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STELLA - In situ Investigations of the Very Local Interstellar Medium. Decadal Survey for Solar and Space Physics (Heliophysics) 2024-2033 white paper e-id. 433

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STELLA – In situ Investigations of the Very Local Interstellar Medium

Synopsis:

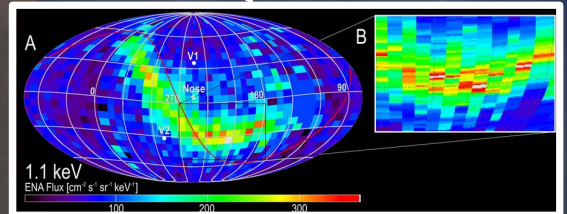
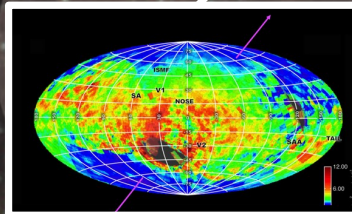
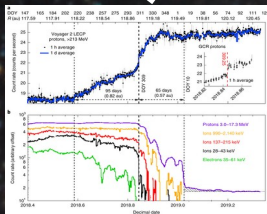
The discovery of a myriad of exoplanets in the past decades has revolutionized the understanding of our place in the universe. How different are exoplanets and do some of them harbor life, just like Earth? To do so, their parent stars must drive a stellar wind and carve what we call astrospheres into the surrounding interstellar medium. Astrospheres are ubiquitous in our immediate neighborhood and show very similar structure to our heliosphere. Voyager 1 & 2, Ulysses, Cassini, and IBEX have shown that the interaction between interstellar medium and solar wind is much more complex and involved than previously believed. This stellar-interstellar interaction is key to understand astrospheres and the shielding they provide to the planetary systems they harbor. This whitepaper proposes to study this interaction in situ at the heliospheric boundaries and to explore the very local interstellar medium beyond. It highlights possible European contributions to a NASA-led Interstellar Probe (ISP).

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1 Executive Summary

A huge amount of work has been done in the past decades that has led to show that an interstellar probe (ISP) is today a feasible, timely, and compelling mission that would enable humanity’s journey to interstellar space. A 498-page study led by the Johns Hopkins University (JHU) / Applied Physics Laboratory (APL) provides a detailed account of the science goals and questions, the mission concept, scientific and technical implementation, as well as programmatics and concepts for the managements of such a 50 year mission [6]. This white paper draws heavily from that study, as well as from white papers submitted previously to the European Space Agency (ESA) [12, 13, 14] in response to its Cosmic Vision and Voyage 2050 calls, and the STELLA proposal submitted to ESA’s 13 December 2021 call for a medium-size mission opportunity [1]. In line with the JHU/APL study, we propose an Interstellar Probe (ISP) that would reach 350 au after 50 years and highlight possible European contributions to such a NASA-led mission.

All aforementioned ISP mission proposals aim at answering fundamental questions about heliophysics which can be summarized in the following top-level questions:

TQ1: How is our heliosphere upheld by the physical processes from the Sun to the Very Local Interstellar Medium (VLISM)?
TQ2: How do the Sun’s activity as well as the interstellar medium and its possible inhomogeneity influence the dynamics and evolution of the global heliosphere?
TQ3: How do the current VLISM properties inform our understanding of the evolutionary path of the heliosphere?

Table 1: ISP top-level science questions [6].

In addition, an ISP would enable **planetary science** with its fly-by of Jupiter and and its moons after the JUICE era and to fly by a Kuiper-Belt Object (KBO), very similar to the successful New Horizons example. On its way to the VLISM, ISP would allow **bonus science goals** from a variety of scientific disciplines and perform a **fundamental measurement** to test the $1/r^2$ law of gravitation at a hitherto unverified distance scale. Thus, an ISP would serve a large scientific community by addressing top-level questions given in Tab. 1 and more detailed questions, some of which are shown in Tab. 2 and discussed in more detail in sec. 2.

The following technological and managerial challenges would need to be addressed:

Propulsion: Proposals have included solar sails, nuclear ion propulsion, electric sails, heavy launcher, with or without gravity assist manoeuvres [see 7, for a summary]. A super heavy-lift launch vehicle (SHLLV) with one or two additional stages and a Jupiter gravity assist manoeuvre currently looks like the most pragmatic solution [8]. This would allow an escape speed twice that of the fastest solar-system escaping spacecraft, Voyager 1, of up to 7.2 au/year.

Power: Nuclear power would be unavoidable. NASA is currently developing the Next-Generation Radioisotope Thermoelectric Generator (NextGen RTG) through the Radioisotope Power Systems (RPS) Program at Glenn Research Center. The RPS Program is on track to provide the first flight-qualified NextGen RTG by 2028, well before 2036 when Interstellar Probe would require units. Power supply electronics and distribution units could be reused from New Horizons and Parker Solar Probe (PSP). See Sec. 5.9 in [6] for more details.

Reliability: Strategies to the ensure reliability of ISP for 50 years (or longer) of operations in space will need to be developed. Our knowledge of how to assess reliability has greatly improved over the past decades and has resulted in missions which have significantly exceeded their planned lifetimes, as is exemplified by the Voyagers, SOHO, Ulysses, and other missions. For instance, studies have shown that parts failures can be more accurately associated with inadequacies in design or improper handling of components or workmanship [see 6, Sec. F.2].

Management: Finally, an ISP would also pose a management challenge by necessitating a well-organized and continuous transfer of knowledge from one generation of engineers, scientists, and managers to the next as discussed in Sec. 3.3.

Communication: While communication across hundreds of au may be viewed as a technological challenge, the Voyagers have shown that this can be done. Current technology on Earth, paired with spacecraft communication equipment from the 1970s already allow this reliably across more than 150 au. The STELLA proposal to ESA [1] and the JHU/APL study [6] give more details about possible improvements. Nevertheless, investments in communications would improve science return, and also benefit other outer-solar-system missions (e.g., to the giant planets and icy moons).

Investments in these fields would significantly enhance humanity’s space-faring capabilities and benefit (solar system) space science.

Scientific Requirements for notional European instruments	Measurement requirements for notional European instruments
Neutral Gas Mass Spectrometer (NGMS), e.g., University of Bern, Switzerland	
ISP Science Objectives: Advance knowledge and understanding of the galactic neighborhood's origin and evolution	
NGMS Science Question (Q1): What is the composition of the VLISM gas?	
Determine the chemical and isotopic composition of the VLISM gas of all major species entering the heliosphere: H, He, O, Ar.	Mass-spectrometric measurements of thermal gas with $m/\Delta m = 300$ and sensitivities at $1\#/m^3$.
NGMS heritage: NGMS on Luna-Resurs, NIM / PEP on JUICE	Resources: mass 9.8 kg; power 11 W
Plasma Science System (PSS), e.g., IRAP, Toulouse, France; IRF, Kiruna, Sweden	
ISP Science Objectives: Resolve the birth and evolution of interstellar and inner-source PUIs; Understand acceleration processes and pressure balances in the solar wind and at the heliospheric boundaries; Establish the nature and structure of the heliopause, the ribbon, and the ring; Investigate how the heliospheric boundary is modified by solar dynamics; Determine the extent and impact of solar disturbances in the VLISM.	
PSS Science Question (Q2): How is our dynamical heliosphere upheld and how does it change from the Sun to the VLISM?	
Determine 3D distribution functions of ions and electrons	Measurements of differential fluxes of ions and electrons in the range < 3 eV to < 20 keV.
PSS heritage: PAS on Solar Orbiter, SWEA on STEREO and MAVEN, HIA and CODIF on Cluster, PSS on Voyager, PIMS on Europa Clipper	Resources: mass 9.2 kg; power 15 W
Cosmic Ray Spectrometer (CRS), e.g., University of Kiel, Germany	
ISP Science Objectives: Understand the nature and detailed origin of GCRs; Establish the exact nature of heliospheric shielding against GCRs; Establish how far solar disturbances reach into the VLISM.	
CRS Science Question (Q3): What is the origin and role of galactic cosmic rays in the solar system and beyond?	
Determine the (isotopic) composition of the GCR; Determine the abundance of Li-Be-B; Determine GCR pitch-angle distributions	Large geometry factor ($> 2\text{cm}^2$ sr); Mass resolution ~ 0.1 amu; Multiple viewing directions, measurements of the magnetic field
CRS heritage: RAD on Mars Science Laboratory, EPD HET on Solar Orbiter, AHEPaM on Athena	Resources: mass 7 kg; power 5 W
Ly-α Spectrometer (LyS), e.g., Laboratoire Atmosphère Milieux, France	
ISP Science Objectives: Understand the filtration as the VLISM passes the heliospheric boundaries and processes responsible for structuring the VLISM at the heliospheric interface (the Hydrogen wall) and beyond.	
LyS Science Question (Q4): How does the local interstellar medium become structured when it meets the heliosphere?	
Determine hydrogen populations properties, number density and velocity distribution, in the inner heliosheath, the hydrogen wall, and the VLISM	Directional, high-resolution (< 20 km/s Doppler shift) Lyman- α spectra and their variation with distance from the Sun
LyS heritage: Imaging UltraViolet Spectrograph on MAVEN	Resources: mass 12.5 kg; power 12 W
Radio Science (RS), e.g. Università La Sapienza, Rome, Italy	
ISP Science Objectives: (New and unique for the European contribution). Explore the gravity law on the scale of VLISM	
RS Science Question (Q5): Are there any deviations from the gravity law on the scale of VLISM?	
Determine the spacecraft acceleration	Measure the two-way range to an accuracy of 20 cm @ 100 s integration time
RS heritage: BepiColombo; VERITAS	Resources: no additional mass or power needed

Table 2: Notional European payload provision to ISP, the science questions addressed by it, and its measurement requirements. Other possible payload provisions could be a magnetometer (e.g., Imperial College London), a radio-plasma-wave instrument (e.g., LESIA, Observatoire de Paris), etc.

2 Science Goals

Today there is a growing awareness of the significance of the physics of the outer heliosphere. Its understanding helps to clarify the structure of our immediate interstellar neighborhood, contributes to the clarification of fundamental astrophysical processes like the acceleration of charged particles at a stellar wind termination shocks and beyond, and also sheds light on the question to what extent interstellar-terrestrial relations are important for the environment of Earth and exoplanets.

Even with the increased knowledge from space missions, the global shape and dimensions of the heliosphere remains a contested topic [2, 9, 10]. Moreover, the total plasma pressure in the heliosheath as a function of time and the relative importance of the various plasma populations (in particular at low energies < 200 eV) are only poorly constrained with present-day observations [4, 15].

Attempts to explain consistently the known observations are currently roiled in controversy, with no clear trend towards a consensus. All the diverse in situ and remote observations obtained to date only serve to emphasize the need for a new generation of the more comprehensive measurements that will be required to understand the global nature of our Sun's interaction with the local galactic environment. Only an ISP with modern in situ and remote-sensing capabilities and science requirements informed by the now available observations can answer the open questions highlighted in Tabs. 1 and 2.

After the exciting in situ observations of the termination shock, heliosheath, and heliopause, both Voyagers have now entered "interstellar space" [11]. "Interstellar Space" is shown in quotation marks because it is not the pristine VLISM, but rather this space still influenced by the Sun and heliosphere. We don't expect the Voyagers to last long enough to enter the undisturbed, pristine VLISM which is likely situated way beyond their current locations and remaining lifetime. Nevertheless, the Voyager results allow us to design an ISP to perform measurements of all quantities relevant to characterize and understand the VLISM.

Although anchored in heliophysics, ISP inevitably offers ground-breaking discoveries across astrophysics and planetary science. Any outward trajectory, dictated by the heliophysics objectives, offers flybys of at least one of the 130 dwarf planets or 4000 KBOs, to understand the almost unexplored world of the outer solar system. Remote and in situ dust observations would provide an unprecedented view of the circumsolar dust disk, critical for understanding the formation and evolution not only of our solar system, but also to understand planetary formation in surprisingly young dust disks. Be-

yond the zodiacal cloud, the infrared universe opens up to measure the poorly constrained extragalactic background light providing insight in to galactic and stellar evolution since 200 My after the Big Bang.

The following paragraphs highlight the science questions addressed by a notional European payload on which this white paper is based.

Q1: What is the composition of the VLISM gas?

Early determinations of the VLISM composition were from pickup ions in the solar wind, from anomalous cosmic rays, and from spectroscopic observations towards nearby stars. All these methods are indirect and depend on modelling for the determination of the composition of the VLISM neutral gas. Interstellar Boundary Explorer (IBEX) provided us with first direct measurements of VLISM H, He, O, and Ne. However, the absolute values of their abundances in the VLISM are very uncertain because of the strong and variable photoionization in the inner solar system and filtration at the heliospheric boundary. Key ratios for planetary evolution studies, e.g. Ne/O and D/H, are not known with sufficient accuracy, and are limited by their small fluxes at 1 AU. Other VLISM species (C, N, Na, Mg, Al, Si, P, S, Ar, Ca, Fe) as well as the isotopic composition of He, O, Ne, have not been measured directly at all. For example, C is not able to penetrate the heliopause because it is fully ionized in the interstellar medium. This also prevents the use of indirect methods. ISP would for the first time directly measure all major neutral gas species in the VLISM.

The abundances of elements and their isotopes in the solar system present a snapshot in time of the composition of the interstellar medium from which the Sun formed 4.57 Gyr ago. The evolution of interstellar matter that our solar system encountered on its journey through the galaxy can be inferred from the present state of the VLISM by measuring these elements and their isotope ratios. Measurements of the isotopic ratios of interstellar neutrals H/D, $^3\text{He}/^4\text{He}$, and $^{20}\text{Ne}/^{22}\text{Ne}$ with high accuracy will constrain our understanding of the chemical evolution of our galaxy.

Q2: How is our dynamical heliosphere upheld and how does it change from the Sun to the VLISM?

The solar wind expands from the Sun and interacts with the neutral gas in the VLISM to form the heliosphere. This interaction also serves as a model for how stellar winds interact with their VLISM to form astrospheres, but is further complicated by the inflow of neutral VLISM gas. This gas is ionized in the inner heliosphere, thus creating a population of pickup ions (PUIs) which is highly non-thermal and defines the pressure balances in the heliosheath (HS) and at the heliopause

(HP) against the flow of the VLISM. This crucial role of PUIs in the global solar wind-VLISM interaction can not be studied with Voyager 1 and 2 because they were not equipped to measure PUIs.

PUIs experiencing a secondary charge exchange process with interstellar neutrals become Energetic Neutral Atoms (ENAs). Knowledge of PUI properties is crucial for understanding ENA images of the global heliospheric interaction. IBEX has imaged heliospheric ENAs over a solar cycle which show substantial variations and demonstrate that solar activity drives the global response of the entire heliosphere and its interaction with the VLISM. But how multi-scale solar wind structures propagate and evolve in the outer heliosphere; how they influence suprathermal and energetic particles; what plasma flows they cause in the heliosheath; and how locations of boundaries change because of pressure pulses, shocks, and waves in the solar wind is not known. Voyager 1 detected shocks and pressure waves beyond the heliosphere which were likely driven by transient solar events. Our understanding of the multi-component, multi-scale plasma physics in the outer boundary layers of the heliosphere and its coupling to the neutral component of the VLISM is extremely limited.

IBEX discovered the ENA ribbon, an enigmatic band of intense ENA fluxes in the sky. The ribbon is an “imprint” of the complex physical processes between charged and neutral particles controlled by the interstellar magnetic field. Understanding its origin will tell us about the fundamental physics of the heliosphere’s boundary, and thus about other astrospheres. The Interstellar Mapping and Acceleration Probe (IMAP, launch 2025) will explore ENAs in much more detail but it will not be able to investigate the micro-physical processes in this complex plasma. A launch of ISP in late summer of 2036 would let it traverse the ribbon and perform in situ particle measurements to establish its origin.

Q3: What is the origin and role of galactic cosmic rays in the solar system and beyond?

Galactic Cosmic Ray (GCR) anisotropies are sensitive to remote field variations and can therefore be used as an effective remote diagnostic of the field configuration of the heliosphere, and once beyond the heliopause, they provide insight into how solar disturbances can propagate deep into the VLISM. The Voyagers’ cosmic ray instrument had limited look directions, and confounding, species-dependent anisotropies in GCR angular distributions have been reported. There is no current consensus on what causes those anisotropies. With its improved instrumentation, ISP would offer a new opportunity to study the nature of GCR anisotropies, GCR shielding by the heliosphere, and the properties of the unshielded GCR spectra in the VLISM, including rare species and

isotopes, that could not be observed by the Voyagers. Measurements of rare and unstable cosmic ray isotopes can be used to determine GCR source regions via spallation and direct acceleration, galactic escape rates, and solar modulation. For instance, the abundance of Li, Be, and B at cosmic ray energies is comparable (same order of magnitude) to that of C, N, and O, and thus more than four to six orders of magnitude higher than their relative abundance in the solar system. Observations of Li-Be-B can offer the capability to distinguish solar from interstellar from mixed plasmas in the HS, HP, and boundary layer(s), and VLISM. Studies of the unobserved species of GCRs in the VLISM are of importance not only to heliophysics and the nature of particle acceleration and consequences of GCRs in the heliosphere, but also to astrophysics and the nature of the universe itself. Observations of particularly rare GCR isotopes, GCR electrons, and antimatter in the VLISM can even shed light on and further constrain models of the nature of the Big Bang and dark energy. However, because of heliospheric shielding of lower-energy GCRs, the critical observations required to answer such open questions rely on observations of these GCR species in the unperturbed VLISM by an ISP.

Q4: How does the local interstellar medium become structured when it meets the heliosphere?

The Local Interstellar Cloud surrounding the heliosphere primarily consists of atomic hydrogen (H). Approaching the heliosphere, interstellar H atoms pile up and form a Hydrogen Wall, found to be a common feature of astrosphere-ISM interaction. The heliospheric Hydrogen Wall was detected remotely, however, it was never explored with in situ measurements leaving open questions about its extent, peak density, and 3D structure. Despite being critical for the global heliospheric structure, properties of interstellar H atoms far away from the heliosphere in the LIC and their variations due to ion-neutral coupling at the heliosphere boundary remain largely unknown. Measuring solar Lyman- α (121.567 nm) emission backscattered from interstellar H atoms is a powerful technique to probe interstellar H atoms. The spectral shape of the Lyman- α emission line holds key information on the spatial and velocity distribution of interstellar H and enables to infer momentum exchange between hydrogen and plasma. The study of the Lyman- α line profile in the outer heliosphere allows characterizing the distribution (bulk velocity and temperature) of the hot hydrogen population, which is created by charge exchange in the inner heliosheath. After crossing the heliopause, these same measurements will provide the hydrogen atom distribution in the outer heliosheath and the Hydrogen Wall. As the probe moves

away to larger distances only the pristine interstellar H population will remain thus allowing to derive the true number density, bulk velocity, and temperature in the Local Interstellar Cloud.

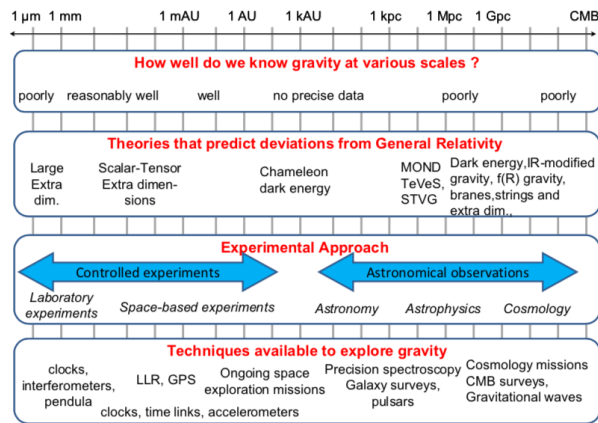


Figure 1: Gravity at all length scales. [3]

Q5: Is the $1/r^2$ law of gravitation valid at scales of hundreds of au? The laws of gravity are unevenly tested at different spatial scales (Fig. 1). The most precise knowledge is obtained from solar system dynamics, where space probes allowed the most accurate tests of general relativity to date. Violations of the $1/r^2$ law, associated with the Compton wavelength of the graviton, have also been tested precisely in the solar system. But at short spatial scales (at the atomic level) or beyond the solar system (>50 au) gravity has never been accurately tested. ISP offers the opportunity to carry out an accurate test of the $1/r^2$ law at distances beyond 50 au and up to 350 au, by precise range and range rate measurements of the probe. In addition, ISP could determine or set up an upper limit on the density of dark matter in a sphere of radius approximately equal to the heliocentric distance of the probe. Gravitational signals from TNOs could also be detected providing a new “window” for discovering these objects.

Bonus Science Opportunities The five science questions discussed above are examples of heliophysics and fundamental physics questions that would be addressed by an ISP. We highlight some astrophysical science “teasers” to demonstrate the breadth of ISP:

- B1:** Measure extragalactic background light (and other astronomical targets in the infrared) undisturbed by the solar system Zodiactal light.
- B2:** Determine the soft X-ray background in the heliosphere and solar-wind planet interactions.
- B3:** Acquire Ly- α absorption spectra against known

stellar neighbors to map out the neutral hydrogen density structure in the local neighbourhood. The increasing distance of an interstellar probe would gradually build up this 3D information.

3 Mission Description

Apart from describing important science goals of an ISP, Tab. 2 also hints at possible European provisions of payload elements (instruments). Obviously, this would have to be subject to further refinement by a joint NASA - ESA science definition team and a competitive process. The instruments mentioned are given to illustrate European expertise and possible contributions. While these instruments have sufficient heritage and already have or will have TRL 6 by 2026, they would have to be qualified for a 50 year (or longer) mission duration. NASA and ESA would have to play a key role in this process.



Figure 2: Apollo Complex of 34-m BWG antennas at the Goldstone DSCC.

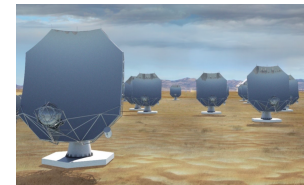


Figure 3: Artistic view of the NRAO ngVLA array of 18-m antennas.

One of the key European industrial and programmatic contributions could be an upgrade of the European deep space communication facility that would allow the precise range and range-rate measurements of the probe to address **Q5** but would also provide additional down-link of ISP data and thus increase the ISP science return. The facility would be a critical augmentation of the European Deep Space Antennas (DSA) not only for ISP but also for other planned missions, e.g., to the icy giants. Less than a decade after its launch, returning data from ISP would require a receiving station with the equivalent of 4 35-m dishes or more than 16 18-m dishes, i.e., the equivalent of a 75-m dish. The architecture of the array (Figs.2 and 3) should be studied during an early phase of the mission (0/A). European industries are among the world leaders in the field. mtex antenna technology (Germany) is the sole prime to develop a production-ready design and produce a prototype 18-m antenna for the US National Research Observatory (NRAO) Very Large Array (ngVLA) facility. Thales/Alenia (France/Italy), Schwartz Hautmont (Spain) are heavily involved in the development of the new 35-m DSA antenna.



Figure 4: ISP with a possible ESA contribution, the communication system including the High Gain Antenna.

At the other end of the communication system, Europe could also provide the spacecraft high-gain antenna (HGA) and communication system which should supply, together with the ground segment, a telemetry rate of at least 200 bps at 350 au and would allow to address Q5. It would have to be a fully redundant X-band system; optical communication would very likely pose too stringent pointing requirements on the spacecraft. Hardware for this subsystem is mature technology with ample deep space heritage. The antenna complement would include a 5-m High Gain Antenna (HGA, Fig. 4), a 0.4-m Medium Gain Antenna (MGA) coaligned with the HGA, and fore and aft Low Gain Antennas (LGAs).

3.1 Cost Estimates

We provide an estimate of a notional ESA contribution to an ISP in Tab. 3. Note that instruments are contributed by ESA member states which have very diverse cost accounting systems. Therefore, the cost of the instruments provided by Europe is not estimated and not included in Tab. 3. The cost of a NASA-only ISP has been estimated in the JHU/APL study [6], a top-level cost breakdown is given in Tab. 4.

3.2 Notional Schedule

The JHU/APL study [6] gives a top-level schedule which is repeated in Tab. 5 for completeness. While an optimal launch window with a Jupiter Gravity Assist Maneuvre occurs every 13 months, the launch date of August 2036 is the first opportunity after 2030 to pass through the “IBEX (Interstellar Boundary Explorer) ribbon” and exit the heliosphere within 90° of the incoming interstellar wind.

Cost Element	MEUR
ISP X-band Communication system	55
Payload Product/Quality assurance assistance (13 years at 1 MEU/year)	13
Programmatic and payload management support	8
4 35-m radio dishes at 35 MEU each	140
Operation of European payload, 10 years at 7 MEU/year	70
ESA project (14%)	76
Total w/o margin	362
Margin (12%)	43
Total incl. margin	405

Table 3: ROM cost estimate for a notional ESA contribution to an ISP but without possible European payload (from [1]).

Cost Item	FY25M\$
Project Management	167
Systems Engineering	
Mission Assurance	
Science	40
Payload	361
Spacecraft	388
Mission Operations & Ground Data Segment	37
Nuclear Launch Approval	26
Integration & Testing	95
Subtotal	1126
Phase A-D Unencumbered Reserves	563
Phase A-D Total	1689
Phase E Subtotal	1164
Phase E Unencumbered Reserves	291
Phase E Total	1455
Total Project Cost	3144

Table 4: JHU/APL cost estimate for an ISP without international contributions (from [6]).

3.3 Maintaining a Long-Term Mission

This 50-year (or longer) mission will require careful handling of mission operations and knowledge transfer:

Mission operations: We would envision that NASA assumes the main responsibilities for ISP flight dynamics and operations, and that ESA’s primary responsibility would be to operate the European payloads, and provide a dedicated link to ISP to drastically increase ISP’s science return. ESA would also perform the special operations required by the European Radio Science experiment and could provide additional uplink. This envisaged contribution (Tab. 3) only covers operations for the first 10-year segment of the 50-year nominal life-

Project Milestones	Date
Phase A Start	Sep. 2028
System Readiness Review	Mar. 2029
Mission Design Review	Aug. 2029
Phase B Start	Sep 2029
Preliminary Design Review	Jul. 2031
Phase C Start	Sep 2031
Critical Design Review	Nov. 2032
System Integration Review	Aug. 2033
Phase D Start	Sep. 2033
Operational Readiness Review	Feb. 2034
Pre-Environmental Review	Mar. 2035
Pre-Ship Review	Mar. 2036
Mission Readiness Review	Apr. 2036
Launch Readiness Date	Aug. 2036
Phase E Start	Sep. 2036
Phase F Start	Sep. 2086
Phase F End	Sep. 2087

Table 5: Top-level schedule (from [6]).

time because it is foreseen to divide the ISP mission up into 10-year segments which would be reviewed individually.

Knowledge Transfer: The very long duration of the mission necessitates the broad involvement of young and mid-career scientists as well as encouraging scientists who were not necessarily involved in the hardware phase to join the mission. We envision that PIs will change for the different phases of the mission.

For each 10-year segment of the mission, all project and instrument teams will be requested to include three categories of their team members:

- Senior members with extensive experience. These would typically be mentors of mid-career and junior scientists and potential PIs.
- Mid-career scientists who lead smaller teams and are in charge of important subsystems or projects.
- Junior scientists who lead individual ISP science investigations.

Through the course of the mission, scientists will flow through these categories to ensure knowledge transfer and succession. ISP as the anchor will enable an entire half-century of scientists to gain mission experience.

4 Technology Developments

Apart from obvious technology developments (TDs, mentioned in Sec. 1) such as the development of the power sources and ensuring the powerful launcher needed for ISP, the following TDs would be needed for an ISP:

Development and implementation of qualification procedures for missions with nominal lifetimes of 50 years and beyond. This would provide the community with knowledge of designing long-lived space equipment and be helpful for other programs such as Artemis.

Studies of using integrated X/Ka deep space transponders (IDSTs) on an ISP mission. IDSTs will be flown on NASA’s Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) mission as a contribution from the Italian Space Agency and are already at high TRL level. The possible use of Ka-band relies on the pointing accuracy of the spinning spacecraft and requires dedicated studies.

Studies of the deep space communication facility architectures, and of an upgrade of the DSA to provide a dedicated link for ISP: 4x 35-m dishes or more than 16 18-m dishes, antenna’s location, numbers in each site. The study would also consider the use of the ESA facility for other missions to the icy giants and outer solar system.

The required technology development activities should be kicked-off as early as possible to ensure completion by the end of phase 0/A.

5 International Context

An Interstellar Probe with varying names has been proposed to different space agencies. Apart from NASA [6], ESA has commissioned such studies [5], and China is also studying an interstellar probe which would reach 100 AU by 2049 to celebrate the 100-th anniversary of modern China. It was discussed in the 639th Academic Symposium of the renowned Xiangshan Science Conference series in October 2018. An international meeting on this topic was held at ISSI in Beijing in November 2019. Numerous mission white papers have been submitted to ESA [12, 13, 14] and laid the ground work for the STELLA mission proposal [1]. The necessarily long duration and ensuing cost of such a mission strongly suggest a coordinated NASA-ESA effort.

6 Final Remarks & Thanks

If an ISP is recommended in first rank order of Large Strategic Missions and/or US Congress demands such a mission, then it would be prudent for NASA to establish a Science and Technology Definition Team (STDT) in consultation with ESA.

The STELLA proposal [1] and this white paper were developed using information from the JHU/APL ISP study [6]. We thank the many individuals who have contributed to it and many other ISP mission studies and proposals.

References

- [1] S. Barabash and R. F. Wimmer-Schweingurber. Europe's contribution to interstellar probe – humanity's journey to interstellar space. Technical report, Swedish Institute of Space Physics, Kiruna, Sweden, 2022.
- [2] K. Dialynas, S. M. Krimigis, D. G. Mitchell, R. B. Decker, and E. C. Roelof. The bubble-like shape of the heliosphere observed by Voyager and Cassini. *Nature Astronomy*, 1:115, Apr 2017. doi:10.1038/s41550-017-0115.
- [3] Fundamental Physics Roadmap Advisory Team (FPR-AT). A roadmap for fundamental physics in space. Technical report, European Space Agency, ESA, 2010. URL: <https://sci.esa.int/science-e/www/object/doc.cfm?fobjectid=47597>.
- [4] A. Galli, P. Wurz, N. A. Schwadron, H. Kucharek, E. Möbius, M. Bzowski, J. M. Sokół, M. A. Kubiak, S. A. Fuselier, H. O. Funsten, and D. J. McComas. The downwind hemisphere of the heliosphere: eight years of IBEX-Lo observations. *The Astrophysical Journal*, 851(1):2, dec 2017. URL: [https://doi.org/10.3847/2F1538-4357/aa988f](https://doi.org/10.3847/2F1538-4357%2Faa988f), doi:10.3847/1538-4357/aa988f.
- [5] A. E. Lyngvi, M. L. van den Berg, and P. Falkner. Study overview of the interstellar heliopause probe. Technical Report SCI-A/2006114/IHP, issue 3, rev. 4, ESA, 2007. URL: <https://sci.esa.int/science-e/www/object/doc.cfm?fobjectid=40926>.
- [6] R. L. McNutt, M. V. Paul, P. C. Brandt, and J. D. Kinnison. Interstellar probe. Technical report, Applied Physics Laboratory, Johns Hopkins University, 2021. URL: <https://interstellarprobe.jhuapl.edu/>.
- [7] R. L. McNutt, R. F. Wimmer-Schweingruber, M. Gruntman, S. M. Krimigis, E. C. Roelof, P. C. Brandt, S. R. Vernon, M. V. Paul, B. W. Lathrop, D. S. Mehoke, D. H. Napolillo, and R. W. Stough. Near-term interstellar probe: First step. *Acta Astronautica*, 162:284–299, Sep 2019. doi:10.1016/j.actaastro.2019.06.013.
- [8] R. L. McNutt, R. F. Wimmer-Schweingruber, M. Gruntman, S. M. Krimigis, E. C. Roelof, P. C. Brandt, S. R. Vernon, M. V. Paul, R. W. Stough, and J. D. Kinnison. Interstellar probe - Destination: Universe! *Acta Astronautica*, 196:13–28, July 2022. doi:10.1016/j.actaastro.2022.04.001.
- [9] N. V. Pogorelov, H. Fichtner, A. Czechowski, A. Lazarian, B. Lembege, J. A. le Roux, M. S. Potgieter, K. Scherer, E. C. Stone, R. D. Strauss, T. Wiengarten, P. Wurz, G. P. Zank, and M. Zhang. Heliosheath processes and the structure of the heliopause: Modeling energetic particles, cosmic rays, and magnetic fields. *Space Science Reviews*, 212(1):193–248, Oct 2017. doi:10.1007/s11214-017-0354-8.
- [10] N. A. Schwadron and M. Bzowski. The heliosphere is not round. *The Astrophysical Journal*, 862(1):11, jul 2018. URL: [https://doi.org/10.3847/2F1538-4357/2Faacbcf](https://doi.org/10.3847/2F1538-4357%2Faacbcf), doi:10.3847/1538-4357/aacbcf.
- [11] E. C. Stone, A. C. Cummings, B. C. Heikkila, and N. Lal. Cosmic ray measurements from Voyager 2 as it crossed into interstellar space. *Nature Astronomy*, 3:1013–1018, Nov. 2019. doi:10.1038/s41550-019-0928-3.
- [12] R. F. Wimmer-Schweingruber. In situ investigations of the local interstellar medium. Technical report, Christian-Albrechts-University, Kiel, Germany, 2013.
- [13] R. F. Wimmer-Schweingruber. In situ investigations of the local interstellar medium. Technical report, Christian-Albrechts-University, Kiel, Germany, 2019. URL: https://www.cosmos.esa.int/documents/1866264/3219248/Wimmer-SchweingruberR_2019-08-04-interstellar-whitepaper.pdf/b349a5f8-e0ce-7e62-f8cd-aa7a9b122d35?t=1565184756770.
- [14] R. F. Wimmer-Schweingruber, R. McNutt, N. A. Schwadron, P. C. Frisch, M. Gruntman, P. Wurz, and E. Valtonen. Interstellar heliospheric probe/heliospheric boundary explorer mission—a mission to the outermost boundaries of the solar system. *Experimental Astronomy*, 24(1-3):9–46, May 2009. doi:10.1007/s10686-008-9134-5.
- [15] E. J. Zirnstein, R. Kumar, J. Heerikhuisen, D. J. McComas, and A. Galli. Stochastic acceleration of ~ 0.1 – 5 keV Pickup Ions in the heliotail. *The Astrophysical Journal*, 860(2):170, jun 2018. URL: [https://doi.org/10.3847/2F1538-4357/2Faac3de](https://doi.org/10.3847/2F1538-4357%2Faac3de), doi:10.3847/1538-4357/aac3de.