Generation of Magnetic Field by Radiation Pressure of First Stars

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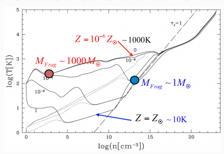
Abstract

We investigate magnetic field generation in the early universe by radiation force of first stars. In the previous study with steady assumption, large amplitude(～10^{-11}G for QSOs) is predicted. In this study, we formulate this issue in unsteady framework. Then, we consider a specific model of magnetic field generation around a vey massive first star. Consequently, we find steady assumtion is not valid in realistic situation, which results in much smaller magnetic field strength than predicted by Langer et al. (2003). In addition, we find momentum transfer process through photoionization is more important than Thomson scattering. The resultant magnetic flux density around first star is ～10^{-19}G. These seed magnetic field do not affect subsequent star formation in the neighbor of first stars.

Transition from POPIII to POPI

Metals



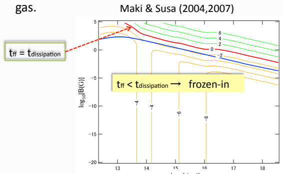
$Transition@Z \sim 10^{-5} Z_\odot$?

Omukai ,Schneider, Tsuribe

Magnetic Field

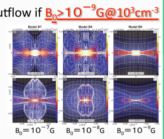
Magnetic field is always frozen in the primordial gas.

Maki & Susa (2004,2007)



1. Strong Bipolar outflow if $B_0 > 10^{-9}$G@10^3cm^{-3}

Machida et al. (2006)



2. MRI is activated in accretion disk if $B_0 > 10^{-10}$G@10^3cm^{-3}

Tan & Blackman (2004) $t_{diffusion} > 1/\Omega$

Radiation pressure driven B Generation

Intense radiation from first stars cause charge separation in their HII region.

↓

Eddy current is formed at the boundary of the shadow.

↓

Magnetic field is generated.

How strong?

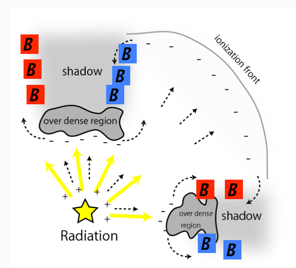
According to Langer et al. 2003

Steady equation indicates

$B \approx 10^{-15}$G for first stars

$B \approx 10^{-11}$G for QSOs

Is this correct?



Basic Equations

force balance on electrons

$$0 = -e\boldsymbol{E} + \frac{e}{\sigma_c}\boldsymbol{j} + \boldsymbol{f}_{\rm rad} - \frac{\nabla p_e}{n_e} - \frac{e}{c}\boldsymbol{v}\times\boldsymbol{B} + \frac{1}{cn_e}\boldsymbol{j}\times\boldsymbol{B}$$

Maxwell Equations

$$\nabla\cdot\boldsymbol{E} = 4\pi\rho, \quad \nabla\times\boldsymbol{E} = -\frac{1}{c}\frac{\partial\boldsymbol{B}}{\partial t}, \quad \nabla\cdot\boldsymbol{B} = 0, \quad \nabla\times\boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{j} + \frac{1}{c}\frac{\partial\boldsymbol{E}}{\partial t}$$

$\nabla\times$ (force balance on electrons) combined with (Maxwell Equations)

$$\frac{1}{c^2}\frac{\partial^2 B}{\partial t^2} - \nabla^2 B + \frac{4\pi\sigma_c}{c^2}\frac{\partial B}{\partial t} = \frac{4\pi\sigma_c}{c^2}\nabla\times(v\times B) - \frac{4\pi\sigma_c}{c^2}\nabla\times\left(\frac{j\times B}{en_e}\right) - \frac{4\pi\sigma_c}{cen_e^2}\nabla n_e\times\nabla p_e - \frac{4\pi\sigma_c}{ce}\nabla\times f_{\rm rad}$$

$t \approx 10^6$ yr $L \approx 1$kpc $\frac{1}{4\pi\sigma_c} \approx 10^{-12}$s

$$\frac{\partial\boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B}) - \frac{c}{en_e^2}\nabla n_e\times\nabla p_e - \frac{c}{e}\nabla\times\boldsymbol{f}_{\rm rad}$$

advection term | Biermann Battery Term | Radiation Term

Rate equation of ionization

$$\frac{\partial n_e}{\partial t} + \nabla\cdot(n_e\boldsymbol{v}_e) = \Gamma - \alpha n_e n_p$$

Radiation force by Thomson Scatt.

$$\boldsymbol{f}_{\rm rad,T} = \frac{\sigma_T}{c}\int_0^{\nu_L}\boldsymbol{F}_{0\nu}d\nu + \frac{\sigma_T}{c}\int_{\nu_L}^{\infty}\boldsymbol{F}_{0\nu}\exp\left[-\tau_{\nu_L}a(\nu)\right]d\nu$$

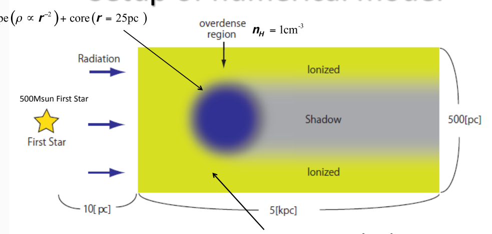
Radiation force by photoionization

$$\boldsymbol{f}_{\rm rad,I} = \frac{1}{2}\frac{n_{\rm HI}}{cn_e}\int_{\nu_L}^{\infty}\sigma_{\nu_L}a(\nu)\boldsymbol{F}_{0\nu}\exp\left[-\tau_{\nu_L}a(\nu)\right]d\nu$$

T=10^4K is assumed (isothermal). -> Biermann Battery Term vanishes.

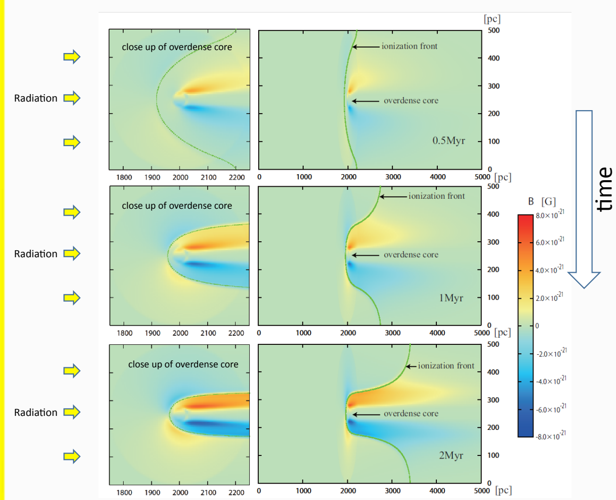
Setup of numerical model

envelope $(\rho \propto r^{-2})$ + core $(r = 25\text{pc})$



IGM@z=20 $n_H = 10^{-2}$cm^{-3}

Results



1. B=10^{-21}-10^{-19}G is generated when we change the parameters within reasonable range (distance 200pc-2kpc, central density 1cm^{-3}-10cm^{-3}).
2. Momentum transfer through photoionization process is more important than Thomson scattering.

Summary

- Radiation force by first stars generates magnetic field < 10^{-19}G in their HII regions.
- Steady assumption is not valid.
- Magnetic field strength generated in this process is too weak to affect second generation star formation.