**Notes about misinterpreting some plasma properties**

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## Purposes of this Note

This Note summarizes some physical properties of the solar wind that might be relevant to a question sent to me from my friend Paul Gilster on November 16, 2014. Question regards the so-called Bolonkin objection (henceforth called the objection, for short), which is contained in his paper entitled Theory of Space Magnetic Sail Some Common Mistakes and Electrostatic Sail, AIAA-2006-8148 http://arxiv.org/ftp/physics/papers/0701/0701060.pdf .
I do not know whether Mr. A. Bolonkin revised his considerations, which appeared in AIAA-2006-8148. Anyway, I am concerned in no way with his work. My answer is chiefly for Mr. Gilster and his readers.

I divided this Note into five parts plus a very short bibliography: the first one regards some basic properties of plasma; the second one reports a few important features of the solar wind (SW), whereas the third one briefly regards how it interacts with magnetic objects. The fourth section deals with the specific aspects of AIAA-2006-8148 regarding the objection. The conclusions are in the fifth section. The technical level of the Note will be kept as simple as possible, but hopefully strict to help the reader to evaluate the objection. Items [1−7] of the Bibliography may help the reader deepen what is discussed in the following sections.

## 1. A Few Words about Plasma

For simplicity, let us consider a gas and in some way increase its temperature. If the temperature is sufficiently high, some molecules of this gas ionize and then dissociate; if we continue to put energy into the fluid, atoms eventually ionize, and we get a sea of unbound electrons. We have got an ionized gas, either partially or completely, which can be used for many and various purposes in the modern life. This fluid consists of many species, namely, ionized atoms, electrons, ionized molecules, and also neutral atoms provided that the temperature is not very high. However, we have not yet obtained plasma, in general.

However, if the characteristic scale of such fluid mass is larger than the length - called the Debye length – say, $l_D$, then (according to Langmuir and the current plasma physics researchers) the considered ionized gas behaves as *plasma* (often inappropriately named the fourth state of matter). This $l_D$ describes the simultaneous and combined shielding actions of ions and electrons. Let us spend some words about this length as it might be a source of misunderstanding.

Suppose you build a probe capable of measuring the charge of a volume $v$ containing ionized gas such that $v \ll {l_D}^3$. If you make measurements of the charge of $v$ during various (disjoint) time intervals $\Delta t_j$ $(j = 1..n)$, then you will read values (of charge) significantly different from zero and between them, in general. In other words, the probe senses charge variations inside the chosen volume; such changes are to be ascribed to the thermal fluctuations of the particles. What happens if one measures the charge of a volume $V \gg {l_D}^3$ ? The observer will detect a charge very close to zero, no matter when the measurements are made or where the measurement volume is chosen. Said equivalently,

**Property-1a**: Plasma exhibits a *quasi*-neutral behavior *at large scales*.

Let us now think of (slowly) inserting a charged test particle $Q$, e.g. a positive ion, into this sea of uniform and homogeneous density (where thermal gradients are virtually zero). The plasma will react by surrounding the $Q$ with a negative cloud while the resident positive ions are repelled farther. This charge displacement results in a (small) electrostatic potential, which decreases the effect of the perturbing charge. As a point of fact, as seen from a sufficiently distant probe, $Q$ and its cloud are measured (not $Q$ solely); thus, charge shielding is observed. It is possible to prove that the shielding distance is just $l_D$ .

In the above reasoning, a "team" behavior of the plasma particles is implicit, namely, they respond *collectively* to perturbations: electrons and ions work together to vanish the perturbing effect. In plasma, various particle species live together with their thermal "agitations" and under the action of internal and external fields. In general, one should not make the mistake to consider one species, in a certain problem, and simultaneously neglect the other ones.

**Property-1b**: Plasma particles respond to a perturbation *collectively*.

**Note-1**: Property-1a does not exclude electric fields in plasma, of course. Just only as an example, the highly conductive plasma such as the solar wind has a (weak) electric field – observed in a heliocentric inertial frame. Its norm is approximately equal to the product of the wind bulk speed by the magnetic induction.

**Property-2**: Plasma lives much longer than the reciprocal of the (electron) plasma frequency. This is another aspect of the collective behavior of plasma. When a plasma is perturbed (no magnetic field), the heavy ions will take a long time for reaching a new equilibrium configuration. In contrast, the electrons promptly oscillate and reach the new equilibrium.

**Remark-1**: Three quantities are particularly important in the plasma study: the density of particles, the temperatures of the various particle species, and the steady-state magnetic *induction* field.

**Note-2**: About the official nomenclature, according to the Naval Research Laboratory (NRL, USA), **B** denotes the magnetic *induction* field (measured in tesla [T]), whereas **H** is the general symbol for the magnetic *intensity* field (measured in ampere-turn/m [A/m]). The reader can refer to the general NRL Plasma Formulary 2013. 'Magnetic field' with no other attribute is meant as **B**. This is the field that, cross multiplied by the velocity of a moving charge, induces a vector force (called the electromagnetic or Lorentz force) on the charge itself. This force is observed in the same reference frame where the charge motion is described.

## 2. Some Aspects of the Solar Wind

Solar Wind (SW) is the dynamical expansion of the solar corona, which cannot be confined like a hydrostatic neutral atmosphere. More specifically, the SW is the plasma that permeates the heliosphere, the (variable) sizes of which are determined by the interaction of the solar wind with the local interstellar wind.

*Solar Wind belongs to the family of the weakly-coupled classical plasmas, the vast majority of the ones in the Universe.*

Let us mention some plasma properties – which are of concern here - of the solar wind as observed far from the solar corona, say R > 10 solar radii ($R_s$ ), reminding the reader that 1 AU = $215\ R_s$.

(a) SW is supersonic (and superalfvénic).

(b) SW consists chiefly of two components:

  1. The slow wind, which originates from low-latitude coronal holes, with bulk speed typically in 250-400 km/s range;
  2. The fast streams, coming from polar coronal holes (around the minimum in a solar cycle), with bulk speed usually in the 700-800 km/s range (though speeds higher than 1,000 km/s have been observed).

(c) SW exhibits very high electric conductivity: therefore, it transports the field lines of the Heliospheric Magnetic Field (HMF); equivalently, the field lines are *frozen in* the plasma.

(d) SW's bulk kinetic energy density is much higher than the magnetic energy density.

(e) SW is *collisionless* plasma, namely, inter-particle collisions are very rare.

(f) At distance $R$ [AU] from the Sun, the order of magnitude of the Debye length may be roughly expressed as $l_D \sim 7R^{0.5}$m, namely, ~7 meters at 1 AU.

**Remark-2:** at lengths much larger than $7R^{0.5}$ – like the supposed radius of a magsail current loop – the solar wind is neutral; only a tiny deviation from the exact neutrality may occur statistically.

**Problem-1**:

Suppose that, at a certain distance from the Sun, the Debye length of solar wind is ~10 meters, according to property-(f), with a number density of (10 protons +10 electrons)/cm$^3$. We would like to know what may be the charge imbalance (between ions and electrons) if we think of building a space device (sensing this plasma), of a characteristic size of 10 km. Well, the quasi neutrality requires a charge density $q = e(n_p - n_e),\ |q| < 10^{-6} e n_e$ [C/m$^3$] or ten electrons (or ten protons) in a cube of 1-meter side! (We neglected the rare ions heavier than protons in the solar wind and used the usual symbol $e$ for the absolute value of the electron charge). Note that $q$ is *not* a deterministic charge density, but a *statistical* quantity with mean value equal to zero.

Yet, when the solar wind *as a whole* impinges orthogonally on a surface of characteristic linear size ~ 10 km, the overall current density would amount to Q < $10^{-6}$ x (10 x $10^6$ [m$^{-3}$]) x $e$ [A s] x W [m s$^{-1}$], where W is the *bulk* speed of the wind. Thus, we obtain Q < 10 x $e$ W [A/m$^2$], where we used the International System (SI) units (in particular, 1 Coulomb = 1 Ampere x 1 second, $e$ = 1.602 $10^{-19}$C).

If we had made the mistake to consider either the electron or the proton flow in the plasma-surface interaction, then we would have got a charge flux of $10^7$ x $e$ W [A/m$^2$]!!

Please *note* that such current density is the length of a vector, namely, $\mathbf{Q} = q\,\mathbf{W} = e(n_p - n_e)\,\mathbf{W} \cong 0$, due to thermal fluctuations affecting the charge neutrality of the volume $V$, and should not be confused with the actual plasma current density **J**($t$), which is the sum of the current densities of every charged particles at time $t$. Again, the mean value of **Q** is zero.

Still more specifically, suppose that the surface is a circle of radius 50-km radius and W=400 km/s; if we go on (erroneously) thinking of the plasma as two independent unbalancing flows, then the electron (or proton) current hitting the surface would be $10^7$ x $e$ W [A/m$^2$] x π 50,000$^2$ [m$^2$] ≅ 5,033 A. Actually, according to the right plasma view of quasi-neutrality as above explained, the actual upper limit of this impinging current amounts to 5,033/10,000$^2$ A = 50 μA. This is because the ratio of the circle size on the Debye length takes on (2 x 50,000)/10=10,000 for this case. We will remember this example later below.

**Remark-3**: Why in the literature of particle-beam propulsion do authors consider a plasma flow launched toward a field sail, instead of a high current of like particles? For getting a significant propulsive effect (i.e. high delta-V), one should deliver a beam exhibiting high mass flow rate and high speed or, equivalently, a high dynamical pressure acting for a long time. If the driving beam were a high current of like particles, then it would spread greatly and only a small fraction would reach the sail. Thus, even though the field of the sail interacts with the incoming charged particles, quasi-neutrality (at large scales ) is necessary to focus the beam on the sail field. If the sail field senses mainly one species among those ones of the incoming plasma, like for the electric-sail, then also a charge balance device has to be designed.

A remarkable property of the solar wind is represented by very large fluctuations. Plenty of SW-related quantities fluctuate, as measured by the instruments onboard many spacecraft. Turbulence characterizes the solar-wind plasma. From a propulsion viewpoint, i.e. for a solar-wind to push a sail efficaciously, both dynamical pressure and bulk speed are of basic importance. Figure 1 shows how these have been changing since 2000, in particular. In the caption, we wrote the related units in boldface.

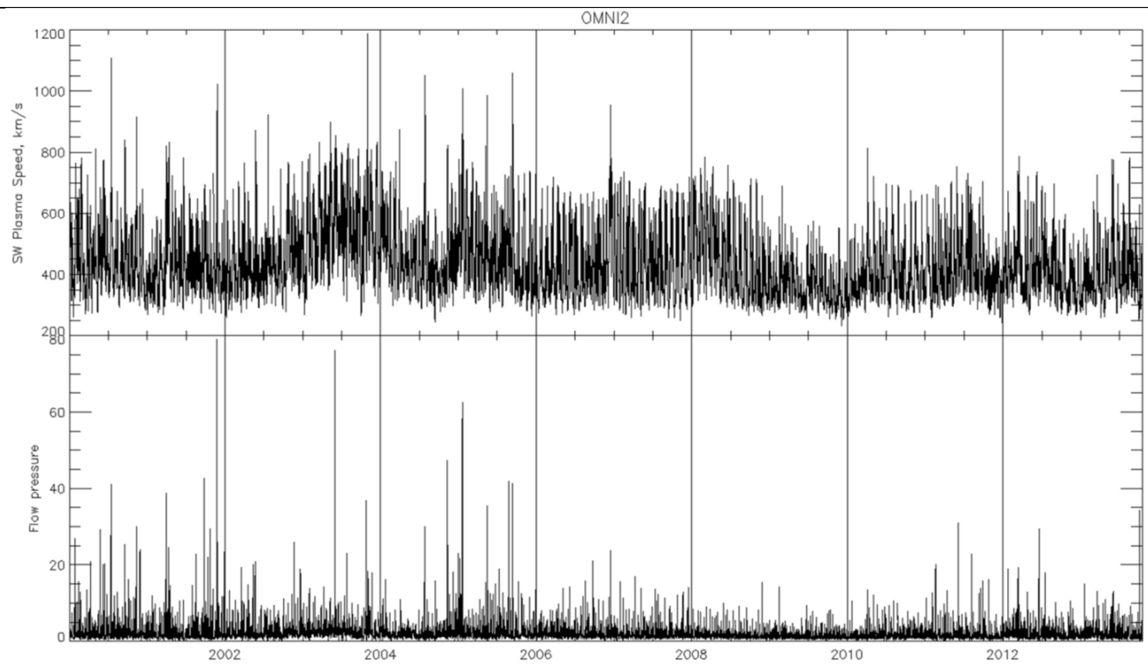


**Fig. 1** Observed time-series of the solar-wind's plasma speed (**km/s**) and dynamical pressure (**nPa**) in the interval 2000-2014 (Courtesy of NASA, http://omniweb.gsfc.nasa.gov/).

■ The statistical analysis of the time series shown in Fig. 1 tells us that, in particular, the dynamical pressure has a standard deviation almost equal to the mean, a big problem for magnetic sails and similar concepts.

| Solar wind* | Symbol | Value at 1 AU | units |
|---|---|---|---|
| Number density | $n_p \approx n_e$ | 6.1 | $cm^{-3}$ |
| Magnetic induction | $B$ | 4.5 | nT (or $10^{-5}$ G) |
| Temperature | $T_p \approx T_e$ | $1.1\times10^5$ (9.5) | K (eV) |
| Plasma beta | $\beta$ | ~ 2 | |
| Momentum flux on magnetic pressure ratio | $\beta_{dyn}$ | ~ 200 | |

*Time series of solar wind data from NASA OMNIWeb interface

$$\beta = \frac{P_{gas}}{P_{mag}} = \frac{n\,k\,T}{B^2 / 2\mu_0}$$

$$\beta_{dyn} = \frac{\rho V_{bulk}^{\;2}}{P_{mag}} = \frac{\left(m_p\,n_p + m_e\,n_e\right) V_{bulk}^{\;2}}{B^2 / 2\mu_0}$$

**Tab. 1** Averages of the number density, temperature, and magnetic induction of the solar wind in cycle 23 at 1 AU from the Sun. Also, the plasma beta and the ratio of the dynamical pressure (or the momentum flux) on the magnetic pressure have been computed. Note that $n = n_e + n_p \cong 2n_e$ . The meaning of the other symbols is standard.

Relatively to the solar cycle #23, the averages applied at 1 AU are reported in Tab. 1. One can see that the magnetic induction field – the lines of which are frozen in the plasma flow – is remarkably low (from a propulsion viewpoint). (For comparison, one should remember that the magnetic induction at the Earth equator takes on about 0.3 gauss or $3 \times 10^{-5}$ tesla). The plasma beta – an important dimensionless quantity in plasma physics – is of order of unity, namely, the solar wind exhibits a gas pressure comparable with the magnetic pressure. In contrast, the dynamical pressure is well higher: SW is thus momentum-dominated plasma. This is at the basis of solar-wind sail concepts, namely, this is the common principle all of them have.

Next section describes some features of the interaction between the solar wind and objects in space.

## 3. How does solar wind interact with objects in space?

Though the interactions are various and complicated, nevertheless we try to figure out some general guidelines. There are three main properties of space objects (either natural or artificial) that one has to consider in describing the solar wind impinging on them:

i. the object type and its environment;
ii. the object size relatively to the main scales of the solar wind;
iii. the object's magnetic induction field, if any.

Out of many examples of strong diversity, we mention insulating bodies with no atmosphere (like the Moon), conducting and insulating bodies with no atmosphere (like a future large solar-photon sail), non-magnetized objects with ionosphere (like Venus), and magnetized objects with ionosphere (like the Earth). Since we are concerned with large magnetic sails here, we will shortly focus on the main features of the interaction between the solar-wind plasma and a body (typically a planet) endowed with a magnetic dipole-like field

First, we have to compare the typical size of such an object to the electron and ion gyro-radii. If it is larger than these, and the planet's magnetic moment is sufficiently high, then the solar wind sees a large volume (much larger than the body's physical one) filled by magnetic field. For simplicity of description, let us assume that the SW mass density is $\rho$ and has a bulk speed **V** orthogonal to the planet's magnetic moment $\boldsymbol{\mu}$. Because SW is supersonic, a shock wave is generated on the sunward side, many radii from the planet surface. Just after the shock (which typically is some proton gyro-radius thick) the plasma becomes subsonic and slows down smoothly until a *stagnation* point is achieved. In the neighborhood, the plasma is diverted and wraps around the planet's magnetized volume, which now has been compressed. The diverted wind moves in a region (the *magnetosheath*) determined by the bow-shock surface and another surface called the *magnetopause*. What determines the magnetopause? Always remembering the plasma's collective behavior, at the stagnation point the SW dynamical (or ram) pressure is balanced by the total pressure due to the planetary magnetic field *at that distance*. A more detailed analysis by magnetohydrodynamics (MHD, one of the plasma mathematical descriptions) shows that the “nose” of the magnetopause is located where the following (approximate) equation holds:

$$\frac{7}{8}\rho V^2 \cong \left(2B_\mu\right)^2 / 2\mu_0 \ , \qquad B_\mu = \frac{\mu_0}{4\pi}\frac{|\boldsymbol{\mu}|}{r_m^3} \qquad (1)$$

In equations (1), the planetary field (along the magnetic equatorial plane) $B_\mu$ is supposed to scale as a pure dipole, $r_m$ denotes the minimum distance of the magnetopause from the planet’s center, and $\mu_0 = 4\pi \times 10^{-7}$ in SI units, denotes the permeability of vacuum. The first of (1) takes into account the downstream side of the bow shock and the fact that – by the Ampère law – the magnetopause has to carry a current sheet, which practically doubles the field just inside it. For the Earth, we have $|\boldsymbol{\mu}_{earth}| \cong 8\times 10^{22}\ \mathrm{Am}^2$. Figure 2 shows (approximately) how the Earth magnetosphere is re-configured; actually, it is continuously modified by the solar wind. From Fig.1, using a low dynamic pressure of 8 nPa, eqns.-1 give us $r_m \cong 11.8 r_\otimes$ where $r_\otimes$ denotes the Earth’s equatorial radius (or about 6378 km). Thus, at the magnetopause nose, we have $B_\mu \cong 18.8\ \mathrm{nT} = 188\ \mu\mathrm{G}$. As the ram pressure increases, the magnetopause gets nearer the Earth.

Equation (1) comes from *macroscopic* considerations about the interacting solar wind; the particle or microscopic view would be much more complicated – unless justified by, for instance, some important feature not otherwise explained.

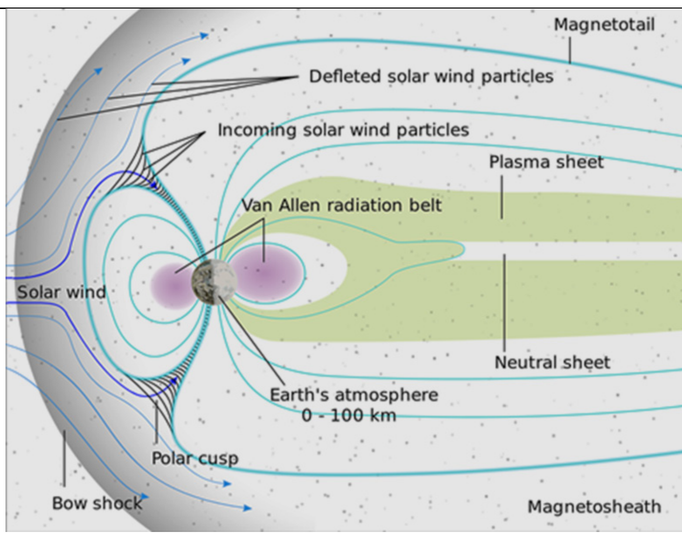


Figure 2. Some key aspects of the Earth magnetosphere under the solar-wind flow (adapted from the original picture by Aaron Kaase).

Figure 2 shows some peculiar aspects of the Earth’s magnetosphere (continuously) shaped by the solar wind. The planet is protected by the solar wind flow by its intense magnetic field (compared to that of the solar wind). However, minor particle flows hit the Earth ionosphere through the so-called polar cusps. Under particular conditions, such flows could be so strong as to cause extensive damage to (unprotected) terrestrial telecommunication systems and electric-energy transport lines.

**Remark-4**:

One may object that a plasma permeated by a magnetic induction field behaves as a diamagnetic object, i.e., the magnetic field coming from particle cyclotron motion opposes the background field where the particle is revolving. However, once again, one should view the plasma phenomena as collective evolution. Diamagnetic current can arise, but this phenomenon is a direct consequence of *pressure gradients orthogonal to the magnetic field*, and has <u>no meaning</u> in the context of single particle description of plasma. Please note that gradient of pressure encompasses gradient of temperature and/or the inhomogeneity of the *guiding* centers. This pressure includes the magnetic pressure and the *gas* pressure (not the dynamical one!) originating from the distribution of the particle velocity components orthogonal to the magnetic field. Various drift phenomena, including the diamagnetic drift, have been studied in detail for finding agreement between the macroscopic plasma description (essentially, the MHD models) and the single particle description.

Going back to the solar wind impacting on a magnetic volume (like that of a magsail), the interaction will evolve similarly to that characterizing a planet endowed with a magnetic field (at the surface) much higher than the solar-wind field.

## 4. Specific Comments on paper AIAA-2006-8148

The validity or non-validity of the objection made by Bolonkin in his paper may be summarized in the meaning of formulas (2), in particular

$$i = \pi R^2 \, q \, N \, V \qquad \text{(B1)}$$

that here we renamed by (B1) (with B standing for Bolonkin). According to Bolonkin, "$i$ is the electric current of the solar wind electrons", whereas $R$ denotes the radius of the "MagSail ring", $N$ is the number density at 1 AU, and V is the bulk speed of the solar wind at 1AU. Bolonkin took on 400 km/s for $V$, "$10^7$ 1/m$^3$" for $N$, 50 km for $R$, and carried out "$i$=5024 A". From these values, the reader can infer very easily that he put $q = 1.6\ 10^{-19}\ coulomb$, namely, the elementary charge $e$. In words, he considered a volume of 1 cubic meter endowed with charge $10^7 e$ moving at speed $V$.

This is the *first* conceptual pitfall! In the above **Problem-1** we explained that the *statistical* current impacting on the magsail loop of 50 km is 50 μA, *at most*. The plasma is *one* entity in its response to external disturbance. In any case, this statistical current is not utilizable because fluctuation time is very, very short, and its mean value vanishes.

Now, let us emphasize the *second* conceptual pitfall coming in the Bolonkin paper. According to the above Section 3 (that agrees with observations by many spacecraft), the solar-wind plasma macroscopically compresses the external-**B** region via its dynamical (or ram) pressure, which does **not** depend on particle charges!

Section "Theory" in the Bolonkin paper repeats the same mistakes in his formulas (3). In addition, when the MagSail (MS) interaction with the solar wind brings about a bow-shock and a magnetopause downstream, the thrust on the MS-body comes from the integration of the ram pressure distribution in the flow around the magnetopause; therefore, also equation-6 of the Bolonkin-paper is far from reality for a magnetized body. His conclusions in that section can be then disregarded.

To sum up, the objection made by Bolonkin to "hundreds of researchers, professors at famous universities, audiences of specialists, . . ." has **no** physical foundation, *absolutely* **no** basis.

## 5. Final Considerations

The actual feasibility of any magsail concept or, more recently, magnetoplasma sail concepts does not depend only on their technological implementation, which are objectively very difficult. Before that, there is another conceptual and practical problem. Let us explain it shortly.

The flight design of any space mission relies on the implicit assumption that we are able to calculate a set of *deterministic* transfer trajectories (baseline, nominal, backup, etc.) with errors (the error ellipsoids) sufficiently small for the desired targeting. Now, the original concept of magnetic sails and subsequent versions, the magnetoplasma concept and its variants, all suffer the same drawback: the source of external momentum to be transferred to the space-vehicle *fluctuates remarkably*. Magnetic and electric sail propulsion concepts should be investigated not as made so far via deterministic equations. Instead, *stochastic* differential equations should be used with a number of controls higher than one for trying to use the wind fluctuations. We remind the reader that the solar wind exhibits slow flows, fast streams, and a number of interplanetary structures that will add accelerations to a real wind-sail vehicle. So far, such aspects (to the author's knowledge) have been ignored by the wind-sail supporters, presumably because of their considerable mathematical complexity.

The reader may receive a very fine and quantitative impression by visiting the Australian website http://www.ips.gov.au/Solar/1/4, where solar-wind information is reported every 10 minutes. For instance, at the time of writing these lines here (2014-12-27 12:52 UTC), the following data (based on the NASA ACE spacecraft) could be read:

Bulk speed = 438 km/s
$B_Z$ = -1 nT
Number density = (4 protons + 4 electrons)/cm$^3$
Dynamical pressure = 0.64 nPa

and ten minutes later:

Bulk speed = 441 km/s
$B_Z$ = +2 nT
Number density = (3 protons + 3 electrons)/cm$^3$
Dynamical pressure = 0.49 nPa

Comparing them with the averaged figures of Tab. 1 gives the reader an even "pallid idea" of what solar wind fluctuations could mean for propulsion.

***Personal note***:
Because of the very low fluctuations of the Total Solar Irradiance (TSI, 0.10–0.15 percent of the mean value), and the fact that the TSI pressure (or the solar-radiation pressure) is three orders of magnitude higher than the ram pressure of the solar wind, in 1992 this author switched from solar-wind-based propulsion studies to active research into solar-photon-based propulsion. The success of JAXA IKAROS, NASA NanoSail-D2, and the current projects at NASA and JAXA, together with the extensive research at prestigious universities of USA, Japan, Italy, UK, Germany, and China and have been showing that a quality jump in space transportation and mission range pertains undoubtedly to the near/medium term Solar-Photon Sailing (SPS), even though a future smart utilization of the solar wind might not be excluded, in general. The most recent publications on SPS can be found in the items [8–10] of Bibliography. There, one can read about peculiar properties of SPS that the solar-wind propulsion concepts do not have because the interaction of light with a material surface is of quite a different nature.

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