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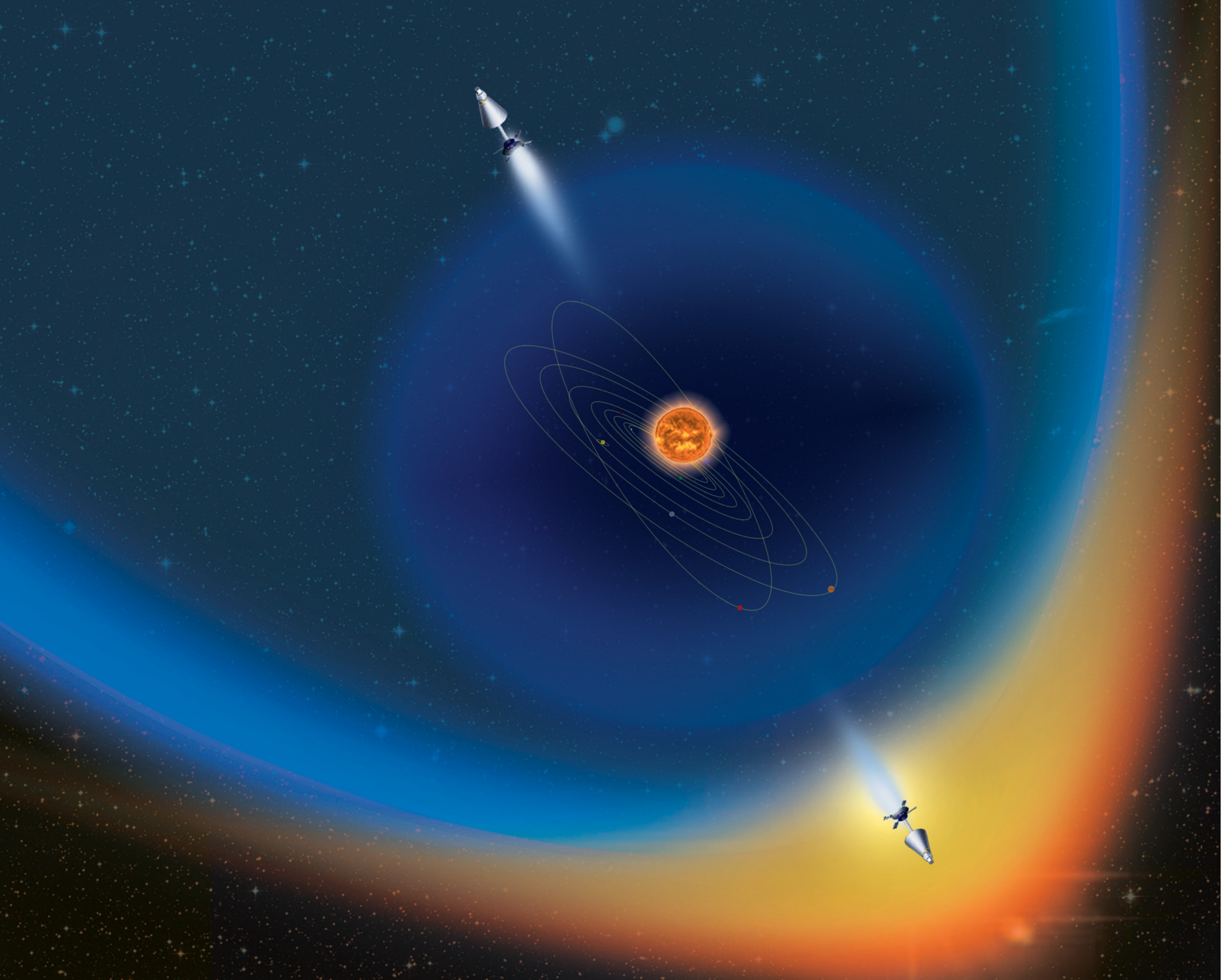
EXPLORATION OF OUTER HELIOSPHERE AND NEARBY INTERSTELLAR MEDIUM



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FRONT COVER

Deep exploration probes
Image Credit: Wu, Weiren et al. (2019). System engineering research and application foreground of space nuclear reactor power generators. Scientia Sinica Technologica, 49, doi: 10.1360/N092018-00374.

ABSTRACT 摘要

自从美国NASA在1977年将旅行者1号和2号放射进入太空后，对全人类而言一个新的太空纪元开始了。旅行者号承载着人类对探索浩瀚宇宙的期望，陆续地飞跃几大行星并分别于2004年和2007年穿越终止激波，于2012年和2018年穿越日球层顶。之后旅行者号进入了星际空间，开启了新的星际旅行。然而，很长时间里，如果不考虑已经早已失去联系的先锋10和11号飞船的话， 两颗旅行者号飞船一直寂寞地飞行在远离太阳的路上。直到2006年，美国的新视野号发生升空，目前它已经飞越过冥王星，在朝向旅行者号相似的方向上一路飞驰。然而，科学家们很早就意识到，由于当初探测任务的限制，旅行者号及新视野号并没有携带完备的空间环境测量仪器，因此设计专门的星际飞船成为人类下一步的计划，比如美国的Interstellar Probe方案。

而随着中国综合科技能力的提升，发射中国自己的星际飞船已经开始进入中国科学家们的讨论议题。拥有很重要的科学意义，与探月的嫦娥工程类似，中国的星际飞船计划也中国的科学家和工程师们已经开始着手做相关准备。由于中国此前从未有过这类长程航天计划，科学上在外日球层的相关研究方面离国外尚有差距。因此借鉴欧美等先进国家的经验显得非常重要。科学应是没有国界的，与国外优秀的日球层科学家一起交流相关科学知识是很重要的，也有助于提升中国自身研究日球层科学的实力。我们讨论的科学目标最终也是中国星际飞船计划的科学指南。ISSI-BJ提供了一个很好的国际交流平台，在这里各国科学家们讨论未来的星际飞船计划，这将对中国未来的星际飞船计划之相关科学任务人及国际合作提供有利的帮助。

FOREWORD

Symbolically marking the first anniversary of NASA-led Voyager 2 mission since it first entered the interstellar space on November 5, 2018, the forum "Exploration of outer heliosphere and nearby interstellar medium" represented one of the most relevant activities held at ISSI-BJ in 2019 thanks to the pioneering researches and results thoroughly discussed by international scientists during two days, on 7-8 November 2019.

Convened by internationally renowned scientists — Prof. Wang Chi (NSSC, CAS, China), Dr. Ralph L. McNutt Jr. (Johns Hopkins University, USA), Prof. Robert Wimmer-Schweingruber (University of Kiel, Germany), Prof. John D. Richardson (MIT, USA), Prof. Li Hui (NSSC, CAS, China), and myself — the event attracted more than 20 experts devoted to the study of heliophysics, space physics, and space exploration.

The invited scientists aimed to identify the key problems related to some still uncharted territories, including the heliosphere, the interstellar medium, our solar system, and their interactive dynamics. Experts were also faced with the complexity of a new interstellar mission proposal, i.e., the Interstellar Express (IE).

Following the 2014 Scientific Pioneer Program of Space Science of the Chinese Academy of Sciences (CAS) as well as the 2018 Xiangshan scientific conference, fundamental issues related to such interstellar undertaking were tackled. The mission, whose probes are meant to move in two opposite directions — towards the "nose" of the heliosphere as well as towards its "tail" — is supposed to be launched in 2025, if everything will be ready by then. Its significance also lies in the potential for a better understanding of the interactions between the hot, low-density plasma of the solar wind and the cool, higher-density plasma of the interstellar space.

This mission would be of great scientific interest to the broad international community since it goes into exploration beyond traditional heliophysics to encompass plasma physics, astrophysics, and fundamental physics studies.

The scientists' presentations focused on the magnetic field as well as galactic cosmic rays in the outer heliosheath, and on the heliospheric shield, as clearly shown in the present report. Furthermore, the interstellar mission represented the pivot of the discussions, as its scientific objectives were examined and payload suggestions were brought forward, such as ENA imager(s), plasma- and magnetic field instruments, and L-y spectometer, among others.

The far-reaching and well-promising approach of this mission has attracted the interest of the international scientific community, leaving the call for worldwide collaboration still open and therefore, reflecting ISSI-BJ's greater goals to reach deeper and more international interactions among researchers in the field of space science studies.

I would like to express my gratitude to the conveners and managers of this forum for their excellent and professional organization of the thematic schedule and for putting forward such a groundbreaking project. I would also like to thank the ISSI-BJ staff — Lijuan En, Xiaolong Dong, and Laura Baldis — for taking care of the administrative and practical aspects of this forum. Finally, my special thanks also go to the authors of this report for their insightful and ambitious work that will greatly contribute to the advances in space research.

Maurizio Falanga,

Executive Director

ISSI-BJ

1. INTRODUCTION

The heliosphere is the bubble-like region surrounding the Sun and the solar system that is formed because of the interaction between the outward-propagating magnetized solar wind and the interstellar medium, the hydrogen and helium gas that permeates the Milky Way Galaxy. The solar wind streams away from the Sun in all directions at supersonic speed of several hundred km/s until it reaches the termination shock, where it slows down abruptly to subsonic speed. Then, the solar wind continues to decelerate as it passes through the heliosheath, reaching a boundary called 'heliopause', where the interstellar medium and the solar wind's pressures find a balance at about 120 astronomical units (AU; 1 Astronomical Unit = 150 million km) from the Sun.

The heliosphere resides in the Local Interstellar Cloud inside the Local Bubble, which is a region in the Orion Arm of the Milky Way Galaxy. Beyond the heliopause, the interstellar space is filled with interstellar medium, which made of plasma, dust, magnetic field, cosmic rays, as well as gas in ionic, atomic, and molecular form.

By mass, the interplanetary medium found beyond 10 AU is in fact dominated by neutral atoms of interstellar origin rather than by solar wind protons (Gruntman 1993). The coupling proceeds indirectly through the ionization of the neutrals by various mechanisms (photoionization, charge-exchange, electron-impact ionization; see Zank 1999a). Consequently, the physics of the outer heliosphere beyond 10 AU is very different from that in the inner heliosphere, which is determined by material of solar origin. Thus, the exploration of the outer heliosphere offers the opportunity to learn about both the interplanetary and the interstellar medium, and the way in which they interact.

The outer heliosphere and its interaction with the surrounding interstellar space is still an uncharted territory in heliophysics. Although in-situ observations from the two Voyagers as well as remote observations from IBEX and Cassini are providing significant new information about the heliospheric boundary region, a targeted interstellar probe with modern instruments and measurement requirements — better defined by these recent observations — can offer new answers to some scientific questions, e.g.,:

1. What is the nature of the nearby interstellar medium?

2. How does the solar wind evolve and interact with the interstellar medium?

3. What are the structure and the dynamics of the heliosphere?

4. How did the matter in the solar system as well as the interstellar medium originate and evolve?

NASA and ESA have conducted many pre-studies on a targeted interstellar mission.

Since 2014, China has begun to carry out some concept studies on a similar kind of mission, such as the Strategic Priority Research Program of Chinese Academy of Sciences. In 2018, the Xiangshan Science Conference was held in Beijing to discuss the feasibility of launching two interstellar probes in opposite directions as part of a Chinese project. One probe is expected to fly towards the heliospheric "nose" region, while the other one should be launched towards the heliotail.

In order to receive inputs and advice from the community to tackle the primary scientific questions as well as the trends of future explorations of the outer heliosphere and the local interstellar medium, a forum was organized by ISSI-BJ on 7-8 November 2019. The event was sponsored by ISSI-BJ with partial support from the State Key Laboratory of Space Weather as well as the National Space Science Center, Chinese Academy of Sciences, (NSSC, CAS, China). More than 20 experts devoted to the study of heliophysics, space physics, and space exploration were invited to ISSI-BJ to attend this two-day forum. The goals of the forum included the understanding of the global nature of our local galactic environment, which is significantly more complex than thought in the past. During the activity, the participants had the chance to discuss:

1. What are the most significant scientific objectives of the two probes sent in two different directions?

2. How can we maximize the scientific outputs during the journey to the heliospheric boundary?

3. Payload suggestions and specifications

This TAIKONG magazine issue presents the outcome of the debates held during the forum, covering various topics, such as some scientific questions related to the outer heliosphere and the nearby interstellar medium, the scientific objectives of an interstellar mission, the overall payload suggestions and specifications, and potential international collaborations.[1]

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1 The participants of the forum and contributors of the chapters are listed below:

1. Introduction (C. Wang, H. Li)
2. Interstellar probe - An overview (R. L. McNutt, Jr.)
3. Recent progresses in understanding the outer heliosphere and nearby interstellar medium I (J. Richardson, V. Izmodenov, M. Opher, I. Baliukin)
4. Recent Progresses in understanding the outer heliosphere and nearby interstellar medium II (V. Florinski, L. Xi, X. Guo)
5. Scientific objectives of the interstellar mission (Q. Zong, W. Ip)
6. Payload suggestions and specifications (L. Wang, Q. Zong, H. Xue, A. Zhang)
7. Conclusions (W. Ip)

2. INTERSTELLAR PROBE - AN OVERVIEW

2.1. Beginnings

Travel to the stars might be, to borrow a line from Shakespeare's character Prospero in The Tempest "such stuff as dreams are made on," but the reality is very, very difficult. Technical speculation emerged in the early years of the 20th century from the first tier of investigators of practical spaceflight: Tsiolkovsky, Goddard, and Oberth. All three worked in relative isolation from each other and worked with next-tier leaders, whom they effectively mentored: Tsander by Tsiolkovsky and von Braun by Oberth. Goddard in the U.S. was inspired in the closing days of the previous century by H. G. Wells novel of a war between Earth and Mars, with Wells himself borrowing his "cylinders" from Jules Verne. Oberth, in recovering from scarlet fever as youth was inspired by Verne's novel "From the Earth to the Moon." Similarly, Tsiolkovsky in studying Jules Verne's 1865 novel of using an enormous gun to propel three men "from the Earth to the Moon" and back, showed that such a means was unworkable and developed his theories of spaceflight, all published in 1903, as an alternative.

Against this backdrop, on 14 January 1918, Robert Goddard initiated the discussion of interstellar travel when he asked: "Will it be possible to travel to the planets which are around the fixed stars, when the Sun and the Earth have cooled to such an extent that life is no longer possible on the Earth?" (Goddard 1983).

In reviewing a table of contents for a planned book "Flights to Other Planets and the Moon" in 1925 Tsander touches upon relativity, atomic power, and interstellar flight for two chapter titles (Tsander 1967):

> XII. Reaching other solar systems by atomic energy or special energy from decomposition of radium.
>
> XIII. Slowing of life and possibility of returning to earth alive after millions of years, by flying at velocity near the speed of light, according to Einstein's theory of relativity. Possibility of flying through all of interstellar space.

This is perhaps the first written reference of making use of relativistic speeds and time dilation to enable human flight within a lifetime between different star systems. In 1929, Bernal looked back to Goddard's original migration question and considered anew the question of what have become referred to as "world ships" (Bernal 1969):

> Interstellar distances are so large that high velocities, approaching those of light, would be necessary; and though high

velocities would be easy to attain — it being merely a matter of allowing acceleration to accumulate — they would expose the space vessels to very serious dangers, particularly from dispersed meteoric bodies.

Extensions of both the special and general theories of relativity to uniformly accelerated reference frames (Marsh 1965; Marder 2008) had been well known for over a decade by that time (Romain 1963; Born 1909; Kottler 1914a; Kottler 1914b; Kottler 1916; Kottler 1918) but applied only to problems of fundamental physics.

The study of relativistic space travel and its consequences for rocket systems began in earnest in 1946 (Ackeret 1946; Ackeret 1947) soon followed by considerations of nuclear energy for powering rockets (Shepherd and Cleaver 1948a; Shepherd and Cleaver 1948b; Shepherd and Cleaver 1949). An explicit in-depth study of these two combined fields was carried out by the founder of modern Chinese astronautics H. S. Tsien (Tsien 1949). Shepherd considered the general problem of relativistic interstellar travel (Shepherd 1952) and noted the "ultimate" propulsive concept of the "photon rocket", as introduced by Sänger (Sänger 1961; Sänger 1961-2; Sänger 1963; Stuhlinger 1959) and also studied by Peschka (Peschka 1956). Even more novel was Bussard's concept of using fusion of interstellar matter in a "ram-jet" mode (Bussard 1960).

Although studies of the general problem continued (Dole 1964; Forward 1975), it became clear that even with multiple nuclear stages (Spencer and Jaffe 1962), the profound energy requirements for relativistic travel were, and continue to be, a significant limitation (Von Hoerner 1962; Purcell 1963; Asimov 1966; Sagan 1963).

However, with the beginning of the "Space Age" following the launches of the Soviet Sputnik I (4 October 1957) and the American Explorer I (31 January 1958), plans were made in the United States under the auspices of the National Academy of Sciences via the Space Science Board (now the Space Studies Board) to consider scientific uses of space. This accelerated already existing plans for a U.S. Earth-orbiting satellite as part of the International Geophysical Year (IGY) activities (Stoneley 1960)[2]. In March 1960, "Committee 8 - Physics of Fields and Particles in Space" (also known as "the Simpson Committee" for its Chair, Professor John A. Simpson of the University of Chicago) proposed three "'special probes", the second of which was listed as "Outer solar system probe: to be aimed away from the Sun in the plane of the ecliptic. (It is hoped that motion away from the Sun to the extent of 5 or 6 astronomical units per year could be accomplished by 1965)" (Simpson et al. 1960)[3].

2 See also https://history.nasa.gov/sputnik/

3 The first was "Solar probe: specially designed payload, capable of withstanding high temperatures; to be aimed close to the Sun." – currently operating as Parker Solar Probe launch 12 August 2018 and still in its primary mission, and the third was "Probe "perpendicular" to the ecliptic. Here an increased velocity is needed and it may be necessary to compromise and accept a trajectory which has a strong component perpendicular to the field and thus moves in a spiral

2.2. Science Meets Reality: Planning Robotic Missions

The Simpson Report was the beginning of multiple studies and reports for the following 55 years. These included:

- 1960: The Space Studies Board "Outer solar system probe: to be aimed away from the Sun…"
- 1965: Eugene Parker advocates mission to heliospheric boundary region
- 1971: Session "The Next Step Beyond the Solar System"; American Astronautical Society Meeting
- 1977: Voyager launches; JPL study of an Interstellar Probe
- 1990: The Interstellar Probe report to NASA by Holzer et al. NASA Science Team
- 1999: JPL Study (NASA Science and Technology Definition Team)
- 2001: NASA Institute for Advanced Concepts (NIAC) Study, APL
- 2005: Innovative Interstellar Explorer – NASA "Vision Mission" study by McNutt et al.
- 2009: The Interstellar Heliopause Mission - proposal to ESA by Wimmer-Schweingruber et al.
- 2015: Keck Institute of Space Studies (KISS) Report.

2.3. The Current Study and Two Distinct Questions

In looking at the details of new, ambitious robotic space missions such as Interstellar Probe, one always begins with two different, but very necessary questions:

1. *What should we do?* This is the question of the appropriate and compelling scientific focus. As such it is a question for a future Science Definition Team (SDT) or equivalent and the science community overall via Decadal Surveys
2. *What could we do?* That is, given a level of resources, e.g., funds, personnel, and a schedule, what type of mission can be carried out. Usually, the level of resources is not specified a priori, and so one of the study goals is to look at an array of mission

out of the plane of the ecliptic. This is probably the most difficult shot." – which was the Ulysses mission of the European Space Agency (ESA) on the U.S. Space Shuttle Discovery mission STS-41 on 6 October 1990 and concluded operations on 30 June 2009.

types and levels to provide both the science community and policy makers and planners a set of trades which they can use as tools to guide their thinking. This is the question at hand for this study.

The Johns Hopkins University Applied Physics Laboratory (APL) has been tasked by the NASA Heliophysics Division to (re-)study a robotic Interstellar Probe mission (as of 13 June 2018). The top level requirement is to provide input to help support the next round of "Decadal Surveys" in the United States, which are now ongoing. In this case, the focus is on the upcoming Solar and Space Physics Decadal Survey with a nominal time frame of performance from 2023 to 2032. Could we launch a scientifically compelling Interstellar Probe mission during that decade? — This is a technical question but not without science, policy, and financial implications.

The notional "starting place" for such a study is to remember this is heliophysics engineering study informed by science. At the same time there could be advantages in engaging a broader science community, so one should look for possible synergies across the other Divisions (Planetary Science, Astrophysics, and Earth Science) within NASA's Science Mission Directorate (SMD). Given the timing constraint for a potential mission, the study name is the "First Pragmatic Interstellar Probe Mission Study" with "pragmatic" meaning to focus on the nearer term and existing technology. Hence, we are considering payload (scientific instruments) masses within current payload-to-spacecraft mass ratios and for technology, the guidance is that all required technology shall be ready for flight by 1 January 2030.

These study requirements are needed to conduct the engineering analysis. One can then think of this as the "parameter space" that we have chosen deliberately to make sure that the study is "pragmatic."

2.4. The Compelling Science Case

The relevant science questions span NASA Science Divisions. An emerging theme is the investigation and understanding of what makes our system, and, in particular our planet, habitable. In turn, how can we apply this knowledge to the growing number of exoplanet systems that we are observing now and in the future. Following this chain of thought, we can consider three science goals (Brandt et al. 2019):

1. *Science Goal 1: The Heliosphere as a Habitable Astrosphere.*
   The Global Nature of the heliospheric interactions.

2. *Science Goal 2: Origin and Evolution of Planetary Systems*
   Properties of dwarf planets/KBOs and large-scale structure of the circumsolar debris disk.

3. *Science Goal 3: Early Formation and Evolution of Galaxies and Stars*
   Uncovering the Diffuse Extragalactic Background Light.

2.5. A "Menu" Approach

In order to provide study results that resonate with as many people in the scientific and technical community as possible, the study approach has been to look widely across those communities and assemble a "Menu" of what has been done and what can be done with respect to Interstellar Probe desires and concepts past. By its nature this assemblage is a "superset" of what might be implemented; "ordering" from the menu will we a charge to a future SDT — at NASA's discretion. As with going to a large restaurant with many choices, one does not order everything from the menu. But the diner always would like the assurance about what orders can be placed — and delivered to the table — and what they would cost. This approach has been adopted successfully in the past in providing input to the Decadal Surveys, with the emphasis on informing the Survey participants of valid possibilities, which not dictating a single "best" solution.

The components of such a menu cannot be totally random. They must flow from the compelling top-level science goals, through questions and corresponding hypotheses, explicit measurement requirements to confirm or refute those hypotheses, instrumentation to make those measurements, and then an assessment of how those measurements have provided "closure" to the investigation, i.e., have addressed the science goals. Such a scheme is a requirement for demonstrating that such a mission is worth the time and resources of all stakeholders involved from technicians through policy makers, and not just the members of the interested science community.

Such a demonstration usually takes the form of a science traceability matrix (STM). At the time of the ISSI-BJ meeting (7-8 November 2019), a version of the STM at the time is shown in Figure 1. A corresponding list of scientific instruments, which could be of use in implementing the missions is shown in Figure 2. For this type of engineering "menu" study, the instrument possibilities, with representative masses and power requirements, are required to help assess, the overall spacecraft cost, mass, and achievable speed for a given launch vehicle configuration. These are examples, as the details have and will continue to evolve as the engineering aspects mature and as more people throughout the international scientific community continue to contribute their ideas.

A significant part of the trade space is that of identifying a "target direction" on the sky.

Most initial studies focused on trying flying in what was thought to be the closest direction to the heliopause, as defined by the incoming direction of the neutral interstellar wind. This "nose" direction of closest access has been called into question with an alternative concept of a more spherically symmetric diamagnetic bubble. The latter is driven by recent Voyager measurements of a stronger local interstellar magnetic field than previously

Goals	Questions	Specific Questions	Measurements
The Heliosphere as a Habitable Astrosphere	What is the Global Structure of the Heliosphere?	Structure of Heliopause, Bowshock, H-Wall	Probe boundaries in-situ and image structure in ENAs and UV, radio
		Nature of heliosheath, Energy partitioning	Particle distributions
		Acceleration at astrophysical shocks	
	How do the Sun and the Galaxy Affect the Dynamics of the Heliosphere?	Shock and HP response	In-situ, ENA, UV, radio
		Extent of influence in to ISM	ISM properties
		Effects on inner heliosphere	In-situ
	What is the Nature of the Interstellar Medium?	ISM vs solar system composition	Isotopic composition
		Recent nucleosynthesis in the ISM	
		Interstellar Dust	Dust composition
Origin and Evolution of Planetary Systems	How did Matter in the Solar System Originate and Evolve?	Circum-Solar Debris Disk	In-situ dust, IR 10-100 μm
		Current state of evolution, collisional processes of KBO and dwarf planets	VISNIR imaging
		Dynamical and compositional state of the Kuiper Belt	
		Sub-surface oceans and atmospheres of KBOs and dwarf planets	VISNIR, UV, magnetic field
The Universe Beyond the Circum-Solar Dust Cloud	How did Galaxies Form and Evolve in the Universe?	Diffuse Extragalactic Background Light	Diffuse EBL IR spectral measurements 10-100 μm

Figure 1: A potential Science Traceability Matrix for an Interstellar Probe mission. The topics and supporting measurement continue to evolve. Other examples can be found in McNutt et al. 2005 and Brandt et al. 2019.

Instrument	Mass (kg)	Power (W)	Data rate (bps)	Spacecraft Requirements	TRL	Heritage
Vector Helium Magnetometer	1	2	6	Boom >10 m, Spinning	6	Cassini, rocket flights
Fluxgate Magnetometer	5.6	2.2	1200	Boom >10 m, Spinning	>7	Voyager (3.6 m boom)
Plasma Wave Instrument	6	1.5	100	>10 m antennas, Spinning	6	Voyager, Van Allen Probes, MMS
Cosmic-ray spectrometer	3	2	2	Spinning	3 (compact)	ACE
Dust Detector	14	25	579	Deployable cover, Ram pointing	6	Cassini/CDA, Europa Clipper, IMAP, NASA Matisse
Neutral Ion Mass Spectrometer	3.5	5	1	Ram pointing	7	Bepi Colombo, Rosetta, JUICE
Low-Energy ENA	3	3	100	Scanning Platform	6	IBEX-Lo comparison: 11.5 kg, 3.46 W 122 bps
Medium-Energy ENA	7.37	0.65	99	Spinning	9	IBEX-Hi values shown Heritage: IBEX-Hi
High-Energy ENA	7.2	6.5	500	Spinning	>7	Cassini/INCA, IMAGE/HENA, JUICE/JENI, IMAP-Ultra
Ly-alpha Spectrograph	12.5	11.86	24	Scanning Platform	7	DMSP SSUSI; NASA TIMED/GUVI; SSUSI-Lite
VisNIR Imager	8.6	15	16	3-axis, Pushbroom operations	6	LORRI, DRACO, EIS heritage
VISNIR/FIR Mapper	4	3	10	Spinning	5	Rosetta, LORRI
Total	75.77	77.71	2637			

Figure 2: Example potential instrument types, which could be flown, with example parameters from other missions. This is not inclusive; other examples can be found in McNutt et al. 2005 and Brandt et al. 2019.

thought as well as the heliopause crossing distances of Voyagers 1 and 2 (Dialynas et al. 2017). There is also the question of sending the spacecraft toward the "ribbon" of energetic neutral atom emissions observed by the Earth-orbiting Interstellar Boundary Explorer (IBEX), believed to be associated with the interaction of the heliosphere and the nearby "very local interstellar medium" (VLISM) (McComas et al. 2009). In addition, there are a variety of Kuiper Belt Objects (KBO) between the sizes of Pluto and its large moon Charon, as well as the planets Uranus and Neptune, which could all be observed during in-depth flyby missions on the way to the interstellar medium. That said, it is again a question of the menu and which subsets of potential science targets are the most tempting. An indication of some of these targets and their location on the sky is shown in Figure 3.

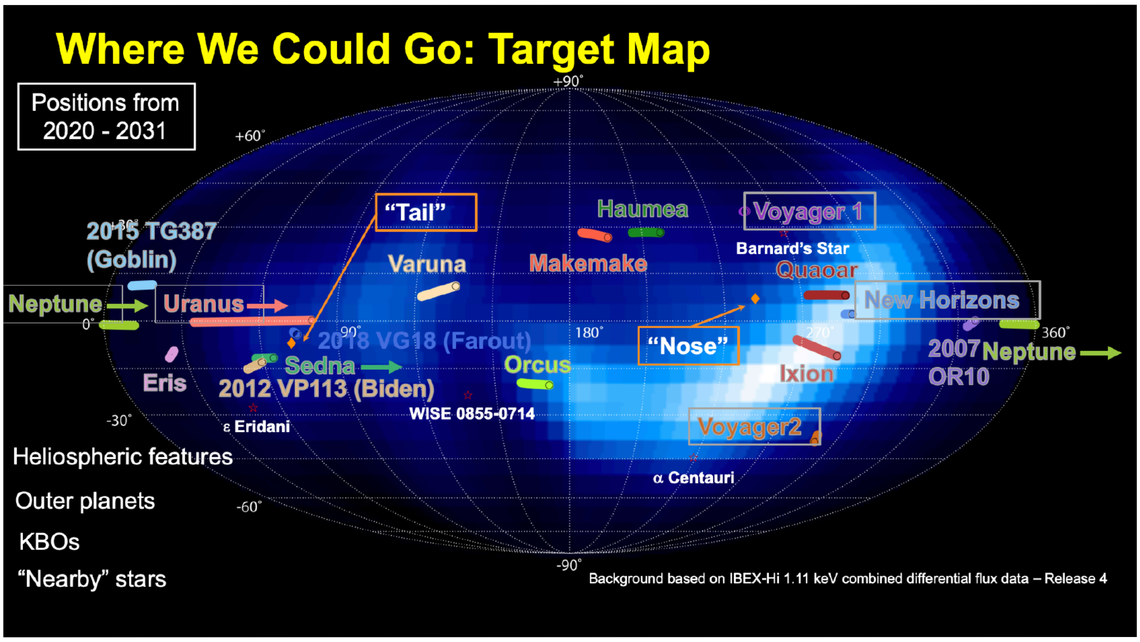


Figure 3: An all-sky (Mollweide projection) map showing potential "targets" for an Interstellar Probe mission. Coordinate are Earth ecliptic centered on 180°. The lines and arrows indicate the predicted movement of the objects depicted for the 2020-2031 time frame. For reference, locations of the nearby stars Alpha Centauri, Barnard's star, WISE 0855-0714, and Epsilon Eridani are also shown.

2.6. Trades and Technologies

With the long history of studies, it should be of no surprise that neither critical trade-offs nor enabling technologies are new. For example, with a given launch system the total energy that can be imparted to the spacecraft is fixed. Thus, with a given set of planetary gravity assists there is a trade between the maximum asymptotic escape speed from the Sun and the total mass of the spacecraft, which, in turn, tends to scale with the spacecraft mass (McNutt 2010). As a starting point this suggests considering a range of spacecraft ("wet", i.e., including initial propellant) masses from ~300 to 800 km, corresponding roughly to Pioneer (251.8 kg) through Voyager (825.4 kg), with New Horizons intermediate between these (478.3 kg wet at launch) (McNutt et al. 2019). A corresponding payload mass to begin would be ~40 to 50 kg (McNutt 2011) with a power requirement ~40 to 30 W electric (We) (McNutt 2010).

Communications downlink is similar. In the near term, microwave downlink (X-band or Ka-band) is well developed, known, and robust. While optical laser communication might achieve far higher downlink rates, it requires extreme pointing stability, and the associated lifetime needs investigation.

Enabling technologies are also not new. The need and capability for radioisotope power systems (RPS) for powering deep-space robotic spacecraft operating far from the Sun is well established (NRC 2009; Huang et al. 2009; Cui et al. 2004) and will be required for Interstellar Probe as well. Similarly, in this study the use of the Space Launch System (SLS) cargo version (Smith 2017) is in use along with upper stages (McNutt et al. 2019). The extreme lift capability of the SLS was previously designed for the U.S. Saturn V and U.S.S.R. N-1 human lunar launch vehicles.

2.7. Engineering Requirements

As with any other study of this type, initial engineering requirements must be imposed to begin an inherently iterative process of design. Engineering requirements are needed to frame the engineering study and "bound the box" —– but allow for trades. As with other aspects of this study, these are also still evolving:

1. Enable a mission that can be launched no later than 1 January 2030 (as noted).

2. Have the capability to operate from a maximum range of not less than (NLT) 1000 astronomical units (a.u.) from the Sun.

3. Require no more than 400 Watts of electrical power (We) at the beginning of mission (BOM) and be able to operate at

no less than half of the BOM amount at the end of mission (EOM)[4].

4. Achieve a mission lifetime of NLT 50 years with a probability of success of NLT 85%[5].

2.8. Mission Concepts

Given the requirement of near-term flight, low-thrust, in-space propulsion systems, such as nuclear electric propulsion (NEP) and solar sails are not under consideration as part of this study. Here we focus entirely upon ballistic solutions with Jupiter Gravity Assists (JGA) in order to maximize the asymptotic solar escape speed while not being overly limited with multiple planetary gravity assists. Hence, three options are under study. The first two use prograde gravity assists at Jupiter; the third uses a retrograde gravity assist and a powered "Oberth maneuver" near the Sun (Oberth 1970):

1. **Option 1**: Unpowered Jupiter Gravity Assist (JGA)
   Burn all stages directly after launch
   Follow with optimized prograde JGA

2. **Option 2**: Active Jupiter Gravity Assist
   Take one stage to Jupiter and burn it at optimized perijove
   Opposite of orbit insertion maneuver

3. **Option 3**: JGA + Oberth Maneuver Near the Sun
   Reverse JGA to dump angular momentum
   Fall in to the Sun without actually hitting the Sun, maximizing your incoming speed
   Burn final stage(s) at (close) perihelion

While option 3 appears to offer significant advantages in increasing the asymptotic flyout speed, there are a number of substantial engineering constraints that will increase the mass and potentially negate these advantages. As a starting point we have considered what a New Horizons type spacecraft would require in terms of a thermal shield and control. To begin this analysis, we have estimated thermal shield for perihelia of 3 solar radii (from the center of the Sun, R_S), 4 R_S, and 5 R_S. For each case we verify thermal performance, estimate thermal shield mass, and estimate system performance. The thermal environment is based upon a combination of carbon- carbon and tungsten shields suggests temperatures ~2200°C to 2600°C (hottest) at 5 R_S. As an example of several configurations under study, the Option 3 configuration with a notional New Horizons — like spacecraft and a CASTOR 30XL stage with thermal shields for 3 R_S, 4 R_S, and 5 R_S perihelia show that the kick-stage engine dominates the required shield area (Figure 4).

4 This was the requirement at the time of the meeting; at the current time (June 2020), the 400 We BOM has been increased to 600 We BOM.

5 The 50-year lifetime requirement remains in play, but exactly how to characterize it in terms of probabilities remains in detailed study.

The realities of flight near the Sun connect with Parker Solar Probe. But you can't "go at night." At the end of Parker Solar Probe (PSP) mission (in seven years) we will be at a perihelion passage of 9.86 R_S but this is not close enough to gain the potential advantages of an Oberth maneuver. Nonetheless, Parker Solar Probe (designed at APL) may be a pathfinder toward solutions.

Potential performance gains from using a Solar Oberth Maneuver look promising, but the simplest notions cannot currently be built or flown. The situation is analogous to that facing Parker Solar Probe development team for its thermal protection shield (TPS) in 2002. The issues associated with Option 3 are under ongoing study.

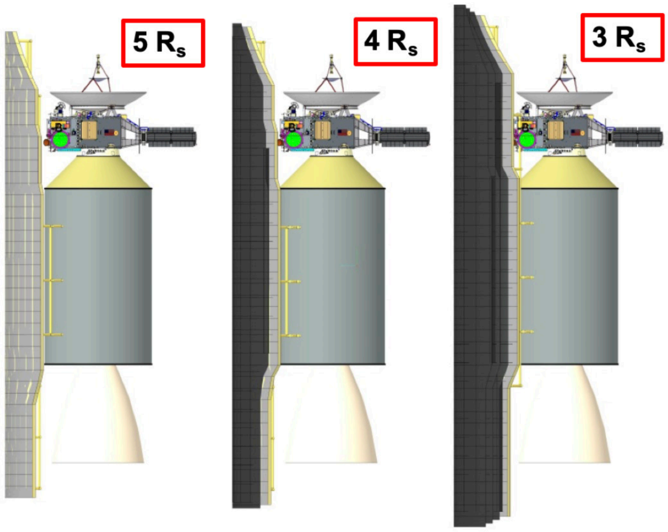


Figure 4: A New Horizons spacecraft mated with a CASTOR 30XL upper-stage solid rocket engine and corresponding thermal shield for the indicated solar perihelia distances (referred to the center of the Sun). Temperature and shield mass increase with decreasing perihelion distance (left to right).

2.9. A Possible Mission

As the study continues and matures in an iterative process, we also evaluate possible missions as part of the study to help illuminate issues and potential problems. At the time of the ISSI-BJ meeting, a recent study looked at the possibility of having a rapid flyby of the KBO Quaoar (and its small moon Weywot)

(Figure 5) (Fraser 2010) with a spacecraft of the mass of New Horizons:

- Mode: Option 1
- Immediate Target: Quaoar and its system
- Final Target: VLISM
- Launch: 24 February 2030
- Arrival at Quaoar: 28 January 2037
- Time to Quaoar: 6.93 years
- Flight time to Jupiter: 9.77 months
- Launch C3: 329 km^2/s^2
- Jupiter perijove: 5.26 R_J
- Asymptotic speed: 5.97 AU/yr
- Quaoar flyby speed:29.07 km/s
- Distance at Quaoar: 42.29 AU

Figure 5: Fig. 5. Hubble Space Telescope image of cubewano 50000 Quaoar and its moon Weywot, taken on 14 February 2006. (From Wikimedia Commons - Produced by the Space Telescope Science Institute (STScI) for NASA under Contract NAS5-03127).

In this case, the asymptotic escape speed from the Sun is less due to Quaoar's location above the plane of the ecliptic. This is one example of a possible mission that could fly (1) by a KBO, (2) through the "ribbon", and (3) near to the heliospheric "nose." Other such multi-faceted trajectories are also possible; all details continue to remain in play in the trade space under study.

2.10. Conclusion

With this current study well underway, there is a growing consensus, both within the U.S. and in the international community, that the time has come for a dedicated Interstellar Probe mission. The Voyagers in their greatly extended missions have shown again that there is no substitute for in-situ measurements for advancing our knowledge of our home in the cosmos. That said, those venerable spacecraft are coming to the end of their operational lifetimes, as did Pioneer 10 and 11 before them, and New Horizons, the only other Sun-escaping spacecraft currently does not have the power margins or speed to reach as far as the Voyagers.

New advances require new steps if they are to be brought to fruition. The growing list of successes of Parker Solar Probe in unraveling the mysteries of the outer solar corona once more demonstrate that the challenge of a difficult space mission can pay handsome rewards. In humanity's quest for new knowledge from the Sun to the stars, the real journey has only just begun…

3. RECENT PROGRESSES IN UNDERSTANDING THE OUTER HELIOSPHERE AND NEARBY INTERSTELLAR MEDIUM I

3.1. Voyager Observations near the Heliopause

Voyager 1 (V1) crossed the heliopause (HP) in August 2012 (day 238) at 121.7 AU, while Voyager 2 (V2) crossed it in November 2018 (day 308) at 119.0 AU. Thereafter, we have compared these two crossings to see which features are intrinsic in a HP boundary and which may be time and/or location-dependent. Figure 6 shows that both HP crossings have a broad HP boundary region with a complex structure. The V1 HP crossing is marked by an abrupt increase in the magnetic field strength B, a decrease of heliosheath (HSH) energetic particles, and an increase in the galactic cosmic ray (GCR) counting rate. Several precursors were observed at V1, with smaller decreases in B and the energetic particles, and increases in the GCRs centered on day 212 and day 230 of 2012 (Stone et al. 2013; Krimigis et al. 2013; Burlaga et al. 2013). After the HP, B remained high and steady, energetic particles disappeared, and GCR intensities plateaued. Plasma wave data confirmed the densities were high as expected in the very local interstellar medium (VLISM) (Gurnett et al. 2013). The precursors may be flux tubes moving from the VLISM into the HSH.

The V2 crossing in Figure 7 did not have precursors like those at V1. At day 309, the magnetic field strength sharply increased, the HSH energetic particles decreased, the GCR counting rate increased, and the radially outward plasma currents dropped to background levels (Burlaga et al., 2019; Krimigis et al., 2019; Richardson et al. 2019; Stone et al., 2019). This enhanced field region is called the Magnetic Barrier.

The dashed vertical lines show the beginning of the HP boundary region (blue), precursors to

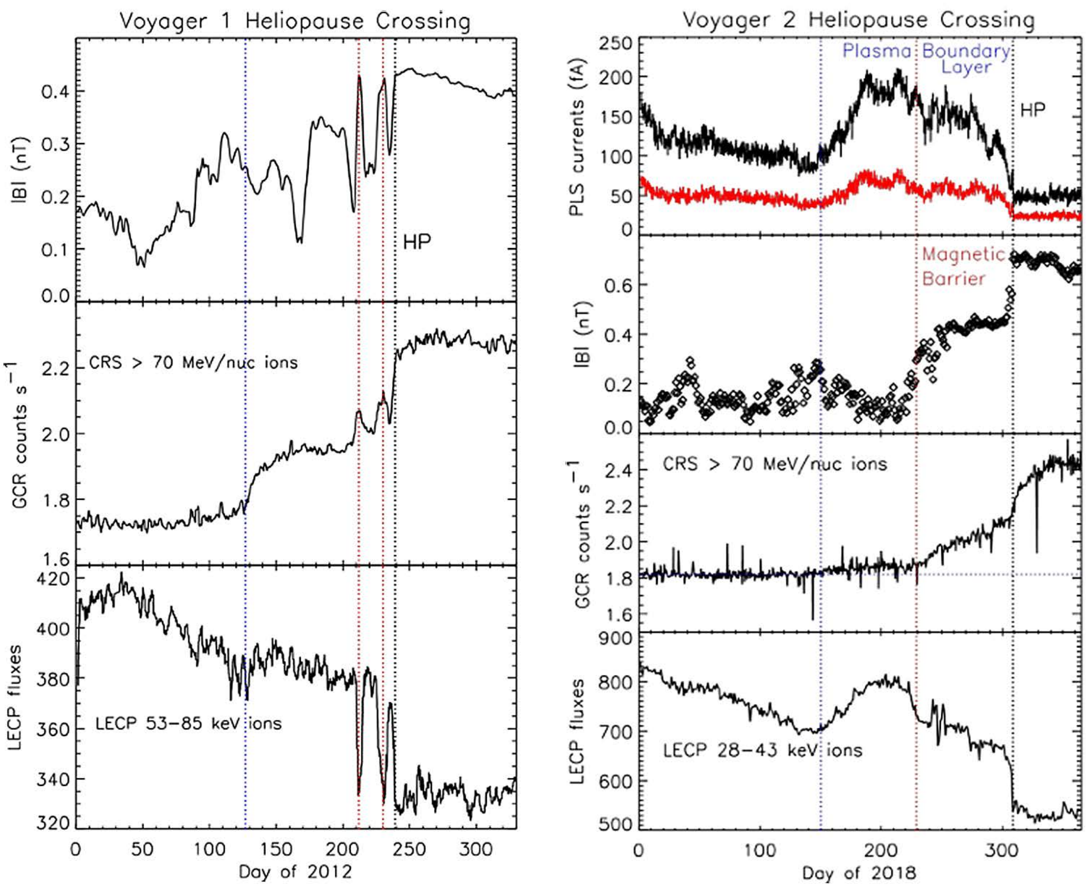


Figure 6: The V1 and V2 HP crossings. The V1 panels show the magnetic field magnitude, the >70 Mev/nuc cosmic ray count rate, and the 53–85 keV ion intensities.

the HP (red), and the HP (black). The V2 panels show currents in the sunward-looking plasma B (black) and C (red) detectors, the magnetic field magnitude, the >70 Mev/nuc cosmic ray count rate, and the 28–43 keV ion intensities. The dashed vertical lines show the beginning of the plasma boundary region (blue), the beginning of the HP boundary region and magnetic barrier (red), and the HP (black).

The biggest surprise of the V1 HP crossing was that the direction of the magnetic field B did not change (Burlaga et al. 2013; Burlaga and Ness 2014). Models disagree on whether this lack of B rotation was a coincidence of geometry or if the rotation of the VLISM B toward the Parker spiral direction was an intrinsic HP feature. Figure 7 shows that at the V2 HP crossing the direction of B again did not change (Burlaga et al. 2019). At V1 the magnetic field direction near the HP was nearly constant but different from the Parker field direction of 270° by about 20° in azimuth and 18° in elevation angle. At V2, the azimuthal angle was very close to 270°

but the elevation angle was about 20°. No measurable rotation occurred at the HP itself. We are currently working on understanding these observations.

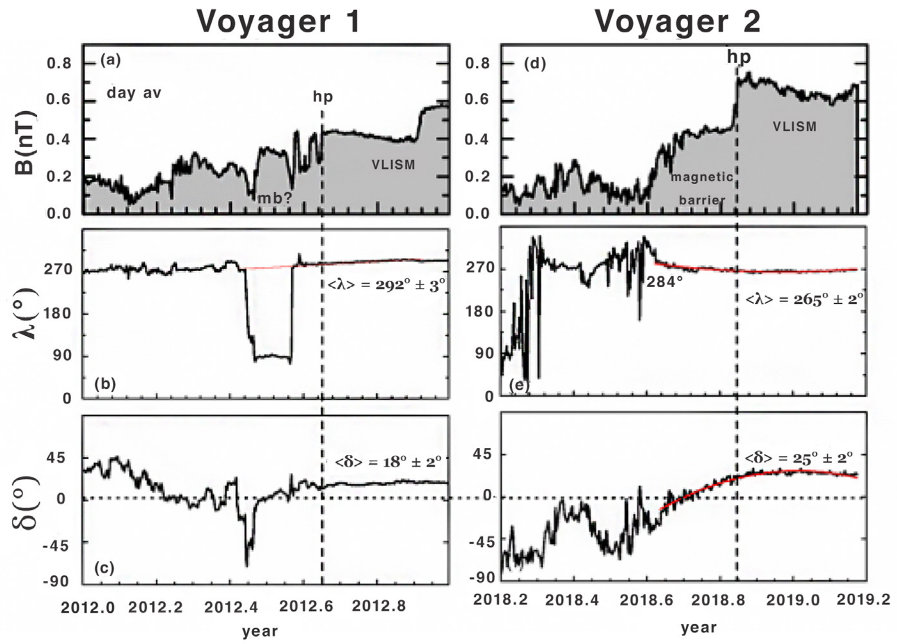


Figure 7: Magnetic field observations by V1 and V2 near the HP.

3.2. Magnitude and Direction of the Local Interstellar Magnetic Field inferred from Voyager 1 and 2 Interstellar Data

We have set ourselves a specific question: what constraints on pristine (i.e., unperturbed by the interaction with the Sun) Local Interstellar Magnetic Field (IsMF) can be established from the data of magnetometer instruments onboard Voyager 1 and 2 spacecraft (Burlaga et al. 2018, 2019a, and 2019b)? The magnetometers onboard Voyager 1 and 2 measured, for the first time, the IsMF after they crossed the heliopause. We provided a detailed comparison of the three IsMF components measured by Voyagers 1 and 2 with those obtained in the model. The analysis was performed with the help of our kinetic-magnetohydrodynamic model of the global heliosphere. We consider the consequences of two observational phenomena:

1. The radial component of the magnetic field B_R is positive in Voyager 1 direction, and negative (but close to zero) in Voyager 2 direction

2. The B_T component of the IsMF in radial tangential normal (RTN) coordinate system is negative in both directions

These facts provide restrictions on the local shape of the heliopause in the directions of the crossings and also on the topology of the interstellar magnetic field around the heliopause.

If we assume an ideal non-dissipative approach (as in the model), then the heliopause is a tangential discontinuity with $B_n = 0$, where B_n is the projection of the magnetic field vector to the normal of the heliopause surface. Therefore, the magnetic field vector should be parallel to the surface of the heliopause. In this case, the sign of the B_R component depends on the local shape of the heliopause. If the heliopause is locally spherical, then B_R is equal to 0. If the projection of the normal to the heliopause on the X-axis (toward upwind) is larger than the X-axis projection of the unit radius vector, then heliopause has a blunt shape (Fig. 8, panel A1). Otherwise, the shape is oblong (Fig. 8, panel A2). The sketches in panels A1 and A2 also show that in the case of negative B_T, B_R is bigger than 0 for the blunt case, while B_R is smaller than 0 for the oblong one. In the direction of Voyager 1, $B_T < 0$, and $B_R > 0$, and therefore, the heliopause has to have a blunt shape in this direction. In the direction of Voyager 2, $B_T < 0$ and $B_R < 0$, and thus, the heliopause has to have an oblong shape in this direction. Panels B1 and B2 of Fig. 8 clearly illustrate the stretching and pushing of the heliopause. In the case of

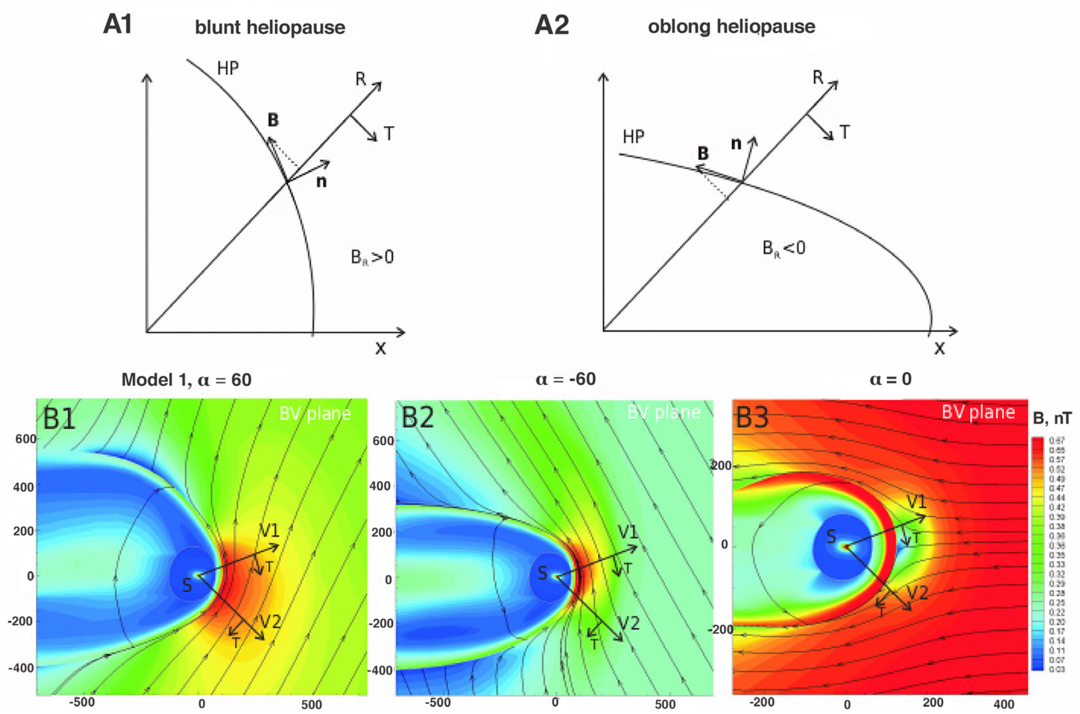


Figure 8: Panels A: sketch of the blunt (A1) and oblong (A2) shape of the heliopause. Panels B: magnetic field lines and magnitudes of the magnetic field in the plane determined by V_{LISM} and B_{LISM} vectors. Panel B1: a model with the magnetic field critical point above Voyager 1; panel B2: a model with the magnetic field critical point (B = 0) below Voyager 2; panel B3: a model with the critical point located in between Voyager 1 and 2 (B3).

panel B1, the heliopause has a blunt shape in the direction of Voyager 1, and an oblong shape in the direction of Voyager 2. Therefore, $B_R > 0$ and $B_R < 0$ in the directions of Voyager 1 and 2, respectively. These calculations are in accord with the observations of Voyager. For the case shown in panel B2, the heliopause is oblong and $B_R < 0$ in the direction of Voyager 1, while the heliopause is blunt and $B_R > 0$ in the direction of Voyager 2.

We conclude that the signs of B_R and B_T components measured in the directions of Voyager 1 and 2 provide qualitative constraints on the magnetic field configurations in the vicinity of the heliopause. Namely, the configuration should be qualitatively similar to the case shown in panel B1, that is, the critical point of the magnetic field should be above the Voyager 1 direction. The scenarios shown in panels B2 and B3 are ruled out.

Assuming the magnetic field to be lying on the hydrogen deflection plane, we performed parametric calculations by varying the magnitude of the interstellar magnetic field, the angle α (between vectors of the interstellar velocity and magnetic field), and the interstellar proton and H atom number densities. From the comparison of the model results with Voyager data, we have found that the model provides results that are comparable with the data for the interstellar magnetic field of B_{LISM} = 3.7–3.8 μG in magnitude and directed towards ≈125° in longitude and ≈37° in latitude in the heliographic inertial coordinate system (Izmodenov and Alexashov 2020).

3.3. Our Heliospheric Shield

As the Sun moves through the interstellar medium, it carves a bubble called the heliosphere. A fortunate confluence of missions has provided a treasury of data that will likely not be repeated for decades. The in situ measurements carried out by the Voyager and New Horizon spacecraft, combined with the all-sky ENA images of the heliospheric boundary region by the Interstellar Boundary Explorer (IBEX) and CASSINI missions, have transformed our understanding of the heliosphere. However, many fundamental features of the heliosphere are still not well understood. These aspects include the basic "shape" of the heliosphere, the extent of its tail, the nature of the heliosheath, and the structure of the local interstellar medium (LISM) just upstream of the heliopause (HP).

Other still open questions are:

1) The acceleration region and mechanism for anomalous cosmic rays (ACRs). The two Voyager spacecraft found no evidence of acceleration of high-energy ACRs at the termination shock (TS), but instead detected their increase of the ACRs as they moved across the heliosheath (HS).

2) The HS is 30-50% thinner than what current models predict.

3) The plasma flows (Figure 9) and energetic particles intensities are drastically different at V1 and V2. At V1 there is a stagnation region where the there is no radial flow for 8 AU in front of the HP, while at V2 the radial speeds remain high until very close to the HP.

4) The magnetic field direction doesn't change at the HP and we don't know how far from the HP does the solar wind influence extend.

5) The significant increase in Galactic Cosmic Rays (GCRs) just prior to the HP crossings by both V1 and V2 as well as the unusual anisotropies observed in the LISM are not understood yet.

The ENA observations are to be added to the list of unanswered riddles. IBEX detected a global feature, the ribbon, that seems to be caused by the interstellar magnetic field. INCA on CASSINI measured a similar yet broader feature at higher energies. The source of these features is controversial; the models proposed to explain these features rely on assumptions for the interstellar conditions such as the draping of the interstellar magnetic field and the level of turbulence in the LISM.

When V1 crossed the HP, it discovered that the heliosphere shields 75% of the harsh galactic radiation environment coming from Earth (Figure 10), protecting life on our planet and throughout the heliosphere.

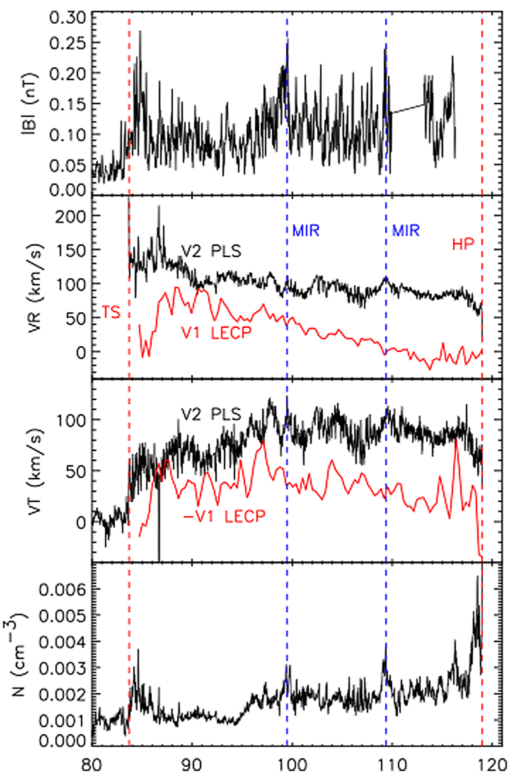


Figure 9: An overview of the heliosheath (HS). The top panel shows the magnetic field which varies by a factor of four across the heliosheath. The second and third panels show the radial and tangential speeds observed by the V2 plasma instrument (black lines) and those derived for from the V1 low energy charged particle (LECP) data. The V1 data are time-shifted to align the TS and HP locations at each spacecraft. The bottom panel shows the densities at V2. AU propagating toward the HP. Note the very different speed profiles at V1 and V2, with radial and tangential speeds much higher at V2 than V1 (-VT is plotted for V1 to highlight the magnitude difference). These differences are not understood.

We have currently a Phase I DRIVE Science Center (DSC) called SHIELD. The goal of this DSC is to develop a new predictive global model for the heliosphere. SHIELD (Solar wind with Hydrogen Ion charge Exchange and Large-Scale Dynamics) uses a combination of observations, theory, localized kinetic, and MHD models to achieve this goal. To do it, this DSC answers the following questions:

1. What is the global structure of the heliosphere?

2. How do pickup ions evolve from "cradle to grave" and affect heliospheric processes?

3. How does the heliosphere interact with and influence the local interstellar medium (LISM)?

4. How do cosmic rays get filtered by and transported through the heliosphere?

The heliosphere is an immense shield that protects the solar system from harsh galactic radiation. This radiation affects both life on Earth and human space exploration. The heliosphere is a window into processes occurring in all other astrospheres. Understanding these processes makes predictions about the astrospheric conditions necessary to create habitable planets possible.

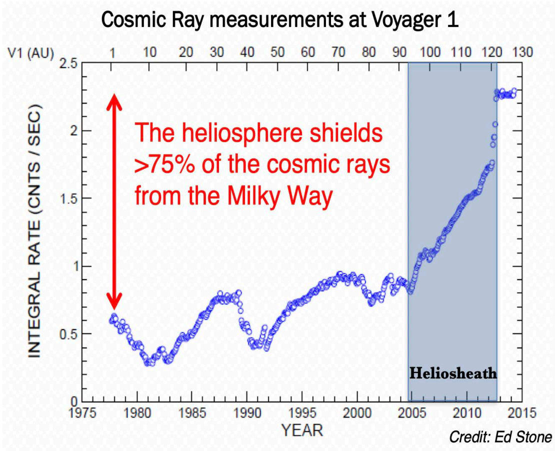


Figure 10: The heliosphere shields 75% of the harsh galactic radiation.

3.4. Interstellar Neutrals (H, He, O, Ne) in the Heliosphere measured by IBEX-Lo

The local interstellar medium (LISM) contains neutral elements such as H, He, O, and Ne that have a large mean-free path for charge exchange, which is equal (for H and O) to or larger (for He and Ne) than the characteristic size of the heliosphere. Therefore, these atoms can penetrate the heliosphere due to the relative motion of the Sun and LISM and can be measured at Earth's orbit by the Interstellar Boundary Explorer (IBEX) spacecraft. The distribution of these atoms carries information about their abundance in the LISM and also about the properties of the heliospheric boundary.

The fluxes of H atoms measured by the IBEX-Lo instrument (0.01 – 2 keV) were analyzed in detail by Schwadron et al. (2013), Katushkina et al. (2015), and Galli et al. (2019). The comparison between the model calculation's results and the data showed some qualitative differences, which remain unexplained. For example, all existing models predict a larger count rate in energy step 2 (20 – 41 eV) than in energy step 1 (11 – 21 eV), while data shows the opposite scenario. The He fluxes obtained by IBEX-Lo were also studied by many authors (for instance, Kubiak et al. 2014; Swaczyana et al. 2018). The main result of these works is the discovery of the so-called "Warm Breeze", which is the slowed and warmer secondary helium population produced by charge exchange of He ions with He atoms ($He^+ + He \rightarrow He + He^+$).

In 2015, the first quantitative data with measurements (by IBEX-Lo sensor) of interstellar O and Ne atom fluxes were presented by Park et al. (2015). A qualitative analysis of these data showed that, along with primary interstellar oxygen atoms that directly penetrate the heliosphere from the interstellar medium, a secondary component was also measured, which is formed in the vicinity of the heliopause due to the charge exchange of interstellar O ions with H atoms ($O^+ + H \rightarrow O + H^+$). Park et al. (2019) performed the characterization of the secondary ISN O population and estimated its velocity and temperature at the heliospheric boundary.

In the course of our work, self-consistent calculations of the velocity distribution function of O atoms were performed using the global model of SW/LISM interaction (Izmodenov and Alexashov 2015). The calculations were carried out for two different configurations of the interstellar magnetic field B_{LISM}:

- Model 1 - B_{LISM} = 4.4 μG, the angle between the B_{LISM} and V_{LISM} vectors is 20° (corresponds to the parameters from the model by Izmodenov and Alexashov 2015)

- Model 2 - B_{LISM} = 3.75 μG, the angle between the B_{LISM} and V_{LISM} vectors is 60°

The magnetic field configuration in Model 2 was chosen in such a way that the global heliospheric calculations fit the Voyager 1/2 spacecraft data. The influence of the interstellar magnetic field leads to asymmetry of the heliosphere and deviation of the plasma flow in the vicinity of the heliopause. As a result, atoms that originated by charge exchange of O ions in this region (secondary component) also receive a deviation of the average velocity from the direction of the interstellar wind. Therefore, the configuration of the interstellar magnetic field near the heliopause affects the spatial distribution of atoms inside the heliosphere.

We studied the distribution of interstellar O atoms in the heliosphere using our kinetic model, which takes into account the filtration of primary and the production of secondary interstellar oxygen in the SW/LISM interaction region. Such a model allowed us to perform a quantitative comparison of simulation results with data obtained on the IBEX spacecraft (Baliukin et al. 2017). A comparison of the results of numerical calculations performed with different configurations of the interstellar magnetic field allowed us to evaluate the possibility of using IBEX-Lo data to diagnose the interstellar magnetic field properties near the heliospheric boundary.

Figure 11 shows the sky map of O and Ne atom fluxes in ecliptic coordinates according

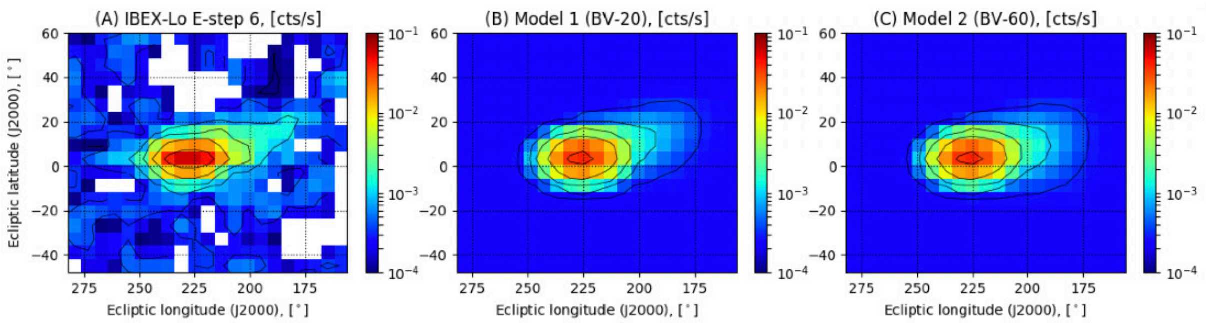


Figure 11: (A) flux map (in ecliptic coordinates) of O & Ne atoms obtained by IBEX-Lo (Park et al., 2015); (B) flux map according to the calculations using the Model 1; (C) flux map according to the calculations using the Model 2.

to the IBEX-Lo data of energy step 6 (A), as well as the model flux maps by numerical calculations using two different configurations of the interstellar magnetic field - Model 1 (B) and Model 2 (C). A similar structure is visible in all maps: the so-called extended "tail" — the fluxes of the secondary component — go away from the region of the maximal fluxes, shown in red in the figures and formed by primary oxygen atoms, towards lower longitudes and higher latitudes. Although model 2 (Fig. 11B) predicts a greater amount of secondary hydrogen atoms (~50%) at the heliospheric boundary, which is better consistent with IBEX-Lo data compared to Model 1, the differences between the model flux maps are almost negligible. We also see that on the used model of the interstellar magnetic field there is a weak dependence of the "tail" geometry in the map of fluxes formed by the secondary O atoms. The results of these calculations make it clear that the current geometry of IBEX observations in conjunction with the energy and spatial discretization of the IBEX-Lo instrument does not allow us to perform a quantitative diagnosis of the magnetic field at the heliosphere boundary. So, for these purposes, other experiments with improved accuracy and, probably, different observational geometry are needed.

4. RECENT PROGRESSES IN UNDERSTANDING THE OUTER HELIOSPHERE AND NEARBY INTERSTELLAR MEDIUM II

4.1. Magnetic Trapping of Galactic Cosmic Rays in the Outer Heliosheath

The direction and strength of the interstellar magnetic field has not been measured to date. Voyager 1 and 2 are measuring a field that has been wrapped ("draped") around the heliosphere (the surface separating solar plasma from the interstellar medium, ISM), and points tangentially to the surface of the heliopause. Remote sensing observations using energetic neutral atoms (ENAs) believed to originate in the region of space beyond the heliopause feature a prominent circular structure known as the "ribbon" (McComas et al. 2009). According to the prevalent theoretical paradigm, the center of the ribbon marks the direction of the interstellar magnetic field far away from the heliosphere (Heerikhuisen et al. 2010). This conjecture has not been independently verified via in situ observations. Because the matter is of great astrophysical importance, it is hoped that future deep space missions will reveal the true direction and strength of the magnetic field in the ISM.

There exists a certain preferred direction where the draped field does not deviate too much from interstellar direction. Several models of the

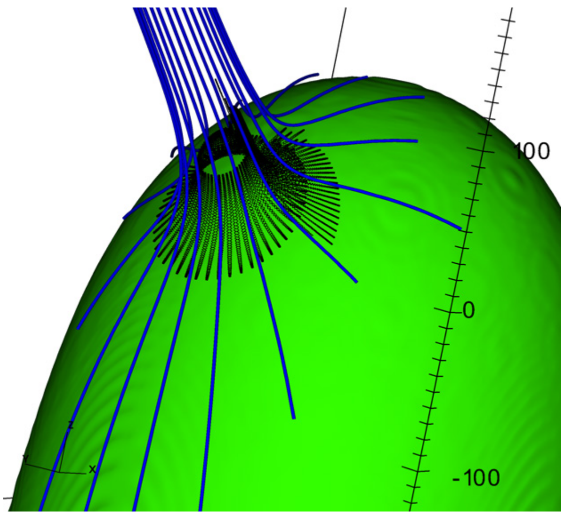


Figure 12: Magnetic field lines (blue) and cosmic-ray trajectories (black) inside a magnetic trap. Figure produced based on an analytical model of the plasma flow around the surface of the heliopause, shown in green (Röken et al. 2015).

heliosphere predict such a region (e.g., Chalov et al. 2010); its location is somewhat uncertain but it is likely to be north of the heliographic equator and on the forward facing part of the heliopause. This special region is where the magnetic field lines approach the heliosphere at a right angle. Field lines extend themselves in this direction, enveloping the heliopause. A region of weaker field surrounded by a stronger field is called a magnetic trap. Energetic charged particles shut in the trap bounce between the regions of strong field unable to leave the confines of the trap.

Galactic cosmic rays (GCRs) might enter the magnetic trap as a result of field reconfiguration due to transient structures impacting the heliopause from the solar wind or local instabilities (e.g., Florinski 2015). Some cosmic rays also reach the interior of the trap via non-adiabatic processes, such as pitch angle scattering. Because the field lines forming the trap spread over the entire surface of the heliopause (see Figure 12), it might be expected that the bulk of GCRs would enter the heliosphere from the direction of the field in the ISM, i.e., the center of the IBEX ribbon. The GCR storage time inside the trap should be comparable to the length of the drift cycle (associated with the approximate conservation of the third adiabatic invariant), which is of the order of one year.

Particle escaping from the trap in the direction of the heliopause would create a streaming anisotropy whose magnitude depends on their rate of heliopause crossing. A second order anisotropy might develop as a result of the process called 'drift shell splitting', where particles with different pitch angles take different paths around the trap. While in most other directions GCR intensities are spatially uniform and isotropic (Cummings et al. 2016; Guo and Florinski 2015), more variation is expected inside the magnetic trap. It would be a promising direction to be explored with the next generation of interstellar explorers.

4.2. Study Galactic Cosmic Ray Modulation using the Interstellar Probe

As the solar wind expands, it interacts with the interstellar medium, and as a result, a bubble-like structure is formed, which is what we now call 'heliosphere'. As galactic cosmic rays (GCR) travel into this region, the interaction with the solar wind causes the GCR intensity to vary along with solar activity, which is the so-called 'solar modulation' (Potgieter 2013). Currently, the ground-based neutron monitor and lots of heliospheric missions have accumulated lots of observational data for the GCR solar modulation phenomena. In particular, recently the already launched PAMELA mission as well as the AMS02 mission provide an accurate measurement of the proton spectrum.

It is known that Voyager 1 crossed the heliopause (HP) in August 2012. The GCR intensity sharp change is one of the signatures for this historic jump. According to Cummings 2016, the GCR intensity remains constant after the HP crossing event. This suggests that Voyager 1 has already measured the pristine GCR Very Local Interstellar Spectrum (VLIS). The observation also suggests that there is no modulation happening beyond the HP. Since Voyager 1 only provides the cosmic ray spectrum below ~300 MeV/nucleon, for the Local Interstellar Spectrum measured there is still a gap between the lower energy part and the higher end obtained from the near-Earth instruments, e.g., PAMELA. In such circumstance, the Interstellar Express mission can be used to measure the VLIS for various elements of GCR, and it can specifically focus on the current spectrum gap between ~300 MeV/nucleon and 30 GeV/nucleon. Considering the weight requirement for the payload and other technique issues, it is still possible to measure the GCR up to 1GeV/nucleon.

Since GCR is coming from outside of the heliosphere, its intensity will become higher as the heliocentric radial distance increase. The radial gradient, namely

$$Gr = \frac{d \ln J}{dr}$$

is used to measure this spatial variation quantitatively. A long-lasting puzzle is the effect of the Termination Shock (TS) on GCR modulation (Caballero-Lopez et al. 2014; Jokipii 1993), and because of the shock acceleration introduced by the TS, the GCR radial gradient will become larger across the TS. By using a MagneticHydroDynamic (MHD) simulated plasma background, Ball et al. (2005) showed that the intensity of GCR can be even higher than the VLIS magnitude near the TS; Florinski and Pogorelov (2009) illustrated that the GCR radial gradient vary little across the TS; Luo et al. (2013) demonstrated that for lower energy GCR (<1GeV) the GCR radial gradient increase across the TS, while the effect is not pronounced for higher energy GCR. The interstellar express can be used to measure the radial gradient across the TS, providing a good opportunity to clarify this issue.

4.3. Solar Wind Events and their Consequences in the Outer Heliosphere

As well known, the heliosphere is the product of the interaction between the expanding solar wind and the inflowing interstellar medium. There are two discontinuities, the termination shock and the heliopause explored by the two Voyager probes, and when the solar wind propagates into the outer heliosphere, some consequences will be observed and recorded by the spacecrafts, e.g., plasma waves or pulses. Voyager 1 observed the two forward shocks and a possible reverse shock from the magnetic field data from 2012 to 2014. It was believed that the solar wind events from the inner heliosphere are the origin of this kind of shock events.

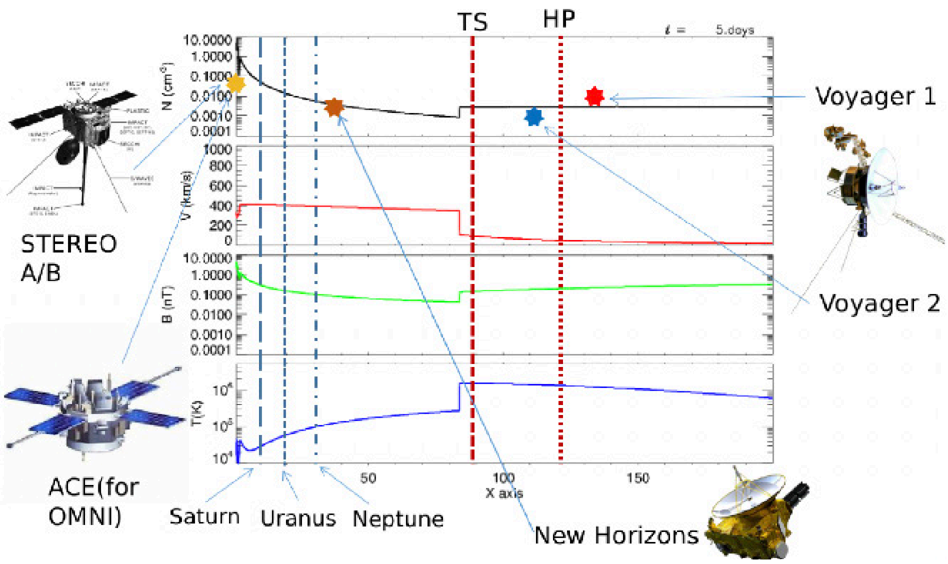


Figure 13: Simulated solar wind evolution from 1 to 200 AU.

One of the typical solar wind events is called coronal mass ejection (CME), which carries a huge amount of solar mass and energy into space. CME is released from the solar corona, and when it leaves the Sun, it forms the well-known interplanetary coronal mass ejection (ICME) in the interplanetary space. Another typical solar wind event consists in the stream interaction regions (SIRs), which are produced by the interaction between slow and fast solar wind, and are always present in the solar wind. SIRs become the co-rotating interaction regions (CIRs) once they co-rotate with the Sun during the solar minimum. Compared with the abrupt ICMEs, SIRs or CIRs are observed much more frequently. Both types of solar wind events contribute to the main mass, momentum, and energy transport from the Sun to the interplanetary space and beyond.

So, the question arises on how to connect the solar wind events in the inner heliosphere, at around 1 AU from the Sun, and the shock events detected in the interstellar medium which exists beyond ~120 AU? A possible answer is to run the numerical simulation of magneto-hydrodynamics (MHD) to track the evolution of solar wind events. We use a simplified MHD model to simulate the propagation of solar wind in the heliosphere. First, the solar wind is assumed to be a spherically symmetrical flow near the equatorial plane; thus, there is no side impact for the solar wind during its radial propagation. Under such an approximation, the solar wind input will be greatly simplified. We have additional effects, e.g., solar gravity and charge-exchange with interstellar neutrals in the model. No interstellar plasma is taken into account, thus no HP is expected. We use the MUSCL numerical scheme and HLLC Riemann solver and Runge-Kutta to implement the MHD equations, with a second order accuracy for the spatial reconstruction and time evolution. The observations from OMNI, STA, and STB are

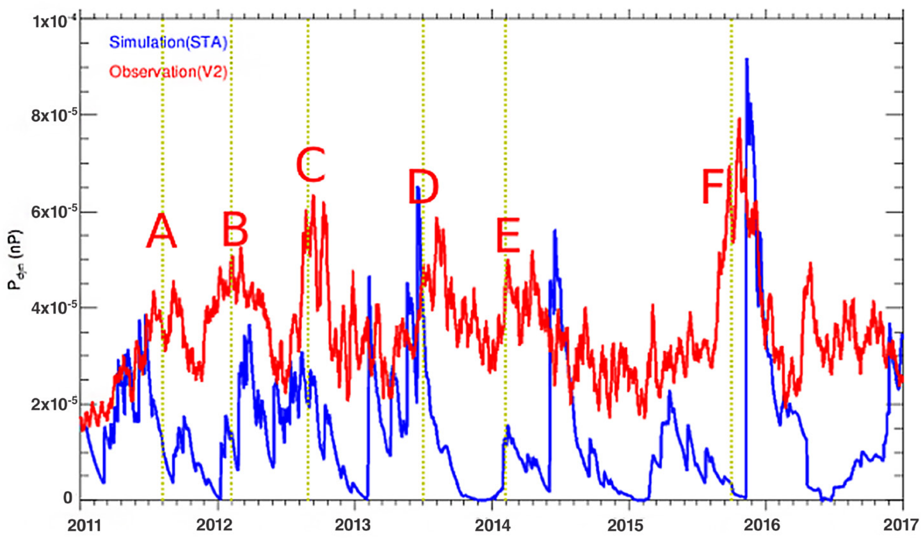


Figure 14: Dynamical pressure comparison between simulation and observation by Voyager 2 in the inner heliosheath.

used as the input at 1 AU for the simulation, within a time frame of eight years, from 2010 to 2018.

Figure 13 shows the propagation of the solar wind from 1 to 200 AU. From top to bottom, the panels give the time-dependent profiles of the solar wind, including density, velocity, magnetic field strength, and temperature. The STEREO A/B and OMNI observations are input at 1 AU, as the yellow star shows. From left to right, the vertical lines show the position of Saturn, Uranus, Neptune, the termination shock, and the heliopause, respectively. The positions of NH, Voyager 1 and 2 are also illustrated. Note that during this period, Voyager 1 was beyond HP and the detected interstellar medium, while Voyager 2 was still in the heliosphere and the detected solar wind. We can see that the solar wind propagates along the radial direction, merging at different distances and forming the well-known merged interaction regions, shocks are developed, they move fast outward, and should be detected by the three spacecrafts. Three virtual spacecrafts with similar radial distances as New Horizons, Voyager 1, and Voyager 2, will be set to detect the simulated solar wind variations. The results will be compared with the real observations.

We then looked at the time-dependent variation of the dynamic pressure of the solar wind in the inner heliosheath from 2011 to 2017, as Figure 14 shows. The previous work indicated that the pulses of dynamical pressure in the inner heliosheath observed by V2 are potentially linked to the shocks observed by V1 in the interstellar medium. Blue curves indicate simulation results, and red ones the observations by Voyager 2. The vertical lines roughly sketch the time when the observed dynamic pressure reached a local maximum. However, different from the estimation made from the observation, we argue that the second forward shock may be linked with pulse E, not D as mentioned by the published paper.

In reality, the evolution of the solar wind is very complicated. The comparison between numerical simulations and observations in the outer heliosphere is still a big challenge for researchers. This simple modelling of solar wind may have some hints for our future investigation of solar wind evolution in the outer heliosphere.

5. SCIENTIFIC OBJECTIVES OF THE INTERSTELLAR MISSION

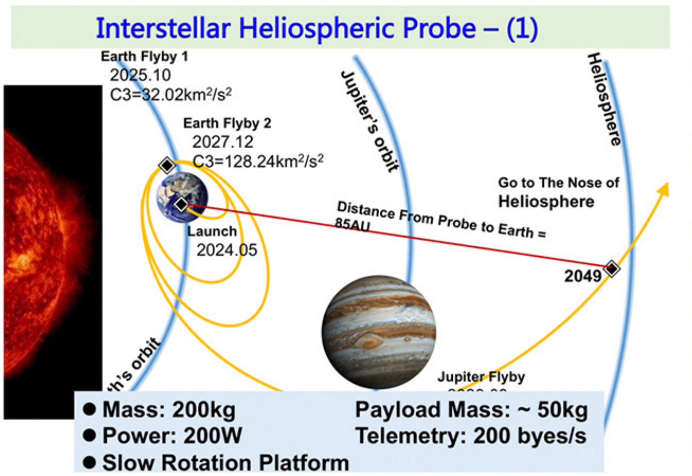
5.1. From the Earth‘s Magnetospheres to the Outer Heliosphere and beyond

In the solar system, planets, including Mercury, Earth, Jupiter, Saturn, Uranus, Neptune, and some moons, can generate and maintain magnetospheres, the region of space defined by the interaction of the solar wind with the planet's intrinsic magnetic field. Similarly, the heliosphere is the Sun's magnetosphere, a colossal cavity of magnetism embedded in the surrounding interstellar flows; but there is one obvious difference that it's inflated by the solar wind. The outer heliosphere is the "plasma interface" of our solar system and the galaxy, which was crossed by Voyager 1 in August 2012 and led to the detection of a sudden increase in cosmic rays. On one hand, all the planetary bodies inside the heliosphere are affected by the extended atmosphere of the Sun, and on the other hand, they are partly shielded from the impact of the galactic cosmic rays. The Sun, the planetary environments, and the heliosphere can be regarded as elements of a single interconnected system that evolves in response to the Sun's explosive energy output and interstellar conditions.

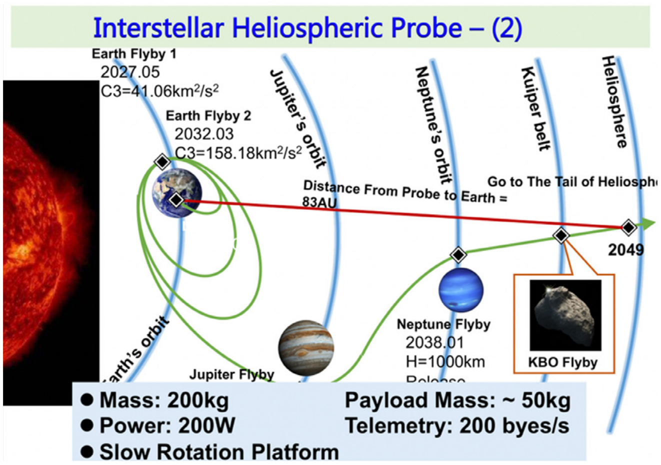
To understand what can affect the habitability of a planet and to navigate safely beyond our planet to a vaster space, we must achieve a comprehensive understanding of the Sun, our heliosphere, as well as the objects inside of it, the universe, and their inter-relationships. Our heliosphere is a kind of environment that is very commonly found in many other stellar systems. But we can only study our hands-on giant plasma physics laboratory.

The Interstellar Heliospheric Probes, a planned mission by CNSA, will provide a great opportunity for significantly facilitating the study of the solar wind's interaction with the interstellar wind, which focus on the measurements of pickup ions, anomalies in cosmic rays, energetic neutral atoms, and the evolving shape of the heliosphere. This mission consists of two probes heading in different directions (see Figure 15) to maximize the scientific outputs:

1. Probe 1 towards the 'nose', exploring the typical observational region to provide reliable observations for scientific theories and hypothesis
2. Probe 2 towards the 'tail', currently without observations, aiming at multi-goal monitoring and expecting more innovative discoveries



(a)



(b)

Figure 15: The Interstellar Heliospheric Probes and the planned roadmaps.

The Interstellar Heliospheric Probes mission will target the following scientific objectives:

1. Determine the change between solar wind ions and interstellar wind neutral particles.

2. Measure the location and shape of the termination shock in the heliospheric tail to find out whether it's simmetrical to the shape in the 'nose' direction.

3. Check the existence of anomalous cosmic rays in the tail-heliosheath region, and whether or not the heliosphere bound is closed.

4. Measure the primordial galaxy cosmic ray and the interstellar medium turbulence outside the solar system.

5. Visit Neptune to explore the mystery of the supersonic jet and the retrograde orbit of Triton.

6. Make fly-by measurement to the Kuiper belt bodies near the ecliptic plane, and search for the original information of solar system formation.

5.2. Icy Giants (and Planet Nine) as the Windows of Opportunity in Outer Heliospheric Exploration

The Interstellar Express now under consideration by the CNSA provides a unique opportunity for the Chinese planetary science community and their international colleagues to explore the outer solar system in a cost-effective manner. At the same time, there is a preliminary discussion on sending an orbiter to Jupiter around 2030 with a special emphasis on the study of the fourth Galilean moon, Callisto. In the current planning cycle, a Uranus flyby mission has been proposed also. Under the assumption that this dual (Jupiter/ Uranus) mission would be approved after successful scientific assessment study and detailed technical preparation, we can embark on developing a possible roadmap for the near-term spacecraft exploration of another icy giant, Neptune, and a number of dwarf planet targets — thus, taking advantage of the Interstellar Express Initiative.

The description given in the previous sections shows that there would be three components in the Interstellar Express mission: (a) one deep-space probe for the frontside heliopause, (b) the second one for the tailward side, and (c) the third one moving along a highly inclined trajectory. We might envision that spacecraft (a) would have the possibility of making a close flyby of a dwarf planet with (50000) Quaoar (~2040) as the prime target. The spacecraft (b) would be able to make a swing-by of Neptune on its way out. Furthermore, a close-up observation sequence of Triton should be planned with the aim to fill in the knowledge gap of this Pluto-sized (dwarf planet) moon. The data sets of

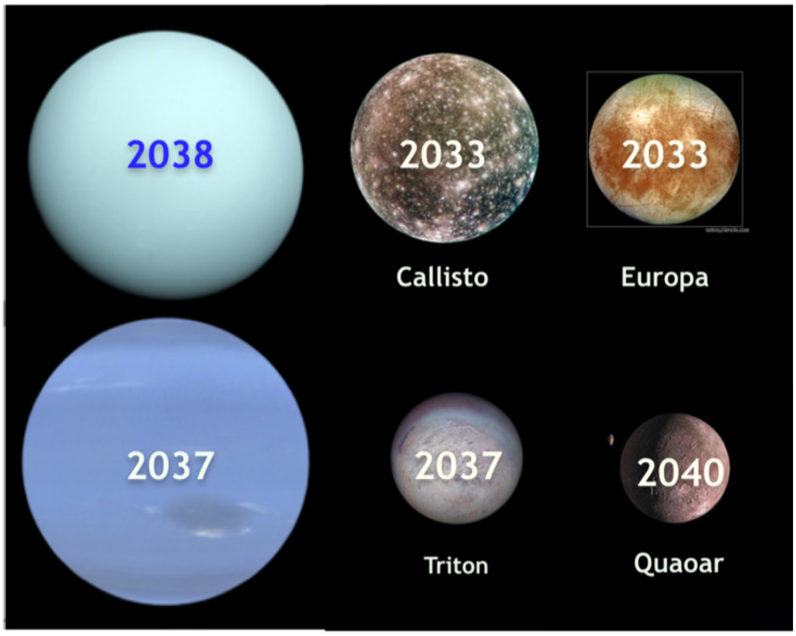


Figure 16: An ambitious program of space exploration of Uranus and Neptune and dwarf planets could be implemented in the time frame of 2030–2040 in parallel to the Interstellar Express mission

Quaoar and Triton yielded together with the scientific information on Pluto from the New Horizons mission would be essential to our understanding of the dwarf planets as a whole. Needless to say, the Neptune flyby (~2038) in the Interstellar Express mission plus the Uranus fly (~2039–2040) in the Jupiter-Uranus project would have a similar impact on the comparative study of these two icy giants.

Concerning the high-inclination component (c) of Interstellar Express, the so-called Extreme Kuiper Belt Objects possibly injected from the distant Oort Cloud would be natural targets. Because of its late schedule (to be launched around 2030), the spacecraft (c) should have more flexibly in designing its interplanetary trajectory. The exciting possibility of intercepting an interstellar stray object entering the solar system should not be ruled out at this point in time.

Due to the very stringent limitations on the mass and power of scientific instruments to be carried onboard the Interstellar Express spacecraft, it is not likely that extra payloads such as an atmospheric probe to Uranus or a Triton penetrator system could be accommodated. It would be a different story for the dual Jupiter orbiter/Uranus flyby mission. In this event, we would like to draw attention to the scientific importance of an Europa penetrator and an Uranus atmospheric probe, respectively. The addition of an Europa penetrator experiment would trigger a quantum jump in the discipline of astrobiology. The in situ measurements by an Uranus atmospheric descent probe would be indispensable to the investigation of the

Time	Mission	Science	Remark
2032	Jupiter/Callisto Orbiter	Jupiter/Callisto origin	J-U
2032	Europa penetrator	Astrobiology	J-U
2038	Neptune/Triton flyby	Neptune/ Dwarf planet	IE(b)
2039	Uranus flyby/probe	Uranus origin	J-U
2040	Quaoar flyby	Dwarf planet	IE(a)
2040	EKBO flyby	Dwarf planet	IE(c)

Table 1: A hitchhiker's guide to the outer planets.

chemical composition and origin of this icy giant.

In summary, the Interstellar Express project, when paired together with the initiative for a CNSA Jupiter/Uranus mission, would allow the establishment of a viable program for the study of the icy giants and dwarf planets in the time frame of 2030–2040. Table 1 indicates how different building blocks might be integrated together. This program, if realized, should make significant impacts on planetary science in parallel to the advance to be made by NASA and ESA in this area. Needless to say, this sequence of (still hypothetical) planetary projects would pave the way for a comprehensive exploratory program of the outer solar system and heliosphere.

6. PAYLOAD SUGGESTIONS AND SPECIFICATIONS

6.1. PKU ENA Imager

In the heliosphere, energetic plasma ions can charge exchange with cold neutrals, e.g., from the interstellar neutral wind, neutral planetary coronas, etc., to produce energetic neutral atoms (ENAs) that retain the parent ion's velocity and freely escape from the plasma source along a ballistic trajectory (e.g., Gruntman et al. 2001; Wang et al. 2010). Thus, ENAs provide a unique, powerful way to remotely probe the properties of distant plasmas (especially for energetic protons).

Under the support of NSFC major scientific instrument development grant #41627805 (PI: Qiugang Zong), our group in Peking University (PKU) has been developing a grid-modulated ENA imager with high sensitivity and resolutions, in order to image the planetary magnetospheres, as well as the heliospheric boundaries. This imager is hereafter referred to as the "PKU ENA Imager".

The PKU ENA Imager utilizes thin-window, low-noise, pixelated silicon semiconductor detectors (SSDs) to detect hydrogen atoms at 8 - 250 keV, with energy resolution of 3 keV (Table 2). As shown in Figure 17, this imager adds a parallel-plate electrostatic deflection system in front of these SSDs to sweep out electrons and ions at energies up to 45 keV to opposite sides, for clean measurements of 8 - 45 keV ENAs. The PKU ENA Imager is also designed to distinguish oxygen atoms from hydrogen atoms at 20 - 45 keV, by subtracting the measurements in SSDs with different window thicknesses.

Inspired by the RHESSI's imaging concept (Lin et al. 2002), the PKU ENA imager adopts a novel ENA imaging technique that combines Fourier-transform imaging and coded-mask imaging by placing a multi-pitch-grid collimator in front of pixelated (spatially sensitive) SSDs with the CMOS readout ASICs (Figure 17), to enable the ENA imaging of sources over a wide range of spatial scales with good spatial and time resolutions. For the PKU ENA imager, the angular resolution is 2°×2°, the time resolution is 10 seconds, and the geometric factor is 5.2 $cm^2 \cdot sr$.

The PKU ENA imager will be launched onboard the Chang'E-7 relay satellite around 2023–2024. Its design and specifications can also be updated to meet the requirements of the deep space missions and interstellar exploration.

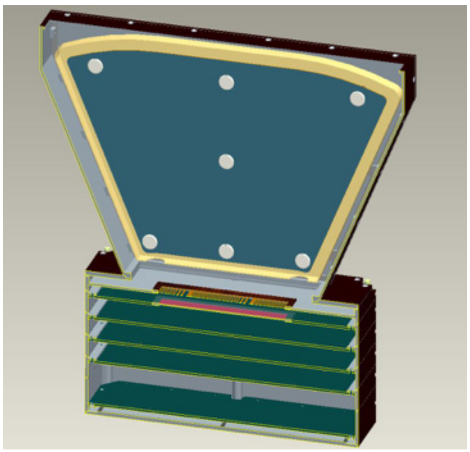


Figure 17: Cross section of PKU ENA Imager (one module).

Characteristic	Value
Energy interval Hydrogen Oxygen	 8 – 250 keV 20 – 45 keV
Energy resolution	3 keV
Time resolution	10 seconds
Geometric factor	5.2 $cm^2 \cdot sr$
FOV	90°×45°
Angular resolution	2°×2°

Table 2: PKU ENA Imager characteristics.

6.2. Prospect of Vector Atomic Magnetometer in the Exploration of Outer Heliosphere and Nearby Interstellar Medium

In the exploration of the outer heliosphere and nearby interstellar medium, scientists need accurate magnetic field data for their scientific concerns. Because the field is very weak, the required data accuracy is even less than 0.01 nano-Tesla (nT) which is ~1,000,000 times weaker than the earth's magnetic field. Such accuracy is a big challenge for the instrument under the severe deep-space environment for a period of several decades long.

Fluxgate magnetometers (FGMs) were used on Voyager 1 (1977), which has reached the termination shock region. The advantages of FGMs are high reliability and long lifetime. But the accuracy of FGMs are deteriorated by the zero-level offset (about ±0.2 nT/year) (Behannon 1977). The data accuracy after the inflight calibration was improved from 0.02 to 0.05 nT.

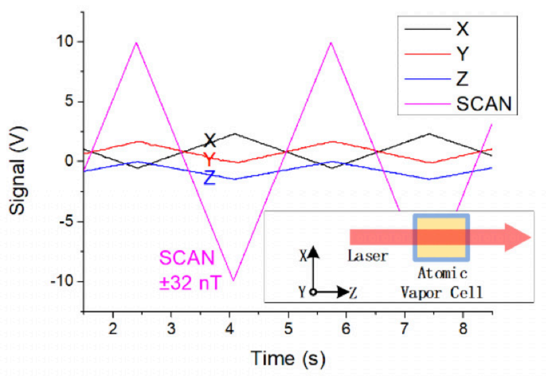


Figure 18: Simultaneous measurement of three-axis magnetic field by the VAM of NSSC.

The Vector Helium Magnetometers (VHMs), a kind of Vector Atomic Magnetometers (VAMs), have been applied to Pioneer 10 and 11. But their lifetime are 23 and 21 years, respectively, which are less than that of FGMs on Voyager 1 and 2. The accuracy of the instruments were 0.025 nT without any inflight calibration, which is more accurate than FGMs. In recent years, the accuracy of VHMs has been improved to <0.01 nT by JPL in the Interplanetary Nano Spacecraft Pathfinder In Relevant Environment (INSPIRE) project. Therefore, due to the natural stability of atomic resonances, VHM/VAM seems to be a better choice for higher data accuracy.

However, due to the long-term helium gas leak, the lifetime of helium atomic cells and lamps of VHMs, it is hard to meet the requirements of outer heliosphere exploration missions. Therefore, we turn our attention to the alkali-metal atomic magnetometer, which has developed rapidly in recent years. The alkali-metal atoms and buffer gas can be maintained in a Pyrex glass cell in the sensor for a long time. And the lifetime of some special diode lasers is much longer than that of lamps, at least 30–40 years. Therefore, the lifetime of alkali-metal atomic magnetometer is expected to meet the requirements of long lifetime. In addition, the alkali-metal atom magnetometer is currently almost the most sensitive magnetometer in the world. This type of magnetometer is expected to reach the level of sensitivity and accuracy expected by the space physicists. However, atomic magnetometers generally cannot measure triaxial magnetic fields simultaneously. A coil system should be combined to realize vector measurement. As shown in Figure 18, based on rubidium atom and a single laser, the VAM of NSSC has realized simultaneous measurement of three-axis magnetic field. We are working on the prototype for the deep-space exploration missions, such as Interstellar Express. We believe that the VAM has a good prospect in the future deep-space explorations.

6.2.1. Conclusions

For the magnetic field measurement, vector atom magnetometer will become an optional payload for future missions in deep space, such as Interstellar Express. However, although the vector atom magnetometer is more sensitive and accurate, its reliability and lifetime are still to be improved. Considering both instrument accuracy and reliability, a more reasonable plan is suggested to equip miniaturized vector atom magnetometers and fluxgate magnetometers together in the future missions of the outer heliosphere and nearby interstellar medium.

6.3. Payloads Proposal for Chinese Interstellar Express Mission

The main scientific objectives for Chinese Interstellar Express Mission are as follows:

1. Distribution of invasive medium from interstellar space.
    - Pick-up of solar wind- plasma/pick-up ion/ magnetic field.
    - Modulation of galactic cosmic rays by heliosphere - High energy and energetic charged particle.
    - Gravitational focusing of interstellar neutral atoms and dust.
    - Other celestial bodies in solar system.
    - Characteristics of ice giants and their satellites- optical, UV, and infrared/ plasma/magnetic field
    - Centaurs- optical, UV, and infrared
    - Kuiper belt- optical, UV, and infrared

2. Boundary structure of solar system

  - Characteristics of heliospheric termination shock- Plasma, pick-up ion, magnetic field

  - Origin and acceleration of anomalous cosmic rays-High energy and energetic charged particle

3. Extragalactic background light- optical, UV and infrared

According to the science requirements above, parameters to be measured and proposed payloads are shown in Figure 19.

In addition to the performance requirements indicated above, the payloads should be also miniaturized and low power for up to 100 AU distance. The overall mass of the payload is 50 kg and the power is 150 W, which meet the preliminary mass and power budget from the spacecraft.

The technical heritage of this payload from Chinese institutes and universities is very positive. Due to the unique characteristics of this mission, there are several issues for the payload tthat need to be tackled recently, such as miniaturization, high reliability, long lifetime, etc.

There have been successful international collaborations for some payloads of Chinese space missions, and international collaborations about both science and payload development on this mission are also recommended.

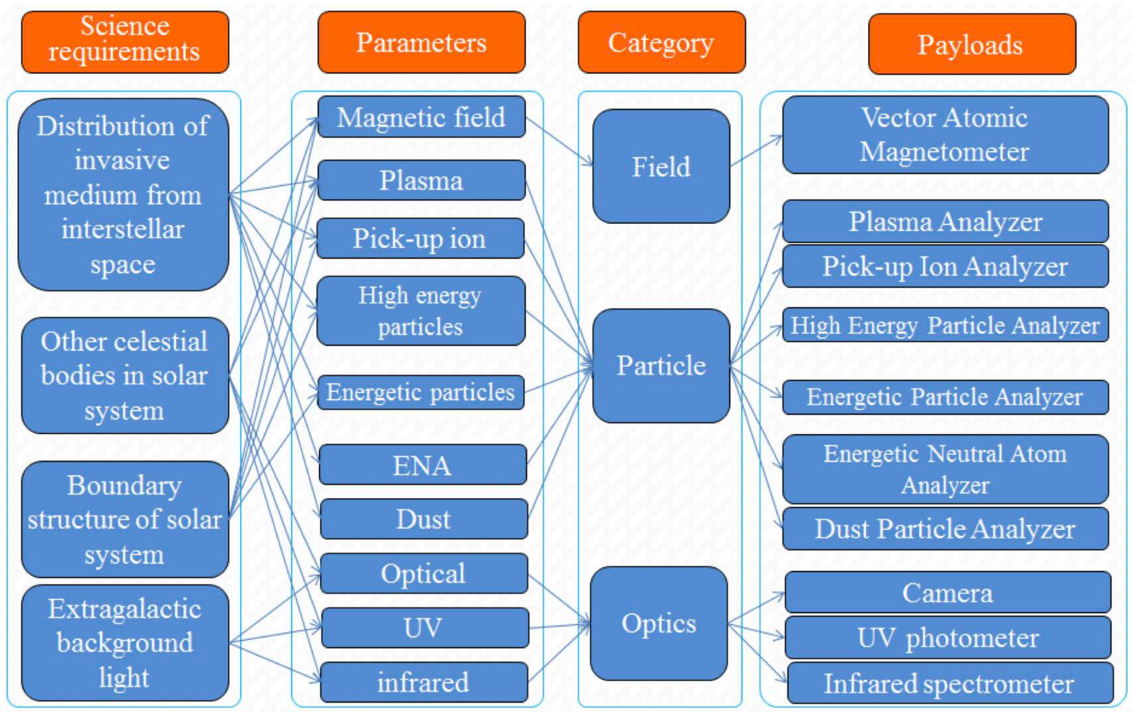


Figure 19: Proposed payload.

	Payload		Performance
1	Vector Atomic Magnetometer		Narrow range : ±8nT Wide range: ±70000nT Sensitivity of narrow range: ≤0.001nT/$Hz^{1/2}$ Accuracy of narrow range: ≤0.05nT Sensitivity of wide range: ≤0.05nT/$Hz^{1/2}$ Accuracy of wide range: ≤3nT
2	Plasma Analyzer		Ion energy range: 0.005~30keV Electron energy range: 0.005~30keV Energy resolution: 8% Field of view: 180º×8º Angle resolution: 22.5º×8º
3	Pick-up Ion Analyzer		Energy range: 0.002~40keV Energy resolution: 5% Field of view: 180º×8º Angle resolution: 22.5º×8º Mass resolution: H^+, He^+, $He2^+$, N^+, O^+, Ne^+
4	High Energy Particle Analyzer		Proton energy range: 7MeV-300MeV Electron energy range: 200keV-10MeV Heavy ion energy range: 10-300MeV/n Angle resolution: 3 directions, 40º/direction
5	Energetic Particle Analyzer		Proton energy range: 20keV-7MeV Electron energy range: 20keV-400keV Heavy ion energy range: 0.5-20MeV/n Angle resolution: 3 directions(e/p/i), 30º/direction
6	Energetic Neutral Atom Analyzer		Energy rang: 10eV ~300keV Mass resolution: H, He, O, Ne Field of View: 180º×2º(H), 160º×9º(L) Angle resolution: 3º*2º(H), 30º×9º(L)
7	Dust Particle Analyzer		Area (cm^2): 400 Mass (kg): 10^{-17}~10^{-9} Speed (km/s): 1~5*103 Charge (C): 10^{-16}~10^{-13}
8	Carmera	Narrow field of view with multi-spectra	Focal length:1200mm, Aperture:150mm, F number:8 Field of view:0.78º×1.05º, Wave length:460-1000nm, number of spectra channels:6-8
		Wide field of view with multi-spectra	Focal length: 150mm, Aperture: 37.5mm, F number: 4 Field of view: 6.28º×8.34º, Wave length: 460-1000nm, number of spectra channels:6-8
		Wide Angle	Focal length: 38mm, Aperture: 20mm, F number: 1.9, Field of view: 30º×90º(4 identical cameras with field of view 30º×23.4º), Wave length: 600-1000nm
9	UV photometer		Wave length: 121.6nm, 58.4nm Field of view: 4º×4º
10	Infrared spectrometer		Spectrum range: 1.0μm~16.0μm Spectrum resolution: ≤9cm^{-1} Field of view: ~0.5º

Table 3: Performance requirements.

7. CONCLUSIONS

In this Forum on Exploration of Outer Heliosphere and Nearby Interstellar Medium, different mission scenarios were presented and discussed. The technical challenges are clearly tremendous. For example, a mission life time of about 50 years for a 1000-AU Interstellar Probe as envisaged by NASA would certainly push aerospace technology to extreme limits. The dual-probe mission concept of the Interstellar Express under assessment by CNSA is no less daunting. However, what is important is that the world-wide space science community, either in the East or in the West, is now ready to make additional steps to investigate the local interstellar medium far away from the cradle of human civilization. The idea alone is breath-taking. Let us hope that, in a not so distant future, a forum will be dedicated to the discussions and preparation of joint efforts in this landmark adventure.

8. ACKNOWLEDGMENTS

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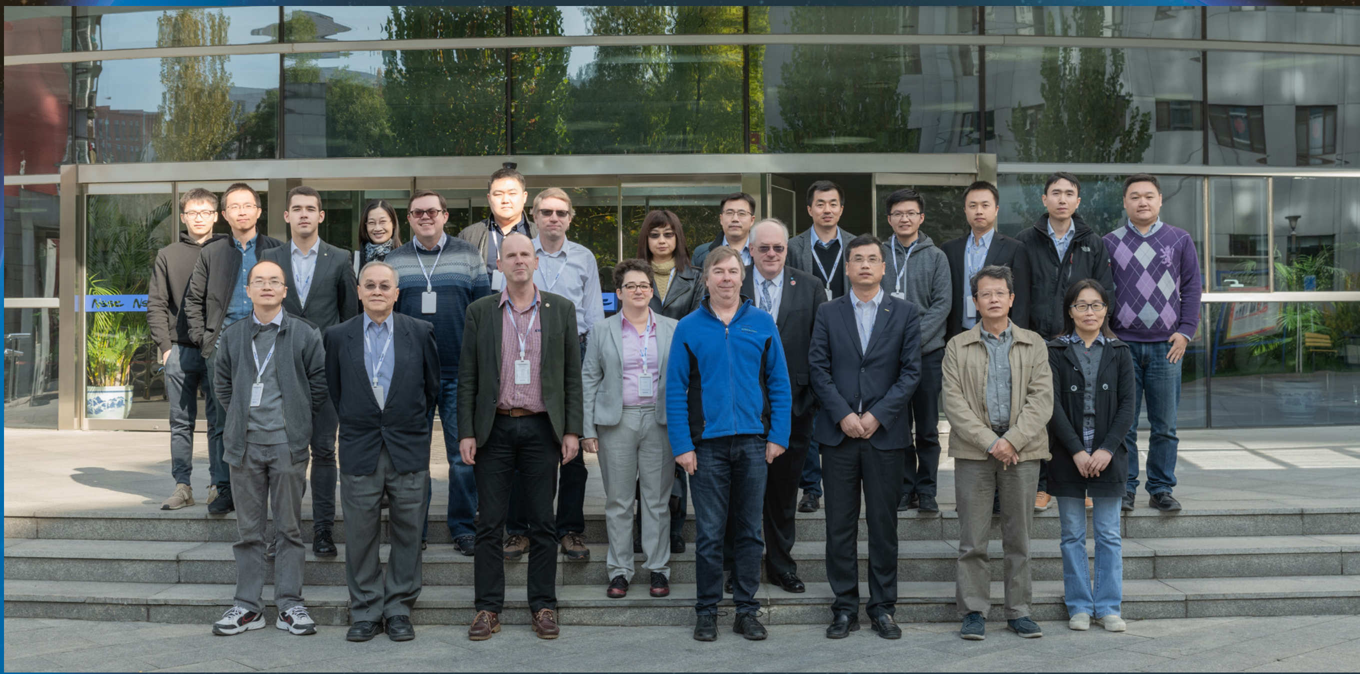

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