Two-fluid Dynamics in Extremely Strong Magnetic Field

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Strong Magnetic Fields

◇ Pulsar Magnetosphere :Steady outflow to nebula
◇ Magnetars: (Giant) Flares
◇ GRBs?: DC Model or AC Model?

$\Rightarrow$ Strong magnetic fields $\sim 10^{12} - 10^{15}$G
(+ Rapid rotation)

Numerical simulation of plasma outflows is one of important issues.

Physical range of magnetic field strength relevant to our simulation

∘ Electro-magnetic field energy dominates matter energy.
$\rightarrow$ Thermal pressure is neglected.

$$(n_e m_e \gamma c^2)/(B^2/(8\pi)) \ll 1$$

∘ 'Large scale' structure, or long time-scale behavior
$\rightarrow$ Plasma motion is constrained by magnetic field lines.

$$(eB/(m_e c\gamma))(\ell/c) \ll 1$$

Numerical Codes for Pulsar Magnetosphere

∘ Time-dependent MHD code

Asano, Uchida and Matsumoto (2005) PASJ 57, 409

Komissarov(2006) MN. 367, 19

∘ Time-dependent Force-free EM code

McKinney(2006) MN. 368, L30

Spitkovsky(2006) ApJ. 648, L51

EM field structure for the solution of GS (pulsar) equation in stationary state is confirmed.

Unsolved issues

$\vec{E} \cdot \vec{B} = 0$? $|E| \leq |B|$?

plasma, (charge, current) distribution? its dependence?

Our Numerical Code

Two-fluid approach to include many physical effects

- ◦ Axially symmetric (r, θ), $v_\phi \neq 0$ (2.5D)
- ◦ Time-dependent
- ◦ Solving the Maxwell eqns.: $(\vec{E}, \vec{B})$ from $(\rho_e, \vec{j})$

  $\partial_t \vec{E} = 0$, $\vec{E} + \vec{v} \times \vec{B}/c = 0$ are not assumed.

  (ideal MHD $\vec{E} \cdot \vec{B} = 0$)
- ◦ Relativistic fluid dynamics (density, velocity) of two components (electrons + positrons)

  $|q_-/m_-| = |q_+/m_+|$, $(|q_-/m_-| \neq |q_+/m_+|)$.
- ◦ EM force only: $(n_\pm, \vec{v}_\pm)$ from $(\vec{E}, \vec{B})$

  gravity, thermal pressure, etc are ignored.

Maxwell equations and Fluid Motions

$$\frac{1}{c}\partial_t \vec{B} = -\vec{\nabla} \times E.$$

$$\frac{1}{c}\partial_t \vec{E} = \vec{\nabla} \times B - \frac{4\pi}{c}(\rho_+ \vec{v}_+ - \rho_- \vec{v}_-).$$

$$\vec{\nabla} \cdot \vec{B} = 0.$$

$$\vec{\nabla} \cdot \vec{E} = 4\pi(\rho_+ - \rho_-).$$

$$\partial_t n_\pm + \vec{\nabla} \cdot (n_\pm \vec{v}_\pm) = 0.$$

$$(\partial_t + v^k \nabla_k)(\gamma_\pm \vec{v}_\pm) = \frac{q_\pm}{m_\pm}(\vec{E} + \frac{\vec{v}_\pm}{c} \times \vec{B}).$$

Guiding center approximation

$$\frac{d}{dt}\gamma v_\parallel = \frac{q}{m}\vec{E} \cdot \vec{b},$$

$$\frac{d}{dt}\gamma \vec{v}_\perp = \frac{q}{m}\left[\vec{E} - (\vec{E} \cdot \vec{b})\vec{b} + \vec{v} \times \vec{B}\right] = \frac{q}{m}(\vec{v} - \vec{v}_D) \times \vec{B}$$

where $\vec{b} = \vec{B}/|B|$ and $\vec{v}_D = \vec{E} \times \vec{B}/B^2$.

$\vec{v}_\perp = \vec{v}_D$ if $|E| < |B|$, direct time-integration otherwise.

Numerical Results (Examples)

Animations

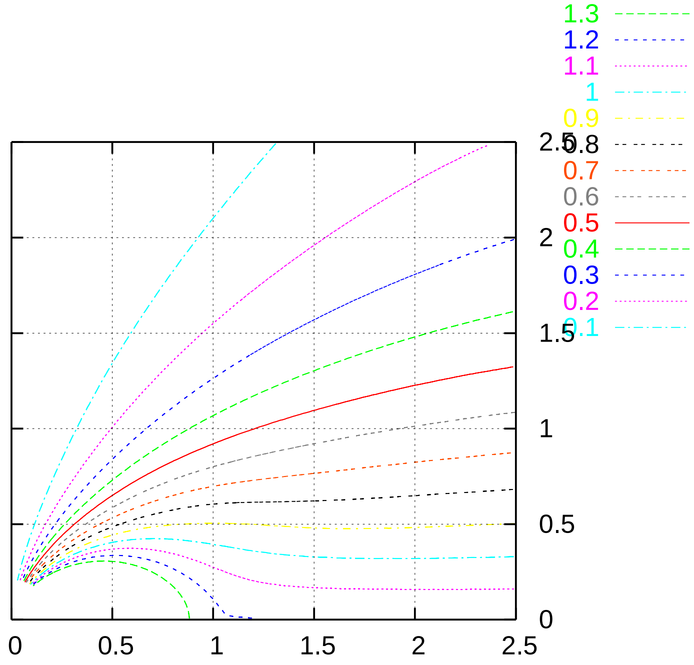
- Charge density (Charge separated plasma)
- Acceleration of particles (γ factor)

Pulsar magnetosphere in a steady state

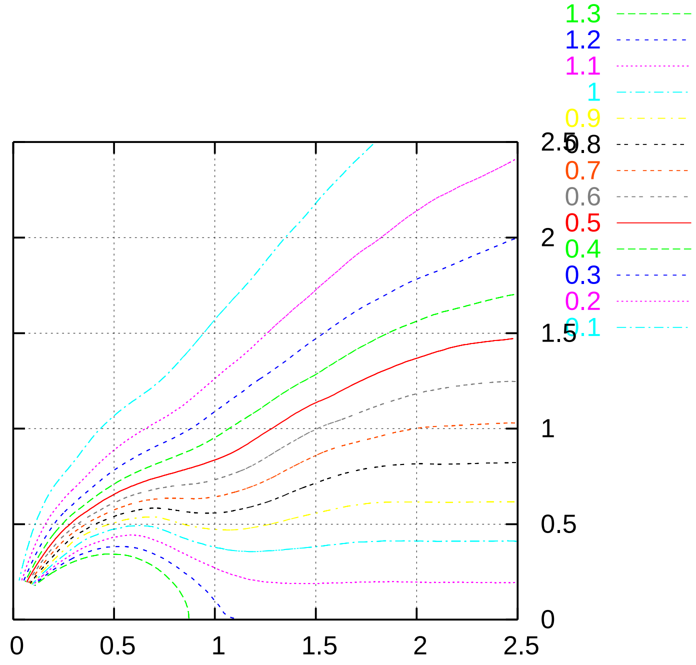
- Magnetic field function
- Acceleration of particles (γ factor)
- $\cdots$

Pulsar Magnetosphere

$\rho_{in} = 1$

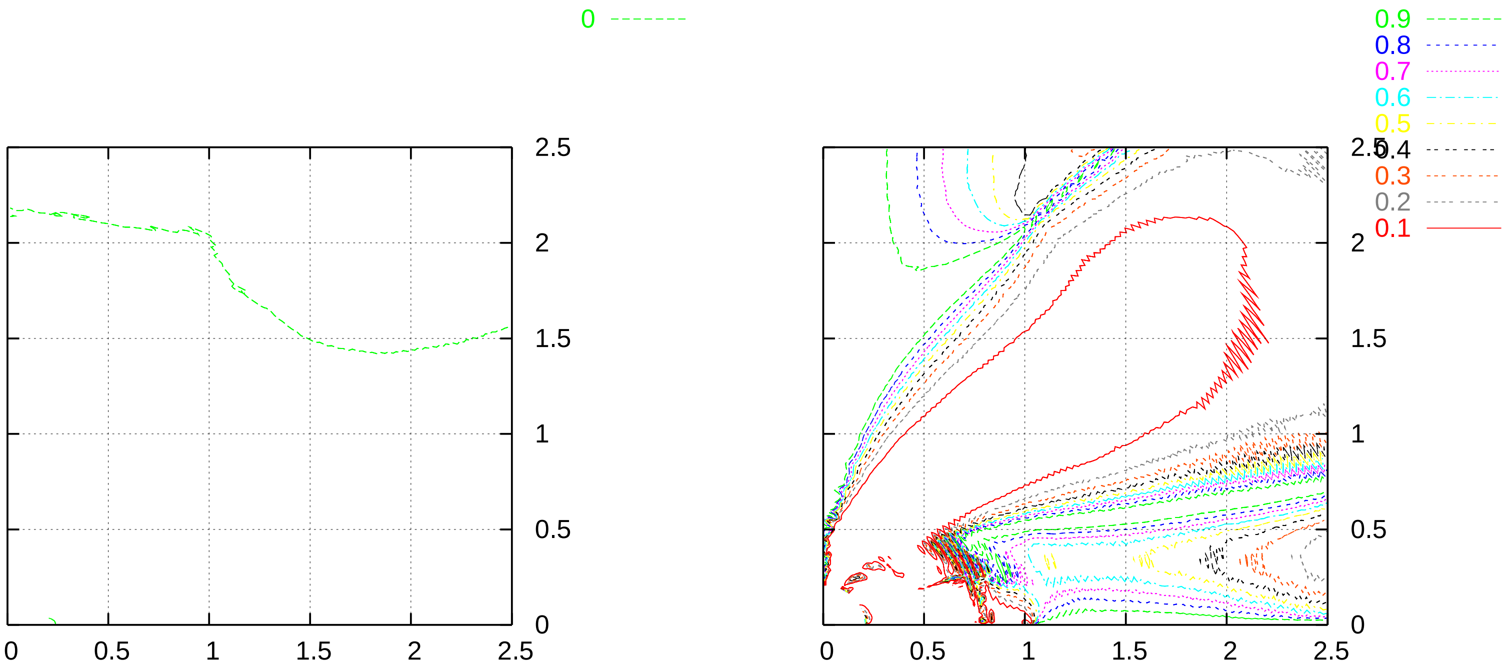


$\rho_{in} = 10$



Magnetic flux function G is shown. The results are the same as those of force-free approximation. Luminosity increases with $(\rho_{in})^2$. $L \approx \mu^2\Omega^4/c^3(\rho_{in}/10)^2$, since $L \sim E_\theta B_\phi, \quad E_\theta, B_\phi \propto \rho_{in}$.

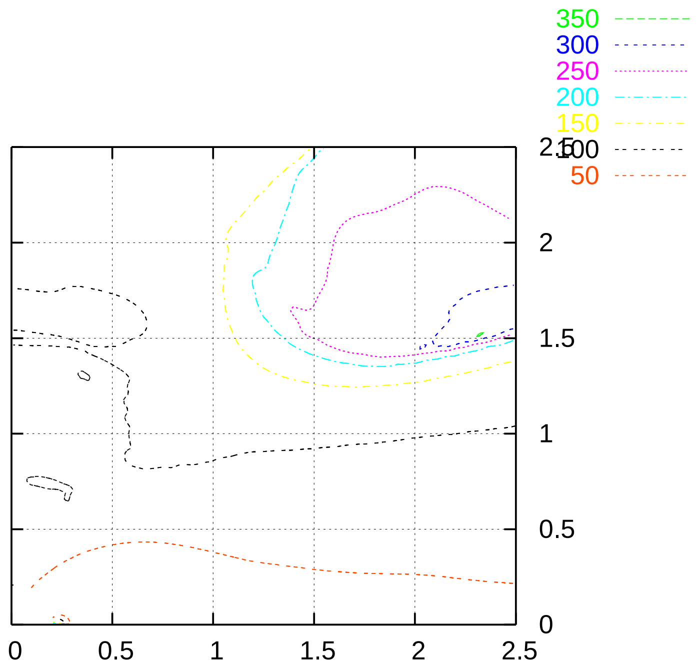
Electro-magnetic Field Structure



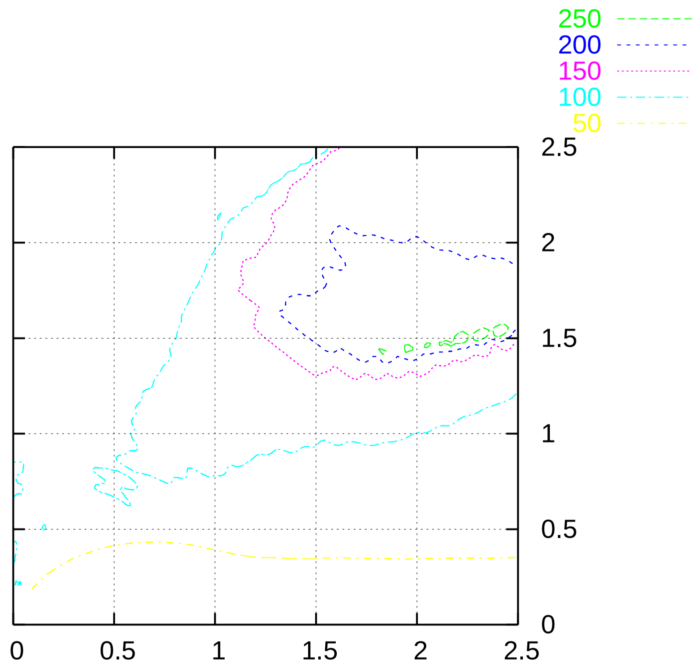
$B^2 - E^2$(left) and $(\cos\theta)^2 = ((\vec{B}\cdot\vec{E})/(|B||E|))^2$ (right) are shown.

Acceleration of plasma

γ for negative particles

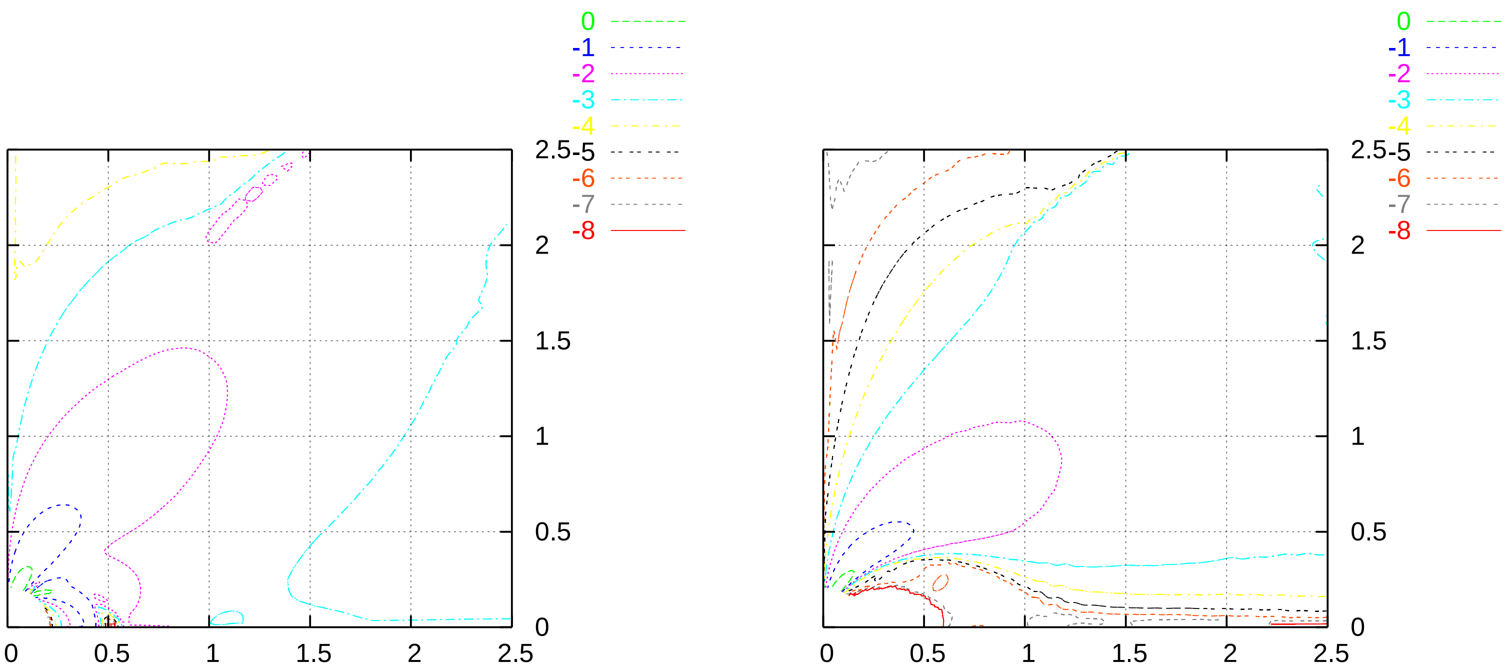


γ for positive particles



Kinetic energy of plasma increases a few times from the initial value 100 in this model.

Density contours



Density contour for negative (left) and that for positive (right) are shown.

Summary

Present status

∘ Numerical code is developed for two components plasma coupled with time-dependent EM fields.

∘ Parameter dependence ⇒ Understanding the physical process.

This is a new approach, and a first step toward more realistic case.

Future

∘ More physics should be included into the code.
e.g, Radiation from accelerated particles,
Pair creation/annihilation, $\cdots$