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# Earth's magnetosphere

## INTRODUCTION

The magnetosphere was discovered in the early years of the space era. Magnetospheric physics became the first new scientific discipline conceived in the space age, although it was in the beginning called space plasma physics, auroral physics, or ionospheric physics, as the concept magnetosphere did not exist yet. Auroral and ionospheric physics were important items in the research program of the 'International Geophysical Year' (IGY), which, after long preparations, was implemented in the 18 months starting on 1 July 1957 and thereafter was followed up in a number of international research programs. Being the largest international co-operative research program ever, it resulted in important progress of magnetosphere-related research fields – such as the aurora – based on worldwide ground-based observations. IGY had also in its program the launching and operation of the first man-made satellites, both Soviet Sputniks and American Explorers and Vanguards, for *in situ* measurements in space. Still, Sputnik 1 caused an enormous sensation when it appeared in the sky on October 4, 1957.

The physics of near space came to dominate space research in the first decade or more after Sputnik. That had to do with the fact that the early satellites, which were stabilized by spinning, were well suited for accommodating the instruments of the space physicists, who were also very eager to send their instruments into space to measure directly on that hot plasma, the effects of which in the form of aurora, ionspheric variations and energetic particles at Earth's surface, they had studied for long from the ground. The astronomers could generally not be well served by the early satellites and in addition they were not used to build own instruments suitable for launch into space. Besides from auroral and ionospheric researchers, the magnetosphere recruited its workers from nuclear physics – generally via the cosmic rays and solar energetic particles fields – and laboratory plasma physics (ionized gases) groups. The magnetospheric physics community is still one of the largest in the solar system sciences.

In the four decades of the space era magnetospheric research has reached a certain degree of maturity. It is, however, still a young field in the sense that unexpected, 'surprising' results continue to constitute the most important new results from practically all new space missions. Earth's magnetosphere has become the main 'laboratory' for studies of space plasma physics. We rely on nature to make most of the 'experiments' in that laboratory, but some 'active' experiments have been made by researchers.

That the concept magnetosphere did not exist when Sputnik 1 was launched does not mean that no physical concepts of major importance in magnetospheric physics were known before the space age. A first attempt to describe what happens when a plasma cloud from the Sun reaches Earth with its strong internal magnetic field was made by Chapman and Ferraro already in the early thirties and in the late thirties and early forties Alfvén introduced large-scale electric fields around Earth and magnetic fields into the solar plasma interacting with Earth, as well as magnetohydrodynamics and the guiding center approximation.

Still, we must conclude that before the satellite era our knowledge of magnetospheric physics was very limited and many early ideas have turned out to be very far from reality. This is not astonishing considering what we now know of the complexity of magnetospheres. The complexity is so great that it is very difficult, if not impossible, to

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derive more than a very limited amount of information from basic principles. Only *in situ* observations can generally tell what happens and theory needs a strong guidance from experiments in order to find its right directions. But the unavoidable limitations of observational possibilities in the huge magnetospheric system makes theoretical and numerical models of the system essential for the interpretation of the few scattered observations available when nature makes its 'experiments' around and within the magnetosphere. Thus, theory and experiments depend strongly on each other for progress. That the most important results of new magnetospheric missions are unexpected, as mentioned above, means that many theoretical and numerical models are in an early, incomplete, or even wrong state.

To learn to understand what are the prevailing processes among the many possible ones in the complex magnetosphere is, of course, an important task from a basic scientific point of view and it is important also because many of the basic magnetospheric processes, which can be studied in detail only in our own magnetosphere, certainly play important roles in the physics of the plasma universe in general, thus not only around the other bodies in our solar system and in the heliosphere as a whole, but around other stars and in the interstellar space. To the basic scientific interest adds that understanding of magnetospheric physics is a requirement for the exploration of space for various applications. 'Space weather' is affecting an increasing amount of human activities in the environment of humankind.

The present review deals with some of the most important results of magnetospheric research from the point of view not only of understanding the magnetosphere but for basic plasma physics and astrophysics in addition. The early part of the paper is organized mainly regionally. The first section describes the discovery of the magnetosphere, i.e. of the magnetopause and the bow shock and the physical processes there. Thereafter come in turn the inner magnetosphere, the high-latitude magnetosphere with the aurora-related phenomena, the magnetotail, the boundary layers. These regional sections are followed by some on processes: magnetospheric convection, substorms and storms, plasma sources and losses, and wave-particle interactions. Finally, future directions of research and the roles of magnetospheric research in the investigation of the universe are discussed briefly.

## THE CELLULAR STRUCTURE

Chapman and Ferraro (1931, 1932), in a study of the cause of magnetic storms on Earth, had shown that a plasma cloud emitted by the disturbed Sun when reaching Earth would enclose the geomagnetic field and compress it in the direction of the Sun. This effect was only expected during magnetic storms. The existence of a permanently occurring solar wind was discovered by Biermann (1951) from his observations of comet tails and Parker (1958) gave a theory for it. From the presence of an always-present solar wind follows an always-present boundary to the geomagnetic field. The name 'magnetosphere' for the elongated volume within this boundary was used for the first time by Gold (1959). Several of the early US satellites with eccentric orbits showed a fluctuating and irregular magnetic field beyond certain distances (Pioneers 1 and 5 and Explorer 10), then considered as a broad, unstable boundary region. Explorer 12, launched in August 1961, was the first to provide a clear determination of the boundary of the magnetosphere in the subsolar region (Cahill and Amazeen, 1963). The sharp boundary, called the magnetopause, was found to be located in the range from 8 to 12 $R_E$ near noon. The expected compression of the outer subsolar geomagnetic field was observed and the magnetic fluctuations were found to be larger outside the magnetopause than inside.

Less than two years after Cahill and Amazeen had made the first observations of the sharp boundary of the magnetosphere, Ness *et al.* (1964), in data from IMP-1, succeeded in interpreting the irregular variations in the magnetic field outside of the magnetopause and identified for the first time the bowshock of the magnetosphere in the solar wind. Their results are reproduced in Figure 1. That there would exist a bowshock in the collisionless plasma of the solar wind had been suggested by Axford (1962) and Kellogg (1962) shortly before, however without specifying the processes which replace the collisions in an ordinary gas. A collissionless shock wave had never been seen before. Collective plasma processes have in them taken the place of collisions in ordinary gases for the scattering and thermalization of the ions and electrons.

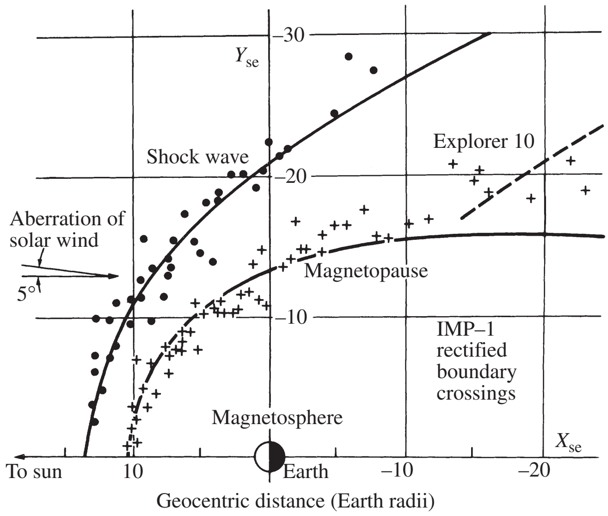


**Figure 1** Observations of spacecraft crossings of the magnetopause and the standing shock wave in front of Earth's magnetosphere (after Ness *et al.* 1964).

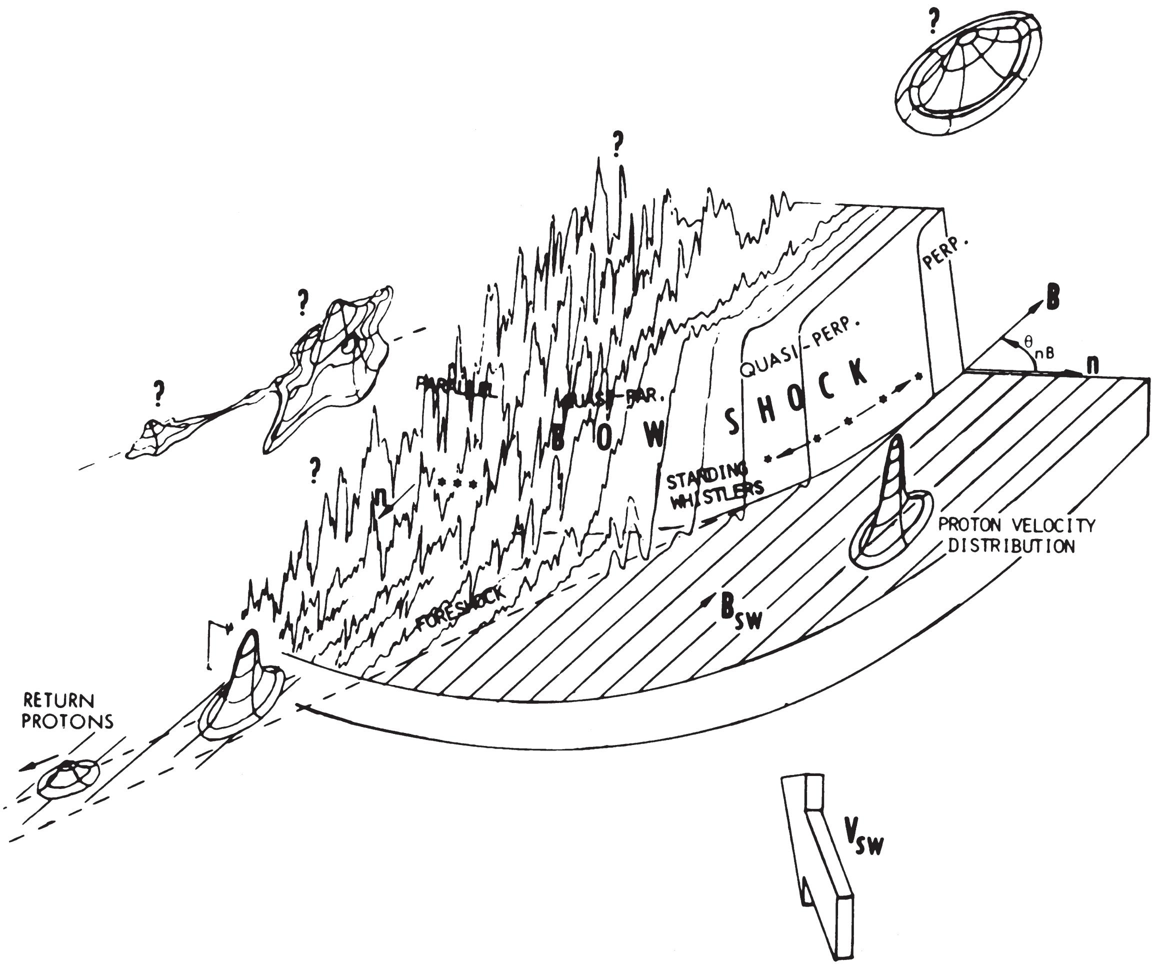


**Figure 2** Schematic representation of magnetic field profiles at different locations of Earth's bowshock (after Greenstadt and Fredricks 1979). Field magnitude is plotted vertically. The superposed three-dimensional sketches represent solar wind proton thermal properties as number distributions in velocity space.

Collisionless shockwaves in hot magnetized plasmas are difficult to produce and investigate in the laboratory and most of what is known about them has been learnt from space measurements. Major efforts, both experimental and theoretical, have been devoted to the investigation of such shock waves since the middle of the sixties. A representation of observational results from Earth's bowshock is shown in Figure 2 (after Greenstadt and Fredricks 1979). It illustrates the complexity of the shock.

Collisionless shock waves are quite important for the acceleration of particles in the solar system and in the whole universe. Besides the bow shocks in front of planets, many travelling shocks generated near the Sun have been observed. There are still many aspects of the shock waves that are poorly understood and the experimental investigation of them in space will certainly go on for a long time. The reader is referred to e.g. Tsurutani and Stone (1985) for detailed information.

The magnetopause separates the comparatively dense and not too hot plasma of the solar wind from the thinner and hotter plasma in the magnetosphere. The transition takes place over a thin boundary layer. Also the magnetic fields in the two regions are different. An important result of space plasma physics research is the demonstration that this kind of thin boundary between plasmas of quite different properties characterizes the solar system as a whole and not only the vicinity of Earth. All planets have similar boundary layers and the interplanetary magnetic field sector boundaries are other examples. The solar system thus has a kind of cellular structure and it is most likely that this is true for the universe as a whole. The 'cell walls' are not possible to observe by remote sensing techniques but only by *in situ* measurements.

Such a cellular structure of the plasma universe may be of major astrophysical importance. Alfvén (1981) has even suggested that a consequence of the ability of plasma to concentrate differences between different populations into very thin boundary layers between them may be that a matter – antimatter symmetric universe may possibly exist in spite of lacking observational evidence, with matter and antimatter separated from each other by thin ‘cell walls’ and therefore the interaction between matter and antimatter in these thin boundaries being too weak to be observable from Earth.

The interaction of solar wind and magnetospheric plasmas and fields at the magnetopause is an interaction between two collisionless, high-temperature plasma populations containing different magnetic fields and moving relative to each other with supersonic and super-Alfvénic velocities. Such interaction is of basic interest and importance from both a general plasma physics and an astrophysics point of view. It is a complicated and difficult matter, still far from being understood in all its aspects. Practically all existing experimental knowledge about it has been obtained from space plasma physics investigations at the boundary between the solar wind and the magnetosphere of Earth. The investigations have shown that the magnetosphere is not closed but open in a way proposed by Dungey (1961) in the early space era and illustrated in Figure 3. How the interconnection of the magnetic fields of the solar wind and the magnetosphere really occurs, a process generally called reconnection and discussed in a special chapter of this book, is still a front line item of magnetospheric research. The dependence of the interaction on the direction of the interplanetary magnetic field being opposite to the direction of the magnetospheric field, or at least having a strong such component, was demonstrated observationally already a few years after the discovery of the magnetospause (Fairfield and Cahill 1966). The reconnection process has become an important tool in magnetospheric research as well as in many fields of astrophysics, although what really happens in the reconnection volume – the diffusion region – has not yet been demonstrated experimentally. Many conclusions about effects of reconnection

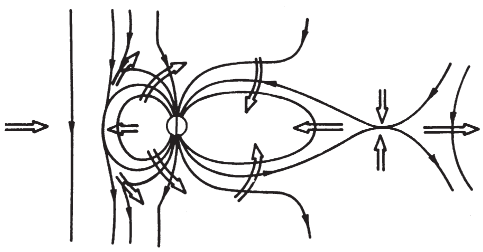

**Figure 3** The ‘open’ magnetosphere proposed by Dungey (1961), in which the magnetic field lines of the solar wind plasma are connected with the geomagnetic field lines on the sunward side of Earth and they are disconnected again in the geomagnetic tail.

can, however, be drawn, and are being drawn, without a detailed understanding of what happens in the diffusion region. That reconnection occurs under certain conditions must be considered as experimentally demonstrated beyond doubt, but a lot of work remains before the process is well understood. The magnetopause region of Earth will certainly be the main region for experimental investigations also in the future.

Another kind of interaction between the solar wind and the magnetosphere was proposed in the same year as Dungey published his reconnection-produced open magnetosphere, namely some kind of viscous processes at the magnetopause (Axford and Hines 1961). Although most evidence suggests that reconnection is quantitatively more important than viscous processes for the transfer of plasma and energy across the magnetopause, the latter processes are likely to occur and may even dominate the interaction when the interplanetary magnetic field is pointing northward. What micro-processes are most important for the viscous effects is still unknown.

That the differences between the properties of two plasma populations which are streaming relative to each other are concentrated to a thin boundary between them, does not mean that they do not affect each other beyond the boundary layer. All the phenomena to be reviewed below are in fact driven by the streaming of the solar wind around the magnetosphere. The characteristic solar wind speed of 400 km/s corresponds to a voltage difference over the width of the magnetosphere of several hundred kilovolts. Part of this voltage is transferred into the magnetosphere and causes convection and acceleration of the plasma. The solar plasma dynamic pressure on the magnetopause also has direct effects in the form of variable compression of the day-side magnetosphere caused by the variable solar wind and on the penetration of plasma in the polar cusp regions (see Figure 23) and possibly elsewhere.

The transient re-organizations of the inner magnetosphere that give rise to magnetospheric substorms and storms (see later section) involve power levels of the order of $10^{12}$ Watt or even more for the intense cases. Those processes use, at least partly, energy accumulated within the magnetosphere during longer periods than it is dissipated in, but the supply of energy by the solar wind is more than enough for running such processes continuously. That it does not happen is not because of too little energy in the streaming solar wind. In Earth’s magnetosphere the rotation of the planet contributes significant energy to the magnetosphere but much less than the solar wind. For Jupiter, the opposite is true: the planetary rotation is a more important energy source for the magnetosphere than the solar wind.

A comparison: For an average rate of dissipation of energy within the near-Earth magnetosphere and the ionosphere of one tenth of the figure mentioned above for

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