PULSAR MAGNETOSPHERE WITH CONSPICUOUS TRANS-FIELD FLOW*

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Abstract. It is shown that (1) in the pulsar magnetosphere the violation of the ideal-MHD condition, \( E + v \times B \neq 0 \), i.e., conspicuous trans-field motion and non-zero field aligned electric field \( E_\parallel \neq 0 \) appears owing to relativistic large inertia, and (2) an axisymmetric numerical model with tenuous plasma suggests that in the region of the trans-field flow a vacuum-like electric field and a closed current circuit develop.

1. Introduction

It is widely known that, under the ideal-MHD condition, no self-consistent model of a pulsar magnetosphere can be constructed. The reason for this, and the real global structure of the magnetosphere is not clear, however. It has been pointed out that the difficulty may be removed by introducing a circulating flow instead of a steady outflow (Jackson, 1976; Mestel et al., 1979). We intend to solve two main problems to keep the circulation model alive. The problems are (1) the reason for the transfield flow, and (2) the way that the electromagnetic field and the plasma behave in the region of the trans-field flow.

2. Appearance of the Trans-Field Flow in the Pulsar Magnetosphere

The slowdown of pulsar rotation suggests that a poloidal current circuit is produced in the magnetosphere. This corresponds to the auroral circuit I in planetary magnetospheres (Alfvén, 1977). The total current \( I \) is determined by the total resistance of the circuit, so that within local theory \( I \) should always be a free parameter, and will be determined as a part of the solution when we determine an overall structure of the magnetosphere. From the output power of pulsars we may estimate \( I \) to be \( \alpha R_0^3 \Omega_0 B_0/c \), where \( \alpha \) is a numerical factor of about unity, and \( R_0, \Omega_0, B_0 \) and \( c \) are the stellar radius, the angular velocity of the star, the strength of the magnetic field at the poles, and the velocity of light, respectively (Sturrock, 1971).

When the Lorentz factor \( \gamma \) of the flowing particles is sufficiently less than a critical value \( \gamma_c \) (typically \( 10^7 \)), the inertial force is relatively so small that the plasma flows nearly along the magnetic field lines and \( E_\parallel \simeq 0 \). In this situation we can adopt the 'quasi-force-free approximation', in which the small inertial term is included only in the energy and angular momentum conservation laws (Mestel et al., 1979). By using a


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guessed current density with $\alpha \sim 1$ and this approximation, we find a divergence of $\gamma$ well within the light cylinder. An example of such a solution is shown in Figure 1. The reason of the divergence is as follows. The condition $E_{\parallel} \simeq 0$ determines the local charge density (i.e., the Goldreich–Julian density $\eta_{\text{G,J}}$). In a charge separated plasma the charge density is linked to the particle density. Therefore, the condition $E_{\parallel} \simeq 0$ controls the flow velocity through the mass conservation law with suitable boundary conditions (including those for the current density). As a result, if the magnetic field parallel to the rotational axis $B_{\parallel}$, which is proportional to the compelled charge density $\eta_{\text{G,J}}$, decreases sufficiently along the magnetic field lines, $\gamma$ becomes large enough to allow trans-field flow. Though we assumed the magnetic field to be a dipole one here, if the modification due to the toroidal current is incorporated, the region of the trans-field flow will extend more.