STELLA

Europe's contribution to INTERSTELLAR PROBE Humanity's Journey to Interstellar Space

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on behalf of the "Stella Team"

In response to
Call for a Medium-size mission opportunity in ESA's Science Programme

Executive summary

Europe has been the home of explorers for centuries. It is in the spirit of this great tradition that we propose Stella, Europe's contribution to exploring interstellar space. Stella will enable to reach the furthest target defined by ESA's Voyage 2050 and travel farther from our origins than ever before.

Stella is a proposed European contribution to NASA's Interstellar Probe (ISP), a large-strategic mission candidate. This ESA call for M-class mission proposals is the best and only currently available option for the European science community to contribute to the astronomically constrained ISP launch window in 2036 – 2037. Traveling with a speed of 7.0 au/year ISP will reach 350 au during its nominal 50-year life-time. The proposed Stella contribution to ISP includes two core and two optional elements for the full complement:

- Core: Provision of European scientific instruments;
- Core: Provision of the European ISP communication system including the spacecraft's 5-m high gain antenna;
- Full complement: ESA deep space communication facility: an extension of ESA's DSA with a new antenna array;
- Full complement: Contribution to ISP operations to increase drastically the ISP and European payloads science return.

ISP's main goal is to understand our habitable astrosphere and its home in the galaxy. Stella contributes to achieving the ISP goal by answering five Stella-specific science questions:

- Q1: What is the composition of the local interstellar medium?
- Q2: How is our dynamical heliosphere upheld and how does it change from the Sun to the local interstellar medium?
- Q3: What is the origin and role of galactic cosmic rays in the solar system and beyond?
- Q4: How does the local interstellar medium become structured when it meets the heliosphere?
- Q5: Are there any deviations from the $1/r^2$ gravity law on the interstellar scale?

Stella assumes **a model European ISP payload**: a neutral gas mass spectrometer, plasma package, cosmic ray spectrometer, UV spectrograph, and radio science (utilizing the S/C radio for the fundamental physics question), which would be provided by the Member States.

The total cost of Stella to ESA is 102MEUR (core) and 382MEUR (full complement).

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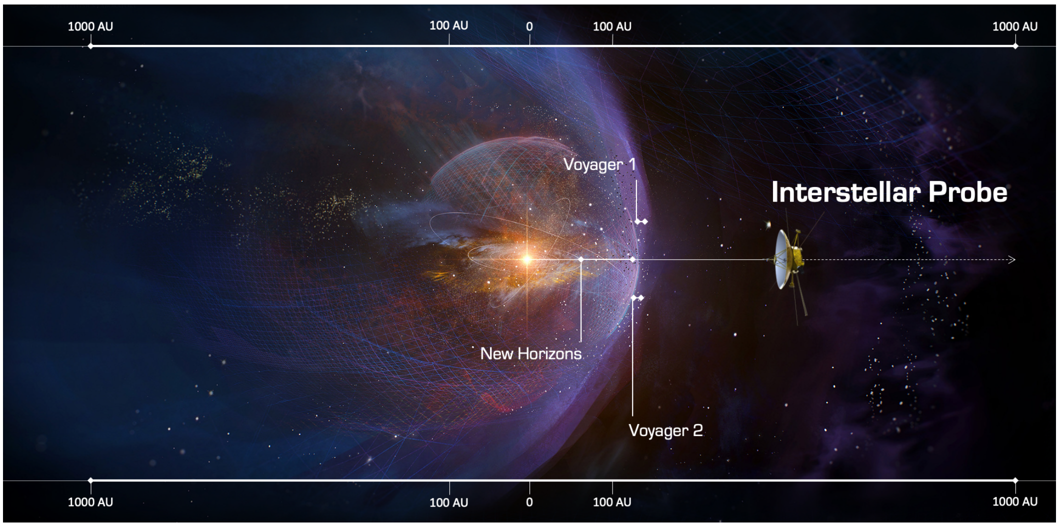

Fig. 1. The expanding solar wind carves out a vast magnetic bubble as the Sun plows through the Very Local Interstellar Medium (VLISM). This protective bubble, the heliosphere, cocoons the entire solar system and shields it from the full force of galactic cosmic rays (GCRs) and interstellar material. Sending an Interstellar Probe far beyond the Voyagers, into the VLISM, represents humanity's first, explicit step into the galaxy and will allow us to understand where our home in the galaxy came from and where we are going (*Image credit Johns Hopkins /APL)*

1 Science case for Interstellar Probe

The Earth and the solar system are embedded in the vast Very Local Interstellar Medium (VLISM, <~2000 au) out of which the Sun carves a large cavity, the heliosphere, by driving the solar wind (Fig.1). Interstellar Probe (ISP) is a scientific mission to capture a unified understanding of our global heliosphere and its surrounding in interstellar space. On its journey ISP will travel through the outer solar system, the heliospheric boundary and into the VLISM, where it will for the first time sample its unknown properties, structures and dynamics that will allow us to understand where our home came from and where we are going. With a nominal design lifetime of 50 years, ISP will reach 350 au and has resources and reliable systems to even reach beyond to, at least, 525 au.

During its history, the solar system has revolved around the galactic centre about 20 times and has plowed through variety of interstellar environments. 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 (*Medvedev et al., 2007*). Along this evolutionary path, high interstellar cloud densities and ionization fractions have likely compressed the heliosphere down to below 25 au (*Müller et al., 2009*). Evidence is emerging for supernovae explosions as recent as 3 million years ago at only 20–50 pc from the Sun that probably compressed the heliosphere even below the orbit of Saturn and perhaps more, exposing the terrestrial planets to almost the full force of interstellar material and GCRs (*Wallner et al., 2020*). 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. 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. The heliosphere serves as a shield against this changing interstellar neighbourhood - yet our understanding of its structure and especially its boundaries is severely limited. On the *other side* is the interstellar medium that has provided the primeval materials 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 at other times and in different places.

1.1 Science questions

With its limited planetary payload, the Voyagers discovered that the heliospheric boundary represents a whole new regime of space physics that is decisive not only 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 main goal of Interstellar Probe (ISP) – to understand our habitable astrosphere and its home in the galaxy – can be broken down into three science questions given in Tab. 1.1.1.

Table 1.1.1: Interstellar Probe top-level science questions

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

1.2 NASA Interstellar Probe mission

To address top-level science questions TQ1-TQ3 NASA completed an ISP concept study (*Interstellar Probe: NASA Solar and Space Physics Mission Concept Study, 2021* https://interstellarprobe.jhuapl.edu/, reference*: CSR, 2021)* performed by the Johns Hopkins University/Applied Physics Laboratory (JHU/APL). The ISP mission (Fig. 1.2.1) will propel an ~860 kg spacecraft out of the heliosphere at a speed of 7.0 au/year using a heavy-lift launch vehicle such as the Space Launch System – B2 (SLS-B2) with two additional stages and a Jupiter Gravity Assist Manoeuvre (JGAM). ISP will reach 350 au in its 50-year nominal design lifetime, but with system resources to reach beyond to, at least, 525 au. The spacecraft is powered by Radioisotope Thermal Generators (RTGs) providing up to 300 W after 50 years. As demonstrated on New Horizons, ISP will use reliable hydrazine-thruster controlled attitude and passive spin stabilization, but avoid conventional reaction wheels, that imposes using X-band for downlink communications. The on-board 5-m high-gain antenna (HGA) provides 200 bps (at 350 au) to a 4x35-m equivalent dish array. Total payload mass is 89 kg *(CSR, 2021)*.

Fig. 1.2.1. ISP with a possible ESA contribution, the communication system including the High Gain Antenna.

NASA's study has shown that an ISP is realistic and can be designed, built, and launched by 2036**.**

1.3 Stella and NASA Interstellar Probe

Stella is the European contribution to ISP studied by NASA (*CSR, 2021*). The ISP mission will be assessed in the heliophysics decadal survey which is performed by the US National Research Council (NRC). This process is currently being kicked off and the final report will be published around the end of 2023 or in early 2024. Given the tremendous momentum behind ISP we expect that this mission will feature prominently in the decadal survey. The ESA Medium mission opportunity 2021 (M7) is the only currently available option for the European science community to contribute to ISP that will launch in the window 2036-2037 to utilize the required JGAM.

1.4 Stella and Voyage 2050

An ESA contribution to a NASA Interstellar Probe is mentioned explicitly in Section 3.2.3 of the ESA senior committee's report on Voyage 2050. The committee states that "*The exploration of the interstellar medium with an Interstellar Probe travelling up to ~200 au represents a very compelling science case with a unique in situ observatory and a high potential for discoveries to answer unsolved questions on the local interstellar medium and more generally on the formation of astrospheres. […] If this concept [i.e., interstellar probe] is selected, a contribution from ESA bringing the European expertise in both remote and in situ observation is of significance for the international space plasma community, as exemplified by the successful joint ESA-NASA missions in solar and heliospheric physics: SOHO, Ulysses and Solar Orbiter.*" The Stella proposal is submitted to achieve this goal.

1.5 Stella: the next step for European heliospheric research

European scientists have made fundamental contributions to heliospheric science ever since the discovery of interstellar matter in the heliosphere in 1970s. Following a theoretical paper by *Blum and Fahr* (*1970*), *Bertaux and Blamont* (*1971*), at the same time as *Thomas and Krassa* (1971) discovered the Lyman-α glow from interstellar hydrogen. Since then the European heliospheric community has had an excellent track record in providing key instruments, measurements, conceptual and theoretical models, and the analysis and interpretation for understanding how our Sun shapes the heliosphere and interacts with VLISM *(Bertaux and Lallement, 1985; Quémerais et al., 1999; Fichtner, 2001; Witte, 2004; Lallement et al., 2005; Saul et al., 2013; Galli et al., 2019)*. Ulysses, SOHO, and now Solar Orbiter continue to expand our understanding of the linkage between the Sun and the inner heliosphere.

Stella is the essential next step in our physical exploration of the Universe and in understanding the role of the VLISM in shaping the heliosphere, which protects the solar system from the hostile interstellar medium.

1.6 Stella and science community involvement

Although anchored in heliophysics, ISP inevitably offers ground breaking discoveries across astrophysics and planetary science. Any outward trajectory, dictated by the heliophysics objectives, offers flybys of at least one of the 130 dwarf planets or 4000 KBOs, to understand the almost unexplored world of the outer solar system. Remote and in-situ dust observations would provide an unprecedented view of the circumsolar dust disk, critical for understanding the formation and evolution of not only our solar system, but also to understand planetary formation in surprisingly young dust disks. Beyond the zodiacal cloud, the infrared universe opens up to measure the poorly constrained extragalactic background light providing insight in to galactic and stellar evolution since 200 My after Big Bang.

ESA's contribution to ISP opens access to data and opportunities for research not only for the heliospheric science but also for very broad European communities and disciplines.

1.7 Stella science questions

Stella proposes **a model** European payload consisting of a neutral gas mass spectrometer, plasma package, cosmic ray spectrometer, UV spectrograph, and radio science (the latter without hardware) to answer the following four Stella-specific science questions (Executive Summary, Q1-Q4) derived from the top-level ISP questions (Tab. 1.1.1.). In addition, ISP will allow testing the $1/r^2$ gravity law at previously unexplored scales of 50 – 350 au (Q5) making a significant contribution to fundamental physics as outlined in *A Roadmap for Fundamental Physics in Space, ESA, 2010,* reference RFP, 2010). Questions Q2 – Q4 are relevant to all astrospheres.

1.7.1 Q1: What is the composition of the VLISM gas?

Interstellar Boundary Explorer (IBEX) provided us with first direct VLISM neutral gas flow measurements of H, O, He (*Möbius et al. 2009*), of D/H (*Rodríguez et al. 2013, 2014*), Ne/O (*Bochsler et al. 2012*) and detailed measurements of VLISM He flow parameters (*McComas et al. 2015*). However, the absolute values of their abundances in the VLISM are very uncertain because of the strong and variable photoionization in the inner solar system (*Bzowski et al, 2013)* and filtration at the heliospheric boundary. Key ratios for planetary evolution studies, e.g. Ne/O and D/H, are not known with sufficient accuracy, and are limited by the small fluxes at 1 AU. Other possible VLISM species (C, N, Na, Mg, Al, Si, P, S, Ar, Ca, Fe) as well as the isotopic composition of He, O, Ne, have not been measured directly at all.

Earlier determinations of the VLISM composition are from pickup ions in the solar wind (*Gloeckler and Geiss, 2004*), from anomalous cosmic rays (*Cummings et al. 2002*), and from spectroscopic observations towards nearby stars (*Frisch et al. 2011*). All these methods are indirect and depend on modelling for the determination of the composition of the VLISM neutral gas. Additionally, some interstellar species, like C, seem to be unable to penetrate the heliopause because they are fully ionized in the interstellar medium, which prevents the use also of the indirect methods. Stella will for the first time directly measure all major neutral gas species of the interstellar medium, H, He, Ne, and O.

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

With the recent realization that the ISM is highly structured and that we are entering a new interstellar cloud now *(Linsky et al., 2019)*, neutral gas measurements at 100's au scales will be critical for assessing any spatial changes and what lies ahead.

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

The solar wind expanding from the Sun and interacting with the neutral gas in the VLISM shapes the heliosphere, its domains, and boundaries (Fig. 1.7.1).

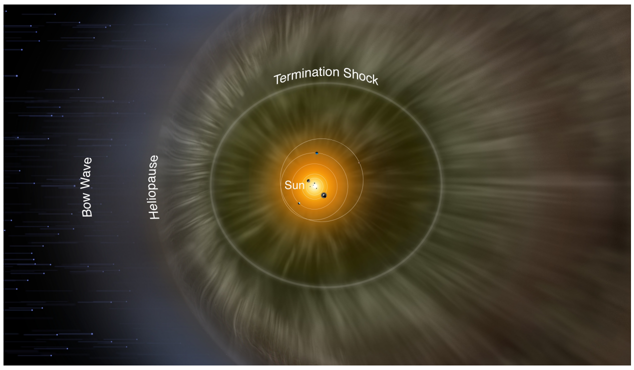

Fig. 1.7.1. Our astrosphere, the heliosphere is dominated by the solar wind. The termination shock (TS at 75 – 90 au) is created by the supersonic to subsonic transition of the solar wind flow, the heliopause (HP at 110 – 130 au) is a pressure balance boundary of the subsonic solar wind and the interstellar medium flow. The inner heliosheath (HS) is a region between the heliopause and the termination shock. The outer heliosheath consisting of VLISM materials extends to the bow shock or bow wave. (*Image: NASA / IBEX / Adler Planetarium*)

The interaction of the solar wind with the VLISM is unique for space plasma physics because the non-thermal component created by pick-up ions (PUI) defines pressure balances in the heliosheath (HS) and at the HP against the flow of the VLISM (*Rankin, et al., 2019*). The crucial role of PUIs in the global solar wind-VLISM interaction and, particularly, in the nature of the heliosheath region could not be studied with Voyager 1 and 2 because PUIs were and are not measured by those spacecraft. While the physics of PUIs within the inner heliosphere has been previously addressed with Ulysses/Solar Wind Ion Composition Spectrometer (SWICS) and Advanced Composition Explorer (ACE)/SWICS observations (*Allegrini et al., 2005; Geiss et al., 1995; Gloeckler et al., 1992; Gloeckler & Geiss, 1996; Schwadron et al., 2000; Wimmer-Schweingruber & Bochsler, 2003*), the lack of full 3D velocity distribution function measurements and the small geometric factor of SWICS inhibited progress in understanding PUI evolution through acceleration and transport processes in the heliosphere.

PUIs experiencing a secondary charge exchange process with interstellar neutrals become Energetic Neutral Atoms (ENAs). Knowledge of PUI properties is crucial for understanding ENA images of the global heliospheric interaction.

Heliospheric ENAs imaging performed by IBEX over a solar cycle shows substantial variations of ENA images from solar minimum to maximum, demonstrating that the Sun's activity drives the global response of the entire heliosphere and its interaction with the VLISM (*McComas et* *al., 2020*). But how multi-scale solar wind structures propagate and evolve in the outer heliosphere; how they influence suprathermal and energetic particles; what plasma flows they cause in the heliosheath; and how locations of boundaries change because of pressure pulses, shocks, and waves in the solar wind are open questions but important also in the astrophysical context because they can be measured by ISP.

Voyager 1 data revealed an unexpected discovery detecting shocks and pressure waves beyond the heliosphere in the VLISM (*Burlaga et al., 2013; Gurnett & Kurth, 2019*). These VLISM structures are likely driven by solar transient events, which evolved in the heliosphere and interacted with the heliospheric boundaries. The very different physics of the VLISM affects the properties of shocks and turbulence in this region. Our understanding of VLISM dynamics, drivers for shocks and waves, as well as their properties and evolution in the VLISM is very limited.

IBEX discovered the ENA ribbon, an enigmatic band of intense ENA fluxes in the sky (*McComas et al. 2009; Fuselier et al. 2000*). The ribbon is an "imprint" of the complex physical processes between charged and neutral particles controlled by the interstellar magnetic field. Understanding its origin will tell us about the fundamental physics of the heliosphere's boundary, and thus about other astrospheres. The Interstellar Mapping and Acceleration Probe (IMAP, launch 2025) will explore the ENAs in much more detail but it will not solve the problems in the same way as an in situ measurement in the heliosheath and interstellar space. Although not decided yet (*CSR, 2021*), a favored trajectory of ISP will pass through the ribbon to perform in situ particle measurements to establish its origin.

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

Galactic Cosmic Rays (GCR) anisotropies are sensitive to remote field variations and are therefore used as an effective remote diagnostic of the field configuration of the heliosphere, and once beyond the heliopause, they provide insight into how the solar disturbances can propagate deep into the VLISM (*Gurnett et al., 2015; Hill et al., 2020; Krimigis et al., 2013; Rankin, et al., 2019*). The Voyagers' cosmic ray instrument had limited look directions, and *Rankin et al.* (*2019, 2020*) reported confounding, species-dependent anisotropies in GCR angular distributions. There is no current consensus on what causes those anisotropies. With its improved instrumentation, ISP would offer a new opportunity to study the nature of GCR anisotropies, GCR shielding by the heliosphere, and the properties of the unshielded GCR spectra in the VLISM, including rare species and isotopes, that could not be observed by the Voyagers.

*Mewaldt (2013), Wiedenbeck et al., 2007 (*and references therein) and *Wiedenbeck (2013)* discussed how measurements of rare and unstable cosmic ray isotopes can be used to determine GCR source regions via spallation and direct acceleration, galactic escape rates, and solar modulation. For instance, the abundance of Li, Be, and B at cosmic ray energies is comparable (same order of magnitude) to that of C, N, and O, and thus more than four to six orders of magnitude higher than their relative abundance in the solar system (e.g., *Wiedenbeck et al., 2007*). Observations of Li-Be-B can offer the capability for distinguishing solar from interstellar from mixed plasmas in the heliosheath, HP and boundary layer(s), and VLISM. Studies of the unobserved species of GCRs in the VLISM are of importance not only to heliophysics and the nature of particle acceleration and consequences of GCRs in the heliosphere, but also to astrophysics and the nature of the universe itself. Observations of particularly rare GCR isotopes, GCR electrons, and antimatter in the VLISM can even shed light on and further constrain models of the nature of the Big Bang and dark energy. However, because of heliospheric shielding of lower-energy GCRs, the critical observations required to answer such open questions rely on observations of these GCR species in the unperturbed VLISM by an ISP.

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

The Local Interstellar Cloud surrounding the heliosphere primarily consists of atomic hydrogen (H). Approaching the heliosphere, interstellar H atoms pile up and form a Hydrogen Wall (*Baranov and Malama, 1993; Linsky and Wood, 1996*), discovered to be a common feature of astrosphere-ISM interaction. The heliospheric Hydrogen Wall was detected remotely, however, it was never explored with in-situ measurements leaving open questions about its extent, peak density, and 3D structure.

Despite being critical for the global heliospheric structure, properties of interstellar H atoms far away from the heliosphere in the LIC and their variations due to ion-neutral coupling at the heliosphere boundary remain largely unknown.

Measuring solar Lyman-a (121.567 nm) emission backscattered from interstellar H atoms is a powerful technique to probe interstellar H atoms. The spectral shape of the Lyman-α emission line holds key information on the spatial and velocity distribution of interstellar H and enables to infer momentum exchange between hydrogen and plasma. The study of the Lyman-α line profile in the outer heliosphere allows characterizing the distribution (bulk velocity and temperature) of the hot hydrogen population, which is created by charge exchange in the inner heliosheath. After crossing the heliopause, these same measurements will provide the hydrogen distribution in the outer heliosheath and the Hydrogen Wall. As the probe moves away to larger distances only the pristine interstellar H population will remain thus allowing to derive the number density, bulk velocity, and temperature in the Local Interstellar Cloud.

1.7.5 Q5: Are there any deviations from the gravity law on the interstellar scale?

The laws of gravity are unevenly tested at different spatial scales (Fig. 1.7.2). The most precise knowledge is obtained from solar system dynamics, where space probes allowed the most accurate tests of general relativity to date. Violations of the $1/r^2$ law, associated with the Compton wavelength of the graviton, have also been tested precisely in the solar system. But at short spatial scales (at the atomic level) or beyond the solar system (>50 au) gravity has never been accurately tested. Stella offers the opportunity to carry out an accurate test of the $1/r^2$ law at distances beyond 50 au and up to 350 au, by precise range and range rate measurements of the probe. In addition, Stella could determine or set up an upper limit on the density of dark matter in a sphere of radius approximately equal to the heliocentric distance of the probe. Gravitational signals from TNOs could also be detected providing a new "window" for discovering these objects.

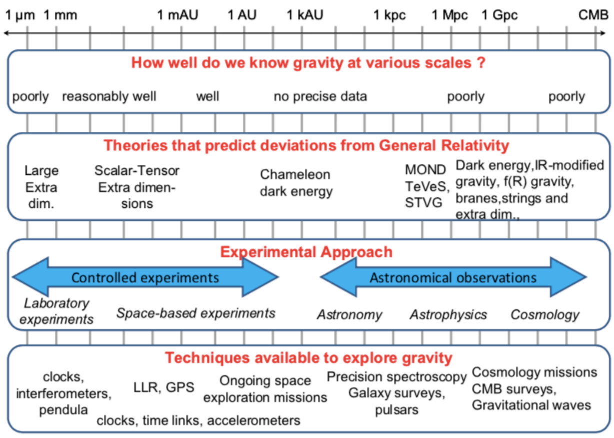

Fig. 1.7.2. Gravity at all length scales (*RFP, 2010*).

2 Scientific requirements and payload

The European model payload provides critical contributions to achieve, in combination and with other ISP instruments, the ISP science objectives. Tab. 2.1 traces the Stella instrument measurements requirements to the ISP objectives.

Tab. 2.1.Traceability of the scientific objectives and key measurement requirements for the European payloads to the ISP science objectives as in *CSR (2021)*

Scientific requirements for European instruments	**Measurement requirements for European instruments**
Neutral gas mass spectrometer (NGMS). Provider: University of Bern, Switzerland	
ISP Science objectives: Advance knowledge and understanding of the galactic neighbourhood's origin and evolution	
NGMS Science question (Q1): What is the composition of the VLISM gas?	
Determine the chemical and isotopic composition of the local interstellar gas of all major species entering the heliosphere: H, He, O, Ne, and Ar.	Mass spectrometric measurements for thermal gas, with $m/\Delta m = 300$, with sensitivities at 1 # m^{-3}.
Plasma Science System (PSS). Provider: IRAP, Toulouse, France; IRF, Kiruna, Sweden	
ISP Science Objectives: Resolve the birth and evolution of interstellar and inner- source PUIs; Understand acceleration processes and pressure balances in the solar wind and at the heliospheric boundaries; Establish the nature and structure of the heliopause, the ribbon, and the ring; Investigate how the heliospheric boundary is modified by solar dynamics; Determine the extent and impact of solar disturbances in the VLISM.	
PSS Science Question (Q2): How is our dynamical heliosphere upheld and how does it change from the Sun to the VLISM?	
Determine 3D distribution functions of ions and electrons.	Measurements of differential fluxes of ions and electrons in the range < 3 eV to > 20 keV.
Cosmic Ray Spectrometer (CRS). Provider: University of Kiel, Germany	
ISP Science Objectives: Understand the nature and detailed origin of GCRs; Establish the exact nature of heliospheric shielding against GCRs; Establish how far solar disturbances reach into the VLISM.	
CRS Science Question (Q3): What is the origin and role of galactic cosmic rays in the solar system and beyond?	
Determine the isotopic composition of the GCR Determine the abundance of Li-Be-B Determine GCR pitch-angle distributions	Large G-factor (> 2 cm^2 sr) Mass resolution ~ 0.1 amu Multiple viewing directions, measure magnetic field
Lyman-a spectrometer (LyS). Provider: Laboratoire Atmosphère Milieux, France	
ISP Science Objectives: Understand the filtration as the VLISM passes the heliospheric boundaries and processes responsible for structuring the VLISM at the heliospheric interface (the Hydrogen wall) and beyond.	
LyS Sci. Question (Q4): How does the local interstellar medium become structured when it meets the heliosphere?	
Determine the hydrogen populations properties, number density and velocity distribution, in the inner heliosheath, the Hydrogen wall, and the VLISM	Directional high-resolution (< 20 km/s Doppler shift) Lyman-a spectra and their variation with distance to the Sun

Radio Science (RS). Provider: Universita' La Sapienza, Italy	
ISP Science Objective (New and unique for the European contribution). Explore the gravity law on the scale of VLISM	
RS Science Question (Q5): Are there any deviations from the gravity law on the scale of VLISM?	
Determine the spacecraft acceleration	Measure the two-way range to an accuracy of 20 cm @ 100 s integration time

3 Stella mission configuration

The Stella mission includes two core and two optional elements for the full complement *(1)* the European contribution to the ISP payload (core), *(2)* the European ISP communication system (core), *(3)* the European deep space communication facility (full complement), and *(4)* the contribution to ISP operations (full complement). The final selection is the subject of ESA – NASA negotiations.

The elements *(3)* and *(4)* are linked and form with *(2)* an end-to-end communication system. The ESA-provided end-to-end communication system will *(a)* increase drastically the science return of ISP, *(b)* enhance European competitiveness in the field, and *(c)* simplify programmatic interfaces for the radio science experiment. If the development of the European deep space communication facility starts early enough, it will greatly increase science return from other deep space missions, for example, to the Ice Giants.

3.1 European contribution to the ISP payload (core)

To address its science questions Stella proposes the model payload given in Tab. 3.1.1 and 3.1.2. The Radio Science experiment does not require any spacecraft resources. The payload is a subject of further refinement by a joint NASA – ESA science definition team and competitive process. The instruments listed in this proposal are given to illustrate the European expertise and possible European contributions. While the instruments have sufficient heritage and already have or will have TRL 6 by 2026 (Tab. 3.1.3), they have to be qualified for a 50-year nominal life-time. ESA will have to play the key role in this process (Sec.4.3). It is critical to engage now. If European groups are to be at the right TRL to participate, there is no time to wait a few years for NASA to decide before the work in Europe starts.

Tab. 3.1.2. Stella instrument resource budgets

Instr.	Mass (kg) / CSR Allocation	Power (W) / CSR Allocation
NGMS	9.8 / 10.0	11 / 11
PSS-A	6.2 / n/a, partial contribution	10 /
PSS-F	3.0 / n/a, partial contribution	5 /
CRS	7.5 / 8.0	7 / 7
LyS	12.5 / 12.5	12 / 12

PSS-A: Plasma Analyzer; PSS-F: Faraday cup

Tab. 3.1.1. Stella science payload and the key performance

Instrument	Key Measurements	Key performance
Neutral gas mass spectrometer (NGMS)	Composition and isotope composition of the interstellar gas.	m/Δm > 100, species H – Fe
Plasma Science System (PSS)	Ion and electron 3D velocity distribution functions and plasma moments	Energy range 0.1 eV – 20 keV Dynamical range in fluxes up to 10^{11}
Cosmic Ray Spectrometer (CRS)	Composition and isotope composition of energetic particles.	Δm ~0.1 amu, H – Sn G-factor > 2 cm² sr
Lyman-α spectrometer (LyS)	Lyman-α line profile and hydrogen distribution	R > 15000, <20 km/s Doppler resolution (req.), 10 km/s (goal)
Radio Science (RS)	Two-way range measurements	20 cm for 100-1000 s integration time

Tab. 3.1.3. Stella instruments heritage TRL

Item	TRL (by year)	Reference instruments (on spacecraft/mission)
NGMS	6 (2026)	NGMS on Luna-Resurs, NIM / PEP on JUICE
PSS-A	6 (2026)	PAS on Solar Orbiter, SWEA on STEREO and MAVEN, HIA and CODIF on Cluster;
PSS-F	6 (2026)	PSS on Voyager, PIMS on Europa Clipper
CRS	6 (2026)	RAD on Mars Science Laboratory, EPD HET on Solar Orbiter, AHEPaM on Athena
LyS	6 (2026)	Imaging UltraViolet Spectrograph on MAVEN
RS	6 (2022)	BepiColombo; VERITAS

3.2 European ISP communication system (core)

The ISP baseline communications system (*CSR, 2021, Sec. 5.1.3,* Tab. 3.2.1) is a fully redundant X-band system. The hardware in this subsystem represents mature technology with heritage in deep space. The antenna complement includes the 5-m High Gain Antenna (HGA), a 0.4-m Medium Gain Antenna (MGA) co-aligned with the HGA, and fore and aft Low Gain Antennas (LGAs). The MGA will be used early in the mission to allow high data rates without the high pointing constraints of the HGA.

Tab. 3.2.1. ESA-provided ISP communication system

Parameter	NASA ISP Value *(CSR, 2021)*
Frequency	8.4 GHz (X-band)
Range	350 au (50-years mission)
Transmitter antenna ø	5 m
Transmit power	52 W
Min data rate	200 bps (to 4x35-m @ 350 au)

3.3 European deep space communication facility (full complement)

In addition to the core Stella components, we propose two optional contributions to fully complement the European science payload. One is the European deep space communication facility to serve as a **dedicated link for ISP.** NASA’s Deep Space Network (DSN) is aging and oversubscribed and the new European facility would increase drastically the ISP and European payload science return. The facility would be a dearly needed augmentation of the European Deep Space Antennas (DSA). DSA is in need of a significant upgrade not only for ISP but also for other planned missions, e.g., to the icy giants. Less than a decade after its launch, returning data from ISP will require a receiving station with the equivalent of 4x 35-m dishes or more than 16 18-m dishes. The architecture of the array (Tab. 3.3.1, Fig. 3.3.1) would be studied during phase 0/A.

European industries are among the world leaders in the field. mtex antenna technology (GER) is the sole prime to develop a production-ready design and produce a prototype 18-m antenna for the US National Research Observatory (NRAO) Very Large Array (ngVLA) facility. Thales/Alenia (FRA/IT), Schwartz Hautmont (Spain) are involved in the development of the new 35-m DSA antenna.

Tab. 3.3.1. Options for European deep space communication facility (all numbers are preliminary, X-band)

Parameter	35-m Opt.	18-m Opt.
Antennas array	4x35-m	16x18-m
Effective aperture, m^2	3846	3629
Gain (dBi)	75.1	74.9
System noise temp (K)	49	49

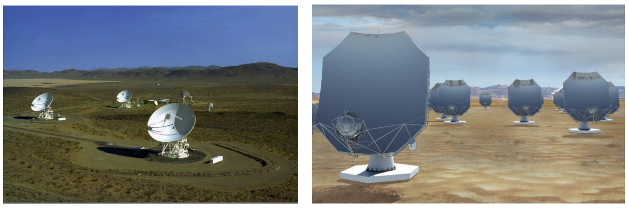

Fig. 3.3.1. Left: The Apollo Complex of 34-m BWG antennas at the Goldstone DSCC (early version of the proposed Stella 4x35-m dishes array, Vilnrotter et al., 2008) Right: Artistic view of the NRAO ngVLA array of 18-m antennas (https://public.nrao.edu)

3.4 Contribution to ISP operations (full complement)

While NASA assumes the main responsibilities for ISP flight dynamics and operations, ESA’s primary responsibility would be to operate the European payloads, and provide a dedicated link to ISP to drastically increase ISP’s science return. ESA would also perform the special operations required by the European Radio Science experiment and may provide additional uplink. This Stella proposal covers operations for the first 10-year segment of the 50-year nominal life-time (Sec. 4.5).

3.5 Technology development requirements

Stella requires the following technology developments and studies:

(1) Development and implementation of qualification procedures for missions with nominal lifetimes up to 50 years. This would provide ESA with key knowledge in designing long-lived space equipment.;

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

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

The required technology development and studies are anticipated to be kicked-off in 2023/2024 to ensure completion by the end of phase 0/A.

4 Management

The following is a possible scenario for how the Stella project can be managed but with such a complex international multi-partner project many routes are also possible.

4.1 Mission implementation

Stella is the European contribution to NASA’s ISP, a large strategic mission candidate. The mission implementation follows the scheme in which “*a part of the budget allocation of an M mission is used to implement a junior European contribution to a mission led*” by NASA (*ESA Call for an M and an F launch* opportunity*)*.

ISP is a unique mission and attracts unusually great interest from the science community as documented in *CSR (2021, p.1-2*). It also relies on international collaboration, in particular, for its ground segment (*CSR, 2021, page F-85).*

4.2 Collaboration with NASA

This proposal has been developed in collaboration with the APL ISP Study Team. The Solar and Space Physics Decadal Survey is projected to complete around the end of 2023. The Stella Phase-2 proposal will be made available to the US decadal survey panel as a reference.

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

4.3 Payload and subsystem procurement

Stella payloads are provided by Member States. However, Stella’s nominal mission duration of 50 years requires a new and especially thorough PA/QA program which may be challenging for payload-providing institutes. To ensure a common understanding and implementation of these unusual requirements, Stella assumes a much stronger and deeper involvement of ESA than in previous missions. ESA would serve as the programmatic interface with NASA, closely supervise instrument development, be in control of the payload PA/QA program, and provide assistance in critical areas. Such an approach is the logical consequence of the lessons learned from JUICE (JUpiter Icy moons Explorer) and other recent missions. Its implementation already in Phase 0 would ensure full oversight and significantly reduce risk in later phases of the project.

4.4 Science management

Stella assumes that all data from the European payload are made public after a verification/validation period of 90 days, as is the de-facto new standard for ESA missions. As the mission matures, this validation period will decrease. The aim is to release the data directly. Instrument and mission data shall be open. Because this proposal is for a European contribution to a NASA mission, the data policy will require further discusions with NASA.

4.5 Mission longevity management

To manage ISP's nominal lifetime of 50 years Stella follows the approach proposed in *CSR (2021)* by dividing it into 10-year time segments. At the end of each segment comprehensive mid-term mission and payload reviews are performed and a "go/no-go" decision for the next 10-year segment is given. ESA's reviews would be synchronized with those of NASA and adopt the strategy proposed by *CSR (2021)* or agreed in the ISP STDT.

4.6 Management of knowledge transfer

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

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

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

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

4.7 Sustainability of interstellar research in Europe

With its unique experience in managing long-lasting missions such as SOHO, Cluster, XMM-Newton, Integral, Gaia, etc., ESA and the European space science community have demonstrated their capability of ensuring the successful transfer of critical knowledge from one generation of scientists to another. Stella would build on this experience and enable a vibrant and robust science community by networking existing programs (e.g., EU, Marie-Curie, ERC, national funding agencies, non-EU European countries programs) into a virtual Interstellar Probe Institute (IPI). The IPI will train future generations of space scientists, involve the community with workshops following the highly successful ISSI-model (International Space Science Institute), and engage the public by reporting the exciting discoveries made by humanity's pathfinder to the stars – Stella!

4.8 Stella schedule

The M7 launch date is well aligned with the astronomically constrained launch window of ISP opening in 2036-2037 towards the forward hemisphere of the heliosphere (*CSR, 2021*, *Fig. 4-29,*). The M7 mission selection in 2026 is compatible with the completion of the Solar and Space Physics Decadal Report no later than 2024. The Stella Definition phase starts in 2027 and is also aligned with the completion of the Planning, Programming, Budgeting, and Execution (PPBE) process on the NASA side in 2027.

Delaying definition of the European contribution to NASA's ISP until the completion of the Decadal Report in 2024 results in too short (3 years, 2025-2027) time available for budgeting, selection, and mission adoption processes on the ESA side to comply with the start Phase A on the NASA side in 2028. An early start of Stella Phase 0 in 2023 provides sufficient schedule margins to synchronize activities on the ESA and NASA sides.

4.9 Stella costs for ESA

The Stella contribution to the ISP mission is estimated to **102MEUR** for the core elements and **382MEUR** for the full complement (Tab. 4.9.1). The ISP communication costs based on *CSR (2021, Tab. 6-6)* with the 20% margin added. Because of the complex PA/QA requirements, Stella includes 21MEUR for payload management. The cost of the 16x18-m array is approximately 20% less than the 4x35-m array costs used in the breakdown.

Table 4.9.1: Stella cost breakdown
(green – core, blue –full complement)

Elements	Stella (MEUR)
ISP X-band communication system	55
Payload Product/Quality assurance and assistance (13 y@1MEUR/year)	13
Programmatic and payload management support	8
ESA Project 14% (core)	14
Total w/o margin (core)	**90**
Margin 12% (core)	12
Total for ESA, MEUR (core)	**102**
Array 4x35-m dishes @ €35MEUR each (envelope for 16x18-m array)	140
Operations, 10 years (@7 MEUR/y)	70
ESA Project 14% (full complement)	52
Total w/o margin (full complement)	**338**
Margin 12% (full complement)	44
Total for ESA, MEUR (full complement)	**382**