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Perspectives in space plasma theory

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Abstract

The past half century has been characterized by the birth of space plasma physics and its rise to maturity which has led into a certain mood of satisfaction and partial saturation with its achievements. Indeed, on the global scale our knowledge about the magnetosphere, the solar wind from the Sun out to its boundaries, even of the conditions on the surface and in the atmosphere of the Sun and the Sun's interior has to a high degree become complete. The degree of completion is indeed such that it allows predicting up to a certain precision their behavior. New names like solar seismology, solar meteorology, and space weather have been coined indicating the transition of some of the sub-field of Space Plasma Physics into the domain of an industry of monitoring and predicting in the interest of the needs of a general society. This is an entirely healthy evolution of a scientific field that is on the path of completion. Still there is a large number of questions which should and can hopefully be answered by space plasma theory. Some of them will be listed here in view of what has been achieved and in which direction future theory could proceed in order to contribute to their resolution when addressing the already operating and the new and upcoming space missions like Cluster, the planned Magnetospheric Multi-Scale mission MMS and others, respectively, most of which are designed to become multi-spacecraft enterprizes and also in view of the new theoretical and computational techniques and methods that have been developed during the past decades. These directions reach from the detailed understanding of the processes in the solar atmosphere and solar wind through the detailed physics of the formation of collisionless shocks, magnetosheaths and turbulence, the microphysics of reconnection and particle acceleration, and the substorm mechanism to the detailed understanding of planetary magnetospheres, the outer heliosphere with its heliospheric termination shock, heliosheath and boundary layer. All this research though already in flow has by far not been completed yet. It requires new efforts as it implies resolution of the smallest though still non-atomic scales, but it has high implications for the understanding of the processes in space plasma and, in extension, of processes in the remote astrophysical systems which can be understood only by observation of their radiation in all wavebands.

Keywords: Reconnection; Plasma simulations; Auroral dynamics

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1. Introduction

Space plasma theory deals with open systems: the interaction between the solar wind and the magnetosphere of the Earth, cometary or other planetary environments. In addition, most of the problems it encounters are caused by the intrinsic non-linearity of the processes in space plasma. Only a very small number of processes taking place in space plasma can be treated in the framework of linear physics. These facts let space plasma physics become a very complex and complicated field of research. Moreover, verification of the predictions of space plasma theory is complicated by the experimental impossibility of preparing the system in an accessible state. As a consequence of their openness space plasmas are non-stationary; they are driven from the outside. This is in contrast to conditions in the lab-

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oratory where the state of a system can be prepared in a way that all effects can be excluded, except the one of interest. Finally, because of the large dimensions of space plasmas, spacecraft and rockets launched into it being armed with instrumentation in their majority merely provide point measurements not giving an instantaneous global view of the system. These facts seem to exclude any reliability of space plasma theory.

Nevertheless, within the past half a century space plasma theory has been successful in constructing a rather complete and reliable global picture of the magnetosphere including some of the processes that determine its stability and dynamics. Fig. 1 shows a sketch of this model. The essential features included in this model are the existence of the bow shock wave in front of the magnetosphere as an obstacle in the supersonic solar wind, the existence of the magnetopause as the outer boundary of Earth's magnetic field, the interconnection of the interplanetary (solar wind) and geomagnetic fields across the magnetopause, the filling of the magnetosphere with solar wind plasma, and the tail plasma sheet containing the narrow cross-tail current in its center. Fig. 2 schematically includes a few of the plasma processes inside the magnetosphere. Reconnection either at the dayside magnetopause or poleward the cusps enables plasma to flow across the magnetopause. Distant reconnection in the cross-tail current feeded by the plasma inflow from the lobes causes current instability and plasma jetting into the inner magnetosphere as well as release of a plasmoid downtail into the solar wind. Also indicated is filling of the magnetosphere by ionospheric plasma outflow.

This global picture is now well established and is supported by a multitude of spacecraft observations. Roughly spoken, space plasma theory has fulfilled its duty on this scale. It has combined information provided by in situ and remote observations into a globally consistent stationary picture of the magnetosphere and its interaction with the solar wind. However, when looking at smaller scales both in space and time and at higher resolution, the picture changes completely. It not only becomes highly complex but it is also obscured either by observational facts which do not fit into the global picture or by lack of observational facts in order to support theory.

Doubtlessly, there are problems in space plasma physics that have been solved theoretically up to a state where further investigation is not expected to add any important insight. Space plasma theory has had its ups during the past half century, stimulated by the availability of in situ data rather than imagination pushing its explosive development and successes during the past decades. One of the problems that has ultimately been solved is the stability of the radiation belts. It has been given its shape early in history when Kennel and Petscheck (1966) applied the then young quasilinear theory (Vedenov et al., 1961) to resonantly excited whistlers in the radiation belts. It should be mentioned that this was one of the few occasions when quasilinear theory was astonishingly successful. In most cases in plasma the conditions for an application of mean field theory are not given, and the plasma readily evolves into a different non-linear state. However, at that time quasilinear theory was on its rise and with some modifications was applied to almost every problem, from the depletion

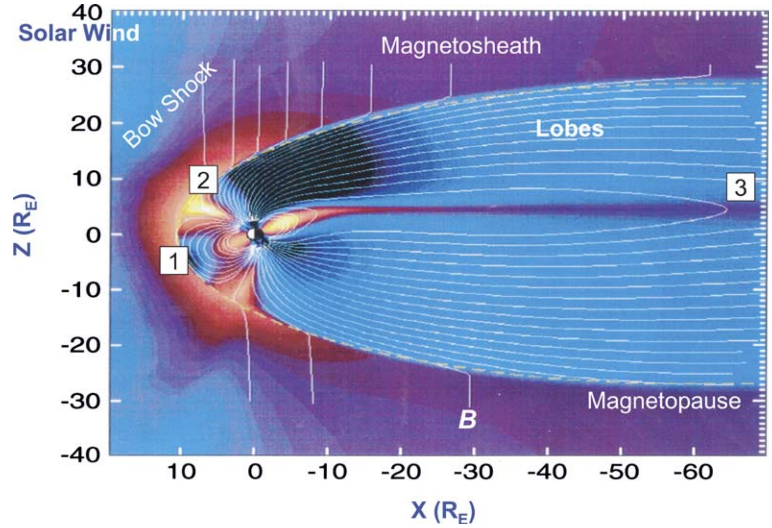

Fig. 1. Schematic meridional GSE cross-section through the Tsyganenko model magnetosphere (Tsyganenko, 1989) showing the main features of the magnetosphere: The bow shock wave in front of the magnetopause, the connection of interplanetary and magnetospheric field lines across the magnetopause as caused by reconnection at the subsolar point [1], the tail plasma and neutral current sheets, the lobes, the cusps [2], and the tailward magnetic neutral X-point [3]. Color shading indicates the presumable plasma filling in this particular ecliptically inclined geometry, with the dilute solar wind, hot magnetosheath and cusp plasmas, the almost empty near-Earth lobes, the plasma sheet, and the dilute distant lobes.