A SELF-CONSISTENT MODEL OF THE MAGNETOSPHERE
WITH CENTRIFUGAL WIND, I

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Abstract. Under the purely centrifugal approximation (gravity and pressure force are neglected), stellar magnetospheres are classified into three main types of different physical properties in the two-dimensional parameter space. They are characterized essentially by the strength of the magnetic field and the plasma density, at the base of the magnetosphere. Among the three types, the type II magnetosphere has moderate surface densities for a given field strength, and is expected to possess a centrifugal wind blowing across the magnetic field lines without affecting them appreciably. Such a situation may be realized through a modification of the electric field from that under the ideal-MHD condition, owing to the inertia of a plasma. In order to illustrate this mechanism, the type II magnetosphere is taken up for a numerical simulation. The effect of artificial viscosity is avoided by integrating the characteristic equations for both components of the plasma, instead of solving the fluid equations directly. Our model reproduces a disk-like outflow of the centrifugal wind across the magnetic field lines which are closed through the equatorial plane.

1. Introduction

The investigation of a purely centrifugal wind seems to be the most suitable way to clarify the basic physics of the wind-field interaction in the stellar magnetospheres. In such a problem, the effects of the gravity, the thermal and radiation pressures and of other drag forces are neglected for simplicity. The magnetic field transfers stellar rotation to the magnetospheric plasma, so that the centrifugal force acting on the rotating plasma drives a centrifugal wind. Therefore, the wind is driven only by the electromagnetic field through the stellar rotation, and the field, in turn, is deformed owing to the passage of the wind. Though this situation may be an oversimplification for most of the actual magnetospheres, there seems to be a few candidates for which the centrifugal wind is expected to be realized: e.g., the pulsar magnetospheres and possibly the Jovian magnetosphere.

Since the centrifugal wind is driven by the inertial force (i.e., the centrifugal force), the inertial term should be treated carefully. In the conventional treatments of this problem, however, the ideal-MHD condition is usually employed in which the inertial term is neglected completely. It is written as

\[ \frac{1}{c} E + \mathbf{V} \times \mathbf{B} = 0, \]  

where \( E, B, \) and \( V \) are the electric, magnetic, and the velocity fields, respectively, and \( c \) is the light velocity. It has been shown (Kaburaki, 1982) for a corotating plasma (i.e., \( V = \Omega_0 \times R = u \)), where \( \Omega_0 \) is the angular velocity of a star and \( R \) is the position vector.
from the center of the star) that the presence of the inertial force modifies the ideal-MHD condition to give

$$\mathbf{E} + \frac{1}{c} \mathbf{V} \times \mathbf{B} = -\nabla \left( \frac{m}{2e} \mathbf{u} \cdot \mathbf{u} \right),$$

(2)

where $m$ and $e$ are the mass and charge of the proton, and only the convection current has been taken into account. Owing to the appearance of the right-hand side, the electric field becomes to have the component along the magnetic field, $E_\parallel$. This example gives a good illustration of the fact that the centrifugal acceleration in the frame co-moving with a plasma can be interpreted as the electromagnetic acceleration in the inertial frame. Indeed, though the centrifugal force vanishes in the inertial frame, it affects the plasma motion through the modification of the electric field as seen in Equation (2). If the plasma motion deviates from the corotation as a result of the centrifugal acceleration, the right-hand side of Equation (2) becomes, in general, non-irrotational. Corresponding to this fact, the magnetospheric plasma experiences a inertial drift across the magnetic lines of force. As shown from an order-of-magnitude estimate which neglects the pressure term (Kaburaki, 1982; Section 2 of the present paper), this effect is expected to become important beyond the inertial radius which usually lies far from the stellar surface. In general, however, the inertial effect is shown to play an important role (Kaburaki, 1983, 1984) in terms of the diamagnetic current, in the presence of the pressure gradient, even in the inner magnetosphere well within the inertial radius.

There is another possibility for the development of $E_\parallel$. If the plasma is so tenuous as to provide at most the Goldreich-Julian density which is derived from Equation (1) as $N_{G-J} = \text{div} E/4\pi e$, the decrease in the number density of the plasma caused by an acceleration would directly affects the charge distribution and, hence, the electric field. This is called the 'space-charge limited' flow (Michel, 1974). Fawley et al. (1977) have solved the equation of motion, that of continuity and the Poisson equation to obtain the local electric field which is consistent with the plasma flow along given magnetic lines of force. The result shows that $E_\parallel$ appears in a thin layer on the stellar surface and the plasma acceleration really takes place, though it is insufficient to explain the energetic particles around the pulsars. However, this kind of problems should be solved self-consistently with the global structure of the magnetosphere.

Another problem which may arise associated with the centrifugal wind is whether the magnetic field lines are open or closed in a global sense. Though the standard pulsar model (Goldreich and Julian, 1969) has an open magnetic field structure which is required as a consequence of the ideal-MHD condition, there is no such a priori need in the presence of the inertial drift of a plasma. Indeed, the numerical solution of the pulsar magnetosphere calculated by Kuo-Petravic et al. (1974, 1975) has a closed field structure. The pulsar wind blows in their model across the magnetic lines of force. However, some doubt has been cast on the reliability of their calculation: i.e., it is not clear whether the drift motion is due to the inertial effect or to the artificial viscosity which has been introduced for numerical stability.