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Interstellar Probe: Humanity's exploration of the Galaxy Begins

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ABSTRACT

During the course of its evolution, our Sun and its protective magnetic bubble have plowed through dramatically different interstellar environments throughout the galaxy. The vast range of conditions of interstellar plasma, gas, dust and high-energy cosmic rays on this "solar journey" have helped shape the solar system that we live in. Today, our protective bubble, or Heliosphere, is likely about to enter a completely new regime of interstellar space that will, yet again, change the entire heliospheric interaction and how it shields us from the interstellar environment. Interstellar Probe is a mission concept to explore the mechanisms shaping our heliosphere and represents the first step beyond our home, into the interstellar cloud to understand the evolutionary journey of our Sun, Heliosphere and Solar System. The idea of an Interstellar Probe dates back to the 1960's, when also the ideas of a probe to the Sun and its poles were formed. An international team of scientists and a team of engineers at the Johns Hopkins University Applied Physics Laboratory (APL) are funded by NASA to study pragmatic mission concepts that would make a launch in the 2030's a reality. The ground breaking science enabled by such a mission spans not only the discipline of Solar and Space Physics, but also Planetary Sciences and Astrophysics. Detailed analyses including the upcoming SLS Block 2 and powerful stages demonstrate that asymptotic speeds around 7 Astronomical Units (au) per Year are already possible with a Jupiter Gravity Assist. Here, we give an overview of the science discoveries that await along the journey, including the physics of the heliospheric boundary and interstellar medium, the potential for exploration of Kuiper Belt Objects, the circum-solar dust disk and the extra-galactic background light. The scientific rationale, investigations and implementation of an Interstellar Probe are discussed including also example payload, trajectory design and operations.

1. Introduction

An Interstellar Probe escaping the solar system to explore its protective magnetic bubble (the Heliosphere) and the surrounding Very Local Interstellar Medium (VLISM) has been discussed since about 1960 [1]. The science is anchored in what we today call Heliophysics (or Solar & Space Physics). The science spans the wide-ranging field of how the expanding solar wind interacts with the VLISM, which is not only important for understanding how the boundary region shields the inner solar system, but constitutes also the only way to understand other astrospheres harboring potentially habitable exoplanetary systems. The Voyager 1 and 2 spacecraft remain the only mission that have made it through this boundary, but their power supplies or temperatures will fall below critical levels for operation around 2030. Voyager 1 crossed the Heliopause (HP) in August of 2012 at a distance of 122 AU. It continues to represent mankind's farthest and fastest robotic exploration of space

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with its current distance of 154.1 au from the Sun and at a speed of 3.58 AU/year. Voyager 2 crossed the HP in November of 2018 at about 119 AU with a current speed of 3.24 AU/year and distance of 128.2 au. New Horizons is currently at 51.53 AU from the Sun at a current speed of 2.96 AU/year and its power supply is projected to last through the Termination Shock (TS) to about 100 au, which is well in to the boundary region (the "heliosheath"). All current distances and speeds are from 27 September 2021. See Fig. 1 for a depiction of the relative locations of these missions with respect to the heliosphere.

With their limited payloads, the Voyager 1 and 2 mission has uncovered multiple mysteries at the boundary region to interstellar space that have elevated this to the most outstanding Space Physics problem of today. The IBEX, Cassini and soon the IMAP missions are remotely exploring the boundary region and are revealing emission patterns that are currently not fully explained [2–4] and have provided a glimpse of a heliosphere that is far from the cometary shape that was anticipated [5]. These missions, and more, have revealed how little we know and understand about this important border to interstellar space.

Here, we present the science results as of the writing of this brief report (September 2021) from the 4-year study of a pragmatic Interstellar Probe including the science questions, instrument requirements, example payload to science and mission operations. The study completes in April 2022 and a more complete report will be given in future publications. Previous overviews of the evolution of science formulation, implementation and mission architectures over the course of the study is given by Refs. [6,7]. A more detailed overview of the mission architecture concurrent to this paper is given by Ref. [8].

2. Science rationale

During the evolution of the solar system, the Sun and its protective magnetic bubble – the heliosphere - have completed nearly twenty revolutions around the galactic core. The evolving Sun and its expanding solar wind have been, and continue to be, decisive for the dynamics of the outer heliosphere and its boundary to the very local interstellar medium (VLISM). During this "solar journey" around the galaxy, the heliosphere has plowed through widely different interstellar environments and witnessed dramatic supernovae events that have all shaped the system we live in today. The orders-of-magnitude differences in interstellar properties have had dramatic consequences for the penetration of interstellar gas, dust, and galactic cosmic rays (GCRs) that have affected elemental and isotopic abundances, chemical atmospheric evolution, and perhaps even biological evolution [9]. Along the evolutionary path, high interstellar cloud densities and ionization fractions have likely compressed the heliosphere down to below 25 au. Evidence is also emerging for supernovae explosions as recent as 3 million years ago at only 20–50 pc distance that probably compressed the heliosphere even below the orbit of Saturn and perhaps more, exposing the terrestrial planets to the full force of interstellar material and GCRs [9–11].

As far as we know, only some 60,000 years ago, the Sun entered what we call the local interstellar cloud (LIC) and is now either at the very edge of it or already in contact with four of the surrounding clouds [12,13]. Estimates place the heliosphere in a completely different interstellar environment in less than 2000 years, which will continue to shape the evolution of the heliosphere.

With its limited planetary payload, Voyager made it clear that the heliospheric boundary represents a whole new regime of space physics that is not only decisive for our own heliosphere, but also for understanding other astrospheres that potentially host habitable exoplanetary systems, whose atmospheric and surface habitability is controlled by the stellar and interstellar environment. The exploration of the outer heliosphere provides a unique way to understand the critical mechanisms by which inflowing interstellar plasma, including its magnetic field and its neutral, ionized, and nonthermal particles, controls the shape and properties of astrospheres. In-situ measurements of the pristine interstellar medium and the modifications produced by the solar wind and magnetic field are needed to provide realistic predictions of the properties of astrospheres and the exoplanets that reside within them.

An Interstellar Probe on a fast, escaping trajectory through the outer heliosphere and into the VLISM would represent a snapshot of our place along the Solar Journey through the galaxy, to determine the current state of the heliosphere and its surrounding VLISM, to understand ultimately where we came from, and where we are going.

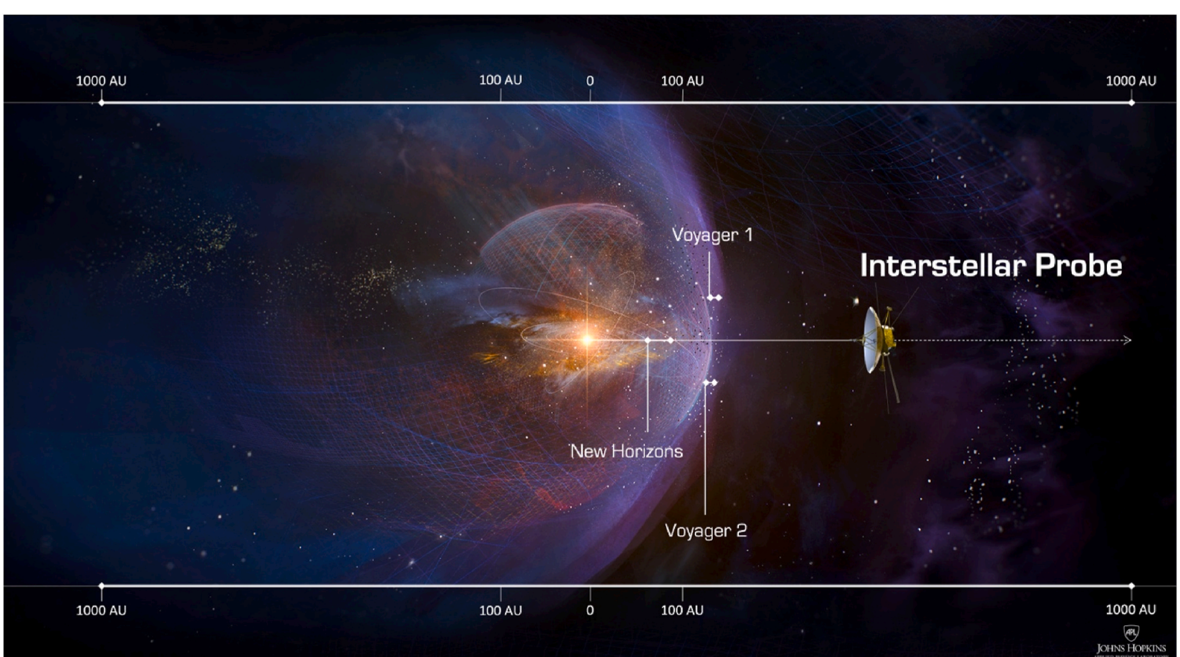

Fig. 1. Interstellar Probe on a fast trajectory to the Very Local Interstellar Medium would represent a snapshot to understand the current state of our habitable astrosphere in the VLISM, to ultimately be able to understand where our home came from and where it is going.

3. Science goals and questions

The science rationale above is captured in the primary goal of Interstellar Probe: *Understand our Habitable Astrosphere and its Home in the Galaxy*.

Since the first idea and discussion of an Interstellar Probe in 1960, the primary science goal has always revolved around the exploration of the heliospheric boundary and the VLISM. In this study, the goal has been formulated to also encapsulate the more recent discoveries of a range of other astrospheres (Fig. 2) around other stars [14]. Also, the emphasis on habitability has to be made by the obvious reason that our astrosphere is habitable, amplified by the context of the explosion of detections of exoplanetary systems around other stars.

Below we will discuss each of the three science questions that support this goal and their associated investigations and objectives.

3.1. *Science question 1: how is our heliosphere shaped by the physical processes from the Sun to the VLISM?*

To uniquely understand the physics that shapes and upholds our heliosphere one must measure the plasma and electromagnetic field environment *in-situ* through the TS, the Heliosheath and the HP. In particular, the density, temperature and flow of plasma must be measured in the range of 10 eV to 10's of keV ("plasma") of major ion species, together with energetic major pick-up ion (PUI) species in the range of 10 keV–100's keV. This is a critical energy range where the predominant repartioning of energy occurs as the solar wind crosses the TS that is responsible for the force balance (or plasma pressure) that upholds the heliosheath against the flow of interstellar plasma [15]. A full angular coverage of all directions is required to derive the important flow vectors of plasma and energetic particles throughout the heliosheath traversal. Simultaneous measurements of the magnetic field direction and magnitude is critical since the charged particle motion is guided by the magnetic field.

The combination with these *in-situ* measurements and remote ENA imaging techniques is an especially powerful approach to connect the detailed physical processes with their global manifestations. ENA observations in the energy range beyond 10 keV would provide global images of the ion distributions in the heliosheath that is responsible for upholding the force balance. Beyond about 50 keV, the lifetime of ions convecting in the heliosheath is much longer than for lower energies and would therefore reveal the larger-scale structure of the heliosheath, particularly important once an Interstellar Probe is outside of the heliosphere to capture the first external image.

In the energy range below 10 keV down to about 0.4 keV, ENA imaging would provide information on the source of the mysterious ribbon/belt [16,17] and how that relates to the direction and magnitude of the interstellar magnetic field.

It is vital to follow the acceleration pathways of how low-energy ions are accelerated, not only across the TS, but also across the HS to form the so-called Anomalous Cosmic Rays up to energies of 10's of MeV, whose source is still elusive. Following these pathways are in general very important for understanding how shocks of solar origin propagate through the heliospheric boundary and accelerate particles. Measurements of the plasma waves generated by such propagating shocks provide an important diagnostic of the acceleration processes themselves.

The lack of proper plasma and particle measurements during the Voyager crossings of the HP severely hampered the interpretation of its physical nature. Dedicated measurements of plasma flows, densities and temperatures, together with magnetic field and particle measurements up to GCR energies of 100's MeV would be the required measurements to understand the processes that form the HP and how the heliosphere shields us from those GCRs.

The region beyond the HP may turn out to be decisive for understanding the interaction with VLISM. In particular, it is unknown how the solar-like magnetic field detected by Voyager 1 and 2 [18] transitions to the unperturbed interstellar magnetic field of a very different orientation and how the "leakage" of energetic ions from the heliosheath occurs [19]. The nature of a bow shock is still unclear and depends on exact conditions in the VLISM. With most recent estimates it appears that a bow wave is more likely than a shock structure [20]. The properties of the wall of neutral hydrogen piling up beyond the HP is critical

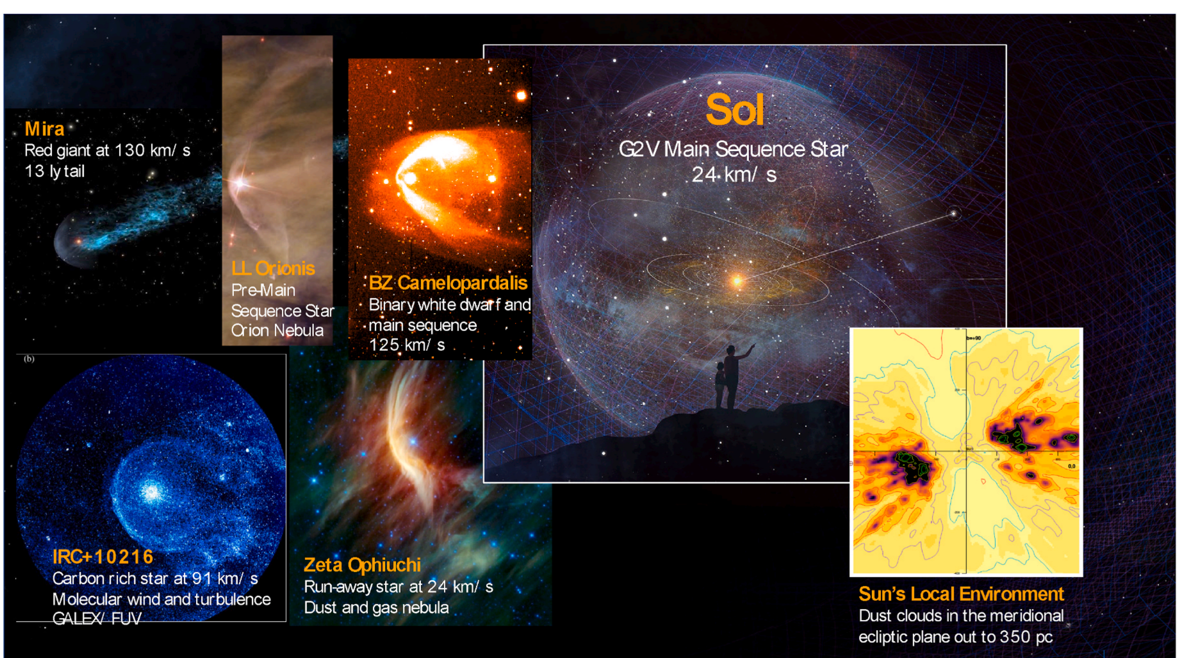

Fig. 2. As our type G2V star plows through the galactic interstellar medium it forms our habitable astrosphere harboring our entire solar system we live in. Of all other astrospheres, one of our habitable type has never been observed, and yet we are only at the very beginning of uncovering our own. An Interstellar Probe through the heliospheric boundary in to the VLISM would enable us to capture its global nature and represent humanity's first step in to the galaxy, where unpredictable discoveries await.

for understanding how neutral interstellar gas is ionized and interacts with the heliosphere [21], and is also what can be observed in front of other astrospheres. An Interstellar Probe would provide a unique opportunity for characterizing this Hydrogen Wall in detail for the first time with spectroscopically resolved Ly-alpha observations and in-situ neutral gas measurements.

3.2. Science question 2: how do the Sun's activity, the interstellar medium and its possible inhomogeneity influence the dynamics and evolution of the global heliosphere?

The global heliosphere and its boundaries are far from static, but dynamically changes as the active Sun ejects magnetized plasma that form shocks with magnitudes and frequencies that are modulated by the solar cycle. The shocks propagate throughout the heliosphere, across the heliosheath and perturb the space even well beyond the HP [22,23]. As Voyager 1 and 2, IBEX and Cassini have demonstrated, the properties and location of the TS can dramatically change and the apparent insensitivity of the HP to solar-cycle changes is not understood [4,24]. Conversely, the shape and size of the entire heliosphere is sensitive to the magnetic field, charge fraction and densities in the VLISM [25].

An Interstellar Probe traversing the boundaries would characterize the detailed magnetic field and plasma environment as shocks would propagate through. It would be likely that also multiple crossings of the TS and HP could be encountered as these boundaries would move over the relatively slow-moving spacecraft. Plasma waves emitted from the interaction between the propagating shocks and the charged particles would provide important in-situ and remote diagnostic on, not only the particle acceleration, but also on how the shocks would interact with the HP.

3.3. Science question 3: how do the current VLISM properties inform our understanding of the evolutionary path of the heliosphere?

The biggest science discoveries likely lie beyond the HP once Interstellar Probe reaches the VLISM. Our heliosphere is now exiting the Local Interstellar Cloud (LIC) at a speed of 26 km/s in the direction of the neighboring G cloud. Upper limits on the amount of interstellar Mg II absorption in this direction predict that the heliosphere will leave the outer shell of the LIC in less than 1900 years and therefore constitutes a major event [12,13,26–28]. Fig. 3 shows the four clouds in contact with the heliosphere, the direction of the inflowing VLISM and the Sun's relative motion. The size of the heliosphere, the properties of the solar wind and the composition of gas in the heliosphere will change for either scenario. The size of the heliosphere controls the number of cosmic rays hitting the Earth, which may play an important role in atmospheric chemistry and perhaps even for biological evolution [9]. Determining the largely unknown properties of the VLISM (density, temperature, charge fraction, composition, etc) is critical for understanding the interaction with the heliosphere and to ultimately be able to extrapolate to conditions in the past evolutionary history.

We are now moving away from an old picture of a quasi-static VLISM to a medium that is changing on scales down to 1000 au and perhaps below [29]. There is no reason to believe that the very low-density plasma in the VLISM is in thermal or ionization equilibrium or that non-thermal particles do not dominate the ionization and total pressure. Timescales for ionization and recombination are on the order of 10 million years [30], but shock waves from recent supernovae in the nearby Scorpio-Centaurus Association could have produced high ionization in the VLISM that is still recombining.

Magnetic fields will be important in shaping the morphology of partially ionized clouds if the magnetic pressure exceeds the gas pressure in the VLISM clouds. [31] estimated the local interstellar magnetic field strength to be 2.93 ± 0.08 μG on the basis of energetic neutral atom emission from the "ribbon" feature observed by the Interstellar Boundary Explorer (IBEX) satellite. This magnetic field strength is close to equipartition with the gas pressure in the LIC, $P_{gas}/k \approx 2500$ cm^{-3}K. More recently, [32]estimated the interstellar magnetic field strength to be about 5 μG from Voyager-2 charged particle measurements in the heliopause and Cassini data. A field strength this large would dominate

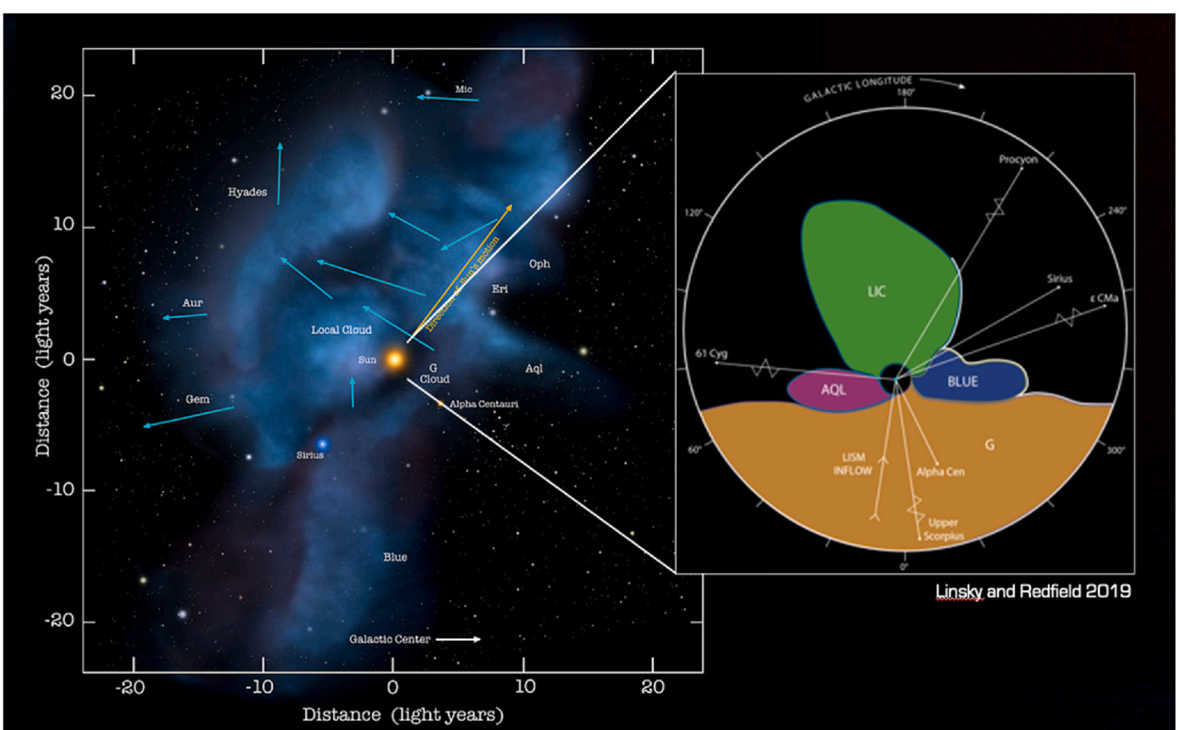

Fig. 3. Recent studies suggest that the Sun is on the path to leave the Local Interstellar Cloud (LIC) and may be already in contact with four interstellar clouds with different properties. (Left: Image Credit to Adler Planetarium, Frisch, Redfield, Linsky).

the gas pressure and thereby shape the partially ionized VLISM clouds.

The relative importance of these and potentially other sources of ionization and morphology in the VLISM need to be understood. Only direct measurement of plasma (thermal and non-thermal) and magnetic fields in the VLISM can accomplish this.

This first sampling of the VLISM would not only provide understanding of the local environment our heliosphere is immersed in, but would represent also a sampling of the material between the stars originating from supernovae and condensed outflows from stars. Determining isotopes of unshielded gas, plasma, GCRs and also ISDs would therefore also bring knowledge on the chemical evolution of the galaxy and nucleosynthesis.

4. Cross-divisional opportunities

The boundaries between pre-defined disciplines inevitably become blurred as space exploration is pushed outward. The heliophysics primary goal and its investigations outlined above, unavoidably have components of astrophysics and planetary disciplines (Fig. 4). Understanding our heliosphere requires exploration also of the VLISM and understanding our home in the galaxy requires new insight into the evolutionary path of our heliosphere through the variable galactic environments. Interstellar Probe will serve as a bridge to span the divide between Heliophysics and Astrophysics by providing the first in situ observations from an astrophysical regime (interstellar space), a regime which is also responsible for helping to shape the heliosphere itself. Measurements of interstellar PUIs do not only provide insight into the force balance of the heliosheath, but also insight into the composition of the VLISM and in turn, strong constraints on galactic chemical evolution. The direct sampling of the VLISM does not only provide upstream environment important for the heliospheric interaction, but also allow us to gain insight into physics of our surrounding interstellar clouds and the local bubble. An Interstellar Probe is therefore a pathfinder for the inevitable cross-divisional science approach necessary for pushing the boundaries of space exploration.

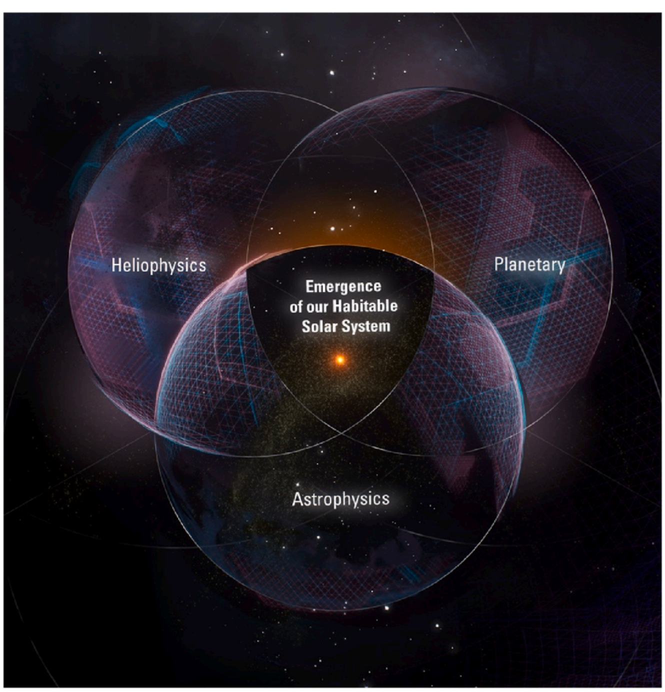

Fig. 4. Scientific disciplines inevitably become blurred together as our exploration of space pushes outward. The baseline concept of an Interstellar Probe is a pragmatic pathfinder for such a necessary cross-divisional approach and, with only modest augmentations to payload and architecture, it will return science on the level of large individual planetary and astrophysics missions.

An outward trajectory through the outer solar system provides natural opportunities for also planetary and astrophysics with relatively modest augmentations to payload and mission architecture (Fig. 5). The exploration of the outer solar system is just beginning to uncover the Kuiper Belt with discoveries that will revise our understanding of planetary system formation. Hundreds of dwarf planets and thousands of planetesimals in the Kuiper Belt have now been detected using ground telescope surveys such as Subaru lending strong support to the idea that the Kuiper Belt is much more extended than previously thought. At Pluto, New Horizons revealed a planet that was far from inactive, but instead hosted active geological phenomena, atmospheric haze, and a potential sub-surface ocean [33,34]. The flyby observations of 2014 MU69 Arrokoth uncovered an oblate contact binary with far reaching implications on planetary formation and the collisional history of the Kuiper Belt.

Any of the fly-out directions dictated by the heliophysics investigation will offer at least one flyby of a compelling planetesimal or dwarf planet in the Kuiper Belt. For example, Orcus with its moon Vanth lies roughly 80° west of the nose direction just some 20° south of the ecliptic and potentially hosts an icy world with cryovolcanism. Quaoar with its moon Weywot is approximately 40° east of the nose just 12° south of ecliptic and is believed to be a different world in its final stages of losing its atmosphere. Multiple others exist that all would provide order-of-magnitude increase in our understanding of the formation of our solar system comparative planetology among dwarf planets.

In the context of all other exoplanetary systems discovered in the past decade, the distant vantage point offered by an Interstellar Probe would be a natural observation platform to understand our solar system as an analogue of a habitable exoplanetary system. A dedicated “family portrait” of the solar system from afar, supported by scientific observations such as light curves and spectra would provide an important, but accessible, ground truth to better inform other exoplanetary observations.

As a planetary system accretes it leaves behind a large-scale dust disk surrounding the star. This dust disk is created from relic planetesimals left over from the earliest epochs of the formation of the planetary system. Our mature 4.6-billion-year-old solar system contains the relic bodies of the Asteroid and Edgeworth-Kuiper Belts and the Oort Cloud that have produced the circum-solar dust disk we have today. New Horizons is currently the only mission that have revealed the coarse distribution of this dust along its orbit near the ecliptic [35]. However, very little information exists on its large-scale structure to inform models [36]. Therefore, the large-scale structure and distribution of the circum-solar dust disk remains the most important constraint on models to understand planetary formation and planetary migration. Its importance is amplified by recent observations of proto-planetary disks that have revealed planetary formation taking place already at less than 1 million years from the birth of the star, which has necessitated a complete revision of planetary formation theories [37,38]. Understanding our own circum-solar dust disk would therefore also be extremely valuable in understanding the formation of other star systems. A dust analyzer and an imaging IR spectrometer on board an Interstellar Probe would provide one of the most critical observations to planetary system formation to date.

Beyond a few 10s of au, the foreground IR emissions from the zodiacal cloud drops to levels where the so-called extragalactic background light (EBL) becomes detectable. The EBL represents all the redshifted, diffuse emissions from all galaxies and stars that have ever shone and therefore holds a large missing piece of information for understanding the early galaxy and star formation some 200 Ma after Big Bang. The same IR spectrometer targeting the circum-solar dust disk, with proper modifications, could serve a dual purpose and also make discovery observations of the EBL. In summary, the outward trajectory of an Interstellar Probe would provide a scientific return on the level of a full astrophysics and planetary mission with only a modest instrument augmentations.

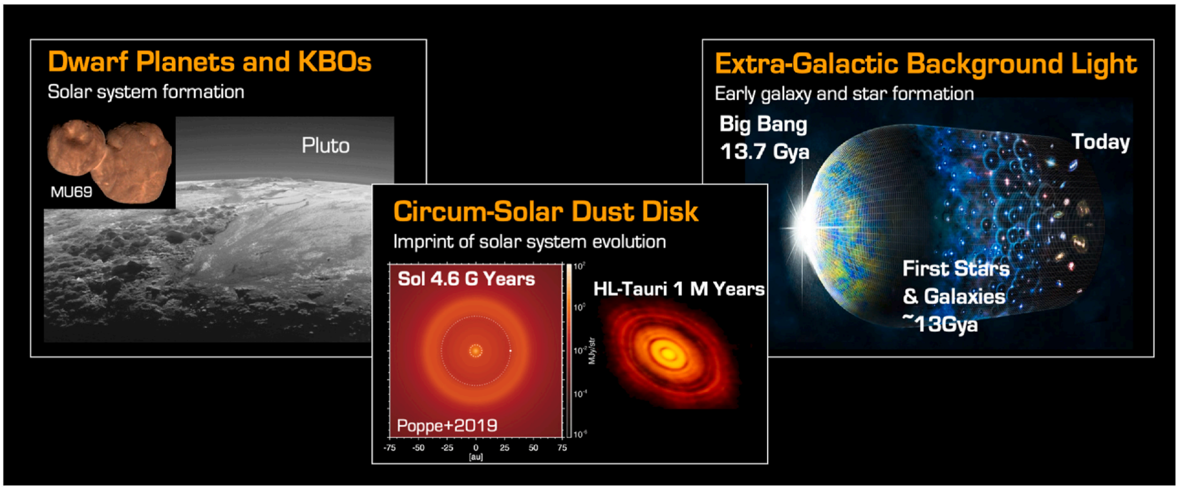

Fig. 5. (Left Panel) There are over 130 dwarf planets and 4000 KBO's in the outer solar system. Any fly-out direction dictated by heliophysics science will therefore be able to accommodate one flyby of a compelling object. (Middle Panel) A modest IR detector can reveal the large-scale disk structure critical for understanding the evolution of planetary systems. (Right Panel) Beyond the obscuring Zodiacal cloud, IR observations can uncover the Extragalactic Background spectrum missing from our understanding of early galaxy formation.

5. Payload examples

To ensure a realistic trade exercise in the study, a fixed mass allocation has been defined of about 90 kg. This allocation stems from historical ratios between payload and spacecraft dry mass, and is 11% in this case (Voyager for reference is ~14%). Within this mass allocation, two example payloads have been assembled from discussions with the science community and that meets the Interstellar Probe science questions. Several important trades with other possible instruments have been made. The first payload addresses the primary goal, and the second payload includes two other instruments that also address the cross-divisional goals.

While it is crucial to optimize the science performance, mass, power and data volume of instrumentation, it is important to realize that the science discoveries offered by an Interstellar Probe is enabled by its trajectory in to an unexplored region of space. Therefore, there are no critical technologies that need to be invented to ensure mission success. However, there ought to be funded development programs dedicated to the optimization of such payloads.

The baseline example payload is shown in Fig. 6. Here, magnetometers (MAG), placed on a boom away from the spacecraft, will be one of the most critical instruments in the payload. Although both vector helium magnetometers and fluxgate magnetometers have heritage, because of the lengthy duration of this mission, fluxgates may prove to be a more reliable instrument.

Charged particle instruments play a key role in understanding the heliospheric interaction and the VLISM properties. First, a plasma system (PLS) would detect thermal ions and electrons up through light PUIs with energies in the 10's to 10,000's eV. Detecting energetic ions, electrons, inner-source PUIs, and PUIs in the VLISM would require an energetic particle system and dedicated PUI instrument (EPS and PUI) for particles with energies in the 10's - 1000's keV. A cosmic ray system (CRS) would account for the highest energy particles, measuring ACRs and GCRs with energies likely ranging 1 MeV/nucleon to several GeV/nucleon. This would be particularly important for characterizing the spectrum of GCR isotopes that otherwise is shielded by the heliosphere and to provide insights in to recent supernova activity [11,39].

Each of these systems would need as close to full coverage of the sky as possible, most likely achieved through angular coverage provided by a spinning spacecraft.

A plasma wave subsystem (PWS) would be vital for measuring plasma waves that provide direct and independent measurements of the local electron density and temperature [40]. In addition, PWS provides also remote information of interactions beyond the HP between shocks and electron density gradients. The PWS measurements would be achieved by four 50-m wire antennas that would be centrifugally deployed early in the mission for the baseline.

An ENA camera offers remote images of the interaction between singly-charged ions and neutral gas, and is therefore a powerful tool for imaging the boundary region – the heliosheath – and the enigmatic ribbon and belt [16,41] that to this day eludes a full explanation. In particular, ENA images would allow scientists to gain insight into what our astrosphere looks like from the outside for the very first time.

A Neutral Mass Spectrometer (NMS) would provide key compositional insight during the mission by measuring neutral gas and dust in the VLISM, as well as the neutral hydrogen wall and neutral VLISM gas and dust inside the heliosphere. The instrument would be placed facing the ram direction. Co-boresighted to perform complementary measurements to the NMS would be an Interstellar Dust Analyzer (IDA), which would not only characterize the detailed in-situ, dust mass and spatial distribution across the entire dust disk, but also establish the properties of interstellar dust and how it affects our heliosphere.

Measurements of low-energy (<1 keV) ENAs would provide important remote information on the interaction of the interstellar plasma and gas with the heliosphere. Such measurements can be achieved by a single field-of-view instrument similar to IBEX-Lo [42] or IMAP-Lo [3]. For the example payload presented here, this instrument was not included in the fixed example mass allocation. A final payload will be a trade and decision by a future Science and Technology Definition Team established by NASA.

Lyman-alpha spectrograph (LYA) would provide remote information about interplanetary and interstellar hydrogen that penetrates the heliosphere. This would enable studies of the neutral hydrogen wall and the properties of the VLISM as well as the influence of the Sun and heliosphere on them. LYA would characterize the diffuse galactic Lyman-α to constrain radiation transfer in galaxies. The spectral resolution of the instrument would need to be sufficient to resolve ideally $\leq$10 km/s, with a sensitivity of <1 Rayleigh/resolution element. The FOV would maximize angular coverage (>2π sr) while maintaining a Sun exclusion zone, with a placement of the spectrograph on the ram side of the spacecraft. Heritage for such an instrument includes missions such as MAVEN.

The augmented example payload trades the LYA for a Visible-Near IR camera for flyby observations and an IR detector for observing emissions from the circumsolar dust disk, dust in the nearby interstellar medium,

EXAMPLE MODEL BASELINE PAYLOAD

Payload Mass and Power

87.4 KG | 86.7 W

PERCENTAGE OF SCIENCE OBJECTIVES ADDRESSED

Charged Particles	Fields and Waves	ENA Imaging	Dust	Neutrals	Lyman-Alpha
38%	35%	11%	3%	5%	8%

PERCENTAGE OF PAYLOAD MASS

Charged Particles	Fields and Waves	ENA Imaging	Dust	Neutrals	Lyman-Alpha
30%	19%	14%	12%	11%	14%

INSTRUMENT *Heritage*	MEASUREMENT REQUIREMENTS		MISSION REQUIREMENTS	SCIENCE DRIVER
Magnetometer (MAG) (MMS/DFG)	0.01–100 nT; 0.01 nT (1e–8 nT^2/Hz turb.)	≤60 s; (100 Hz)	Two FG, 10-m boom	LISM (turbulence)
Plasma Waves (PWS) (Van Allen/EFW)	~1 Hz – 5 MHz; Δf/f ≤ 4% ≤ 0.7 μV/m @ 3 kHz	≤60 s (≤4 s at TS)	4 x 50 m wire; spin plane	LISM n_e, T_e (QTN), turbulence
Plasma Subsystem (PLS) (PSP/SWEAP/SPAN-A)	< 3 eV/e to 20 keV/e e, H^+, He^+, He^{++}, C^+, N-O^+	~4π; ≤60 s	Spinning	Flows, n_e, T_e, n_i, T_i Force balance
Pick-Up Ions (PUI) (Ulysses/SWICS)	0.5-78 keV/e H, ^2H, ^3He, ^4He, ^6Li, ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{22}Ne, Mg, Si, Ar, Fe, charge states	iFOV ≥ 90° x 15°	Spinning	Interstellar, inner PUI Force balance
Energetic Particles (EPS) (PSP/EPI-Lo)	20 keV – 20 MeV H, ^3He, ^4He, Li, C, O, Ne, Mg, Si, Ar, Fe	~4π; ≤60 s	Spinning	S/W, HS and ACRs Force balance
Cosmic Rays (CRS) (PSP/EPI-Hi, in development)	H to Sn; 10 MeV/nuc – 1 GeV/nuc; m/Δm ≥ 10 electrons; 1–10 MeV	2 directions; hours	Spinning	ACRs, GCRs LiBeB cosmic story
Interstellar Dust Analyzer (IDA) (IMAP/IDEX, in development)	1e−19 to 1e−14 g, 1–500 amu; m/Δm ≥ 200	iFOV ≥ 90°	Ram direction Coboresighted NMS	ISDs, galactic heavy ion composition
Neutral Mass Spectrometer (NMS) (LunaResurs/NGMS, JUICE/NMS)	H, ^3He, ^4He, ^{14}N, ^{16}O, ^{20}Ne, ^{22}Ne, ^{36}Ar, ^{38}Ar, m/Δm ≥ 100	iFOV ≥ 10°; weekly	Ram direction Coboresighted IDA	LISM composition
Energetic Neutral Atom Imager (ENA) (IMAP/Ultra, in development)	~1–100 keV H	iFOV: ≥ 170°	Spinning, 2 heads	Shape, force balance, ribbon/belt
Lyman-Alpha Spectrograph (LYA) (MAVEN/IUVS, in development)	±100 km/s Doppler range, <10 km/s resolution	iFOV: ≤ 5°; 140° monthly	Spinning	LISM and heliosheath H

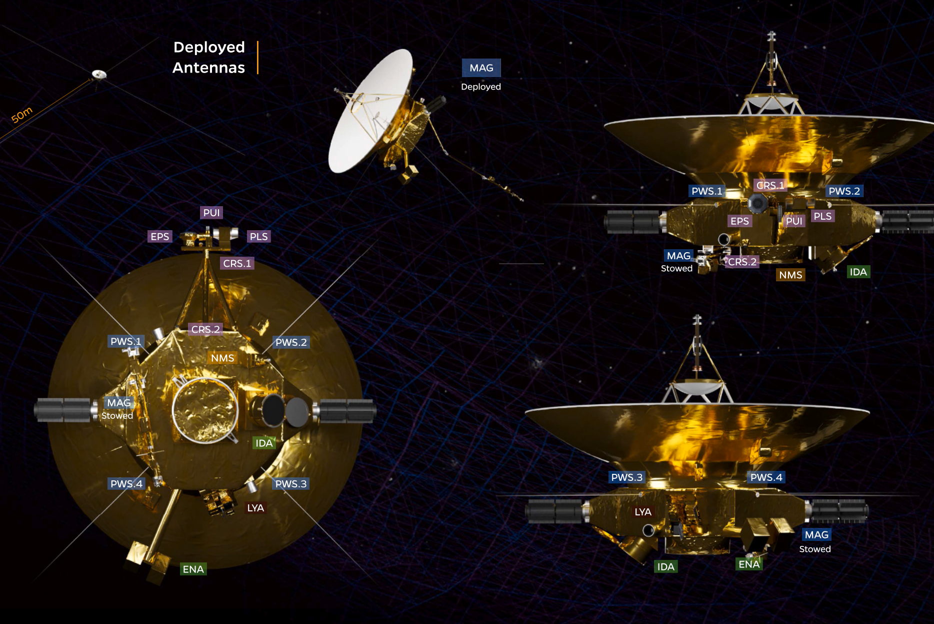

Fig. 6. Example baseline payload of Interstellar Probe.

and the EBL. Here, the mission operations would be driven by the need for 3-axis stabilization and tracking during a dwarf planet or KBO flyby. This necessitates the use of rigid PWS antennas of shorter length that could retain at least the science achieved from the Voyager PWS investigation that utilized two 10-m rigid antennas. The option to centrifugally deploy 50-m wire antennas after a flyby has been discussed, but remains a severe risk to the mission due to the round-trip light travel time of more than 10 h out to a potential flyby target. While a centrifugal deployment of 50-m wire antennas near earth can be achieved safely during the course of a month with real-time commanding and monitoring, performing such a long operation in the outer solar system would have to be done autonomously with no chance of intervening in real time.

6. Mission architecture

Details of the mission architecture is covered by Ref. [8]. Here, we only briefly outline the trade space and the current status. To ensure that the trade space stays within the limits of what is currently possible, a set of engineering requirements have been defined.

- The study shall consider technology that could be ready for launch on 1 January 2030.
- The design life of the mission shall be no less than 50 years.
- The spacecraft shall be able to operate and communicate at 1000 AU.
- The spacecraft power shall be no less than 300 W at end of nominal mission.

The following three mission architecture scenarios are under study.

- Option 1: Direct inject to Jupiter for unpowered Jupiter Gravity Assist (JGA)
- Option 2: Direct inject to Jupiter for powered JGA
- Option 3: Direct inject to Jupiter for unpowered, retrograde JGA followed by a powered Oberth Maneuver close to the Sun

While Options 1 and 2 have been studied for a launch in the 2030's, Option 3 carries with it, extreme mission risk due to the need for an active stage firing very close to the Sun (<4 Solar Radii). The feasibility of such a burn and the necessary heat shield are under a separate study and will not yet drive an example mission architecture.

Options 1 and 2 have been shown to offer asymptotic speeds of up to 8.5 AU/year using realistic stacking configurations of SLS Block 2 and a Star 48 BV Solid Rocket Stage.

The requirement for power is fulfilled by carrying two Radioisotope Thermal Generators (RTG) and are sufficient for allowing all science instruments to operate throughout the design lifetime of 50 years. Beyond the nominal lifetime it may be necessary to power cycle or turn off some instruments.

The baselined communication is X-band with a 5 m dish antenna and the use of the next-generation VLA systems once the probe would reach about 70 au. Ka-band is also under study, but requires higher pointing accuracy. Although, optical laser communication offers high data rates, it imposes an unrealistic pointing requirement on the mission architectures under study.

7. Trajectory trades

Given a direct launch to Jupiter for either a passive or a power JGA, the heliospheric boundary and VLISM can be reached through the leading hemisphere of the heliosphere through a series of launch opportunities beginning around 2036 as shown in Fig. 7 [43]. The speed map was computed assuming an SLS Block 2 launch with an Atlas V Centaur and Star 48 BV kick stage that are all used shortly after launch for a direct inject to Jupiter, where a passive ("ballistic") JGA follows. Speed maxima arise from the dependence on the relative orbital velocity between Earth and Jupiter with a recurrence roughly every 13 months. The decade-long modulation seen across the maxima arise from Jupiter's and Earth's relative positions.

Launch options across the leading hemisphere of the heliosphere are preferred since they go through a scientifically interesting region of space, where the heliosphere first meets the VLISM. The force balance and heating mechanisms across this region in the heliosheath seem to display solar cycle variations as seen through IBEX and Cassini

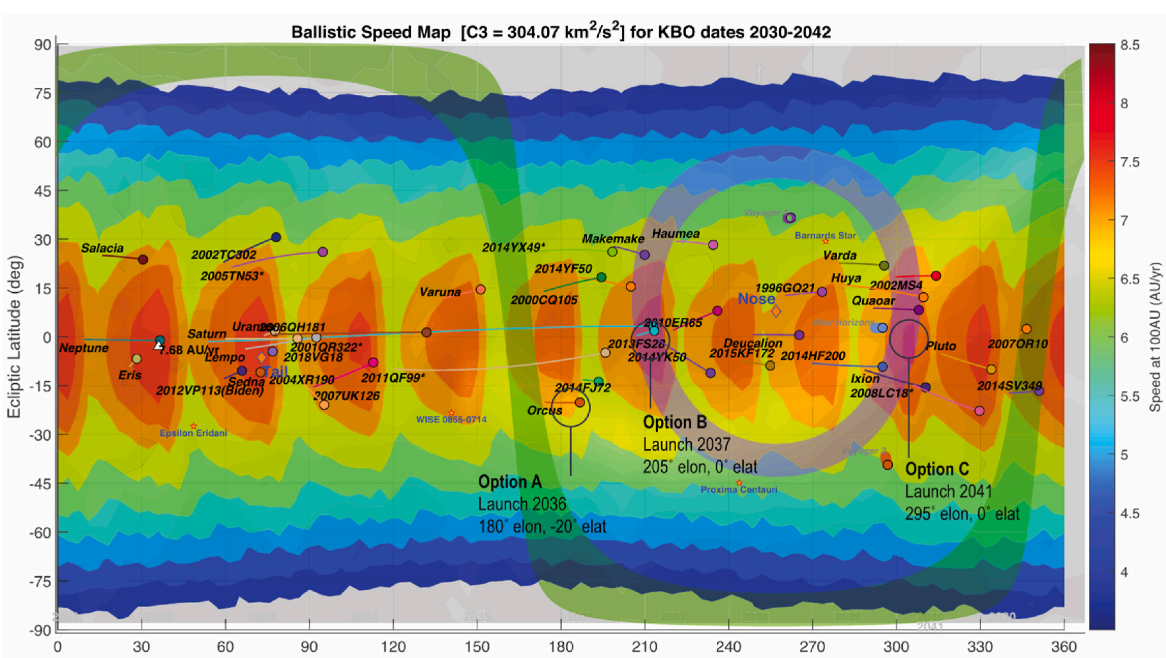

Fig. 7. Colored contours of spacecraft speed at 100 au across the sky achieved by an SLS Block 2 with an Atlas V Centaur and a Star-48 BV. Launch date runs with ecliptic longitude and resulting speed depends on the relative position of Jupiter and Earth. The green and purple bands mark 90° and 45° off the nose direction, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

observations, that will be critical for understanding the global nature and dynamics of the interaction. Also, the spatial variation of the heliosheath thickness serve as a very important constraint to finally resolve the mystery of the thin heliosheath. Although predictions vary widely, the estimated distances to the HP in the forward hemisphere fall within a range that delivers an Interstellar Probe beyond the HP and well out into the VLISM within the nominal lifetime of 50 years. Travelling in the general upwind direction also ensures that interstellar gas, dust and plasma ram flows are high and therefore possible to measure by in-situ instrumentation. In the down-wind direction it would be problematic to detect such flows given that the space speed is generally higher (30–35 km/s) than the VLISM apparent flow speed (26 km/s).

The first option has a launch in 2036 has been chosen as the example baseline trajectory to inform the mission design. It goes through approximately 180° elon, −20° elat (Option A in Fig. 7). This direction is about 80° away from the heliospheric nose and is well separated from the Voyager and New Horizons directions. While Cassini observations indicate a bubble-like heliosphere with comparable heliosheath thicknesses (~30 au) in all directions, IBEX observations imply a distance of the HP of approximately 150–200 au in this direction [44]. Models predict a distance to the TS of 91 au and a distance to the HP of 148 au (Shresta, Personal Communication), which corresponds to a heliosheath thickness of 57 au. Thus, this direction places a particularly important constraint on models. The angle of exit relative to the nose direction of about 80° offers also a clear side-view for ENA and UV imaging of the heliosphere once beyond the HP that could discern a possible existence of any extended tail structures. And lastly, the ecliptic latitude has been chosen to intersect the ribbon, although somewhat weaker on this side of the nose. This is also the general direction towards Orcus with its moon Vanth that provide a very compelling flyby target at only 30 au for potential planetary augmentation of the mission concept.

Trajectories in the down-wind direction provide valuable exploration of the possible tail structure, turbulent regions of potential jets, and directions towards strong EUV stars to explore ionization process in the LIC. However, the distances to the HP in these down regions have generally high uncertainties on the order of 100's au and the net ram speed of interstellar material would be low making it more challenging for in-situ measurements of interstellar gas, dust and plasma.

8. Concept of operations

The baseline Interstellar Probe primary science mission uses a simple concept of operations to operate ten instruments autonomously continuously for long periods. Interstellar Probe science instruments do not require specific pointing of the spacecraft nor does the payload depend on mechanisms operated by the spacecraft after magnetometer boom and the 50-m wire antennas are deployed. Measurement sequences are self-contained and are performed simultaneously with little or no impact on spacecraft or other instruments. Instrument calibrations and table or parameter changes are infrequent and mainly occur when crossing from one mission phase to the next. The majority of the prime mission is conducted over the course of three nominal phases, consisting of operation in the heliosphere (approximately 1–90 AU), the heliosheath (approximately 90–120 AU), and the interstellar medium (>120 AU).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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