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Solar–terrestrial physics: an overview

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Solar–terrestrial physics is concerned with the near-Earth space environment, that is with the solar wind, magnetosphere, ionosphere and thermosphere. It deals with this region, now often termed geospace, in both its ideal, steady-state situation and its transient response to dramatic events occurring on the Sun or in the interplanetary medium.

I start by asking four questions about this topic: why? where? when? and how? Why do we study solar–terrestrial physics? Nine reasons which illustrate the value of solar–terrestrial physics to Man nowadays are as follows:

(i) geospace is the only natural, cosmic plasma accessible to Man for carrying out *in situ* physical investigations;

(ii) the results of such detailed studies may be applied to other plasma physical situations occurring elsewhere in the Universe;

(iii) both astronauts and sensitive electronic components or instruments, aboard Earth-orbiting satellites or the Space Station, have to operate satisfactorily in the charged particle environment of space;

(iv) the lifetimes of satellites are determined by the density of the thermosphere, which can vary by a factor of a hundred or more as a function of solar and geomagnetic activity;

(v) observations made by a radar altimeter or a synthetic aperture radar aboard a satellite are affected by the ionospheric plasma;

(vi) radio communications are upset by solar flares and by energetic charged particle events;

(vii) large electromotive forces are induced by magnetospheric transients, in long conductors; these cause large electric currents to flow which can disrupt electrical power grid systems and telephone cables, or accelerate corrosion in pipelines;

(viii) aeromagnetic prospecting for natural resources, particularly at high latitudes, is upset by geomagnetic disturbances; and

(ix) laboratory plasma devices, designed for fusion, are susceptible to plasma instabilities which can be well studied in geospace.

Such research is thus not only of relevance to more universal problems or of purely academic interest; it takes on increasing practical importance as we use geospace nowadays for an increasing number and diversity of satellites.

I now consider briefly the where, the when and, particularly, the how of solar–terrestrial physics. Details will be filled in by other contributors.

The outermost atmosphere of the Sun is the corona at a temperature of over one million kelvins. It is the source of the omnipresent solar wind plasma, a mixture of electrons and ions that is electrically neutral on average. The expanding supersonic solar wind, with a speed in excess of one million kilometres per hour, encounters the Earth's magnetic field (figure 1). This

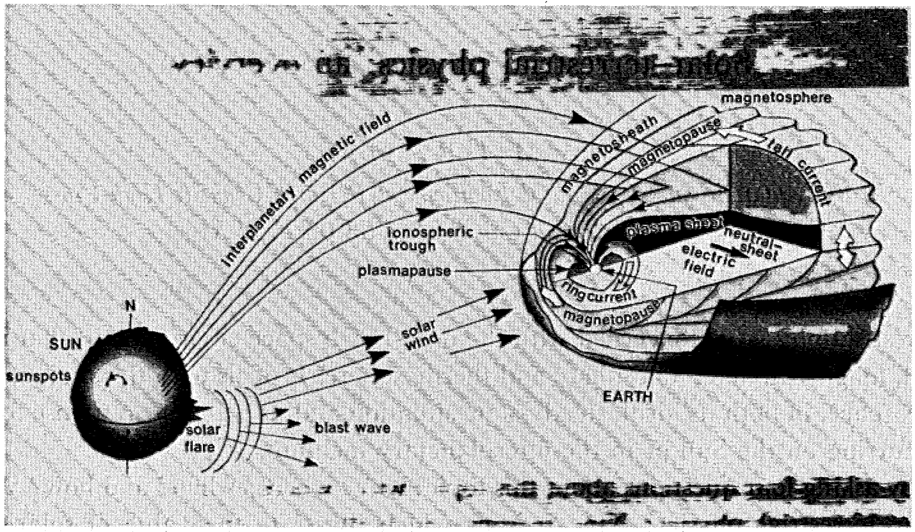

Figure 1. This diagram illustrates the connection, via interplanetary magnetic field lines, between the Sun and the Earth's magnetosphere. (From Shapland & Rycroft 1984.)

acts just like a model obstacle in a supersonic wind tunnel. Upstream a bow shock is formed. The decelerated and thermalized solar wind compresses the dayside geomagnetic field. Deflected around the magnetosphere, it draws geomagnetic flux tubes out into a long, comet-like tail. Flux tubes on the outer boundary of the magnetosphere may become connected to interplanetary magnetic flux tubes that are rooted to the Sun. Plasma from the Sun thereby gains entry to the magnetosphere, the efficiency of this mechanism depending on the relative orientation of the interplanetary and geomagnetic flux tubes. Near the Earth, the ionospheric feet of these flux tubes are pulled from the dayside, across the polar cap, to the midnight region within two hours.

A southward component of the interplanetary magnetic field carried by the solar wind past the magnetosphere causes a dawn–dusk electric field to exist across the magnetosphere. This drives the return flow of convecting plasma in the magnetospheric equatorial plane that is associated with the convection of plasma from noon to midnight across the polar cap. The electric field in the high-latitude ionosphere is shown in figure 2*b*. The ionospheric return flow is between 60° and 70° geomagnetic latitude, both on the morning side and evening side. Thus, a twin-cell convection pattern is established, in the horizontal plane (see figure 2*d*), in both the northern and southern polar ionospheres.

Within the magnetospheric tail is the plasma sheet, at the centre of which is a neutral sheet, between regions of oppositely directed geomagnetic flux tubes. By processes that are not yet fully understood, some of these flux tubes can become connected in the centre of the tail. Charged particles on these flux tubes are accelerated to a few thousand electronvolts. Electrons are catapulted towards the Earth as the flux tube along the high-latitude boundary of the plasma sheet becomes shorter. These electrons may be accelerated further by other plasma physical processes at an altitude of about one Earth radius (6.37×10^6 m). They reach the Earth's uppermost atmosphere, termed the thermosphere, at a geomagnetic latitude near 67°. There they collide with atmospheric molecules and atoms just above 100 km altitude and excite them into higher energy states. The excited species then fall back to their ground state, emitting blue, green or red line radiation that is characteristic of their species. In this way, the

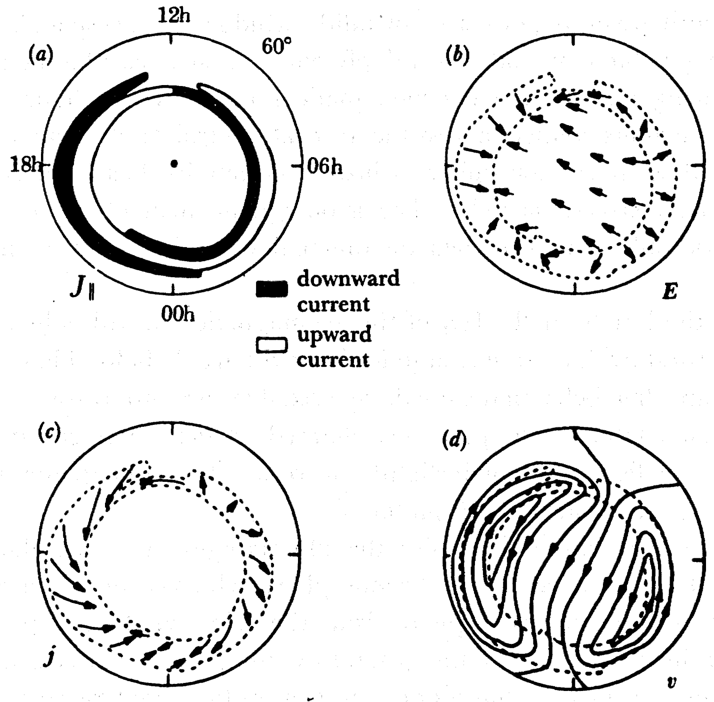

Figure 2. This diagram is of the northern polar region, from 60° magnetic latitude to the magnetic pole, and for different magnetic local times (MLT), which shows (*a*) the location of the feet of the geomagnetic flux tubes carrying field-aligned currents, $J_{\parallel}$; (*b*) the electric field distribution in the auroral oval and polar cap ionospheres, $\boldsymbol{E}$; (*c*) the closure of the field-aligned currents by horizontal currents crossing the auroral oval, $\boldsymbol{j}$; and (*d*) the characteristic twin-cell convection pattern of ionospheric plasma, flowing at velocity $\boldsymbol{v}$ across the polar cap and around the auroral oval. (From Wolf & Spiro 1984.)

aurora australis is produced in the South and the aurora borealis in the North, as large rings of light, the centre of each ring being near the geomagnetic pole.

Quanta of energetic electromagnetic radiation (extreme ultraviolet and X-radiation) arrive at the Earth eight minutes after the energy, which is contained in the magnetic fields of the solar corona and associated with a sunspot group, is explosively released. These quanta perturb the dayside ionosphere. Energetic solar protons are guided by the interplanetary magnetic field and geomagnetic field into the polar atmosphere some hours afterwards. The enhanced ionospheric plasma densities which they produce cause difficult radio propagation conditions at high latitudes. Two days or so later, a plasma shock wave often passes over the Earth, enveloping it in a dense, hot and strongly magnetized plasma that compresses the magnetosphere. Auroral substorms, which are clearly time-dependent phenomena, increase in frequency and intensity. Hot plasma is injected into the Earth's magnetosphere to form an enhanced ring current which creates the geomagnetic field decrease that indicates the main phase of a magnetic storm. Auroral charged particle precipitation and light production intensify. Because of increased distortion of the geomagnetic field, the auroral ovals move to lower geomagnetic latitudes, creating a disturbed ionosphere there. Intense thermospheric wind systems, with winds of several hundred metres per second and sometimes of a world-wide scale, are generated during magnetic storms. There is considerable Joule heating along the auroral oval (the dotted rings in figure 2). The energy input to the auroral oval is some tens of thousands of megawatts or more. Energy is carried away by, for example, gravity waves propagating to lower latitudes.

The north and south polar regions are splendid 'windows to geospace'. They are ideal locations for studying polar cap and auroral phenomena such as plasma instabilities and electric currents flowing up and down geomagnetic flux tubes (see figure 2*a*). Figure 2*c* illustrates how these currents connect across the auroral electrojet: Hall currents measured in millions of amperes flow in the ionosphere whose conductivity has been enhanced by the precipitating energetic charged particles. The geomagnetic field observed at ground level below the auroral ionosphere is disturbed on timescales ranging from a minute to several hours.

Somewhat nearer the Earth, at the feet of the geomagnetic flux tubes lie at slightly lower latitudes than the auroral oval, are the energetic charged particle belts. These are the trapped radiation belts, the van Allen belts, that were discovered 30 years ago by using a Geiger counter aboard one of the first satellites. The positively charged particles here constitute a westward flowing ring current (see figure 1) which slightly decreases the geomagnetic field strength on the Earth's surface, especially near the Equator.

In the vicinity of the radiation belts lies the plasmapause, the boundary between the plasmasphere that is the uppermost part of the ionosphere, which corotates with the Earth, and the plasma which enters the magnetosphere from the solar wind. The plasmasphere and plasmapause are well investigated from the ground by using very low-frequency radio waves. These signals are from lightning discharges or from transmitters used for communicating with submarines. The radio waves propagate along geomagnetic flux tubes through the magnetosphere in the whistler mode. They can cause the precipitation of van Allen belt electrons in the upper atmosphere. The plasmapause, a longitudinally aligned set of flux tubes, maps down to the ionosphere near the mid-latitude trough, where shear can occur. This region of unexpectedly low F-region ionization density is pronounced in the winter night, when locally produced solar photoionization is absent, and may be explained by plasma flow out of the region or by a locally enhanced electron–ion recombination rate which could be associated with enhanced temperatures.

The purpose of the Discussion Meeting is to review recent research on the physics of solar–terrestrial relations and on the closely coupled solar-wind–magnetosphere–ionosphere system. In this field, both satellite and ground-based studies are crucial, as are theoretical investigations. This meeting has been structured with such considerations very much in mind.

It is my sincere hope that the subject of solar–terrestrial physics will definitely come of age within the next decade. Ten years hence, I look forward to another Discussion Meeting at the Royal Society on the first results of the International Solar Terrestrial Physics (ISTP) programme. This programme will involve the European SOHO and Cluster missions, the NASA Global Geospace Science programme, the Japanese satellite deep into the magnetospheric tail, and ground-based observations in both the northern and southern high-latitude regions. The ISTP will undoubtedly carry the subject forward, beyond its current status which is presented in this volume.

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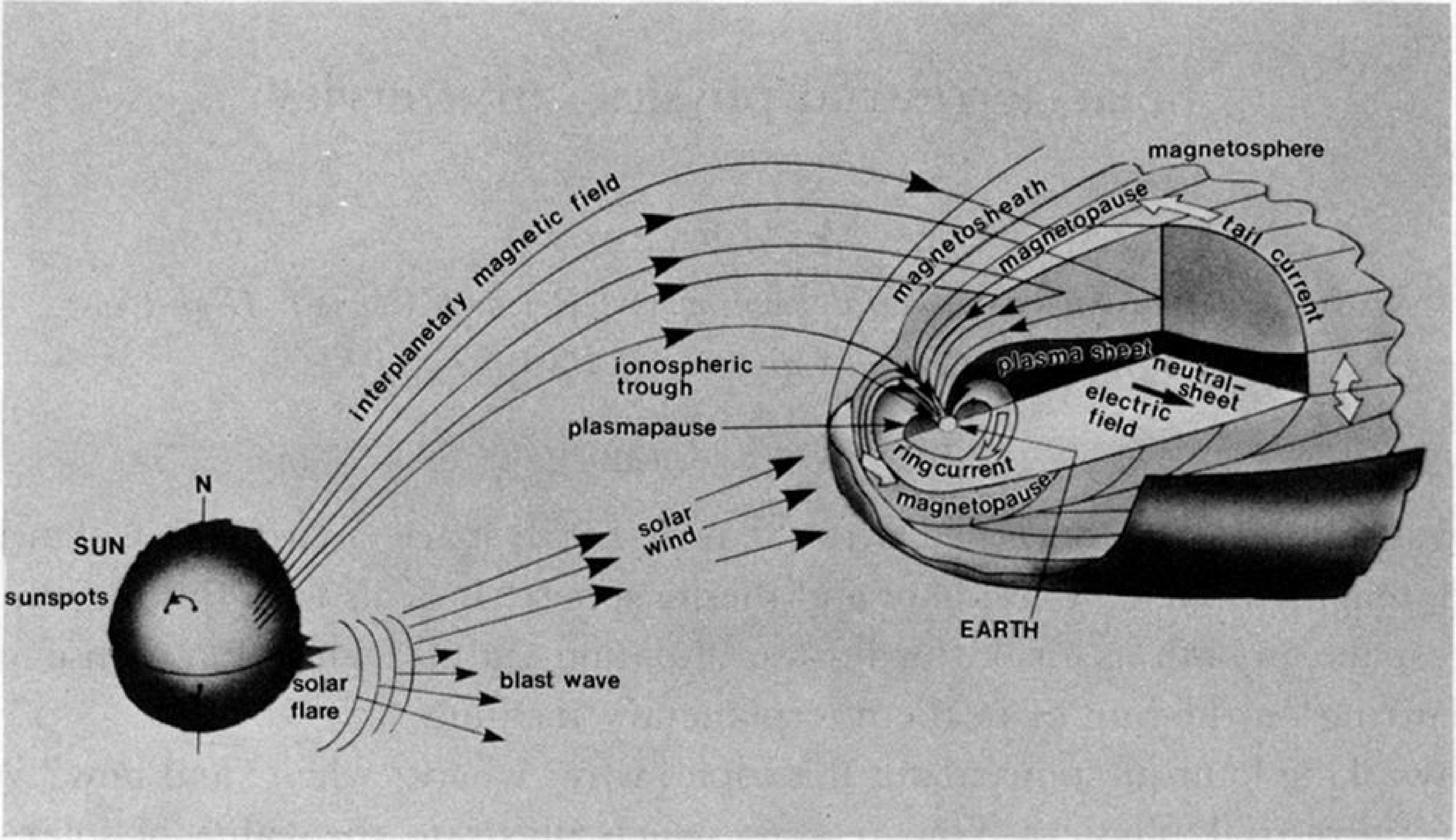

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