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A New HLL Approximate Riemann Solver for Magnetohydrodynamics including Cosmic-Ray Effects: Application to the Fermi Bubbles

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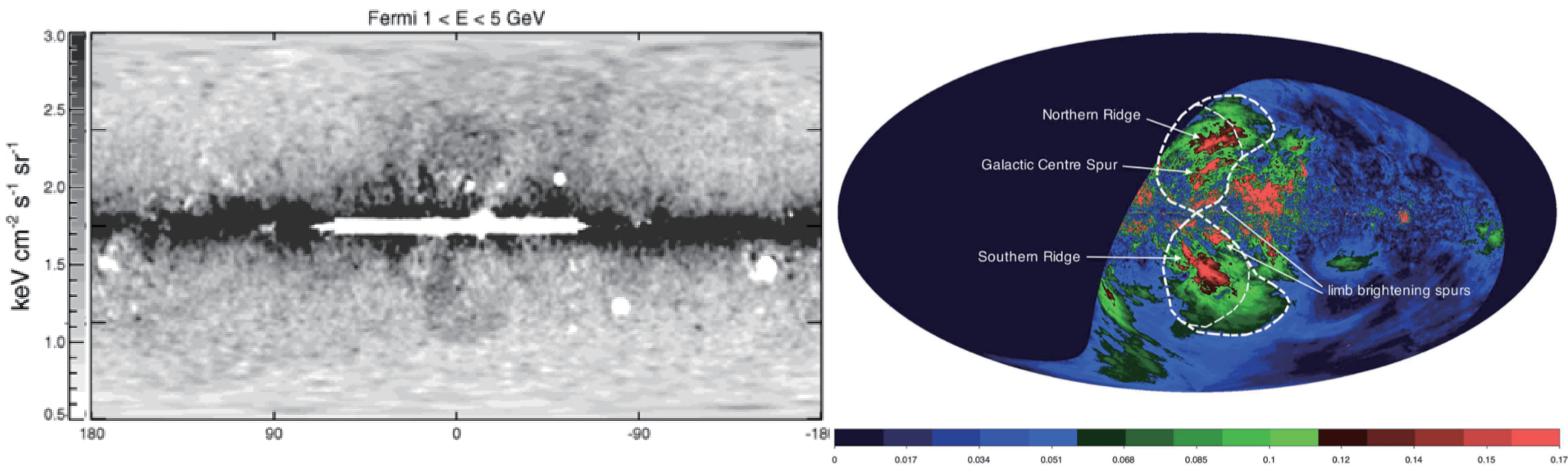
Abstract

We developed a new numerical magnetohydrodynamic (MHD) solver in which effects of the Cosmic-Ray(CR) pressure is taken into account when the speeds of the fast magneto-acoustic wave are calculated in the Harten-Lax-van Leer (HLL) Riemann solver. The sound speed in usual HLL Riemann solver is replaced by the effective sound speed which is combined fluid of gas and CRs. Diffusive propagation of the CR is also solved. To treat diffusion term of the CR as flux term, diffusion of the CR is solved by explicit method. In this presentation, we explain the fundamentals of our method and show results of test problem and application to Fermi bubbles.

1. Motivation (Why CRs ?)



Left: 1<E<5GeV gamma-ray surface brightness (Su+, 2010)
Right: 2.3GHz linear polarizated intensity (Carretti+, 2013)

Fermi bubbles created by large episode of energy injection from GC

① a recent AGN jet activity ?

② nuclear starburst & SNe around GC ?

In order to understand Fermi bubbles, we need to solve MHD equation with CR effects.

2. Basic Equations

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \mathbf{v}) = 0$$

$$\frac{\partial}{\partial t}(\rho\mathbf{v}) + \nabla\cdot\left(\rho\mathbf{v}\mathbf{v} + p_{\rm tot} - \frac{1}{4\pi}\mathbf{B}\mathbf{B}\right) = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla\cdot(\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = 0$$

$$\frac{\partial e}{\partial t} + \nabla\cdot\left\{(e+p_{\rm tot})\mathbf{v} - \frac{1}{4\pi}(\mathbf{B}\cdot\mathbf{v}) - \boldsymbol{\kappa}\cdot(\nabla e_{\rm cr})\right\} = 0$$

$$\frac{\partial e_{\rm cr}}{\partial t} + \nabla\cdot\{e_{\rm cr}\mathbf{v} - \boldsymbol{\kappa}\cdot(\nabla e_{\rm cr})\} = -p_{\rm cr}(\nabla\cdot\mathbf{v})$$

ρ: gas density, v: velocity, $p_{tot}=p_{th}+p_{cr}+B^2/8\pi$, B: magnetic fields,
e : $0.5v^2+e_{th}+e_{cr}+B^2/8\pi$, e_{th}: internal energy of gas,
p_{th} : gas pressure($=(\gamma_g-1)e_{th}$),
e_{cr} : CR energy density, p_{cr} : CR pressure($=(\gamma_{cr}-1)e_{cr}$),
γ_g : specific heat ratio of gas(=5/3),
γ_{cr} : specific heat ratio of CR(=4/3)
κ :diffusion coefficient tensor

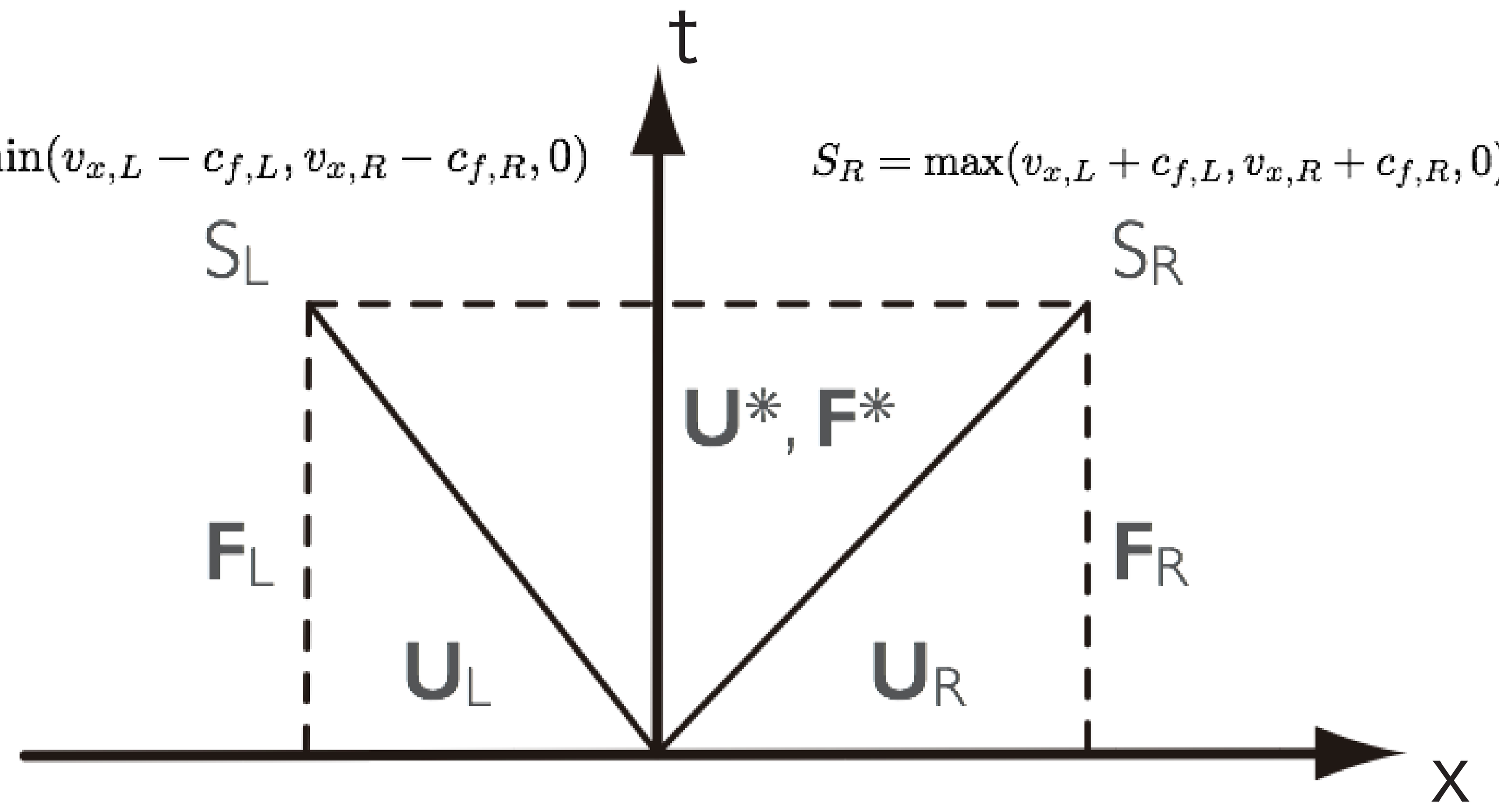
$$\boldsymbol{\kappa} = \kappa_{\parallel}\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot(\nabla e_{\rm cr}) + \kappa_{\perp}\{(\mathbf{I}-\hat{\mathbf{b}}\hat{\mathbf{b}})\cdot(\nabla e_{\rm cr})\}$$

$\hat{b}$: unit vector of magnetic fields
(Braginskii 1965, Ryu et al., 2003, Judelgas et al., 2008, Hanasz+2009, Yang+ 2012)

3. Methodology: a new HLL

$S_L = \min(v_{x,L} - c_{f,L}, v_{x,R} - c_{f,R}, 0)$

$S_R = \max(v_{x,L} + c_{f,L}, v_{x,R} + c_{f,R}, 0)$



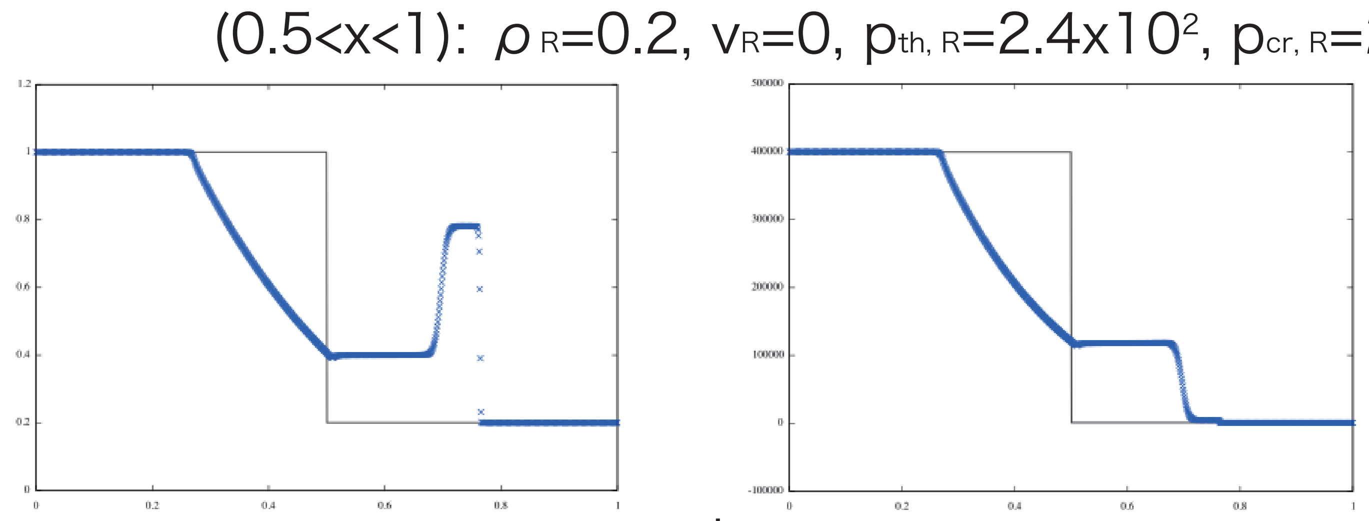
$$c_f = \left\{\frac{(C_s'^2 + v_{A,x}^2 + \sqrt{(C_s'^2+v_{A,x}^2)^2 - 4C_s'^2 v_{A,x}^2}}{2}\right\}^{1/2} \qquad C_s' = \sqrt{\frac{\gamma_{\rm gas}p_{\rm gas} + \gamma_{\rm cr}p_{\rm cr}}{\rho}}$$

We just chang from the speed of sound to "effective speed of sound" (Miniati 2007). Using C_s' , we computed c_f, S_L & S_R.

4. Test Suite

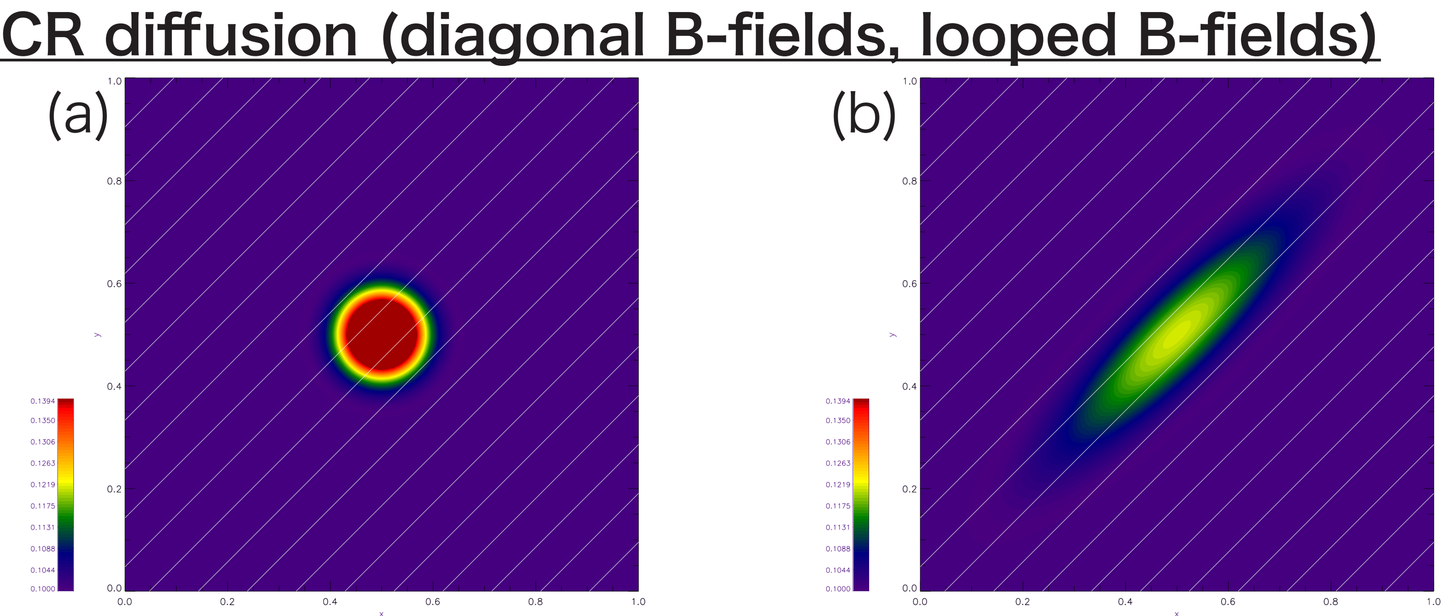
①1D-Shock Tube(no-B fields)

Initial condition(0<x<0.5): $\rho_L=1$, $v_L=0$, $p_{th,L}=6.7\times10^4$, $p_{cr,L}=1.3\times10^5$
(0.5<x<1): $\rho_R=0.2$, $v_R=0$, $p_{th,R}=2.4\times10^2$, $p_{cr,R}=2.4\times10^2$

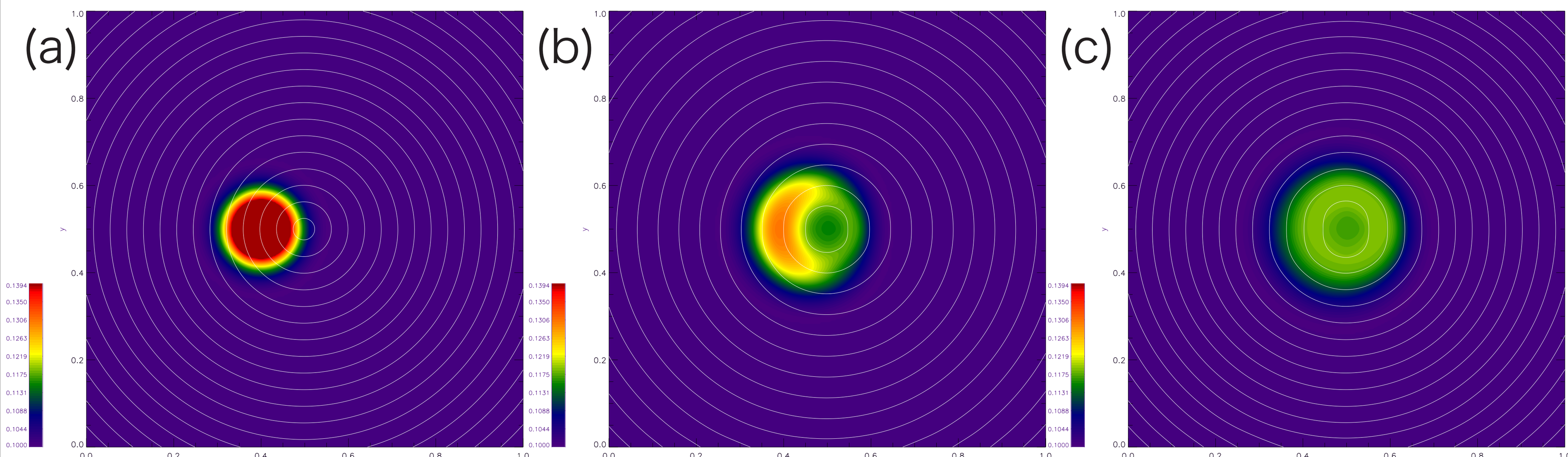


Left: ρ, right: e_{cr}

②2D-CR diffusion (diagonal B-fields, looped B-fields)



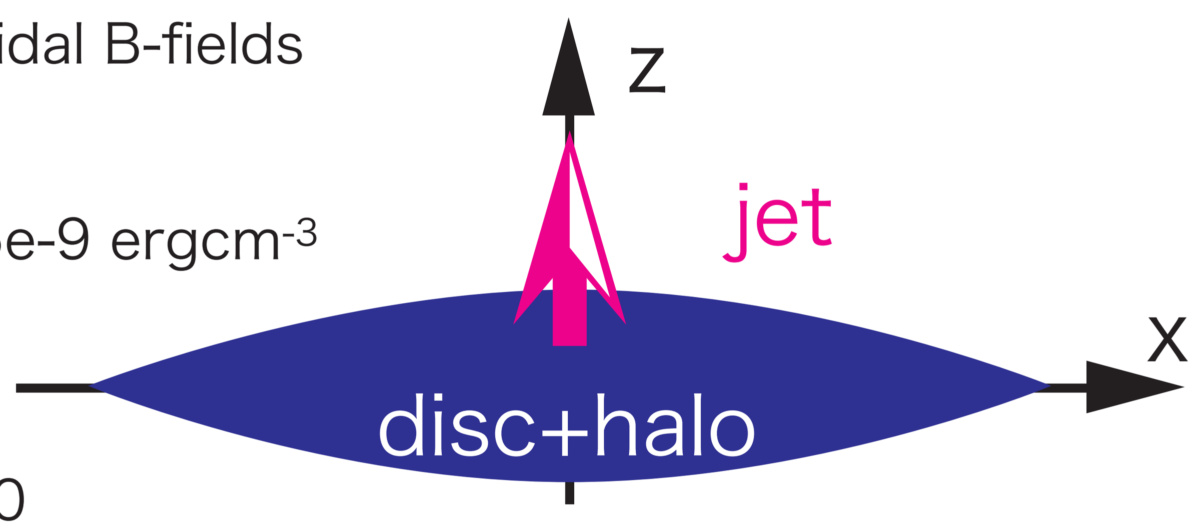
color: e_{cr}, white lines: B-fields line, (a)t=0, (b)t=1.0
CR diffuse in the diagonal direction along the field lines as expected.



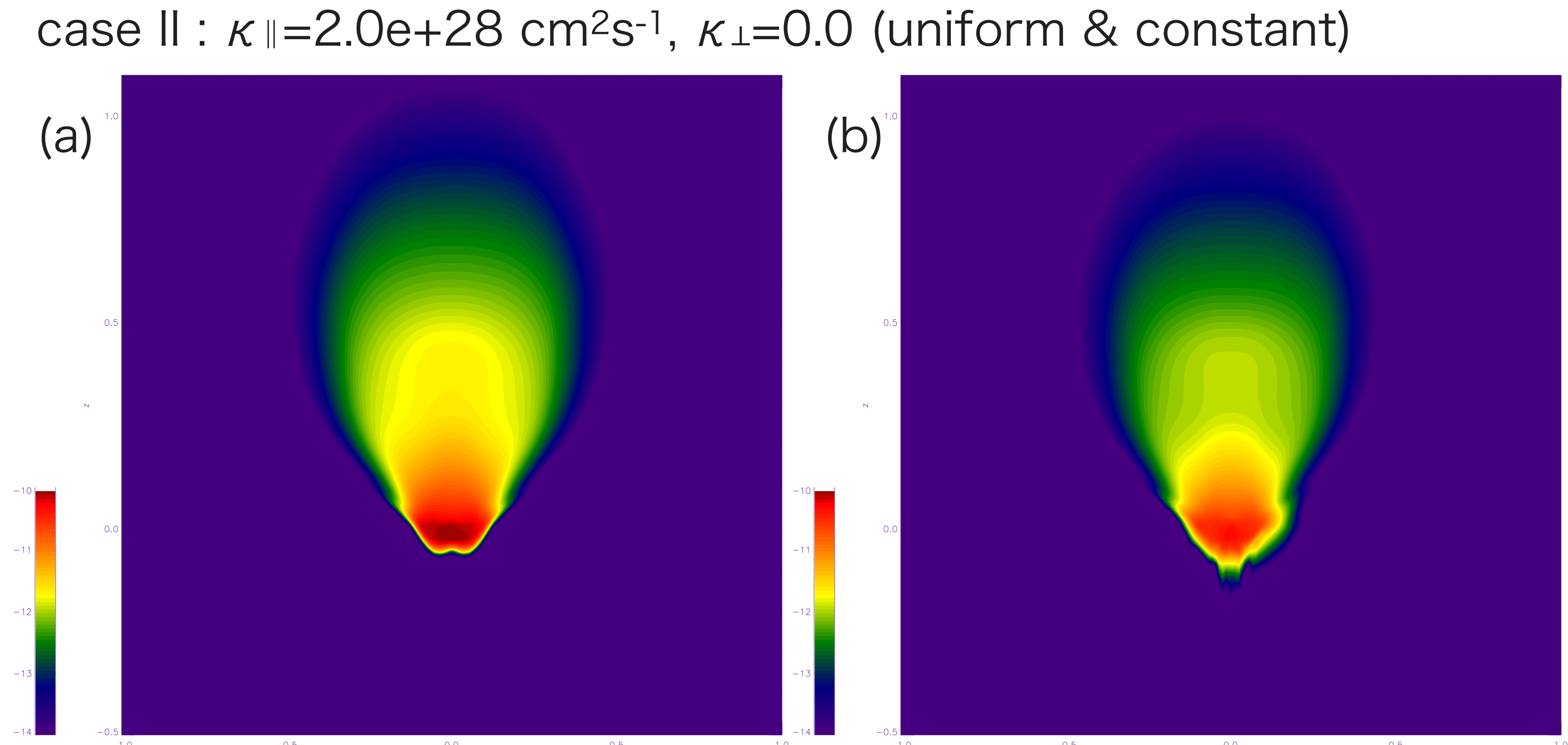
color: e_{cr}, white lines: B-fields line, (a)t=0, (b)t=0.5, (c)t=2.0
CR diffuse along the looped field lines, and go around to the ather side.

5. Application to Fermi Bubbles

We consider CR, toroidal B-fields injections GC.
ρ=1.672e-25 gcm^{-3},
v_x=0.0, v_y=0.0, e_{th}=1.5e-9 ergcm^{-3}
v_z=0.01c, B_Φ=20μG
e_{cr}=1.5e-9 ergcm^{-3}



case I : $\kappa_{\parallel}$=0.0, $\kappa_{\perp}$=0.0
case II : $\kappa_{\parallel}$=2.0e+28 cm^{2}s^{-1}, $\kappa_{\perp}$=0.0 (uniform & constant)



simulation result @ 1.5Myr, color: e_{cr}. (a)case I, (b)case II

6. Conclusion & Future Works

We have proposed a new HLL solver for MHD with CR-effects.
=>It' s successful in some tests.
In our Fermi bubbles model, CR distribution is not sharp edge & not flat brightness.
=>we need more model (starburst, AGN jet duration, multipumping)
In order to compare with observation, we should make Synchrotron intensity & polarization map.