In-situ Investigations of the Local Interstellar Medium

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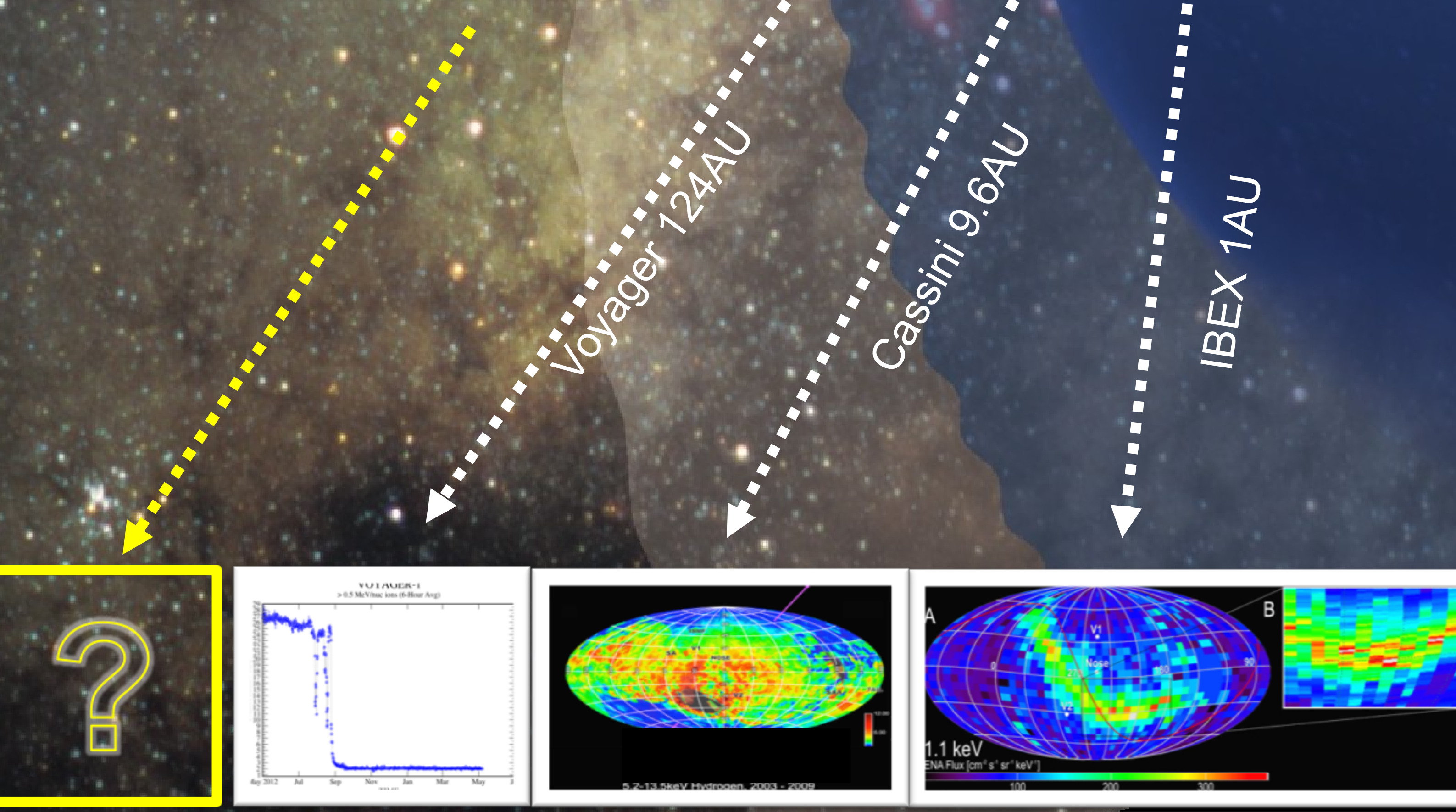

1 Executive Summary

The discovery of a myriad of exoplanets in the past decade has revolutionized the understanding of our place in the universe. How different are they and do some of them harbor life, just like Earth? To do so, their parent star must drive a stellar wind and carve what we call an astrosphere into the surrounding interstellar medium. Astrospheres are ubiquitous in our immediate neighborhood (117) and show very similar structure to our heliosphere. Voyager, IBEX, and Cassini have shown that the interaction between interstellar medium and solar wind is much more complex and involved than previously believed (75). This stellar-interstellar interaction is key to understand the ubiquitous phenomenon of astrospheres and the shielding they provide to the planetary systems they harbor. This interaction must be studied directly on the edge of our heliosphere and beyond to answer the following questions:

H: How do the solar wind and interstellar medium interact to form the heliosphere and how does this relate to the universal phenomenon of the formation of astrospheres?

A: What are the properties of the very local interstellar medium and how do they relate to the typical ISM and the material from which planetary systems are made?

F: How do plasma, neutral gas, dust, waves, particles, fields, and radiation interact in extremely rarefied, turbulent, and incompletely ionized plasmas?

In addition, such a mission would enable planetary science (**P**) with its fly-by of Jupiter and other planetary targets of opportunity. The former would allow investigation of Jupiter's moons and atmosphere after the JUICE era, the latter could be a Kuiper-Belt Object (KBO), very similar to the successful New Horizons spacecraft.

1.1 Scientific Relevance to Voyage 2050

ESA has a distinguished history of excellence in realizing scientific missions to investigate the Sun (SOHO) and heliosphere (Ulysses). This whitepaper proposes to build on and gather this Euopean expertise beyond Solar Orbiter, scheduled for launch in early 2020. After investigating the inner heliosphere (understood here to include Ulysses) it is now time to explore the outer heliosphere, its boundaries and the surrounding interstellar medium with new instrumentation which is tailored to the unique environment "out there".

While we will focus mainly on a mission toward the bow region of the heliosphere, an option going in the aft direction should also be studied carefully. After all, it has never been explored, it would allow us to decide whether our heliosphere has no, one, or two tails; we could study the dynamics of the interstellar medium in more detail because of the lesser relative speed between probe and ISM; we would explore the interstellar environment which we have traveled through in the past.

1.1.1 Strawman Mission Concept:

An interstellar probe has been studied by ESA (65) and NASA (e.g., 76, and references therein) in the past, and is being studied again by NASA (78) and in China. All agencies have shown it to be a technologically feasible yet challenging mission. Thus, it is an ideal candidate for a European-led L-class mission or a significant European contribution to a cooperative mission between ESA/NASA of ESA/China. The following two technological drivers would need to be addressed:

- **Propulsion**: Proposals have included solar sails, nuclear ion propulsion, electric sails, heavy launcher (see 76; 78, for a summary).
- **Power**: Nuclear power would be unavoidable, payload power sharing strategies may be needed.

Solving both would significantly enhance European space-faring capabilities. Both technological developments are required for a reasonable mission duration.

The payload would need to be highly optimized and may even require a power-sharing strategy among the payload, and, possibly, the data downlink system.

1.1.2 Bonus Science Goals:

On its way to the heliopause and beyond, the interstellar probe will allow the following bonus science goals (**B**) from a variety of scientific disciplines:

- Measure extragalactic background light (and other astronomical targets in the infrared) undisturbed by the solar system Zodiacal light.
- Determine the soft X-ray background in the heliosphere and solar-wind planet interactions.
- 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.

Thus, this mission proposal would serve a large scientific community by addressing questions summarized in the following Table 1.

Science Goal	Science Question	Req. Measurements
Heliospheric Science (H)		
How do solar wind and interstellar medium interact to form the heliosphere and how does this relate to the universal phenomenon of the formation of astrospheres?	**H1:** How does the heliosphere shield against cosmic rays and neutral particles and what role does it play in the interstellar-terrestrial relations?	GCR, energetic particles, ENAs, plasma, B-field, waves
	H2: How do the magnetic field and its dynamics evolve in the outer solar system?	energetic particles, ENAs, plasma, B-field, waves
	H3: How do heliospheric structures respond to varying boundary conditions?	Plasma, B-field, ENAs, Ly-alpha
	H4: How do the boundary regions in the heliosphere modify the intensities of the various particle populations?	GCR, energetic particles, ENAs, plasma, B-field, waves, dust
	H5: How does the interstellar medium affect the outer solar system?	GCR, energetic particles, ENAs, plasma, B-field, waves, dust
Astronomy and Astrophysics (A)		
What are the properties of the very local interstellar medium and how do they relate to the typical ISM?	**A1:** What is state and origin of the local interstellar medium?	Charge-state and element composition, waves, B-field, Ly-alpha, ENAs
	A2: What is the composition of the local interstellar medium?	Composition
	A3: What is the interstellar spectrum of the GCR beyond the heliopause?	GCR
	A4: What are the properties of the interstellar magnetic field?	B-field, waves, plasma
	A5: What are the properties and dynamics of the interstellar neutral component?	ENAs, dust, plasma
	A6: What are the properties and dynamics of interstellar dust?	Dust, B-field, plasma
Fundamental Physics (F)		
How do plasma, neutral gas, dust, waves, particles, fields, and radiation interact in extremely rarefied, turbulent, and incompletely ionized plasmas?	**F1:** What is the nature of wave-particle interaction in the extremely rarefied heliospheric plasma?	Distribution functions, energetic particles
	F2: How do the multiple components contribute to the definition of the local plasma properties within the heliospheric boundary regions?	Plasma, ENAs, energetic particles, composition, waves, B-field
	F3: What processes determine the transport of charged energetic particles across a turbulent magnetic field?	Plasma, ENAs, energetic particles, composition, waves, B-field
Planetary Science (P)		
Investigation of planeatary targets of opportunity.	**P1:** Dynamics of the Jupiter moons	IR/Vis & multi-wavelenth imaging
	P2: Dynamics of the Jupiter atmosphere	IR/Vis & multi-wavelenth imaging
	P3: Origin of Kuiper Belt Objects (KBOs)	IR/Vis & multi-wavelenth imaging
	P4: Planet Nine	IR/Vis & imaging
Bonus Science (B)		
Bonus Science achievable with interstellar probe.	Extragalactic Background Light, Soft X-ray background, Multispacecraft studies, Ly-α absorption	IR/Vis wide-field imaging soft X-ray & UV measurements, time series

Table 1: Science goals, science questions, and required measurements for an interstellar probe.

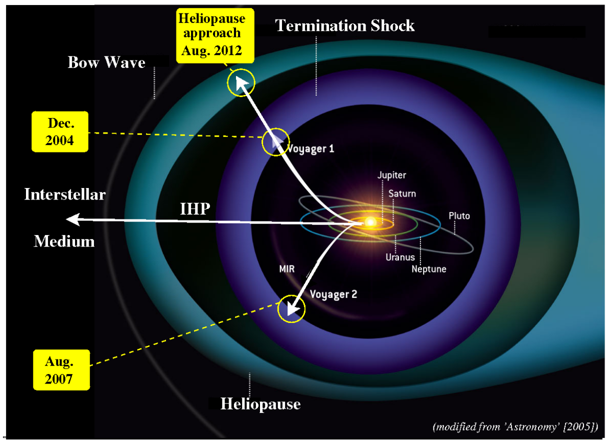

Figure 1: The positions of the Voyagers in the heliosphere. In August 2012 Voyager 2 entered a region likely to be associated with the heliopause. Voyager 1 has just recently entered this region. Neither Voyager will be able to probe the interstellar medium proper, necessitating an Interstellar Probe.

2 Introduction

After the exciting in-situ observations of the termination shock and the entry of the Voyager 1 spacecraft into the inner regions of the outer heliosheath (see Fig. 1), 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 (e.g., 12), contributes to the clarification of fundamental astrophysical processes like the acceleration of charged particles at a stellar wind termination shock (e.g., 34) and beyond, and also sheds light on the question to what extent interstellar-terrestrial relations are important for the environment of and on the Earth (38) and exoplanets.

In order to explore the boundary region of the heliosphere, it is necessary to send a spacecraft to perform advanced in-situ measurements particularly in the heliosheath, i. e., the region between the solar wind termination shock, and the heliopause, as well as in the (very) local interstellar medium (VLISM). Solar activity is decreasing to "normal values" below those of the Grand Solar Maximum (4) which was typical of the space age so far (Fig. 8). This is likely to reduce the size of the heliosphere and allows us to study a "normal" heliosphere by launching an Interstellar Probe (IP) which will also provide within a shorter time than previously believed the first comprehensive measurements of key parameters of the local interstellar environment such as its composition, state, and magnetic field. Together with an accurate determination of the state of the heliospheric plasma across the heliosphere, these quantities are crucial to understanding how the heliosphere, and, much more generally, astrospheres, are formed and how they react to varying interstellar environments. Our current understanding of the interstellar medium and heliosphere is undergoing dramatic changes. Today, we understand the interstellar medium as a turbulent environment with varying degrees of ionization, highly variable composition and dust-to-gas ratio interacting with a complex magnetized and highly ionized heliospheric plasma - all in a complex background field of UV, cosmic rays, and neutral particles which is modified by the interaction itself. Thus, the heliosphere and its boundary regions serve as the worlds largest laboratory for complex plasmas. This complex region strongly modulates the flux of galactic cosmic rays which account for one half of the natural background radiation that life is exposed to on Earth and shields Earth and solar system from highly reactive neutral hydrogen atoms, thus ensuring the habitability of Earth (and, in analogy, of potential life-supporting exoplanets). How does this shielding function depend on the strongly varying interstellar environment? How does this shielding depend on the solar activity-induced heliospheric structure (Fig. 2)? What is the role of (anomalous) cosmic rays in these interstellar-terrestrial relations?

The ongoing Voyager Interstellar Mission (VIM) and recent observations from the Interstellar BoundaryExplorer (IBEX) (67) and Cassini missions (57) have revealed the interaction of the heliosphere with the VLISM to be much more complex than heretofore assumed. With new observations have come significant new puzzles for describing the physics of the interaction between solar (stellar) wind and the surrounding interstellar medium. In-situ instruments on Voyager 1 and Voyager 2 up to very recently have revealed significant fluxes of energetic particles in the heliosheath, including a well-defined suprathermal ion "tail" in which the differential intensities fall off $\sim E^{-1.5}$ above ∼30 keV (25). At higher energies (∼100 MeV), there is no "unfolding" of the energy spectrum of the anomalous cosmic rays (ACRs), thus pointing to a more remote location for the modulation region and source (91; 94). Most strikingly, direct measurements of the shocked solar wind flow speed obtained from Voyager 2 revealed that the flow remains supersonic in the heliosheath beyond the termination shock (90). All of these particle observations, taken together, unambiguously imply that the bulk of the energy density in the plasma resides in a non-thermal component that extends to very high energies. Strong implications, both quantitative and qualitative, follow from this fact for the overall heliosheath structure. We have never encountered a large-scale plasma regime in which the non-thermal ion pressure dominates the thermal pressure and overwhelms the magnetic field stresses. The closest known analogies are regions of planetary

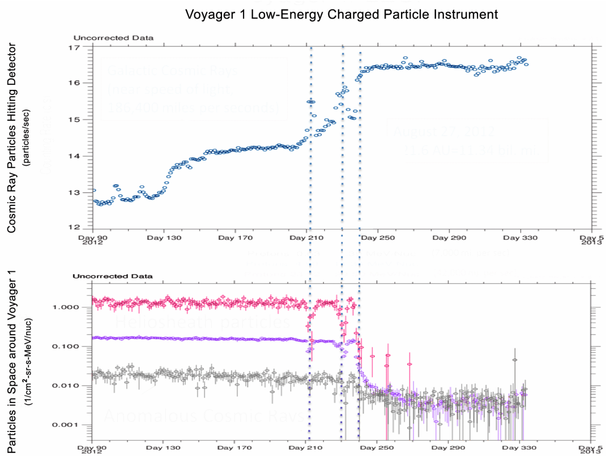

Figure 2: Voyager-1 measurements of the flux of GCR (top panel) and low-energy particles (bottom panel) show dramatic changes in both particle populations around the end of August 2012, indicating that Voyager 1 may have detected the heliopause or its precursor.

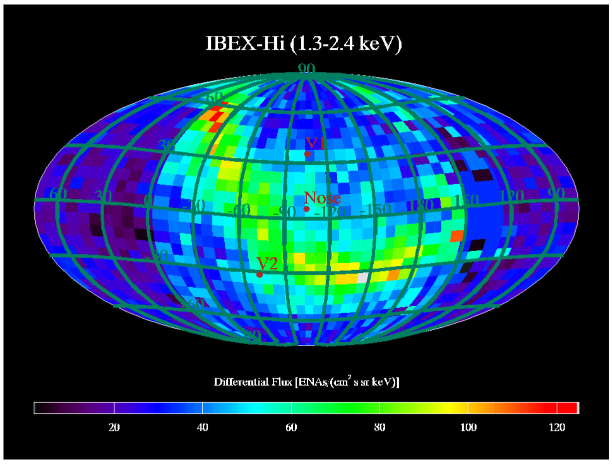

Figure 3: IBEX map of energetic neutral hydrogen atoms (ENAs) from 1.3 - 2.4 keV shows the "ribbon" and has the nose and Voyager 1 & 2 positions indicated.

magnetospheres during extremely disturbed conditions, but in the heliosheath these conditions apply on a much larger scale. Even sophisticated MHD models failed to predict anything like the striking new features that have been observed in the last few years. There was however a foretelling of this recent revelation. Voyager 1&2 beginning in 1983 and continuing to the present had detected remarkable long-lasting radio emissions in the 1.6 - 3.4 kHz range that were identified with major disturbances in the heliosheath produced by giant coronal mass ejections (CMEs) (58). The higher frequency emissions were localized, coming from an extended arc confined to the hemisphere toward the interstellar flow (i. e., the "nose" of the heliosheath), and lying close to, but not actually in the galactic plane (45). These authors noted that the arc could perhaps be the curve on the heliopause (the boundary between shocked solar wind and interstellar plasma, see Fig. 1) where the interstellar magnetic field was normal to that surface ($\mathbf{B} \cdot \mathbf{n} = 0$), in accordance with the "hydrogen deflection plane" defined by the $\sim 4°$ difference between the arrival directions of interstellar H atoms (61) (affected by charge exchange in a heliosheath deformed by the interstellar magnetic field) and the unaffected interstellar He atoms (114).

Over the last two decades, imaging of energetic neutral atoms (ENAs) by IBEX (71), Cassini/INCA (57), and other space instruments in the inner solar system (40) has revealed the energy spectrum of heliosheath proton populations and stunningly unexpected structures in the outer heliosphere. IBEX data show a relatively narrow "ribbon" of atomic hydrogen emission from ∼200 eV to ∼6 keV, roughly circular, but asymmetric in intensity (69; 24), suggesting that it is ordered by the interstellar magnetic field (Fig. 3). It passes through, rather than being centered on, the "nose" at which the local, neutral interstellar plasma flow around the heliosphere stagnates. This suggests that the flow is not the primary driver of the system as has been thought, but rather it is the pressure of the interstellar magnetic field that configures the heliosheath. The neutrals from both the glow and ribbon are also characterized by non-thermal distribution functions. The Ion and Neutral Camera (INCA) on Cassini sees at higher energies (10s of keV) a "belt" of emission in ENAs, broader than the ribbon and tilted significantly away from it and exhibiting a much steeper energy spectrum than observed in the IBEX energy range (56) (Fig. 4). The rise in GCR shown in the top panel illustrates the shielding provided by the heliosphere.

After a trip of now more than 40 years, both Voyager spacecraft have now crossed the termination shock and the heliopause at roughly 120 AU close to the upwind direction of the heliosphere (14; 105; 106; 26). As discussed in the previous section 1 and in the following, a number of questions still remain. A key point here is that we now know what kind of instruments are needed to make the relevant measurements in interstellar space.

Even with the increased knowledge from space missions, the global shape and dimensions of the heliosphere remains a contested topic (83; 27; 95). 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 (121; 41).

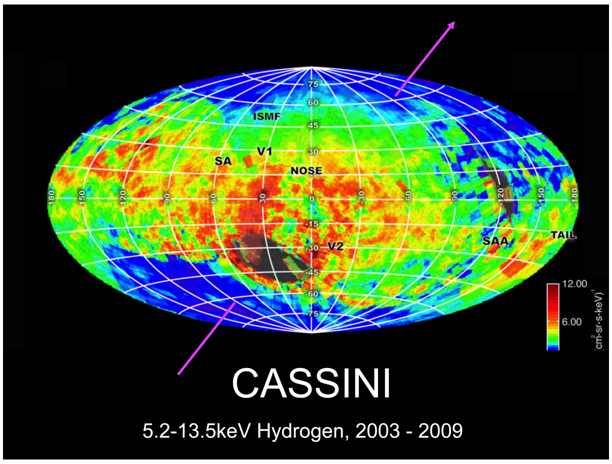

Figure 4: ENA map from the INCA instrument on Cassini. The map is an equal-area projection that shows the emission "belt". The nominal "nose" of the heliosphere from which there is a general flow of neutral atoms is indicated along with the outgoing asymptotic trajectories of Voyager 1 (V1) to the north and Voyager 2 (V2) to the south, respectively, of the plane of the ecliptic.

Attempts to explain consistently all the aforementioned fascinating 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 interstellar probe with modern in-situ and remote sensing capabilities and science requirements informed by the now available observations can answer these open questions.

The interstellar medium is the primeval material which the Sun, the planets, and ultimately terrestrial life were made of some 4.6 billion years ago, just as many other stars and planetary systems were formed at other times in different places. Exploring our local interstellar neighborhood will vastly enhance our understanding of the origin, formation, and evolution of stars, their planetary systems, and possibly of life.

Thus, this grand science theme addresses the following Core, Opportunity, and Bonus Science Goals (see Tab. 1):

Heliospheric Science - H How do the solar wind and interstellar medium interact to for the heliosphere and how does this compare to the ubiquitous phenomenon of astrospheres? (H1-H5)

Astronomy and Astrophysics - A What are the properties of the very local interstellar medium and how do they relate to the typical ISM and the material from which planetary systems are made? (A1-A6)

Fundamental Physics - F How do plasma, neutral gas, dust, waves, particles, fields, and radiation interact in extremely rarefied, turbulent, and incompletely ionized plasmas? (F1-F3)

Planetary Science - P Investigation of planeatary targets of opportunity. (P1 - P4)

Bonus Science - B Bonus Science achievable with interstellar probe. (B1 - B4)

The Science Goals mentioned above can be broken down into more detailed questions which illustrate the breadth and importance of the overall Science Theme, as shown in Table 1.

3 Science Objectives

3.1 H: How do solar wind and interstellar medium interact to form the heliosphere and how does this relate to the universal phenomenon of the formation of astrospheres?

The better we understand the physical processes at work on our Sun, the more we view our sun as a typical stellar object. The processes that give rise to our solar wind are clearly at work at other stars. We are beginning to understand not only how the Sun heats its corona and powers the solar wind, but how these processes relate generally to stellar coronae and winds. We thus understand our heliosphere as one example of an astrosphere inflated by the stellar wind of its host star.

H1: How does the heliosphere shield against cosmic rays and neutral particles and what role does it play in the interstellar-terrestrial relations? Cosmic rays are high-energy charged particles which bombard Earth from above the atmosphere. Several thousand pass through a person's body every minute. These can cause biological damage but also cause mutations which accelerate evolution. The majority of GCRs present in interstellar space are shielded out by the outer heliosphere (Fig. 5), presumably via a strong magnetic barrier that forms in the inner and outer heliosheath, where the solar wind slows down and is deflected by the interstellar flow (See, e.g., 35, but see also the discussion below of the relevant physics which was quite unexpected.). Figure 5 shows the flux of GCRs from beyond the heliosphere to inside the heliosphere at 1 AU. A small fraction of

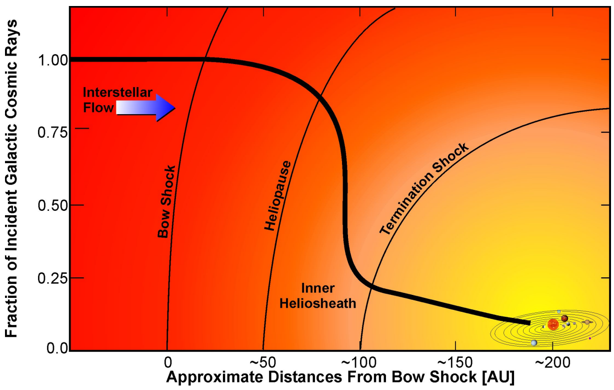

Figure 5: The fraction of incident GCRs on the heliosphere is most strongly reduced in the inner heliosheath where the slowdown of solar wind creates a large magnetic barrier to GCRs; this barrier is the dominant shield against GCR radiation in the solar system.

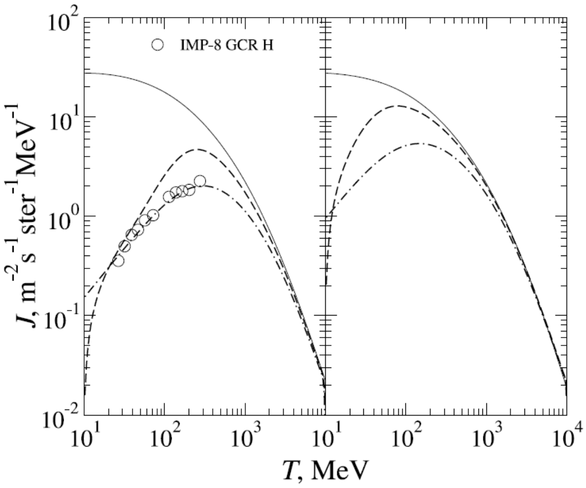

Figure 6: Galactic cosmic rays differential intensities in the heliosphere during the present day, left, and a future or past period when the heliosphere was smaller, with termination shock near 20 AU, due to a larger (×10) density in the interstellar medium (35).

GCRs penetrate into the heliosphere and propagate toward the Sun and planets. These residual GCRs are modulated by the solar wind's magnetic field in the inner heliosphere.

What we know about the dominant shielding of GCRs in the inner heliosheath region is very limited and based mostly on models and theory. It is nonetheless clear that the solar wind must slow down prior to meeting the interstellar flow. This slowdown must result in a strong pile-up of magnetic field since the magnetic field is frozen in to the solar wind. This magnetic barrier is believed to be the primary shield against GCRs entering the inner heliosphere (e.g., 35), although some additional modulation in the outer heliosheath appears to be needed (94). Recent data from Voyager 1 show a dramatic drop in low-energy particles associated with a strong rise of GCR particles (109), providing further illustration of the complexity of the physics responsible for the shielding/modulation by the heliosphere.

Large changes in the LISM have dramatic effects on the heliosphere and the radiation environment of the solar system. For example, a typical enhancement in the density of the local interstellar medium by a factor of 10 causes the entire heliosphere to shrink to about a quarter of its current size (120), and increases the fluxes of GCRs at Earth by a factor of 2–6 (93), as can be seen in Fig. 6, discsussed below. Such large changes in the LISM have certainly occurred in the past and will occur again in the future (120).

Figure 6 shows the differential intensity of GCR protons, on the left for the present day, and on the right for a period when the heliosphere was smaller due to a larger density (×10) in the local interstellar medium. Shown are external boundary conditions (72), conditions near the termination shock (dashed), and near Earth (dashed-dotted). Circles show IMP-8 data from (49). The large increase in the levels of GCR radiation (right panel) reveals the critical influence of local interstellar conditions on the radiation environment of the solar system. The estimations made in Fig. 2 are purely theoretical. We do not currently have the observational knowledge required to understand how the local interstellar medium interacts with the heliosphere; observations of that global interaction are essential for understanding the radiation environment that must be traversed by astronauts for long missions to distant destinations, such as Mars.

On Earth, the radioisotope ^{10}Be provides a recent record of cosmic ray fluxes (Fig. 7). The isotope is produced in Earth's upper atmosphere by spallation reactions of cosmic rays (CR) protons with energies higher than about 100 MeV and secondary neutrons with atmospheric nitrogen and oxygen. ^{10}Be records in Antarctic ice show two prominent peaks 35,000 and 60,000 years ago, when the radioisotope production rate was about twice the current value for about 1500 and 2000 years, respectively, which has been interpreted as due to supernovae in the vicinity of the heliosphere (86). Could the GCR fluxes in the heliosphere change rapidly in the future due to changing conditions in the LISM? Again, the ^{10}Be record from ice cores can be used to show that at least in the past 300 years this has not been the case (8). Nevertheless, because of the critical hazard posed by GCR radiation, future manned space travel will rely heavily on a better understand of the LISM's influence over the heliosphere, and the

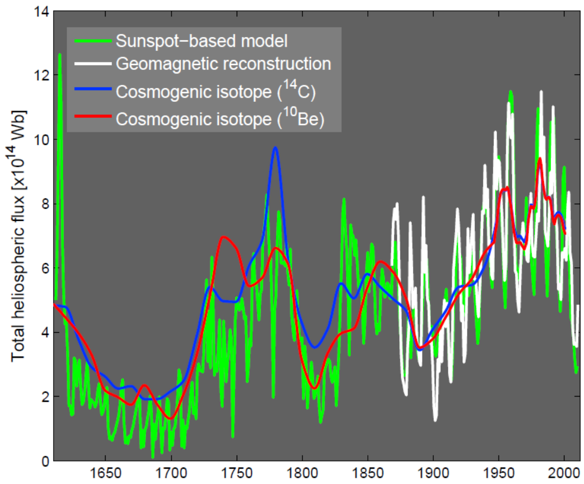

Figure 7: The total heliospheric magnetic flux over the last 400 years, as estimated by geomagnetic, cosmogenic isotope and sunspot number reconstructions. The space-age has been a period of anomalously high solar activity, which is currently drawing to a close. Adapted from (81).

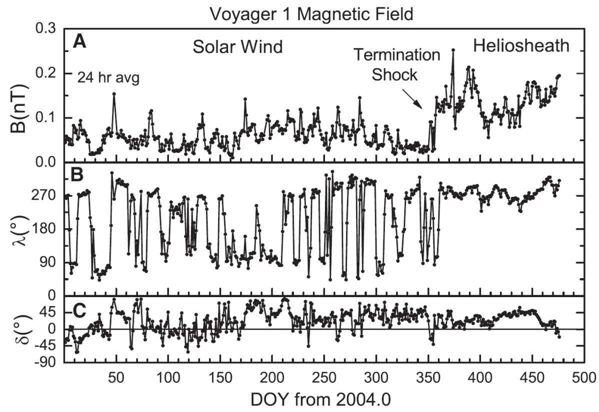

Figure 8: Compression of the magnetic field across the termination shock (14).

potential short and long-term changes to the radiation environment. Figure 7 also shows a peculiarity which has only recently begun to be realized and appreciated, namely that the space age has been one of rather high solar activity (81). How does the heliospheric modulation react to the changes in solar activity?

H2: How do the magnetic field and its dynamics evolve in the outer solar system? Figure 8 shows Voyager measurements of the expected compression of magnetic field at the termination shock. However, no sector boundaries were observed in the heliosheath during the first few months after the shock encounter, which could only be interpreted as due to a much lower convection speed (∼17 km/s) of the local plasma relative to the spacecraft than expected. Further evidence for a significantly altered magnetic field in the downstream region comes from its fluctuations, which are much stronger in the heliosheath than in the heliosphere. Moreover, the statistical distribution of field magnitude changed (14) from lognormal (upstream) to Gaussian (downstream heliosheath), a transition that is not understood. This abrupt change in the nature of the magnetic field across the termination shock has important consequences for the acceleration of particles at the termination shock, as these are affected by turbulent motions of the surrounding plasma. The level of low-frequency turbulence in resonance with the high-energy particles accelerated at the termination shock is unknown but key to understanding the modulation of galactic cosmic rays and the acceleration of anomalous cosmic rays.

H3: How do heliospheric structures respond to varying boundary conditions? Observations by SWAN on SOHO have shown that the magnetic field in the very local interstellar medium lies at a significant angle to the galactic plane (Fig. 9) (61), a result recently independently confirmed with Voyager radio data (80). On the other hand, general considerations about a galactic dynamo suggest that it should lie in the galactic plane at least on large scales. Thus, the very local field lies at a significant angle to the large scale field which is interpreted as a consequence of turbulent motions in the local interstellar cloud. Furthermore, the overabundance of carbon (see Science Objective A2) indicates an inhomogeneous local cloud. Together with observations of differences in flow angles, these observations imply an unexpected variability in the immediate interstellar vicinity of the heliosphere. Thus, we may expect that the heliosphere must react to these varying interstellar boundary conditions as well as to the solar-cycle variations at the inner boundary condition, the Sun.

Based on modeling efforts we expect that several heliospheric structures will react quite sensitively to changes in the interstellar medium (30). Density fluctuations in the hydrogen wall should propagate around the heliosphere and thus give us a record of past variations in the heliosphere's very local interstellar neighborhood. The three-dimensional structure of the hydrogen density surrounding the heliosphere can be measured, thus giving us access to this archive.

Because we do not know the strength of the interstellar magnetic field, we do not know whether the heliosphere has a bow shock, although there are stong indications from IBEX, that there is none (67). The presence of a bow shock has important consequences for the turbulence in the outer heliosheath, i.e., between the bow shock and the heliopause. The shock generates downstream turbulence that translates into locally decreased spatial diffusion of energetic particles, thus contributing to a shielding against galactic cosmic rays (See 94, who also show that there is substantial modulation beyond the heliopause.).

Furthermore, the trajectories of interstellar dust particles are altered by a bow shock, thus, the presence of a bow shock can be determined by a surprisingly simple measurement of the inflow direction of interstellar dust particles in a given mass range. Simulations (66) show that the flow direction of small particles is deflected by approximately 10° from the undisturbed direction when a sharp bow shock is present. Assuming that the inflow direction of gas and dust is the same, a measurement of the dust flow direction thus gives us the possibility to remotely detect the presence of a bow shock and, hence, indirectly determine a lower limit on the magnitude of the interstellar magnetic field.

Figure 7 illustrates the timeliness of investigating heliospheric response now. There are strong indications that the Grand Solar Maximum (GSM) is coming to an end and that the Sun transitioning into an extended period of reduced activity (4). This has two important implications. First, we expect to see a different heliosphere in the coming decades due to the changing inner boundary conditions. Second, reduced solar activity will likely result in a smaller heliosphere which would allow an interstellar probe to reach the LISM sooner than previously believed.

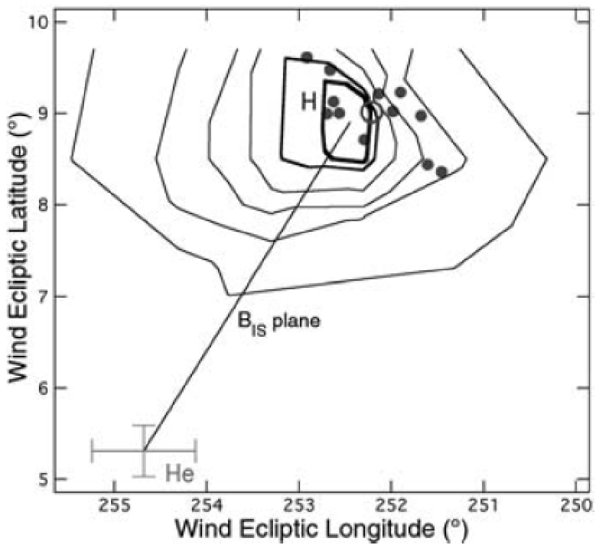

Figure 9: Observations with SOHO/SWAN indicate that the direction of the very local magnetic field is deflected from the average galactic plane direction by turbulent motions in the local interstellar cloud. From (61).

H4: How do the boundary regions in the heliosphere modify the intensities of the various particle populations? Early cosmic ray observers discovered an unusual subset of cosmic rays which consisted of singly ionized ions (instead of fully stripped nuclei) with energies of 1–50 MeV/nuc (79). They were called Anomalous Cosmic Rays (ACRs). Most of the ACRs are species which have high ionization thresholds, such as He, N, O, Ne, and Ar. Until recently, ACRs were thought to arise only from neutral atoms in the interstellar medium (33) that drift freely into the heliosphere through a process that has four essential steps: first, there is a source of neutral particles, traditionally thought to be only interstellar neutral atoms that stream into the heliosphere; second, the neutrals are converted into ions, called pickup ions since they are picked up and swept out by the solar wind; third, pickup ions are pre-accelerated by shocks and waves in the solar wind (see also 97); and finally, they are accelerated to their final energies at the termination shock (82) or beyond it. Easily ionized elements such as C, Si, and Fe are expected to be strongly depleted in ACRs since such elements are not neutral in the interstellar medium and therefore cannot drift into the heliosphere.

Due to instruments like SWICS on Ulysses, we have been able to detect pickup ions directly, and due to ongoing measurements by cosmic ray detectors on spacecraft such as Voyager and Wind, researchers have been able to detect unusual components of the ACR (e.g., 21). There is a growing understanding that, in addition to the traditional interstellar source, grains produce pickup ions throughout the heliosphere: grains near the Sun produce an "inner source" of pickup ions, and grains from the Kuiper Belt provide an "outer" source of pickup ions and anomalous cosmic rays (see, e.g., 96; 111; 1, and references therein).

Not only are recent observations calling into question the sources of ACRs, but also the very means by which they are accelerated. The prevailing theory until V1 crossed the TS was that pickup ions were energized at the TS to the 10–100 MeV energies observed (82). However, when V1 crossed the TS, it did not see a peak in the ACR intensity as the aforementioned theory predicted (73; 105). Instead the ACR intensities continued to increase in the heliosheath. Various suggestions have been proposed (e.g., 15; 14; 70; 73), but so far none has been able to explain all aspects of these puzzling observations. The dramatic fall in the intensity of the ACR shown in Fig. intro-2 promises valuable information on both their propagation and the boundary layer properties if investigated by a future probe.

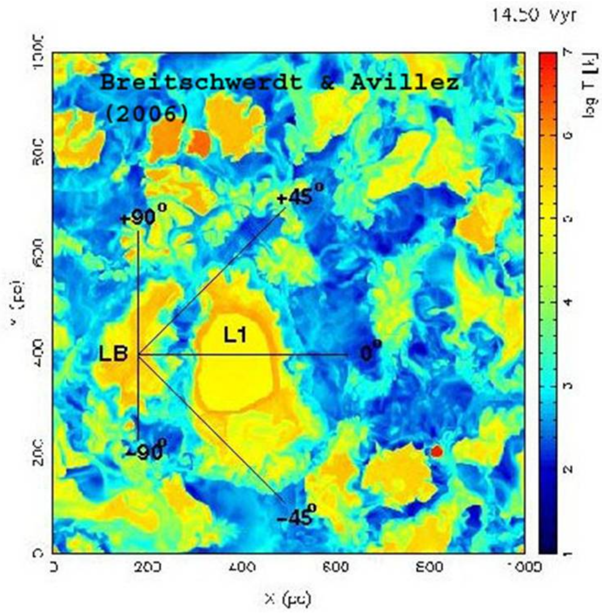

Figure 10: A model for the present day temperature distribution and extension of the Local Bubble (labeled LB) and the Loop I superbubble (L1) in a section through the Galactic mid-plane about 14.5 million years after their origin. The solar system is located at the intersection of the various lines-of-sight (solid lines in the Figure) in the LB (12).

H5: How does the interstellar medium affect the outer solar system? Interstellar dust entering the heliosphere interacts with the small planetary objects that are located beyond the orbits of the giant planets of our solar system. This region is believed to consist of remnants of planetesimals that were formed in the protoplanetary disk and studying the small objects in this trans-Neptunian regions is of basic interest for comparing the solar system to extra-solar planetary systems. The flux of the interstellar dust is considered as a source of dust production by impact erosion in this trans-Neptunian region (119; 92) and also limits the lifetime of the outer solar system dust cloud. Observations of the zodiacal dust itself can provide unique insights not only into the history and content of our Solar System, but also provide a detailed template that can be used to understand the exo Zodiacal dust in other solar systems.

The Science Questions discussed so far show clearly that we need to understand better out immediate local interstellar neighborhood and naturally lead to the following Science Goal.

3.2 A What are the properties of the very local interstellar medium and how do they relate to the typical ISM?

A1: What is the state and origin of the local interstellar medium? Is the Sun close to a conductive interface between hot and warm gases? The Local Interstellar Cloud (LIC) belongs to a flow of low-density ISM embedded in the very low density and hot (T $\sim 10^6$ K) Local Bubble (LB, see e.g. Fig. 5 of (17) for its computed map based on absorption of the light of nearby stars, to be compared with results from a hydrodynamical model by (12) shown in Fig. 10). The bulk motion of this cluster of tenuous interstellar clouds points toward the center of the Loop 1 super-bubble (L1). Within this overall flow, distinct structures have been identified with unique velocities. It is not entirely clear whether such masses of interstellar matter at different velocities are fully distinct clouds embedded in the same hot medium as reconstructed in 3D by (88) or a unique larger cloud with large scale velocity gradients as proposed by (44). Recently (89) showed that the multiple cloud morphology model provides a better fit to all available datasets. Such a distinction is important since in this case conductive interfaces between hot and warm gas must be present, and in particular such an interface should be present in the immediate vicinity the Sun. As a matter of fact, the motional direction of the cloud currently feeding interstellar gas into the heliosphere (the LIC) has been determined in situ with the GAS experiment on Ulysses (113) and coincides with the motion derived from absorption Doppler shifts for all nearby stars distributed in about two thirds of the sky. However, interestingly it is not aligned with the motion of the matter observed towards a region of the sky around α-Cen and towards the close star itself. In this region of the sky the so-called G cloud is detected, and found to be a few km/s slower. Because absorptions due to the LIC towards the G-cloud region have very small upper limits, this implies that the heliosphere is at or close to its edge (59; 87, less than about 2000A.U., see). Consequently, the material surrounding the heliosphere could change on time scales as short as the duration of IP (see, e.g., 38, for a review).

The nature and physical properties of hot-cold or hot-warm interfaces is still a matter of debate, because the influence of the magnetic field on the conduction and neutral-ion charge-exchange processes both affect the nature of the transition (98; 84). For this reason, measurements of the velocity distributions beyond the heliopause would be of very high interest since suprathermal tails would constrain the presence of a conductive interface and its distance. Ionization states would also be of crucial interest. Based on the analyses of EUV spectra of nearby white dwarfs (115) found that helium is about 40% ionized in the local ISM, and, independently, the same ionization level of helium has been very recently measured for the interstellar flow at the Sun using IBEX data by (16). The origin of such a high level of ionization of helium is still unclear and is key information missing in the global picture of the Local Bubble and embedded clouds. The ionization could be maintained by UV emissions from hot-warm conductive interfaces (98) or could be a remnant of high ionization from the past as predicted by evolutionary models of the ISM under the effects of supernovae (13, (the delayed recombination effect, see). Measuring the ionization states of various species with an IS probe should constrain the phenomenon at work in the Sun vicinity, with an important impact on our understanding of the nearby ISM history, the Local Bubble hot gas and the local cloud physical states.

Studies of the orientation of the local interstellar field also appear to indicate the importance of a highly turbulent interstellar flow (see Science Objective A4). The associated timescales are comparable to the present duration of the space age and our understanding of the importance of the heliosphere in shielding us from the interstellar medium. For instance, neutron-monitors, first introduced in 1957 with the International Geophysical Year, have shown that the galactic cosmic ray intensity at Earth varies with solar activity. Galactic cosmic rays produce the important climate tracer ^{14}C by spallation of nitrogen in the Earth's atmosphere. We currently base much of our modeling efforts for climate physics on uncertain understanding of the relation between GCR-produced ^{14}C and solar activity based on historic records of sunspots. Given that one of the time scales of the variability of the interstellar boundary conditions is roughly the same as the time scale as the neutron monitor data or maybe the sunspot record, the question naturally arises whether the naive assumption that the modulation of GCR by the heliosphere is only determined by solar activity may not be overly simplified. Heliospheric structure and modulation is determined by time-varying boundary conditions at the Sun and in the local interstellar medium.

A2: What is the composition of the local interstellar medium? Compositional studies have established themselves as an extremely successful tool to understand the origin and evolution of astronomical and solar system bodies. Based on studies of the solar system, we believe that the central star and its planets are made of the same material with only small compositional gradients in similarly behaving elements across the planetary system (if any at all). The driving fractionation processes are condensation and heating. Similar studies of galactic composition and its evolution are hampered by these often neglected but important processes. Frequently, the composition of the ISM can only be determined in the gas phase using, e.g., absorption lines. The missing elements (relative to a "universal" galactic composition, derived from solar composition) are then thought to be locked into interstellar dust grains. The composition of dust is very hard to measure remotely, some progress has been made using measurements of extinction, polarization and emissivity over a wide range in wavelengths. However, the effects of space weathering on individual dust particles is hardly understood and accounted for. Thus, it is safe to say that the composition of the interstellar medium is only understood in a qualitative way. To make the next step to quantitative understanding of the composition in the galaxy, we need to understand this critical process. The only accessible interstellar cloud is the local cloud, and, hence, we need to measure its composition in the dust, gas, and plasma phase. A key ingredient in this respect is the dust-to-gas mass ratio which is different when measured in the LIC and in-situ in the heliosphere. Radiation pressure, solar gravity, and Lorentz forces modify the flux of the dust into the solar system and the acting forces vary with the dust properties as well as with the plasma and magnetic field conditions (see, e.g., 37; 43; 101, for reviews). As a result, both the dust fluxes in the interstellar medium and in the outer solar system, and, hence, the corresponding dust-to gas mass ratios, are estimated with great uncertainty, because the small particles, which probably make up the majority of the dust number density, are deflected at the boundaries and inside the heliosphere (22; 46; 62; 103). The in-situ heliospheric measurements are affected by solar activity and polarity and the detailed structure of the heliospheric interfaces, hence measuring the time dependence of this ratio gives important information on the latter boundaries and on the properties of interstellar dust.

A further key measurement will be the abundance of certain abundant elements in the VLISM and comparison with measured abundances of interstellar ions (in the form of pickup ions) and atoms (in the form of neutral gas) within the heliosphere. Understanding the filtration effects on various elements will allow us to generalize them to other elements and thus to finally derive the elemental abundances in the very local interstellar medium from in-situ measurements within the heliosphere. The measurement of the abundances of elements in the LIC can only be done if we can measure the ionization state of hydrogen (or of oxygen (or N) because it readily charge exchanges with H). This is the most prominent hurdle in establishing the metallicity of the LIC (Fig. 11).

This becomes even more important if we want to compare the local interstellar composition with that of the solar system. Intriguingly, we observe

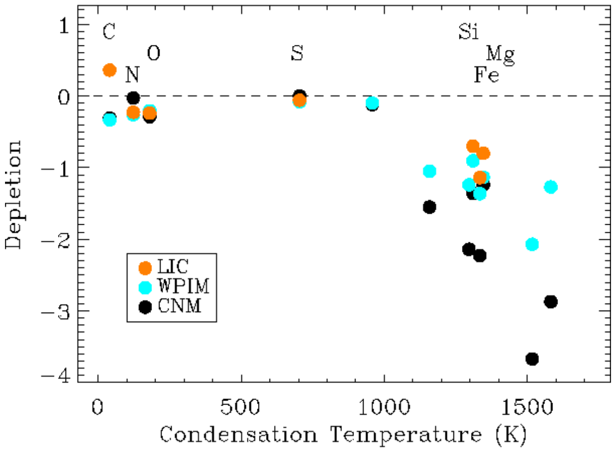

Figure 11: Compositional patterns for the local interstellar environment. Orange symbols show LIC composition from model 26 of (100), cyan symbols show warm partially ionized matter,and black symbols show cold neutral material. The differences show the importance of measuring all the phases (plasma, gas, and dust) of the interstellar medium.

that the Sun (and solar system) appear to be isotopically heavier than the interstellar medium at a similar galactocentric distance. This is currently the only indication that the solar system must have migrated several kiloparsec within its galactic environment. In other words, studying the differences between solar system and galactic abundances is the only opportunity we have to quantitatively assess the effects of galactic dynamics.

A further important topic is the carbon abundance of the LIC. In the interstellar gas the C abundance is a factor of about 2.5 below solar abundances, and, as discussed above, the missing carbon is thought to be locked up in interstellar dust grains or giant carbonaceous molecules such like PAHs. A contradictory estimate of the carbon abundance in the LIC has been presented by (99). Based on published data for the sightline towards the star ϵCMa, they found that carbon appears to be significantly overabundant in the LIC gas phase, for reasons not understood. This appears to indicate not only total destruction of carbonaceous dust grains locally, but also inhomogeneous mixing of gas and dust within the cloud, which in turn has consequences for the nature of turbulent mixing in the LISM. As carbon is a direct pre-requisite for life as we know it, this intriguing puzzle deserves more attention. Direct measurements of singly-ionized and the small expected amount of doubly-ionized carbon, as well as the dust composition, will shed light on the life-cycle of carbon in the Milky Way.

A3: What is the interstellar spectrum of the GCR beyond the heliopause? The GCR is believed to originate in particles accelerated at supernova-driven shock fronts. These shocks likely accelerate surrounding material, dust, gas, and plasma particles. Thus, GCRs offer a unique way to sample the composition of the galaxy and to understand the energetics of supernova shock expansion. Current modeling efforts show large variations in the possible interstellar spectrum (47; 48; 94; 107). One of the difficulties in these studies is the influence of the heliosphere which modifies the GCR spectrum as measured at the Earth. Tremendous gains in the understanding of the above topics could be made if we knew the undisturbed interstellar spectrum. This would allow us to understand and accurately model the filtering effect of the heliosphere and, hence, to much more accurately interpret the information brought to us by galactic cosmic rays. IP will be able to address this question by measuring the unfolding of the GCR spectrum up to 100–300 MeV/nuc between the outer heliosphere and beyond the heliopause.

A4: What are the properties of the interstellar magnetic field? Observations with SOHO/SWAN (61) as well as Voyager radio observations (80) indicate that the magnetic field (likely frozen into the interstellar medium as it also is in the solar wind) does not lie in the galactic plane as would be expected on large scales, but is distorted by the turbulence present in the LIC (46; 80). The direction, strength, and variability of the interstellar magnetic field are key to understanding the overall asymmetric structure of the heliosphere. Current modeling efforts are severely limited by the uncertain knowledge of the interstellar magnetic field and its influence on the heliosphere, a magnetized astrosphere immersed in a turbulent magnetized interstellar environment. The magnetic field strongly influences the flow of charged particles (and, through charge exchange, of neutral particles) and anisotropies of energetic particles and does so on time scales given by the level of interstellar turbulence. The latter is important for the propagation of galactic cosmic rays and for the properties of a number of astrophysical objects. Part of the variability may also be explained by reconnection of the heliospheric and interstellar magnetic field, a fundamental process in astrophysics. Thus, understanding and modeling of the heliosphere, its shielding effects, etc. remain severely limited because the strength of the local interstellar magnetic field is unknown.

A5: What are the properties and dynamics of the interstellar neutral component? There is overwhelming evidence from the analysis of interstellar absorption lines for the existence of a hydrogen wall ahead of the heliosphere (42; 63; 117).

Such structures have been observed around other stars (50; 117) as have been bow shocks, indicating that our heliosphere is not unique but rather a typical example of an astrosphere forming around wind-driving stars. However, we do not know the properties of the neutral component beyond the heliopause, yet alone understand sufficiently its dynamics in the hydrogen wall and interstellar medium.

So far, the aging Voyager spacecraft have provided some direct information on the plasma environment in the outer heliosphere. However, Voyager 1 (at ~ 146 AU) has now passed into a region of very low fluxes and can no longer provide this information. Moreover, the state of the neutral gas is unknown, and no observations will be available beyond ~ 160 AU, when the power supply on board the Voyagers will become insufficient. Ulysses has measured neutral interstellar gas directly out to $\sim$5 AU, and first observations of energetic neutral atoms (ENAs) are confirming their likely production in the (inner) heliosheath between the solar wind termination shock and the heliopause (39; 118), but, confusingly, also beyond (67). These pioneering measurements are now routinely performed by the Interstellar Boundary Explorer, IBEX (68). On the other hand, IBEX will not provide us with measurements beyond this region, especially within the hydrogen wall. These will be performed by IP, thus providing us with a detailed understanding of the interstellar neutral component.

A6: What are the properties and dynamics of interstellar dust? Understanding the nature of the interstellar medium and its interaction with the solar system includes the dust properties in the outer solar system and in the interstellar medium. Moreover improving our knowledge of interstellar dust properties and quantifying the dust to gas ratio in the interstellar medium is of fundamental astrophysical interest, e.g., in star and planetary formation, and galactic evolution. The Ulysses data allowed constraining models of the local interstellar medium physics as well as of interstellar dust (37). The measurements within the solar system provide valuable information, but they improve our understanding of the interstellar dust only within certain limits and important parameters like the size distribution of interstellar dust and the dust-to-gas mass ratio can not be measured within the solar system (see A2).

A recent result and its implications illustrate perfectly the limitations of dust measurements within the heliosphere and the need for data beyond the heliopause. Interstellar dust grains have been measured at Saturn with the Cassini's Cosmic Dust Analyzer (2). Their analysis surprisingly revealed a very low and potentially null carbon abundance, in apparent contradiction with state-of-the-art interstellar dust models based on many types of astronomical observations that predict a significant fraction of carbonaceous dust particles in addition to olivine-type & pyroxene-type silicates. Following these measurements it was been suggested that this lack of carbon detection is due to the selective exclusion from the heliosphere of the carbonaceous grains, as a result of their low mass and high charge-to-mass ratio, hence stronger deflection by the solar wind (10). Silicate grains only, being denser, succeed in entering deep in the heliosphere where they can be detected. If this is the correct interpretation, dust analyzers on board an interstellar probe should measure a greater carbon abundance than Cassini instruments and constrain the relationship between grain size and composition. An alternative explanation is the full evaporation of the small grains and release of all the carbon in the gas phase in the circumsolar LIC, as discussed in A2. The detection of organic grains is of crucial importance after the discovery of the very large fraction (more than 30%) of organic matter of comet Churyumov-Gerasimenko with the Rosetta mission, and, especially, of the most likely pristine nature of this organic fraction (23). It could also shed light on the potential accretion on the grains of the carbonaceous macro-molecules that cause the hundreds of diffuse interstellar absorption bands (DIBs) that contaminate the spectra of highly reddened stars, including the bands recently identified as due to the fullerene cation C60+ (18).

The Science Questions discussed above all point to some fundamental issues which affect the physics of the interstellar medium and lead to the questions discussed in the following paragraphs.

3.3 F: How do plasma, neutral gas, dust, waves, particles, fields, and radiation interact in extremely rarefied, turbulent, and incompletely ionized plasmas?

Our understanding of the physics of complex interstellar plasmas is extremely limited. At least part of the problem lies in the multiple components constituting the interstellar medium which all contribute similarly to, e.g., the pressure in the LISM and the heliospheric boundary region.

F1: What is the nature of wave–particle interaction in the extremely rarefied heliospheric plasma? As discussed in question H4, the pre-acceleration of the anomalous component is incompletely understood. Why do ACR not peak at the termination shock? Obviously, the magnetic structure in this interface region plays a major role, as does the detailed wave–particle interaction in this turbulent region. While the spectra at higher energies can be modeled fairly accurately with a combination of first order diffusive (shock) acceleration and second-order (stochastic) Fermi acceleration, together with limited adiabatic heating, the injection problem at lower energies still remains unsolved. Here, detailed measurements of magnetic field variations and distribution functions of suprathermal particles, especially below ∼40 keV/nuc, are key to understanding this problem which, of course, is not limited to particle injection and acceleration in the heliosphere, but must occur at all astrophysical shocks. Thus, it is a prominent example of energy gain by wave–particle interaction.

F2: How do the multiple components contribute to the definition of the local plasma properties within the heliospheric boundary regions? Several contributors are about equally important contributors to the pressure in the interstellar medium. GCR, thermal plasma, pickup-ions, magnetic field, but especially the non-thermal particle populations are key players in determining the complex properties of the heliosheath. The influence of the non-thermal population is occasionally observed during highly disturbed situations in planetary magnetospheres, but the other contributions are unique to the outer heliosphere and can only be measured in situ.

F3: What processes determine the transport of charged energetic particles across a turbulent magnetic field? Impulsive solar particle events have long been observed at longitudes which appeared to be badly magnetically connected, indicating perpendicular transport, implying action of coronal shocks, or a considerably more complicated magnetic configuration than generally assumed. Similarly, Ulysses observations of recurrent energetic particle enhancements at much higher latitudes than the accelerating corotating interaction regions (CIRs) appear to imply perpendicular transport or a more complicated heliospheric magnetic configuration that connects CIRs to high latitudes (see, e.g., 32, and references therein). Similarly, again, detailed observations of low-energy particle distribution functions in CIRs near Earth were best explained by substantially enhanced transport of particles perpendicular to the magnetic field (28). Intriguingly, similar phenomena have proved to be extremely puzzling in the fusion community. Cross-field transport is a limiting factor in magnetically confined fusion.

3.4 P: Planetary Science

Because the proposed mission would necessarily fly by Jupiter and could be deflected towards a Kuiper-Belt Object (KBO), there is an excellent planetary science case to be made. Careful choices would need to be made about the required payload and synergies should be exploited.

P1: Dynamics of the Jupiter moons The moons of Jupiter are remarkably diverse and hardly fully understood today. Because an interstellar probe would very likely perform a (probably powered) fly-by of the Jupiter system, this would allow imaging of Jupiter moons, similar to what was done with NASA's New Horizons mission. An interstellar probe would arrive at Jupiter well after ESA's JUICE prime mission phase (2029 - 2033) and so would add to our understanding of the surface dynamics of Jupiter's moons, e.g., their volcanism (102), or changes in their icy surfaces.

P2: Dynamics of the Jupiter atmosphere Imaging of Jupiter itself during the gravity-assist fly-by should be a top priority of this mission. New Horizons showed that Jupiter is always good for a surprise (3). Usually stormy with thick ammonia clouds, Jupiter showed itself in an unusually quiet mood which showed that it changes on time scales of decades and which allowed the detection of lightnings in it atmosphere.

P3: Origin of Kuiper Belt Objects: Depending on the trajectory chosen based on the heliospheric and astronomical mission objectives, potential KBO targets should be identified and – ultimately – one of them visited, following the exciting example of New-Horizons (104). This will clearly engage the planetary science community.

In addition, running a wide-angle VIS camera system for a substantial part of the probe's outer heliospheric trajectory may allow for discovery of new KBOs. Despite the fact that the telescope would necessarily have to be smaller than the Hubble Space telescope (HST), an interstellar probe would have the advantage of proximity and integration time.

P4: Planet Nine: Batygin & Brown (5) showed that distant orbits within the scattered disk population of the Kuiper belt exhibit an unexpected clustering in their respective arguments of perihelion. They interpreted this as due the to existence of a "Planet Nine", because of the low probability of such a clustering to appear randomly. Thus observation and determination of the exact orbital parameters of a KBO belonging to this class would greatly advance our understanding of Planet Nine. Because the disturbed class of KBOs (or Trans-Neptunioan Objects, TNOs) are likely to have a large inclination (7), a close fly-by of one of them is not very likely.

3.5 B: Bonus Science Goals

Moving from close to the Sun to far-flung regions in the solar system has the potential of enabling science otherwise not possible. We present three examples of bonus science goals which could be achieved by sending an Interstellar Probe far from the Sun.

B1: Soft-X-Ray Background: ROSAT observations of the soft X-ray (0.25 keV) background were initially interpreted as a signature of hot (10^6 K) plasma filling the Local Bubble (60, and references therein). However, this was difficult to reconcile with the observed abundance of O VI ions (19). The soft X-ray background is contaminated by foreground emission from solar-wind charge exchange (SWCX) reactions. When highly energetic heavy ions ("metals") in the solar wind encounter neutral hydrogen and helium (of either solar or interstellar origin) they can exchange an electron, leaving them in a highly excited state from which they relax by emitting X-ray photons. This process has been unambiguously observed in comets (64), and is thought to occur in the boundaries of the heliosphere. However, the location of the emission and the relative contribution to the background are currently unknown. Best current observations indicate that SWCX is responsible for anything between 20% and 100% of the soft X-ray background (20; 55; 60, and references therein). Attempts to separate the contributions using spectroscopy have been unsuccessful (20), and are unlikely to solve the problem. However, measurements of the X-ray background will allow a) an understanding of a fundamental physical process occurring in the heliosphere (SWCX); b) determination of the properties of the material filling the Local Bubble; c) measurement of the local X-ray ionization rate, which plays a crucial role the heating and chemistry of the ISM (116). Carrying this type of instrument on an interstellar probe would also allow to study the interaction between solar wind and solar system bodies in X-rays.

B2: Extragalactic Background Light: The extragalactic background light (EBL) is made up of the redshifted emission from the first stars, protogalaxies and supermassive black holes to form in the universe. Accurate measurements of the flux and spectrum of the EBL can provide key constraints on the objects responsible for reionising the universe, as well as on models of galaxy and AGN evolution. However, sufficiently accurate measurements of the EBL in the optical/near-IR are not possible from the Earth or the inner Solar System because they are dominated by the foreground emission from the Zodiacal Dust. A mission travelling beyond the orbit of Jupiter will escape this dominant foreground and can make observations of sufficient accuracy to provide these uniquely powerful cosmological observations. This study would require addition of a wide field optical/near-IR imager (11) and would make observations during the journey to the heliopause, once the spacecraft is beyond the zodiacal dust.

B3: Ly-α absorption spectra – tomography of the heliosheath: Hydrogen is the most abundant element in the universe and is ionized in the atmospheres of most stars and neutral in the interstellar medium and heliosheath. Thus heliosheath hydrogen absorbs the light from stars in the narrow Ly-α wave-length band. The exact line profile can inform about the temperature and line-of sight velocity of the absorbing material, the depth gives the column density. This can be utilized to determine the hydrogen column density toward nearby stars (63). These authors found that they needed to add a second, less abundant but hotter component to fit the line profiles and interpreted it as due to heliosheath H. They used the Hubble Space Telescope for typical integration times for H Ly-α on the order of minutes. Scaling this to a much smaller telescope with a diameter of, say, 12 cm, would require integration times of $\sim 10^3$ minutes or on the order of one day.

On its way to the edges of the heliosphere, an interstellar probe would enable such observations of nearby stars from a slowly varying vantage point. Repeating the same observation sequence every year would thus gradually build up a 3D “tomographic” image of the nearby interstellar neighborhood. Assigning 2 days per target, Ly-α absorption spectra towards a total of 15 target stars could be performed in one month. The optimal stars would need to be determined, of course, but this would be an other opportunity to engage a larger community of astronomers. Depending on the importance given to this bonus science topic, more time could be allocated to observe absorption spectra towards more stars. We note here, that this is a unique opportunity that is only possible because of the very long base line that is covered with an interstellar probe.

4 Strawman Mission Concept

4.1 Top-Level Mission Requirements

M1 The top-level mission requirement is obviously the direction in which to fly. This needs to be coordinated with the interested international partner(s) (see section 6).To ensure broadest community and agency support and solid technological feasibility, the exact trajectory should be chosen based on a series of workshops, similar to the landing-site workshops in the Mars community. There are several interesting options:

M1a The shortest travel time is presumably towards the nose (+7°, 252° Earth ecliptic coordinates);

M1b a more interesting trajectory would point at ∼-60 degrees in Fig. 3 and would penetrate the ribbon;

M1c if another agency goes towards the nose or ribbon, a mission towards the heliotail would also be scientifically compelling.

M2 Provide data from 5 AU to at least 200 AU.

M3 Arrive at 200 AU 'as fast as possible', ideally within 25-30 years.

A large variety of solutions exist and have been demonstrated to be feasible to achieve these mission requirements, see, e.g., (51) - (53) and (74) - (78) and references therein. Possible mission designs always rely on nuclear power and some propulsion system to achieve high escape velocities of several AU per year. Not all can achieve the short travel times envisaged in M3, but several do so by utilizing a heavy launcher and Jupiter or solar gravity assist maneuvers. Of course, even a mission duration of 25 - 30 years requires that scientific and technical mission know-how be maintained over multiple decades and possibly generations of scientists and engineers. Ulysses, SOHO, the Pioneers and especially the Voyagers have shown that this is important and can be achieved by careful mission management. We propose to investigate going a step further in mission science planning by having different PIs for different phases of the mission. For instance, the early stages would be dominated by planetary science interests[1], once the spacecraft starts approaching the heliospheric boundary layers a different science team should take over and, in turn, be replaced by yet a different team once it reaches undisturbed interstellar space. Such a scenario would be optimally adapted to requirement M2 and is an important contributor to the scientific success of the mission because it keeps the community 'alive' and excited about planetary and heliospheric physics and science.

4.2 Mission design

Voyager 1 at ∼ 3.6 AU/yr is currently the fastest object to ever leave the solar system. An inter-

[1]E.g., for imaging the Jupiter system and one or more KBOs.

Mission	nominal	effective
Ulysses	5 years	18.67 years
SOHO	2 years	23+ years
Cluster	2 years	19+ years
ACE	5 years	21.9+ years
Wind	3 years	24.67+ years

Table 2: Nominal and effective durations of a number of interplanetary missions.

stellar probe should be at least twice as fast, resulting in travel times of ∼15 years to the termination shock and ∼ 20 years to the heliopause. Studies have shown that using a heavy launcher and a big kick-stage in combination with a Jupiter fly-by can attain escape speeds exceeding 6-8 AU/year, typical values being around 10 AU/year (see, e.g., (75) - (78)), thus shortening previous travel times considerably. The long duration of such a mission naturally places strong requirements on the reliability of spacecraft and payload. On the other hand, countless scientific missions have outlasted their design durations and shown that this can be done, see Tab. 2.

4.3 Propulsion

Getting to 200 AU within 25 to 30 years or quicker requires very high speeds on the order of $6 - 10$ AU per year (possibly after a significant acceleration time). Several options have been proposed and studied (See, (75, e.g.,) - (78), for some detailed study results.), some of which are briefly summarized here to show that solutions do exist and are either ready to be implemented or close to being tested:

4.3.1 Heavy launcher - with and w/o fly-by:

Most mission implementations would profit from a substantial excess escape energy ($C_3 \geq 100$ km^2/s^2) which can only be achieved with a heavy launcher. While solar sail studies forfeit this advantage in view of the large acceleration offered by photon assists, all other low-thrust implementations would have to rely on a substantial boost at the beginning of the mission. Heavy launchers include the Ariane 6, Atlas V 551, Ares V, or a Falcon 9 or Falcon Heavy, of which the last two are probably the most cost-effective (see Space-X's web site for a quoted price of 90 M$ for a launch of more than 8.0 tons to GTO (accessed August 4, 2019)). All would launch the probe and an upper 'kick-stage' to provide the extra excess energy. (76) show that a heavy launcher with nuclear electric ion propulsion (and possibly a Jupiter gravity assist) is an other flexible option to get an interstellar probe out to 200 AU within 25-30 years. In a more recent

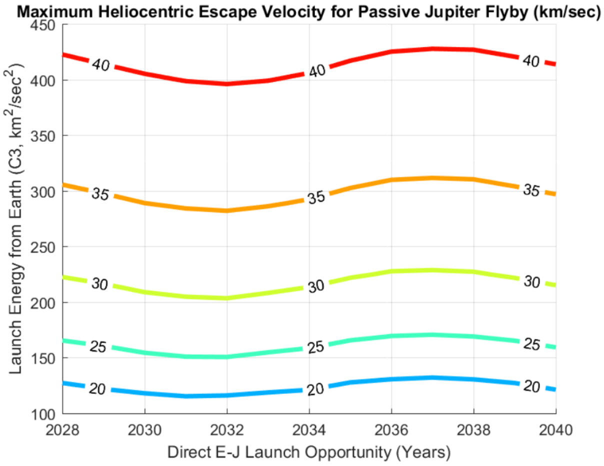

Figure 12: Maximum heliocentric escape velocity for passive Jupiter flyby opportunities (74).

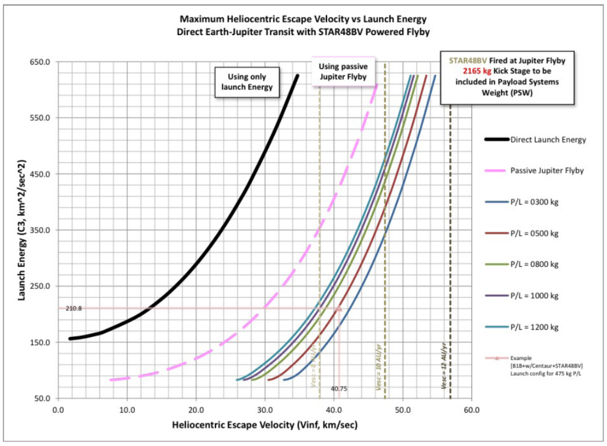

Figure 13: Maximum heliocentric escape velocity for a powered Jupiter flyby with a STAR48BV kick-stage burn (74).

study (74) show that an unpowered gravity assist at Jupiter can realistically provide escape speeds of up to approximately 8 AU/year, see Fig. 12.

Detailed investigations of a powered Jupiter flyby show a remarkably large trade space (74). An example case, shown in Fig. 13 , produces an escape velocity from the Sun of 40.75 km/sec for a powered Jupiter flyby using a STAR 48BV kick stage pushing a 475-kg spacecraft. This example was caculated for launch vehicle configuration comprised of an SLS Block 1B+ with a Centaur third stage and a STAR 48BV fourth stage. All four launch stages fire at Earth to send the 'fly-by spacecraft' (with a mass of 2640 kg) on an Earth escape trajectory with a C_3 of 210.8 km^2/sec^2. This produces a heliocentric escape velocity equivalent of approximately 8.6 AU/yr. At the upper ranges of the launch departure C_3 region, the powered Jupiter flyby with a STAR 48BV kick stage could produce escape velocity speeds in the range of 11 AU/yr. The large range of C_3 shown in this figure can narrowed down as the variability in launch energy from differing launch vehicle configurations and performance upgrades is reduced.

Similar escape velocities can be achieved with a powered solar flyby, but at the cost of an added heat shield and all its complexity (74).

4.3.2 Solar Sails

ESA has studied a baseline mission in which a solar-sail spacecraft was launched from Earth with $C_3 \sim 0$. The spacecraft would need to approach the Sun to within 0.25 AU where solar sails are highly effective. Through two such 'photon assists' in the inner solar system, an escape velocity approaching 10-11 AU can be achieved. The large sail would be jettisoned at $\sim$ 5 AU because no significant acceleration is obtained from it anymore. Thus, the science phase could begin after this initial acceleration phase after approximately 7 years. This mission design is attractive because it achieves very high speeds and an early beginning of the science phase compared to some other scenarios discussed further down. Because high speeds are already acquired early, it requires no additional gravity assists at the outer planets and therefore has launch windows repeat every year. Thus, a solar sail implementation has many advantages. In addition, implementing such an approach would establish European leadership in this important and highly enabling propulsion technology. There is also significant know-how and interest in solar sails in European industry. On the other hand, having to go close to the Sun for two photon assists is non trivial and adds considerable mass to the sailcraft for thermal control. An other difficulty lies in the availability of ultra-thin solar sail material and deploying the large sail needed for this mission. While Helios, BepiColombo, Solar Orbiter, and even more so, Parker Solar Probe, all show that going close to the Sun is achievable, these missions also show that this is a tough task and should not be underestimated. The thermal-control system would require significant mass, thus reducing the overall efficiency of the sailcraft.

4.3.3 Nuclear Electric Ion Propulsion:

After the great success of ESA's Smart-1 mission, electric ion propulsion is also a good candidate for a long-duration space mission. While Smart-1 relied on solar generators, an interstellar mission would need to use nuclear power, e.g., radioisotope thermoelectric generators (RTGs) or some kind of 'next-generation' Stirling radioisotope generator (SRG). Both would need to provide a relatively high power output of at least 8W/kg (i.e., a specific mass of 125 kg/kW). This approach would also require a high excess escape energy, $C_3 \geq 100\text{km}^2/\text{s}^2$, followed by a long period of electric propulsion of at least 15 years. However, this solution would also be very flexible in allowing many possible gravity assists at the outer planets, especially Jupiter (31). An optimal gravity assist at Jupiter can result in a Δv of 28 km/s, other outer planets provide somewhat less, but a combination with Jupiter can result in similar values for an additional Δv. The orbital period of Jupiter means that there are such opportunities only every 12 years, but several less optimal ones repeat every 13 months around them. Fig. 8 in (31) shows five opportunities with trip times to 200 AU less than 30 years for launches around 2014[2]. Jupiter gravity assists pose the difficulty of the intense radiation experienced by the spacecraft when inside Jupiter's radiation belts. This would require additional shielding and could add extra mass to the spacecraft. Nevertheless, with ESA now preparing the implementation of JUICE, this problem should be well understood and under control. In fact, a flyby of an interstellar precursor mission would likely be after the scientific phase of JUICE but could potentially add to the scientific impact of both missions by providing information about the temporal evolution of the Jupiter system.

4.3.4 Venus and Earth gravity assists

Venus and Earth gravity assists would certainly aid in achieving high escape speeds early on in the mission. However, these are generally not studied in more detail because they would add complexity to the mission. A Venus flyby would increase the mass of the thermal control system because the spacecraft would have to cope with about two solar constants there, but has to be designed for large distances from the Sun. An Earth flyby could be even more effective, but we consider it unwise to add the political uncertainties of using this technique with a nuclear powered spacecraft.

4.3.5 Electric sails

Electric 'sails' would use the pressure exerted by the solar wind on an electrically charged 'wire-sailcraft'. The penetration distance of the high voltage tether's electric field at 1 AU is about 10 times the Debye length of 10m, i.e., about 100m, so wires or wire structures do not need to be space-filling to present the solar wind with a large cross section. Of course, the solar wind carries with it much less momentum that solar photons, but it is also much easier to deploy thin wires and and charge them to high voltage (51; 52; 85). A Cube-Sat demonstrator mission (ESTCube-1) was undertaken by Estonia (Pekka Janhunen, PI) to demonstrate opening a 10 m tether in orbit and measure the Coulomb drag force acting on it. ESTCube-1 was successfully launched from Kourou spaceport on May 6$^{\text{th}}$, 2013; in March 2014, the attitude determination and control system software reached its full functionality. Shortly after this however, a strong magnetic disturbance within the satellite was discovered, which did not allow spinning up the satellite around the axis predetermined for the E-sail experiment. A follow-on mission, ESTCube-2 (29) is slated for launch in 2020 [3]. Initial estimates scaling this concept to an interstellar probe show that it could reach 200 AU within 25 years (85).

4.3.6 Summary of propulsion options

Given the uncertainties in many of the propulsion systems discussed above, as well as the often unnecessarily long cruise phases, we favor the 'heavy launcher' scenario. The technology is being developed and is expected to be ready within the coming decade.

4.4 Power

Because an interstellar probe necessarily needs to travel far from the Sun, only nuclear power is a realistic option. Several studies have already been performed on new, next-generation power systems, mainly in the US. ESA's study (53) and previous proposals have assumed a specific power of at least 8W/kg. This is not unrealistic and is considered the design minimum for nuclear power sources under development (76). A realistic nuclear electric ion propulsion system would require on the order of 1 kW of electric power. Accounting for the ^{238}Pu half life of ~88 years, this would still leave ample power for payload and telemetry during the science mission which would follow the cruise phase. On the other hand, our favored 'heavy launcher' option would not require such a large RTG and can thus be more readily implemented.

4.5 Spacecraft Bus

Depending on the exact mission implementation, especially on the choice of propulsion system, the spacecraft bus will have to be optimized for the ensuing specific requirements. Some key drivers may be the thermal control system, radiation shielding, etc. A previously proposed mission design came up with a spacecraft bus smaller that the ones given in Tab. 3 below (e.g., 112), while electric propulsion would require higher mass (76) mainly because of the substantial power requirements and the mass (>400 kg) of the Xenon fuel.

[2] This launch date illustrates how long an interstellar probe has been studied. At the time of this study (31) it was in the future.

[3] https://www.nanosats.eu/sat/estcube-2

Mission	Mass [kg]	Power [W]	Pay-load [kg]
Voyagers (54)	825	470 (90 + 10)	105
New Horizons (36)	478	245	30.4
Ulysses (110; 9)	367	294 (53)	55
Pioneers (77)	252	155 (24)	33

Table 3: Overview of key properties of spacecraft which can serve as models for an interstellar probe. Mass and power are given at the time of launch, power in parenthesis is payload (and heater) power.

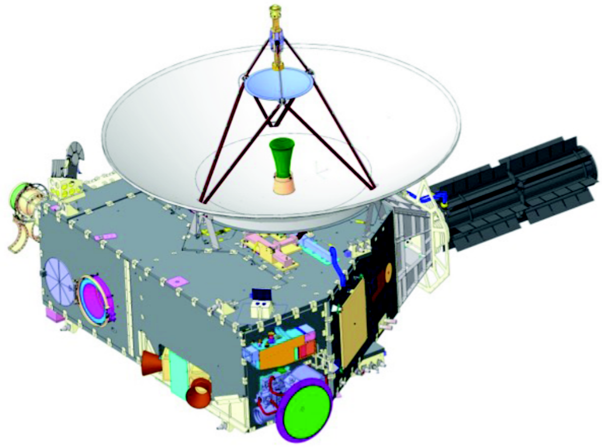

Figure 14: The New Horizons spacecraft (74).

There have been several missions which utilized spacecraft buses which can serve as a model for an interstellar probe. In order of decreasing mass (given in parentheses) these are: the Voyagers (825 kg), New Horizons (478 kg), Ulysses (367 kg), and the Pioneers (252 kg). We provide a view of the New Horizons spacecraft as a representative example for a bus for an interstellar probe in Fig. 14.

4.6 Payload

Most mission studies have considered the same baseline payload, similar to that summarized in Tab. 4. It is driven by the measurement requirements summarized in Tab. 1. Typical resource requirements are on the order of 25 – 35 kg and 25 – 35 W. Depending on the mission implementation, additional shielding or thermal equipment may be needed, thus increasing payload and resource demands. The design of every interstellar spacecraft will be driven by the power and telemetry system, especially the large high-gain antenna (2-3m diameter). Table 3 shows that there is ample reserve both for mass and power if we consider New Horizons and Ulysses as good examples for an interstellar probe spacecraft.

Of course, an interstellar probe does not have the same science goals in mind as New Horizons did, but, nevertheless, New Horizons is a good example which demonstrates the power of an optimized low-mass and low-resources payload (108). It would obviously be well adapted to the Planetary and Bonus Science goals (P and B in Tab. 1). Adaptations and augmentations would need to be studied in much more detail to arrive at an optimized payload for an interstellar probe which at the same time allows a vibrant science program while en-route to its ultimate destination, our interstellar neighborhood.

4.7 Telemetry

Several options for telemetry have been studied, but unrealistic constraints on attitude control allow only classic radio communication. A constant data acquisition rate of up to 500 bps (compressed) would need to be relayed to Earth in typically two weekly passes (2x8 hours nominal), thus requiring a downlink capability of 5.8 kbps also at 200 AU. This could be achieved with 35 m antennae in the initial mission years, but a 70 m antenna would be needed once the spacecraft reached larger distances.

For reference, the New Horizons 2.1 m antenna was designed to enable 600 bps downlink at 36 AU. The downlink system is designed such that the entire Pluto data set (estimated to be 5 Gbits after compression) could be transmitted in 172 days with one 8 hour pass per day using the DSN 70 m antennae using only on TWTA (36).

Acronym	Instrument	Mass [kg]	Power [W]	Telem. [bps]	Volume [cm^3]	Measurements
MAG	Magnetometer	2.0	1.5	50	500	1 Hz magnetic fields
PA	Plasma Analyzer	3.5 (2)	3.5 (2)	60 (20)	2 x 25x25x25	Plasma composition
NA	Neutral Analyzer	2.5	3.5	50	25x25x25	Neutrals, limited composition
PW	Plasma Waves	5	4	30	25x25x25	Radio and Plasma waves
DA	Dust Analyzer	1	1	10	25x25x30	Dust mass, velocity, composition
EP	Energetic Particles	4.5 (2)	5 (2)	60	2 x 25x25x25	H: 4 keV – 300 MeV ions: 5 keV/n – 400 Mev/n e-: 2keV – 20 MeV
ENA	Energetic Neutrals	5	5	50	60x60x20	Hydrogen ENAs: 0.05 – 5 keV Key elemental composition
LA	Ly-alpha	1.2	1.5	50	tbd	Ly-alpha broad-band photometry
IRV	IR/VIS imager	(5)	(5)	(50)	tbd	Wide-field infrared and visible imaging
SXR	Soft-X-Ray	(5)	(5)	(50)	tbd	Soft X-ray background, solar wind – planet interactions
Total		**25**	**25**	**360**		

Table 4: Strawman payload. Augmentation (bonus) payload is indicated in parentheses and not included in mass and power total. Initial studies have shown that such a payload complement could measure the expected small signals (fluxes, fields, etc.). Alternatively, the payload on NASA's New Horizons mission (108) can also serve as a strawman payload. It would however, need to be adapted to the science objectives of an interstellar probe.

5 Role of ESA in this Proposal

The call for white papers requests a brief description of how a space mission would address the scientific questions discussed in this proposal. Table 1 discusses the science goals, questions, and the measurements required to address them. These are all measurements which need to be performed in-situ, i.e., at the location being investigated. Thus it is obvious that the science of an interstellar probe necessarily requires a space mission.

Because an interstellar probe mission will take a long time to reach interstellar space, the entire mission will necessarily be a large one. In fact, the mission may even be too large to fit into an ESA L mission. It is for this reason that we propose in the following section 6 that ESA enter discussions with NASA and China about possible bilateral and/or cooperative missions.

The involvement of ESA and of European scientists in an interstellar probe would thus be a matter of priorities in ESA's science program (which reflects the vibrant European science community) and the desire for technological development. As discussed in section 3, multiple scientific fields would profit from such a mission, depending on the effort the scientific community is willing to put into an interstellar probe. Possible breakthroughs range from an improved understanding of the heliosphere, of our interstellar neighborhood, the physics of very complex, multi-component, non-thermal plasmas, to the investigation of one or more Kuiper-Belt Object(s) and/or extra galactic background light. In addition, the European space sector has substantial expertise which could be relevant for this potentially high-profile mission and could contribute significantly to solving the technological challenges associated with such a long-term mission.

Thus ESA's involvement into an interstellar probe could range from junior partner to lead agency. As a minimum, member states could lead or contribute to scientific instruments for such a mission without any ESA involvement or only minimal ESA involvement, e.g., with tracking support. At the other end of the spectrum, ESA could lead such a mission with other agencies and countries as equal or junior partners. We believe that it is pre-mature to discuss ESA's involvement at this stage because other big agencies are still in the stage of making their plans for such a mission (see section 6). It is, however, crucial that ESA enter discussions with potential partner agencies.

6 International Context

An Interstellar Probe with varying names has been proposed to different space agencies, and - some may argue - has been realized with NASA's Voyagers. We have already discussed that results from the Voyagers allow us to better design an interstellar probe which would be better equipped to measure the multiple components contributing to interstellar space. The necessarily long duration and ensuing cost of such a mission strongly suggest a coordinated international effort.

NASA has repeatedly studied possible interstellar probe missions since about 60 years and most recently commissioned a study (74) which has shown that escape velocities of 8 - 10 AU/year are feasible with different combinations of heavy launcher (SLS Block 1B+) and kick stages with a Jupiter flyby (78). Similar studies should be carried out for the heavy European launchers, but we believe that a US SLS is probably the best option to get an interstellar probe "out there" within a reasonable time.

On the other hand, China is currently also studying an interstellar probe, but information is more difficult to obtain about their trajectory concept. The ambition is to get a probe out to 100 AU by 2049 to celebrate the 100-th anniversary of modern China. While this is an ambitious goal, and somewhat out of synch with ESA's schedule for Voyage 2050, the studies mentioned in the previous paragraph show that such a mission could, in principle, be feasible if launched in the near future. Plans for such a mission were discussed in the 639th Academic Symposium of of the renowned Xiangshan Science Conference series in October 2018. An international meeting on this topic is being organized at ISSI in Beijing in November 2019.

The discussion in this section has shown that there are serious efforts being made both in China and the US. In the past, ESA has commissioned similar studies (65). All concepts rely on a nuclear power source which would require Europe (and ESA) to cooperate with either the US or with China for an interstellar probe. To our knowledge, Europe does not have any plans for a viable, high power density RTG[4]. Thus Europe could not realize an interstellar probe on its own and will be required to cooperate with the US or with China. Apart from the political benefits of a bilateral mission, this is an effective way to reduce cost for the two partner agencies and to increase the scientific output.

On the other hand, the substantial international interest in our interstellar neighborhood could also allow a coordinated program with one interstellar probe moving towards the nose or the ribbon and one towards the tail.

[4]The efforts being made are all for RTGs with much lower power density, on the order of 2 W/kg which does not compare favorably with the nearly 10 W/kg of the Ulysses RTG (9).

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In situ Investigations of the Local Interstellar Medium

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Table 5: List of national (and mission) contacts for the whitepaper "In situ Investigations of the Local Interstellar Medium".