

Particle simulation for an axisymmetric pulsar magnetosphere

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Abstract. We developed a new particle simulation code which includes pair creation (magnetic pair creation and photon collision process), propagation of gamma-ray, inertia of particle, interaction of plasma and multi-pole stellar field for steady axisymmetric pulsar magnetosphere. The photon path is solved stochastically by an analytical solution of the mean free path of pair creation processes at the photon position. The superimposed quadrupole magnetic field forms asymmetric electrostatic clouds on the poloidal plane and the accelerating region is different from the dipole case. Here, we demonstrate some results of a test run for our simulation. We will adopt the code for more complicated cases, such that all above-mentioned effects will be considered together in future work.

Keywords. pulsars: general, plasmas

1. Introduction

A highly magnetized and rapidly rotating neutron star is an accelerator for charged particles. Such a star becomes a unipolar dynamo. The plasma is accelerated by the induced electric field and emits gamma-rays by bremsstrahlung. Successively, the gamma-ray photon converts into an electron-positron pair which forms an outflow of plasma with a relativistic kinetic energy (i.e., the pulsar wind) and is a persistent energy source of the surrounding synchrotron nebula. Where, and why, these particles are accelerated in the pulsar magnetosphere is a longstanding problem.

The gamma-ray pulsations at the rotation period mean the local accelerating region co-rotates with star, and that there should be a region of plasma deficiency. Recent observations by the Fermi Gamma-ray Space Telescope have promoted an understanding of the emission from gamma-ray pulsars (Abdo *et al.* 2010). Although some conventional gap models had been discussed phenomenologically, recent observation of gamma-ray pulsar indicates an outer gap (Cheng *et al.* 1986ab) is the origin of the high energy photons (Abdo *et al.* 2009c).

We reported a steady solution where outflow of plasma and outer gaps coexist (Wada & Shibata 2007, 2011). But the artificial treatment of pair creation made large gaps in middle latitudes for the solution. For detailed discussion of the structure of magnetosphere, more realistic treatment of pair creation was needed. That is, the mean free path of gamma-ray and energy dependence of photon for path should be considered. We have further developed our simulation code to work out the problem for our previous work.

2. Outline of particle simulation

In this paper, because we consider the case of dipole plus quadrupole magnetic field with the star. Then stellar magnetic field is written by

$$\begin{aligned} \mathbf{B} &= \mathbf{B}_{\text{dip}} + \mathbf{B}_{\text{quad}}, \\ \mathbf{B}_{\text{dip}} &= B_0 \frac{R_0^3}{r^3} \cos \theta \mathbf{e}_r + \frac{B_0}{2} \frac{R_0^3}{r^3} \mathbf{e}_\theta, \\ \mathbf{B}_{\text{quad}} &= \frac{B_2}{2} \frac{R_0^4}{r^4} (3 \cos^2 \theta - 1) \mathbf{e}_r + B_2 \frac{R_0^4}{r^4} \sin \theta \cos \theta \mathbf{e}_\theta. \end{aligned} \quad (2.1)$$

Where \mathbf{e}_r and \mathbf{e}_θ are unit vectors in spherical coordinates and r , θ , R_0 , $B_2 = \delta B_1$, indicate distance from origin, colatitude, stellar radius and magnetic field intensity on the pole, respectively. δ taken to be a constant in our model.

We assume pulsar is perfect conductive sphere and force-free condition on the stellar surface. Such as

$$\mathbf{E}(R_0, \theta) = -\frac{R_0 \sin \theta \Omega_0}{c} \mathbf{e}_\varphi \times \mathbf{B}(R_0, \theta). \quad (2.2)$$

Where, Ω_0 is stellar angular velocity and \mathbf{e}_φ is unit vector for azimuthal direction. The induced electric field is calculated by the solution of Laplace equation with the boundary condition (2.2). They are written by

$$\mathbf{E} = \mathbf{E}_{\text{mono}} + \mathbf{E}_{\text{quad}} + \mathbf{E}_{\text{oct}}. \quad (2.3)$$

\mathbf{E}_{quad} and \mathbf{E}_{oct} are induced by dipole and quadrupole magnetic field, respectively. We demonstrate particle simulation in which charge of plasma is given by q in steady state. And therefore, the static electro-magnetic field formed by magnetospheric charge and current are given by

$$\mathbf{E}_q = \sum_{i=1}^n q_i \left[\frac{\mathbf{r} - \mathbf{r}_i}{|\mathbf{r} - \mathbf{r}_i|^3} - \frac{R_0}{r_i} \frac{\mathbf{r} - (R_0/r_i)^2 \mathbf{r}_i}{|\mathbf{r} - (R_0/r_i)^2 \mathbf{r}_i|^3} - \left(1 - \frac{R_0}{r_i}\right) \frac{\mathbf{r}}{r^3} \right], \quad (2.4)$$

$$\mathbf{B}_q = -\sum_{i=1}^n q_i \frac{\mathbf{v}_i \times (\mathbf{r}_i - \mathbf{r})}{|\mathbf{r}_i - \mathbf{r}|^3}. \quad (2.5)$$

Where subscripts i represent i -th particle and \mathbf{r} is position vector. We can calculate the interaction between plasma rapidly, with using special purpose programmable computer GRAPE-DR. Relativistic equation of motion of plasma is written by,

$$m_i \frac{d\gamma_i \mathbf{v}_i}{dt} = q_i \left(\mathbf{E}_i + \frac{\mathbf{v}_i}{c} \times \mathbf{B}_i \right) + \mathbf{f}_{\text{rad},i}. \quad (2.6)$$

Where, m , \mathbf{v} , \mathbf{f}_{rad} are mass, velocity, radiation drag force for particle, respectively. The outline of our particle simulation is as follows.

- (a) Start the calculation from the vacuum condition.
- (b) Replace the surface charge density with simulation particle.
- (c) Compute the electromagnetic field at the particle positions.
- (d) Renew the position and velocity of particle with equation of motion.
- (e) Create gamma-ray photon where $E_{\parallel} > E_{\text{cr}}$.
- (f) Compute the position where gamma-ray convert into pair and insert plasma at the position
- (g) Go back to step (2), unless the steady state is established.

Where E_{\parallel} is intensity of electric field along the magnetic field and E_{cr} is critical field intensity that we just consider parameter for pair creation in current model. We choose

pair creation processes; magnetic pair creation and photon collision process (Thermal X-ray photon from stellar surface and gamma-ray photon by curvature radiation). The pair creating position is calculated stochastically by mean free path of analytical solution of the pair creation processes is calculated by in numerical simulation.

3. Result

We carried out test run for our simulation code with magnetic pair creation dominant case (A), photon collision process dominant case in dipole stellar magnetic field and quadrupole field dominant case in dipole stellar magnetic field (See Fig. 1 and 2). Panels A and B show that the pair creating position is different for each pair creation process. For $\delta = 2$, C shows outer gap structure is changed compared with pure dipole case. These simulations were carried out just in one rotation period. Although these solutions are quasi-steady, longer-running simulations are needed to obtain steady solution.

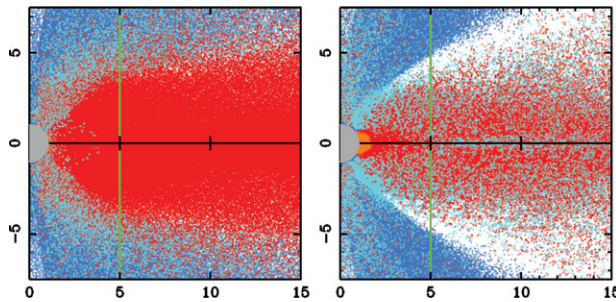


Figure 1. Distribution of particle on the poloidal plane; left panel is (A) and right panel is (B), red and orange dots are positive particle and blue and cyan dots are negative particle, respectively. Green line is light cylinder.

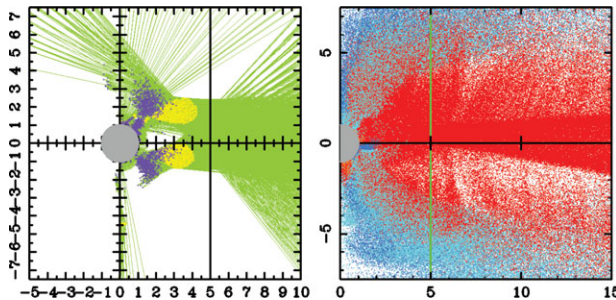


Figure 2. Left panel; green line is path of gamma-ray, yellow dot is gamma-ray emitting region and magenta dot is pair creating point, respectively. Right panel; distribution of particles on the poloidal plane, for quadrupole field dominant case in dipole stellar magnetic field (C).

References

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