The effects of non-helical component of hypermagnetic field on the evolution of the matter-antimatter asymmetry, vorticity, and hypermagnetic field

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- Introduction
- Chiral Vortical Effect (CVE) and Chiral Magnetic Effect (CME)
- Anomalous Magneto Hydro Dynamics (AMHD)
- Non Helical Hyper Magnetic Field (NHHMF)
- Results

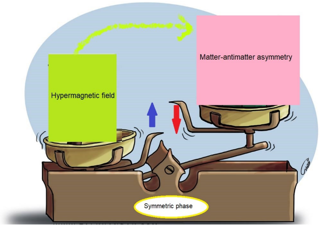
Magnetic field:

- The Universe is magnetized on all scales that we have observed so far, planets, stars, galaxies, and galaxy clusters.
- galaxies $\rightarrow B \sim 10^{-6} G$ &, $\lambda_c \sim kpc$.
- Intra-cluster medium (ICM) in clusters $\rightarrow B \sim (1-10)10^{-6} G$ &, $\lambda_c \sim (10-100) kpc$.
- Intergalactic medium (IGM) $\rightarrow B \sim (10^{-16} - 10^{-9}) G$ &, $\lambda_c \sim Mpc$.

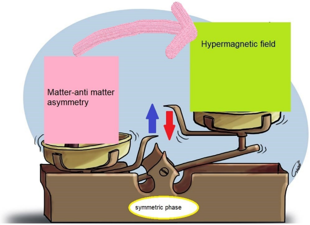
Magnetogenesis models:

- Astrophysical models (Biermann Battery mechanism, Dynamo Mechanism ,...)
- Models based on early universe processes (Inflationary scenario, Phase transition, Asymmetries in the early Universe)

In fact, the matter-antimatter asymmetry generation and the (hyper)magnetogenesis are strongly intertwined via the $U(1)_Y$ Abelian anomalous effects: $\partial_\mu j^\mu \sim F_{\mu\nu}\tilde{F}^{\mu\nu} \sim \vec{E}_Y.\vec{B}_Y$.



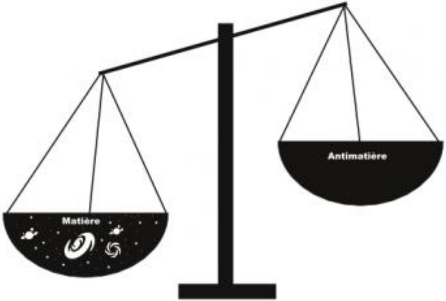
(a)



(b)

Baryon asymmetry:

- Our Universe contains more matter (baryons) than the antimatter (antibaryons) with the measured baryon asymmetry of the order $\eta \sim 10^{-10}$.
- Sakharov stated three necessary conditions for generating the BAU:
  (i) baryon number violation,
  (ii) *C* and *CP* violation,
  (iii) departure from thermal equilibrium.



Anomalous current:

- CME: The chiral magnetic effect refers to the generation of an electric current parallel to the magnetic field in an imbalanced chiral plasma, $J^{\mu}_{\mathrm{cm,r}} = \frac{rQ_{\mathrm{r}}^2}{4\pi^2}\mu_{\mathrm{r}}\vec{B}_Y$.
- CVE: The chiral vortical effect, generically induced by the rotation of chiral matter, refers to the generation of an electric current parallel to the vorticity field, $\vec{J}_{\mathrm{cv,r}} = rQ_{\mathrm{r}}\left(\frac{T^2}{24} + \frac{\mu_r^2}{8\pi^2}\right)\vec{\omega}$.

Anomaly + Magneto Hydro Dynamic (MHD)
$\Rightarrow$ Anomalous Magneto Hydro Dynamic (AMHD).

Anomalous MagnetohHydroDynamics:

The energy-momentum tensor $T^{\mu\nu}$ and the total electric current J^{μ} are given by

$$T^{\mu\nu} = (\rho + p)u^{\mu}u^{\nu} - pg^{\mu\nu} + \frac{1}{4}g^{\mu\nu}F^{\alpha\beta}F_{\alpha\beta} - F^{\nu\sigma}F^{\mu}{}_{\sigma} + \tau^{\mu\nu}, \tag{1}$$

$$J^{\mu} = \rho_{\rm el}u^{\mu} + J^{\mu}_{\rm cm} + J^{\mu}_{\rm cv} + \nu^{\mu}, \tag{2}$$

$$J^{\mu}_{\rm cm} = \sum_{i=l,q}(Q_{\rm R_i}\xi_{\rm B,R_i} + Q_{\rm L_i}\xi_{\rm B,L_i})B^{\mu} = c_{\rm B}B^{\mu}, \tag{3}$$

$$J^{\mu}_{\rm cv} = \sum_{i=l,q}(Q_{\rm R_i}\xi_{\rm v,R_i} + Q_{\rm L_i}\xi_{\rm v,L_i})\omega^{\mu} = c_{\rm v}\omega^{\mu} \tag{4}$$

$$\nu^{\mu} = \sigma E^{\mu} \tag{5}$$

where, $u^{\mu} = \gamma(1, \vec{v}/R)$ is the four-velocity of the plasma normalized such that $u^{\mu}u_{\mu} = 1$. ν^{μ} and $\tau^{\mu\nu}$ denote the electric diffusion current and viscous stress tensor, respectively. $B^{\mu} = (\epsilon^{\mu\nu\rho\sigma}/2R^3)u_{\nu}F_{\rho\sigma}$ is the magnetic field four-vector, $E^{\mu} = F^{\mu\nu}u_{\nu}$ is the electric field four-vector, and $\omega^{\mu} = (\epsilon^{\mu\nu\rho\sigma}/R^3)u_{\nu}\nabla_{\rho}u_{\sigma}$ is the vorticity four-vector, with the totally anti-symmetric Levi-Civita tensor density specified by $\epsilon^{0123} = -\epsilon_{0123} = 1$.

$$\xi_{\mathrm{B,R}} = \frac{Q_{\mathrm{R}}\mu_{\mathrm{R}}}{4\pi^2}, \tag{6}$$

$$\xi_{\mathrm{B,L}} = -\frac{Q_{\mathrm{L}}\mu_{\mathrm{L}}}{4\pi^2}, \tag{7}$$

$$\xi_{\mathrm{v,R}} = \frac{\mu_{\mathrm{R}}^2}{8\pi^2} + \frac{1}{24}T^2, \tag{8}$$

$$\xi_{\mathrm{v,L}} = -\frac{\mu_{\mathrm{L}}^2}{8\pi^2} - \frac{1}{24}T^2. \tag{9}$$

The equations of AMHD consist of:

- The Maxwell's equations:

$$\nabla_\mu F^{\mu\nu} = J^\nu, \qquad F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu$$
$$\nabla_\mu \tilde{F}^{\mu\nu} = 0, \qquad \tilde{F}^{\mu\nu} = \frac{1}{2R^3}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}, \tag{10}$$

- The energy-momentum conservation

$$\nabla_\mu T^{\mu\nu} = 0, \tag{11}$$

- Anomaly equations:

$$\nabla_\mu j^\mu_{\rm R,L} = C_{\rm R,L} F_{\mu\nu}\tilde{F}^{\mu\nu} \tag{12}$$

$$j^\mu_{\rm R} = n_{\rm R} u^\mu + \xi_{\rm B,R} B^\mu + \xi_{\rm v,R}\omega^\mu + V^\mu_R \simeq n_{\rm R} u^\mu,$$
$$j^\mu_{\rm L} = n_{\rm L} u^\mu + \xi_{\rm B,L} B^\mu + \xi_{\rm v,L}\omega^\mu + V^\mu_L \simeq n_{\rm L} u^\mu, \tag{13}$$

Maxwell's equations: $\nabla_\mu F^{\mu\nu} = J^\nu, \qquad \nabla_\mu \tilde{F}^{\mu\nu} = 0$

$$\frac{1}{R}\vec{\nabla}.\vec{E}_Y = 0, \qquad \frac{1}{R}\vec{\nabla}.\vec{B}_Y = 0, \tag{14}$$

$$\frac{1}{R}\vec{\nabla} \times \vec{E}_Y + \left(\frac{\partial \vec{B}_Y}{\partial t} + 2H\vec{B}_Y\right) = 0, \tag{15}$$

$$\frac{1}{R}\vec{\nabla} \times \vec{B}_Y - \left(\frac{\partial \vec{E}_Y}{\partial t} + 2H\vec{E}_Y\right) = \vec{J} \tag{16}$$

$$\vec{J} = \underbrace{\sigma\left(\vec{E}_Y + \vec{v} \times \vec{B}_Y\right)}_{\vec{J}_{\rm Ohm}} + \underbrace{c_{\rm B}\vec{B}_Y}_{\vec{J}_{\rm cm}} + \underbrace{c_{\rm v}\vec{\omega}}_{\vec{J}_{\rm cv}}, \tag{17}$$

$$\vec{E}_Y = \frac{1}{\sigma R}\vec{\nabla}\times\vec{B}_Y - \frac{c_{\rm v}}{\sigma}\vec{\omega} - \frac{c_B}{\sigma}\vec{B}_Y - \vec{v}\times\vec{B}_Y. \tag{18}$$

$$\frac{\partial\vec{B}_Y}{\partial t} = \frac{1}{\sigma R^2}\nabla^2\vec{B}_Y + \frac{c_{\rm v}}{\sigma R}\vec{\nabla}\times\vec{\omega} + \frac{c_B}{\sigma R}\vec{\nabla}\times\vec{B}_Y + \frac{1}{R}\vec{\nabla}\times(\vec{v}\times\vec{B}_Y) - \frac{\vec{B}_Y}{t}, \tag{19}$$

CVE and CME coefficients:

$$c_{\rm v}(t) = \sum_{i=1}^{n_G} \Big[\frac{g'}{48} \Big(- Y_R T_{R_i}^2 + Y_L T_{L_i}^2 N_w - Y_{d_R} T_{d_{R_i}}^2 N_c - Y_{u_R} T_{u_{R_i}}^2 N_c + Y_Q T_{Q_i}^2 N_c N_w \Big) + \frac{g'}{16\pi^2} \Big(- Y_R \mu_{R_i}^2 + Y_L \mu_{L_i}^2 N_w - Y_{d_R} \mu_{d_{R_i}}^2 N_c - Y_{u_R} \mu_{u_{R_i}}^2 N_c + Y_Q \mu_{Q_i}^2 N_c N_w \Big) \Big], \tag{20}$$

$$c_{\rm B}(t) = -\frac{g'^2}{8\pi^2} \sum_{i=1}^{n_G} \Big[- \left(\frac{1}{2}\right) Y_R^2 \mu_{R_i} - \left(\frac{-1}{2}\right) Y_L^2 \mu_{L_i} N_w - \left(\frac{1}{2}\right) Y_{d_R}^2 \mu_{d_{R_i}} N_c - \left(\frac{1}{2}\right) Y_{u_R}^2 \mu_{u_{R_i}} N_c - \left(\frac{-1}{2}\right) Y_Q^2 \mu_{Q_i} N_c N_w \Big], \tag{21}$$

$$Y_L = -1, \quad Y_R = -2, \quad Y_Q = \frac{1}{3}, \quad Y_{u_R} = \frac{4}{3}, \quad Y_{d_R} = -\frac{2}{3}. \tag{22}$$

$$c_{\rm v}(t) = \frac{g'}{8\pi^2} \left(\mu_{e_R}^2 - \mu_{e_L}^2 \right), \qquad c_{\rm B}(t) = -\frac{g'^2}{8\pi^2} \left(-2\mu_{e_R} + \mu_{e_L} - \frac{3}{4}\mu_{\rm B} \right), \tag{23}$$

Continuity and Navier-Stokes equations: $\nabla_\mu T^{\mu\nu} = 0$

$$\frac{\partial \rho}{\partial t} + \frac{1}{R}\vec{\nabla}.\left[(\rho + p)\,\vec{v}\right] + 3H\,(\rho + p) = 0, \tag{24}$$

$$\left[\frac{\partial}{\partial t} + \frac{1}{R}\left(\vec{v}.\vec{\nabla}\right) + H\right]\vec{v} + \frac{\vec{v}}{\rho + p}\frac{\partial p}{\partial t} = -\frac{1}{R}\frac{\vec{\nabla} p}{\rho + p} + \frac{\vec{J}\times\vec{B}_Y}{\rho + p} + \frac{\nu}{R^2}\left[\nabla^2\vec{v} + \frac{1}{3}\vec{\nabla}\left(\vec{\nabla}.\vec{v}\right)\right], \tag{25}$$

$$\Rightarrow \frac{\partial \vec{v}}{\partial t} = \frac{\vec{J}\times\vec{B}_Y}{\rho + p} + \frac{\nu}{R^2}\nabla^2\vec{v}, \tag{26}$$

$$\nu \simeq 1/(5\alpha_Y T)$$

Anomaly equations: $\nabla_\mu j^\mu_{\mathrm{R,L}} = C_{\mathrm{R,L}} F_{\mu\nu}\tilde{F}^{\mu\nu}$,

$$\Rightarrow \partial_t \eta_{R,L} = \frac{-4C_{\mathrm{R,L}}}{s}\langle \vec{E}_Y.\vec{B}_Y \rangle, \tag{27}$$

where $\eta_i = (n_i - \bar{n}_i)/s$, $s = (2\pi^2 g^* T^3)/45$ is entropy, and $g^* = 106.75$ is the number of relativistic degrees of freedom.

The non-helical hypermagnetic field, vorticity and asymmetry

Since $\vec{\nabla}.\vec{B}_Y = 0$, the hypermagnetic field can be written as $\vec{B}_Y = (1/R)\vec{\nabla} \times \vec{A}_Y$, where $\vec{A}_Y$ is the vector potential of the hypermagnetic field. For incompressible fluid, $\vec{\nabla}.\vec{v} = 0$, in analogy with the hypermagnetic field, the velocity field can be written as $\vec{v} = (1/R)\vec{\nabla} \times \vec{S}$, where $\vec{S}$ is the vector potential of the velocity field. Now we choose the configurations for our hypermagnetic field and the velocity field by using the following orthonormal basis $\{\hat{a}(z,k) = (\cos kz, -\sin kz, 0),\ \hat{b}(z,k) = (\sin kz, \cos kz, 0),\ \hat{z}\}$.

$$\vec{B}_Y(t,z) = B_z(t)\hat{z} + B_a(t)\hat{a}(z,k) + B_b(t)\hat{b}(z,k), \tag{28}$$

$$\vec{v}(t,z) = v_a(t)\hat{a}(z,k) + v_b(t)\hat{b}(z,k), \tag{29}$$

$$\frac{1}{R}\vec{\nabla} \times (\vec{v} \times \vec{B}_Y) \neq 0, \qquad \textit{and} \qquad \frac{\vec{J} \times \vec{B}_Y}{\rho + p} \neq 0 \tag{30}$$

$$\langle \vec{E}_Y.\vec{B}_Y \rangle = -\frac{c_{\mathrm{B}}}{\sigma}\left[B_z^2(t) + B_a^2(t) + B_b^2(t)\right] + \frac{k'}{\sigma}\left[B_a^2(t) + B_b^2(t)\right] - \frac{c_{\mathrm{V}}}{\sigma}k'\left[v_a(t)B_a(t) + v_b(t)B_b(t)\right]. \tag{31}$$

$$
\begin{aligned}
\frac{\partial B_a(t)}{\partial t} =& k' \left[v_b(t)B_z(t)\right] + \left[-\frac{k'^2}{\sigma} + \frac{k' c_{\mathrm{B}}}{\sigma}\right] B_a(t) + \frac{k'^2 c_{\mathrm{v}}}{\sigma} v_a(t) - \frac{B_a(t)}{t},\\
\frac{\partial B_b(t)}{\partial t} =& - k' \left[v_a(t)B_z(t)\right] + \left[-\frac{k'^2}{\sigma} + \frac{k' c_{\mathrm{B}}}{\sigma}\right] B_b(t) + \frac{k'^2 c_{\mathrm{v}}}{\sigma} v_b(t) - \frac{B_b(t)}{t},\\
\frac{\partial B_z(t)}{\partial t} =& - \frac{B_z(t)}{t},\\
\frac{\partial v_a(t)}{\partial t} =& \frac{k'}{\rho + p}\left[B_b(t)B_z(t)\right] - k'^2 \nu v_a(t),\\
\frac{\partial v_b(t)}{\partial t} =& - \frac{k'}{\rho + p}\left[B_a(t)B_z(t)\right] - k'^2 \nu v_b(t).
\end{aligned}
\tag{32}
$$

$$\begin{aligned}
\frac{d\eta_{e_R}}{dt} &= \frac{g'^2}{4\pi^2 s}\langle \vec{E}_Y.\vec{B}_Y\rangle + \left(\frac{\Gamma_0}{t_{EW}}\right)\left(\frac{1-x}{\sqrt{x}}\right)(\eta_{e_L}-\eta_{e_R}), \\
\frac{d\eta_{e_L}}{dt} &= \frac{d\eta^L_{\nu_e}}{dt} = -\frac{g'^2}{16\pi^2 s}\langle \vec{E}_Y.\vec{B}_Y\rangle + \left(\frac{\Gamma_0}{2t_{EW}}\right)\left(\frac{1-x}{\sqrt{x}}\right)(\eta_{e_R}-\eta_{e_L}), \\
\frac{1}{3}\frac{d\eta_B}{dt} &= \frac{d\eta_{e_R}}{dt} + 2\frac{d\eta_{e_L}}{dt},
\end{aligned} \tag{33}$$

where the variable $x=\frac{t}{t_{EW}}=(\frac{T_{EW}}{T})^2$, $t_{EW}=\frac{M_0}{2T_{EW}^2}$, $M_0=M_{Pl}/1.66\sqrt{g^*}$, and M_{Pl} is the Plank mass, and $\Gamma_0=121$.

First scenario:

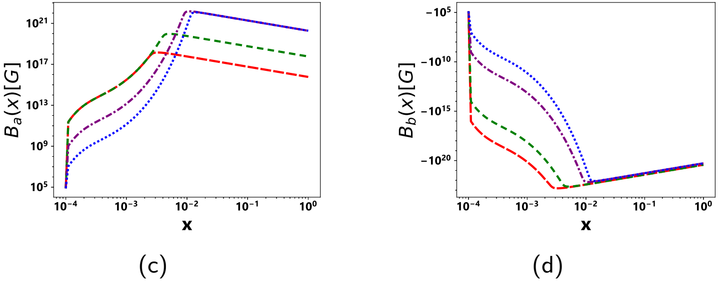


Figure: The time plots of the helical components $B_a(x)$ and $B_b(x)$, with the initial conditions $B_a^{(0)} = B_b^{(0)} = 0$, $\eta_{e_R}^{(0)} = 3.56 \times 10^{-4}$, and $\eta_{e_L}^{(0)} = \eta_B^{(0)} = 0$. Large (red) dashed line is for $v_a^{(0)} = 10^{-7}$, $v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{19}$G, dashed (green) line for $v_a^{(0)} = 10^{-7}$, $v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{17}$G, dotted-dashed (violet) line for $v_a^{(0)} = v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{19}$G, and dotted (blue) line for $v_a^{(0)} = v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{17}$G.

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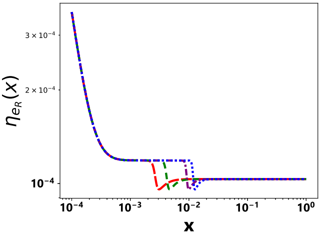

(a) (b)

Figure: The time plots of the the right-handed electron asymmetry $\eta_{e_R}(x)$, the left-handed electron asymmetry $\eta_{e_L}(x)$ with the initial conditions $B_a^{(0)} = B_b^{(0)} = 0$, $\eta_{e_R}^{(0)} = 3.56 \times 10^{-4}$, and $\eta_{e_L}^{(0)} = \eta_B^{(0)} = 0$. Large (red) dashed line is for $v_a^{(0)} = 10^{-7}$, $v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{19}$G, dashed (green) line for $v_a^{(0)} = 10^{-7}$, $v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{17}$G, dotted-dashed (violet) line for $v_a^{(0)} = v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{19}$G, and dotted (blue) line for $v_a^{(0)} = v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{17}$G.

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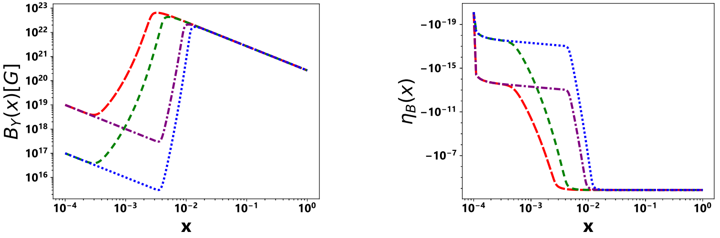
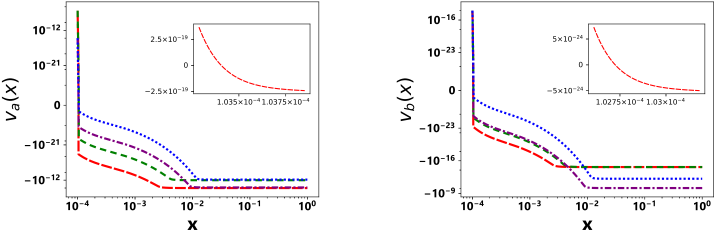


(a) (b)

Figure: The time plots of the hypermagnetic field amplitude $B_Y(x)$, and the baryon asymmetry $\eta_B(x)$ with the initial conditions $B_a^{(0)} = B_b^{(0)} = 0$, $\eta_{e_R}^{(0)} = 3.56 \times 10^{-4}$, and $\eta_{e_L}^{(0)} = \eta_B^{(0)} = 0$. Large (red) dashed line is for $v_a^{(0)} = 10^{-7}$, $v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{19}$G, dashed (green) line for $v_a^{(0)} = 10^{-7}$, $v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{17}$G, dotted-dashed (violet) line for $v_a^{(0)} = v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{19}$G, and dotted (blue) line for $v_a^{(0)} = v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{17}$G.

First scenario:



(a) (b)

Figure: The time plots of the $v_a(x)$ and $v_b(x)$ with the initial conditions $B_a^{(0)} = B_b^{(0)} = 0$, $\eta_{e_R}^{(0)} = 3.56 \times 10^{-4}$, and $\eta_{e_L}^{(0)} = \eta_B^{(0)} = 0$. Large (red) dashed line is for $v_a^{(0)} = 10^{-7}$, $v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{19}$G, dashed (green) line for $v_a^{(0)} = 10^{-7}$, $v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{17}$G, dotted-dashed (violet) line for $v_a^{(0)} = v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{19}$G, and dotted (blue) line for $v_a^{(0)} = v_b^{(0)} = 10^{-14}$, and $B_z^{(0)} = 10^{17}$G.

Second scenario:

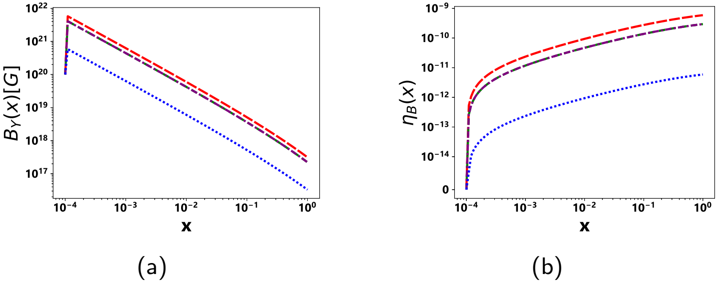
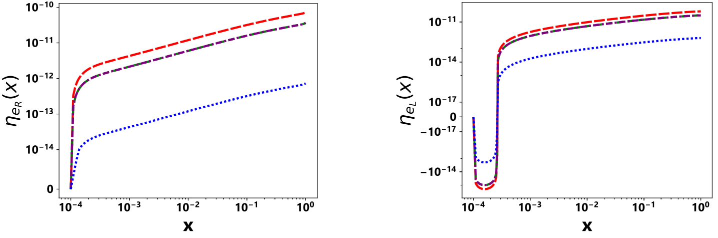


Figure: The time plots of the hypermagnetic field amplitude $B_Y(x)$, the baryon asymmetry $\eta_B(x)$, in the presence of the viscosity, with the initial conditions $B_z^{(0)} = 10^{20}$G, $B_a^{(0)} = B_b^{(0)} = 0$, and $\eta_{e_R}^{(0)} = \eta_{e_L}^{(0)} = \eta_B^{(0)} = 0$. Large dashed (red) line is for, $v_a^{(0)} = v_b^{(0)} = 10^{-2}$, dashed (green) line for $v_a^{(0)} = 10^{-2}$, $v_b^{(0)} = 0$, dot-dashed (violet) line for $v_a^{(0)} = 0$, $v_b^{(0)} = 10^{-2}$, and dotted (blue) line for $v_a^{(0)} = v_b^{(0)} = 10^{-3}$.

Second scenario:



(a) (b)

Figure: The time plots of the the right-handed electron asymmetry $\eta_{e_R}(x)$, the left-handed electron asymmetry $\eta_{e_L}(x) \simeq \eta_{\nu_L}(x)$, in the presence of the viscosity, with the initial conditions $B_z^{(0)} = 10^{20}$G, $B_a^{(0)} = B_b^{(0)} = 0$, and $\eta_{e_R}^{(0)} = \eta_{e_L}^{(0)} = \eta_B^{(0)} = 0$. Large dashed (red) line is for, $v_a^{(0)} = v_b^{(0)} = 10^{-2}$, dashed (green) line for $v_a^{(0)} = 10^{-2}$, $v_b^{(0)} = 0$, dot-dashed (violet) line for $v_a^{(0)} = 0$, $v_b^{(0)} = 10^{-2}$, and dotted (blue) line for $v_a^{(0)} = v_b^{(0)} = 10^{-3}$.

Third scenario:

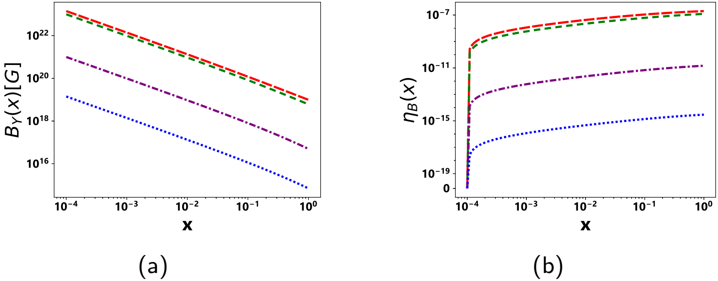
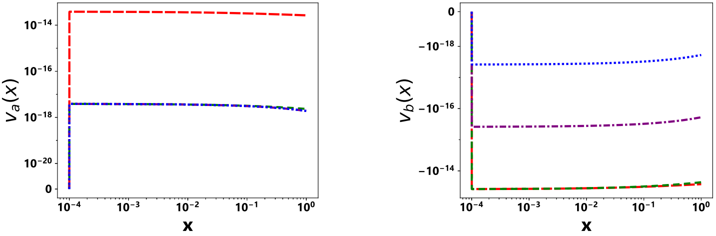


Figure: The time plots of the the hypermagnetic field amplitude $B_Y(x)$, the baryon asymmetry $\eta_B(x)$, with the initial conditions $B_z^{(0)} = 10^{17}$G, and $\eta_{e_R}^{(0)} = \eta_{e_L}^{(0)} = \eta_B^{(0)} = v_a^{(0)} = v_b^{(0)} = 0$. Large (red) dashed line is for $B_a^{(0)} = B_b^{(0)} = 10^{23}$G, dashed (green) line for $B_a^{(0)} = 10^{23}$G, $B_b^{(0)} = 10^{19}$G, dotted-dashed (violet) line for $B_a^{(0)} = 10^{21}$G, $B_b^{(0)} = 10^{19}$G, and dotted (blue) line for $B_a^{(0)} = B_b^{(0)} = 10^{19}$G.

Third scenario:



(a) (b)

Figure: The time plots of the velocity fields amplitude $v_a(x)$ and $v_b(x)$, with the initial conditions $B_z^{(0)} = 10^{17}$G, and $\eta_{eR}^{(0)} = \eta_{eL}^{(0)} = \eta_B^{(0)} = v_a^{(0)} = v_b^{(0)} = 0$. Large (red) dashed line is for $B_a^{(0)} = B_b^{(0)} = 10^{23}$G, dashed (green) line for $B_a^{(0)} = 10^{23}$G, $B_b^{(0)} = 10^{19}$G, dotted-dashed (violet) line for $B_a^{(0)} = 10^{21}$G, $B_b^{(0)} = 10^{19}$G, and dotted (blue) line for $B_a^{(0)} = B_b^{(0)} = 10^{19}$G.

$$B_A = B_Y \cos\theta_W \simeq 0.88 B_Y$$
$$B_Y(T_{EW}) \sim 10^{17-20} G \quad (34)$$

$$\eta_B = (n_B - \bar{n}_B)/s$$
$$s = 2\pi^2 g^* T^3/45, \qquad g^*(T > T_{EW}) = 106.75$$
$$g_0^* = 43/11$$
$$\eta_B(T_0) = 27.3 \times \eta_B(T_{EW}) \quad (35)$$
$$10^{-15} < \eta_B(T_{EW}) < 10^{-8}$$
$$\eta_{BBN} = 5.8 \pm 0.27 \times 10^{-10}$$
$$\eta_{CMB} = 6.16 \pm 0.15 \times 10^{-10}$$

- In this study, the hypermagnetic field configurations which include both helical and non-helical components, are considered. It is shown that in the presence of weak vorticity and a large right-handed electron asymmetry, the helicity can be generated and amplified for an initially non-helical hypermagnetic field. The vorticity also grows, even in the presence of the viscosity, in contrast to the case in which a fully-helical hypermagnetic field is assumed. In a different scenario it is also shown that in the presence of a strong non-helical hypermagnetic field and large vorticity, helicity and baryon asymmetry can be generated and amplified.

Thank you for your attention