1
Introduction

Space plasma phenomena have attracted particular interest since the beginning of the exploration of space about half a century ago. Already a first set of pioneering observations (e.g., Ness, 1969) discovered that matter and electromagnetic fields in space have a complex structure, which was largely unpredicted. Terrestrial and, particularly, spacecraft observations of solar plasmas and fields point in the same direction. In fact, our present picture of the plasma and the electromagnetic fields in space throughout the solar system (and beyond) is that of an extremely complex medium with spatial and temporal variations on large ranges of scales. The wealth of dynamical phenomena observed in space plasmas has steadily increased as more and more refined observational techniques have become available, and it can be expected that important processes still await their detection.

An outstanding class of space plasma phenomena is addressed here under the notion of *space plasma activity*. Quite generally, in the area of space and astrophysical plasmas the term *activity* is used for a set of particular magnetospheric, stellar or galactic phenomena, which, although vastly different regarding their space and time scales and their dominant physical processes, have an important characteristic property in common. In all cases they show sudden transitions from relatively quiet states with less pronounced time-dependence to dynamic states in a strongly time-dependent evolution. (Note that this property by no means is restricted to plasma phenomena, volcanic activity being a prominent example from another discipline.)

The term *activity* is commonly used in two different ways. In a narrow sense *activity* refers to the strongly time-dependent dynamic phase alone. In a wider sense, it means the entire phenomenon including the relevant quiescent intervals. The latter meaning is adopted for the title of this book and, to a large extent, also for the text. It will be clear from the context, when, occasionally, we will use the narrower meaning.

Strictly speaking, as is the Earth's atmosphere, the plasma in space is always in a time-dependent evolution. Therefore, in a strict sense it is impossible to identify intervals where the space plasma (in some region) is *quiet*. However, as in the atmosphere, it often does make sense to speak of quiet and dynamic plasma conditions in an approximate way. There is a qualitative difference between a situation where during an atmospheric storm a strong gust blows across a countryside and the comparatively quiet state of the air before the gust arrives. It is in this sense that we will speak of *quiescent* and of *dynamic* space plasma states. Also, as we will see, the notion of *quiescence* can be an important theoretical tool even if the real system considered has a level of superimposed time-dependent phenomena.

Generally, for systems with multiple time scales *quiescence* and *dynamics* are relative terms; what counts is that the processes that one compares occur on different, well-separated time scales. A more precise definition of activity in the present context does not seem to be available, nor is it necessary for our purposes. From a phenomenological point of view we simply refer to the processes described in Chapter 2.

For magnetospheric activity, the most direct visual evidence is provided by auroral light emission. Here, a corresponding black and white reproduction (Fig. 1.1) should suffice to indicate strong temporal variations of the

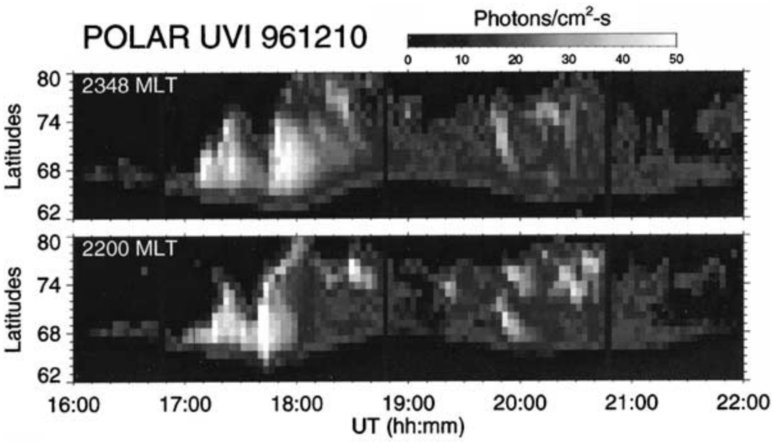

Fig. 1.1 Auroral luminosity enhancement at two magnetic meridians during a magnetospheric substorm approximately lasting from 17:10 to about 19:00 Universal Time (reproduced from Sergeev *et al.* (2001) by permission of the American Geophysical Union).

aurora occurring in connection with magnetospheric activity. A quiescent state ends near 17:10 UT (*Universal Time*), when the dynamic phase starts. Such strong enhancement of auroral emissions are important signatures of *magnetospheric substorms* (Akasofu, 1968), to be addressed in detail later. There are many manifestations of such changes in the signatures of characteristic plasma quantities, monitored by spacecraft in the Earth's magnetosphere (see Section 2.1).

A most spectacular class of activity processes in the solar system involves large plasma outbursts from the solar corona into interplanetary space. Such events are called *coronal mass ejections*. An example is shown in Fig. 2.8; a brief survey is given in Section 2.2.

Part I sets the scene with regard to the phenomenological background and to the basic plasma models. Concerning the latter, the kinetic description follows from basic principles, specifically Newton's mechanics, Maxwell's theory of electromagnetism and statistical mechanics, while the fluid pictures involve additional simplifications. The models are presented without derivations, but their physical meaning is outlined. For more on the foundations the reader should consult introductions to plasma physics.

Parts II and III are devoted to theoretical tools, specific to space plasma activity. Their splitting into two parts reflects the fact that it makes sense to distinguish the quiescent from the dynamic phases not only in their phenomenological appearance but also in the choice of appropriate theoretical modelling.

The present tasks are complicated by the fact that the plasmas that we want to study are spatially inhomogeneous. This excludes a considerable fraction of the available methods in space plasma physics, such as the theory of waves, instabilities and wave–particle interaction on a homogeneous background. Such processes will be considered only if a special motive for doing so arises. Our present purpose leads us to consider space plasma processes with background gradients playing an important role.

We mostly deal with situations where the gradients are supported by large-scale magnetic forces. In addition, the present scope does include external gravity in a few instances, but self-gravitation is excluded. Thus, although small scale galactic magnetic field structures may be covered in principle, active galactic nuclei are outside the present scope.

Our approach takes into account that it has proven appropriate to deal with inhomogeneous space plasmas by considering systems with both two and three spatial dimensions, profiting from their characteristic advantages. 3D systems are more realistic, but general analytical results are scarce, so that in many cases numerical simulations are required. For models with two spatial dimensions a considerable wealth of analytical techniques is available, but the results are less realistic. Still, they are often indispensable for providing a qualitative understanding of complex phenomena. Also, 2D results can provide valuable guidance for the interpretation of numerical simulations.

In Part IV it is attempted to discuss particular aspects of magnetospheric and solar activity in the light of Parts II and III. It will become apparent that in some areas the theoretical results are able to provide a deeper physical understanding. In other domains the discussion reveals a strong need for further theoretical investigations.

The provided references should be regarded as typical examples, complete referencing would have exceeded the scope of this book.

Cambridge University Press
978-0-521-85897-7 - Physics of Space Plasma Activity
Karl Schindler
Excerpt
More information

Part I

Setting the scene

2

Sites of activity

Here we will give a qualitative overview on major activity processes in the solar system. Since our main aim is to concentrate on basic aspects and on theoretical results, a full account of the observational background is outside our present scope. However, in the following sections we will summarize the main observational facts that are relevant for our later discussion. For details the reader is referred to the literature. Note that in the present chapter we will largely refrain from giving physical interpretations. They will be discussed in Part IV using the tools provided in Parts II and III.

2.1 Geospace

Magnetospheric activity comprises the major global dynamical phenomena of the Earth's magnetosphere including ionospheric processes. It results from the interaction of the solar wind with the Earth's magnetosphere (Fig. 2.1).

The solar wind is characterized by a fast (supersonic) plasma flow from the Sun into interplanetary space. The magnetosphere is the region above the ionosphere that is dominated by the geomagnetic field. The solar wind compresses the Earth's magnetic field on the day-side and stretches it out to a long tail (*magnetotail*) on the night-side of the Earth (Fig. 2.1). A bow shock wave stands in front of the magnetosphere, which has a rather thin boundary, the *magnetopause*. Its thickness, which varies considerably, can become as small as a few hundred km.

The magnetotail consists of *tail lobes*, where the magnetic field energy density dominates, and the *plasma sheet*, which in its central part (*central or inner plasma sheet*) is dominated by the energy density of the plasma. Since the plasma sheet is particularly important for magnetospheric activity, typical values of plasma sheet parameters are listed in Table 2.1. Because of substantial spatial and temporal variability these numbers can provide only

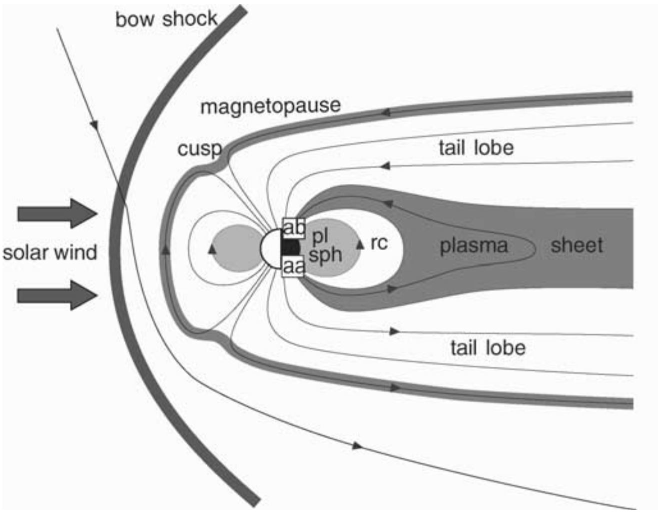

Fig. 2.1 A qualitative sketch of major features of the Earth's magnetosphere. Here 'pl sph', 'rc', 'aa' and 'ab' stand for *plasma sphere*, *ring current*, *Aurora Australis (southern lights)* and *Aurora Borealis (northern lights)*, respectively. An interplanetary magnetic field line is shown for a case with a southward field component.

Table 2.1 *Characteristic properties of the plasma sheet.*

plasma sheet	thickness	20 000 km
	length	500 000 km
central plasma sheet	number density	2×10^5 m^{-3}
	ion temperature	5×10^7 K
	electron temperature	10^7 K
	magnetic field strength	2 nT
magnetic lobes	magnetic field strength	20 nT

a general orientation. Temperatures are not thermodynamic temperatures, they simply measure kinetic energy of random motion. Fig. 2.2 shows a cross-section of the magnetotail.

The solar wind transfers energy into the magnetosphere. Correlation studies (e.g., Bargatze *et al.*, 1985) have established that the energy flux is particularly strong when the interplanetary magnetic field component perpendicular to the ecliptic plane points southward (Fig. 2.1). The magnetosphere responds to the energy input through a set of complex dynamical phenomena.

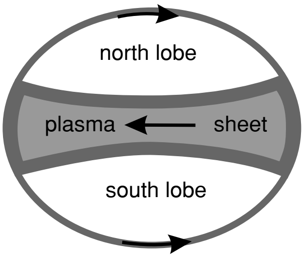

Fig. 2.2 A qualitative sketch of a cross section of the magnetotail. The view is from the tail to the Earth. Black arrows indicate the perpendicular current pattern of the tail. The plasma sheet is surrounded by boundary layers (broad line). The outer boundary is the magnetopause.

Fig. 2.3 gives an example (Sergeev *et al.*, 2001) showing detailed measurements obtained from spacecraft and ground instruments on 10 December 1996. The time interval is the same as that of Fig. 1.1. The panels a and b show the solar wind dynamic pressure P_{D} and a parameter ($Eps3$), which strongly emphasizes the occurrence of a southward component of the interplanetary magnetic field, and which can be regarded as a measure of the energy flux directed into the magnetosphere. The panels c and d show the ground observation indices Dst and AE. Here, Dst measures the disturbance of the mid-latitude magnetic field component parallel to the dipole axis, so that it monitors the intensity of the magnetospheric ring current. The AE index (in panel c shown as a stackplot of magnetograms from several stations) measures magnetic signatures caused by the auroral electrojet (an east-west electric current), which intensifies and changes its location during dynamic periods. The solid curves in panels e, f, g show measurements made aboard the GEOTAIL spacecraft, located at about 25 R_{E} (Earth radii) geocentric distance on the night-side of the Earth. Panel e shows a pressure parameter P_{T}, which is the sum of (scalar) kinetic and magnetic pressure and can serve as a rough measure of the energy density of the magnetotail. The parameters IPS and $LOBE/BLPS$ indicate whether the satellite was in the inner plasma sheet or in the lobe or plasma sheet boundary layer regions (see Fig. 2.2), respectively. Panel f gives the magnetic field component B_z perpendicular to the mid-plane of the plasma sheet (positive in the northward direction) and panel g shows the plasma velocity component in the earthward direction, v_x. Vertical dashed lines show approximate onsets of enhanced auroral activity.

Before 17:10 UT the magnetosphere was in a comparatively quiescent state with a substantial energy flux entering it. A significant fraction of the energy

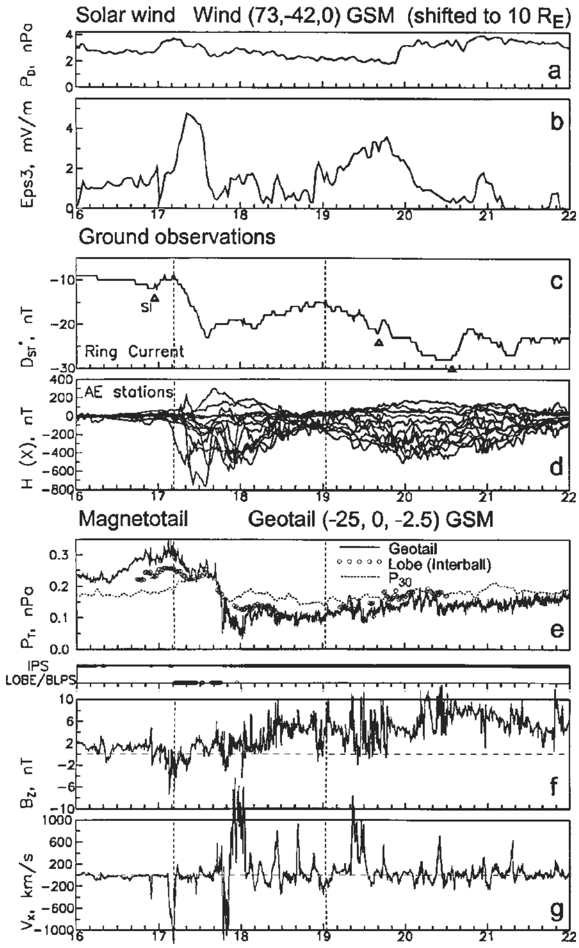

Fig. 2.3 Ground-based and satellite measurements during a dynamic period of the magnetosphere, details are explained in the text (reproduced from Sergeev *et al.* (2001) by permission of the American Geophysical Union).

accumulates in the magnetotail, indicated by a corresponding increase of P_{T}. Near 17:10 UT the magnetosphere suddenly turns into a different state, which is much more dynamic and involves the entire system consisting of the magnetosphere and the ionosphere. This is a *magnetospheric substorm* (Akasofu, 1968).

Under suitable conditions sequences of substorms can be accompanied by a gradual build-up of the ring current (Reeves and Henderson, 2001). A significant increase of $|D\mathrm{st}|$ indicates a *magnetic storm* (Chapman and Bartels, 1940). This means that understanding magnetic storms requires insight into the substorm process. Therefore, the magnetospheric substorm is widely regarded as the basic element of magnetospheric activity.

Substorms, however, cannot account for all large scale activity processes in the magnetosphere. This is clear from the plots in Fig. 2.3 also. In fact, shortly after 19:00 UT a second dynamic period begins. This period does not show the typical substorm signatures. Detailed studies indicate that such periods show features consistent with quasi-steady phases of considerable plasma flow. The plasma flow velocity includes a significant component perpendicular to the magnetic field, the corresponding plasma transport being referred to as *convection* (Axford and Hines, 1961). This has led to the term *convection bay*. (The term *bay* refers to the shape of the magnetograms.)

In the following we discuss a few further properties of magnetospheric substorms. Note that in view of our overall topic we deliberately concentrate on substorms, leaving aside many magnetospheric phenomena that would be of interest from other viewpoints.

One distinguishes three phases of a magnetospheric substorm (McPherron *et al.*, 1973; Russell and McPherron, 1973):

(i) the *growth phase*, which coincides with the quiescent phase before onset, where energy is accumulated in the magnetotail (before 17:10 UT in Fig. 2.3),
(ii) the *expansion phase*, which is the dynamical phase following substorm onset (near 17:10 UT in Fig. 2.3),
(iii) the *recovery phase*, which – at least in a fraction of the cases – can be identified as the phase during which the magnetosphere returns to a more quiescent state. (In the example of Fig. 2.3 the recovery phase does not fully develop as it goes over into the convection bay.)

These and many similar findings have led to the interpretation that during the growth phase (predominantly magnetic) energy is loaded into the magnetotail and is released, i.e., turned into heat, kinetic energy of directed flow and energetic particles, during the expansion phase (Baker *et al.*, 1985). The overall energy transfer that occurs during a substorm has been estimated as amounting to 10^{14}–10^{15} J. The duration of a growth phase is of the order of an hour but shows large variability. The dynamic processes observed after onset have a broad spectrum of time scales, the largest typically being of the order of 10 min.

In the late stages of a growth phase often a new feature occurs in the near-Earth tail, described as the *formation of thin current sheets* (McPherron *et al.*, 1987; Kaufmann, 1987; Mitchell *et al.*, 1990; Sergeev *et al.*, 1990;