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Aspects of Solar Wind Physics

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Abstract

"Pourquoi courir après le vent?" [1].
The wind from the sun has many faces. For some, it is a wind of photons, which might soon drive windjammers through the solar system. But for space scientists, geophysicists, and astronomers, it is a wind of free electrons and protons. This corpuscular wind carries a minute fraction of the solar energy output, yet it is of considerable importance since it bathes the whole solar system and shapes all planetary environments. This mixture of electrons and protons makes a weakly collisional plasma - a state whose physics is not properly understood, so much so that there is no agreement as to how the wind is accelerated to the fast velocity observed. This paper recalls how ideas on the subject evolved over a century and a half, and discusses some basic physics underlining the modelling recipes. The emphasis is on kinetics aspects of the acceleration and on the large scale structure of the wind, whose non-equilibrium state brings about novel properties outside the realm of traditional magnetohydrodynamics.

Based on a talk presented on October 8, 2004,
Institut d'astronomie et de géophysique Georges Lemaître,
Université Catholique de Louvain (Louvain-La-Neuve, Belgique): Eméritat de Joseph Lemaire et Guy Schayes.

[1]Why chase the wind? (Jean Cocteau, 1922, *Antigone*, based on Sophocles' tragic play)

What is the solar wind?

For science-fiction writers and some space engineers, the "wind from the sun" is a wind of light, whose pressure might allow solar sailing and drive space windjammers through the solar system. In the delightful story *The Wind from the Sun*, Arthur Clarke [2] describes an impressive race involving solar sails made of a few square kilometres of aluminised plastic of various shapes, driven by skilful skippers between the Earth and the Moon (Figure 1).

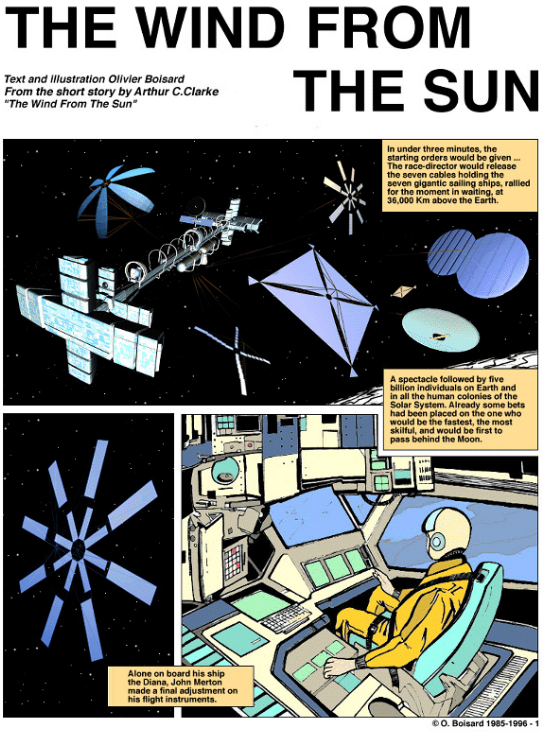


Figure 1: From a comic strip by O. Boisard (www.u3p.net; copyright Olivier Boisard/U3P - 1985/1996), based on the short story by Arthur Clarke: *The Wind from the Sun* [2].

Yet the sun blows another kind of wind, that is not made of photons, but of material particles. This wind amounts to one million tons of hydrogen per second - an amount that alters negligibly the solar mass and carries a minute fraction of the solar energy output, but 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.

What the sun blows is not exactly hydrogen atoms, but their constituents : protons and electrons (plus a small proportion of heavier elements). This mixture produces an unusual kind of matter - a plasma.

The plasma state

What is a plasma?

Every child knows that heating ice may produce liquid water, and - as more heat is put in, gaseous water. At each step, the energy furnished serves to loosen and break up chemical bonds. When still more energy is put in, however, the atoms themselves break up, producing bare ions and electrons: a plasma - the fourth state of matter.

What makes the plasma state a special one?

[2] Arthur C. Clarke (1963) *The Wind from the Sun* (first published under the title "*Sunjammer*").

Ions and electrons produce electric and magnetic fields, and are affected by them, too. This coupling produces bizarre properties: plasmas may conduct heat and electricity as effectively as copper, yet they may behave as elastic rubber; they polarise electromagnetic waves as do crystals, but they also carry sound waves and special waves of their own; and they often exhibit a schizophrenic behaviour, seeming unable to decide whether they are a fluid or a gas.

Plasmas fill most of the universe, and yet they are extremely rare on Earth. Why is it so?

The answer lies in the fact that we are living in a very special place of the universe: a thin shell that is at a temperature too mild for producing a significant ionisation, that is protected from the ionising short-wavelength solar radiation, and that is dense enough that when an atom happens to be ionised, its constituents recombine at once.

Light pushes sails, and plasmas push plasmas

Solar sails are based on a simple concept, even if their implementation is far from simple. The sun emits $L_\odot \simeq 4 \times 10^{26}$ W in the form of electromagnetic waves. This flux of photons moving at speed c produces a pressure of order of magnitude $L_\odot / \left(4\pi d^2 c\right)$ on a sail lying at distance d from the sun; the reflection of photons produces a force per unit surface equal to twice this value in the direction normal to the sail. At one astronomic unit (1 AU $\simeq 1.5 \times 10^{11}$ m), this comes to $P_{rad} \sim 10^{-5}$ Pa.

The solar wind plasma is much less effective at pushing sails. Its (radial) motion at velocity V with mass density ρ produces a dynamic pressure of $P_{plasma} \sim \rho V^2$. With about $2-10$ protons per cm^3 at 1 AU from the sun (decreasing as d^{-2}) moving at $V \sim 800-400$ km/s, this comes to $P_{plasma} \sim 2 \times 10^{-9}$ Pa - a negligible amount compared to the radiation pressure.

But the solar wind plasma interacts very effectively with free charged particles - much more effectively than does the wind of photons. To understand this point, let us compare the cross-sections for interaction.

When two electric charges come close together, their mutual interaction is very different from the one of neutral molecules or of billiard balls. Billiard balls have to come into contact in order to interact. This is not so for electric charges, which interact via the electrostatic Coulomb force. For two electrons of charge e separated by distance r, the energy of interaction is $e^2 / (4\pi\epsilon_0 r)$. They interact effectively when this energy is of the same order of magnitude as their kinetic energy $\sim m_e v^2$, where m_e and v are respectively the electron mass and relative velocity. This means that the cross section of interaction is of the order of magnitude of $\sigma_C \sim r_C^2$ where [3]

$$r_C = \frac{e^2}{4\pi\epsilon_0 m_e v^2} \tag{1}$$

In contrast, the interaction of electrons with electromagnetic waves is determined by the Thomson cross-section, of order of magnitude $\sigma_T \sim r_e^2$, where the so-called classical electron radius is

$$r_e = \frac{e^2}{4\pi\epsilon_0 m_e c^2} \tag{2}$$

Thus the ratio of cross sections is $\sigma_T/\sigma_C \sim v^2/c^2$. Since $v \ll c$, we have $\sigma_T \ll \sigma_C$.

In short, even though the solar wind is much less effective at pushing sails than is the solar radiation, it interacts much more effectively with plasmas.

This picture of plasma interactions misses an important point: the magnetic field. The solar wind carries a magnetic field, which produces a Laplace force making the particles gyrate around the field lines. This tends to link particles to these lines, so that the magnetic field is an important ingredient of the interaction between space plasmas.

Equation (1) embodies an important property: the cross-section of charged particles for mutual interaction varies as v^{-4} - inversely proportional to their energy squared. This makes fast particles interact negligibly with other particles. This behaviour contrasts sharply with the one of neutral gases, whose particles have a cross-section mainly determined by their local structure, thus of the order of magnitude of the typical atomic size - the Bohr radius - squared. We shall return to this point later.

[3] This order of magnitude estimate neglects the long-range interactions, which play an important role since the mean distance between particles is much greater than the mean value of r_C; their accumulation increases the cross-section by typically one order of magnitude in natural plasmas.

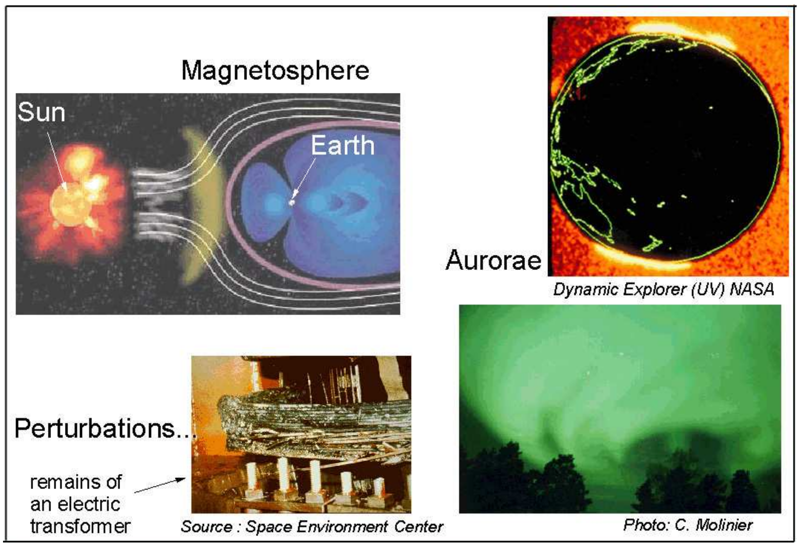


Figure 2: Some examples of the role of the solar wind in geophysics. Not only does the solar wind shape the large scale Earth's plasma environment - the magnetosphere (top/left), but it carries perturbations that strongly disturb it, producing in particular aurorae (right/top, as seen from space; right /bottom, as seen from the ground) and disruptions of our everyday technology (bottom/left).

The solar wind in geophysics, planetology, astronomy, and physics

Figure 2 reminds us of the importance of the solar wind in geophysics. The solar wind shapes the large scale plasma environment of the Earth - the magnetosphere, stirring it into a tail more than a hundred Earth's radii long. It also carries perturbations that may strongly disturb the Earth's environment. Now and then, the hot solar atmosphere - the corona - ejects a huge plasma bullet of $10^{12} - 10^{13}$ kg; in average over the whole sun, this happens a few times per day when solar activity is at a maximum. If one of these bullets strikes the magnetosphere in an adequate way, huge perturbations may result, including aurorae, crashes of power stations, disruption of communications, and even destruction of satellites.

The solar wind plays an important role in planetology, too, since it bathes the whole solar system, as Figure 3 reminds us. It shapes the large scale plasma environment of the planets. It is also responsible for the blue straight tail of comets, as cometary particles are funnelled by the solar wind magnetic field that is draped around the comet's nucleus as a wind sock. And finally, the solar wind carves a huge elongated bubble within the interstellar medium: the heliosphere.

The solar wind has an important role in astronomy, too, as a familiar example of an ubiquitous phenomenon: ejection of matter. Virtually all cosmic bodies blow a wind in some form or another, but the solar wind is the only stellar wind that can be studied *in situ* and is reasonably known - albeit not yet correctly understood.

And finally, till the beginning of space age, the solar wind is a favourite playground for physicists. They find there extreme properties that are impossible to simulate in the laboratory, and these properties can be observed and analysed in much detail, via a huge number of space probes lying from inside Mercury's orbit to much beyond the distance of Neptune, and carrying sophisticated instruments. The *Helios* 1 and 2 spacecraft, launched respectively in 1974 and 1976, have explored the heliosphere near the ecliptic at about 0.3 AU from the sun; a horde of spacecraft are watching the solar wind impinging on the Earth at 1 AU from the sun; *Pioneer* 10 and 11 (launched respectively in 1972 and 1973) [4] and *Voyager* 1 and 2 (launched in 1977) are aiming to the outskirts of the solar system, *Voyager* 1 being at nearly 90 AU from the sun; and finally, *Ulysses* made true a long lasting dream of space scientists: exploring the heliosphere

[4] whose emissions are no longer received at Earth.

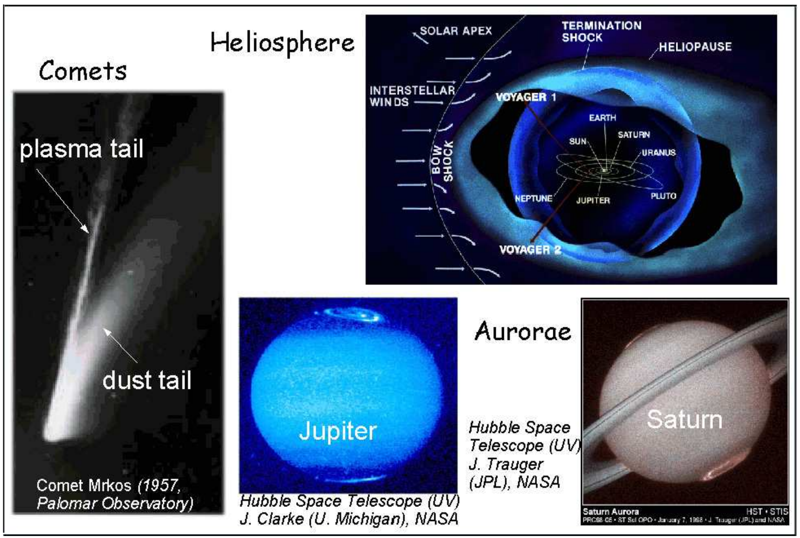


Figure 3: A few examples of the role of the solar wind in planetology. The solar wind carves a huge bubble in the interstellar medium - the heliosphere (top), drives the large scale planetary environments and their aurorae (bottom/right), and cometary plasma tails (left).

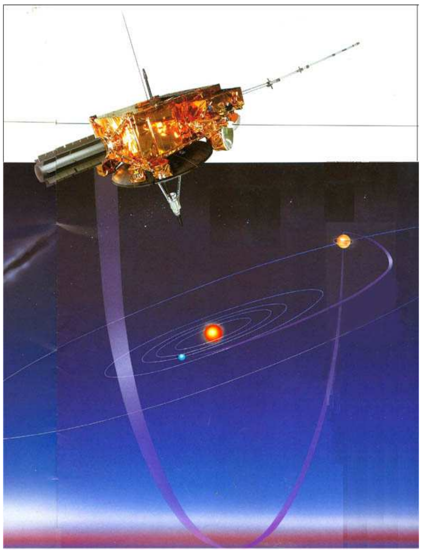


Figure 4: An artist's view of the Ulysses spacecraft - the first and as yet the only one - to have reached high solar latitudes.

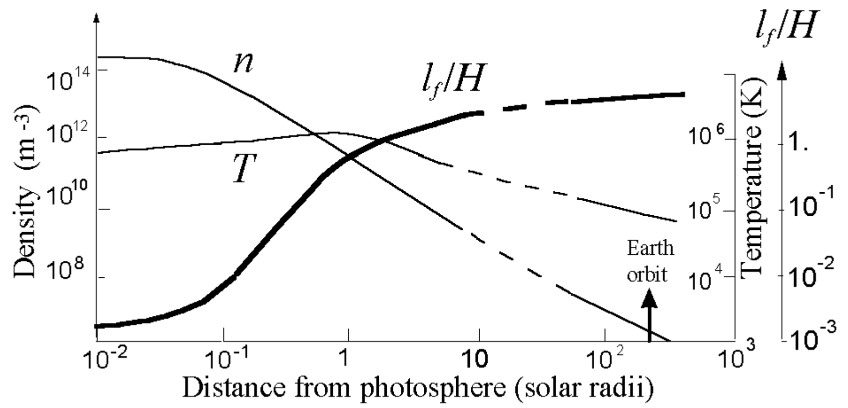


Figure 5: Electron density, temperature, and *mean* free path (normalised to the scale height) as a function of distance from the solar surface.

in three dimensions (Figure 4).

For plasma physicists, the solar wind is a nice example of weakly collisional plasma. This is illustrated in Figure 5 which shows the mean free path l_f of particles (normalised to the scale height H), as a function of distance from the solar surface. One sees that the mean free path is roughly equal to the scale height, nearly everywhere in the solar wind. This has a major consequence: the particles have not enough collisions to behave as a fluid, but they have too much collisions to behave as a collisionless medium. Still worse, the collision behaviour depends on the particle energy. Slow particles are mildly collisional, but fast ones are nearly collisionless, the free path of a particle of speed v varying as $1/r_C^2$ with r_C given in Eq.(1). This makes the problem extremely difficult to solve, to such an extent that the physics of weakly collisional plasmas is much less developed than the one of neutral gases.

A brief history of ideas

Solar wind research has a long history. Eminent accounts by actors of the field may be found in [8] and [33]. That planets are not moving in a vacuum is an old idea, dating back to at least the fourth century BC. In some sense, our modern view of a solar wind filling interplanetary space has replaced the Aristotelian quintessence, the impalpable pneuma of Stoic philosophers, and the swirling "sky" introduced two thousand years later by Descartes (Figure 6).

The solar wind story began in earnest around the middle of the 19th century. In 1859 the British amateur astronomer Richard Carrington, who was drawing sunspots from a projected image of the sun, suddenly saw two patches of peculiarly intense light appear and fade within five minutes in the largest sunspot group visible [3]. Carrington had witnessed what we now call a solar flare: a giant explosive energy release on the sun - and an exceptionally strong one. Some time later, the magnetic field at the Earth's surface was strongly perturbed, and intense aurorae spread over much of the world (c.f. Figure 2). The connection between magnetic perturbations at Earth and aurorae was already known, and Carrington suggested that both phenomena might be due to the special event he had seen on the sun. In fact, Carrington was not the first to suspect the sun of producing aurorae and magnetic effects at Earth, and a correlation between the number of sunspots and geomagnetic disturbances had been noted before, as reviewed in [9].

This idea was taken seriously by some physicists near the end of the 19th century, and George FitzGerald submitted that [11]:

> "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."

In other words, FitzGerald proposed that the Earth was bombarded by intermittent beams of charged

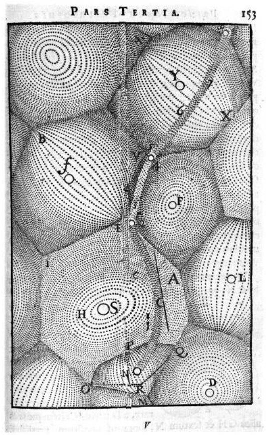


Figure 6: "... pensons que la matière du ciel où sont les planètes tourne sans cesse en rond, ainsi qu'un tourbillon ..." René Descartes, *Principia philosophiae* (Amstelodami, L. Elzevirium, 1644, Bibliothèque de l'Observatoire de Paris).

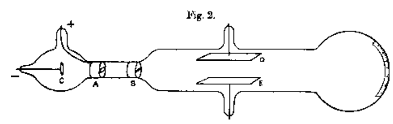


Figure 7: The *cathode ray tube* used by J.J. Thomson (*Phil. Mag.* 44, 293 (1897)).

particles coming from the sun and accelerated by an electrostatic field, just as if the Earth were an electrode of a giant vacuum tube. In the context of the closing years of the 19th century - five years before J. J. Thomson's paper on *"cathode rays"* (Figure 7) - this showed remarkable insight. We shall see below that the heliospheric electric field indeed pushes outwards the protons with a force of a few times the sun's gravitational attraction.

An essential step in this long march was taken by Kristian Birkeland, at the turn of the 20th century. Birkeland worked on three fronts: theory, laboratory experiments with a model Earth, and observation (Figure 8). Not only did he developed 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 [2]. 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*".

Put in modern terms, Birkeland suggested that the sun emits a *continuous* flux of charged particles *filling up interplanetary space*: nearly our modern solar wind! Unfortunately, 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. As a result, Birkeland's work was largely ignored by the scientific community, 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 20th century, when the concept of a continuous solar wind re-emerged through an entirely separate line of work - connected to comets. Comets have two classes of tails, one curving away - made of dust grains pushed by solar radiation pressure, the other nearly straight and pointing away from the sun - made of plasma (c.f. Figure 3). Ludwig Biermann proposed an ingenious explanation of the latter, implying that comets were subjected to a permanent flux of charged particles coming from the sun ([1] and references therein). Since comets' orbits pass at

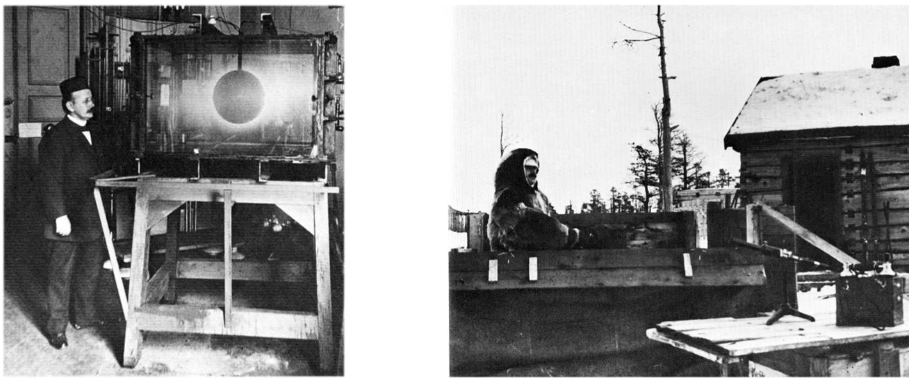


Figure 8: Birkeland on two of his fronts [2]. Left: with his *terella* apparatus - a magnetised sphere subjected to a beam of electrons in a vacuum chamber. Right: with some of his instruments for aurora detection.

all heliolatitudes, this implied that the sun was emitting particles in *all* directions at *all* times. Half a century after Birkeland times, the concept of a continuous solar corpuscular emission resurfaced.

But at the same time a different conclusion was reached by Sydney Chapman through an entirely different path. The outer atmosphere of the sun - called the *corona* - was known to be very hot. Chapman, who had pioneered the calculation of the kinetic properties of gases, showed that this hot ionised atmosphere conducts heat so well that it should remain hot out to very large distances. As a result, particles have so large thermal speeds even far from the sun that they can go very far away against its gravitational attraction; this makes the density decline very slowly, so slowly that this atmosphere should extend well beyond Earth's orbit [6]. This meant that the Earth was immersed in the *static* atmosphere of the sun.

How could the ubiquitous solar corpuscular flux found by Biermann coexist with Chapman's static solar atmosphere? The great achievement made by Eugene Parker in 1958 was to realise that "Biermann and Chapman were talking about the same thing" [32]. 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 from the sun, that neither the solar gravitational attraction nor the pressure of the tenuous interstellar medium can confine it [5].

Parker's theory was an elegant demonstration - based on a fluid theory - that the sun blows a supersonic wind [30]. Barely a few years later, however, Chamberlain took up the problem from a different point of view, and found a very different result: the sun should not blow a supersonic wind but a weak breeze - rather similar to an hydrostatic atmosphere. Chamberlain's theory was based on a corpuscular description of the medium [4]; but he also built a fluid model - with a different boundary condition [5], which confirmed his corpuscular theory.

Who was right? Parker's paper presented a novel point of view that contrasted sharply with the current belief, 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 matter. However, Sputnik had just opened the Space Age, space technology was in its infancy, and measuring the solar wind was an heroic challenge. After a number of unsuccessful or inconclusive attempts, the ultimate proof came in 1962 from the American spacecraft Mariner 2 [28]. As Marcia Neugebauer superbly puts it [27]:

> "We had data! Lots of it! There was no longer any uncertainty about the existence and general properties of the solar wind."

So Parker was right.

But was he really? And how did Chamberlain manage to obtain a breeze?

[5]Not only did the static atmosphere have a large distance pressure far too great to match the one of the interstellar medium, but it was convectively unstable (see J. Lemaire, *Equilibre mécanique et thermique de la couronne solaire*, Thèse de Doctorat, Université de Liège, 1969).

On fluid, exospheric and kinetic models

Despite its success, Parker's theory swept under the carpet a number of fundamental difficulties.

The fluid picture

In essence, this theory is based on the motion of a fluid driven by two oppositely directed forces: the solar gravitational attraction, and the pressure gradient between the dense hot solar corona and the dilute cold interstellar medium. The solution therefore requires two additional ingredients: an assumption on the (isotropic) pressure - or rather on the temperature, through an energy equation - and an adequate boundary condition at large distances - since no wind would blow if the interstellar medium were not so dilute. In this first fluid model of the solar wind, Parker made two crucial assumptions:

- the temperature does not vary with distance,
- the pressure tends to zero at infinity.

The latter assumption appears reasonable, since the interstellar medium is extremely dilute; it enables one to select the only solution of the problem that starts at a small velocity near the sun, passes through a sonic point, and is supersonic farther away. It can be shown that this solution is indeed the only *stable* solution of Parker's problem producing matter ejection [41] [6].

The former assumption, however, is far from justified, and masks a fundamental point. First of all, keeping the temperature constant up to an infinite distance requires an infinite energy, and produces a solar wind speed that increases indefinitely with distance. This problem is not grave since in practice the wind does not have to go to infinity; this assumption was in fact fully relaxed in further papers (see [31], [32]), and replaced by less drastic hypotheses on either the temperature or the heat conductivity.

The grave problem is rather that this kind of assumption masks the inability of the theory to calculate the variation in temperature. Indeed, the rarity of collisions precludes the use of the usual (collisional) thermal conductivity, so that the energy equation involves a term that is not only unknown, but may not be expressible as a local function of the macroscopic properties of the medium (or their derivatives).

Let us explain this point in more detail. In the precise - albeit obtained itself from approximation - kinetic Boltzmann's scheme, the plasma is defined by the particle velocity distributions as functions of space and time. The passage to a fluid description - where the medium is more loosely defined by a few moments of the velocity distributions (particle number density, mean velocity, pressure, ..) - involves an infinite set of coupled equations for the moments, which must be closed and truncated (see for example [39]). The usual procedure for doing so involves an expansion into the ratio of the particle mean free path to the scale length of the problem - the so-called *Knudsen number*; note that the relevant scale length is here the one along the magnetic field, because the particle gyration around field lines comes to the rescue for localising them in the perpendicular directions.

In ordinary gases, this expansion only requires the Knudsen number to be smaller than unity. But in plasmas, the criterion is more stringent and the Knudsen number must be *much* smaller than unity - a condition that is nowhere met in the solar wind (c.f. Figure 5). The fundamental reason of this theoretical difficulty is the steep increase of the particle free path with speed, that we already mentioned. Even when the free path is small for "thermal" particles, it is not so for faster ones, thereby precluding uniform convergence of the expansion, as has been recognised in earnest some time ago (see [40], [37]).

The truncation and closure implied by the fluid schemes require the velocity distributions of particles to be close to Maxwellians - a condition that is not better met in the solar wind than the one on the free path. Figure 9 shows typical distributions for protons and electrons in the fast solar wind - the solar wind state that is the most basic and free from perturbations. They are clearly not at equilibrium. One sees in particular that the electrons have a large excess of fast particles compared to a Maxwellian. This conspicuous suprathermal tail strongly affects heat transport since the heat flux - the third velocity moment in the kinetic picture - depends mainly on the fast particles: the faster the particles, the more efficiently they conduct heat; this is still truer for the higher-order moments which are disposed of in

[6] The finite interstellar pressure can be accommodated with the help of a shock (as usually occurs when a supersonic flow encounters an obstacle), that enables the solar wind to become subsonic before encountering the interstellar medium; this shock is believed to lie at nearly a hundred AU from the sun.

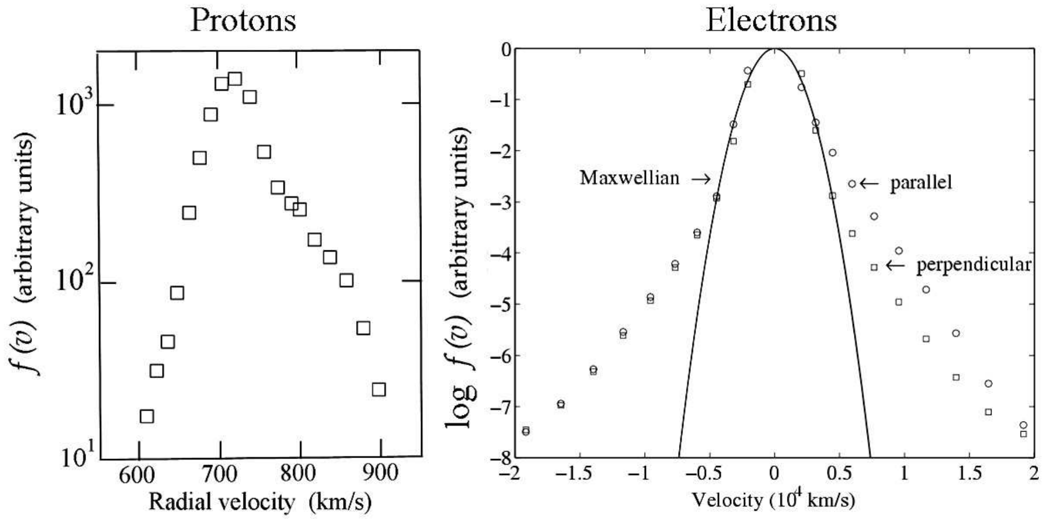


Figure 9: Typical velocity distributions for protons (left) and electrons (right) in the fast solar wind at 1 AU from the sun, showing its non-equilibrium state. Left: proton distribution projected on the radial direction (adapted from [10]). Right: electron distribution projected parallel (circles) and perpendicular (squares) to the magnetic field, compared to a Maxwellian (continuous line); (data courtesy of I. Zouganelis, from [23]).

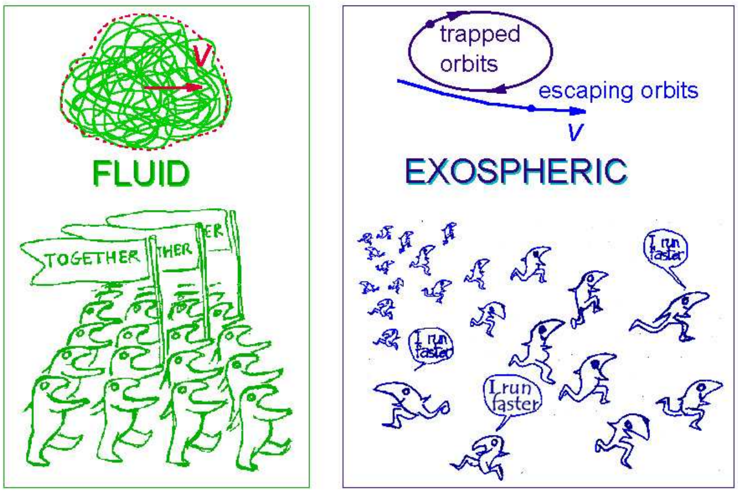


Figure 10: In the fluid picture, the collision free path is assumed to be very small, so that collisions localise the particles (left). In the exospheric (kinetic collisionless) picture, the particles follow orbits determined by boundary conditions and forces (right). In the solar wind, the fluid picture is adequate for subthermal particles, whose free path is small and whose velocity distribution is nearly Maxwellian, while the exospheric picture is adequate for faster particles, which are nearly free; (adapted from [26]; drawing by F. Meyer).

the fluid truncation and closure schemes: the higher the order of the moment, the greater the relative contribution of the fast particles, so that higher-order fluid theories may not improve over the simpler ones.

This difficulty may be understood intuitively by noting that the fluid picture requires the particles to be localised in space, so as to behave as a whole; indeed, if the medium is to be described by differential equations, the rates of change must depend only on the local variables (Figure 10, left). This localisation

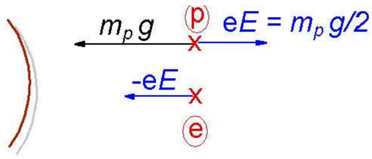


Figure 11: In an hydrostatic electron-proton atmosphere with equal temperatures, the tendency of the (light) electrons to escape from the (heavy) protons sets up a restraining electric field which reduces the net attractive force on a proton to half the solar gravitational force.

requires the particles to travel less than a scale height before coming into equilibrium - a condition that is not met in the solar wind, as in many other space plasmas.

This problem remains a stumbling block even for modern fluid models of the solar wind, which now include several fluids and 16 moments. Furthermore, the early fluid models could not explain the speed greater than 700 km/s observed in the fast wind, which is now known to be the most basic state of the wind, and fills most of the heliosphere around solar activity minimum (see [7] for a review). To produce such a high speed, fluid models now include an arbitrary heating by a flux of Alfvén waves, that is adjusted *ad hoc* to fit the observed solar wind properties, (see for example [21]).

The first exospheric picture

Whereas the fluid picture assumes that there are enough collisions for the medium to be near local equilibrium (Figure 10, left), the exospheric picture considers the other extreme: no collisions (Figure 10, right). Chamberlain's paper [4] was the first model of this kind (detailed reviews may be found in [18] and [19]).

In the exospheric picture the solar wind is viewed as the evaporation of an atmosphere, somewhat as Jean's theory of planetary escape [12], the evaporation flux being made of the particles whose velocity exceeds a critical escape speed. The velocity distributions are set up at some reference level - *the exobase* , and calculated farther away using the Vlasov equation. Once the velocity distributions are calculated, the moments (density, velocity, pressure, ...) can be deduced. Note that, by construction, these moments obey the fluid equations (with anisotropic pressure), with however a fundamental difference from the fluid scheme: the exospheric heat flux is calculated *a posteriori* from the velocity distributions according to its kinetic definition, instead of being set up *a priori* equal to the Spitzer-Härm value or to another postulated value closing the fluid hierarchy.

A crucial difference from the evaporation of neutral gases is that the medium is made of (light) electrons and (heavy) protons. Near the solar surface, the gravitational potential per unit mass is $\Phi_\odot = M_\odot G/R_\odot$, whereas protons and electrons have thermal energies of the same order of magnitude $k_B T$. We have $m_p \Phi_\odot / k_B T \gg 1$ for protons, while $m_e \Phi_\odot / k_B T \ll 1$ for electrons, so that protons tend to be confined by the sun whereas electrons barely feel its attraction. As a result, an electric field must set up in order to preserve charge neutrality.

There lies the error made by Chamberlain, an error which was to have large consequences on the subsequent evolution of the ideas. Chamberlain assumed the electric field to have the value ensuring hydrostatic equilibrium, as schematised in Figure 11. In an hydrostatic electron/proton atmosphere with equal temperatures, this (*Pannekoek-Rosseland*) electric field adjusts to make the electric force on a proton equal to half the gravitational attraction and directed in the opposite sense. In this way, the net force on a proton is half the solar gravity, and is equal to the force on an electron. Both species are thus confined in a potential well whose amplitude at any distance is half the solar gravitational attraction on a proton. There lies the origin of the nearly static atmosphere found in Chamberlain's theory, whose inconsistency with observation caused the disregard of this model as an academic curiosity.

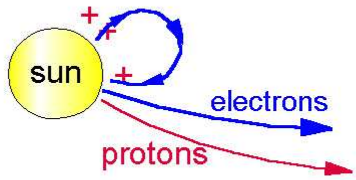


Figure 12: When a wind blows, the electric field is greater than in an hydrostatic atmosphere, in order to restrain the electrons and keep their escaping flux equal to that of the protons, whose thermal speed is much smaller.

The heliospheric electric field

Only in the 1970's was Chamberlain's error corrected independently by Jockers [13], and Lemaire [17]; Joseph Lemaire had already noted the fact in the context of the Earth's polar wind [16]. The basic point is that because of their small mass, electrons have a thermal speed v_{th} roughly $(m_p/m_e)^{1/2} \sim 43$ times greater than the one of protons. With the electric field assumed by Chamberlain, which produces equal escape speeds for electrons and protons, too many electrons would escape from the corona, with a flux 43 times greater (in order of magnitude) than the one of protons, so that the sun would charge infinitely! As a result, the electric field must increase in order to restrain the electrons and keep their escaping flux equal to the proton one (Figure 12). That greater electric field produces a greater outward force than the one assumed by Chamberlain, and accelerates the protons, producing a wind.

It is interesting to estimate the order of magnitude of this electric field [18]. Because of the small electron mass, the mean electric force on electrons: $-ne\mathbf{E}$ (per unit volume) must balance the pressure force, i.e. [7]

$$eE \quad \sim \quad -\frac{1}{n}\frac{\partial\,(nk_BT)}{\partial r} \tag{3}$$

Since the temperature T varies much less rapidly than the density n, we may put T out of the derivative, to obtain the order of magnitude estimate:

$$eE \quad \sim \quad -k_BT/H \quad \text{where} \quad 1/H = (\partial n/\partial r)\,/n \tag{4}$$

We deduce the dynamic time scale of thermal electrons (of thermal speed v_{th}) by dividing the momentum by the force, i.e. $\tau_{dyn} \sim m_e v_{th}/eE \sim H/v_{th}$. Comparing with the (thermal) collisional time scale $\tau_{col} \sim l_f/v_{th}$, we see that both time scales are of the same order of magnitude in the solar wind since the mean free path l_f is of the order of magnitude of the scale height H. This illustrates that collisions and coherent dynamics are of equal importance for thermal electrons, whereas collisions dominate the dynamics for slower particles and are negligible for faster ones (Figure 10).

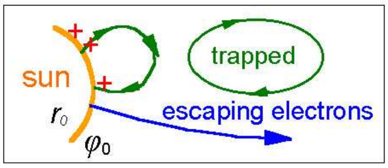
Let us compare the electric and gravitational forces on a proton. Using (4) with $H \sim r/2$ at 1 AU, we find

$$eE/\left(m_p M_\odot G/r^2\right) \quad \sim \quad 2k_BT/\left(m_p M_\odot G/r\right) \sim 2 \tag{5}$$

with a temperature $T \sim 10^5$ K at 1 AU. In retrospect it is amusing to note, from our 21th century vantage point, that FitzGerald was right: solar wind protons are pushed outwards by an electrostatic acceleration of a few times the solar gravitation.

More precisely, with most models (fluid, exospheric, or kinetic with collisions) producing a wind that starts at a small speed and becomes supersonic at some distance, one finds that close to the sun the outward electrostatic force on protons is smaller than the gravitational attraction, but the electric force outweighs gravitation when the wind has just become supersonic, thereby pushing the protons.

[7] Taking an isotropic pressure to obtain an order of magnitude estimate



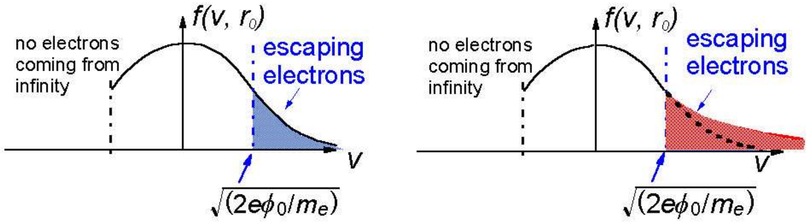


Figure 13: In the exospheric picture, the electrons that escape from the corona are the suprathermal ones (left). If the velocity distribution in the corona has an excess of such electrons, the escaping electron flux tends to increase (right), so that the electric potential rises in order to keep that flux equal to the proton one; the greater electric field accelerates the protons and increases the wind speed.

Modern exospheric models

The seminal paper of Joseph Lemaire [17] led to a revival of exospheric models. The story, however, does not stop there because these early models could explain the slow solar wind, but were as unable to explain the fast solar wind as were the early fluid models. Something more was needed to push the wind.

One possible solution to this problem emerges by looking at the electron velocity distribution measured in the solar wind (Figure 9). Ones sees that *if* the electron distribution has a similar shape in the corona as in the wind proper, having a small suprathermal tail, then the wind speed should increase [29], [38]. This comes about because the electrons escaping from the solar potential well are the suprathermal ones (Figure 13, left), so that even a minute excess of them would increase considerably the escaping electron flux if the potential did not change (Figure 13, right), thereby tending to increase the positive charge in the corona. The electric potential must therefore rise, in order to restrain more the electrons and keep their escaping flux equal to the proton one. And in turn this greater electric field pushes the protons outwards and increases the wind speed (a simple calculation may be found in [25]).

This led to a second revival of exospheric models, with calculations of the speed [22] and temperature [24] profiles, of the effect of the spiral magnetic field [35], and finally, a generalisation of the models to a transonic wind for application to the fast solar wind [14], [42].

Concluding remarks

All these peripeteiae do not mark the end of the story, because the two simplest pictures - the fluid and exospheric ones - have deficiencies. The former implicitly assumes too many collisions, whereas the latter neglects collisions and plasma instabilities (see [10] and references therein). These extreme and opposite hypotheses make these simplified pictures complementary. The fluid picture can easily accommodate a large number of particle species and arbitrary sources of momentum and heat. The exospheric picture enables one to investigate the role of the particle velocity distributions. In order to explain the fast wind, the fluid models introduce a heating by Alfvén waves, whereas the exospheric models introduce suprathermal tails in the velocity distributions. None of these two ingredients has yet been confirmed by observation, not necessarily because they do not exist, but because of the lack of adequate measurements in the corona.

Progress is required in both theory and observation. One needs a kinetic theory with (a few) collisions, and accurate measurements in the corona. The theoretical problem is presently attacked with the help of the Fokker-Planck scheme (see for instance [20], [35] and references therein), and of particle

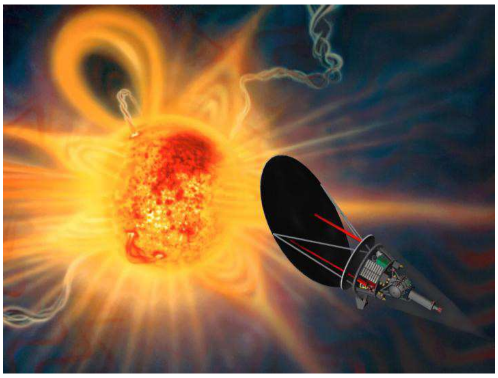


Figure 14: An artist's view of the NASA Solar Probe making a near-sun fly-by: an age-old dream of space scientists that is within the reach of 21th century technology.

numerical simulations [15], but it is not yet fully solved, and the observational front awaits better distant measurements and/or a solar probe making *in situ* observations (Figure 14).

Meanwhile, more than forty years after the first theory and *in situ* measurement of the solar wind, Eugene Parker noted [34]:

> "We cannot state at the present time why the Sun is obliged by the basic laws of physics to produce the heliosphere".

Indeed, even though there is little doubt that the solar wind stems from the large coronal temperature and energy flux - themselves produced by the solar output with the probable mediation of the magnetic field - the basic physics producing the large coronal temperature and the high speed wind acceleration is not known. Are Alfvén waves responsible? Are suprathermal tails responsible? Or both? Or some *Boojum* nobody has yet thought of?

It may turn out that Nature is subtler than we had imagined, and I shall leave the last word to Joseph Lemaire:

> "Quelle sera la prochaine hypothèse *généralement acceptée* dont il faudra se libérer un jour ..? Quels seront les futurs chercheurs qui briseront demain les images d'Epinal et représentations théoriques que nous nous accordons d'accepter aujourd'hui?" [8].

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[8]Proceedings of Seminar GdR Plasmae (Giens, France), 1993.

Bibliography

[1] Biermann L. 1953, Physical processes in comet tails and their relation to solar activity, *Mém. Soc. Roy. Sci. Liège (Ser. 4)* **13** 291

[2] Birkeland K. R. 1908, 1913 *The Norvegian Aurora Polaris Expedition 1902-1903*, vols.1 and 2, H. Aschehoug & Co., Christiania

[3] Carrington R. C. 1860, Description of a singular appearance seen on the sun on September 1, 1859, *Mont. Not. Roy. Soc.* **20**, 13

[4] Chamberlain J. W. 1960, Interplanetary gas. II. Expansion of a model corona, *Ap. J.*, **131**, 47

[5] Chamberlain J. W. 1961, Interplanetary gas. III. A hydrodynamic model of the corona, *Ap. J.*, **133** , 675

[6] Chapman S. 1957, Notes on the solar corona and the terrestrial ionosphere, *Smithsonian Contr. Astrophys.* **2** 1

[7] Cranmer S. R. 2002, Coronal holes and the high-speed solar wind, *Space Sci. Rev.* **101**, 229

[8] Dessler A. J. 1967, Solar wind and interplanetary magnetic field, *Rev. Geophys.* **5** 1

[9] Eather R. H.: 1980, *Majestic Lights*, American Geophysical Union, USA

[10] Feldman W. C. and E. Marsch 1997, in *Cosmic winds and the heliosphere*, ed. by J. R. Jokipii et al., Un. of Arizona Press, Tucson, p. 617

[11] Fitzgerald G. F. 1892, Sunspots and magnetic storms, *The Electrician* **30** 48

[12] Jeans J H 1954 *The dynamical theory of gases* (New-York: Dover)

[13] Jockers K. 1970, Solar wind models based on exospheric theory, *Astron. Astrophys.*, **6**, 219

[14] Lamy H. et al. 2003, A kinetic exospheric model of the solar wind with a nonmonotonic potential energy for the protons *J. Geophys. Res.* **108**, SSH13

[15] Landi S. and Pantellini F. 2003, Kinetic simulations of the solar wind from the subsonic to the supersonic regime, *Astron. Astrophys.*, **400**, 769

[16] Lemaire J. and M. Scherer 1969, Le champ électrique de polarisation dans l'exosphère ionique polaire, CRH Acad. Sci. Ser. **B 269**, 666

[17] Lemaire J. and M. Scherer 1971, Kinetic models of the solar wind, *J. Geophys. Res.*, **76**, 7479

[18] Lemaire J. and M. Scherer 1973, Kinetic models of the solar and polar winds, *Rev. Geophys. Space Phys.*, **11**, 427

[19] Lemaire J. and V. Pierrard 2001, Kinetic models of solar and polar winds, *Astrophys. Space Sci.* **277** 169

[20] Lie-Svendsen O. and E. Leer et al. 200, The electron velocity distribution in hte high-speed solar wind: modeling the effects of protons, *J. Geophys. Res.*, **105**, 35

[21] Lie-Svendsen O. et al. 2001, A 16-moment solar wind model: from the chromosphere to 1 AU, *J. Geophys. Res.*, **106**, 8217

[22] Maksimovic M. et al. 1997, A kinetic model of the solar wind with kappa distributions in the corona, *Astron. Astrophys.* **324**, 725

[23] Maksimovic M. et al. 2005, Radial evolution of the non-thermal character of electron distribution functions in the solar wind, in press

[24] Meyer-Vernet N., Issautier K. 1998, Electron temperature in the solar wind: generic radial variation from kinetic collisionless models, *J. Geophys. Res.* **103**, 29,705

[25] Meyer-Vernet 1999, How does the solar wind blow? A simple kinetic model, *Eur. J. Phys.* **20**, 167

[26] Meyer-Vernet N. 2001, Large scale structure of planetary environments: the importance of not being Maxwellian, *Planet. Space Sci.* **49**, 247

[27] Neugebauer M. 1997, Pioneers of space physics: a career in the solar wind, *J. Geophys. Res.* **102** 26887

[28] Neugebauer M. and C. W. Snyder 1962, The mission of Mariner II: preliminary observations, *Science* **138** 1095

[29] Olbert S. 1981, In *Plasma Astrophysics*, ed. T.D. Guyenne and G. Levy, ESA SP-161, p. 135

[30] Parker E. N. 1958, Dynamics of the interplanetary gas and magnetic fields, *Ap. J.* **128** 664

[31] Parker E. N. 1963, *Interplanetary dynamical processes*, Interscience Pub., Wiley

[32] Parker E. N. 1997, in *Cosmic Winds and the heliosphere*, ed. by J. R. Jokipii et al., University of Arizona Press, Tucson, p. 3

[33] Parker E. N. 2001, in *The Century of Space Science*, ed. by J. A. M. Bleeker et al.,Kluwer, p. 225

[34] Parker E. N. 2001, A critical review of sun-space physics, *Astrophys. Space Sci.* **277** 1

[35] Pierrard V. et al., 2001, Collisionless solar wind in a spiral magnetic field, *Geophys. Res. Lett.* **28**, 223 (2001)

[36] Pierrard V. et al. 2001b, Self-consistent model of solar wind electrons, *J. Geophys. Res.*, **106**, 29305

[37] Scudder J. D. 1992, On the causes of temperature change in inhomogeneous low-density astrophysical plasmas, *Ap. J.* **398**, 299

[38] Scudder J. D. 1992b, Why all stars should possess circumstellar temperature inversions, *Ap. J.* **398** , 319

[39] Shizgal B. 1993, Mathematical and numerical methods in gas dynamics and fluid dynamics, *Institut d'Astronomie et de Géophysique Georges Lemaître* **73** (LLN, Belgium)

[40] Shoub E. C. 1983, Invalidity of local thermodynamic equilibrium for electrons in the solar transition region, *Ap. J* **266**, 339

[41] Velli M. 2001, Hydrodynamics of the solar wind expansion, *Astrophys. Space Sci.* **277** 157

[42] Zouganelis I. et al. 2004, A transonic collisionless model of the solar wind, *Ap. J.*, **606**, 542