Generation of Turbulence and Magnetic Field Amplification behind Shock Wave in the ISM

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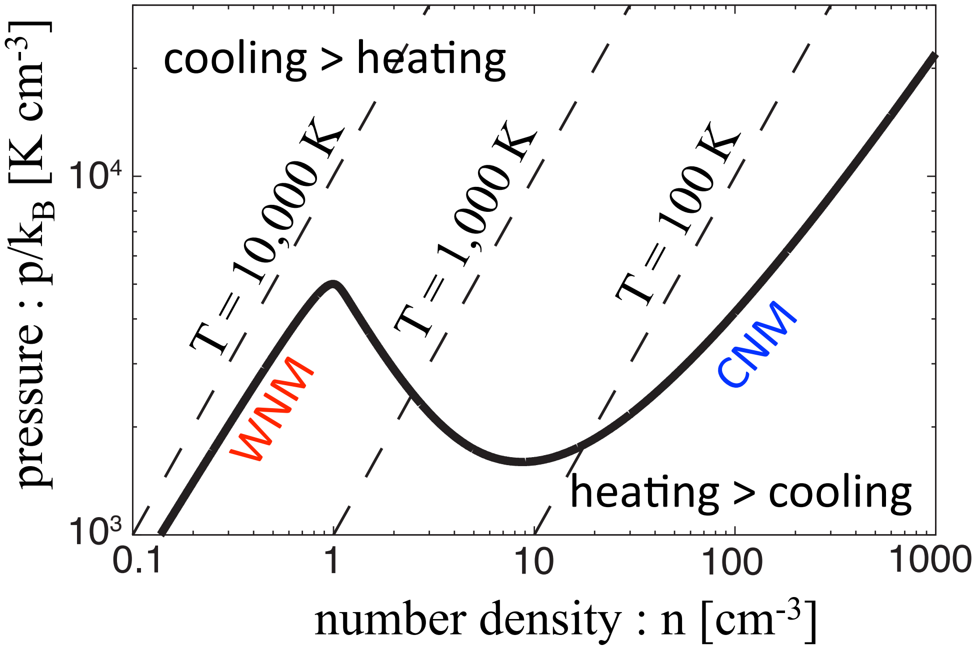
Basic Thermal Property of the ISM

- The ISM is a medium where radiative cooling and heating are effective.
  - Thermal equilibrium curve of typical ISM (Wolfire+ 95).



Cooling source : Line emissions (Ly-α, CII fine structure line, etc.).

Heating source : UV rad. from stars (photo-electric heating by PAHs).

✓ Cold Neutral Medium : HI/molecular cloud

✓ Warm Neutral Medium : diffuse intercloud medium

- The ISM has multiple equilibrium states even under isobaric condition (Field+ 69).
- Intermediate density region between WNM/CNM is thermally unstable in which density fluctuations exponentially grow toward CNM or WNM (Field 65, Balbus 95).

Instability criterion: $\left[\frac{\partial}{\partial T}\left(\frac{\mathcal{L}}{T}\right)\right]_p < 0$ $\mathcal{L}(\rho, T)$: net cooling rate per unit mass

←→ Increase of density enhances cooling rate that leads to runaway condensation.

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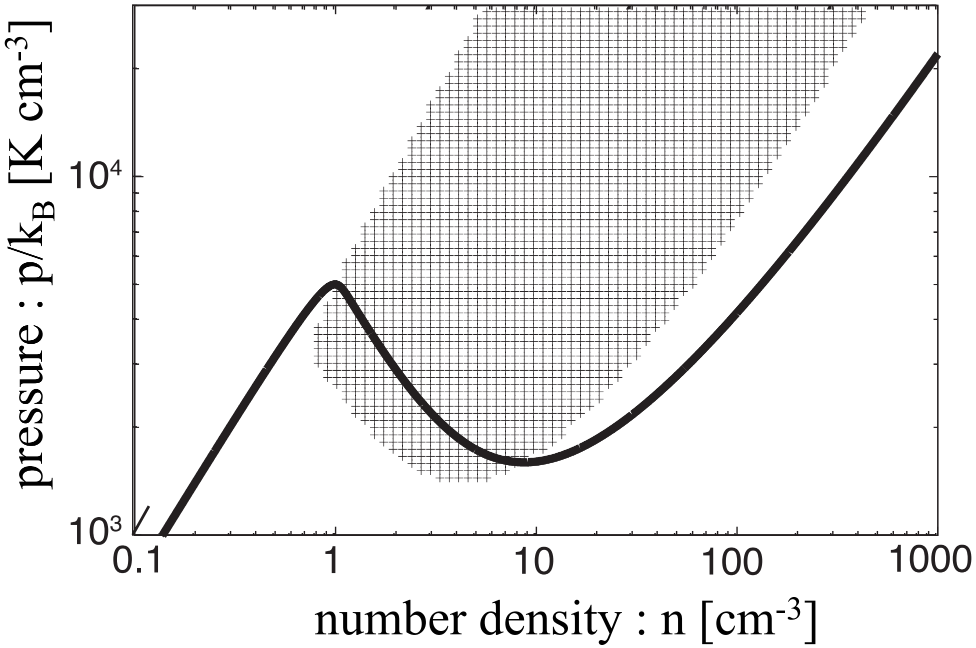

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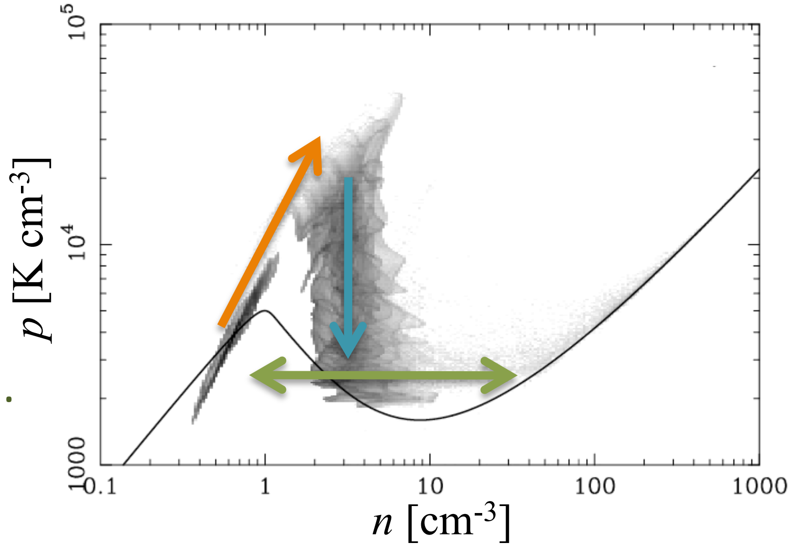
Fragmented Clouds Formed by TI

- The ISM is a dynamic medium that is frequently influenced by SN shocks (Cox & Smith 74).
- Shock generates thermally unstable gas (Hennebelle & Perault 99, Koyama & Inutsuka 00, 02).

● Evolution of magnetized shocked WNM in *n*-*p* plane when $\boldsymbol{n}_{sh}$ and $\boldsymbol{B}$ have finite angle (Inoue & Inutsuka 08,09).

1. Shock compression put off the gas from WNM.
2. Shocked gas is cooled isochorically.
3. Isobaric mode of thermal instability generates cloud.



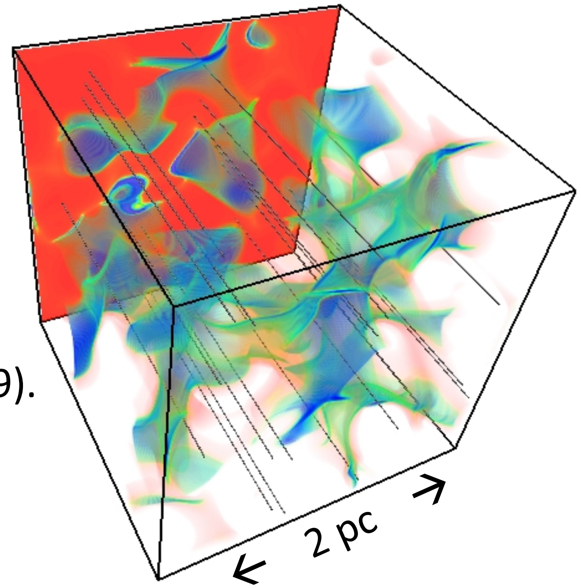
● Fragmentations of cooling gas by the thermal instability generate highly inhomogeneous HI medium.

✓ Condensations by the thermal instability grow along B field line.

→ Formed clouds are basically sheet-like (Heiles & Troland 03).

✓ Cloud surface is always unstable (Inoue+06, Stone & Zweibel 09).

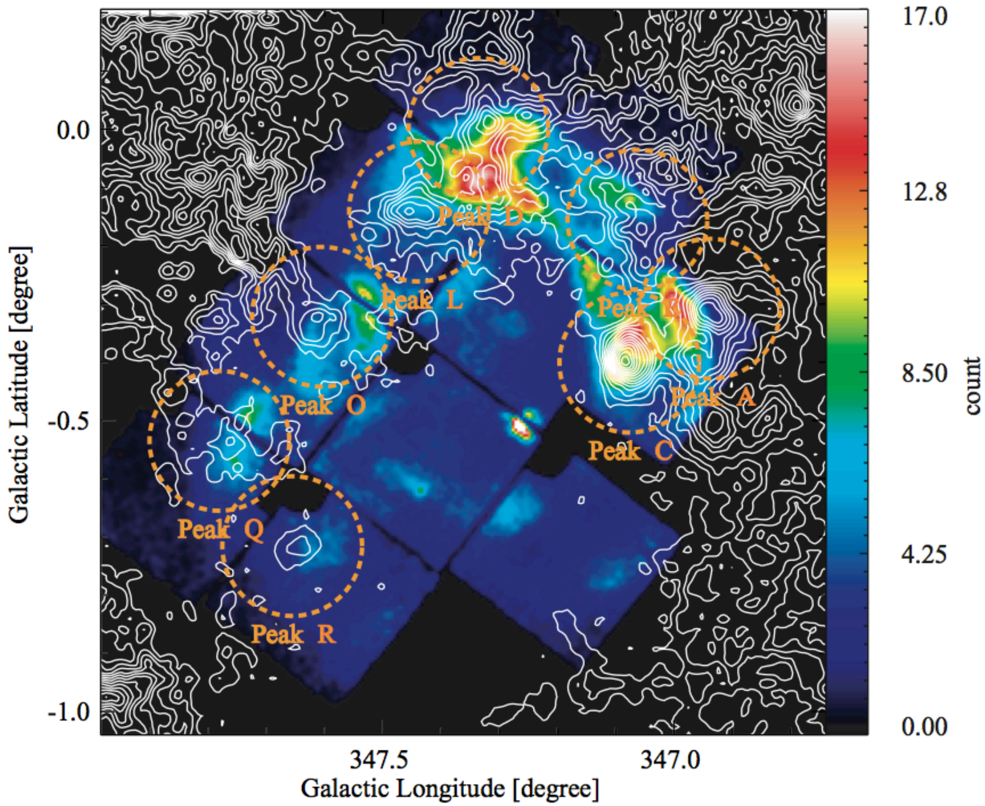
→ Cloud sheets are highly corrugated.



Shock-Cloud Interaction in SNR

- Main topic of this talk: Interaction between shock and highly inhomogeneous ISM.
- Massive stars, which cause SNe, are born in giant molecular clouds.

  → Interaction between SN blast wave shock and clouds is ubiquitously expected.
- Observations suggest that the shock wave in young SNR RXJ1713.7-3946 is interacting with clouds (Fukui+03, Moriguchi+05, Sano+10, Fukui+11).



- Contour: CO line emission map by *NANTEN* telescope (Fukui+03).
- Color: synchrotron X-ray image by *Suzaku* telescope (Tanaka+08).

→Results of observations appear as if shock-cloud interaction enhances synchrotron X-ray radiation.

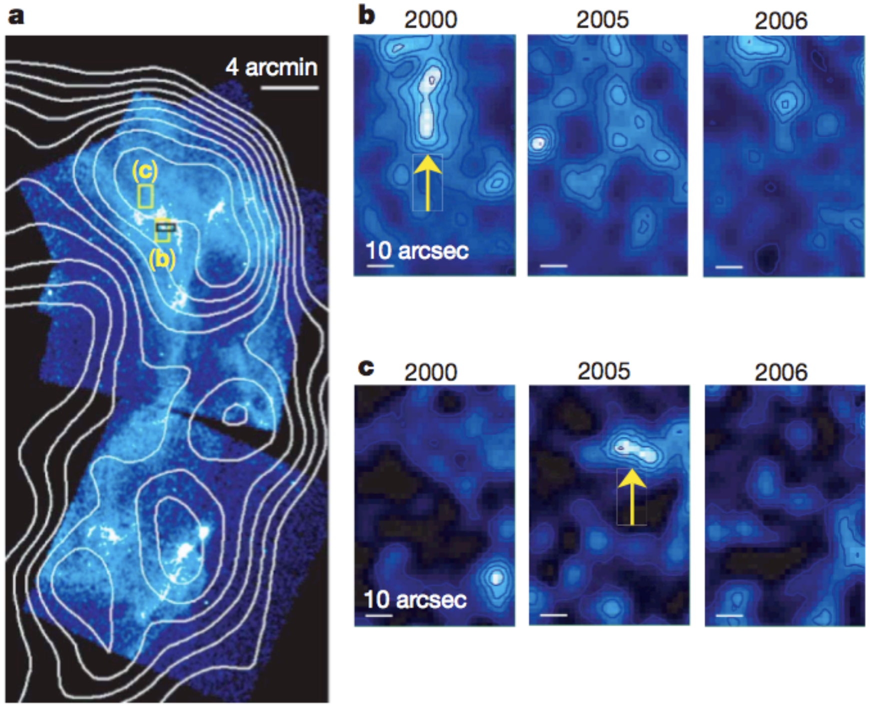
Strong B filed Observed in SNR

- In RXJ1713.7-3946, in addition to the CO line/X-ray correlation, strong B filed amplification is suggested by high-resolution X-ray observation (Uchiyama+07).

There are bright X-ray hot spots that blink with the timescale of a few years.

Synchrotron cooling time :

$$t_{\rm synch} \approx 1.5 \left(\frac{B}{mG}\right)^{-1.5} \left(\frac{\varepsilon}{keV}\right)^{-0.5} \text{year}$$



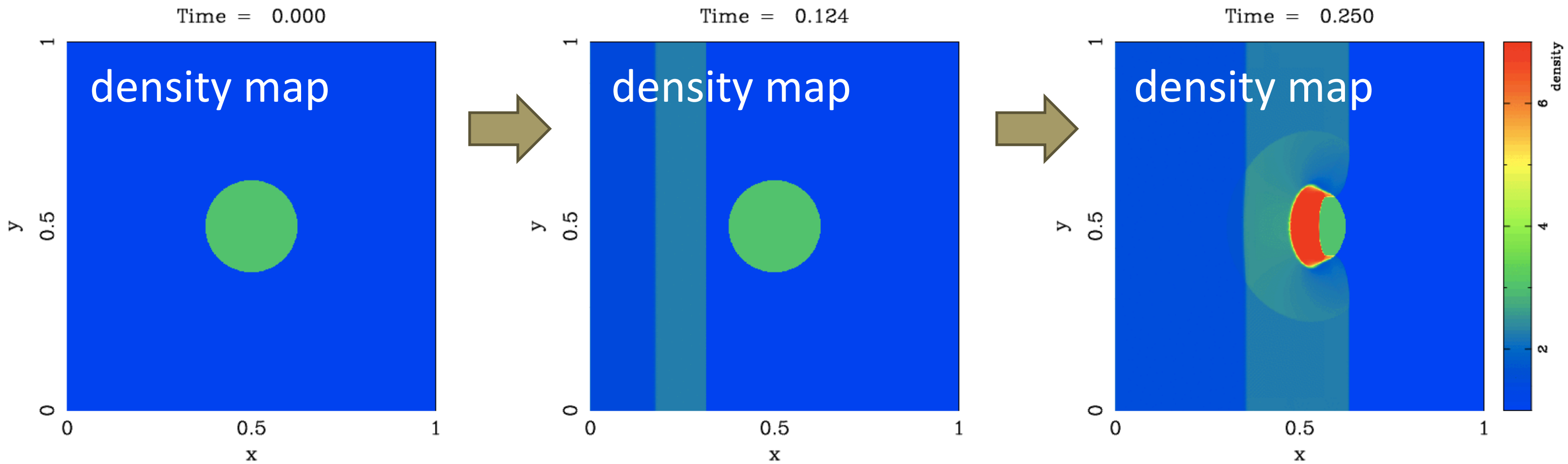
X-ray image of RXJ1713.7-3946 by *Chandra* telescope (Uchiyama+ 07).

→ Decrease of X-ray luminosity within a few years indicates
$B \sim 1\text{mG} \sim 200 \times B_{\rm ISM}$! ($B_{\rm ISM} \sim 6\ \mu$G; Beck 01, Heiles & Troland 05)

- Regions with $B \sim 1$mG are found in CO rich region.
  → shock-cloud interaction seems to play important role in B amplification.

Simple example of shock-cloud interaction

- The most important feature of shock-cloud interaction is vorticity generation.
- Essence of ω generation can be understood by following simple simulation (e.g., Klein+94).
  - Adiabatic 2D HD simulation of shock propagation (M=3) through medium with high-density clump ($\delta\rho/\rho=3$). Animation



✓ Shock is stalled when shock hits clump → deformation of shock (Richtmyer-Meshkov instability; Nishihara+10).

✓ Two types of vorticity generation:

1. Baroclinic effect: $$\frac{\partial \vec{\omega}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{\omega}) + \frac{1}{\rho^2} \underline{\vec{\nabla}\rho \times \vec{\nabla}p} \qquad \omega \sim \frac{2(M^2-1)\,\delta\rho/\rho}{(\gamma+1)M^2 \Delta x} v_{sh}$$

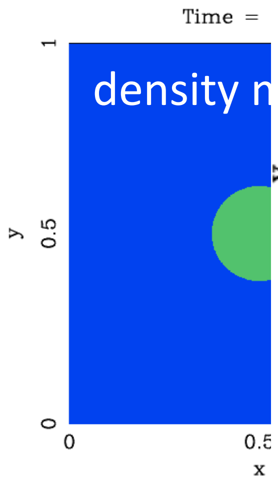
2. Crocco's theorem: vorticity is generated behind curved shock, even if upstrem is uniform.

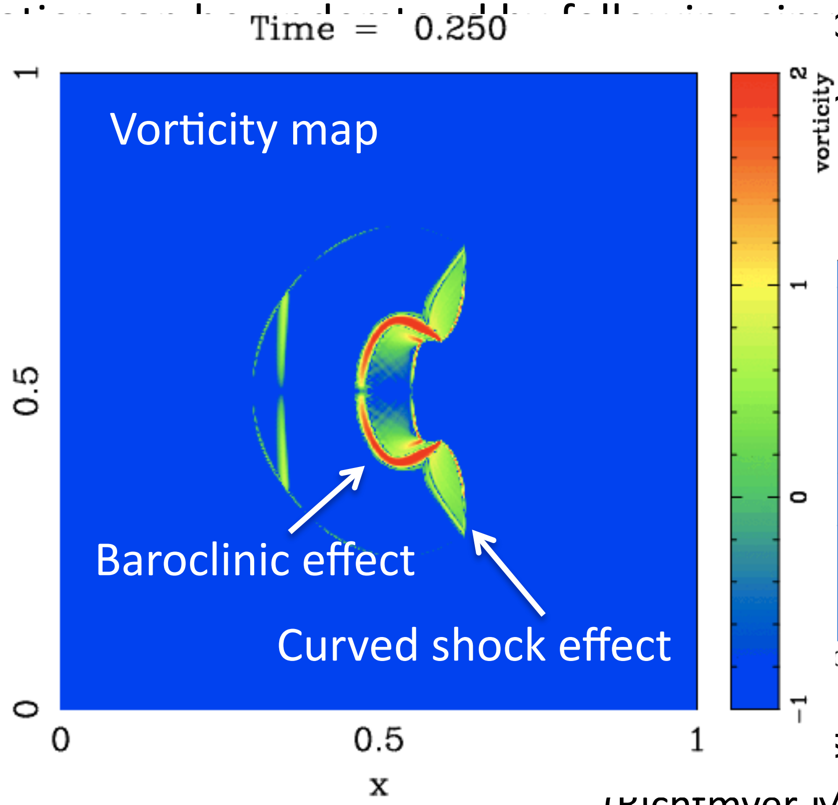
$$\omega \sim \frac{(M^2-1)^2 a}{(\gamma+1)M^2\left\{(\gamma-1)M^2+2\right\}} v_{sh}$$

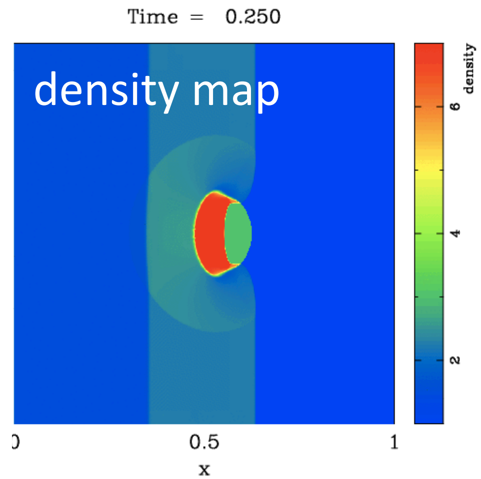
a: shock curvature (Kida&Orszag 90)

Simple example of shock-cloud interaction

- The most important feature of shock-cloud interaction is vorticity generation.
- Essence of ω gen… …ple simulation (e.g., Klein+94).
  - Adiabatic 2D HD… …rough medium with high-density… [Animation]







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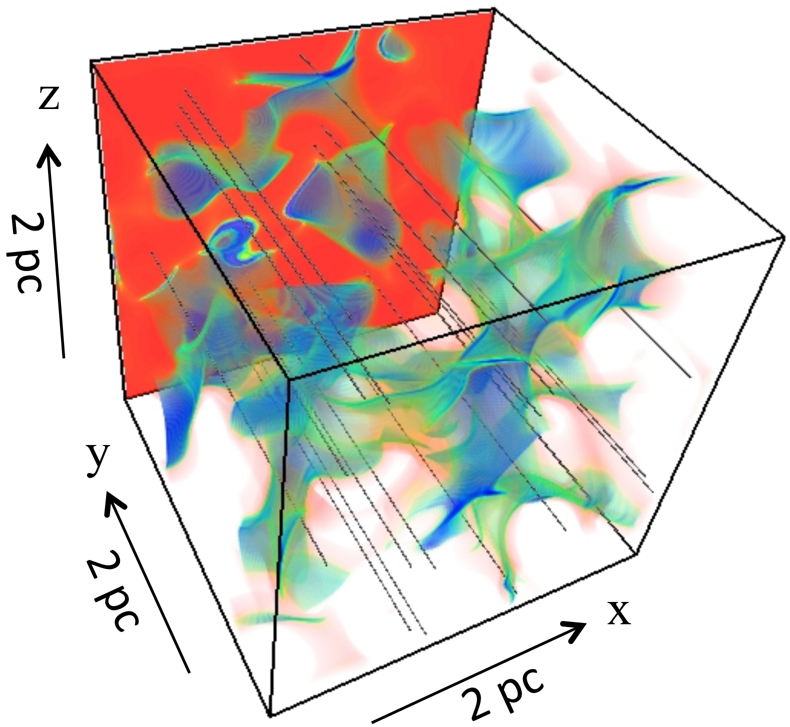
3D MHD Simulation of Shock-Cloud Interaction

- To study realistic shock-cloud interaction in magnetized ISM, we performed high-resolution 3D MHD simulations.
- Setting of 3D MHD simulation.
  - Scheme: 2nd order Godunov-CMOC-CT (Sano+99, Clarke 96) with cooling/heating/ thermal conduction, Resolution: $N_x \times N_y \times N_z = 1024^3$
  - Initial state: HI medium involving clouds formed by the thermal instability with $B_{\rm ini} \sim 5\ \mu$G.



Blue region : clouds (n > 30 cm^{-3})

Transparent region : diffuse gas (n ~ 1 cm^{-3})

Gray lines: magnetic field line

✓ In order to follow the baroclinic ω generation, transition layer between CNM/WNM due to conduction should be well resolved.

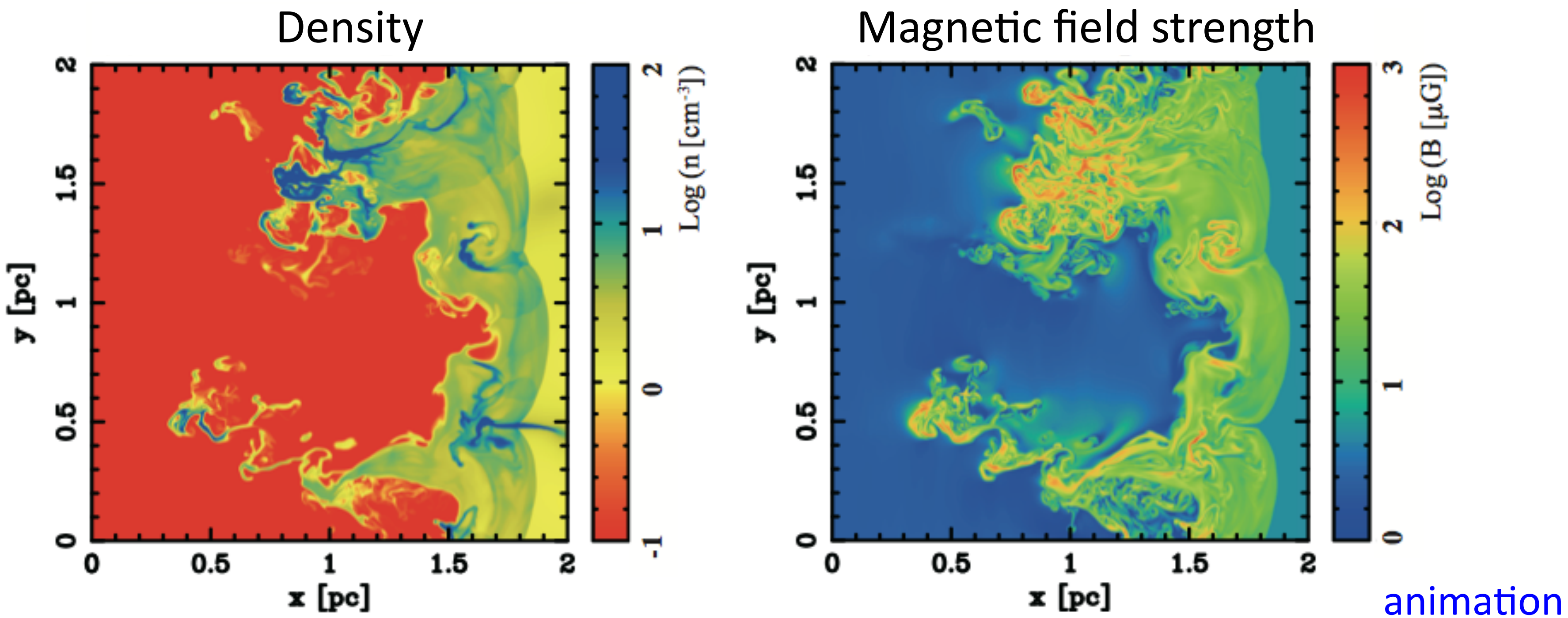
$$l_{tr} \sim \sqrt{\rho \mathcal{L} / \kappa T} \sim 0.05 \text{ pc} >> \Delta x \sim 0.002 \text{ pc}$$

- Shock wave is induced by setting high-pressure gas at left-side boundary.

Result: 2D Slices of n and B

- Result (perpendicular shock case).

Inoue, Yamazaki & Inutsuka 09, 10, 11



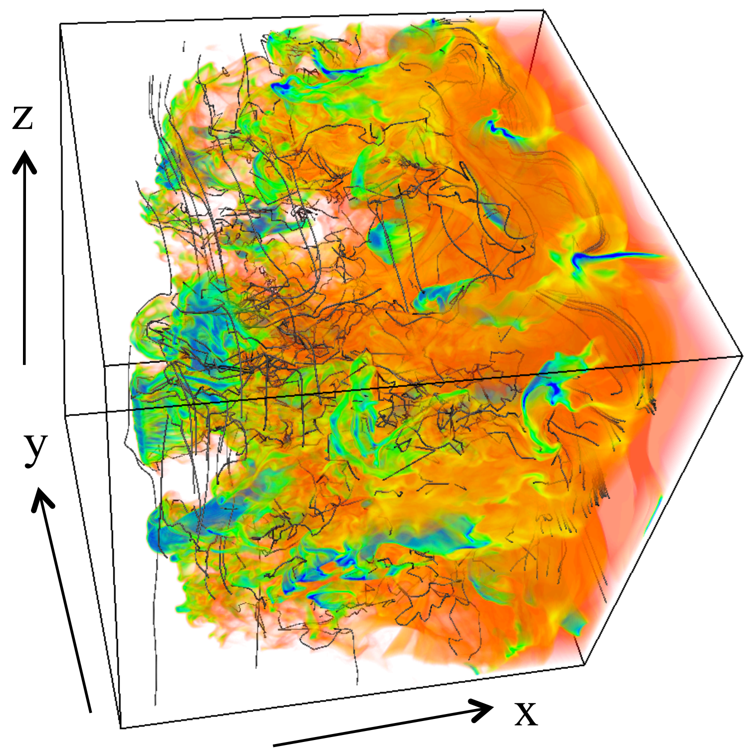
animation

- Average shock speed ~ 2500 km/s that is comparable to v_{sh} in RXJ1713.
- δv in shocked region ~ 0.3 × v_{sh} (independent of Mach number).
- Turbulent flows amplify B field (see also Giacalone & Jokipii 07).
- Maximum $|B|$ reaches 1 mG (200 X B_{ISM})!

Result

- 3D visualizations (perpendicular shock case).

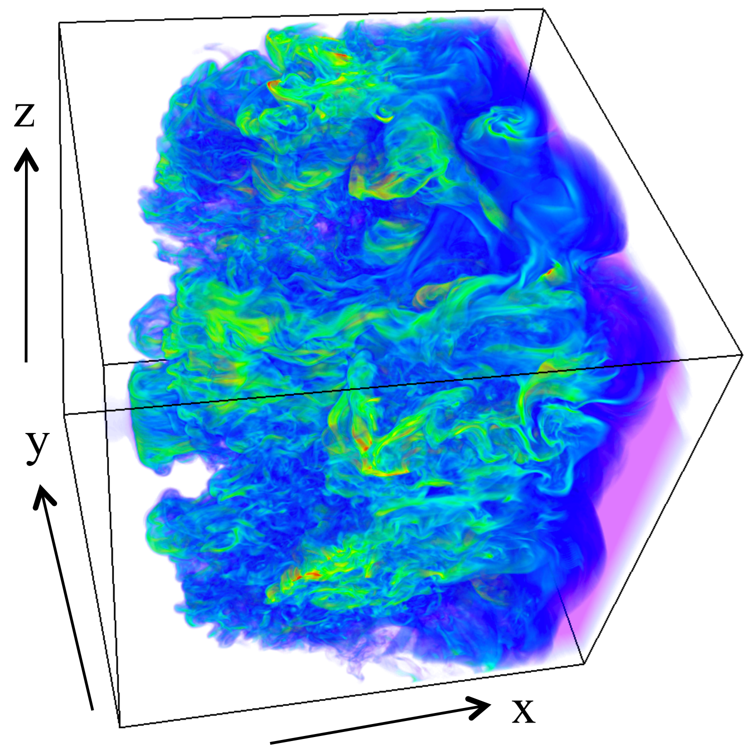
Structure of n



Blue : shocked cloud

Orange : shocked diffuse gas

Structure of $|B|$



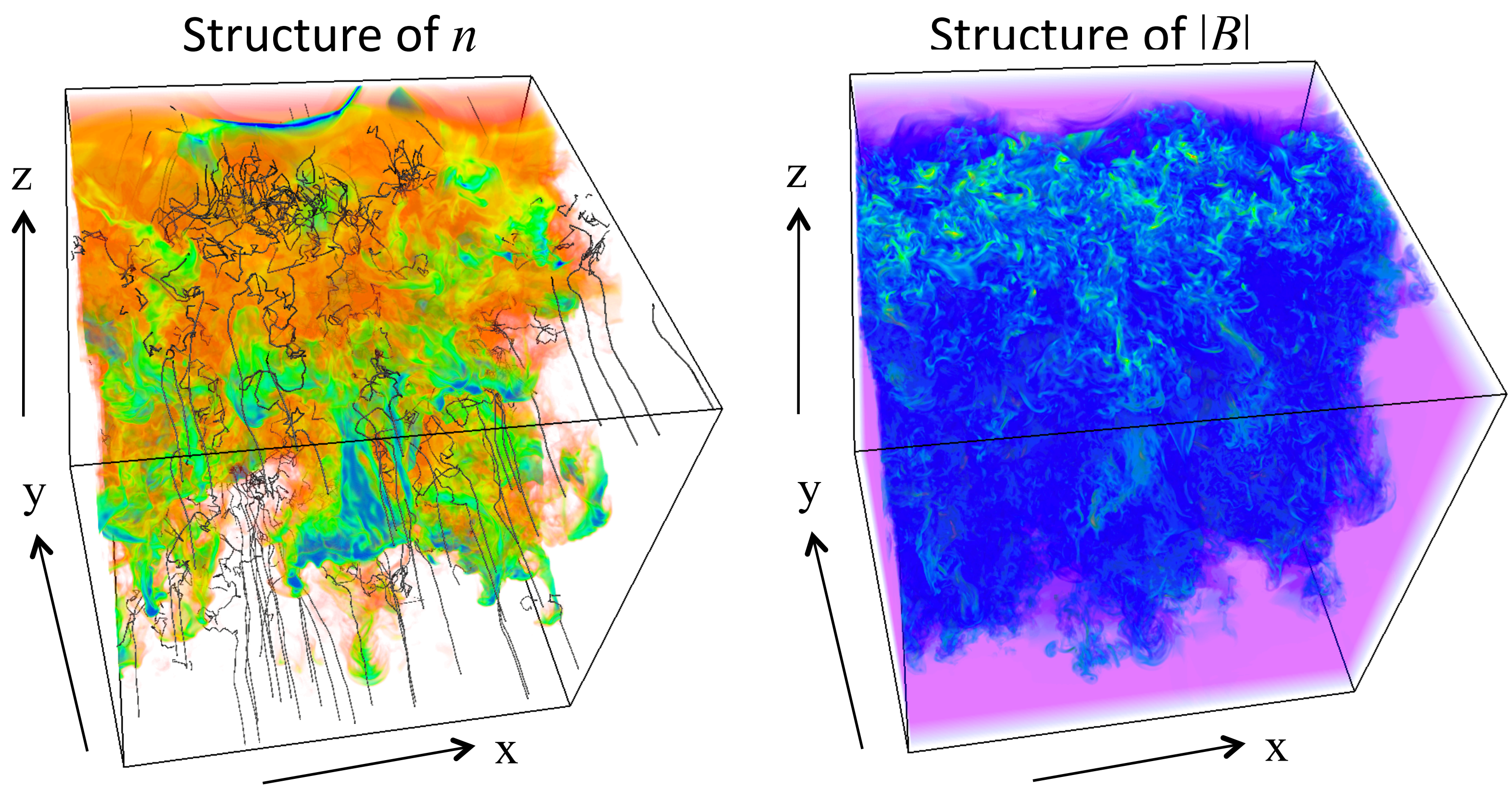
Blue : $10\ \mu G < |B| < 100\ \mu G$

Green : $100\ \mu G < |B| < 500\ \mu G$

Red : $500\ \mu G < |B|$

Result

- 3D visualization (parallel shock case).



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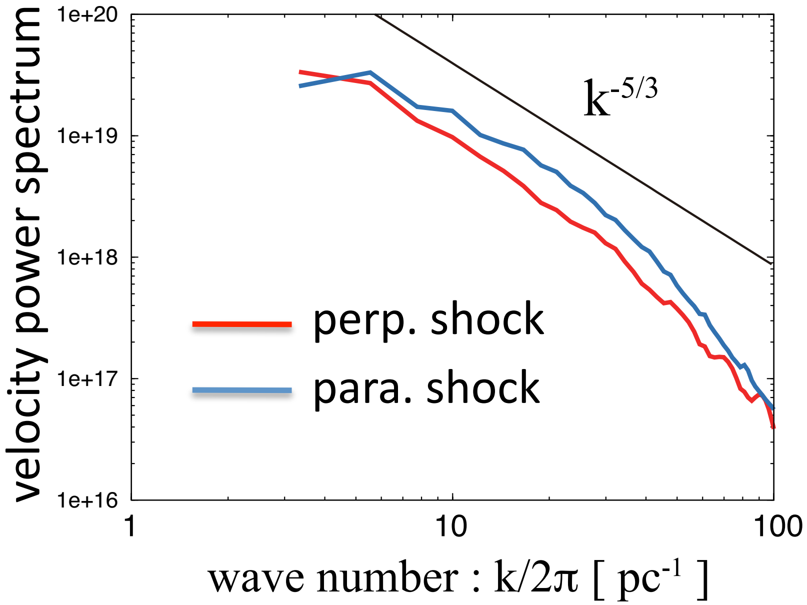
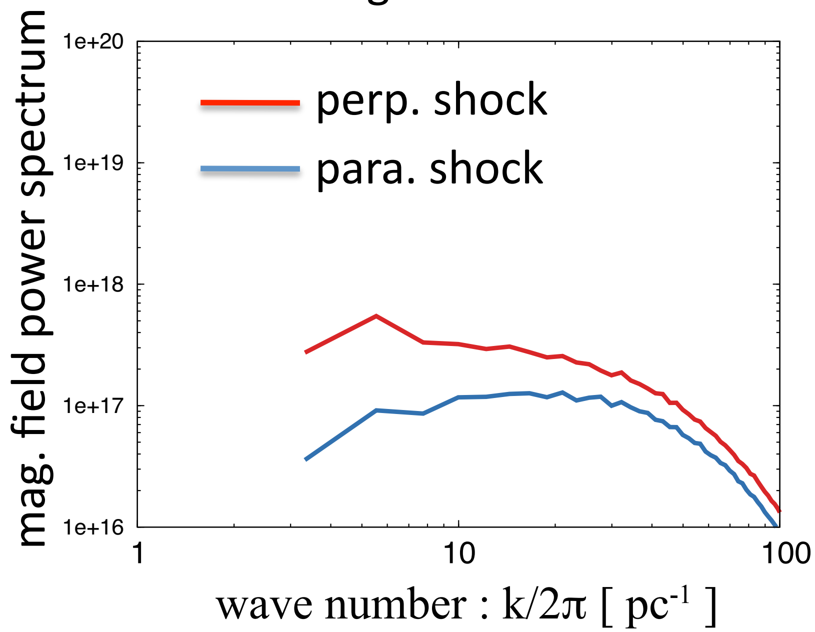
Power Spectra of *v* and *B*

velocity

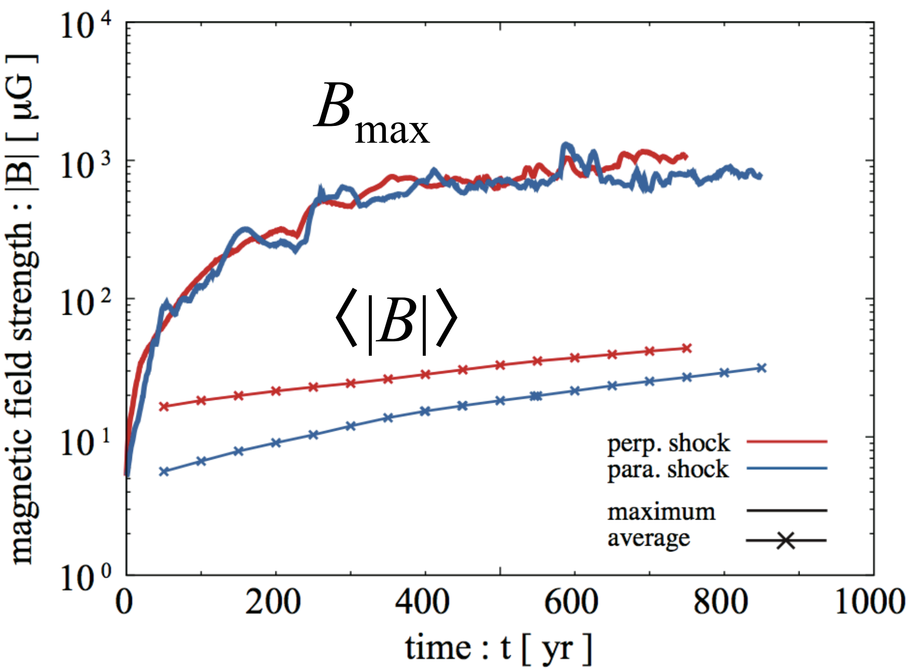


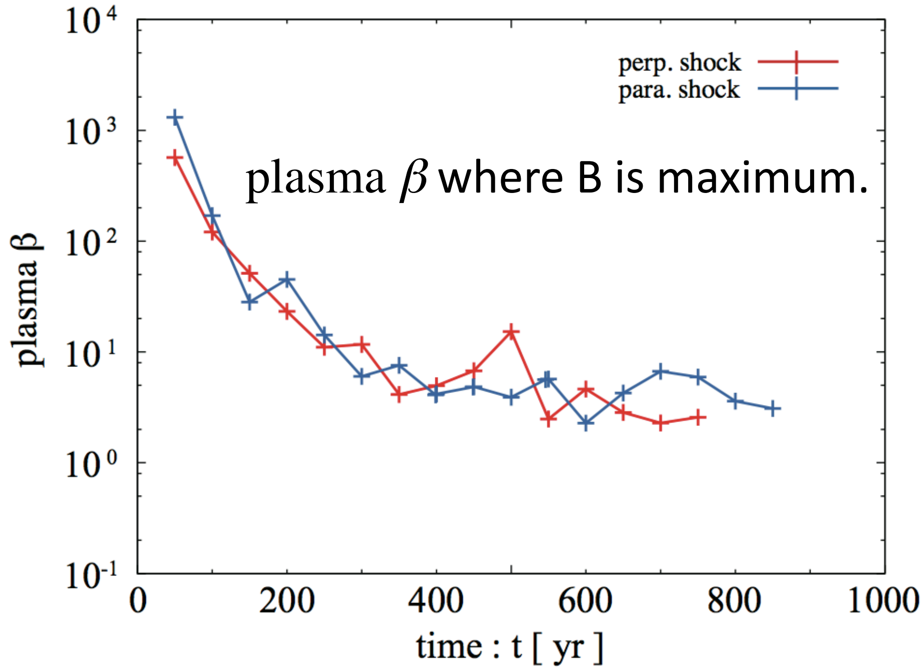
magnetic field



- Power spectra of ***v*** and ***B*** are similar to the results of the numerical experiments of super-Alfvenic turbulence (e.g., Cho & Vishniac 00, Cho+10).
  - ✓ P_v has Kolmogrov poer-law index in large scales.
  - ✓ P_B is roughly flat in large scales.

Evolution of Maximum B and plasma β





- Maximum $|B|$ saturates at 1 mG.
- $B_{max} \sim 1$ mG is determined by the condition of post shock plasma $\beta \sim 1$.
- Average $|B|$ in shocked gas also grow beyond the shock compression factor.

Amplification Mechanisms

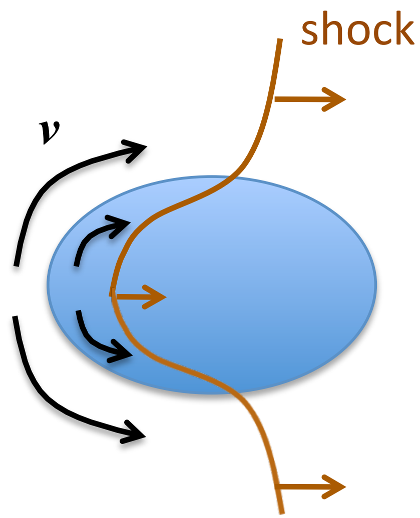
- Shock-cloud interaction generates two types of vorticity
  → two mechanism of *B* amplification (Inoue, Yamazaki & Inutsuka 11).

1. Vorticity created by Baroclinic effect ($\nabla p \times \nabla \rho$).

   - This arises at narrow transition layer between cloud and diffuse gas as strong shear flows.

$$\frac{d}{dt}\left(\frac{\vec{B}}{\rho}\right) = \frac{1}{\rho}(\vec{B}\cdot\vec{\nabla})\,\vec{v}.$$

Velocity shear along *B* filed line amplifies *B* field



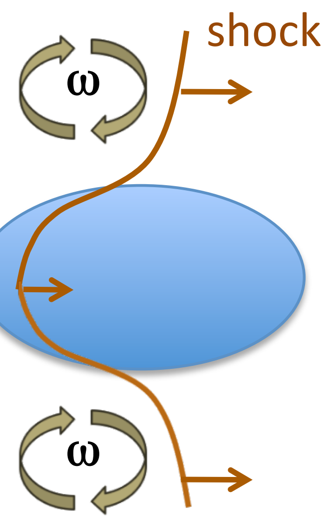
   - Dominant mechanism of local strong amplification up to $B \sim 1\mathrm{mG}$.

2. Vorticity created by curved shock (Giacalone & Jokipii 07).

   - This arises in diffuse gas in the vicinity of clouds.

     → *B* field amplification by stretching filed line (small-scale dynamo).

   - Dominant mechanism in most volume that determine average $|B| \sim 100\ \mu\mathrm{G}$.



Comparison with Observation 1

- Strong B field amplification up to 1mG can explain short-time variability of X-ray not only timescale but also spatial scale (Inoue, Yamazaki & Inutsuka 09, 11).

- In observation, scale of regions where B~1mG is ~ 0.05 pc.

- In simulation, scale of regions where B~1mG is determined by thickness of transition layer between cloud and diffuse gas (the Field length):

$$l_{tr} \sim \sqrt{\frac{\rho \mathcal{L}}{\kappa T}} \sim 0.05 \text{ pc}.$$

$\mathcal{L}$: cooling rate par unit mass.

κ : thermal conductivity.

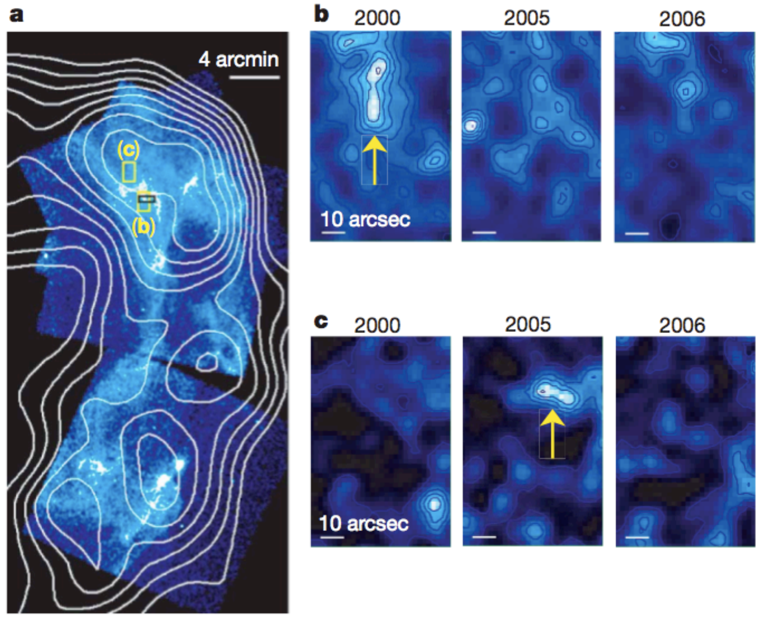
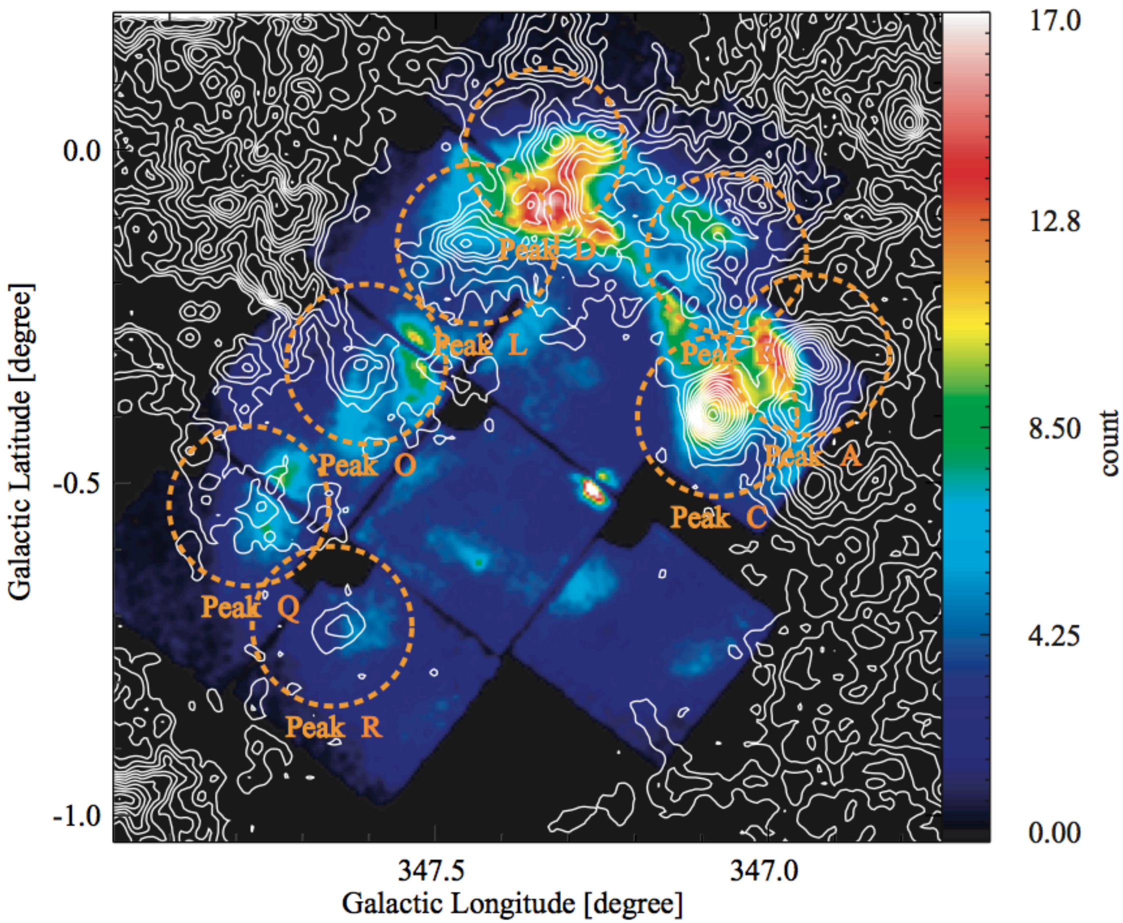


Figure 1 | Chandra X-ray images of the western shell of SNR

X-ray image of RXJ1713.7-3946 by *Chandra* telescope (Uchiyama+ 07).

Comparison with Observation 2

- Spatial correlation between cloud and magnetic field.
  - Simulation shows that B field is amplified around cloud.
    → Synchrotron emission should be enhanced around cloud, because $I_{syn} \propto B^{1.5}$ for DSA.
  - Observation shows that this is indeed the case of SNR RXJ1713.



Contour: CO line emission that traces clouds.

Color: X-ray emission that traces synchrotron radiation.

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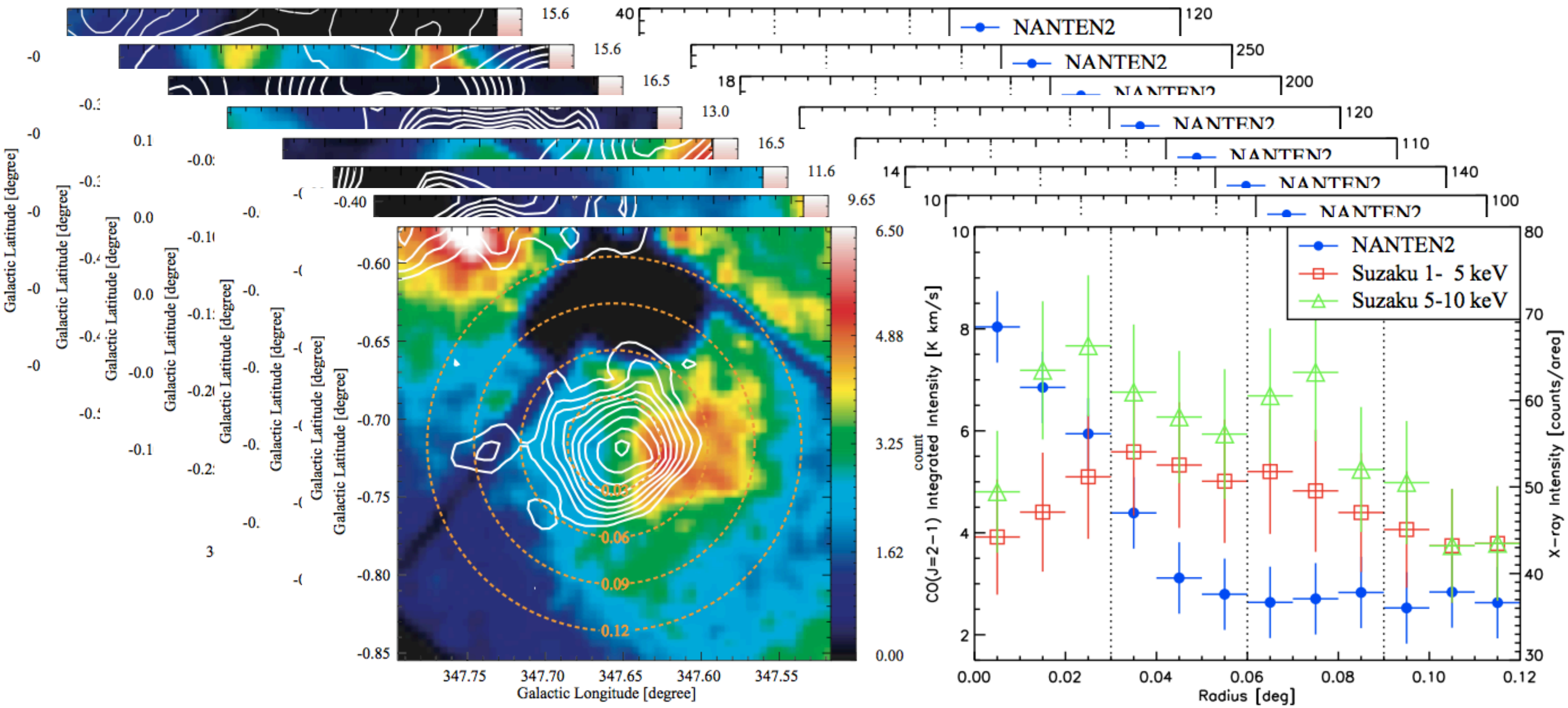
Synchrotron X-ray is enhanced in the vicinity of molecular clouds (Sano+11 in prep.).



Evidence for CR proton acceleration?

- SNRs have been believed to be the site of CR proton acceleration.
  - However, there is no conclusive evidence of proton acceleration at young SNR, because it is hard to distinguish γ-ray emissions due to the accelerated protons (π^0 decay) and electrons (inverse Compton scattering).

- If RXJ1713 is surely interacting with clouds, gamma-ray emission should be attributed to accelerated protons.
  - If origin of γ-ray is electron IC, strength of B in RXJ1713 should be $10\ \mu\mathrm{G}$.

$$\frac{P_{X,syn}}{P_{\gamma,IC}} = \left(\frac{B}{3\mu G}\right)^2 \approx 10$$ from observations (Aharonian+06, Tanaka+08).

  - Shock-cloud interaction inevitably amplify $B > 10\ \mu\mathrm{G}$.

    → possibility of γ-ray emissions due to electrons is rejected.

Our shock-cloud interaction model of RXJ1713 strongly support the yet unconfirmed longstanding paradigm of CR proton acceleration.

Turbulence in Clouds

- If we assume spherical cloud, the shock-cloud interaction can induce turbulent only at the surface of the cloud (Klein+94, Nakamura+06).
  - Observation suggests that HI clouds are sheets, not spherical (Heiles & Troland 03).
  - Simulation of thermal instability in magnetized medium generates sheet-like HI clouds (Inoue & Inutsuka 08, 09).

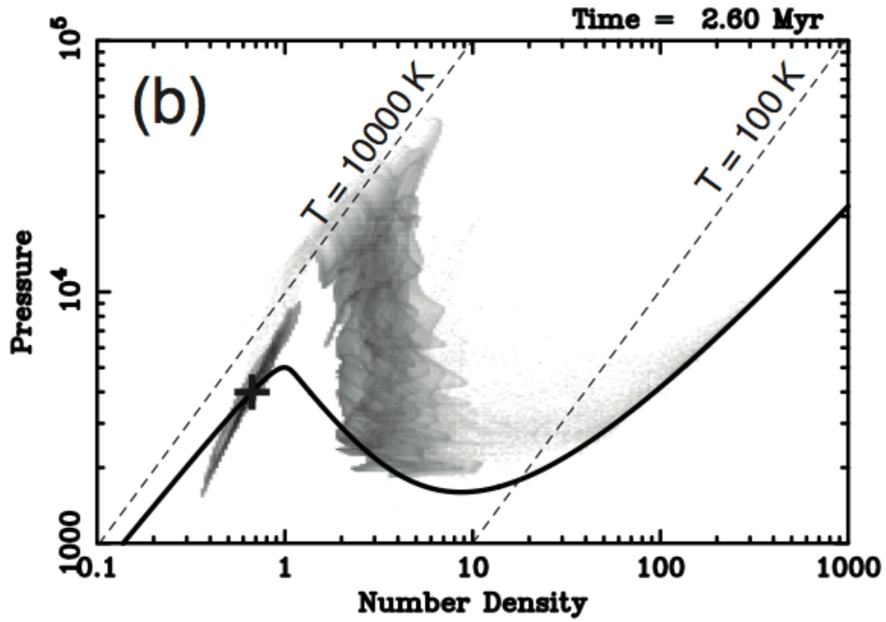
- When HI clouds are sheets, turbulence can be induced more efficiently.
  - Result of our simulations : mass weighted δv in shocked clouds $\sim$ 0.2 $v_{sh,\,\mathrm{d}}$
  - Baroclinic vorticity generation does not substantially depend on Mach number.

$$\omega \sim \frac{2\delta\rho/\rho}{(\gamma+1)l_{tr}} \frac{M^2-1}{M^2} v_{sh}$$

Even when $v_{sh,\,\mathrm{d}} \sim$ 10 km/s (late-phase SN shock), the shock-cloud interaction can induce turbulence $\delta v_{\mathrm{cloud}} \sim \mathrm{a\ few\ km/s}$ in HI clouds (consistent with observation by Heiles & Troland 05).

Summary

- Thermal instability in the ISM generates sheet-like fragmented HI clouds behind shock wave.
- Shock-cloud interaction induce vorticity behind the shock wave mainly by two ways.
  - Baroclinic effect generates strong shear layer between cloud and diffuse gas.
  - Effect of curved shock generate turbulence in diffuse medium in the vicinity of cloud.
- The vorticity generated by the shock-cloud interaction cause *B* field amplification in SNR, which can explain: (1) the short-time variability of synchrotron X-ray and (2) the enhancement of X-ray in the vicinity of molecular clouds observed in SNR RXJ1713.
  - Our shock-cloud interaction model strongly support the hadronic emission scenario of gamma-rays from young SNR RXJ1713.
- When clouds have sheet-like morphology, shock-cloud interaction can drive turbulence more efficiently than spherical case, which can be the driving mechanism of turbulence at lest in HI clouds.


Time = 2.60 Myr
(b)
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T = 100 K
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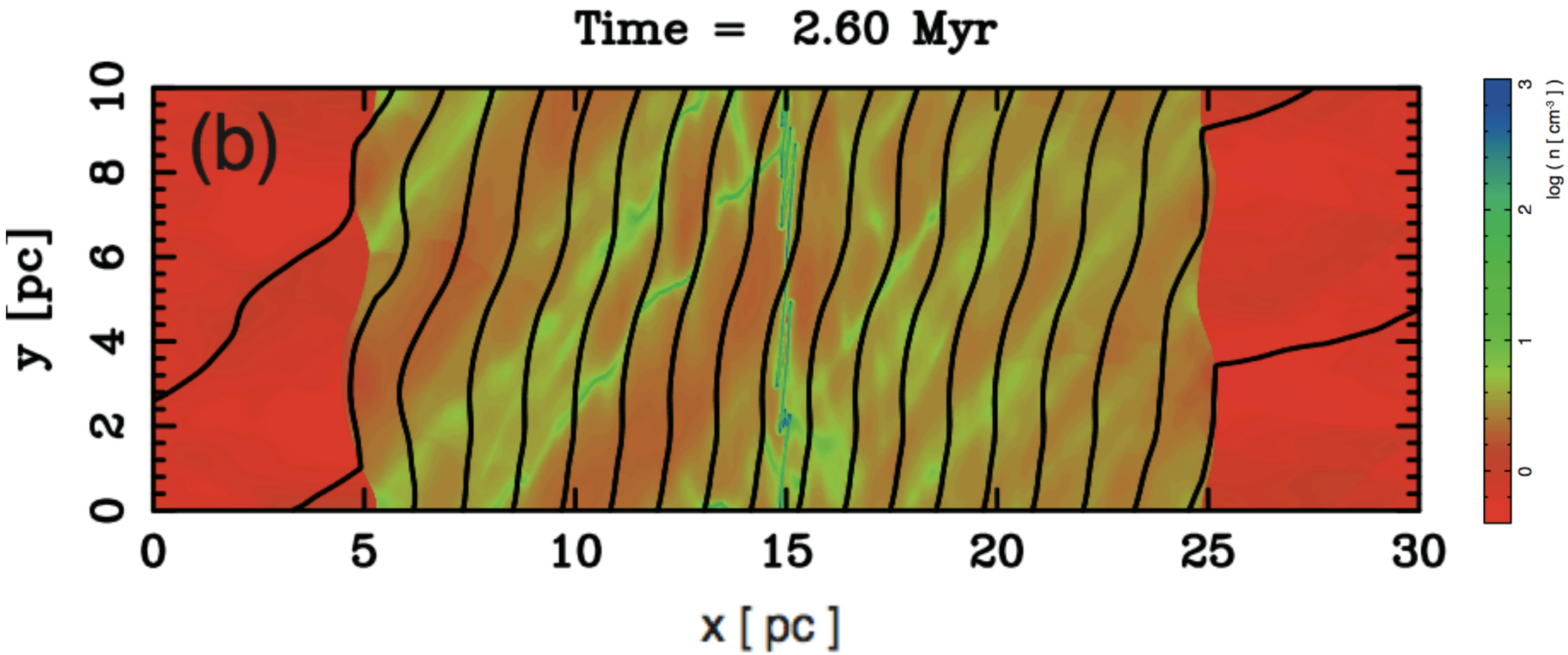
Time = 2.60 Myr
(b)
y [pc]
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