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A magnetospheric energy principle and pressure-driven instabilities

Akira Miura[1]

[1] Earth and Planetary Science, Tokyo Univ

A magnetospheric energy principle is formulated to study pressure-driven instabilities in the magnetosphere, which are subdivided into interchange and ballooning instabilities. Both instabilities are known to play important roles in magnetospheric dynamics. For example, interchange instability has been considered to play an important role in the plasma circulation in planetary magnetospheres and ballooning instability has been considered to be important in the onset of a magnetospheric substorm. Although both instabilities are 3-dimensional ideal MHD instabilities and often confused, they each have their own different characteristics. In this formulation, the magnetospheric plasma is either in a 2-dimensional or 3-dimensional static equilibrium. It is surrounded by lateral perfectly conducting walls and ideal ionospheres in both cases and also by dawn-dusk periodic boundaries in the 2-dimensional case. The 2-dimensional case has a translational symmetry and has no unperturbed magnetic field component in the dawn-dusk direction. Unlike the conventional energy principle for a plasma surrounded by a perfectly conducting wall, field lines are assumed to vertically thread the ionospheric boundary, which is not a perfectly conducting rigid wall. Ideal ionospheric boundary conditions are obtained, so that the force operator becomes self-adjoint and the magnetospheric energy principle is valid. There are four ideal ionospheric boundary conditions to satisfy these requirements: horizontally-free, conducting, free, and rigid. A change in the potential energy becomes equal to the sum of the change in the fluid energy and an ionospheric surface contribution, which is negative and thus destabilizing for horizontally-free and free ionospheric boundary conditions. A minimization condition for the change in the potential energy is obtained. When an unperturbed field-aligned current vanishes, the horizontally-free, conducting, free, and rigid boundary conditions allow interchange, incompressible ballooning, incompressible ballooning, and conmpressible ballooning modes, respectively. Different characteristics of those three pressure-driven modes are clarified. Existing interchange stability criteria are compared and results of several different numerical stability analyses of ballooning instabilities for different magnetospheric equilibria are discussed systematically in light of the present magnetospheric energy principle. The energy balance of the instabilities is clarified.