Turbulence and Magnetic Field Amplification in SNRs

TI, Yamasaki & Inutsuka 2009, ApJ, 695, 825

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Introduction: Strong MF at SNR

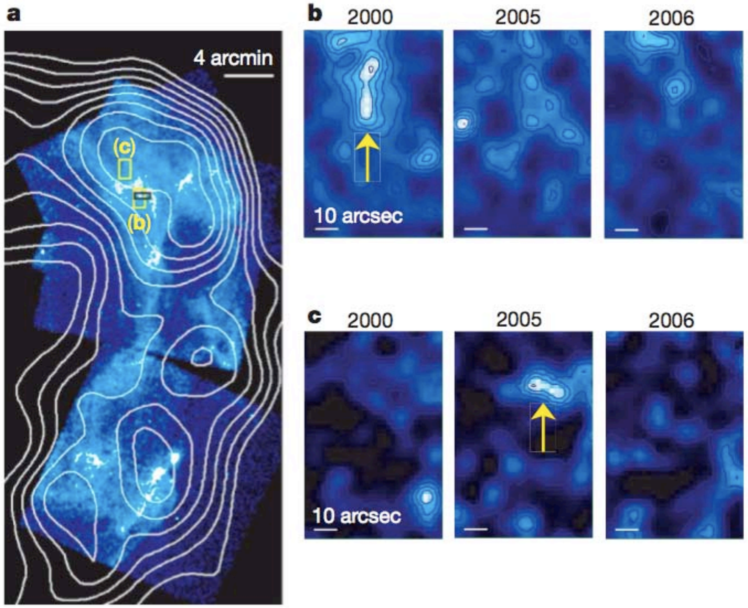
- Recent X-ray observation discovered Strong MF ($\sim 1\mathrm{mG}$) in SNRs

(Uchiyama+ 07, Uchiyama & Aharonian 08)

There are synchrotron X-ray hot spots that blink on a timescale of a few years In RXJ1713.7-3946 and CasA.

Synchrotron cooling time :

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



X-ray image of RXJ1713.7-3946.
(Uchiyama+ 07)

→ Decrease of X-ray luminosity within a few years indicates $B \sim 1\mathrm{mG}$ ($200 \times B_{\mathrm{ISM}}$).

Magnetic Field Amplification

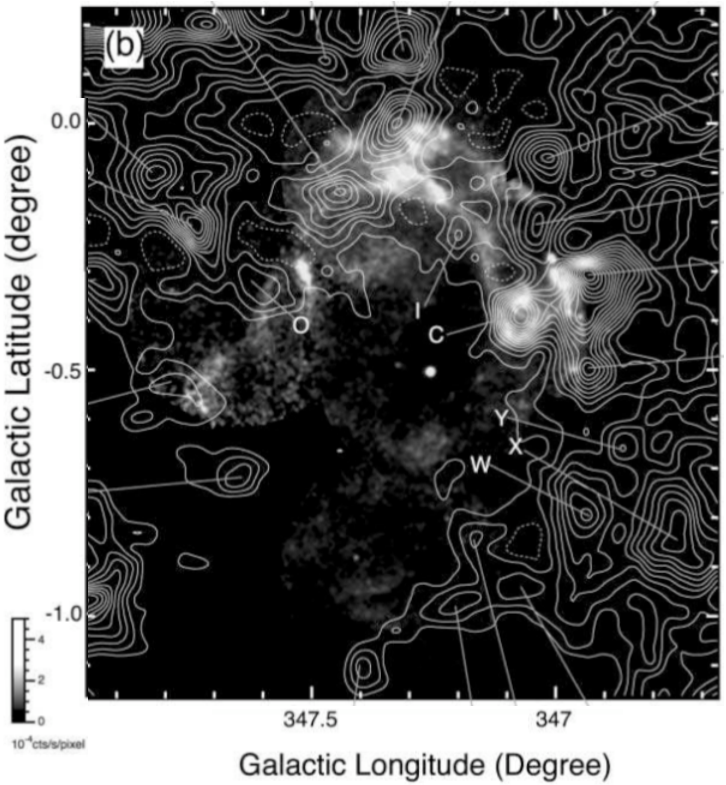
- Some mechanisms are proposed that can amplify B filed at shock.
  - Widely studied ideas are nonthermal processes, e.g., CR streaming instability (Lucek & Bell 00) and Weibel instability.
  - Another idea is dynamo effect caused by the interaction between shock and preshock ρ fluctuations (Giacalone & Jokipii 07; Beresnyac+09).
    - ✓ Source of vorticity: Baroclinic effect.

$$\frac{\partial \vec{\omega}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{\omega}) + \boxed{\frac{1}{\rho^2}\vec{\nabla}\rho \times \vec{\nabla}p} + \vec{\nabla} \times \vec{F}_{\mathrm{Lorentz}}$$

    - ✓ The strength of B amplification depend on the amplitude of ρ fluctuations.
    - ✓ Compressions by interstellar turbulence is usually assumed as ρ fluctuations.

Cloud as a ρ Fluctuation

- In ISM, large ρ fluctuations can be expected around molecular clouds.
  - In the case of RXJ1713.7-3946., the SNR is surrounded by molecular clouds.



Gray scale: X-ray image by XMM-Newton (Hiraga+05)

Contour: CO(J=1-0) intensity by NANTEN (Fukui+03, Moriguchi+05)

Molecular cloud and SNR is interacting!

→ It is natural to assume that ambient ρ structure is highly inhomogeneous in some SNR.

Formation of Clouds

- In order to study SNR formed from cloudy ISM, information about clouds structure is necessary.
- In ISM, thermal instability (cooling collapse) is known as the formation mechanism of clouds (Field 65).

- ISM is thermally bistable medium due to the balance of radiative cooling and heating (Field+69).
- Diffuse gas and clouds can coexist under pressure equilibrium.

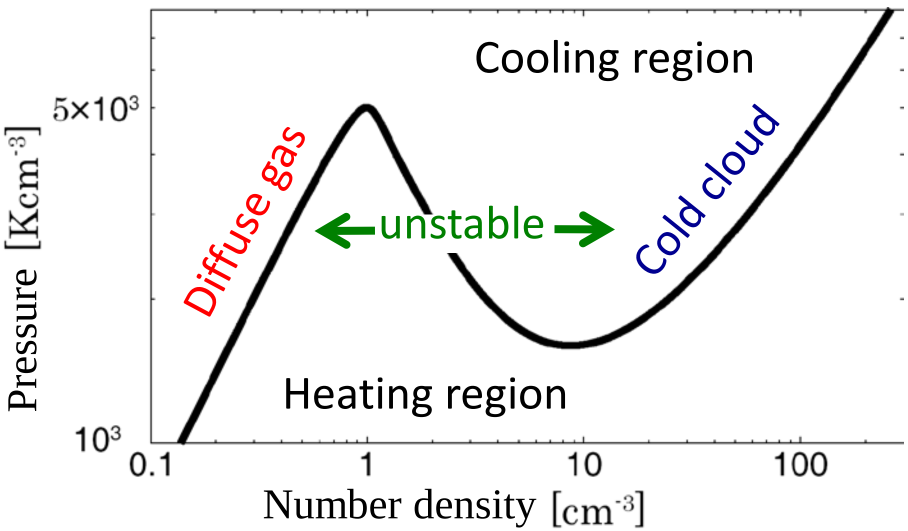


Fig.: Thermal equilibrium state of ISM

- Recent numerical simulations have shown that shock waves in ISM (e.g., SNe/stellar wind/global turbulence) generate thermally unstable gas that leads formation of clouds by thermal instability.

(Hennebelle & Audit 07, TI & Inutsuka 08,09)

Formation of Clouds by 2D MHD Simulation

- In order to generate cloudy medium formed by thermal instability as a preshock ISM, we perform 2D MHD simulation.
  - Basic MHD eqs.: $\frac{\partial\rho}{\partial t}+\boldsymbol{\nabla}(\rho\,\boldsymbol{v})=0\quad \rho\,\frac{d\boldsymbol{v}}{dt}=-\boldsymbol{\nabla}p+\frac{1}{4\,\pi}(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B},$

$$\frac{\partial\boldsymbol{B}}{\partial t}=\boldsymbol{\nabla}\times(\boldsymbol{v}\times\boldsymbol{B}),\qquad \frac{\gamma}{\gamma-1}\frac{dp}{dt}+\frac{p\boldsymbol{\nabla}\cdot\boldsymbol{v}}{\gamma-1}=\underbrace{\boldsymbol{\nabla}\cdot\kappa\boldsymbol{\nabla}T}_{\text{Thermal conduction}}-\underbrace{\rho\,\mathcal{L}(n,T)}_{\text{Heating/cooling fuction}}\,.$$

  - Initial condition: thermally unstable equilibrium + *B* filed (Bx=6μG, By=0).

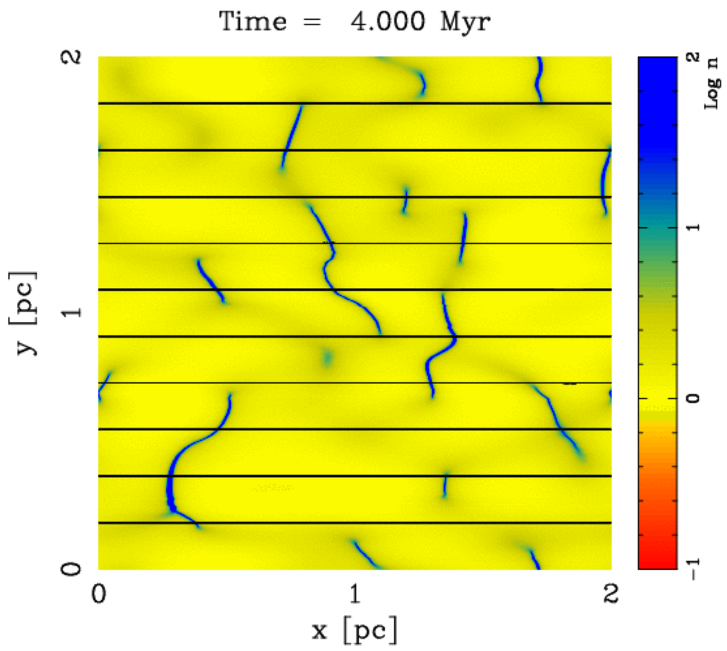
- Results:

Diffuse warm gas : n~1 cm^{-3}, T ~ 8000 K

HI clouds : n~30 cm^{-3}, T ~ 100 K

  - Condensations driven by thermal instability form clouds by piling up gas along *B* field.
  - Scale of HI clouds are determined by scale of thermal instability.
  - Molecular clouds are generally surrounded by HI clouds (Blitz+07).

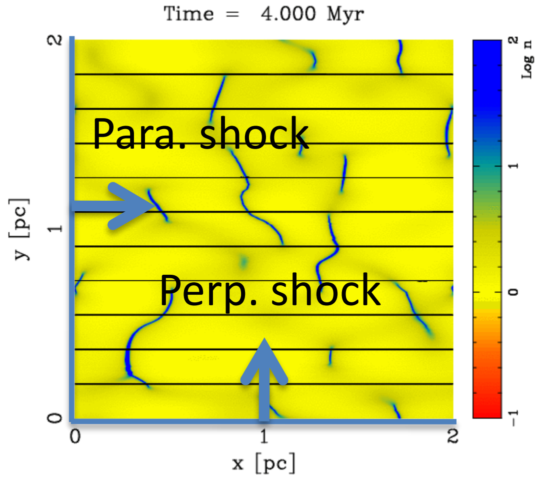
→ This medium corresponds to ambient surrounding of molecular cloud



Resulting density structure

Settings of Simulation

- To examine SNR formed from the cloudy ISM,
we induce shock wave at a boundary of computational domain.



- We set the hot plasma (n=0.1 cm^{-3})
at one side of computational boundary.

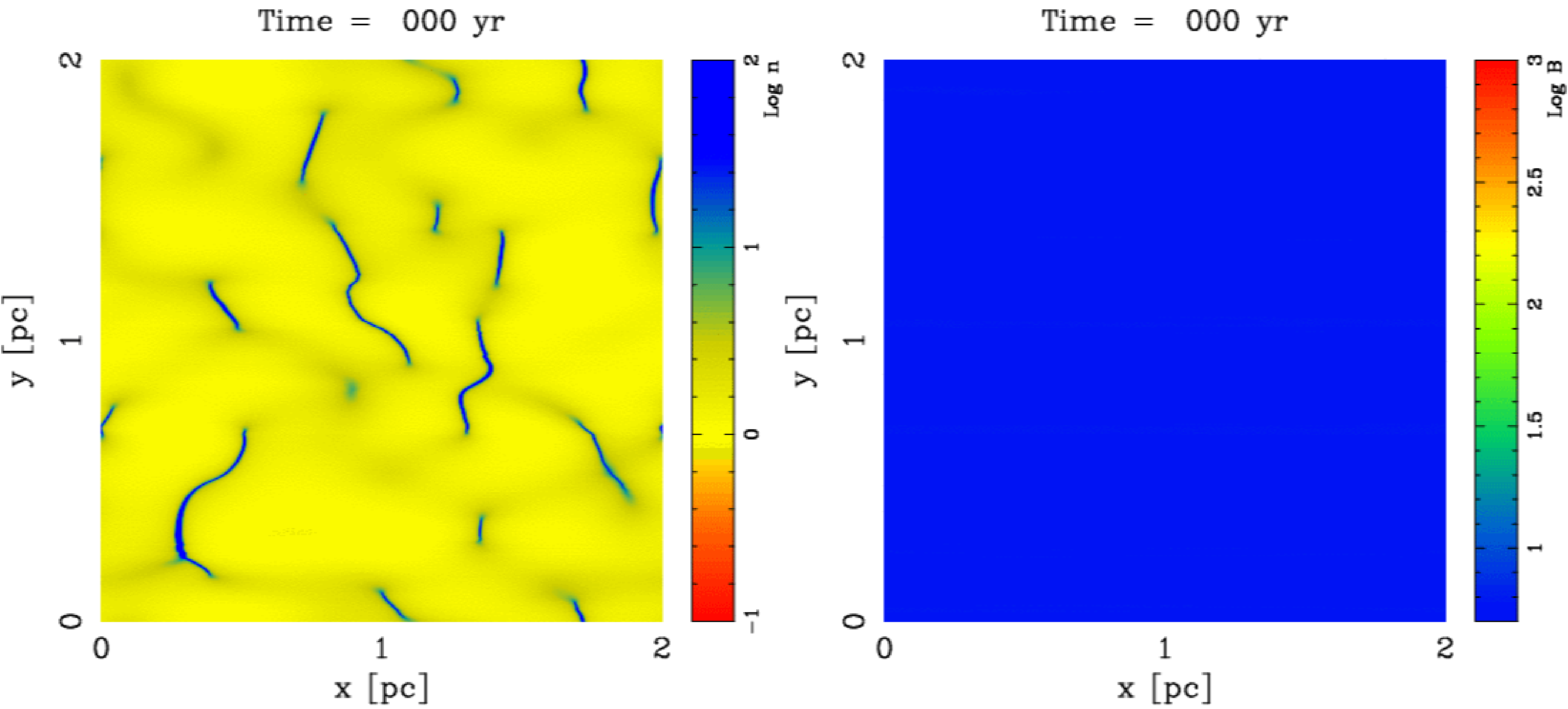
- The thermal pressure of the hot plasma is chosen so that the velocity of the induced shock becomes ~ 1300 km/s.

- We examine the cases of para. and perp. shocks by setting the hot plasma at x=0 and y=0, respectively.

- Effects of cooling/heating/thermal conduction are cut off from here, since timescales of them >> timescale of SNR formation.

Formation of SNR by 2D Simulation

- Case 1: Perpendicular shock ($v_{shock} \sim 1300$ km/s).



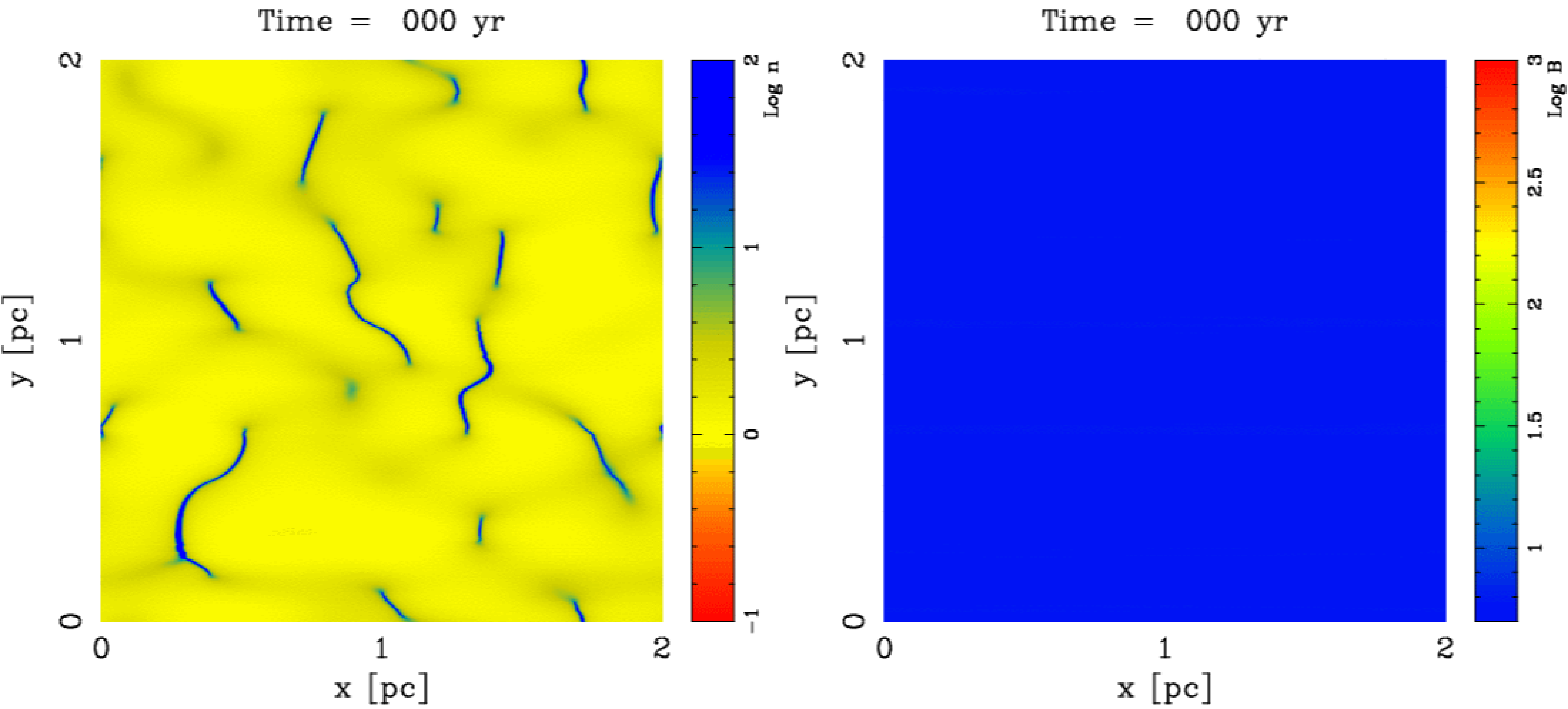
Number Density

Magnetic Field Strength

- In some regions, B field is strongly amplified to the level of 1 mG.
- The regions of high B are located between clouds and diffuse gas.

Formation of SNR by 2D Simulation

- Case 2: Parallel shock ($v_{shock} \sim 1300$ km/s).

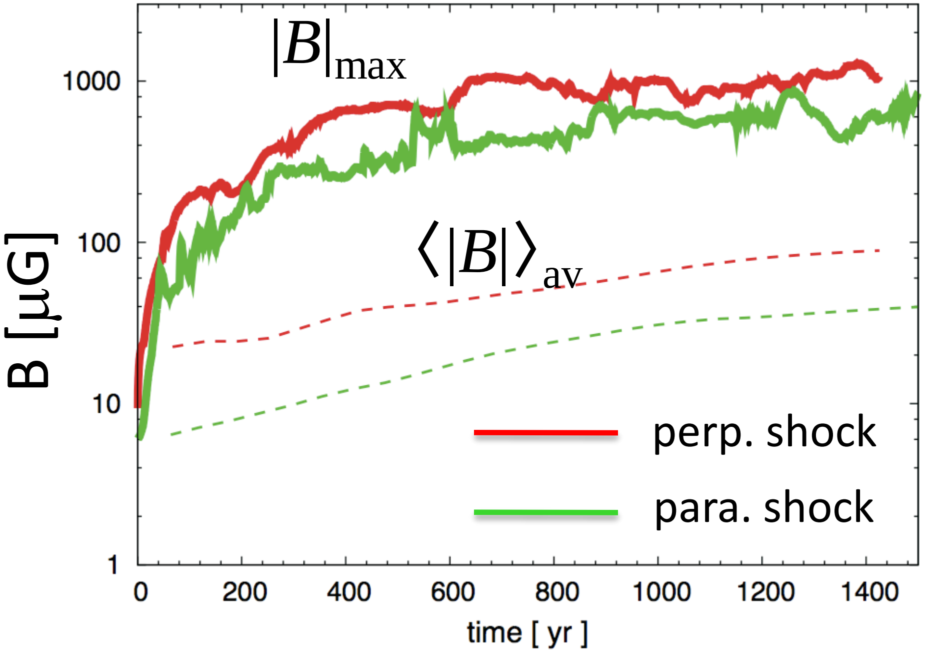


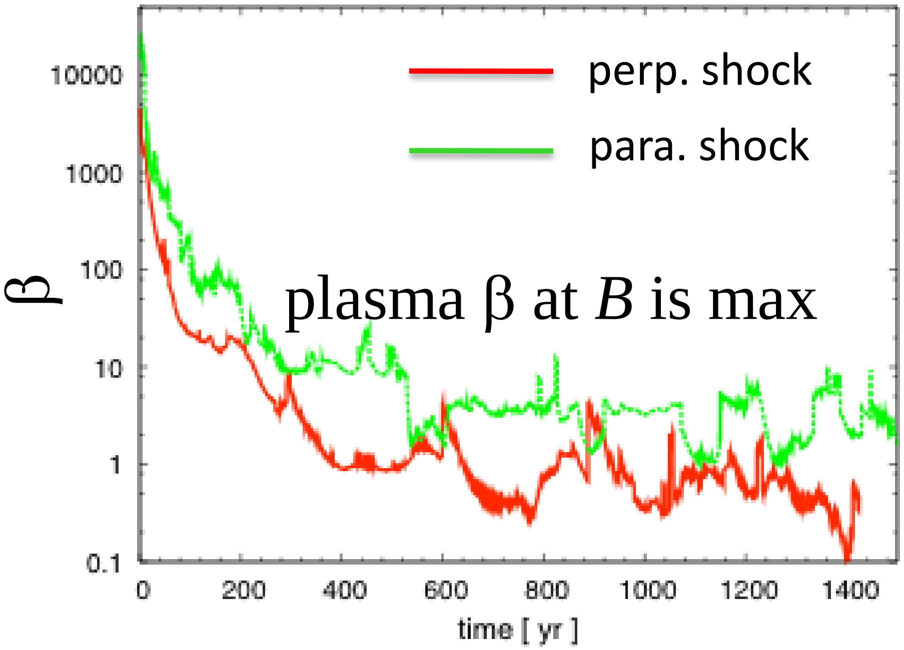
Number Density

Magnetic Field Strength

- B field amplification appears independent of preshock B orientation.

Evolution of Maximum B and β





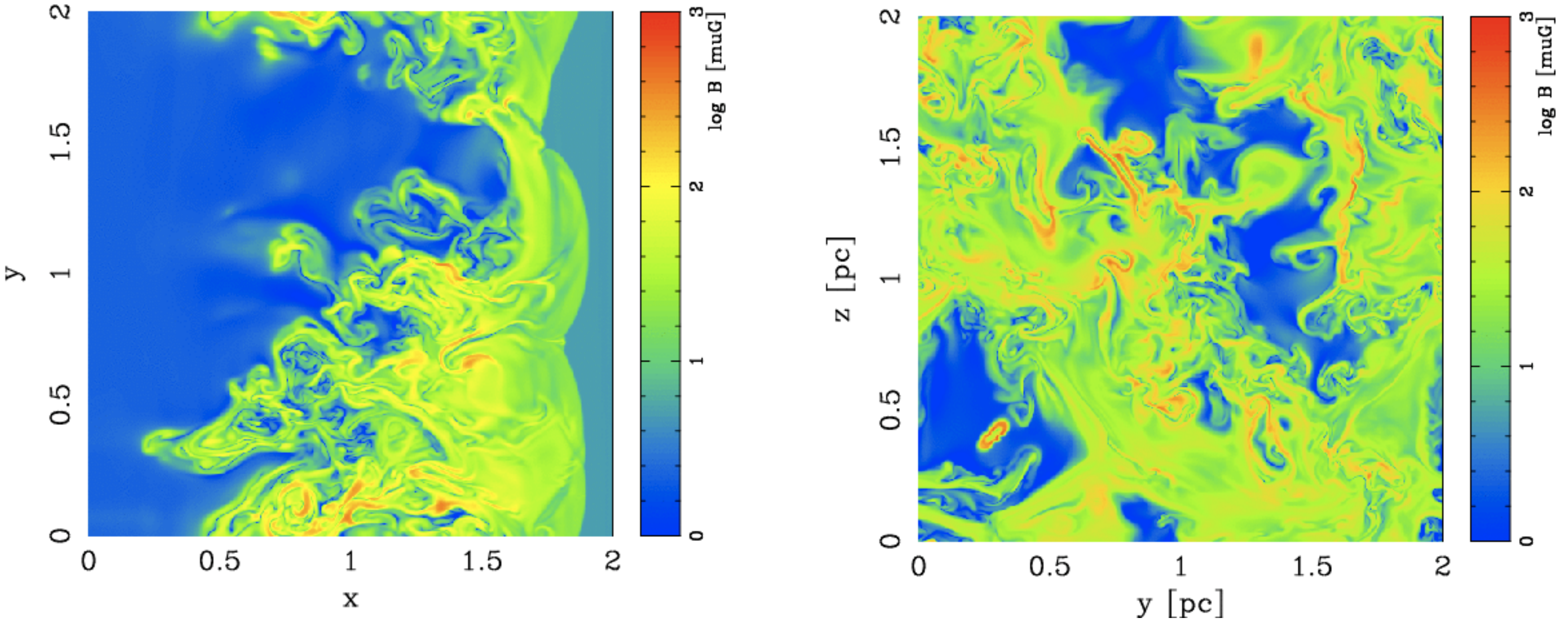
- Maximum B strength saturate at $B \sim 1$ mG.
- Average B in the shell also grow beyond the shock compression value.
- Maximum B strength is determined by the condition $\beta \sim 1$.

3D Simulation

- In MHD, geometric difference between 2D and 3D could lead different result.
- However, preliminary result of 3D simulation done under the similar conditions to the 2D case show that strong B amplification is indeed work.

TI, Yamazaki & Inutsuka in progress.

Structure of $|B|$



x-y cut at z = 1 pc.

y-z cut at x = 1.5 pc.

3D simulation with 512^3 cells

Mechanism of B amplification

- Mechanism of strong B field amplification by cloud-shock interaction.

- Eq. of continuity and induction eq. yield:

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

→B is amplified if velocity filed has shear along B filed line.

- Strong velocity shear is generated when clouds are swept by the shock.

$v_{\rm shock}$ in cloud << $v_{\rm shock}$ in diffuse gas ($\Delta v_{\rm shear} \sim$ Cs in post shock)

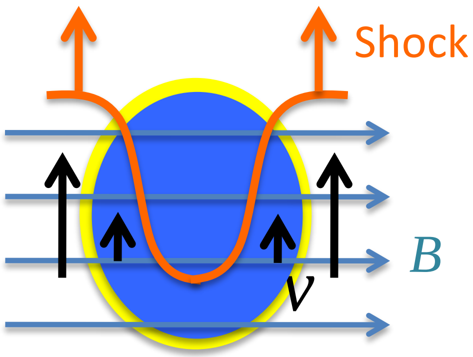
→ post shock gas flows to round HI cloud.

→ The largest velocity shear is induced at transition layer between cloud and diffuse gas.

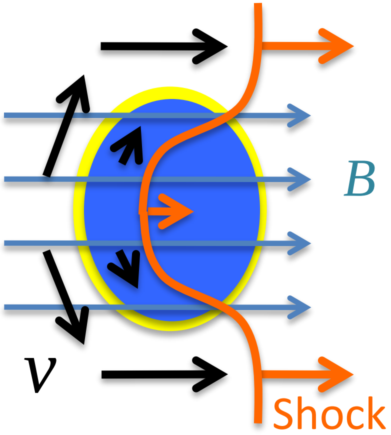
The scale of high B region is essentially determined by the

Scale of the transition layer $l \sim \sqrt{\frac{\rho L}{\kappa T}}$ ~ 0.05 pc (TI+06)

Perp. shock case

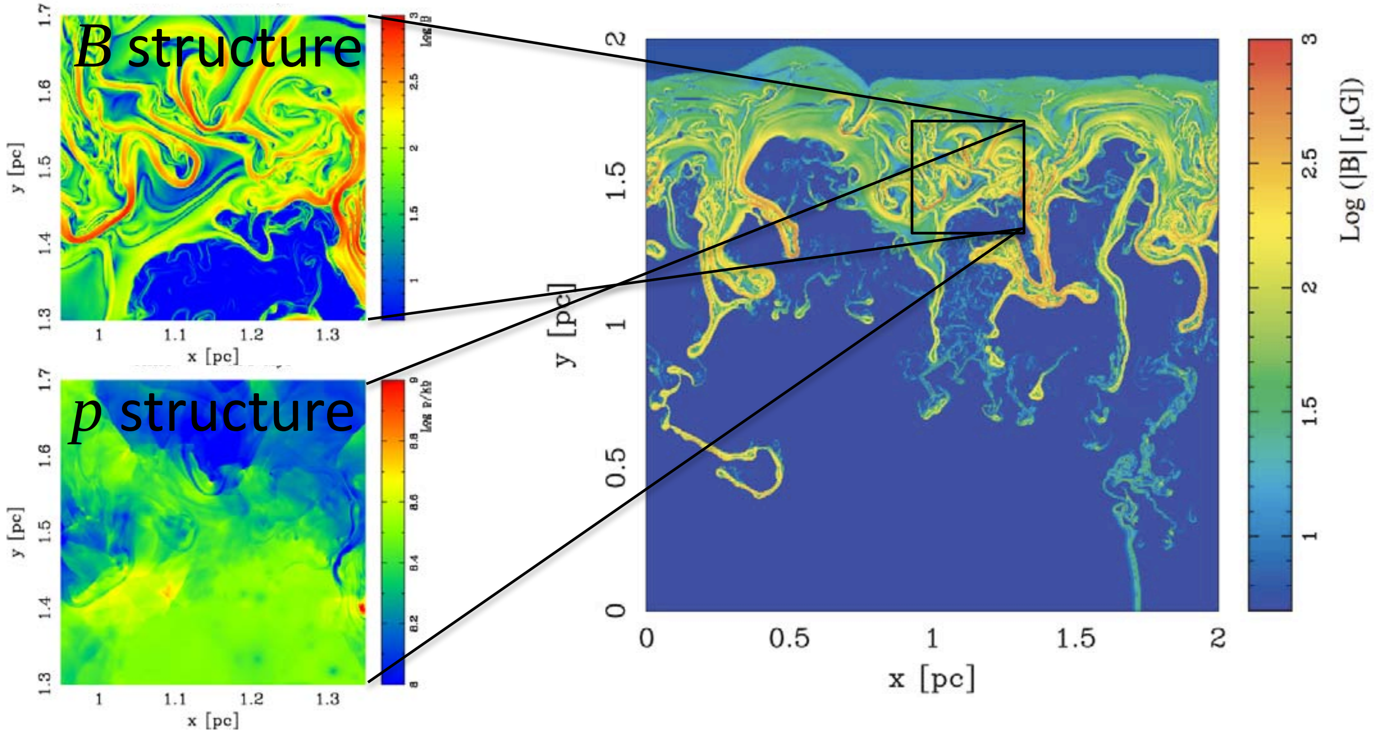


Para. shock case



Secondary Shocks in SNR

- Can post shock turbulence contribute particle acceleration?
  - Downstream B filed amplification alone cannot contribute acceleration.
  - However, many secondary shock waves are formed in SNR shell, due to the turbulent flow ($\langle \delta v \rangle = 0.8\, C_s$ in SNR shell ~ v_{shock}).



- The secondary shocks formed in the shell may enhance particle acceleration.

Summary

- SNR formed from cloudy medium becomes turbulent.
- Velocity shear along B line induced by shock-cloud interaction amplifies B at transition layer between cloud and diffuse gas.
- B strength grows to the order of 1 mG $(\beta \sim 1)$.
- Scale of the regions where B is on the oreder of 1 mG is 0.05 pc, which agrees well with the scale of X-ray hot spots.
- The scale 0.05 pc is determined by the scale of transition layer between cloud and surrounding diffuse gas at which velocity shear is most strongly induced.
- The turbulent flows in the post shock shell ($\langle \delta \mathrm{v} \rangle \sim \mathrm{v}_{\mathrm{shock}} \sim C_{\mathrm{s}}$ in shell) generate the secondary shocks that can enhance particle acceleration.

Spectra

- Spectra of v and B in the shell resemble those of super-Alfvenic turbulence. (e.g., Cho & Lazarian 03)
  - v spectrum: Kolmogorov spectrum ($v_k \propto k^{-q}$, q=11/3 for 3D, 8/3 for 2D)
  - B spectrum: Shallower than the Kolmogorov in large scales.

    Steeper than the Kolmogorov in small scales.