URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Fundamentals of Bow Shocks for Astrophysical Application

P.A. Sedykh
Irkutsk National Research Technical University. 83, Lermontov str., 664074, Irkutsk, Russian Federation;
e-mail: pvlsd@mail.ru

Abstract

The system 'external bow shock-transition layer-heliopause-heliospheric shock' is unique plasma laboratory. 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. 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; two spacecrafts are in the appropriate region, but they do not have the necessary measuring instruments. This essential set of measuring instruments that would enable us to obtain a series of numerical estimates of key parameters. There is bound to be a huge time-lag before Voyager spacecraft 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.

1 Introduction

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 for the external bow shock

Baranov et al. [1] proposed a structure with two shocks, which is now the basis of a concept of the heliosphere shock layer (see Fig. 1). 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.

McComas et al. [4] determined values for local interstellar parameters (e.g. speed, direction, temperature) from IBEX and suggested that these and other recent constraints are not consistent with a bow shock ahead of the heliosphere, as previously believed.

Ben-Jaffel et al. [2] reported a new diagnosis of two different states of the local interstellar medium (LISM) near our solar system by using a sensitivity study constrained by several distinct and complementary observations of the LISM, solar wind, and inner heliosphere. Ben-Jaffel et al. [2] showed that an interstellar bow shock (which is fast) should be standing off upstream of the heliopause.

Scherer and Fichtner [6] demonstrated that including the He+ component of the LISM yields both an Alfven and fast magnetosonic wave speed lower than the LISM flow speed. Consequently, the scenario of a bow shock in front of the heliosphere, as modeled in numerous simulations of the interaction of the solar wind with the LISM, remains valid. IBEX observations indicate that the local interstellar medium (LISM) flow speed is less than previously thought. According to [6], reasonable LISM plasma parameters indicate that the LISM flow may be either marginally super-fast magnetosonic or sub-fast magnetosonic. According to [11], this raises two challenging questions: (1) Can a LISM model that is barely super-fast or sub-fast magnetosonic account for Lyα observations that rely critically on the additional absorption provided by the hydrogen wall (H-wall)? and (2) If the LISM flow is weakly super-fast magnetosonic, does the transition assume the form of a traditional shock or does neutral hydrogen (H) mediate shock dissipation and hence structure through charge exchange? Both questions are addressed using three three-dimensional self-consistently coupled magnetohydrodynamic plasma—kinetic H models with different LISM magnetic field strengths (2, 3, and 4 μG) as well as plasma and neutral H number densities. Zank et al. [11] found that both the super-fast magnetosonic models can account for the Lyα observations, with possibly the bow-shock-free 3μG model being slightly favored. Also, Zank et al. [11] concluded that IBEX may have discovered a class of interstellar shocks mediated by neutral H.

Yet, there has been and is still ongoing a lively debate about the existence of such a bow shock and its very nature. Starting with McComas et al. [4], a discussion ensued whether there is such a shock at all and/or what nature such a shock might be. This discussion includes, in particular, interpretation of Lyman-a backscatter observations concerning the nature of the heliospheric boundary [2], the realization that interstellar He might play a substantial role in the flow dynamics to decide whether there is a shock or not [6], and an assessment, based on global heliospheric simulations, on the nature and strength of a potential shock in light of all known constraints [11]. As one can see from recent papers, the debate is ongoing.

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.

It is known that important relations and equations to calculate **thermodynamical** parameters at transition through the shock front are named in recognition of the work carried out by Scottish physicist William John Macquorn Rankine and French engineer Pierre Henri Hugoniot. The Rankine- Hugoniot relations apply to a one-dimensional planar shock. Attempting to apply them to the geometry of the bow shock is not straight forward since the shape of the shock is not a priori known. In fact, the Rankine- Hugoniot relations must be applied in conjunction with calculating the shock shape, the downstream flow, the heliopause shape, the inner-heliosheath configuration, and the termination shock location. The Rankine-Hugoniot relations are based on energy conservation laws, which have been generalized for different shocks. The interstellar medium is most likely a multi-ion plasma containing both protons and He ions, and the heliosheath is know to contain both thermal solar wind ions, hot pickup ions as well as anomalous and galactic cosmic ray particles, which are not in thermodynamic equilibrium. The local interstellar medium also contains neutral atoms, which interact with the solar wind plasma through charge exchange, electron impact ionization or photoionization. Due to all these complications, one could apply the classical Rankine-Hugoniot relations only with combinations of equations from our studies; and one should take into account the results of recent computer simulations.

Let's also address other key parameters. We can choose the system of coordinates as a base beginning at the center of the Sun (Fig.1). I shall use local coordinate system (l, k, n). I will follow our previously published papers [5, 7-10] in the approach to the external bow shock description.

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):

$$\frac{dP_{2g}}{dl} = \frac{2\rho_1 V_1^2}{\gamma+1} \frac{d}{dl} \sin^2 \alpha;$$

$$\frac{\rho_2}{2}\frac{dV_2^2}{dl} = -\frac{\rho_1 V_1^2 (\delta^2 - 1)}{\delta}\frac{d}{dl}\sin^2\alpha\,; \qquad (1)$$

where $\delta = (\gamma+1)/(\gamma-1)$.
Thus, substituting these expressions into the equation for current density, we can obtain:

$$j = \frac{c}{B_2^2}\left[B \times \left(\nabla p_g + \rho\frac{\nabla V^2}{2}\right)\right];$$

$$j_{2k} = c\left(\frac{dP_{2g}}{dl} + \rho\frac{dV_{2l}^2}{dl}\right)\frac{B_{2n}}{B_2^2}\,; \text{ or}$$

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

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

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

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 [3]. 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.

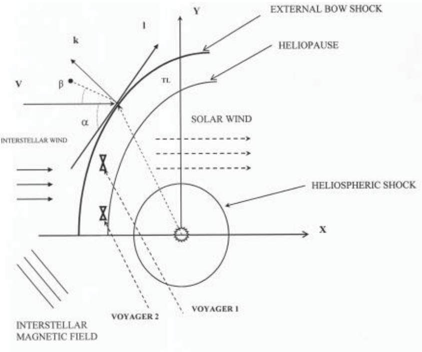

Figure 1. A sketch of the external bow shock, of the Transition Layer (TL), heliopause.

3 Discussion and conclusion

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. This essential set of measuring instruments that would enable us to obtain a series of numerical estimates of key parameters can be presented as follows:

1. Magnetometer. FluxGate Magnetometer (Magnetic Field Vector, spin resolution; Magnetic Field Magnitude).

2. Ion and electron sensor combination that operates in the bulk plasma energy regime/Instrument to measure plasma density and composition (Electron, Proton, and Alpha-particle Monitor).

3. Electron Diagonalized Temperature. Electron Symmetry Vector. Ion Diagonalized Temperature. Ion Symmetry Vector.

4. Electrostatic Analyzer.

5. Electric Field Variation, based on spin plane component.

We should note that to date, this set of measuring instruments is not a hard-to-obtain one, it is readily available on research satellites. There is bound to be a huge time-lag before Voyager spacecraft 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 (about interstellar medium). 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 this instrumentation, almost for sure would be an interstellar probe that continues into the interstellar medium proper. This would make most of the motivation for similar studies. 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.

References

1. Baranov V. B., Krasnobayev K. V., Kulikovsky A. G., Model of the solar wind and interstellar medium interaction, *Reports of Academy of Sciences*. USSR, 1970, 1, 105

2. Ben-Jaffel L., Strumik M., Ratkiewicz R., and Grygorczuk J. The existence and nature of the interstellar bow shock. *The Astrophysical Journal*, 2013, 779:130. doi:10.1088/0004-637X/779/2/130

3. Madelung, E. Die mathematischen hilfsmittel des physikers. Berlin. Gottingen. Heidelberg. Springer-Verlag. 1957. p.500

4. McComas D. J., et al. Global Observations of the Interstellar Interaction from the Interstellar Boundary Explorer (IBEX). *Science*, 2009, 326, 959. doi: 10.1126/science.1180906

5. Ponomarev E.A., Sedykh P.A., Urbanovich V.D. Bow shock as a power source for magnetospheric processes. *Journal of Atmospheric and Solar-Terrestrial Physics*, 2006, 68, p.685–690

6. Scherer K. and Fichtner H. The return of the bow shock. *The Astrophysical Journal*, 2014. 782:25. doi:10.1088/0004-637X/782/1/25

7. Sedykh P.A., E.A. Ponomarev. A structurally adequate model of the geomagnetosphere. *Stud. Geophys. Geod*., 2012, AS CR, 56, doi: 10.1007/s11200-011-9027-3, p. 110–126

8. Sedykh P.A. Transformation of solar wind energy into the energy of magnetospheric processes. *Acta Geodaetica et Geophysica*. Springer; 2014. 49, N1, P.1-15. doi: 10.1007/s40328-013-0036-2.

9. Sedykh P.A. Bow shock: Power aspects. *Advances in Space Research*, Elsevier Science. 2014. JASR11746. doi:10.1016/j.asr.2014.03.015.

10. Sedykh P.A. Bow shock: Power aspects. Nova Science Publ. NY USA, in *Horizons in World Physics*. 2015. 285. p. 23-73

11. Zank G. P., Heerikhuisen J., Wood B. E., Pogorelov N. V., Zirnstein E. and McComas D. J. Heliospheric structure: the bow wave and the hydrogen wall. *The Astrophysical Journal*, 2013, 763:20. doi:10.1088/0004-637X/763/1/20