Yu. I. Gal'perin. *The Magnetospheres of the Earth and the Planets.* The basic problems of the physics of the earth's magnetosphere that remain unresolved despite intensive study are as follows.

a) *The energetics of the magnetosphere.* There are two main sources. The first is the motion of the neutral gas in the ionosphere, including the rotation of the atmosphere with the earth, which creates the atmospheric dynamo effect responsible for the drift motion of the plasma. In the earth's magnetosphere, these effects determine the dynamics of the plasma at low and middle latitudes and in the plasmasphere. The second is the motion of the plasma in the boundary layer near the magnetopause, which is driven by the flow of the solar wind around the magnetosphere (the so-called magnetospheric dynamo) and creates an emf in the magnetosphere in an analogy to the MHD generator. Large-scale plasma convection arises in the magnetosphere as a result. In the earth's magnetosphere, the effects of these two sources become equal approximately at the boundary of the plasmasphere, i.e., on the magnetic shells 1 ~ 4–6 (Fig. 1). No quantitative theory of these sources has been derived with consideration of the inertia of the atmosphere.

b) *The source of the magnetospheric plasma.* Here we may also distinguish two main sources—solar-wind ions (chiefly H^+ and a few percent of He^{++}), which penetrate the magnetosphere in the region of the polar cusps and through the boundary layer, and upper-ionosphere ions (H^+, He^+, O^+), which rise into the magnetosphere in the longitudinal electric currents and are heated to energies of kiloelectron-volt order during magnetic storms. The relative importance of these sources under magnetic-storm conditions remains unclear, but they both contribute significantly to the energetic-ion composition of the magnetosphere.[1]

c) *Nature of heating and acceleration of plasma particles accompanied by a sharp increase in their magnetic moment.* Nonstationary plasma-heating processes of this kind occur during substorm flareups on the earthward-facing inner boundary of the plasma layer[2]; active processes resembling chromospheric flares on the sun have also been observed near the boundary layer in the tail of the magnetospheres.[3] It is known that the convection electric field produces the phenomena of adiabatic auroral-particle acceleration and longitudinal acceleration in the double-layer electric field above auroral arcs, as well as diffusion of trapped particles on inner L shells, which causes acceleration of radiation-belt particles, but magnetic moment is conserved in these processes.

d) *The pattern of the magnetospheric electric currents.* The large-scale surface current forms the magnetosphere–magnetopause boundary, while the convection electric field sets up a complex system of longitudinal currents that are completed through the conductive ionosphere. The Joulean losses of these currents in the atmosphere require a continuous supply of energy to the magnetosphere from the solar wind, the power supplied and even the configuration of the currents being determined by the vector of the interplanetary magnetic

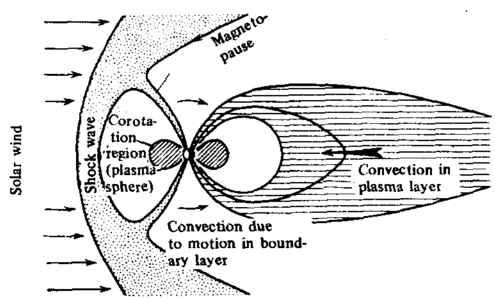

FIG. 1.

field,[4] but the mechanism of this interaction, like the structure of the currents itself, remains unclear.

As we see, magnetospheric physics has encountered a whole tangle of interrelated problems, but, in contrast to the physical experiment in the laboratory, where the roles of individual factors can be isolated or modified, comparison with the magnetospheres of other planets offers the only fundamental possibilities for study of the magnetosphere.

The simplest case is the magnetosphere of Mercury,[5] since the atmosphere and ionosphere are almost completely lacking in this case, and, consequently, there are no dynamo effects (i.e., only the external energy source remains) and no system inertia due to the motions of a neutral gas. The absence of ionospheric conduction eliminates the longitudinal currents, so that the current system contains only the surface currents on the magnetopause and the drift currents in the tail. Construction and analysis of this current system, which holds down the solar-wind dynamic pressure, is an unsolved problem of magnetosphere theory. The dimensions of Mercury's magnetosphere are inadequate for the appearance of a capture zone or radiation belts. Therefore there is no radiation-belt reservoir for energy and plasma like the one in the earth's magnetosphere, which has a long memory for earlier active phenomena (magnetic storms) and is capable of partial damping of new flareups by redistribution of trapped energetic particles. The "simple" magnetosphere of Mercury, in which short-term perturbations similar to magnetic storms also occur, is an ideal though distant proving ground for theoretical magnetopause models.

The effects of the sharp increase in the ionospheric conductivity that results from the decrease in the magnetic field as compared to the earth's ionosphere can be studied in the magnetosphere of Mars.[6] Under these conditions, the electric field of the external source is buried in the ionosphere,[7] and plasma convection is determined by the neutral upper atmosphere (corotation and winds), i.e., the atmospheric dynamo dominates. The resulting plasma-convection pattern influences the configuration of the magnetosphere and the phenomena near the magnetopause (in much the same way as in the magnetosphere of Jupiter; see below). Therefore the results of measurements of boundary-layer structure and phenomena in the tail region of the Martian magnetosphere[6,8] are of exceptional interest.

If there is also a large-scale magnetic field on Venus, the pattern should be similar to that observed on Mars, but without effects of rotation of the planet and with still higher ionospheric conductivity.

Jupiter has the largest and most interesting magnetosphere, which is in many respects similar to the magnetosphere of a pulsar.[9] Its diameter is more than 0.1 a.u., and the length of the magnetospheric tail more than 4.6 a.u. (most probably at least 20 a.u.). All of the unsolved problems of the physics of the earth's magnetosphere that were listed above become even more acute for the Jovian magnetosphere. We indicate only a few of their important aspects:

1) *Energetics.* Here the basic factor is the dynamo effect, which is governed by the rapid rotation of the planet's atmosphere and by turbulent motions in it, combined with the high integral conductivity of the ionosphere.

2) *The magnetospheric plasma* is supplied in large part by dissipation of the atmospheres of the Galilean satellites as they are bombarded by energetic particles. The dissipated neutral particles are gravitationally trapped and form toroidal clouds that extend along the orbits of these satellites and are ionized by energetic particles. Together with protons, significant components of these clouds are S^+, Na^+, and Mg^+ ions. The plasma rotates with a period of ~10 hr, and the centrifugal force gives rise to a drifting motion of the ions. The question as to the resulting appearance of significant radially-outward flowoff of plasma on the daytime side remains open. In the tail, this flowoff is highly probable, and in this case the convection in the tail would differ sharply from that expected from motions in the boundary layer near the magnetopause (Fig. 2).

3) *Heating and acceleration of plasma particles with disturbance of the magnetic moment* are unusually effective and produce high relativistic-electron intensity even near the magnetopause. The intensities of these particles are modulated with a period of ~10 hr not only throughout the entire magnetospheric region crossed by the Pioneer 10 and Pioneer 11 spaceprobes, but also in the near-planet and interplanetary space into which they are ejected, probably from the tail region of the magnetosphere. It remains unclear whether this 10-hr modulation of electron intensity is related to the conditions of their capture and escape into interplanetary space or involves the very process of generation of the relativistic electrons within the magnetosphere.[9]

4) *The magnetospheric-current pattern* has hardly been studied as yet, but it is already clear that the drift of ions under the action of centrifugal force produces an outer-magnetosphere ring current that creates a magnetic configuration similar to the so-called neutral-layer region in the tail of the earth's magnetosphere. Stability of this configuration requires the longitudinal angular distributions of the energetic particles that are actually observed in this region. However, we do not yet have data on the concentration and

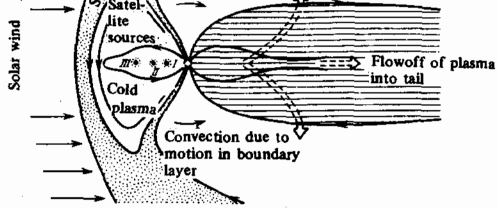

FIG. 2.

composition of thermal ions for this region, or even data on the longitudinal currents and other characteristics of the plasma processes. Generation of the exceedingly powerful dekameter radio emission is related to longitudinal-current instabilities stimulated in the force tubes passing through the satellites (Io and Europa and possibly others).

This far from complete list of striking phenomena in the Jovian magnetosphere makes it particularly interesting to study other variants of the magnetospheres of rapidly rotating planets. The next "copy" of this magnetosphere, that of Saturn, may have only a very weak inner radiation belt (and, consequently, weak synchrotron radiation) due to absorption of trapped particles by the solid matter of the rings. At the same time, this matter may release a large amount of neutral gas and produce a high-density cold plasma in the magnetosphere. The properties of the longwave burst radio emission (~1 MHz[10]) were found to be closely similar to those of the dekameter radio emission of Jupiter[11] and the kilometer radio emission (~0.3 MHz) over the terrestrial auroras,[12–14] an indication that they have a common nature related to longitudinal electric currents.[11,15]

Finally, the last of the magnetospheres that our generation can hope to study is the hypothetical magnetosphere of Uranus.[16] The planet's axis is nearly in the plane of the ecliptic, and we may assume, in analogy to other planets, that its magnetic moment is proportional to the mechanical moment and directed approximately along the axis of rotation. The direction of the planet's axis will begin to cross the sun in 1985, and at this time the hypothetical magnetosphere of Uranus will be approximately axisymmetric, with deviations from symmetry arising only when the field interacts with the interplanetary magnetic field at the magnetopause.

It appears obvious that study of the planetary magnetospheres will be particularly important for clarification of the unresolved problems of the physics of the earth's upper atmosphere and magnetosphere.

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