Magnetic field generation by the first cosmic rays

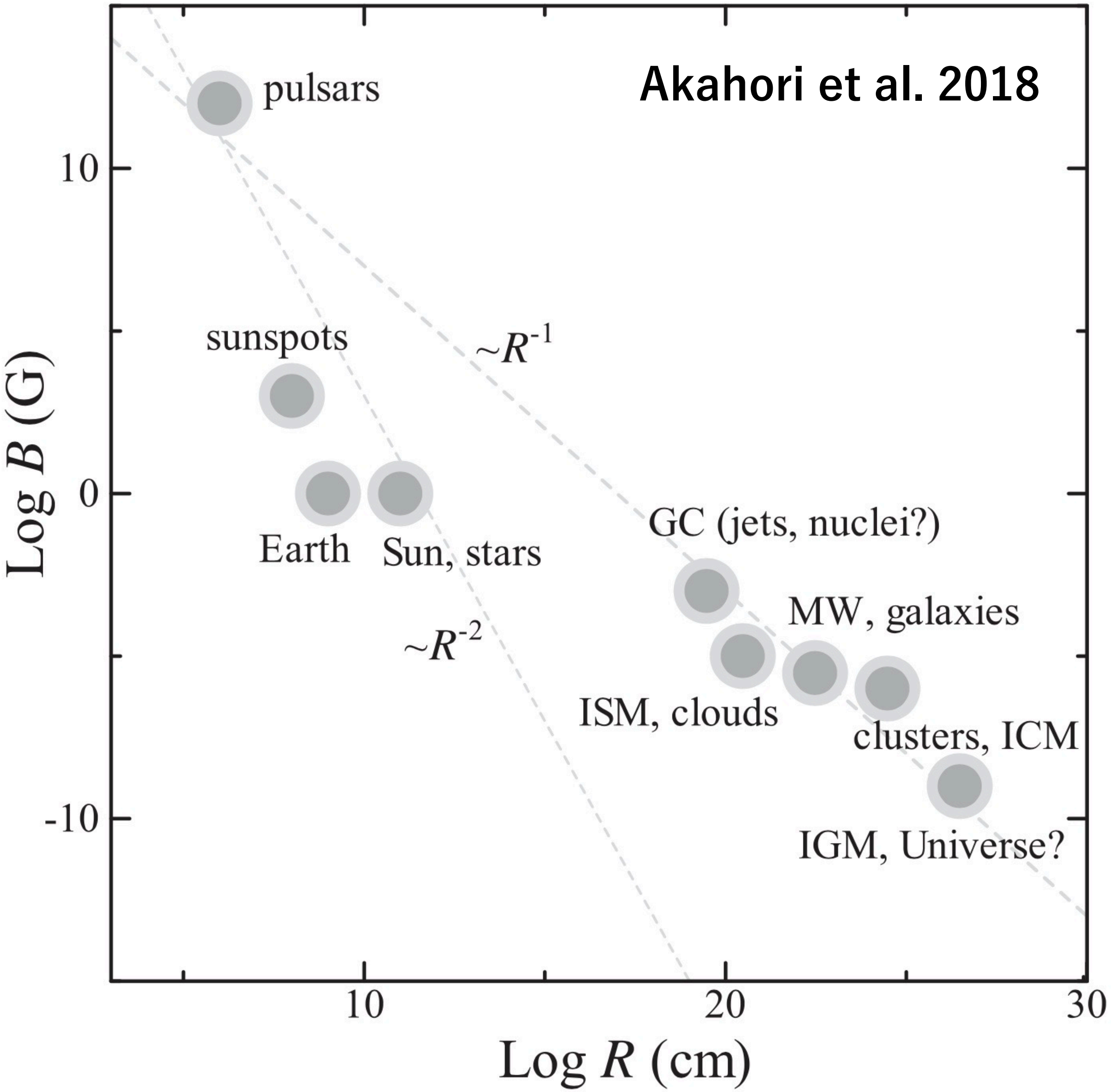
Yutaka Ohira The University of Tokyo

Ref: Ohira & Murase, PRD (2019), Ohira, ApJL (2020), Ohira, ApJ (2021)

Contents

- First cosmic rays at $z \sim 20$ ($t_{uni} \sim 10^8$ yr)
- Magnetic field generation by the streaming CRs 1
- Magnetic field generation by the streaming CRs 2

Magnetic field in the current universe



The magnetic field is ubiquitous in the current universe and plays various roles in different environments.

B ~ 10^{-9} - 10^{-6} G in cluster of galaxies,

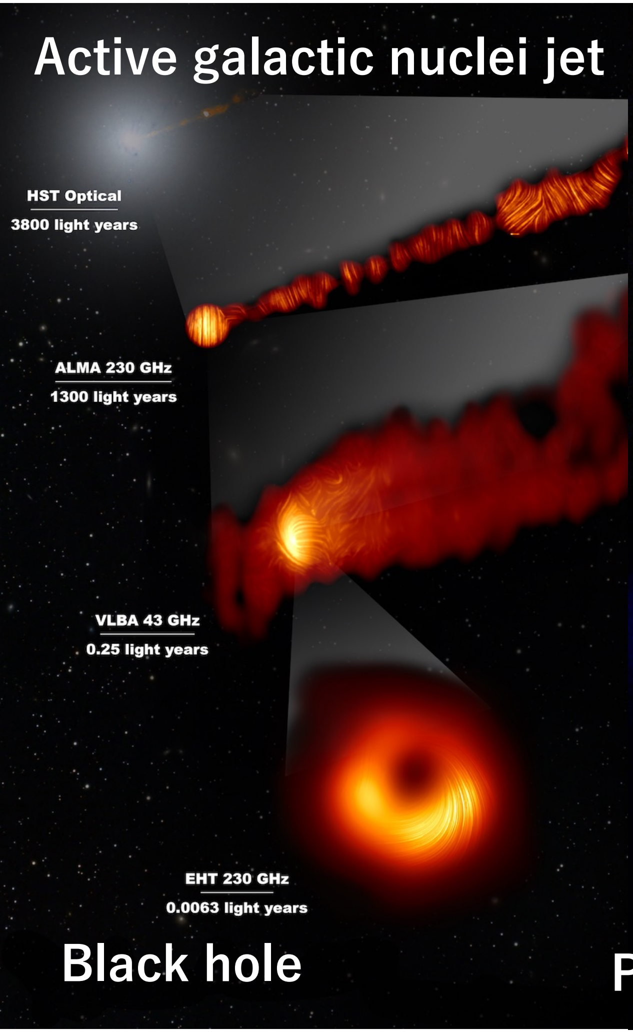
B ~ 10^{-6} G in galaxies,

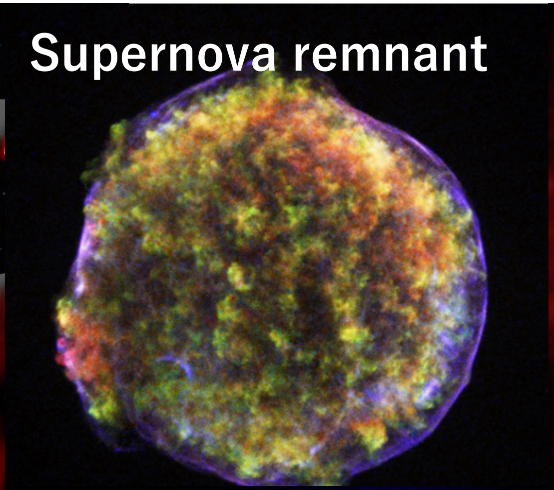
B ~ 10^{0} - 10^{3} G in stars and planets,

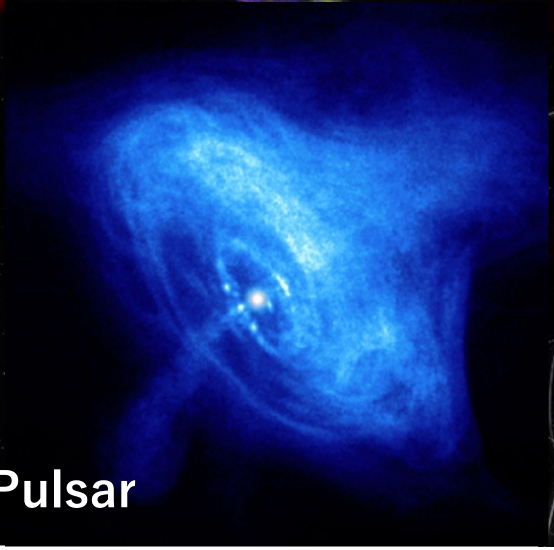
B ~ 10^{12} - 10^{15} G in pulsars

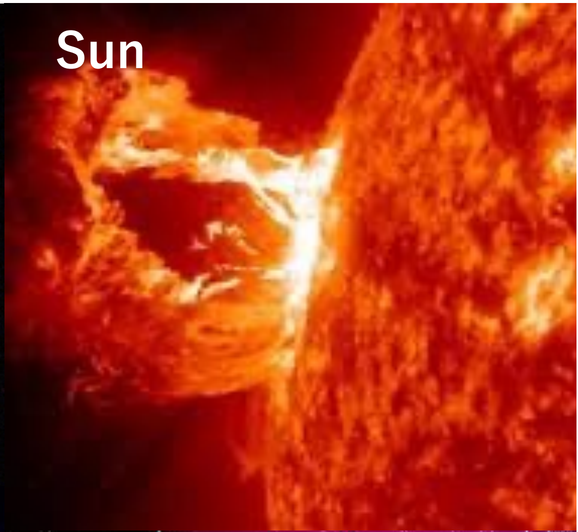
It has not been understood when, where, and how the magnetic field was first generated and amplified in the universe.

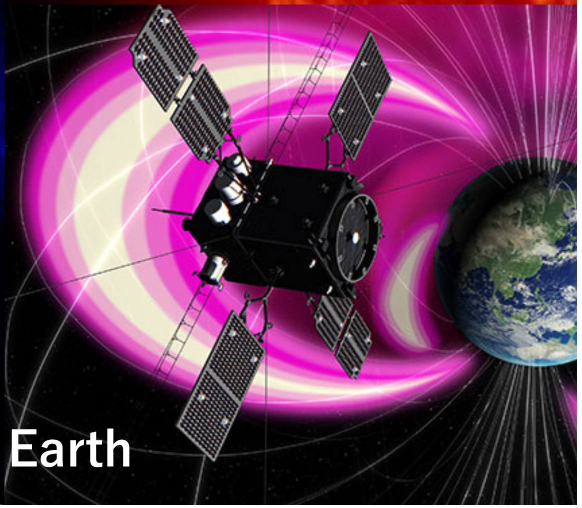
Nonthermal high energy particles in the universe

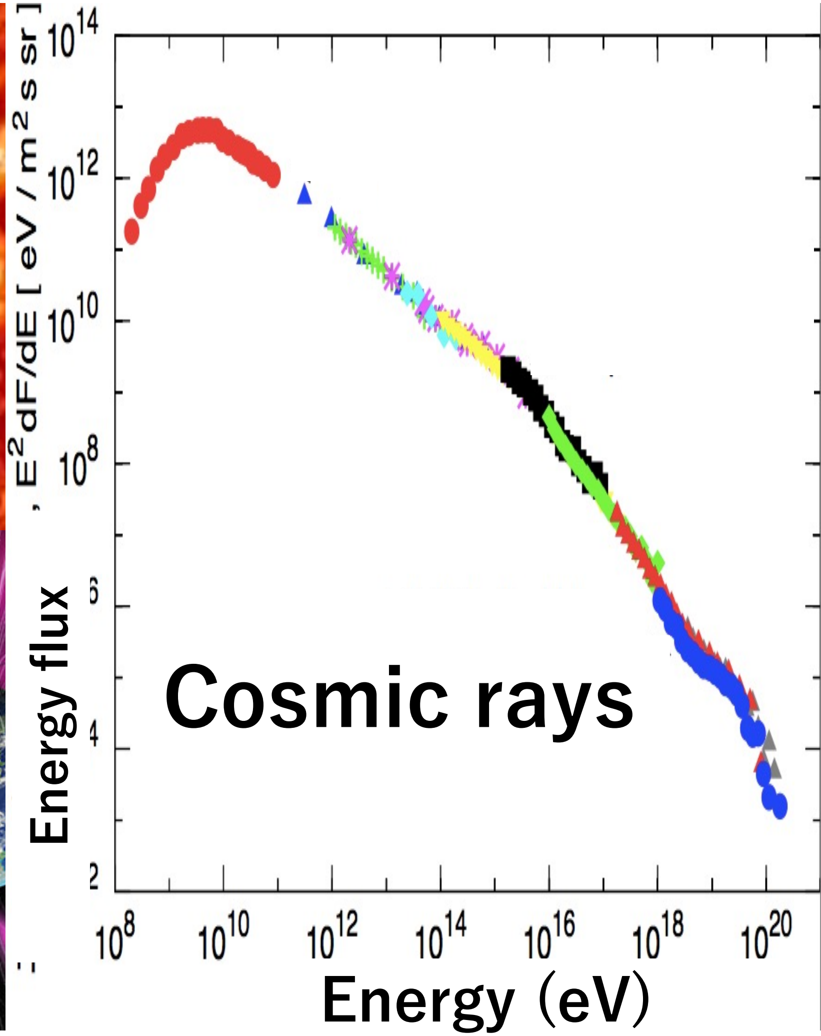












When, where, how were CRs first accelerated since the Big Bang?

Naively, CRs are thought to be accelerated after large-scale magnetic fields are generated and amplified.

Our scenario of magnetogenesis

Generation of large scale magnetic field

Strong collisionless shocks generate small scale magnetic field by the Weibel instability.

↓

The first cosmic rays are accelerated by the shocks with the small scale magnetic fields.

(Ohira&Murase 2019)

↓

The propagating first cosmic rays generate large scale magnetic fields.

+

Amplification

MHD process

- Turbulent dynamo
- Galactic dynamo

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B})$$

In our scenario, CRs are accelerated before the generation of large scale magnetic fields. Then, CRs generate large scale magnetic fields. (Ohira & Murase, PRD 2019)

Magnetic field generation in a plasma with streaming CRs.

Generalized Ohm's law

$$\frac{\partial}{\partial t}\left(\sum_s q_s n_s \boldsymbol{V}_s\right) + \boldsymbol{\nabla}\cdot\left(\sum_s q_s n_s \boldsymbol{V}_s \boldsymbol{V}_s\right) = \sum_s \frac{q_s^2 n_s}{m_s}\left(\boldsymbol{E} + \frac{\boldsymbol{V}_s \times \boldsymbol{B}}{c}\right) + \sum_s \frac{q_s}{m_s}\left(\boldsymbol{f}_s - \boldsymbol{\nabla} p_s\right)$$

Astrophysical plasmas are at least three-component plasmas, electron, proton, and CR proton.

If one of the three plasmas has some inhomogeneities, the second term on the left hand side does not always vanish, which has not been considered for the magnetic field generation.

$$\boldsymbol{E} = \frac{m_{\mathrm{e}}}{e^2 n_{\mathrm{e}}}\boldsymbol{\nabla}\cdot\left(\sum_s q_s n_s \boldsymbol{V}_s \boldsymbol{V}_s\right)$$

←New battery mechanism **(Ohira ApJL 2020)**

For the proton rest frame, $J_{\mathrm{tot}}=0$ → $-en_{\mathrm{e}}V_{\mathrm{e}} + en_{\mathrm{CR}}V_{\mathrm{CR}}=0$.

$$\Sigma\, q_s n_s V_s V_s = -en_{\mathrm{e}}V_{\mathrm{e}}^2 + en_{\mathrm{CR}}V_{\mathrm{CR}}^2 = en_{\mathrm{CR}}V_{\mathrm{CR}}\,(-V_{\mathrm{e}} + V_{\mathrm{CR}}) = en_{\mathrm{CR}}V_{\mathrm{CR}}^2\,[\,1 - (n_{\mathrm{CR}}/n_{\mathrm{e}})\,] \neq 0$$

The Biermann battery induced by the return current

$$\frac{\partial p_{\rm e}}{\partial t} + \boldsymbol{V}_{\rm e} \cdot \boldsymbol{\nabla} p_{\rm e} = -\gamma p_{\rm e} \boldsymbol{\nabla} \cdot \boldsymbol{V}_{\rm e} \Longrightarrow p_{\rm e} = p_{{\rm e},0} \exp\left(-\gamma t \frac{\partial V_{\rm e}}{\partial x}\right)$$

($\nabla p_e = 0$ at $t = 0$, $V_e = V_e\, e_x$)

Since $n_e \sim n_p + n_{CR}$ = constant in time, even though $\nabla p_e \times \nabla n_e = 0$ at $t=0$,

$\nabla p_e \times \nabla n_e \neq 0$ is possible at $t > 0$.

Ohm's law →
$$\boldsymbol{E} = \frac{m_{\rm e}}{e^2 n_{\rm e}} \boldsymbol{\nabla} \cdot \left(\sum_s q_s n_s \boldsymbol{V}_s \boldsymbol{V}_s\right) - \underline{\frac{\boldsymbol{\nabla} p_{\rm e}}{e n_{\rm e}}}$$

$\partial \boldsymbol{B}/\partial t = -c \boldsymbol{\nabla} \times \boldsymbol{E}$, J_{CR} = constant, and $V_p = 0$, $n_e = n_e(x,y,z)$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \frac{m_{\rm e} c}{2e} \boldsymbol{\nabla} \times \frac{\partial V_{\rm e}^2}{\partial x} \boldsymbol{e}_{\rm x} - \underline{\frac{c p_{\rm e} \gamma t}{e n_{\rm b} V_{\rm b}} \boldsymbol{\nabla} V_{\rm e} \times \boldsymbol{\nabla} \frac{\partial V_{\rm e}}{\partial x}}$$

Ohira, ApJ (2021)

Multi-fluid plasma simulation

Initial condition of three plasmas

$$n_{\rm e} = n_{\rm e,0}\left[1 + \delta\left\{\sin\left(\frac{2\pi}{L}x\right) + \sin\left(\frac{2\pi}{L}y\right)\right\}\right]^{-1}$$

$$n_{\rm p} = n_{\rm e} - Z_{\rm b} n_{\rm b,0},$$

$$n_{\rm b} = n_{\rm b,0},$$

$$p_{\rm e} = p_{\rm p} = p_{\rm e,0},$$

$$p_{\rm b} = p_{\rm b,0},$$

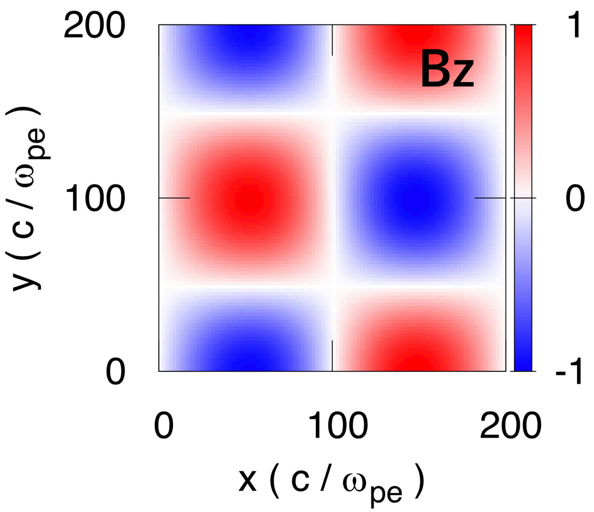
$$\boldsymbol{V}_{\rm e} = V_{\rm e,0}\left(\frac{n_{\rm e,0}}{n_{\rm e}}\right)\boldsymbol{e}_{\rm x},$$

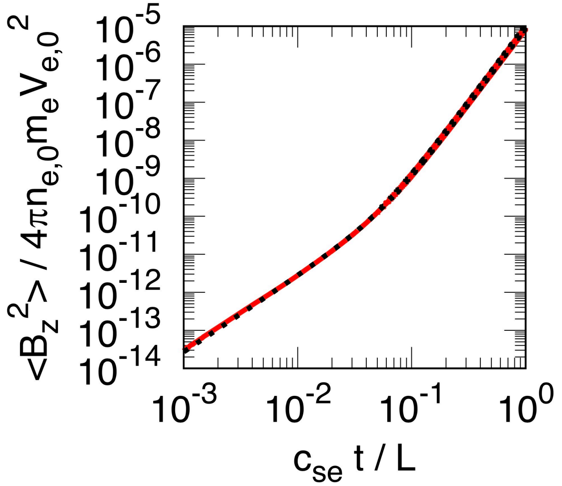
$$\boldsymbol{V}_{\rm p} = 0,$$

$$\boldsymbol{V}_{\rm b} = V_{\rm e,0}\left(\frac{n_{\rm e,0}}{Z_{\rm b} n_{\rm b,0}}\right)\boldsymbol{e}_{\rm x},$$

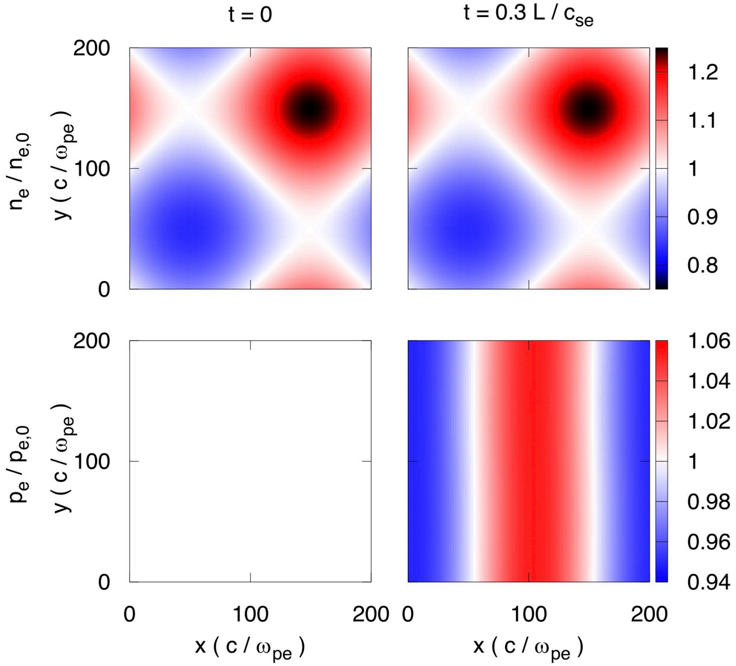
Analytical solution

$$\boldsymbol{B} = -\frac{4\pi^2 m_{\rm e} c V_{\rm e,0}\delta^2}{eL}\cos\left(\frac{2\pi}{L}y\right)\boldsymbol{e}_{\rm z} \times \left\{\left(\frac{V_{\rm e,0}t}{L}\right)\cos\left(\frac{2\pi}{L}x\right) + \pi\left(\frac{c_{\rm se}t}{L}\right)^2\sin\left(\frac{2\pi}{L}x\right)\right\}$$





The dashed line shows the analytical solution.



n_e does not change but
p_e changes as time goes on.

All simulation results are excellently in agreement with the analytical solutions.

(Ohira ApJ 2021)

Order of magnitude estimate

$$\frac{\partial \boldsymbol{B}}{\partial t} = \underline{\frac{m_\mathrm{e} c}{2e} \boldsymbol{\nabla} \times \frac{\partial V_\mathrm{e}^2}{\partial x}} \boldsymbol{e}_\mathrm{x} - \underline{\frac{c p_\mathrm{e} \gamma t}{e n_\mathrm{b} V_\mathrm{b}} \boldsymbol{\nabla} V_\mathrm{e} \times \boldsymbol{\nabla} \frac{\partial V_\mathrm{e}}{\partial x}}$$

Supernova rate ~ 10^{-7}/Mpc^3/yr @z~20, E_{CR} ~ 10^{50} erg/SN → u_{CR} ~ 3×10^{-6} eV/cm^3 @z~20

→ n_{CR} ~ 3×10^{-14} /cm^3 @z~20

n_e ~ 10^{-7}/cm^3 @z~20 → V_e ~ (n_{CR} / n_e) (V_{CR} / c) ~ 0.1 km/s (V_{CR} / c) @z~20

T_e ~ 0.1eV @z~20

$B \sim 7.5 \times 10^{-26}\ \mathrm{G}\ V_{e,0.1km/s}^{2}\ L_{kpc}^{-2}\ t_{100Myr}$

$B \sim 5.5 \times 10^{-21}\ \mathrm{G}\ T_{e,0.1eV}\ V_{e,0.1km/s}\ L_{kpc}^{-3}\ t_{100Myr}^{2}$

These are sufficiently large to be the seed of the magnetic field in current galaxies (e.g. Davis et al. 1999).

Summary

Cosmic rays and magnetic fields have important roles in many current astrophysical systems.

When, where, how were first cosmic rays accelerated?

When, where, how were magnetic fields first generated?

In the standard picture, CRs are accelerated after the generation of large scale magnetic fields.

We proposed a new scenario.

First, supernova remnant shocks of first stars generate small scale magnetic fields.
The small scale magnetic fields and the shocks accelerate first cosmic rays to ~ 110 MeV
at 1.8×10^{8} years after the BigBang ($z \sim 20$).

After the first CRs escape from the first SNRs, they induce a nonuniform electron return flow.

The nonuniform electron return flow drives the Biermann battery mechanism which generates large scale magnetic fields, $B \sim 10^{-20}$ G at $z \sim 20$.