The solar–terrestrial environment

An introduction to geospace – the science of the terrestrial upper atmosphere, ionosphere and magnetosphere.

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Contents

1

The Earth in space

> Far out in the uncharted backwaters of the unfashionable end of the Western Spiral arm of the Galaxy lies a small unregarded yellow sun. Orbiting this at a distance of roughly ninety-two million miles is an utterly insignificant little blue green planet whose ape-descended life forms are so amazingly primitive that they still think digital watches are a pretty neat idea.
>
> Douglas Adams, *The Hitch-Hikers Guide to the Galaxy* (1979)

1.1 Introduction

The solar–terrestrial environment, nowadays sometimes called *geospace*, includes the upper part of the terrestrial atmosphere, the outer part of the geomagnetic field, and the solar emissions which affect them. It could be defined as that region of space closest to the planet Earth, a region close enough to affect human activities and to be studied from the Earth, but remote enough to be beyond everyday experience. Clearly, it is not the familiar atmosphere of meteorology; nor is it the inter-planetary space of astronomy, though it interacts with both. The material found there is mainly terrestrial in origin and strictly a part of the atmosphere of the Earth, though it is greatly affected by energy arriving from the Sun. Starting some 50–70 km above the Earth's surface and extending to distances measured in tens of Earth radii, geospace is a region of interactions and of boundaries: interactions between terrestrial matter and solar radiation, between solar and terrestrial magnetic fields, between magnetic fields and charged particles; and boundaries between solar and terrestrial matter, and between regions dominated by different patterns of flow.

Having an origin in the geomagnetism of the 19th century, our subject first began to develop rapidly about 60 years ago with the increasing use of radio waves in communications and the first scientific studies of the ionosphere during the 1930s. The development of radar just before and during the war of 1939–45 was technically significant, and the technology of war also brought rocketry as a tool for high altitude sounding. Then, in the late 1950s, there took place the first satellite launches which within only a few years brought a great expansion of space activity. Measuring instruments could now be placed in the media of the upper atmosphere, the magnetosphere and interplanetary space, and left there for long periods. Communications and other technological satellites began to be developed for commercial use, and it became possible for human beings to live and work in a space environment for extended periods. There have been problems, but at the present time (1990) it is safe to say that reusable vehicles (the Space Shuttle) are well established, and space station technology (Mir) is already highly developed. We may expect to see further developments in shuttle/space station technology over the next few years in each of the major space centres, and one day we shall perhaps see these competing efforts growing together into a single global enterprise.

All of this depends on a knowledge and understanding of geospace. But in addition to its importance in applications, the science is important in its own right for fundamental studies such as of the properties of tenuous atmospheres and their photochemistry, of wave propagation and of plasma physics. The medium of near space and its physics are not readily reproduced in earth-bound laboratory conditions, and to a large extent geospace provides its own laboratory.

We shall be concerned with three broad regions:

The space between Sun and Earth, across which solar–terrestrial influences propagate;

The terrestrial atmosphere, neutral and ionized, with which the solar emissions react;

The geomagnetic field external to the solid Earth, which influences the ionized atmosphere and controls the Earth's outermost regions.

1.2 The Sun and the solar wind

The rather ordinary star at the centre of the solar system establishes for each planet a radiation environment which controls its temperature and determines the rate of evolution of that planet, the composition of its atmosphere, and its suitability for life. It is our good fortune – though if it were not we should not be here to complain about it – that planet Earth is intermediate between the extreme heat of the planets closer to the Sun and the extreme cold of the outer planets. The Earth's surface temperature permits water to exist in all three phases. Life emerged in the liquid phase and proceeded to alter the composition of the atmosphere, adding oxygen to the nitrogen and carbon dioxide already present. The presence of water as vapour also provided, and continues to provide, a source of hydrogen, which, as we shall see, is important at the atmosphere's higher levels.

Thus the general level of solar radiation, combined with the distance between Sun and Earth, has largely determined the nature of the Earth's atmosphere. While long term change in this energy output may be responsible for slow climatic changes such as produced the Ice Ages, short term changes over days, weeks or a few years appear to have little climatic effect – despite strenuous efforts to discover some. At the higher levels of the atmosphere, though, the changes that accompany variations of solar activity may be large and rapid. The upper atmosphere, where most of the more energetic solar radiations are stopped, and which is heated by them, is very responsive to solar activity variations in general, as well as to the short-lived, intense and localized outbursts known as *solar flares*.

In addition to radiation the Sun also emits a stream of matter. We think of planets like the Earth as stable, self-contained bodies that do not evaporate into space to any significant extent. Not so the Sun, which is not in equilibrium and continuously loses matter as well as radiation into space. This stream of matter is the *solar wind*, which forms the second vital connection between Sun and Earth. Also important is the weak magnetic field, the *interplanetary magnetic field*, which is embedded in the solar wind and is carried with it past the Earth, where it largely determines how strongly the solar wind couples with the matter of the remote terrestrial atmosphere. Although the solar wind does not penetrate down to the ground it is highly significant in geospace; indeed, some of the most remarkable behaviour is directly attributable to the variations of the solar wind and its magnetic field. The interactions are subtle ones and we shall spend some time dealing with them.

1.3 The atmosphere and the ionosphere

Less is known about the Earth's atmosphere than many people imagine. Near the ground the atmosphere is a relatively dense gas, mainly composed of molecular nitrogen and oxygen with smaller amounts of carbon dioxide, water and various trace gases. With increasing altitude the pressure and density decline. At 50 km 99.9% of the mass of the atmosphere is below, and at 100 km all but 1 part per million. Into these rarified upper levels penetrate the ultra-violet and X-ray emissions emanating from the Sun, photons which are sufficiently energetic to dissociate and to ionize the atmospheric species, thereby altering the atmosphere's composition and heating it. The heating creates a hot upper region called the *thermosphere* which is less turbulent than the lower regions, and in which gases of different density may separate. Thus the composition of the atmosphere changes with altitude, the lighter gases, particularly hydrogen, becoming progressively more dominant.

Because of the low pressure above about 100 km, ionized species do not necessarily recombine quickly, and there is a permanent population of ions and free electrons. The net concentration of ions and free electrons (generally in equal numbers) is greatest at heights of a few hundred kilometres, and although the electron concentration may amount to only 1% of the neutral concentration the presence of these electrons has a profound effect on the properties and behaviour of the medium. This *ionosphere* is electrically conducting and can support strong electric currents. The ionized medium also affects radio waves, and as a plasma it can support and generate a variety of waves, interactions and instabilities that are not found in a neutral gas.

The upper atmosphere and ionosphere sit on the lower atmosphere, the domain of the meteorologists. We shall see that some of the behaviour of the higher regions is similar to that taught in meterology, but that there is much more besides.

1.4 Geomagnetic field and magnetosphere

As William Gilbert, physician to Queen Elizabeth I, realized 400 years ago, the Earth is itself a magnet. The geomagnetic field is generated by electric currents flowing deep within the solid Earth and to a first approximation may be represented as though due to a short bar magnet at the centre of the Earth. As a dipole field it extends beyond the planetary surface, through the troposphere on which it has no effect, and into the ionized atmosphere where its effects are considerable. The geomagnetic field affects the motions of ionized particles, and thus modifies ionospheric electric currents and the bulk movement of the plasma. The importance of the magnetic field increases with altitude as the atmosphere becomes more sparse and its degree of ionization increases. At the highest levels, more than a few thousand kilometres above the surface, all behaviour is so dominated by the geomagnetic field that this region is called the *magnetosphere*. There is no sharp boundary between the ionosphere and the magnetosphere, but between the magnetosphere and the solar wind is a boundary, the *magnetopause*, which is very significant. At this boundary energy is coupled into the magnetosphere from the solar wind, and here is determined much of the behaviour of the magnetosphere and of the ionosphere at high latitudes. In the sunward direction the magnetopause is encountered at about 10 Earth-radii, but in the anti-solar direction the magnetosphere is extended downwind in a long tail, the *magnetotail*, within which occur plasma processes of great significance for the geospace regions.

1.5 Nomenclature

The solar–terrestrial environment has many parts, which may be one reason why it has been difficult to find an apposite all-embracing appellation. Relevant material may be found in the literature under various titles. Internationally, the topic is considered a branch of geophysics and is sometimes called *external geophysics*, though in some countries there persists an outdated practice of confining the term 'geophysics' to the solid Earth (properly *internal geophysics*). The *upper atmosphere* is a term of some generality for the higher reaches of the atmosphere, though some use it to mean the neutral gas only. It should not be confused with the meteorologists' 'upper air', which is actually within the troposphere and stratosphere and therefore largely beneath the level of our considerations. The addition of 'physics' to 'upper atmosphere' obviously means that the physical processes of the region are being addressed. *Aeronomy* – literally, 'measurement of the air' – is a good modern term meaning the processes, physical and chemical, of the upper atmosphere. *Ionosphere* refers to the ionized component of the upper atmosphere, and *magnetosphere* to the outermost regions dominated by the geomagnetic field. These regions will be treated in some detail, but there is no clearly defined boundary between them. Much relevant material also appears under the heading of *space physics*, which is not unreasonable because most space data are taken not too far from the Earth in practice. We shall also use the term *geospace*, a recently coined word meaning the region of space relevant to the Earth. As an inclusive term it appears to be as good as any yet suggested.

1.6 Summary

It should be clear from the foregoing sketch that the contents of geospace are rather different from the more familiar atmospheric gas of the troposphere. In this book we shall be dealing with the physics of tenuous gases, with ionization and ionic recombination processes, with electrical conduction in a gas, with particle as well as electromagnetic radiations of various energies, and with the behaviour of a plasma permeated by a magnetic field. None of these has anything like as much significance in the atmosphere near the ground. We shall also be concerned with dynamics and transport, which are important throughout the atmosphere and magnetosphere.

It follows that the science of the solar–terrestrial environment is based principally on

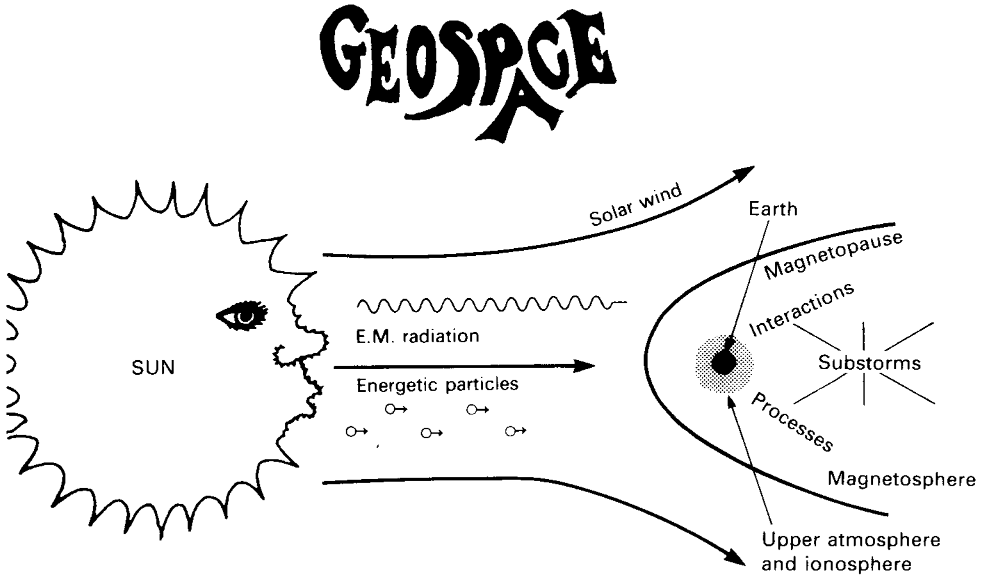

Fig. 1.1 Summary of the solar–terrestrial environment. (After a sketch by J. C. Hargreaves).

classical physics, though some knowledge of chemistry and, of course, mathematics is also needed. In Chapter 2 we shall summarize some aspects of basic physics that are particularly important for an appreciation of the more specialized material to follow.