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# 1

# Prologue

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## 1.1 A voyage through the local cosmos

The place that we call home, the surface of the planet Earth, presents us with an environment in which temperatures range over perhaps 80 kelvins from the cool arctic regions or mountain tops to the hottest deserts or jungles. We are composed largely of liquid water with a density of 1 gram per cubic centimeter; we walk on solid rock with a density that is about five times higher than this and breathe a gas with a density that is 1000 times lower. These conditions are such that chemical reactions and phase transitions between solids, liquids, and gases are the processes that dominate our everyday experience.

When we move away from the Earth's surface, conditions change markedly. Deep in the Earth, for example, where densities are still only a few times higher than those at the surface, the pressure rapidly increases and temperatures reach up to some 20 times those characteristic of the range that is comfortable to mammals. In the Sun's core densities are larger still, almost a hundred times that of liquid water, at temperatures that exceed ten million kelvins. Those same temperatures may be found again in the hottest, flaring parts of the Sun's outermost atmosphere, called the corona, and furthermore are often characteristic of the ion energies high above the Earth around the altitudes where geosynchronous satellites orbit. The temperatures may be comparable in these three domains (at least to astrophysical standards), but the corresponding densities are 17 to 25 *orders of magnitude* different. Overall, from the Sun's center to the solar wind in the outer heliosphere, densities range over about 29 orders of magnitude while temperatures range over five orders of magnitude. This astonishing range in conditions (Fig. 1.1) is compounded by another phenomenon that prevails in most of the sphere of influence of the Sun, i.e. the domain of heliophysics: matter is generally so hot that many electrons are stripped off their atoms by collisions between these particles. This results in a electrically conducting gaseous medium that is known

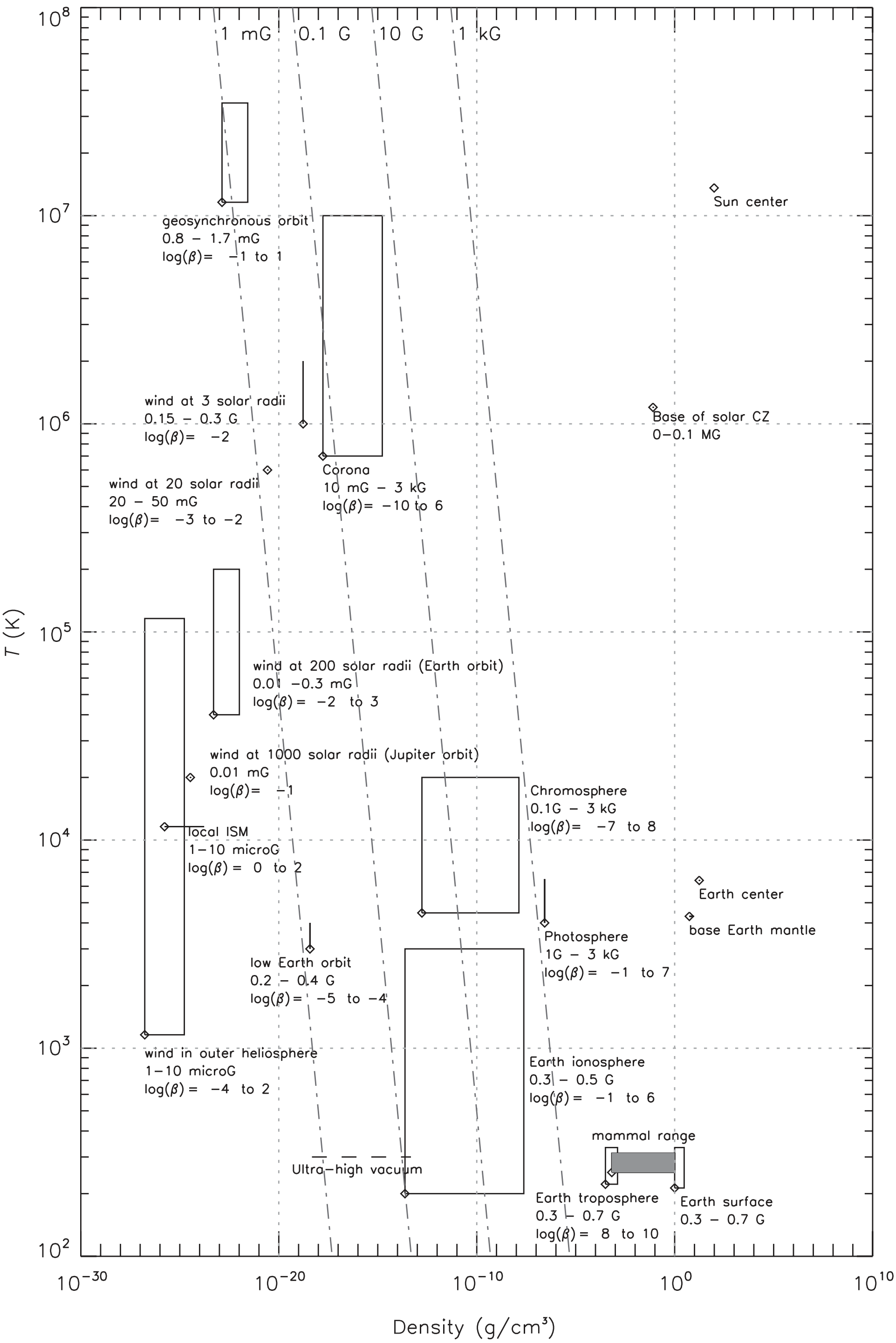
1 mG
0.1 G
10 G
1 kG
geosynchronous orbit
0.8 – 1.7 mG
log(β)= –1 to 1
Sun center
wind at 3 solar radii
0.15 – 0.3 G
log(β)= –2
Base of solar CZ
0–0.1 MG
wind at 20 solar radii
20 – 50 mG
log(β)= –3 to –2
Corona
10 mG – 3 kG
log(β)= –10 to 6
wind at 200 solar radii (Earth orbit)
0.01 –0.3 mG
log(β) = –2 to 3
wind at 1000 solar radii (Jupiter orbit)
0.01 mG
log(β)= –1
Chromosphere
0.1G – 3 kG
log(β)= –7 to 8
local ISM
1–10 microG
log(β) = 0 to 2
Earth center
base Earth mantle
Photosphere
1G – 3 kG
log(β) = –1 to 7
low Earth orbit
0.2 – 0.4 G
log(β) = –5 to –4
wind in outer heliosphere
1–10 microG
log(β) = –4 to 2
Earth ionosphere
0.3 – 0.5 G
log(β) = –1 to 6
mammal range
Ultra–high vacuum
Earth troposphere
0.3 – 0.7 G
log(β) = 8 to 10
Earth surface
0.3 – 0.7 G
T (K)
Density (g/cm³)

Fig. 1.1.

as plasma (often referred to as the fourth state of matter after solids, liquids, and gases).

Whereas for the largest scales of the universe physicists are puzzled by mysterious properties that have become known as "dark energy" and "dark matter", on the scale of the local cosmos it would appear that the classical forces of gravity, electromagnetism, and the weak and strong nuclear interactions are known so well that one may ask what it is that occupies solar, heliospheric, and space physicists. As it turns out, it is not in the nature of the forces that mysteries reside but rather in the complexity of the processes by which they interact within the ionized plasma.

In this series of three volumes on heliophysics we will discuss many of these processes. In this introductory chapter, we will take you on an exploratory journey from within the Sun to the edges of the solar system, to introduce the variety of environments and processes that would be encountered on that journey. In doing so, we also introduce some of the technical terms that form the jargon of the sub-disciplines of heliophysics. This jargon is often specific to a discipline: many terms are used actively only by part of the heliophysics community. These terms may not be familiar to colleagues in relatively distant sub-disciplines, while some terms may even be used by them for distinctly different processes.

### *1.1.1 Solar interior*

Let us start in the deep interior of the Sun, some 200 000 km below the surface. Here we are just underneath the Sun's convective mantle in which hot upwellings alternate with cool downflows to effect a net transfer of heat through the mantle to the visible surface, the photosphere. Here, just below this convectively unstable envelope, we are in an environment that is stably stratified and in which the opacity remains low enough for the Sun's energy to be transported exclusively in the form of electromagnetic radiation. This radiation makes its way from the nuclear furnace

Fig. 1.1. Temperature vs. density for a variety of conditions within the local cosmos. Some typical ranges are indicated, and labeled with magnetic field strengths (in gauss) found in that domain and estimated ranges of the plasma $\beta$, i.e. the ratio of energy density in the plasma and that in the magnetic field (Eq. 3.11). This is but one of many diagrams that characterize the multidimensional world of heliophysics; in other figures collision rates, ionization states, scales of time, length, or velocity could be compared, but this diagram relates directly to our intuitive knowledge of the world around us. The reader is encouraged to experiment with such other diagrams using the data found throughout the three volumes of this series.

in the core to the convective envelope, in a random walk caused by frequent scattering off the ionized plasma particles. The rumbling of distant convective motions overhead is heard as sound waves traveling through this deep domain of the resonant cavity, which shapes the millions of pressure modes into standing wave patterns analyzed by helioseismologists.

Some large-scale plasma flows that occur here are imposed by convective downdraft plumes that overshoot beyond the base of the convective envelope, owing to their large momentum and inertia. As they gradually overturn into upwellings, they may deposit entrained magnetic field into this overshoot region or, conversely, they may dredge up magnetic field from there into the convective envelope. The only other large-scale motion in this region is a weak shearing flow, called the differential rotation, that extends from within the convective envelope to a thin layer, called the tachocline, just below it. The tachocline is sandwiched between the differentially rotating convective envelope, where the rate of rotation decreases from the equator to the pole, and the radiative interior, which rotates essentially as a solid body (except, maybe, for the deep core that may still possess some of the initially high angular momentum from when the Sun – and its attendant planetary system – formed 4.5 billion years ago).

Let us start an imaginary journey by selecting, in this region below the base of the convective envelope, a hydrogen ion embedded in a strand of magnetic field that is in the process of being scooped up by convective overshoot. Shortly after its rise begins into the convective envelope, the opacity increases when electrons begin to recombine with helium (and higher up with hydrogen) ions as the temperature drops. As that happens, the exchange of energy between a moving volume of plasma and its surroundings is impeded. Consequently, when the gas moves and responds to the changing pressure in the gravitationally stratified surroundings these changes will be largely adiabatic, leaving the rising gas hotter and lighter and the sinking gas cooler and heavier: convection becomes the avenue of choice for energy transport as radiative transport decreases in relative importance.

The hydrogen ion that we are tracking is not only driven by the buoyancy of the adiabatically rising gas but also by a magnetic effect. Our ion was, in fact, contained in a region of lower gas pressure because the pressure of the magnetic field around the ion adds to that of the gas, so that the volume of gas has expanded to establish pressure equilibrium with the non-magnetized surroundings. As the temperature between the interior and the surroundings is likely to be equalized by radiative exchange, the result is that field-carrying regions are buoyant relative to regions with weaker field. This makes it hard for field to stay deep within the convective envelope. In fact, many theorists argue that field is stored in the non-convecting overshoot layer or just above it where buoyancy is statistically countered by the downward drag from strong downflows. The overshoot region that we have just left behind may thus be one of the most important domains in heliophysics if indeed that is where much of the solar magnetic field is stored, caught in flows that strengthen it by pulling on it with the shearing winds that we know as the differential rotation (see Chapter 3 and Vol. III).

Most upward convective motions rapidly overturn into downflows again: as we gain altitude the gas pressure rapidly decreases and the density drops; upflows expand and cool adiabatically and return to the depths of the envelope. The small fractions of the gas and field that reach the surface take a few weeks for that journey. This time is comparable with the Sun's rotation period. The rising plasma consequently senses the Sun's rotation, which causes the field strands to have a preferential twist on emergence. This twist, with much scatter from case to case because of interaction with the turbulent convective motions, is opposite in the two hemispheres on either side of the solar equator, imposing some degree of order and resulting in a net dipole moment that is the ultimate cause of the heliospheric structure (Chapter 8 and Vol. III). The coupling of buoyant flows and rotation is an important ingredient in the dynamo theory that aims to describe the evolution of the Sun's magnetic field (Chapter 3 and Vol. III).

Only one in 100 000 ions that start their rise near the bottom of the convective envelope typically makes it to the topmost layers. There, convective flows move fast, at a large fraction of the sound speed, and consequently this is where the convection is, literally, loudest: here most of the power in the helioseismic pressure waves is generated. Here, too, is where upward propagating waves effectively hit a wall and are mostly reflected back down: the pressure gradient becomes so steep in the surface layers that long-period waves lift most of the mass in the overlying atmosphere without generating the elastic restoring forces that allow them to propagate. Above the photosphere it is consequently much quieter, and the deep rumbling with periods of several minutes is replaced by a higher pitch of lower intensity as lower frequencies are reflected and higher frequencies damped by radiative exchange between the compression and rarefaction regions in the waves.

Just below the surface, or photosphere, lies a mystery for solar physicists: the pressure gradient here is so large that it is hard to imagine how anything could avoid enormous expansion on rising. Yet much of the magnetic field that surfaces does so in a fibril state with structures of order 100 km, i.e. smaller than even the dominant scale of convection near the surface, the 1000 km scale of the granulation. As theorists try to understand this phenomenon, one scenario stands out: if the magnetic field is twisted, i.e. if it carries an electrical current, then the increased field tension resists expansion and convective shredding much more effectively. Let us therefore imagine that the ion we are tracking is caught in a magnetic environment that also supports a substantial electrical current.

### *1.1.2 Solar atmosphere*

As the field breaches the solar surface, the plasma that it carries becomes transparent – this is, quite simply, the transition that defines the surface of this gaseous sphere. Once transparent, the photons emitted by the gas travel long distances. Most in fact are free to fly into interplanetary space, or – if they do not run into a planet or satellite – even into interstellar space and beyond. The efficient escape of its thermal energy causes most plasma within the magnetic field to cool down and slump back below the solar surface, sliding down along the emerging field.

As the magnetic field rises from the photosphere, it enters a domain where electromagnetic forces generally dominate over gas pressure and inertia and where the Alfvén speed becomes so large compared with the field's spatial and temporal scales that the field, for the first time, behave as is truly three-dimensional and continuous. Thus the field emerging into the solar atmosphere almost immediately begins to interact with any pre-existing field around it (Chapters 5 and 8, and Vol. II).

The magnetic field in the solar atmosphere (e.g. Figs. 1.2 and 8.1) has characteristics that are very different from those of the geomagnetic field in the observable domain above the Earth's surface (Fig. 1.3). The Sun's atmospheric magnetic field is the result of a multitude of flux ropes that emerge through the solar surface, ranging from millions of small ones that live for only minutes to a few very large ones that persist for weeks (at most a dozen of these exist on the solar surface at any one time even at cycle maximum); they extend over at least six orders of magnitude in total absolute flux, as far as we can currently observe. These fields move about, pushed by (sub-)surface flows ranging from small-scale granulation, with cells the size of Texas, Germany, or the Republic of the Congo, to the largest patterns, associated with the differential rotation and hemispheric meridional advection from the equator to the poles (Chapter 8 and Vol. III). The Earth's magnetic field, in contrast, appears to be dominantly dipolar, which is likely to be in part a consequence of the fact that the higher-order multipoles decay away between the outer layers of the dynamo region (i.e. the outer core) and the top of the Earth's slowly moving mantle: sensitive measurements and computer simulations suggest that the inner field in the Earth has a much more complex dynamic structure (see Vol. III; the same is true for the other magnetized planets, see Chapter 13).

As our hydrogen ion rises within the embedding field into the solar atmosphere, the environment changes rapidly. The density drops by seven orders of magnitude within a few thousand kilometers (which is less than $\sim 0.5\%$ of the solar radius) to values comparable with those in the much cooler ionosphere of the Earth. The only reason why the tenuous region above the solar photosphere, called the chromosphere, is visible to us at all from Earth is that its large volume compensates for the

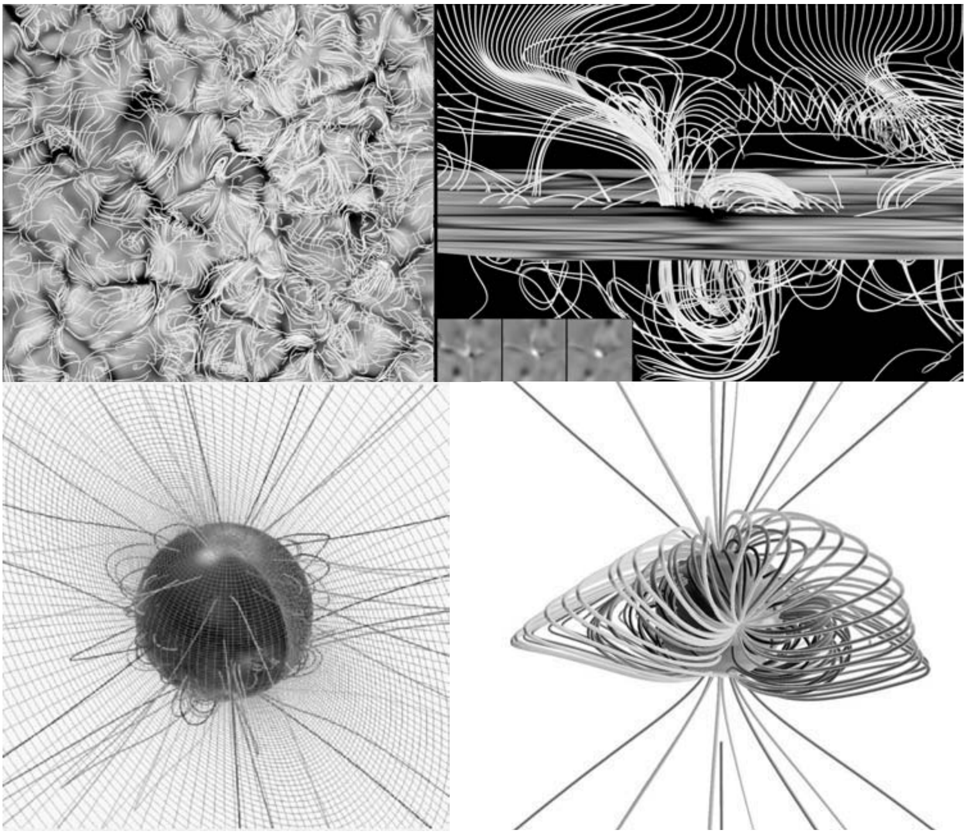

Fig. 1.2. The multitude of scales in the solar magnetic field. The upper panels show a model computation of the magnetic field (by Abbett, 2007; see also Fig. 8.11) on the scale of the dominant convective motions at the solar surface, the 1000 km scale of the granulation (see also Fig. 8.3); the upper left panel is a top view of the solar surface, with sample magnetic field lines (see Section 4.1) overplotted, while the upper right panel shows a vertical cut through one of the convection cells to illustrate how the field in this model can thread the surface multiple times, evolving on a time scale of a few minutes. The lower two panels (from the Center for Integrated Space Weather Modeling) show models of the global solar field, tracing field lines up to the cusps of the streamers that outline the topologically distinct regions of closed field and the field that is open to the heliosphere; this global-scale field evolves on time scales of months to a decade (see Chapters 4 and 9).

low density, resulting in an observable spectral signature. The Earth's ionosphere, in contrast, is virtually invisible from the Earth's surface at visible wavelengths under quiescent daytime conditions – it glows visibly at night and is readily seen looking past the edge of the Earth from space (Chapter 12); the "airglow" is a combination of fluorescence associated with ionization and dissociation processes, resonant

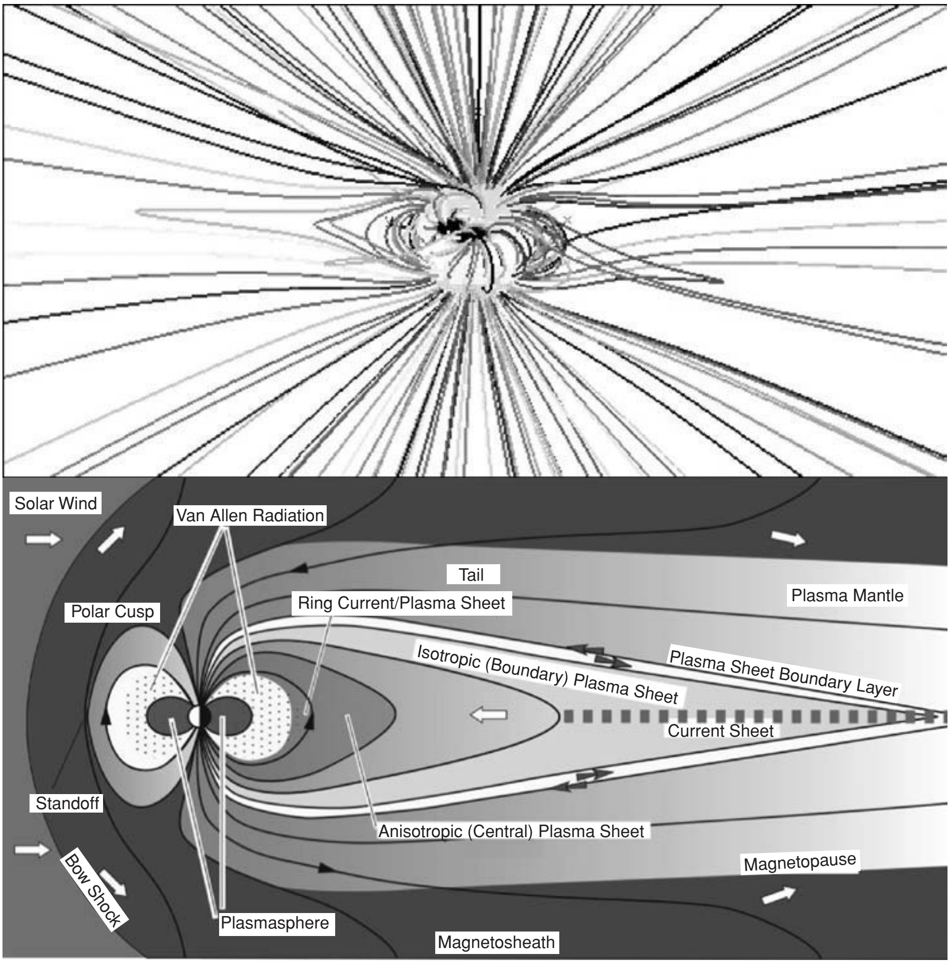


Fig. 1.3. (Upper panel) Magnetohydrodynamic model computation of a simplified solar magnetic field reaching into the heliosphere. The large-scale dipolar field of the Sun is blown open by the solar wind (Chapter 8), stretching out the relatively strong, closed, field of the activity belt into "streamers" with cusps that lie at the base of the heliospheric current sheet. (Courtesy of P. Riley, SAIC.) The stretching of magnetic field arcades into a cusp-and-sheet structure is a common features in space plasmas (compare, for example, Figs. 2.7, 5.1, 6.3, and 10.1 with the lower panel here). (Lower panel) Schematic of the Earth's magnetic field and magnetospheric features. Earth provides the prototype magnetosphere; it is produced by the interaction of the solar wind with the planet's internally generated magnetic field. The boundary of the region dominated by the planet's magnetic field is the magnetopause. The supersonic solar wind is sharply slowed and deflected at the bow shock, flowing around the planet in a magnetosheath boundary layer. It pulls the magnetosphere back behind the planet into a long magnetotail with a current sheet and cusp structures. (Courtesy of L. Weiss.)

scattering by select ions, and recombination emission ranging from infrared to visible spectral lines.

We are now in the low chromosphere, and the environment changes again. For one thing, the acoustic spectrum is different: not only is there less power in the waves but shock waves begin to form. Sound waves traveling upward into the ever more tenuous outer atmosphere steepen, and eventually form shocks that throw chromospheric plasma up to heights of some 10 000 km, before it falls down again to be caught by another shock front. The compression in these shocks can temporarily heat the plasma, but it cools again as it radiates much of that energy away during the passage of the shock. Other, magnetohydrodynamic, waves are also likely to dissipate energy, as do electrical currents in the dynamic magnetic field (Chapter 8). These heat the plasma, by processes that remain to be discovered, to temperatures of 10 000 to 20 000 K. Elsewhere in this environment, temperatures as low as 2500 K may exist because of adiabatic expansion of the now transparent plasma. These low temperatures allow some simple molecules, such as CO and CH, to form. But apart from these cool supra-photospheric regions and the cool sunspots (where e.g. TiO molecular lines can be used to measure the field strength) the Sun contains only monatomic gases.

As the rising field expands into the highest layers of the solar atmosphere, i.e. the corona, very little of the plasma can follow it against gravity. When our ion reaches this domain, the densities are so low that rocket engineers on Earth would effectively call it outer space; these are densities that only high-quality vacuum machines can achieve. But, high in this corona, waves and currents somehow deposit energy which finds its way down to the top of the chromosphere both in the form of energetic particles and as thermal energy conducted largely by electrons. That energy heats a small fraction of the chromospheric plasma (including our proton) to a few million kelvins. This gives the plasma the energy to fill the corona against gravity and to radiate in the extreme ultraviolet or X-rays region. These losses are balanced, at least statistically, by the dissipation of more non-radiative energy as currents or waves; eventually, it is converted to thermal energy.

The field is now so strong relative to the plasma, which has a mass density some 15 to 18 orders of magnitude below that of water, that plasma motions can only occur along the field, leading to the giant glowing arches called coronal loops. The plasma thus embedded by the field can carry electrical currents, and in our case the strong electrical current that emerges with the field leads somehow to an instability: the field and current are subjected to a poorly understood process called reconnection (Chapter 5), and some fraction of the field may temporarily be opened up into the heliosphere, again by processes that are far from being understood. The ion that we are tracking is now no longer on a field line that has two connections with the solar surface.

### *1.1.3 Inner heliosphere*

The heating and acceleration of the solar wind low in the corona remain major problems (Chapter 9). A variety of waves and turbulence mechanisms have been proposed as playing a role: the dissipation of waves can obviously heat the plasma, and this is the primary requirement to start a wind that is slow near the base but supersonic in the heliosphere (as proposed by Parker around the middle of the twentieth century). The density in the nascent solar wind is so low that the constituent species in the plasma begin to decouple. A description of the physics requires that the electron, proton, and ionized helium populations, at the least, be differentially treated; the low mass of the electrons tends to give them a large scale height above the solar surface, which initiates an electric field that pulls the protons and helium ions up and in which helium, as the heavier element, is partly left behind. A similar process happens in open magnetospheres, where a so-called polar wind outflow is driven by the readily escaping electrons, which pull up protons and heavier atmospheric ions with them (Chapters 10 and 12).

Now our ion is on its way to the planets as part of the solar wind. It is interesting to note that the mass lost from the Sun by the solar wind is, in fact, only about half the mass lost by the outflow of light as a result of nuclear fusion in the Sun's core.

As our ion moves away from the Sun the expansion of the plasma causes its temperature to fall (speaking loosely, recognizing that temperature is a concept that applies to a collection of particles), even in this environment of infrequent collisions. The fast electrons conduct energy outward from the lower regions of the solar corona, but more is needed to keep the temperature high enough to match in situ observation in the inner heliosphere. The damping of Alfvénic waves, possibly after conversion into a magnetohydrodynamic (MHD) turbulent state, is a possible source of this heat deposition over much of the inner solar system (Chapter 7).

As the wind flows out, essentially radially, the Sun rotates underneath it (Chapter 9). Faster wind-flows from neighboring regions can thus move underneath and subsequently overtake slower streams that started earlier, and at their interfaces shocks may form if the velocity differential exceeds the Alfvén speed. A few times a day the solar corona is rocked by a massive explosion called a coronal mass ejection (CME). These explosions (Vol. II) are the result of the destabilization of large magnetic configurations associated with the substantial electrical currents in the solar corona. These current systems form either by the direct injection of prefabricated currents that emerge from below the surface or by induction as the atmospheric field is subjected to stress by surface flows. Destabilization occurs perhaps because a newly emerging flux system is at an odd angle with the pre-existing field, because the system is pushed over a limit beyond which the overall field configuration must change, or because of a gradual evolution of the surrounding