Relaxation of a quasi-symmetric rotating plasma - A model of Jupiter's magnetosphere

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Satellite observations [1] of Jupiter's magnetosphere discovered a high-beta, disk-shaped plasma with a high-speed flow corotating with the planet. The pressure falls monotonically toward the boundary, which indicates a confined plasma. In this study, we present a model that explains the creation of such a structure.

As for Jupiter's magnetosphere we have some theoretical models. For example, we have the empirical model that calculates the magnetic field by extrapolating the observational data, and the disk model that calculates the magnetic field and pressure by solving the axisymmetric equilibrium equation that is governed by the stationary ideal magnetohydrodynamics (MHD) equation with a toroidal flow [2]. To obtain the pressure profile, we need to invoke the disk model, however, the ideal equilibrium equation alone is not sufficient to determine the structure of plasma : profiles of some Cauchy data must be given to solve the equilibrium equation. In a dissipation-less plasma, these Cauchy data may assume arbitrary profiles. However, in a real plasma with small but finite dissipation, they may rearrange to achieve a relaxed state. Taylor's pioneering work [3] introduced a variational principle to explain the creation of a force-free relaxed state where the Cauchy data are selected as pressure = 0, flow = 0, and the current parallel to the magnetic field. The idea was the minimization of the total energy with an appropriate constraint. The constraint is imposed by a macroscopic conservation law that is more robust than the constancy of the total energy. Taylor's variational principle invoked the magnetic helicity as the relevant constant of motion.

The present study chooses a similar strategy to model the equilibrium of Jupiter's magnetosphere. Important issues to be addressed here are the characteristic rigid-rotation flow and the high pressure. Both of them are totally contradicting with Taylor's model. There are some related works that attempted to explain different type of relaxed states by assuming different constraints. For example, adding the constraint on the total mechanical angular momentum, we obtain a rigid-rotation flow. However, the pressure rises toward the boundary because of the centrifugal potential of the obtained flow. We need a new input for the model, which forces us to extend the framework of the conventional variational principle. Here, we consider a fragile constant of motion that is conserved in a rather restricted relaxation process.

We propose a variational principle with restricting the total canonical angular momentum. While the total mechanical angular momentum is a robust constant of motion, the total canonical one is conserved when the system stays quasi-axisymmetric. We will show that the restriction of the total canonical angular momentum yields a confined plasma [4]. Its interesting connotation is that the quasi-axisymmetry through the relaxation process is essential for the creation of equilibrium confining a high-pressure plasma. Our finding is that the conservation of the total canonical angular momentum underlies the creation of structure that resembles Jupiter's magnetosphere.

Here, we clarify the target of our model. Since the ideal MHD equations are employed, the model fails to capture the phenomena occurring near the planet, where the non-ideal effects become significant (r is less than 6RJ, RJ is the Jupiter's radius). In addition, since the quasi-axisymmetry during relaxation process plays a crucial role, the model does not apply to the region far from the planet where asymmetry due to the outer current system becomes prominent (r is greater than 30RJ). Therefore, our model applies to the middle region of the magnetosphere.

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