3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Parameters of Interstellar Medium in the External Bow Shock Region

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Abstract

The interstellar medium and solar wind interacting; a complex structure called the heliosphere shock layer is formed. The heliosphere shock layer is multicomponent. The main difficulty of the heliosphere boundary modelling is the multicomponent origin of both the interstellar medium and solar wind. One of the most important sources of information on physical processes at the heliosphere boundary are the Voyager 1 and 2 spacecrafts. In our previous studies, we have obtained important relationships that enable calculating the key parameters at transition through the bow shock front. We can apply important relationships from our papers that enable calculating the key parameters at transition through the external bow shock front. There is bound to be a huge time-lag before Voyager spacecrafts can travel through the interstellar space medium, and we could already be able to learn this medium properties, because the parameters behind the shock front are well-determined by the known laws and relationships. Parameters of the medium behind the front of the external bow shock contain much information about physical parameters ahead of the external bow shock front. Any follow-up mission to the heliospheric boundary that would be worth the effort and that a space agency would be willing to fund, which could carry the instrumentations, almost for sure would be an interstellar probe that continues into the interstellar medium proper.

1. Introduction

The interstellar medium and solar wind interacting; a complex structure called the heliosphere shock layer is formed. The heliosphere shock layer is multicomponent. In this area, essential roles belong to protons and electrons of the solar wind and interstellar medium, trapped ions, interstellar hydrogen atoms, heliosphere and interstellar magnetic fields, and galactic and anomalous cosmic rays components. In the concept accepted at the moment, the shock layer structure is described by two shocks and a contact surface [1]. We shall note that according to some papers, in the presence of interstellar magnetic field strong enough, there might be no external bow shock, since the Mach-Alfven number in the interstellar medium is less than 1. In case of partially-ionized interstellar medium, neutral atoms interact with the disturbed plasma component by recharging. The recharge process leads to formation of a so-called "hydrogen wall" – region in front of the heliopause proximal to the interstellar medium with increased concentration of interstellar atoms. The hydrogen wall is composed of secondary atoms formed resulting from recharging of primary interstellar atoms on decelerated interstellar protons.

One of the most important sources of information on physical processes at the heliosphere boundary are the Voyager 1 and 2 spacecrafts. As early as in 2011-2013, new unique data about heliosphere boundary from the Voyager-1, 2 spacecrafts became available. Starting from spring 2011, the Voyager-1 spacecraft has been recording a practically zero speed of the solar wind and during some periods its radial velocity was negative [3]. In August 2012, Voyager-1 revealed a dramatic reduction in fluxes of anomalous cosmic rays component, and a simultaneous increase of cosmic rays galactic component fluxes (Stone et al., 2013) and increased value of magnetic field induction from ~ 0.2 nT to ~ 0.4 - 0.5 nT. However, the magnetic field vector direction has not changed, coinciding with the direction of heliospheric magnetic field. In April-May 2013, the PWS instrument has detected 2.6 kHz radiation. Analysis of this radiation enabled scientists to get a rough estimate of electron density at the generation point of this radiation, which is ~ 0.08 cm^{-3}, this exceeds considerably the solar wind density. The analysis of the gradient the frequency varies with, depending on distance, led to the conclusion that Voyager-1 crossed the heliopause on August 25, 2012 [2]. According to [11], estimates of parameters of plasma in the local interstellar medium indicate that the speed of the interstellar wind is most likely less than both the fast magnetosonic speed and the Alfven speed (but greater than the slow magnetosonic speed). In the study [11] the authors found that the bow shock would take a different form, what is known as a “slow bow shock”. The authors say that the Voyager 1 probe is expected to pass through the bow shock well after it leaves the heliosphere, although by then, its battery will be long dead [11].

The main purpose of the paper is to study physical processes at the heliosphere boundary (the region of the solar wind interaction with the interstellar medium) by means of theoretical analysis of some experimental data.

With the Voyagers and IBEX returning many new puzzles, this paper could be interesting because it might address in a complementary way questions that are hotly debated in the heliophysics community.

2. Basic equations

Baranov et al. (1970) [1] proposed a structure with two shocks, which is now the basis of a concept of the heliosphere shock layer. Heliopause, which is a tangential discontinuity surface, separates the interstellar medium charged component from the plasma of the solar wind. Because both the solar wind and interstellar medium are supersonic streams, two shocks are formed when flowing around the heliopause: heliospheric shock and external bow shock.

The main difficulty of the heliosphere boundary modelling is the multicomponent origin of both the interstellar medium and solar wind. It is known that the local interstellar medium includes at least five components imposing dynamic effect on the structure of the interaction region: plasma (protons, electrons, helium ions), hydrogen atoms, magnetic field (interstellar), galactic cosmic rays, interstellar dust. The plasma component in the heliosphere consists of the solar wind particles (electrons, protons, alpha particles, etc.), as well as the trapped ions and anomalous components of cosmic rays. For adequate multicomponent shock layer modelling, we have to choose appropriate theoretical description for each of the interstellar medium and solar wind components. Both the interstellar medium charged component (protons, electrons, helium ions) and the solar wind charged component (electrons, protons, α-particles) can be adequately described within the magnetohydrodynamic approximation.

Let's also address other key parameters. We can choose the system of coordinates as a base beginning at the center of the Sun (Figure 1). I shall use local coordinate system (l, k, n). I will follow our previously published papers [5], [6-9] in the approach to the external bow shock description.

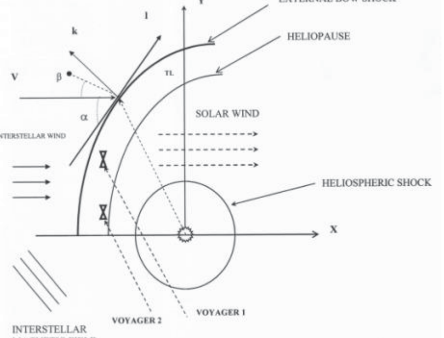

Figure 1. A sketch of the external bow shock, of the Transition Layer (TL), heliopause. The location of the orthogonal coordinate system (X,Y) with the origin in the Sun's center and the location of the local coordinate system (l, k, n).

I assume a spherically symmetric heliospheric bow shock like for the Earth, while there is hypothesis, since the Voyager passages of the termination shock and through IBEX observations, that the heliosphere might be strongly distorted. I need to make such simplification to solve the problem analytically.

The correspondences of the parameters in front of and behind (in TL) the external bow shock will be the following. The plasma density is defined as:

$$\rho_2 = \rho_1 \cdot \delta; \;\; \delta = \frac{\gamma + 1}{\gamma - 1};$$

One can derive the gas pressure:

$$p_{2g} = 2\rho_1 V_1^2 \frac{\sin^2(\alpha)}{\gamma + 1}$$

The tangential velocity component will be:

$$V_{2l} = V_{1l} = V_1 \cos(\alpha)$$

The normal velocity component will be:

$$V_{2k} = \frac{V_{1k}}{\delta} = V_1 \frac{\sin(\alpha)}{\delta}$$

The vertical component of the magnetic field will be:

$$B_{2n} = B_{1n} \cdot \delta$$

The tangential component of the magnetic field is defined as:

$$B_{2l} = B_{1l} \cdot \delta = B_{1eq} \cdot \delta \cos(\alpha + \beta)$$

The normal component of the magnetic field is defined as:

$$B_{2k} = B_{1k} = B_{1eq} \sin(\alpha + \beta)$$

In these equations, numbers 1, 2 correspond to the interstellar medium and the transition layer, respectively; γ – is the adiabatic exponent; α – is the angle between the tangent to the external bow shock front and the X-axis; β – is the angle between the direction of the interstellar wind velocity and the projection of the magnetic field onto the equatorial plane B_{1eq} (see Figure 1).

Besides, knowing numerical values of parameters in the equations, we can set various values of γ. Thus, one can obtain the additional information on properties of medium.

We should note that owing to final curvature of the external bow shock front surface there appears a force (additional) of magnetic tension: $F_n = (B\nabla)B_n/4\pi$. This force must be put in equilibrium by additional Ampere force: $j^*_\tau B_l/c$; here j^*_τ is density of additional current: $j^*_\tau = c \cdot (\partial B_n/\partial l)/4\pi$. We can find the density of the basic current j_τ: $j_\tau = c\,(\delta - 1)B_{0l}/d$, where d is front thickness. Since $d \ll X_h$, X_h - is the distance from the origin of system of coordinates to the shock front, then additional electric current is much less than basic one. The effect of curvature should not be taken into account, at least until δ notably differs from 1. We can obtain the equation for the gradient of plasma pressure and the inertial force behind the external bow shock front (i.e. in the transitional layer):

$$\frac{dP_{2g}}{dl} = \frac{2\rho_1 V_1^2}{\gamma + 1}\frac{d}{dl}\sin^2\alpha; \;\; \frac{\rho_2}{2}\frac{dV_2^2}{dl} = -\frac{\rho_1 V_1^2(\delta^2 - 1)}{\delta}\frac{d}{dl}\sin^2\alpha; \quad (1)$$

where $\delta = (\gamma+1)/(\gamma-1)$.

Thus, substituting these expressions into the equation for current density, we can obtain:

$$j = \frac{c}{B_2^2}\left[B \times \left(\nabla p_g + \rho \frac{\nabla V^2}{2}\right)\right]; \; j_{2k} = c\left(\frac{dP_{2g}}{dl} + \rho \frac{dV_{2l}^2}{dl}\right)\frac{B_{2n}}{B_2^2}$$

; or

$$j_{2k} = -\frac{2B_{1n}}{(\gamma^2-1)B_2^2} c\delta\rho_1 V_1^2 \frac{d}{dl}\sin^2\alpha, \qquad (2)$$

where j_{2k} – is an electric current, which flows across the transition layer;

$$B_2^2 = B_{1n}^2\delta^2 + B_{1eq}^2\left((\delta^2+1) - 2(\delta^2-1)\sin\alpha \cdot \cos\alpha\right); \; (3)$$

The surface density of the current, flowing in the transitive layer along it, will be the integral from j_l across the layer from heliopause up to the external bow shock: $J_l = cB_{1n}\delta \frac{P_g(bs) - P_g(h)}{B_2^2}$; in this expression $P_g(bs)$ and $P_g(h)$ are gas pressure under the external bow shock and on the heliopause, respectively.

One can obtain the important relationship for the physics of the shock layer, in which the hydrodynamic and electrodynamic quantities are in the left and right sides of this equation, respectively:

$$V_e \nabla P_g^e + V_i \nabla P_g^i = Ej - \rho(V_i - V_e)\frac{dV_i}{dt},$$

where e – index for electrons; i – index for ions.

A normal component of velocity of medium on border is equal to zero; hence, the flow of the number of particles, transferable by the electric current, will be $N_{TL} = j_{2k}/2e$; e – is the charge of electron.

We can also assume, that the front form of the external bow shock is given, as well as the form of heliopause. Heliopause may be well approximated by biaxial hyperboloid. One can assume that both heliopause and external bow shock are paraboloids of rotation and differ only in various distances to the nose point. Such step is connected with the fact that the form of heliopause and especially forms of the external bow shock front differ little from paraboloids of rotation, at the same time all analytical expressions drastically become simpler (see corresponding equations in [4]). Parabola is some compromise between ellipsoid (closed model) and hyperboloid (open model). Further, we can apply important relationships from our papers that enable calculating the key parameters at transition through the external bow shock front.

The system 'external bow shock-TL-heliopause-heliospheric shock' is unique plasma laboratory. Thus, if we knew such parameters e.g. as plasma density, plasma pressure, gas pressure gradient, components of magnetic field, electric field, fluxes of particles in the transition layer, we would be able to determine key parameters in front of the external bow shock.

3. Discussion of results

We can use the obtained important expressions and relationships to determine the interstellar medium parameters. It is known that the Voyager-1 spacecraft was equipped with the following scientific instruments: UV spectrometer, interference IR spectrometer, photopolarimeter, low-energy charged particle detector, instrument to determine radio waves of planets, instrument to determine waves in plasma, magnetometer to measure weak magnetic fields, magnetometer to measure strong magnetic fields, cosmic ray detector, and plasma detector. If Voyager-1 was equipped with a broader range of measuring instruments, we could have already provided estimations of the interstellar medium key parameters, using the above mentioned relationships, equations. In other words, if we knew the parameters in the transition layer, we would be able to calculate them ahead the external bow shock front. Thus, we could have now made preliminary conclusions on the behind-the-heliosphere medium, i.e. in the interstellar space. It should be noted that even if the Voyager-1,2 spacecrafts were initially equipped with a great set of measuring instruments, they would need to be protected against cosmic radiation. Otherwise, cosmic ionizing radiation would destroy almost all the electronics inside the apparatus on their way out of the solar system.

I have provided the specific equations. We have all the essential equations to calculate the parameters; we have a developed mathematical apparatus to convert the relevant physical values at transition through the bow shock front, a set of computer programs with the user interface; two spacecrafts are in the appropriate region, but they do not have the necessary measuring instruments. The proposed study would significantly reduce the current uncertainties concerned with the structure of the heliosphere shock layer behind the external bow shock, and with measuring the parameters of the local interstellar medium that surrounds the solar system.

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