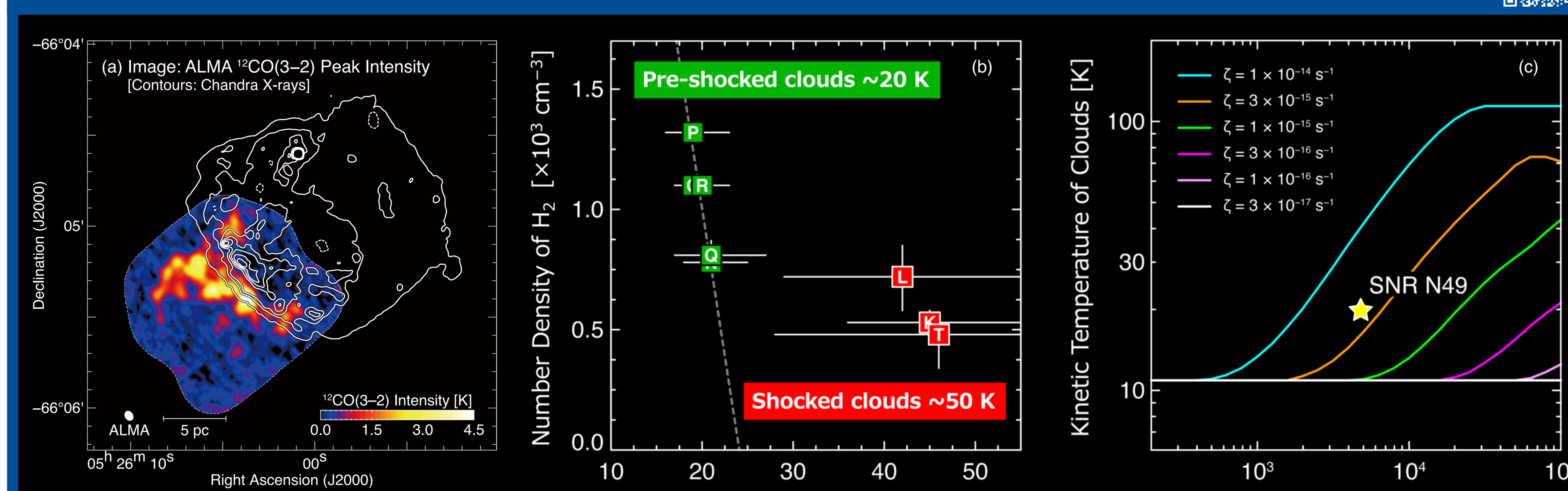


Figure 7. (a) ALMA CO map superposed on the Chandra X-rays. (b) Scatter plot of the clouds temperature and density. (c) SNR age-temperature diagram as a function of cosmic-ray ionization rate.

We revealed that shocked clouds with a temperature of 50 K partially evaporated through shock-cloud interaction but survived shock erosion. The pre-shocked clouds, with a moderate temperature of ~20 K, are dominantly affected by cosmic-ray heating. The cosmic-ray ionization rate is ~ 200 times higher than the solar value.

Summary and Future Prospects

Research using Chandra and ALMA has shed light on various physical processes in SNRs, including cosmic ray acceleration, shock heating and ionization of molecular clouds, and the generation of thermal X-ray plasma. A future challenge lies in advancing spatially resolved X-ray spectroscopy, as demonstrated in the study of N132D, which incorporates the physical properties of the interstellar medium (e.g., spatial distribution, temperature, and density structures). This approach is expected to reveal the microscopic processes of shock-cloud interactions and provide groundbreaking insights into the nature of interstellar medium surrounding SNRs.