ARTIFICIAL SATELLITES, Vol. 58, No. 2 – 2023
DOI: 10.2478/arsa-2023-0003

INTERSTELLAR PROBE: SCIENCE, ENGINEERING, LOGISTIC, ECONOMIC, AND SOCIAL FACTORS

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ABSTRACT. In this publication, we refer to a certain novelty introduced to the presentation at the AGU 2020 conference. This novelty consists of quoting the thoughts, remarks, and comments of six young people who declared their interest in space research after listening to a lecture on the Interstellar Probe journey, organized in June 2020 by the Polish Space Agency. Therefore, they were then asked to express their comments after reading two publications on the Interstellar Probe that were sent to them. As a result, this idea also became the topic of this article. Although the interstellar mission is primarily a research and science project, its engineering, logistics, business (economic), and social aspects, as well as a short commentary on our home in the universe, which is the heliosphere, have also been included in this article.

Keywords: Interstellar Probe mission, science, engineering, logistic, business

1. INTRODUCTION

The purpose of this publication is to present a certain novelty introduced to the presentation at international AGU conferences, namely, the Fall AGU 2020 Meeting. The approach in this form was accepted for the first time in the history of the AGU and favorably received by the participants of the SH019 session. The form of presentation was born in connection with the mission of the Interstellar Probe (IP). The idea was to attract the interest of young people in the IP, the launch of which is scheduled for 2030. For this purpose, two publications on this topic were sent to them, “Near-term interstellar probe: First step” by McNutt et al. (2019) and “Interstellar Probe: Cross-divisional science enabled by the first deliberate step in to the galaxy” by Brandt et al. 2019, and they were asked about their impressions and comments.

In this paper, comments and visions of those young people who were asked are cited. Logistic, business, and social aspects and scientific questions are also considered.

The nonstandard form of this publication is structured in this way: Section 2 with subsections contains the original text written in first person by young people after reading the publications mentioned above. Sections 1 and 3–5 are in standard layout.

2. COMMENTS REGARDING TWO PUBLICATIONS ON THE IP

2.1. Comments by Kajetan Stępniewski

I have read the materials you gave me. The text was very interesting and I mostly agree with it. In my opinion, it is a mistake not to assemble the ship in orbit, as it could be divided into two parts, the propulsion and the probe. This would allow the drive unit to have more fuel, allowing the probe to reach a higher speed and/or carry more attachments on board. Mounting in orbit would also allow sending a better power supply system, for example, a nuclear reactor instead of an X-ray generator, which would extend the probe's operating time and increase the distance it will fly. I know that this will increase the costs of the mission, which is already expensive, but the additional funding will allow you to get more scientific data, and this is worth its weight in gold because it is not known when such a mission will repeat. I have thought this through, and I have the more convinced about my idea. In my opinion, a reactor would be better than a radioisotope generator for several reasons. The reactor produces much more energy, for example, the "kilopower" reactor (Figure 1) is currently being developed – its output power is 1–10 kW, so you can use electric drives such as plasma and ion drives. Besides, the reactor itself (from what I was able to find out) can work 12 years on a single fuel rod, I am sure there could be a technology to replace worn-out fuel rods.

Figure 1. Kilopower reactor prototype

As for the Space Launch System (SLS) rocket, I am not sure if this is the best vehicle for launching the probe (especially in terms of price). In my opinion, you could also consider reusable rockets, for example, (Figure 2) Falcon Heavy (FH; capable of reaching 60 t per orbit) and Starship (SpaceX rocket currently being developed, which can reach over 100 t) or New Glenn (Blue Origin rocket also under development, capable of reaching 45 t). The use of these rockets could reduce the costs of the mission and also allow the probe to be assembled in orbit.

Falcon Heavy New Glenn Starship

Figure 2. Other launch vehicles: Falcon Heavy, New Glenn, Starship

I am in favor of dividing the probe into segments, for example, propulsion with fuel and engine, engine room with a nuclear reactor, heat sinks, command room with scientific instruments, communication antenna, and an on-board computer (Figure 3). The probe will also fly past other scientifically interesting places. One could think of cubesats that could be fired in the right place. In my opinion, this mission should be used as much as possible because as I mentioned, it is not known when this opportunity will repeat itself. A segmented probe, electric or nuclear propulsion could pave a new path for future missions. Another advantage of the modular design is the possibility of modernizing – as technology advances – only selected segments; may be in the future, it will even enable a trip to another star.

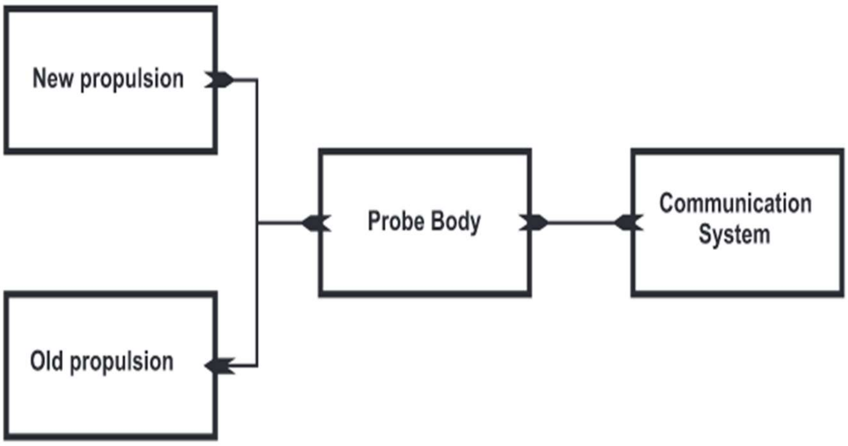


Figure 3. Modular construction

2.2. Comments by Tomasz Miś

The list of devices for recording individual data (devices with large space heritage) is interesting, but the question is whether and how they will be modified in relation to their predecessors. From the perspective of the radiofrequency (RF) research, the receiving circuit working up to 300 kHz (and, more specifically, its accuracy) shall be important. One of the articles mentioned frequencies in the 3-30 kHz range – this is pertinent, however especially with the prospect of visiting small trans-Neptunian objects it must be extended to 300 kHz at least (as shown in Figure 4). The plan of not activating devices close to Earth and during a possible gravitational assistance of Jupiter is highly objectionable – this will significantly and unnecessarily reduce the amount of data for analysis (more so as the quality of the downlink shall be satisfactory due to the distance). Other spacecraft at that time and in such distances were operating successfully and provided valuable data (e.g., Voyager and Cassini).

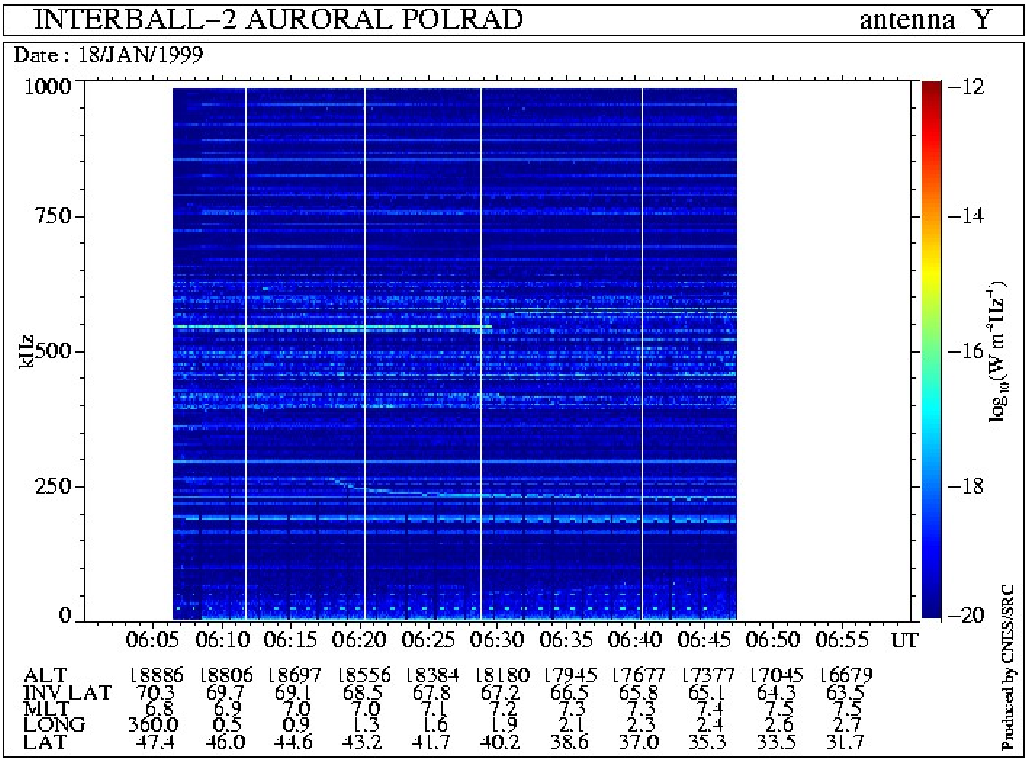


Figure 4. POLRAD experiment sample spectrum – well recorded <300 kHz and higher, 1999 (by CDPP/CNES, public exemplary data set provided through IRAP repository)

If the IP velocity is reached as it was mentioned there, that is, 3× the Voyagers' velocity, then presumably, a better solution (due to the registration of RF signals) would be to continuously record selected parts of the spectrum, not to sweep the entire spectrum under consideration every time with a given small-bandwidth step. This feature would be crucial, especially during a flyby in the near-earth environment (30-35, 162, 171, 225, 540 kHz; see Figure 5) and near gas planets. It seems that the use of the Sun's gravitational assistance, despite its advantages, may result in deep and relatively unnecessary in the long-term modification of the probe (thermal shields, etc.) and imposing additional, unimportant from the point of view of distant parts of the solar system, thermal resistance and heat transfer requirements for on-board equipment.

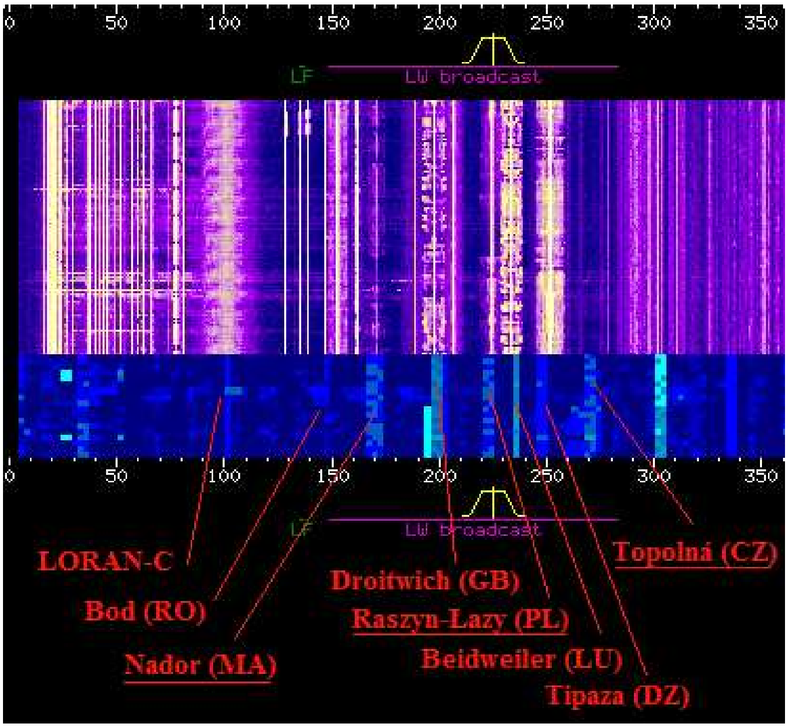
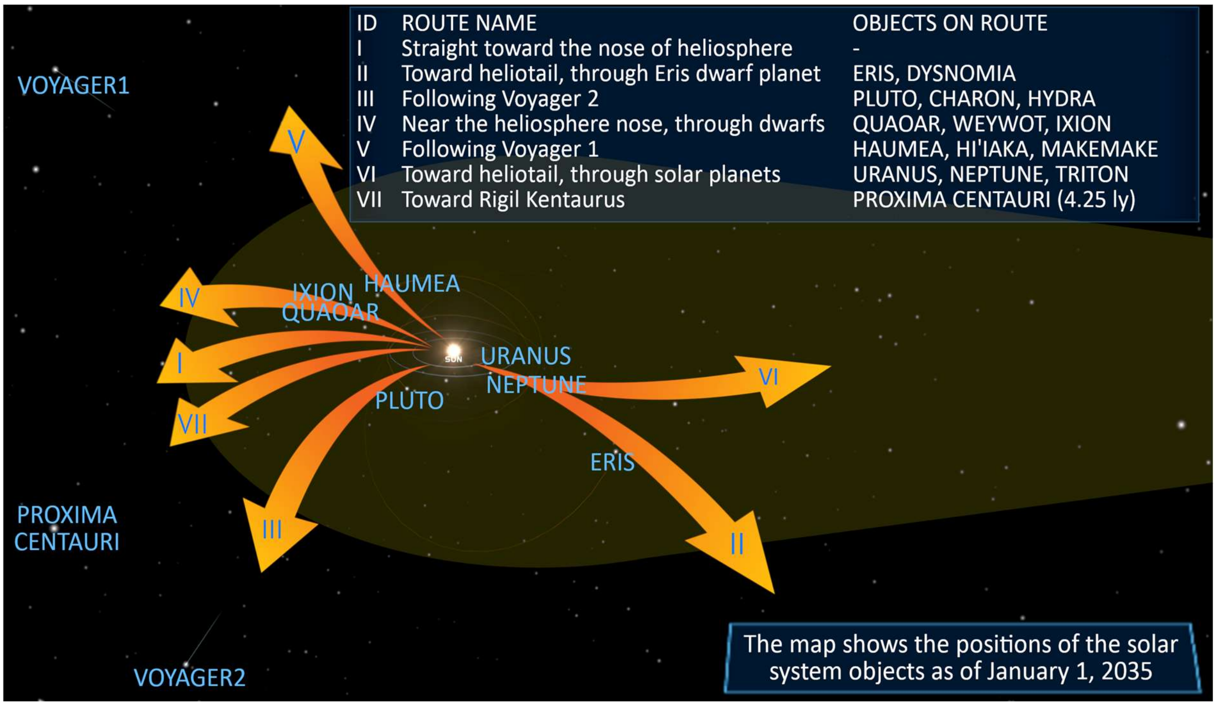


Figure 5. Terrestrial longwave frequencies received by POLRAD, 18 Mm (megametres) from the source (Miś, 2020)

The developed power budget is reasonable. However, to extend the operation time of individual instruments and eliminate the gradually degrading component in the form of thermocouples, a promising solution could be the introduction of at least partial diversification of power sources in the form of small ionization cells (alphavoltaic, semiconductor or liquid), which, by design, do not any emit thermal radiation into space, do not use thermocouples and are powered by, for example, Am-241 (low energies of gamma quanta) and do not significantly increase the mass of the component. Small sensor / data recording systems on intermediate memory registers (limited to a single instrument) could be successfully powered in this way, functioning in longer periods in comparison to the RTG (Radioisotope Thermal Generator)-based power system. These devices could be qualified and tested to successfully operate in the space environment without any major problems. This type of device (the alphavoltaic cell/reactor) was the subject of my master thesis (awarded in the competition for the best works on nucleonics – Polish Nuclear Society. At one time, a large study on this type of cells (but of a different, semiconductor-type) was developed by NASA itself.

2.3. Comments by Piotr Błądek

In both publications, the proposed objects and phenomena that can be observed during the mission are presented in a very general way. They describe various exit scenarios for the Interstellar Probe (IP), which is equipped with research instruments, power supply, and the outline of the structure. The only thing that puzzled me was whether it was necessary to waste time and energy to explore as many things "along the way" as possible, namely, Kuiper belt objects, dwarf planets, Pluto, Neptune, their moons, and other things. Both publications discuss what can be done before the probe reaches the limits of the heliosphere. Wouldn't it be easier, better, cheaper, and more reliable to launch the probe, hibernate it until it reaches the limits of the heliosphere, and then begin its proper mission? Then, it would be possible to take only the equipment needed to study what we want to find in the heliosphere – equipment made only for this specific application. On the other hand, scientific goals of IP published originally by McNutt clearly indicate the desire of the scientific community to also explore the interior of the heliosphere, as well as heliosheath, during the IP mission.



ID	ROUTE NAME	OBJECTS ON ROUTE
I	Straight toward the nose of heliosphere	-
II	Toward heliotail, through Eris dwarf planet	ERIS, DYSNOMIA
III	Following Voyager 2	PLUTO, CHARON, HYDRA
IV	Near the heliosphere nose, through dwarfs	QUAOAR, WEYWOT, IXION
V	Following Voyager 1	HAUMEA, HI'IAKA, MAKEMAKE
VI	Toward heliotail, through solar planets	URANUS, NEPTUNE, TRITON
VII	Toward Rigil Kentaurus	PROXIMA CENTAURI (4.25 ly)

The map shows the positions of the solar system objects as of January 1, 2035

Figure 6. Routes toward different objects for the Interstellar Probe

2.4. Comments by Arkadiusz Tkacz

My point is to focus on how to launch the IP into space and give it the speed necessary to escape. Both articles mention SLS 1B+ as the first stage, without considering any alternatives. While the load capacity and dimensions of the cargo hold are indeed (now and in the near future) unbeatable, taking into account the costs, a different mission configuration can be proposed.

SLS 1B+ has a predicted load capacity to Low Earth Orbit (LEO) up to 105 t, with a cargo space measuring 8.3 × 19 m (diameter × height). This allows you to accommodate the third- and fourth-stage (in the form of two of the shown Castor/Centaur/Interim Cryogenic Propulsion Stage [ICPS]) ships with a total weight of about 70 t and the IP itself (0.5 t), as shown in Figure 7, but the planned cost of a single SLS flight is 800–1600 M$.

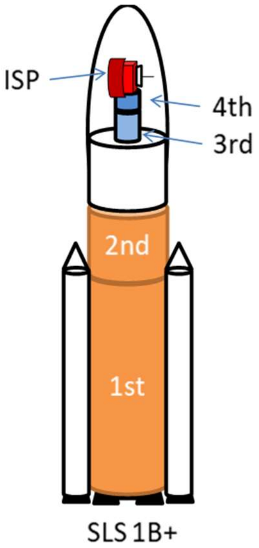


Figure 7. Spacecraft launch configuration in case of using SLS 1B+ as the first-stage rocket

Alternatively, the FH is able to launch the LEO 63 t with a 5 × 13 m hold. This allows you to plan a mission with two FH rockets. In one of them, there would be a third stage, while in the second one, there would be a fourth stage together with IP, as shown in Figure 8. The joining of the last stages would take place at the apogee of the high-elliptical orbit: after the lifting of two approx. 35–40 t charges in both second FH stages, there will still be fuel left. Next, the mission is analogous to using SLS. The argument for the presented plan is, of course, the price: currently, the offered cost of launching a single FH rocket is 90–150 M$, which gives a total of 180–300 M$.

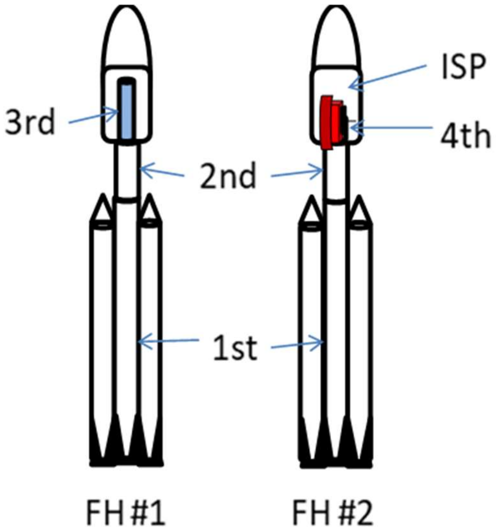


Figure 8. Spacecraft launch configuration in case of using two Falcon Heavies (FH) as the first-stage rocket. Placement of third and fourth stages with IP spacecraft is marked.

From what I was able to determine, the budget of the IP program is currently unknown, but by comparing the presented values, for example, with the budget of the Parker Solar Probe mission (1.5 B$), it is possible to estimate the impact of potentially shifted funds toward the construction of more complex scientific instruments, as shown in Figure 9.

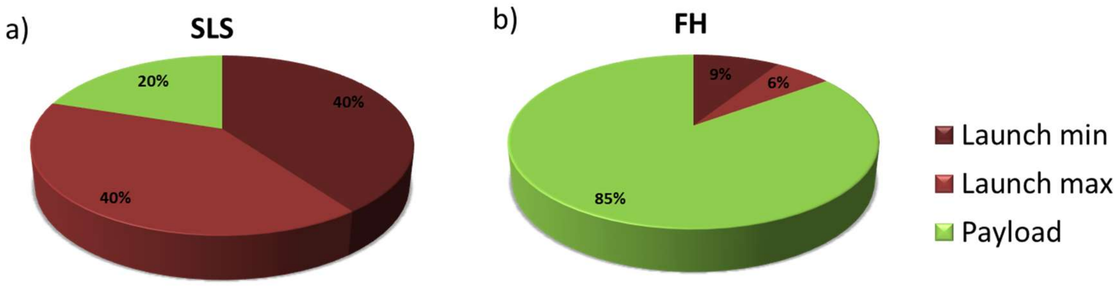


Figure 9. Payload–launch cost participation for 2 B$ mission launched with SLS 1B+ (a) and two Falcon Heavies (b) as the first stage

2.5. Comments by Tomasz Mikołajków

I have read the articles and although many comments came to my mind while reading, practically all of them were resolved in the following parts of the articles. Particularly, for example, I was interested in the selection of the probe's trajectory – which planets/other interesting objects will be passed along the way from a distance, allowing for even fleeting studies, and in which area of the heliopause (HP) it is worth aiming the probe. This, however, was described in some detail in chapters 3.2 and 4 of the article (Brandt et al.).

The second issue of interest to me was the probe's target measurement capabilities, but this topic was also well covered. In turn, the issue of mass optimization, power consumption, and the use of data transfer by probe components is described quite briefly, as if there was no clear concept of what devices should fly. I assume that this issue will be dealt with in more detail as the project progresses.

2.6. Comments by Michał Kozanecki

1) I think many of the scientific instruments can be copied from the Advanced Composition Explorer ACE spacecraft, since they had similar goals at least in terms of studying plasma (e.g., the mass spectrometers mounted there, such as the ultra-low-energy isotope spectrometer and the solar wind ion mass spectrometer).
2) Despite the use of already developed technologies, I think that it would be worth at least considering the possibility of using a different drive, which would be more effective (e.g., Variable Specific Impulse Magnetoplasma Rocket [VASIMR] or other plasma drives). This would shorten the waiting time for data and perhaps ensure that more data is collected from the interstellar medium before the spacecraft goes out of service.
3) I think that detection of cosmic rays is certainly an interesting experiment. This may bring new information about cosmic rays' origin and may lead to new discoveries in this direction. In turn, energetic neutral atoms (ENA) imaging also seems to be a very desirable instrument. I am also wondering whether to consider some devices using the Zeeman effect (e.g., to study the magnetic fields in interstellar medium).
4) When it comes to which maneuver to choose, despite the fact that the protective shield in the Oberth maneuver will weigh a lot (which increases the costs), the prospect of a window every 12 years with the Jupiter gravity assistance is risky to the extent that the Oberth maneuver seems to become a better solution.
5) I believe that in terms of scientific load, we should focus on reducing the weight of the heaviest devices.

6) Studying the chemical composition of the dust is also an interesting experiment. It could significantly advance astrochemistry. Perhaps, instruments such as the Chemin used in Mars rovers could be adapted for this purpose (it is probably smaller than the Cosmic Dust Analyzer from the Cassini probe) or try to collect this dust electrostatically.
7) Based on data from the probe's flyby, it could be investigated whether there is any danger to ships equipped with solar sails or there is a chance to use interstellar wind to propel other ships (e.g., How would the M2P2 solar wind drive do it?).
8) I also wonder if going beyond the heliosphere would help in looking for some biomarkers on exoplanets.

3. NONSCIENTIFIC ASPECTS OF THE SPACE MISSION

Next to the remarks and comments mentioned above are presented the benefits of coordinating nonscientific elements of a space mission, engineering, logistics, economic and social issues.

The space mission (including interstellar mission) is primarily a research and scientific project, but its engineering, logistic, business (economic), and social aspects should not be forgotten. Research teams often treat these factors as auxiliary, yet they have a key impact on the success of the entire project, especially in a situation of limited financial resources.

The contribution of engineering and logistics to the improvement of space missions and the importance of economic and social aspects, including the social responsibility of space missions, in the implementation of these projects are indicated below.

Engineering support activities include, among others, the following:

1) establishing nonscientific mission standards and making technological specifications dependent on them;
2) the use of modern (including niche) technologies in the field of data collection, processing, and sharing, as well as control of technical parameters of the probe, such as artificial intelligence (AI).

Within social sciences, including economic and management sciences, it is logistics that, as part of space project (including interstellar missions) improvement activities, can significantly improve their efficiency and effectiveness. The experience gained by outer space logistics after more than six decades of supporting the presence of a human being in space allows developing a new logistics model for interstellar space missions, changing the form of a one-off mission to a campaign-oriented one (Ho et al., 2016) and putting more emphasis on balancing the scientific, social, economic, and environmental goals (De Weck, 2021). Other space mission support activities provided by logistics include, among others, the following:

1) selection of the optimal route of the probe, including rocket launch site, terrestrial infrastructure supporting the mission, probe route (with an alternative version), and options for using, for example, gravity assist or Lagrange nodes;
2) linking mission logistics to future space infrastructure project;
3) choosing the right logistics operator, taking into account private companies and the recycling rockets they offer.

Economic issues are important in the implementation of space missions. Economic tasks supporting space mission projects include, among others, the following:

1) searching for the synergy effect of the mission objective with the objectives of other space projects (planned and created);
2) creation of a strong business base (e.g., a group of start-ups, think tanks) that will work on solutions intended for the purposes of the missions;
3) obtaining funds at the project preparation stage and using them for education, promotion, and organization of the project.

In the era of intensification of various types of scientific projects, it can be very difficult to distinguish (position) a particular project, when in the meantime the possibility of raising capital and the fate of the mission may depend on it. Therefore, communication, promotion, and development of the concept of social responsibility of the project based on the idea of corporate social responsibility (CSR) should also be indicated as factors determining the effectiveness of space projects. Among the activities undertaken in this area of space mission activity are the following:

1) building a strong and cohesive community around the mission;
2) inclusion of business partners to the project team;
3) promotion of the project;
4) coordinate reference system (CRS) of the project. Sharing data with scientists around the world.

The main benefits of this approach include the following:

1) increasing the scientific effectiveness of the project;
2) increasing the cost efficiency of the project;
3) increasing public support for the project.

4. SCIENTIFIC ASPECTS OF THE SPACE MISSION

Science is represented by a short description of how the heliosphere is created and what is its shape. During the course of its evolution, our Sun was located through significantly different interstellar environments throughout the galaxy. On its journey, the Sun encountered a wide range of interstellar plasma, gas, dust, and high-energy cosmic rays. All this together has formed the planetary system, with the Earth on which we live. The Sun moves through space filled with interstellar material, simultaneously blowing out solar wind. As a result of these two opposing activities, a heliosphere is formed, separated from the interstellar matter by an HP. In the solar wind, on the inside of the HP, a shock wave called termination shock (TS) is created. In the interstellar matter, on the other side of the HP, most probably, a shock wave is also created, called bow shock (BS) (Figure 10).

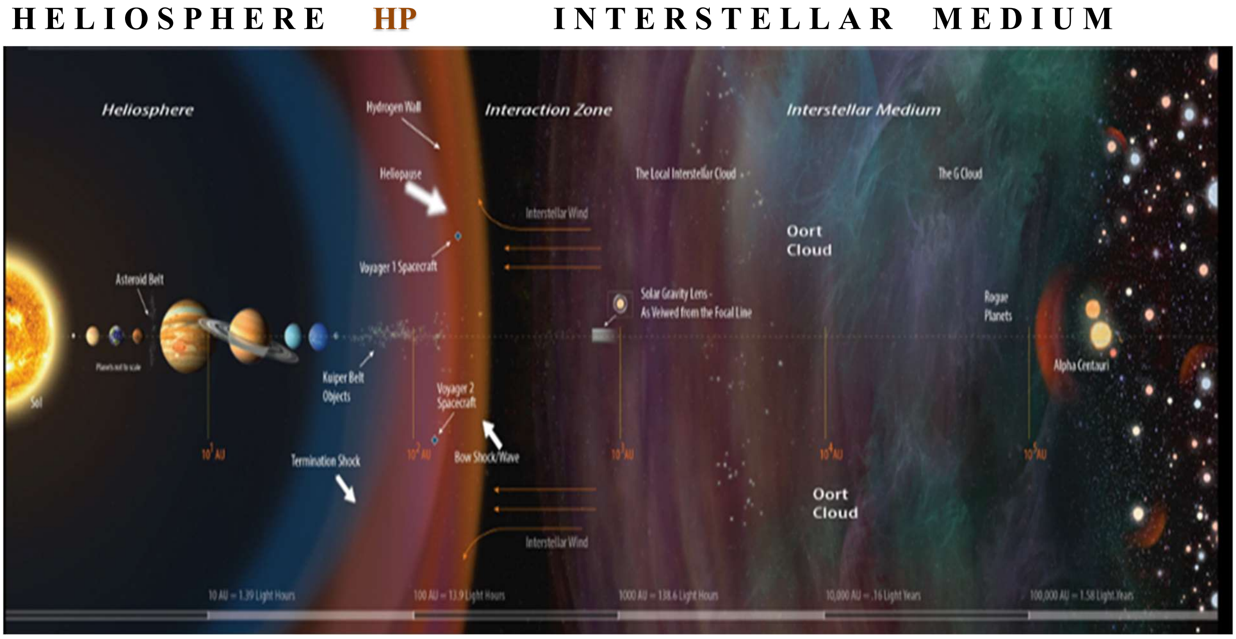
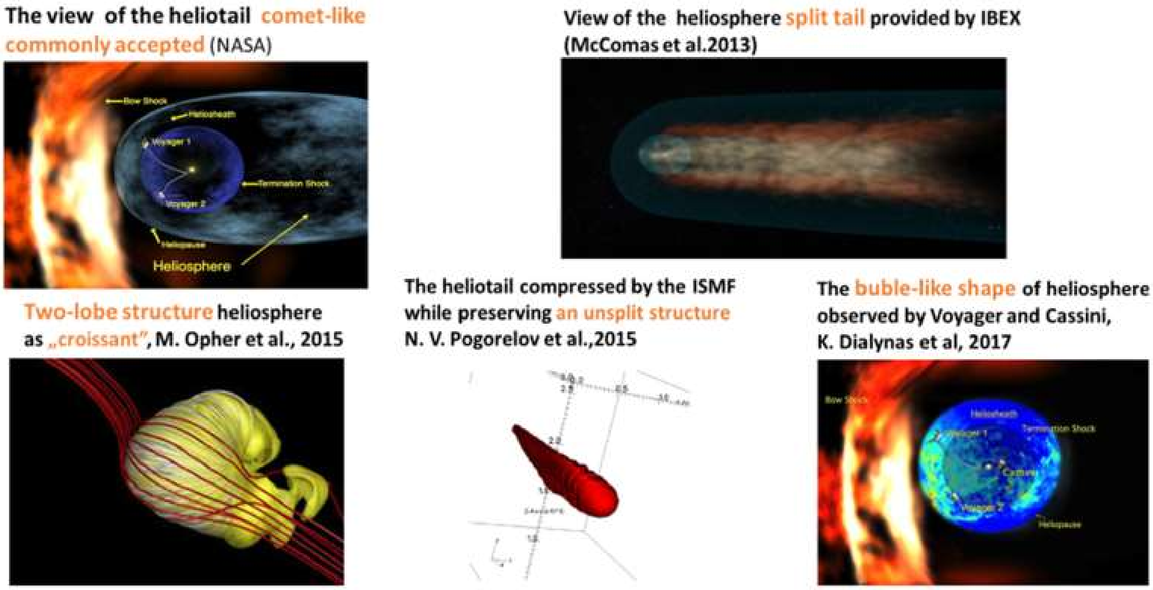


Figure 10. The boundary between the heliosphere and the interstellar medium consisting of the termination shock, heliopause, and bow shock (source JHU APL)

The schematic of the boundary between Solar Wind (SW) and Local Interstellar Medium (LISM) (not in scale) attached in Figure 10 shows how far from the Sun the nearest star, Alpha Centauri, is. Scientists are wondering in which direction to send the probe. This dilemma is directly related to the shape of the heliosphere. Authors of numerical simulations of the heliosphere tried to use all data provided by Voyagers, IBEX, and other space missions to validate created models. However, none of the obtained heliosphere models met all the basic fit criteria.

As a result, we have "different heliospheres" presented in Figure 11: at the top: the heliosphere with comet-like split tail, at the bottom: two-lobe structure heliosphere as "croissant" (left), heliosphere with unsplit tail (center), and the bubble-like shape of heliosphere (right).

So, what is the truth?


The view of the heliotail comet-like commonly accepted (NASA)

View of the heliosphere split tail provided by IBEX (McComas et al.2013)

Two-lobe structure heliosphere as „croissant", M. Opher et al., 2015

The heliotail compressed by the ISMF while preserving an unsplit structure N. V. Pogorelov et al.,2015

The buble-like shape of heliosphere observed by Voyager and Cassini, K. Dialynas et al, 2017

Figure 11. The shapes of the heliosphere obtained by the heliosphere's different models. "What does the heliosphere look like?"

"What does the heliosphere look like?" still remains a mystery, but we are working to unravel it by building a completely new model of the heliosphere. We hope to find out the solution to this puzzle before launching the IP.

5. CONCLUSIONS

In this article, the statements of young people (high school students, polytechnic or university students, freshly minted engineers, and university graduates) are presented literally to show how they react to the expanding space exploration in the world. Due to this principle, their texts have not been corrected and are not provided with any comments from experts. In these statements, young people showed that they can analyze the planned research and take a position on the use of modern technologies to control the technical parameters of the probe as well as the instruments that should be on board. They dared to express their own (correct or wrong) view on the choice (e.g., rockets, the method of launching a mission, or estimating the cost of a space mission).

The attitude of these people inspired experienced scientists from both the Space Research Center and the Institute of Nuclear Physics of the Polish Academy of Sciences and the Wroclaw University of Economics to conduct lectures in preparing them for research in the field of astrophysics, programming, the use of AI techniques, data collection and processing, as well as in the field of engineering, logistics, and other research closely related to the future space probe.

Acknowledgments. R. R. acknowledges Kinga Gruszecka and Szymon Grych from the Polish Space Agency for their support in organizing our Interstellar Probe group and in preparing the presentation for the Fall AGU 2020 Meeting. Authors also thank the reviewers for their very important and useful remarks and suggestions.

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Received: *2022-11-21*

Reviewed: *2022-12-21 (K. Szafran); 2023-01-15 (A. Wiśniewski);*

2023-02-26 (T. Zawistowski)

Accepted: *2023-04-27*