The Structure of the Pulsar Magnetosphere via Particle Simulation

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Abstract

We perform a particle simulation to explain the pulsar phenomena from the first principles. It is shown that the outer gaps indeed appear around the null surface. The origin can be understood simply by strong charge separation by emf of the star in tenuous plasma atmosphere. The gap persists under copious pair-creation, providing the particle source of the pulsar wind as well as the gamma-ray pulses. If pair creation rate is high, then some magnetic flux is opened and pairs flow out along the opened magnetic flux, i.e., the pulsar wind is formed. At the present capability of computer, the equatorial current sheet with closed magnetic flux is till thick. If pair creation rate is low, then the wind is moderate, and strong radiation drag causes a large scale circular flow in the magnetosphere. The side-wall of the polar cap flow is verified, but locates nearer to the polar axis than expected, i.e., the middle latitude dead zone, which is different from the dead zone of the closed magnetic field lines is found.

Key words: pulsars: general — magnetic field — plasmas

1. Introduction

The most prominent activities that pulsars show are (1) the pulsar wind, (2) high-energy pulsed emissions, and (3) the radio pulses. To explain these phenomena, the outer gap, the polar cap particle accelerators and the relativistic centrifugal wind are proposed. We aim to prove the existence of these structures from the first principles via particle simulation.

2. What Happens in the Simulation

Our simulation is very simple: we put a spherical magnet rotating around the magnetic axis in vacuum space and see what happens. We trace the motion of particles extracted from the star surface by the electric field. We use particle simulation method similar to Particle-in-Cell. Therefore, we calculate change of the electric file by the emitted particles. For this calculation, we use the spacial purpose computer for the astronomical N-body simulation, GRAPE-6 at National Astronomical Observatory of Japan. We take into account cross-filed drift motion due to inertia and to radiation drag force. We also take into account pair creation in a region where the field-aligned electric field is stronger than a critical value. Method of calculation is given in the paper by Yuki et. al. in this proceedings.

What we expected in the simulation is as follows. The strong magnetic field (10^{12}G) and fast rotation cause strong charge separation in the plasma around the neutron star. The produced electric field perpendicular to the magnetic field brings about co-rotational motion. Beyond the light cylinder on which co-rotation speed reaches the speed of light, the plasmas will flow out centrifugally. Due to the combination of huge charge separation and loss of particles, gaps are formed along the electric dividing ridge, so-called "null surface", in the middle latitude. The gap is unstable against pair creation cascade. Although pairs diminish the gap, loss of pairs by the wind will causes gaps continually or periodically.

3. Results

The final state reached via our simulation is static clouds with the gaps if pair creation is suppressed. In this first step of our simulation, we reproduced the previous result by Krause-Polstorf and Michel (1985).

In the next step, the pair creation is switched on. The gap is formed around the null surface as shown in Fig. 1. In the gap, the field-aligned electric field is marginally greater than the threshold for the pair creation, and pairs are produced continuously. The pair creation can take place quasi-periodically. However, the resolution of our simulation is not enough to find the periodic pair cre-

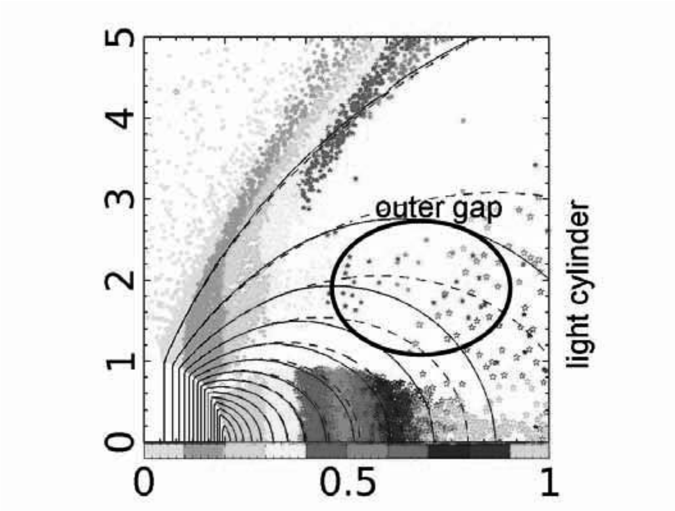

Fig. 1. The inner part of the magnetosphere. The distribution of the particles are plotted with color codes which indicate the azimuthal velocity. The reference colors at the bottom indicate the corotaion speed.

ation at the moment. Most of the place other than the gaps has no field-aligned electric field, and whereby the plasma tends to rotate. More precisely, top of the dead zone rotates faster than the co-rotation speed, and the trapped particles leak out across the light cylinder and the closed filed lines due to radiation-drag-drift. The detailed structure is given in Wada and Shibata (2007).

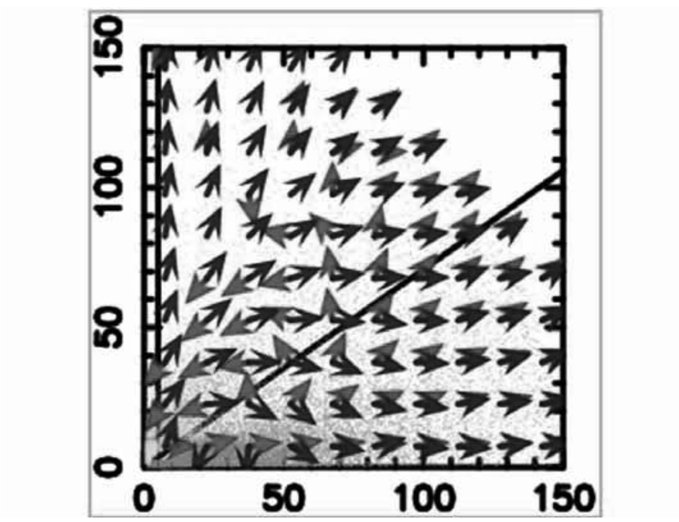

Fig. 2. The global flow. The distance is normalized by the light radius. The red and blue arrows indicate positive and negative particles, respectively.

The positrons produced in the outer gap flow out, while the electrons are emitted backward to the stars. If this continues, the star will charge up negatively. What we see is continuous emission of electrons from the polar caps to compensate the backward flow of the electrons. In the final state, the electrons flow out in the higher latitudes across the outer boundary. Thus the losses of positrons and electrons are balanced. The net charge of the system is automatically determined and is found to be almost zero.

Actually the created pairs partially flow out and partially circulate in the magnetosphere (see Fig. 2.). The reason why particles can flow out across the closed filed is the drift motion by radiation-drag force in azimuthal direction. This means that the rotation speed is very much high due to the perpendicular electric filed.

We find the side-wall, which is assumed in the conventional polar cap and slot gap models. The electric potential is the same as the star on this side-wall, i.e., the non-corotational electric potential is zero. The wall is *not* the outer boundary of the dead zone with closed magnetic field lines. The outside of the wall is a kind of dead zone formed in between the oppositely-directed current lines. The current runs toward the star in the polar magnetic flux surrounded by the side-wall. The oppositely directed current, which goes out from the star, locates in between the side-wall and the traditional dead zone with closed magnetic flux inside the light cylinder (the dead zone of the Goldreich-Julinan model). The slot gap can be placed along the side-wall that we find.

In this step of simulation, the pair creation rate is not so high that the magnetic filed is essentially dipole. In the third step of our simulation, we increased the pair creation rate. As pair creation rate is increased, the original dipole field is modified to make open flux. However, we still see closed magnetic lines in the equatorial region, but the field strength is significantly reduced. In our simulation, the magnetic neutral sheet is still thick with closed magnetic flux. In this region the electric field strength is found to be larger than the magnetic field strength, i.e., ideal-MHD breaks down. The pair creation rate was still higher, the neutral sheet would be thinner and most of the flux will be opened. In such cases, the pair plasma would be much more likely the MHD wind.

References

Wada, T., Shibata, S., 2007, MNRAS, 376, 1460
Krause-Polstorf, J., Michel, F.C., 1985, AA, 144, 72