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DOES THE INTERSTELLAR BOW SHOCK EXIST AROUND THE HELIOSPHERE?

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Abstract

The paper discusses results of global modeling of the heliosphere regarding the existence of the interstellar bow shock (BS) in front of the heliosphere. The Local InterStellar Medium (LISM) velocity vector ($\mathbf{V}_{IS}$) and temperature (T_{IS}) originally determined through the velocity and temperature of the interstellar helium (He) flowing in the inner heliosphere and measured by the GAS instrument on Ulysses, recently have been challenged by new measurements of the He flow by the Interstellar Boundary Explorer (IBEX). These measurements have initiated discussions on the existence of the BS. The purpose of this paper is a brief overview of studies focusing on *in situ* measurements of the He flow by the instruments on Ulysses and IBEX missions and indication of the reasons for discrepancies created in the past few years and associated with the existence of the BS.
Keywords: solar wind, interstellar medium, heliosphere, mhd modeling, bow shock

1. INTRODUCTION

A motion of two media moving towards each other until they collide is known from everyday life. Let's think about two media, one flowing from a bowl through small holes in it like water from a garden sprinkler on which a strong wind is blowing from a certain direction. The spherically symmetric streamlines of water will be deflected by the wind.

The same happens with the expanding solar corona, the solar wind (SW) blowing out from the Sun and carving in the LISM a bubble called the heliosphere. However, the mutual interaction between the SW and the LISM is much more complicated. The SW, mostly a proton-electron plasma, whose speed is already at the Earth's orbit higher than the speed of sound, carries the Sun's magnetic field through the heliosphere. The LISM consists of neutral and ionized components and is immersed in its own magnetic field. As a result of the motion of these two plasmas a separatrix between them, called the heliopause (HP), is created. At the HP thermal and magnetic pressures achieve the equilibrium. The highly supersonic solar wind slows down through the heliospheric termination shock (TS) to reach from the inner side the HP. In the case the LISM plasma is supersonic, the bow shock is created in front of the HP, similarly as a bow shock in front of a plane flying with the speed larger than sound , and the LISM flows around the HP similarly as the wind around the fuselage (see, e.g., [1]-[6], for broader review see, e. g. [7]-[9]). The region between the TS and possible BS with the HP between them, is known as the heliosheath (HS) or a heliospheric boundary layer. The HS is shown schematically in figure 1. The regions with the compressed SW and the compressed LISM are called the inner (IHS) and the outer (OHS) heliosheath, respectively.

The interaction between the SW and the LISM plasmas described above is affected by many processes and factors, such as neutral particles, time-dependent phenomena, anomlous cosmic rays (ACR), galactic cosmic rays (GCR), instabilities, turbulence etc. Since the undisturbed interstellar neutral (ISN) component can deeply penetrate the heliosphere, its measurements from the Earth's orbit provide almost direct information about the LISM. The ISN component consists mainly of neutral hydrogen (H) and He. The ISN He can be measured *in situ* in the heliosphere, and a consistent set of physical parameters has been derived for the ISN He through a coordinated analysis of ISN He data obtained simultaneously through three observation techniques in the inner heliosphere, along with the photo ionization rates and the solar illumination [10]. It is commonly accepted that the neutral and ionized parts of the LISM flow with the same velocity in relation to the direction and magnitude. Since the LISM plasma parameters such as the velocity and temperature are determined through the velocity and temperature of the ISN He, the plasma (sonic) Mach number, equal to the ratio of speeds of the flow and sound (see section 3), depends on the ISN He flow parameters. When the Mach number is larger than 1, the flow is supersonic and the shock is created. Based on the Mach number calculated from the GAS instrument data on Ulysses [10]-[12], which appears to be larger than 1, it was concluded that the interstellar BS exists in front of the HP.

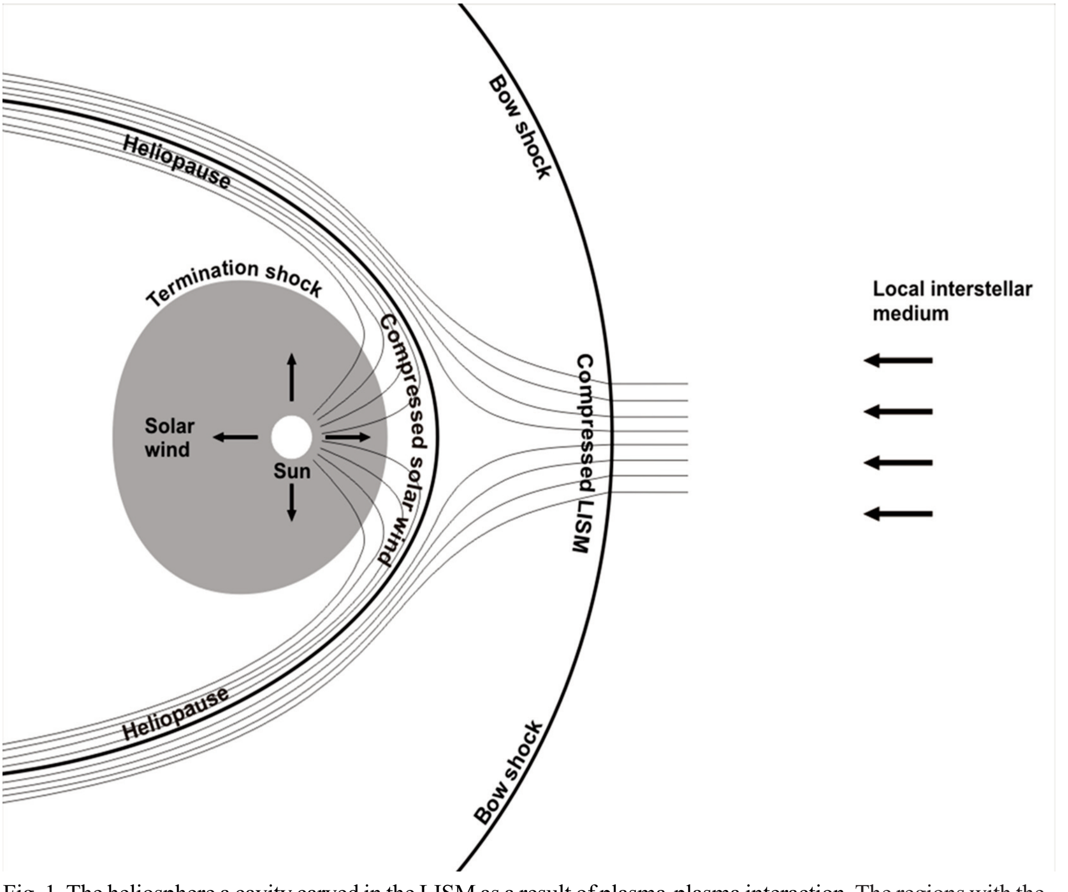

Fig. 1. The heliosphere a cavity carved in the LISM as a result of plasma-plasma interaction. The regions with the compressed SW and the compressed LISM are IHS and the OHS, respectively [Ratkiewicz & Kotlarz, 2016].

Recently, these measurements have been challenged by measurements of the ISN He flow by the Interstellar Boundary Explorer [13] as discussed by Bzowski et al., Moebius et al., and McComas et al. [14]-[16]. Using the IBEX observations to calculate the velocity and temperature of the ISN He, and taking into account a possible range of the strength of the interstellar magnetic field as well as a possible range of plasma density McComas et al. [16] concluded that the BS does not exist, because the inflow velocity of the LISM is lower than the fast magnetosonic speed, which is a combination of a sound and Alfven speeds (for definitions see section 3) resulting in the fast Mach numbers of the order $0.9 < M < 1.0$. This conclusion incited discussions on the existence of the interstellar BS. In the discussion of discrepancies of Ulysses-IBEX data related LISM velocity vector and other LISM parameters a significant role was played by indirect measurements such as pick-up ions measurements or the heliosphere fluorescence from interstellar H and He [10], [17]. However, direct neutral atom imaging provides the full kinematic interstellar flow distribution in the inner heliosphere, taking advantage of the Sun's gravitational deflection of the flow to deduce the flow vector at infinity and for that reason we concentrate only on direct measurements. So far, there are only two space experiments that have directly measured the ISN He, namely Gas/Ulysses in the 1990-2009 years and IBEX-Lo since 2009 up to now. A concise summary of the ISN He parameters is presented in table 1, in which the results of the analysis of data from the Ulysses probe [11], [18]-[19] and the IBEX probe [16], [20] are cited.

Tab. 1. Different sets of ISN He parameters as measured *in situ* by instruments on Ulysses or IBEX [Ratkiewicz & Kotlarz, 2016]

References	Mission	λ [°] ecliptic longitude	β [°] ecliptic latitude	V [km s^{-1}]	T [K]
Witte 2004	Ulysses	255.4 ± 0.5	5.2 ± 0.2	26.3 ± 0.4	6,300 ± 340
McComas et al. 2012	IBEX	259.0 ± 0.47	4.98 ± 0.21	23.2 ± 0.3	6,300 ± 390
Bzowski et al. 2014	Ulysses	255.3+1.2(-1.1)	6.0±1	26.0+1(-1.5)	7,500+150(-200)
Wood et al. 2015	Ulysses	255.54 ± 0.19	5.44 ± 0.24	26.08 ± 0.21	7,260 ± 270
McComas et al. 2015a	IBEX	255.7	5.1	25.4	7,500

2. REVIEW OF RESULTS

The existence and nature of the interstellar BS have been widely discussed by Ben-Jaffel and Ratkiewicz[21]-[22]. Ben-Jaffel and Ratkiewicz [21] have shown that for the J2000 epoch Ulysses-based He parameters the interstellar BS must exist. Using the 2010 epoch IBEX-based He parameters and a magnetic field stronger than ~2.4 μG leads to a plasma configuration that is not consistent with Voyagers TS crossings. The study by Ben-Jaffel et al. [22] brought the conclusion that with Ulysses He flow, their solution is in the expected hydrogen deflection plane (HDP). In contrast, for the IBEX He flow, the solution is ~20° away from the corresponding HDP. Also the long-term monitoring of the interplanetary H flow speed shows a value of ~26 km/s measured upwind from the Doppler shift in the strong Ly-α sky background emission line. Therefore, all elements of the diagnosis seem to support the Ulysses He flow parameters for the interstellar state, hence the interstellar fast BS should be standing off upstream of the HP (see also [6]).

Regarding the results obtained by McComas et al. [16], Scherer and Fichtner [23] noticed that McComas et al. [16] based on the LISM proton density neglecting the contribution of the helium ions. Scherer & Fichtner [23] discussed the influence of the He+ taking into account the effect of interstellar He on the characteristic wave speed. They demonstrate that the Alfven and the fast magnetosonic wave speeds (see section 3) are lower than the LISM inflow speed and showed that a weak BS should exist (see tab. 1, [23]).

Going through the recent literature devoted to the BS existence, another possibility is a bow wave [24] or a slow bow shock [25]. Zank et al. [24] examined a mediation process of shock dissipation by neutral hydrogen and found more smoothly varying plasma parameters and a bow wave, even for parameters that would normally be expected to create a bow shock. Zieger et al. [25] showed that a so-called slow bow shock related to the slow magnetosonic wave mode might exist.

Except the above mentioned papers, in which return to Ulysses measurements are shown, Bzowski et al. and Wood, et al. [18]-[19] revisited Ulysses observation of INS He. Their analysis refines the derived ISN flow parameters with a possible reconciliation between velocity vectors found with IBEX and Ulysses, but at a substantially higher ISN temperature than the result of the analysis conducted by Witte [11].

In the recent study by McComas et al. [27] and Leonard et al. [26] examined data from 2012-2014. Based on the first two seasons of IBEX data, a new range of ISN inflow parameters was explored with independent, complementary techniques of an analytical model [28] that used the unique IBEX viewing geometry perpendicular to the solar direction to assess the interstellar He parameters [15], and a detailed forward model (the Warsaw Test Particle Model - WTPM) which includes all the important geometric and instrumental effects known [14], [29]. A small discrepancy in the ISN He parameters obtained using these two methods [14]-[15] was resolved by McComas et al. [16] to give IBEX's best measurements based on its first two years of ISN observations.

A consistent picture for the local interstellar flow is shown in figure 2 (based on figure 2 [27]), to which two sets of velocity and temperature values from [16] and [20] are added (compare tab.1).

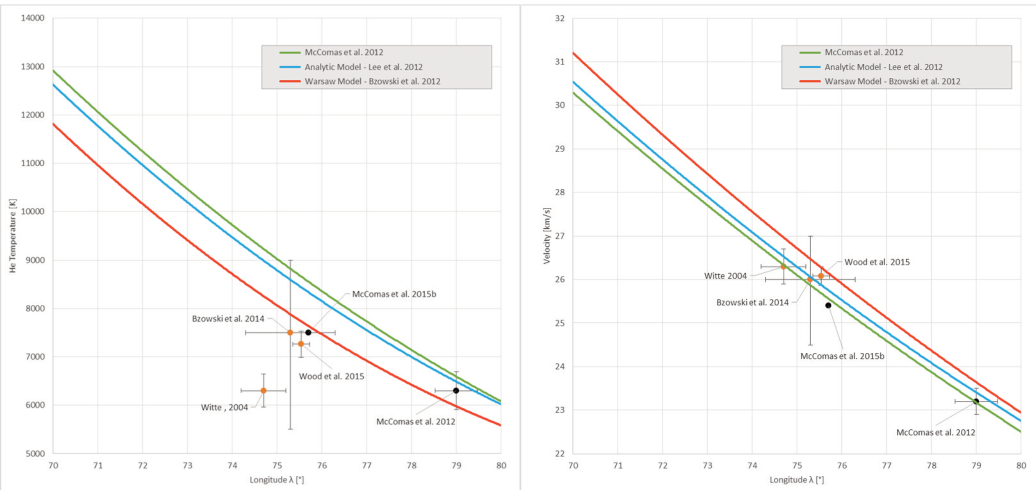

Fig. 2. Interstellar He inflow speed at infinity (right) and temperature (left) as functions of inflow longitude. Ulysses data – orange dots, IBEX data – black dots [Ratkiewicz & Kotlarz, 2016]

Figure 2 brings together new analysis of the Ulysses observations showing significantly higher temperatures than previously thought [18]-[19], a solution consistent with IBEX's previously published four-dimensional tube of coupled parameters [16], and two new independent analyses of more recent IBEX data for orbit segments with the simplest (in ecliptic) spacecraft pointing. Together, all of these indicate a preferred portion of the IBEX tube at slightly higher speeds and significantly higher temperatures than the central values from the earlier studies ([14]-[16]. The combined

IBEX/Ulysses values were presented by McComas et al. [20] and they are: $V_{IS} \sim 25.4$ km s^{-1}, $\lambda \sim 75.7°$, $\beta \sim -5.1°$ and $T_{IS} \sim 7{,}500$ K (tab. 1, fig. 2).

It is worth emphasizing that a comprehensive analysis of data from IBEX mission has been published in the Astrophysical Journal Supplement Series in 2015 (papers AJSS 220:22-35). This series of papers is summarized in McComas et al. [20] paper, which gathers 14 studies in this AJSS Special Issue. The IBEX has been directly observing neutral atoms from the LISM for the last six years (2009–2014). Those papers describe the IBEX interstellar neutral results from this epoch and provide a number of other relevant theoretical and observational results. In particular, several papers are directly or indirectly devoted to the BS existence (see e. g. [20] and [30]-[36]).

Bzowski et al. [30] analyzed measurements from the first six ISN He observation seasons of IBEX using a sophisticated data uncertainty and parameter fitting system developed by Swaczyna et al. [36] and the latest version of the ISN He simulation WTPM by Sokół et al. [34]. They identified a surprisingly strong influence of the Warm Breeze, recently discovered by Kubiak et al. [29],[37] and accordingly performed careful data selection to obtain the cleanest sample of ISN He observations. They found that the ISN He inflow velocity vector seems to be consistent with the velocity vector originally obtained by Witte [11] from analysis of Ulysses measurements, but only for a temperature that is higher by at least 1,100 K. They also found that the Mach number of the neutral He flow ahead of the heliosphere is equal to 5.08. Those findings agree with the results of the Ulysses analysis made by Bzowski et al. [18] and Wood et al [19] with a very high accuracy of 2.5%, and with the recent study of IBEX results obtained by Mc Comas et al. [27]. The Mach number obtained now is in full agreement with the results obtained by Bzowski et al., Moebius et al., and McComas et al. [14]-[16].

Also, a paper by Schwadron et al. [33] is worth mentioning, in which authors use the three-step method to find the interstellar parameters. Previous work on IBEX neutral atom analysis relied, in part, on an approach utilizing closed form analytic approximations [29], [31] for the distribution of neutral atoms observed in Earth's reference frame. The new method together with a new computational tool for simulating neutral atoms through the integrated IBEX-Lo response function moves beyond closed-form approximations and utilize observations of interstellar He during the complete five year period from 2009 to 2013 when the primary component of interstellar He is most prominent.

Many other aspects are covered in this series. A more advanced analysis of the impact of various factors related both to the measurement (i.e. observations) and modeling, is deeply discussed in the paper by Swaczyna, al. [36] and also by Lee et al. [31], Moebius et al. [32] and Sokół et al. [34].

Although the existence of BS is still not a foregone conclusion, all those works are aimed at a better understanding of the phenomena occurring in the heliosphere using observations of the missions Voyager, IBEX and others, and getting the most compatible results on interstellar matter.

3. DISCUSSION

3.1. Modeling of the heliosphere – the boundary conditions

For the numerical modeling of the heliosphere boundary conditions are necessary. The properties of the SW at 1 AU (astronomical unit; roughly the distance from the Earth to the Sun – the inner boundary) are well determined due to the deep interplanetary missions Pioneer 10 and 11, Voyager 1 (V1) and Voyager 2 (V2), as well as the Solar and Heliospheric Observatory (SOHO), and Ulysses. Parameters characterizing the undisturbed LISM (at outer boundary) still remain the subject of observational and theoretical investigations.

As shown in section 2, the LISM velocity vector and temperature originally determined through the velocity and temperature of the ISN He flowing in the inner heliosphere and measured by the GAS instrument on Ulysses, some years ago were challenged by new measurements of the He flow by the

IBEX. Although recently, as described in section 2, ISN He inflow velocity vector seems to be consistent with the velocity vector originally obtained from an analysis of Ulysses measurements, a temperature is substantially higher by at least 1,100 K. The incomplete knowledge of the LISM concerns the number density of ions and atoms. But, the most important problem concerns the LISM magnetic field whose strength and direction are not known at all. This requires a parametric study on the LISM magnetic field.

Up to now, only a fraction of the real complexity of the SW and LISM interaction has been reflected in the results of the global 3D models (see, e.g., [5]-[6], [21]-[22], [38]-[46]). The existing 3D MHD codes fail to describe properly the interaction between the SW and the LISM and to achieve a good verification by the V1, V2, and IBEX data. The main reason of the failure is the fact that using the ideal MHD, we implicitly assume the Maxwellian distributions of the plasma during the whole process of the interaction, which in general is not correct [47], and must be considered as an approximation. However, even based on such imperfect models, calculations concerning the existence of the BS can be made. In order to decide whether the fast/slow BS exists, one has to calculate the fast/slow magnetosonic Mach number $\mathbf{M_{f,s}}$ which is the ratio between the velocity V and fast/slow magnetosonic speeds $\mathbf{C_{f,s}}$:

$$M_{f,s} = \frac{V}{C_{f,s}}$$

where $\mathbf{C_{f,s}}$ is:

$$C_{f,s} = \sqrt{\frac{1}{2}\left(\left(c^2 + b^2\right) \pm \sqrt{\left(c^2 + b^2\right)^2 - 4c^2 b^2 \cos^2(\theta)}\right)}$$

here c denotes sound speed $c = (\gamma\ p/\rho)^{0.5}$ and b denotes Alfven speed $b = B/(4\pi\rho)^{0.5}$, p is a pressure, ρ is a density, γ is the ratio of specific heats, B is magnetic field strength, θ is the angle between the normal to the wave and the magnetic field vector.

The fast BS is created if the $\mathbf{M_f} > 1$. The minimal fast magnetosonic Mach number is achieved when the fast magnetosonic speed achieves its maximum for a given flow velocity. For example, for $\theta = 90°$ the minimal fast magnetosonic Mach number is equal to

$$M_f = \frac{V}{\sqrt{c^2 + b^2}}$$

When the minimal $\mathbf{M_f} > 1$, the flow is superfast. In table 2, we present the example of different Mach number M_f for the undisturbed LISM parameters such as magnetic field strength $\mathbf{B_{IS}}$ in the range 2.0-4.0 μG, velocity $\mathbf{V_{IS}}$ in the range 22.8-26.4 km s^{-1}, temperature $\mathbf{T_{IS}}$ = 6,400 K and proton number density $\mathbf{n_p}$ ~ 0.05-0.13 cm^{-3} assumed at the outer boundary [22]. For V_{IS} = 26.4 km s^{-1} the flow is superfast (or marginally superfast) for the solution B_{IS} ~ 2.2±0.1 μG derived in [21] and for all possible cases of LISM density [48]. For V_{IS} = 22.8 km s^{-1} and the corresponding magnetic field values B_{IS} ~ 2.7 ± 0.2 μG obtained by Ben-Jaffel et al. [22] the flow is subfast for small n_p ~ 0.048 cm^{-3} but marginally superfast for n_p > 0.095 cm^{-3}.

Tab. 2. Mach number M_f for the LISM parameters: B_{IS}, n_p and V_{IS} [22]

n_p (cm^{-3}) / B_{IS}(μG)	2.0	2.2	2.7	3.0	4.0	V_{IS}(km s^{-1})
0.048	1.10	1.03	0.88	0.81	0.63	26.4
0.095	1.36	1.29	1.13	1.05	0.84	
0.130	1.47	1.40	1.25	1.17	0.96	
0.048	0.96	0.89	0.76	0.70	0.54	22.8
0.095	1.18	1.12	0.99	0.91	0.73	
0.130	1.28	1.22	1.09	1.02	0.83	

3. 2. Magnetic Field

The example above shows what an important role the magnetic field plays in creation of the BS. Scherer & Fitchner [23] have also illustrated that the structure of the BS is more complicated than that of a purely hydrodynamic one: i. e. Alfven and magnetosonic wave speeds are lower than the inflow speed of the LISM. In any case, the existence of the BS depends strongly on the strength of the local interstellar magnetic field, and due to the higher LISM speed, the existence of the BS is more likely. The authors remark that if the value of ~26.3 km/s for LISM inflow speed were correct, only magnetic field values above 3.5 μG would remove the BS. New observations of B_{IS} from 2014-2016 show that V1 continued to observe draped interstellar magnetic fields in the OHS with the average value ~4.8 μG, which could indicate the unperturbed value less than 3.5 μG [49-50].

3.3. Temperature

Since the paper by Witte [11] up to now the LISM temperature was believed to be ~ 6,000-7,000 K. The last such result was shown in McComas et al. [16]. Based on recent IBEX result and reanalysis of Ulysses measurements, the LISM around the heliosphere is substantially warmer than previously thought. The temperature is estimated for ~ 7,000–9,500K. These observations indicate that the heliosphere's interstellar interactions are very complex and due to it very interesting.

4. CONCLUSIONS

The speed of ~26 km/s instead of ~23 km/s reopens the question of whether there is a BS ahead of the heliosphere in the LISM. The last set of ISN He parameters recommended by McComas et al. [27] is V_{IS} ~ 25.4 km s−1, λ ~ 75.7°, β ~ −5.1°, and T_{IS} ~7,500 K for the interstellar He inflow at ~1,000 AU upstream. For such warm LISM and recommended velocity, the LISM magnetic field strength would have been restricted to values ≤ 3 μG to achieve minimal $M_f > 1$, if the interstellar plasma number density is > 0.09 cm^{-3}. It seems to be possible as indicated by numerical simulations [6], [21]-[22]. On the other hand, since the existing 3D MHD codes fail to describe properly the interaction between the SW and the LISM due to complexity of the SW-LISM interaction, the new tool for numerical simulations, which could bear the weight of the complexity of the problem is required. Authors think that the code that would solve this problem on the scale of the heliosphere would come from the family of a hybrid-kinetic Particle-in-Cell (PIC) codes [51].

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CZY ISTNIEJE MIĘDZYGWIAZDOWA CZOŁOWA FALA UDERZENIOWA PRZED HELIOSFERĄ?

Abstrakt

W pracy przedyskutowano wyniki globalnego modelowania heliosfery dotyczące istnienia czołowej fali uderzeniowej (BS) przed heliosferą. Wektor prędkości **($\mathbf{V}_{IS}$)** i temperatura **(**T_{IS}**)** lokalnej materii międzygwiazdowej (LISM) oryginalnie wyznaczone przez prędkość i temperaturę międzygwiazdowego helu (He) wpływającego do heliosfery i mierzonego przez przyrząd GAS na sondzie Ulysses, ostatnio zostały zakwestionowane przez nowe pomiary przepływu He wykonane przez sondę Interstellar Boundary Explorer (IBEX). Pomiary te zainicjowały dyskusję na temat istnienia BS. Celem niniejszego artykułu jest krótki przegląd badań poświęconych pomiarom *in situ* strumienia helu przez instrumenty na sondach Ulysses i IBEX oraz wskazanie przyczyn rozbieżności związanych z istnieniem czołowej fali uderzeniowej powstałych w ciągu kilku ostatnich lat [51].
Słowa kluczowe: wiatr słoneczny, materia międzygwiazdowa, heliosfera, modelowanie magnetohydrodynamiczne, czołowa fala uderzeniowa.