A star-forming dense cloud core embedded within the brightest gamma-ray SNR RX J1713.7−3946

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Abstract: RX J1713.7–3946 (hereafter RXJ1713) is the brightest gamma-ray supernova remnant (SNR) in the Galactic plane (H.E.S.S. Collaboration et al. 2017). Gamma-rays of RXJ1713 are believed to be produced by ultrarelativistic cosmic-rays via proton-proton interactions (e.g., Fukui et al. 2012). The young age ~1600 yr means a high level of cosmic-rays will still be trapped inside the SNR shell. RXJ1713 is also interacting with molecular and atomic gases located at ~1 kpc. Sano et al. (2010) revealed that a dense molecular core "peak C" shows strong signs of low-mass star formation including bipolar outflow and a far-infrared protostellar object, and has a steep gradient with a $r^{-2.2\pm0.4}$ variation in the average density within radius r. Synchrotron X-rays are enhanced around peak C, indicating that the dense cloud core is embedded within the SNR shell, and survived shock erosion owing to the shock propagation speed is stalled in the dense core. According to numerical calculations, the shock-cloud interaction excites turbulence and magnetic field amplification around the dense core that may facilitate cosmic-ray electrons in the lower-density inter-clump space leading to enhanced synchrotron X-rays around dense cores (e.g., Inoue et al. 2009, 2012). In this contribution, we will present the low-mass star formation in a unique environment with the high level of cosmic-rays and shock-erosion.

Young TeV gamma-ray SNR RX J1713.7−3946

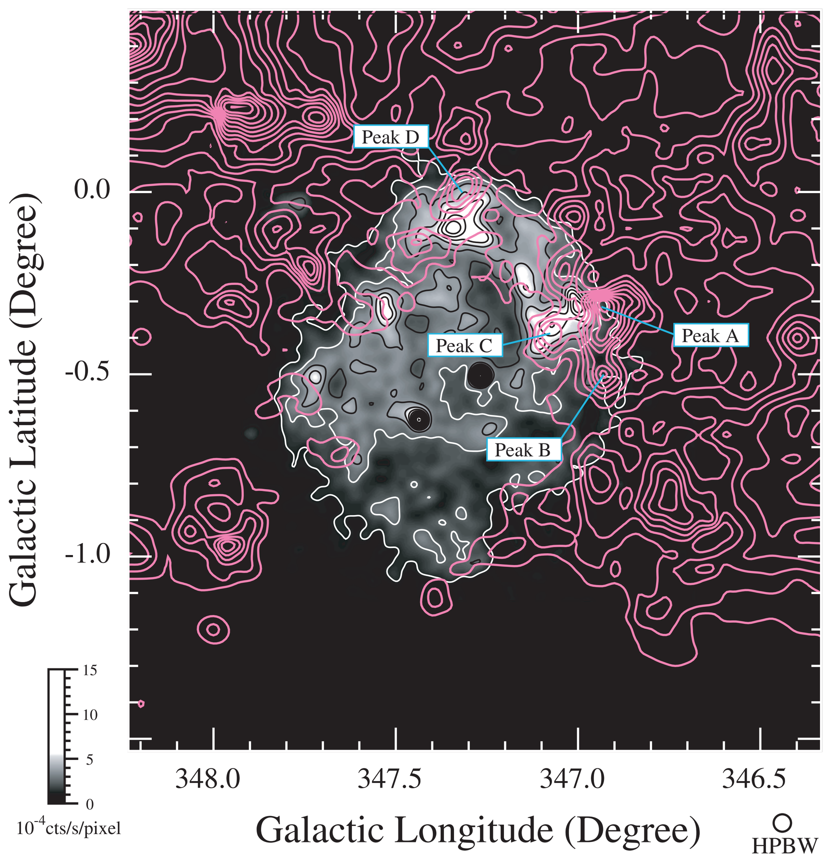


Figure 1: Map of ROSAT synchrotron X-ray image (gray scale) overlaied on the NANTEN2 ^{12}CO(J = 1–0) intensity contours in purple (Fukui et al. 2003). The intensity is derived by integrating the CO spectra from –11 to –3 km s^{-1} , which is considered to be a velocity component inter- acting with the SNR. The lowest contour level and interval of CO are 4 K kms^{-1}.

RX J1713.7−3946 (G347.3−0.5)

- Shell-type & core-collapse SNR
- Distance: ~ 1 kpc (Fukui+03)
- Diameter: ~ 16.4 pc (Fukui+03)
- Age: ~ 1600 yr (Wang+97; Fukui+03)
- Bright in both synchrotron X-rays and TeV γ-rays (e.g., Aharonian+06)
- Interacting with molecular clouds (e.g., Fukui+03; Moriguchi+05)
- Good spatial corespondence between the ISM & γ-rays (Fukui+12)

→ *Evidence for cosmic-ray proton acceleration close knee energy*

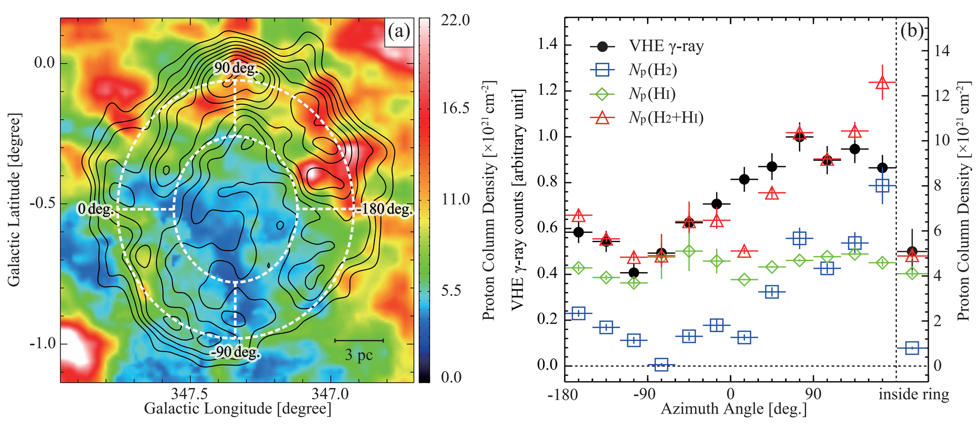


Figure 2: (a) Distributions of column density of the total ISM protons $N_p(H_2+HI)$ in a velocity range from –20 to 0 km s^{-1}. Contours are the TeV gamma-rays (Aharonian et al. 2007). (b) Azimuthal distributions of $N_p(H_2)$, $N_p(HI)$, $N_p(H_2+HI)$, and TeV γ-ray-smoothed counts per beam between the two elliptical rings shown in (a). The proton column densities are averaged values between the rings. Semimajor and semiminor radii of the outer ring are 0.46 deg. and 0.42 deg., respectively, and the radii of the inner ring are half of them. The same plots inside the inner ring are shown on the right side of (b).$^{-1}$. Areas shaded blue and red correspond to the respective color contours in (a).

CO Observations

CO(J = 2–1)
Observed area: ~2 degree^2 (^{12}CO), ~22 arcmin^2 including CO peaks (^{13}CO)
Angular resolution: ~90 arcsec
Noise level: ~0.51 K ch^{-1} (^{12}CO), ~0.66 K ch^{-1} (^{13}CO) (1 ch = 0.38 km s^{-1})

^{12}CO(J = 4–3)
Observed area: ~9 arcmin^2 including peak C
Angular resolution: ~38 arcsec
Noise level: ~0.28 K ch^{-1}

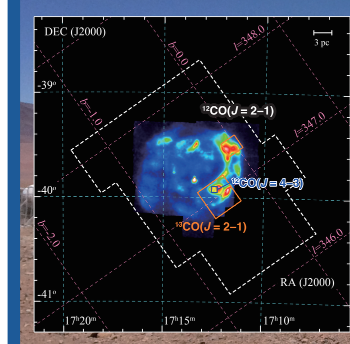


Figure 3: *Suzaku* X-ray image. We also show the observed area in the ^{12}CO(J = 2–1), ^{13}CO(J = 2–1), and ^{12}CO(J = 4–3) lines enclosed by the white dash–dotted, orange, and blue lines, respectively..

NANTEN2 mm/sub-mm radio telescope
Operated by Nagoya University & ~10 International Universities
Installed at the Atacama desert of northern Chile (alt. 4865 m)

Shock-cloud interactions and magnetic field amplifications (Sano et al. 2010, 2013; Inoue et al. 2012)

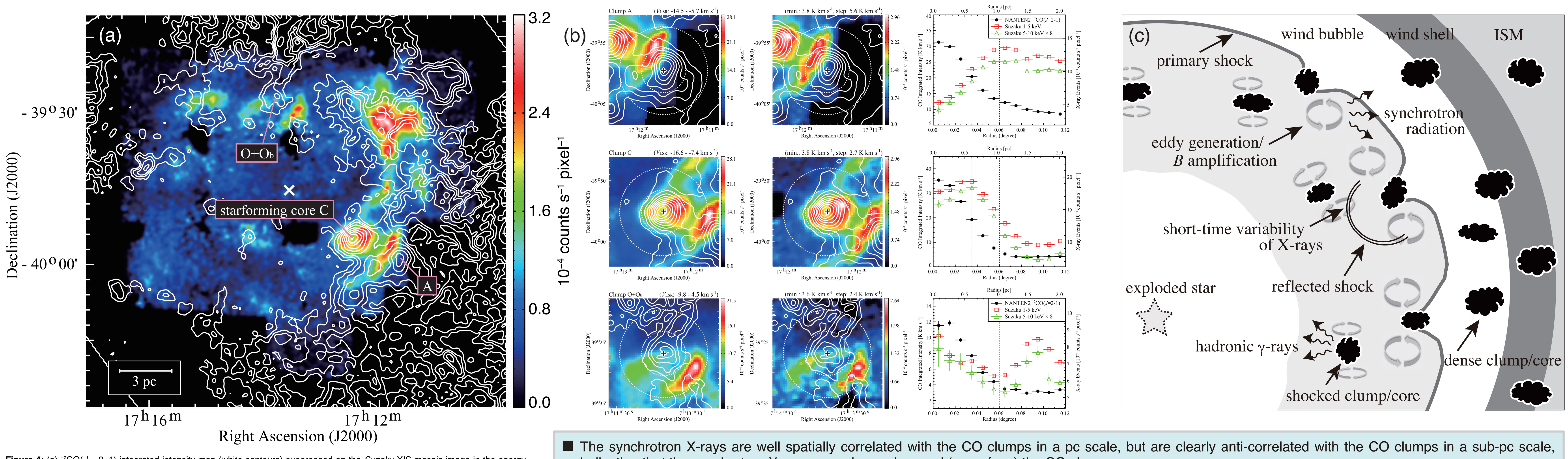
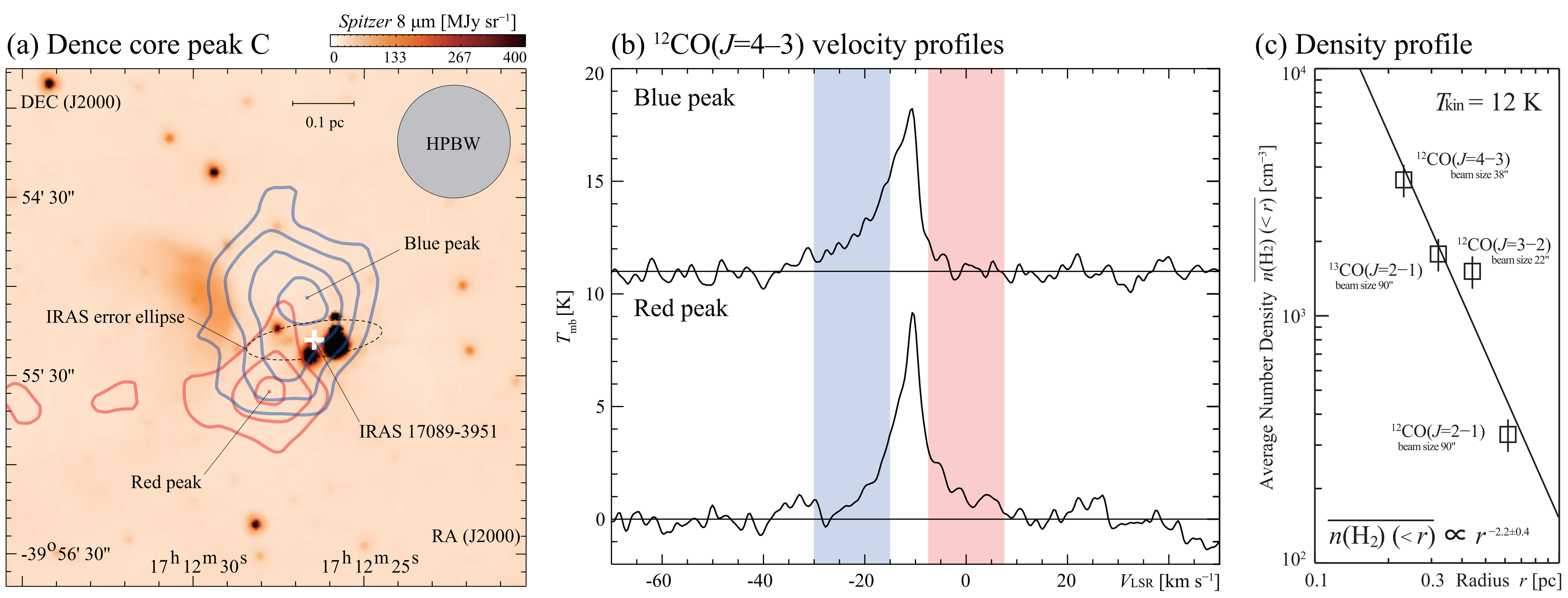
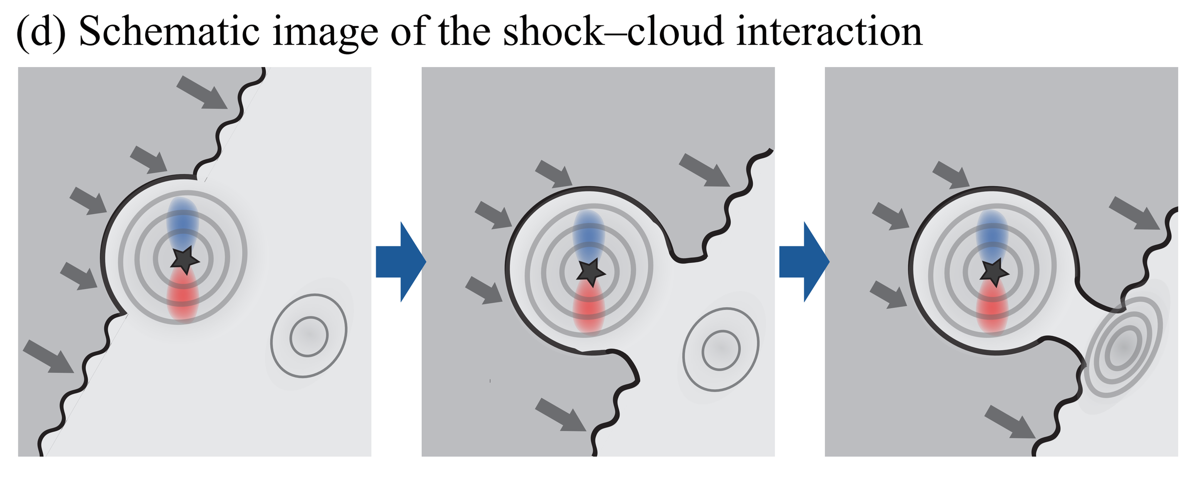


Figure 4: (a) ^{12}CO(J = 2–1) integrated intensity map (white contours) superposed on the *Suzaku* XIS mosaic image in the energy band of 5–10 keV in color scale (Sano et al. 2013). The velocity range is V_{LSR} = –20.2 to 1.8 km s^{-1}. (b) Distribution of ^{12}CO(J = 2–1) emission (white contours) superposed on the *Suzaku* 1–5 keV (left) and 5–10 keV (right) images toward CO clumps A, C and O+O$_b$. The crosses show the position of the center of gravity for each CO clump. The dashed white circles represent radii 0.06 and 0.12 degrees of the center of gravity for each CO clump. Right panels show the radial profiles around each molecular clump in the ^{12}CO(J = 2–1) integrated intensity and *Suzaku* two energy bands (1–5 keV and 5–10 keV). The orange dash–dotted lines indicate X-ray peak radius in the energy band 1–5 keV. (c) Schematic picture of the shock–cloud interaction model (Inoue et al. 2012).

- The synchrotron X-rays are well spatially correlated with the CO clumps in a pc scale, but are clearly anti-correlated with the CO clumps in a sub-pc scale, indicating that the synchrotron X-rays are enhanced around (or surface) the CO clumps.
- The CO clumps have a radius of 0.7 ± 0.2 pc and the X-rays are distributed with a separation 1.2 ± 0.5 pc from the center of each clump.
- We interpolate these results that the magnetic field is amplified around dense CO clumps as a result of enhanced turbulence induced by the shock–cloud interaction. We interpret that thus-amplified magnetic fields enhance the X-ray intensity, which depends on the 1.5th power of the magnetic field strength.

A star-forming dense cloud core survived SNR shock erosion (Sano et al. 2010)





- Peak C is associated with a bipolar outflow as evidenced by the ^{12}CO(J = 4–3) broad wings of at least 30 km s^{-1} velocity.
- The core of clump C has a strong density gradient consistent with an average density distribution of $r^{-2.2\pm0.4}$, where r is the radius from the center of the core.
- The velocity is given as ~3000 km s^{-1} / $\sqrt{n/n_0}$, where the ambient density n_0 = 1 cm^{-3} in the present SNR. The penetrating depth in a typical timescale of the interaction, ~1000 yr, is then estimated to be ~0.1 pc for n = 10^3 cm^{-3}. Peak C has a present diameter of at least 0.6 pc at a density of 10^3 cm^{-3} (Fig. 5c) and should have not been affected significantly by the shock penetration according to the argument above, whereas the ambient lower density gas is significantly disturbed and accelerated in a scale length of the SNR radius.

Figure 5: (a) Overlay map RX J1713.7–3946 *Spitzer* 8 μm image in color scale and ^{12}CO(J = 4–3) intensity contours taken by NANTEN2. The blue con- tours are from –30 to –15 km s^{-1} and the red contours from –8 to 7 km s^{-1}. The lowest contour level of the red and blue contours are 9.6 K km s^{-1} (~4σ) for each. The contour interval of the black contour is 10.2 K km s^{-1} (~3σ), whereas that of the others is 4.8 K km s^{-1} (~2σ). Open cross and enclosed black dashed circle show the positions of the IRAS point source and the 90% confidence region, respectively. (b) ^{12}CO(J = 4–3) spectra covering a velocity range from –70 to 50 km s^{-1}. Areas shaded blue and red correspond to the respective color contours in (a). (c) Molecular density distribution of peak C. The calculations are carried out for T_{kin} = 12 K. The solid line is a regression line obtained by least-squares fitting. Error bars represent only those for the radiation temperature calibration, ±15%. (d) Schematic image of the shock–cloud interaction toward peak C.

Summary and Future prospects

Shock-cloud interaction in the young SNR RX J1713.7−3946

We have performed ^{12}CO(J = 2–1, 4–3) and ^{13}CO(J = 2–1) observations using the NANTEN2 mm/submm radio telescope installed at the northern Chile. We revealed that the synchrotron X-rays are clearly enhanced around the molecular clumps associated with the SNR, suggesting an evidence for the magnetic field amplification via shock-cloud interaction. Numerical simulations of the shock-cloud interaction indicate that a dense clump can indeed survive shock erosion, since the shock propagation speed is stalled in the dense clump (e.g., Inoue et al. 2012). We have also found the star-forming dense cloud core C, which shows a bipolar outflows as enhanced ^{12}CO(J = 4–3) broad wings of at least 30 km s^{-1} velocity. The young stellar object embedded within the SNR has survived SNR shock erosion because of dense enough.

ALMA observations toward the dense molecular core embedded within the SNR

The star-forming dense cloud core C is the best laboratory to study the star-formation in the interstellar environment that contains a large amount of cosmic rays. We plan to propose molecular line observations using ALMA. ALMA's unprecedented sensitivity and spatial resolution will allow us to study the chemical composition and ionization degrees of star-forming dense core embedded within the SNR.

References

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