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1

The wind from the Sun: an introduction

> 'First accumulate a mass of Facts: and *then* construct a Theory.' *That*, I believe, is the true Scientific Method. I sat up, rubbed my eyes, and began to accumulate Facts.
>
> Lewis Carroll, *Sylvie and Bruno*

Not only does the Sun radiate the light we see – and that we do not see – but it also continually ejects into space 1 million tonnes of hydrogen per second. This wind is minute by astronomical standards; it carries a very small fraction of the solar energy output, and compared to the violent explosions pervading the universe it blows rather gently. Yet it has amazing effects on the solar surroundings. It blows a huge bubble of supersonic plasma – the heliosphere – which engulfs the planets and a host of smaller bodies, shaping their environments. It also conveys perturbations that can be seen in our daily life.

The object of this chapter is twofold. To give a concise historical account of the key ideas and observations that made our modern view of the solar wind emerge; and introduce the main properties of the Sun and of its wind, and their interpretation in terms of basic physics. The latter goal requires some tools of plasma physics, and will be developed in the rest of the book.

1.1 A brief history of ideas

The idea that planets are not moving in a vacuum is very old. In some sense our modern view of a solar wind filling interplanetary space has replaced the Aristotelian quintessence, the impalpable pneuma of the Stoic philosophers, and the swirling 'sky' introduced two thousand years later by Descartes. In some sense only, as there is a major difference: the solar wind is made of normal matter whose behaviour is – to some extent – understood, even though this matter is in a special state, a *plasma*, having unusual properties as we will see in Chapter 2.

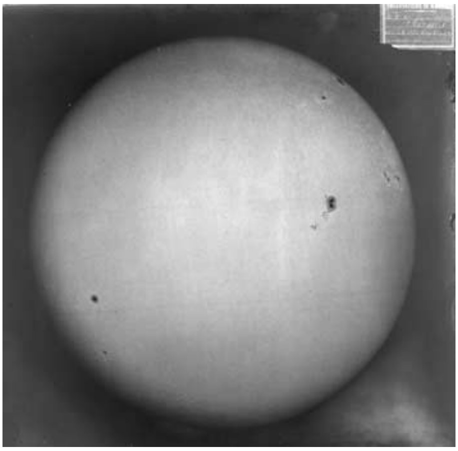

Figure 1.1 An early photograph of the Sun showing sunspots, made by Jules Janssen at the Meudon Observatory on 22 June 1894. (Observatoire de Paris, Meudon heritage collections.)

Ironically enough, the solar wind contains vortices – as did Descartes' sky and also the luminiferous ether imagined later by Maxwell – and even though those vortices have nothing in common with their ethereal ancestors, they are barely better understood. And not only does the solar wind transmit sound and light as did the ancient ether, but it also carries a host of waves that Maxwell could not have dreamt of.

Even though the idea is an ancient one, most of the solar wind story took place over little more than a century. At the end of the nineteenth century, only a couple of far-seeing scientists had imagined that a solar wind might exist. At the beginning of the twenty-first century, hordes of space probes have explored the solar wind and it is honoured with a secure place in astronomy textbooks.

Since there are eminent accounts of how this concept emerged and developed (see for example [9], [25]), it is not my intention here to trace a detailed history. I shall only give a few hints[1] as to how the ideas evolved to fit reasonably well into the logical structure of modern physics and astronomy.

1.1.1 Intermittent particle beams?

When did the story begin? Perhaps around the middle of the nineteenth century, when the British amateur astronomer Richard Carrington, who was drawing sunspots (see Fig. 1.1) from a projected image of the Sun,[2] suddenly saw two patches of peculiarly intense light appear and fade within 5 minutes in the largest sunspot group visible [7], [5]. Carrington had witnessed what we now call a

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[1] Partly taken from Meyer-Vernet, N. 2005, *Bul. Inst. d'Astron. et de Géophys. Georges Lemaître* (Université Catholique de Louvain, Louvain-La-Neuve, Belgium).

[2] By far the safest way for amateurs to observe the Sun.

Figure 1.2 Auroral display seen from the ground in Lapland. (Photo courtesy of C. Molinier.) For hints on auroral physics see Section 7.3.

solar flare: a giant explosive energy release on the Sun – and a very strong one. Some time later, the magnetic field at Earth was strongly perturbed (Fig. 7.22), large disturbances appeared in telegraph systems, and intense auroras spread over much of the world (see Fig. 1.2). The connection between geomagnetic perturbations and auroras was already known, and Carrington suggested that both phenomena might be due to the special event he had seen on the Sun; but he was careful to point out that his single observation did not imply a cause-and-effect relationship. Carrington was correct; we will see later that solar flares are sometimes, although not always, followed by geomagnetic disturbances and auroras; this happens when the Sun releases a massive cloud of gas that reaches the Earth's environment and perturbs it.

Carrington was not the first to suspect the Sun of producing auroras and magnetic effects on Earth, as a correlation between the number of sunspots and geomagnetic disturbances had already been noted. The cause, however, was unclear. And the aurora was not better understood, even though its electric and magnetic nature had been identified a century before – a major improvement over the ingenious scheme based on the firing of dry gases proposed by Aristotle. To summarise the state of auroral physics around the mid 1880s (see [10]): 'The scientific theories . . . are more abstruse than the popular ones, but equally fail . . . ', as the Norwegian scientist Sophus Tromholt put it with splendid irreverence.

All that pointed to a connection between the Sun and terrestrial magnetic disturbances, and the idea was taken seriously by some physicists near the end of the nineteenth century. Assuming 'that the Sun is powerfully electrified, and repels similarly electrified molecules with a force of some moderate number of times the gravitation of the molecules to the Sun', George Fitzgerald suggested that [12]: 'matter starting from the Sun with the explosive velocities we know possible there, and subjected to an acceleration of several times solar gravitation, could reach the Earth in a couple of days'. In other words, the Earth was bombarded by intermittent beams of charged particles coming from the Sun

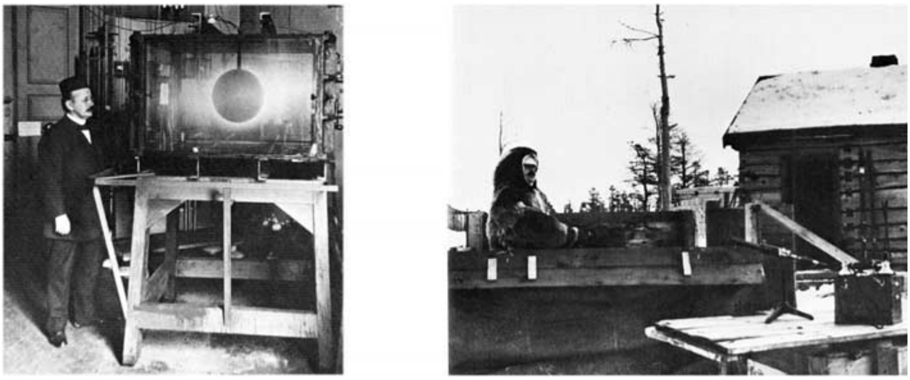

Figure 1.3 Birkeland on two of his fronts [4]. Left: with his *terella* apparatus – a magnetised sphere subjected to a beam of electrons in a vacuum chamber. Right: with some of his instruments for aurora detection.

and accelerated by an electrostatic field, just as an electrode in a giant vacuum tube.[3]

1.1.2 Permanent solar corpuscular emission?

In this context, an essential step was taken by the Norwegian physicist Kristian Birkeland, who worked in the closing years of the nineteenth century and the opening years of the twentieth (Fig. 1.3). These were fabulous times for a physicist: X-rays and radioactive decay were just being discovered, J. J. Thomson was unveiling the electron, Hendrik Lorentz was developing the electron theory and building steps on the route which led Einstein to change our vision of the Universe and Max Planck was explaining the spectrum of radiation, among other major accomplishments. Applied science was rising, too: the first aeroplane was close to being born, and Guglielmo Marconi made the first long-distance radio transmission, an engineering performance which led to the discovery of the Earth's ionosphere.

Birkeland worked on three fronts: theory, laboratory experiments with a model Earth and observation [11]. Not only did he develop the ideas put forward by Fitzgerald and others, but in order to test them he organised several polar expeditions and made the largest geomagnetic survey up to that time [4]. He also put forward a number of ingenious ideas that stand up well today, and above all, he submitted a crucial point: since auroral and geomagnetic activity was produced by solar particles and was virtually permanent, the inescapable conclusion was that the Earth environment was bombarded in permanence by 'rays of electric corpuscles emitted by the Sun'.

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[3] This was written 5 years before J. J. Thomson's 1897 paper on 'cathode rays' (*Phil. Mag.* **44** 293), and showed remarkable insight. The solar wind is made of charged particles – protons and electrons – and we will see later in this book that indeed the heliospheric electric field pushes the protons outwards with a force of a few times the solar gravitational attraction.

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Figure 1.4 An old drawing of Donati's comet, shown over Paris on 5 October 1858. (From A. Guillemin, 1877, *Le Ciel*, Paris, Hachette.) A modern view of cometary physics may be found in Section 7.5.

Put in modern terms, Birkeland was suggesting that the Sun emits a continuous flux of charged particles filling up interplanetary space: nearly our modern solar wind. This was a great change of perspective from the picture of the Sun emitting sporadic beams separated by a vacuum. However, many of these ideas were far ahead of the time, some were incorrect, and above all, the revered Lord Kelvin submitted impressive arguments showing that the Sun could not produce geomagnetic disturbances.[4] As a result, Birkeland's work was largely ignored by the scientific community.

These ideas lay in obscurity for many years. And when the *solar corpuscular radiation* (as it was called) resurfaced – albeit on independent grounds – to explain geomagnetic activity, it was once again in the form of occasional beams emitted by the Sun by some exotic process in a (slightly dusty) vacuum.

This remained the leading view until the middle of the twentieth century, when the concept of a continuous solar emission was to re-emerge through an entirely separate line of work. Comets have two classes of tails, one class nearly straight, made of gas, the other curving away, made of dust (Fig. 1.4). The

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[4] On 30 November 1892, he concludes in his Presidential Address to the Royal Society: 'It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sun-spots is unreal, and that the seeming agreement between the periods has been a mere coincidence' (Kelvin, Thompson, W. 1892, *Proc. Roy. Soc. London A* **52** 300).

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curved shape of dust tails is produced by solar radiation pressure and gravity acting on the dust grains. But the gaseous tails raised an intriguing problem: they were observed to always point straight away from the Sun (with a slight aberration angle)[5] and to exhibit irregularities that appeared to be accelerated away from the Sun. What caused these properties? The current explanation in terms of solar radiation pressure acting on the cometary gas failed by several orders of magnitude.

This problem was brilliantly solved by the German physicist Ludwig Biermann in the early 1950s: solar photons could not do the job, but perhaps solar corpuscular radiation would? Biermann thus developed a model for the interaction of cometary particles with those coming from the Sun, that neatly explained the comets' gaseous tails *if* they were subjected to a permanent flux of charged particles coming from the Sun (see [3] and references therein).

Although Biermann's original arguments regarding the interaction process between particles are now known to be incorrect, this was again a crucial change of perspective from the current view. Since comets' orbits pass at all heliolatitudes, the inescapable conclusion was that the Sun was emitting particles in *all* directions at *all* times. Half a century after Birkeland's work, the concept of a continuous solar corpuscular emission was resurfacing, with stronger observational and theoretical support.

But at the same time a different conclusion was reached by the English physicist Sydney Chapman through a completely different path. The outer atmosphere of the Sun – called the *corona* (see Fig. 1.12) – was known to be very hot. Chapman, who had pioneered the calculation of the kinetic properties of gases, found that this hot ionised atmosphere conducted heat so well that it should remain hot out to very large distances. As a result, particles have such large thermal speeds even far from the Sun that they can go very far against its gravitational attraction; this makes the density decline very slowly, so slowly that the solar atmosphere should extend well beyond the Earth's orbit [6]. In other words, the Earth was to be immersed in the *static* atmosphere of the Sun.

1.1.3 The modern solar wind

How could the ubiquitous solar corpuscular flux found by Biermann coexist with this static solar atmosphere? Both are plasmas and, as we will see later, the coexistence of plasmas having such different bulk velocities has very nasty consequences. The great achievement made by Eugene Parker in 1958 was to realise that [24]: 'however unlikely it seemed, the only possibility was that Biermann and Chapman were talking about the same thing'. So Biermann's continuous flux of solar particles was just Chapman's extended solar atmosphere expanding away in space as a supersonic flow. This comes about because this atmosphere is so hot, even far away from the Sun, that neither the solar gravitational attraction nor the pressure of the tenuous interstellar medium can confine it. At

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[5] With hindsight, the aberration angle of comet plasma tails, determined by the relative speeds of the radially moving solar wind plasma and the comet, yielded a correct solar wind speed of about 400 $\mathrm{km\,s^{-1}}$. For details, see Brandt, J. C. 1970, cited in Chapter 5.

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Figure 1.5 Mariner 2, the spacecraft that served to identify the solar wind, and the first one to have reached a planet other than the Earth. (Image by National Aeronautics and Space Administration (NASA).)

last the modern solar wind concept was born. Parker's theory was not only an eminently elegant solution which brought together existing evidences, but it made numerous testable predictions: in particular the wind was to flow at several hundreds of kilometres per second radially away from the Sun. Irony of ironies, these ideas were so novel that the paper presenting them [23] encountered difficulty in being published in the eminent *Astrophysical Journal*, on the grounds that the author was not familiar with the subject [25]. The referees of the *Astrophysical Journal* were not the only scientists to be displeased by Parker's theory, and a hot debate followed as to whether or not the Sun was capable of emitting a supersonic wind.

Observation was needed to settle the debate. But measuring the solar wind was a heroic challenge in those years when space technology was just springing up. It took four Russian missions and seven American ones – most of which failed due to problems of launching – to get an unambiguous result. The most successful of the Russian spacecraft, Lunik II, launched in 1959 (only 2 years after the first Russian Sputnik went up and the United States launched their first satellite in reply) detected a flux of positive ions; however, this observation was not entirely conclusive because the direction of the particles' velocity was unknown. The ultimate proof came in 1962 from the American spacecraft Mariner 2 [22], which was en route for Venus after having miraculously survived an impressive series of failures (Fig. 1.5). As Marcia Neugebauer superbly puts it [20]: 'We had data! Lots of it! There was no longer any uncertainty about the existence and general properties of the solar wind.'

So ended the first age of the solar wind story. With these results Parker's ideas rose to prominence, and within a few years, in spite of some dissenting voices, the solar wind concept acquired the respected state of a physical reality. Even now, decades later, Parker's ideas serve as a reference for a large part of what is understood on the subject. However, the very elegance of this theory

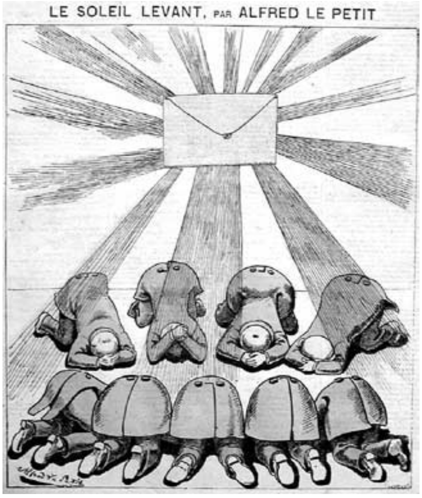

Figure 1.6 Cartoon published in the French journal *Le Grelot* (March 1873).

masked a number of fundamental difficulties that we will examine later, and of which an historical account may be found in [18]. As we will see in this book, the story has many other chapters and there is still a long way ahead.

1.2 Looking at the Sun

My Sun, the golden garden of your hair
Has begun to flame
And the fire has spread over our corn field

Already the green ears are parched
Pressed by the presence of your breath
And the last drop of their sweet is wrung for them

Strike us with the rain of your arrows,
Open to us the door of your eyes,
Oh Sun, source of beneficent light.
(Quecha poem to the Sun[6])

To us the Sun is no longer a god, and we do not have to feed it with hearts and blood to keep it moving across the sky, as did the Aztecs. Modern scientists (Fig. 1.6) worship it by building beautifully instrumented observatories scattered over the Earth's surface, far underground and in space, to analyse its radiation.

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[6] Ferguson, D. 2000, *Tales of the Plumed Serpent*, London, Collins & Brown.

Table 1.1 *Basic solar properties*

Mean distance to the Earth	$d_\oplus = 1.5 \times 10^{11}$ m
Mass	$M_\odot = 2. \times 10^{30}$ kg
Radius	$R_\odot = 7. \times 10^{8}$ m
Luminosity	$L_\odot = 3.84 \times 10^{26}$ W

The last quarter of the twentieth century saw the vertiginous growth of the scope and quality of solar data. A number of new techniques have emerged, making a revolution in the achievements of ground-based telescopes, while several beautifully instrumented spacecraft have been launched, enabling one to study wavelengths inaccessible from the ground. Among others, the satellites Yohkoh (launched in 1991), SoHO (launched in 1995), TRACE (launched in 1998) and RHESSI (launched in 2002) are currently in operation and devoted to solar observations.

We outline below some characteristics of the Sun and make a short survey of what its radiation tells us. We shall try to complete and unify this impressionistic picture later, equipped with the tools of plasma physics. A very accessible survey of solar physics is [13]; general accounts aiming at physical processes are given in [17], [14], [33].

1.2.1 Basic solar properties

Some basic properties of the Sun are listed in Table 1.1. Although these are rounded figures, they are exact to better than 1%, and may be considered as nearly constant by human standards; indeed, as we shall see later, many years will pass before changes in solar properties may oblige human beings to transfer the Earth to a more convenient star (see [2] and references therein).

The solar distance is called the astronomical unit (AU); it is used as a basic unit in the Solar System and beyond. So is the solar mass, which is negligibly altered by the solar wind ejection. Indeed, the solar wind pours out in space roughly 10^9 kg s^{-1}, which amounts to only $10^{-4} M_\odot$ over the Sun's age of a few 10^9 years. Note that the wind is not the only source of solar mass loss; the mass–energy equivalence tells us that the luminosity $L_\odot$ – the energy lost by the Sun per second via electromagnetic waves – yields a mass loss of $L_\odot / c^2 = 4.3 \times 10^9$ kg s^{-1}; this amounts to about four times the mass carried away by the solar wind, and thus barely alters the Sun's mass either; we will return later to the solar energy source.

The Sun's radius is that of the visible disc, which is almost perfectly round and whose diameter is a little more than half a degree as seen from Earth; it is sharply defined because virtually all the light we receive from the Sun originates in a thin layer a few hundred kilometres thick: the *photosphere*, where – going outwards – matter changes rapidly from completely opaque to almost completely transparent, letting radiation escape freely into space.

At the mean distance $d_\oplus$ of the Earth (but outside its atmosphere), the flux received from the Sun in the form of electromagnetic radiation by a surface perpendicular to the rays of sunlight is

$$\begin{aligned} S &= L_\odot/(4\pi d_\oplus^2) \\ &= 1.37 \times 10^3 \ \mathrm{W\,m^{-2}} \end{aligned} \tag{1.1}$$

which is called the *solar constant*. One square metre of the Earth's surface receives, however, much less: around 200 W in average, partly because only half the surface is sunlit and the radiation does not arrive at right angles, and partly because some of the incident energy is absorbed in the atmosphere. This energy sustains virtually all life on Earth; it may also harm it, as the Quecha poem reminds us. Despite its name, the solar constant is more variable than the other basic solar properties; it may vary by up to a few thousandths over several days and even more over long periods; it shows in fact variability at virtually all timescales, thereby raising a strong interest in climatology circles [15].

The solar luminosity enables one to derive one more basic property. If the Sun were radiating as a blackbody, that is if the Sun's disc emitted thermal radiation of temperature T_{eff}, the luminosity would be given by Stefan–Boltzmann law as

$$L_\odot = \sigma_S T_{eff}^4 \times 4\pi R_\odot^2 \tag{1.2}$$

where $\sigma_S = 5.67 \times 10^{-8}$ is the Stefan–Boltzmann constant in SI units. Putting the figures given in Table 1.1 into (1.2), we deduce the *effective temperature* of the Sun

$$T_{eff} = 5800 \ \mathrm{K}. \tag{1.3}$$

This is about 20 times hotter than the temperature at the Earth's surface, and it is this temperature difference that sustains life there. The effective temperature T_{eff} would be the actual temperature of the emitting outward layer of the Sun – the photosphere – if the radiation were thermal. We will see later that the actual photospheric temperature is close to this value.

1.2.2 The solar spectrum

The solar radiation has been studied at virtually all wavelengths, from gamma rays on the short wavelength side of the spectrum, to radio waves on the long wavelength side. How close to thermal is it?

Spectral distribution

Figure 1.7 shows the spectral distribution S_λ of the energy received from the Sun at Earth (outside the Earth's atmosphere) per unit wavelength per unit sunlit surface area perpendicular to the Sun's direction per unit time, at wavelengths ranging from 10^{-13} m to a few metres; in this range the intensity spans over