RAS Techniques and Instruments

RASTAI **2,** 532–547 (2023)
Advance Access publication 2023 August 12

https://doi.org/10.1093/rasti/rzad034

# Synergies between interstellar dust and heliospheric science with an interstellar probe

Veerle J. Sterken ,[1]★ S. Hunziker,[1] K. Dialynas ,[2] J. Leitner ,[3] M. Sommer ,[4] R. Srama ,[4] L. R. Baalmann ,[1] A. Li,[5] K. Herbst ,[6] A. Galli ,[7] P. Brandt,[8] M. Riebe ,[9] W. J. Baggaley,[10] M. Blanc,[11] A. Czechowski ,[12] F. Effenberger,[13,14] B. Fields ,[15] P. Frisch,[16] M. Horanyi,[17] H.-W. Hsu,[17] N. Khawaja ,[18] H. Krüger,[19] W. S. Kurth ,[20] N. F. W. Ligterink ,[7] J. L. Linsky,[21] C. Lisse ,[8] D. Malaspina,[17,22] J. A. Miller ,[23] M. Opher,[23] A. R. Poppe ,[24] F. Postberg,[18] E. Provornikova,[8] S. Redfield ,[25] J. Richardson,[26] M. Rowan-Robinson,[27] K. Scherer ,[13] M. M. Shen,[28] J. D. Slavin ,[29] Z. Sternovsky,[17] G. Stober ,[30,31] P. Strub ,[4,19] J. Szalay [28] and M. Trieloff[3]

*Affiliations are listed at the end of the paper*

Accepted 2023 August 1. Received 2023 July 2; in original form 2022 December 7

## ABSTRACT

We discuss the synergies between heliospheric and dust science, the open science questions, the technological endeavours, and programmatic aspects that are important to maintain or develop in the decade to come. In particular, we illustrate how we can use interstellar dust in the solar system as a tracer for the (dynamic) heliosphere properties, and emphasize the fairly unexplored, but potentially important science question of the role of cosmic dust in heliospheric and astrospheric physics. We show that an interstellar probe mission with a dedicated dust suite would bring unprecedented advances to interstellar dust research, and can also contribute – through measuring dust – to heliospheric science. This can, in particular, be done well if we work in synergy with other missions inside the solar system, thereby using multiple vantage points in space to measure the dust as it 'rolls' into the heliosphere. Such synergies between missions inside the solar system and far out are crucial for disentangling the spatially and temporally varying dust flow. Finally, we highlight the relevant instrumentation and its suitability for contributing to finding answers to the research questions.

**Key words:** cosmic dust – heliosphere – synergies – interstellar – instrumentation – space missions.

## 1 INTRODUCTION AND BACKGROUND INFORMATION

This paper discusses the synergies[1] between heliospheric and dust science that can be harnessed with an interstellar probe (ISP), the open science questions, and pathways forward in the future, including the relevant instrumentation. We refer to Sterken et al. (2019) for a review of the current state of the art of interstellar dust (ISD) research in the solar system (dynamics and composition, measurements and models). This paper (RASTI) was originally submitted to the Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033, 2022 September 7 and would be published in the Bulletin of the AAS (BAAS): Sterken et al. (in preparation) – doi pending. It is modified in this version and includes a discussion on the instrumentation necessary to answer the science questions. Two accompanying white papers were submitted for the decadal survey: Hsu et al. (in preparation), 'Science opportunities enabled by *in situ* cosmic dust detection technology for heliophysics and beyond', and Poppe et al. (in preparation), 'The interactions of ISD with our Heliosphere'. A third accompanying refereed paper (Hunziker et al., in preparation), will provide dust flux predictions in order to illustrate how dust measurements on the way out through the heliosphere may provide new constraints (i.e. the boundary conditions) for heliosphere models, in addition to the already existing magnetic field, plasma, galactic cosmic ray (GCR), and other data from the Voyagers and other spacecraft.

### 1.1 The solar system in the local interstellar cloud

The Sun and planets move through the outer edges of the local interstellar cloud (LIC) and into the neighbouring G-cloud or a mixed region of the two clouds (Swaczyna et al. 2022) after a journey of nearly 60 000 yr in the LIC (Linsky et al. 2022). The ISD in this diffuse cloud may have its origins in supernovae and atmospheres of cool stars or may be recondensed in the interstellar medium (ISM) after being shattered by supernova shocks. These particles cross the solar system due to its relative velocity with the LIC (of about 26 km s$^{-1}$). They can be measured *in situ* by dust detectors

★ E-mail: vsterken@ethz.ch

[1]A Synergy: the interaction or cooperation of two or more organizations, substances, or other agents to produce a combined effect greater than the sum of their separate effects. [Oxford Languages dictionary]

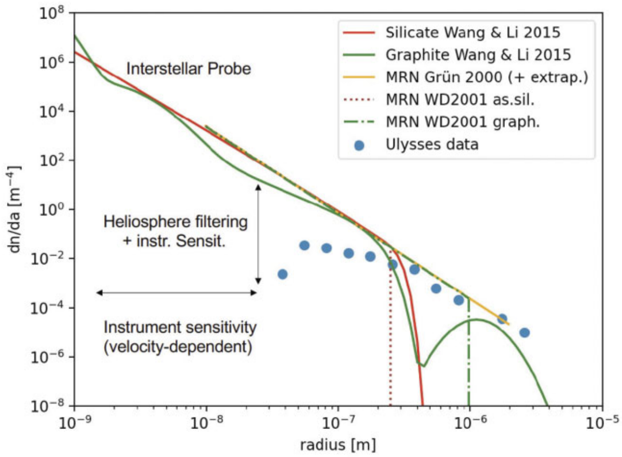


**Figure 1.** The ISD size distribution from astronomical models and *in situ* data by Ulysses (from Sterken et al. in preparation). The smallest ISD particles are the most numerous. Distributions derived from astronomical observations were taken from Wang et al. (2015), Grün & Landgraf (2000), Weingartner & Draine (2001). Ulysses data are from Krüger et al. (2015).

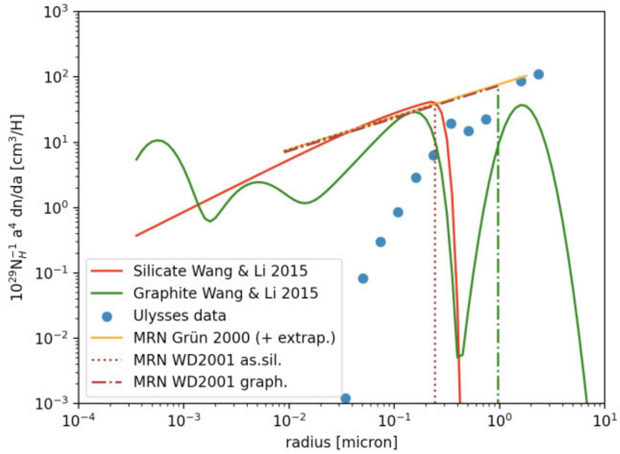


**Figure 2.** The ISD mass distribution from astronomical models and *in situ* data by Ulysses. Most of the mass is in the largest particles, which is important for the determination of the gas-to-dust mass ratio. Units on the vertical axis are chosen to be equal to the units in Wang et al. (2015). Distributions derived from astronomical observations were taken from Wang et al. (2015), Grün & Landgraf (2000), Weingartner & Draine (2001). Ulysses data are from Krüger et al. (2015).

on spacecraft, and hereby provide unique ground truth information about their make-up and dynamics. This ground truth information is complementary to measurements of the dust by more classical astronomical methods like observations of extinction, scattering, and polarization of starlight as well as dust thermal emission, and by observing the gas in comparison to a reference (the so-called 'cosmic abundances', usually the solar composition), where the 'missing component' in the gas phase hints at what must be locked up in the dust (Mathis, Rumpl & Nordsieck 1977; Draine 2003; Draine & Li 2007; Draine 2009; Wang, Li & Jiang 2015). Directly measuring these particles is of utmost importance for astrophysics and is also part of humanity's exploration of our local interstellar neighbourhood.

### 1.2 Dynamics of interstellar dust in the heliosphere

The ISD size distribution extends from nanometres to several micrometres and decreases with increasing particle size (Fig. 1). However, its mass distribution increases with particle size, as illustrated in Fig. 2 (see also, for example, Krüger et al. 2015, fig. 6), and thus the largest ISD particles are the most important for determining the gas-to-dust mass ratio ($R_{g/d}$) in the LIC. The dynamics of the dust in the heliosphere depends on the particle size, optical properties, and on the space environment. This dependence on the space environment turns ISD into a very interesting tracer for the dynamic heliosphere.

**Micron-sized ISD** particles passing through the solar system are gravitationally dominant, may be uncoupled from the LIC, and could, in theory, come from any other direction than the heliosphere nose (note that the interstellar meteoroids are still a controversial topic in the field, e.g. Hajdukova et al. 2020, in preparation; Brown & Borovička 2023).

**Mid-sized ISD** particles (ca. 0.1–0.6 μm radius) can reach the solar system depending on their size, optical properties, composition, and phase in the solar cycle. Their dynamics in the solar system are governed by solar gravitation, by solar radiation pressure force, and by Lorentz forces due to (charged) ISD passing through the magnetic fields of the solar wind plasma that changes with the 22-yr solar cycle, leading to an alternating focusing and defocusing of the dust towards the solar equatorial plane during the solar minima. However, there is

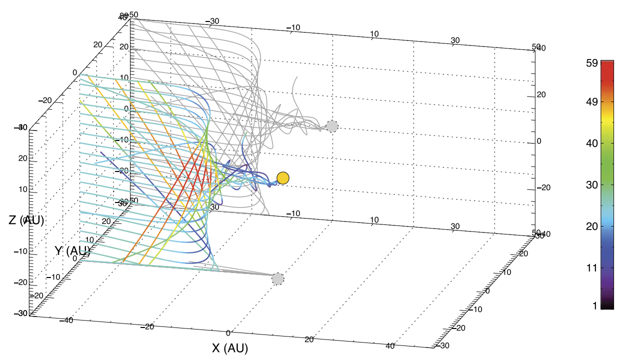


**Figure 3.** A complicated pattern of ISD trajectories for charge-to-mass ratio 12 C kg$^{-1}$, assuming they made it through the heliosheath (Sterken et al. 2012).

an additional (most likely time-dependent) mechanism of filtering in the heliosheath (Linde & Gombosi 2000; Slavin et al. 2012; Sterken et al. 2015).

**Small ISD** particles (30–100 nm) are dominated by the Lorentz force and may partially reach the solar system during the solar focusing phase (e.g. 2029–2036) if the heliospheric boundary regions do not filter the particles already upfront. The higher the charge-to-mass ratio of the dust is, the more the particles move on complicated patterns (e.g. Fig. 3 from Sterken et al. 2012, which may cause 'waves' of higher dust densities to 'roll' into the heliosphere for specific particle sizes; Fig. 4 from Hunziker et al., in preparation). The exact lower cut-off size and time-dependence of particles that can enter the solar system is not yet exactly known, but *Ulysses* and *Cassini* already have measured ISD particles with radii between 50 and 100 nm (Krüger et al. 2015; Altobelli et al. 2016).

**Nanodust** (2–30 nm) cannot enter the heliosphere because it is coupled to the magnetic field lines of the very local ISM (VLISM), and is diverted around the heliopause boundary (Linde & Gombosi 2000; Slavin et al. 2012). These particles may also pile-up at the heliopause (Slavin et al. 2012; Frisch et al. 2022). Polycyclic

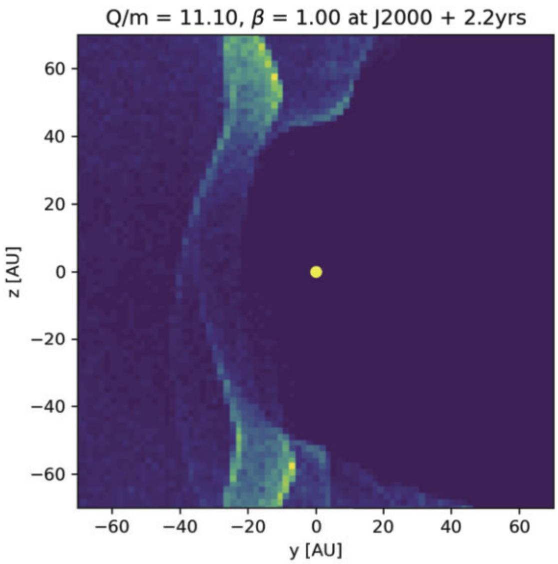


**Figure 4.** Higher dust densities 'rolling' into the heliosphere for Q/m = 11.1 C $kg^{-1}$ (Hunziker et al., in preparation).

aromatic hydrocarbon (PAH) molecules are the smallest carbon nanodust particles in the ISM. They are abundant and widespread in a wide variety of astrophysical regions (Li 2020). Their presence (or absence) in the LIC would provide useful insight into the nature and origin of interstellar PAHs. They are not expected to enter the solar system since they would have been deflected from the heliosphere. However, if PAHs of interstellar origin are detected in the solar system or beyond, their origin (possibly through fragmentation of small carbon dust) would offer valuable insight into the composition and structure of interstellar carbon dust.

### 1.3 Filtering of dust in the outer and inner boundary regions of the heliosphere

The filtering of ISD in the heliosphere likely happens mainly at the heliosphere boundary regions (i.e. at the heliopause and in the heliosheath) and in the region closer to the Sun because (1) the dust acquires the highest charges in the heliosheath (Kimura & Mann 1998; Slavin et al. 2012), and (2) the azimuthal component of the interplanetary magnetic field causing the focusing and defocusing effects is the largest closer to the Sun. Flying a spacecraft through all these regions to measure all parameters simultaneously (magnetic field, plasma densities, dust charging, PUIs, dust flux, velocity, and direction), would be of utmost value for understanding the mechanisms of the dynamics of the dust, the dust–plasma interaction, and the role of dust for heliosphere physics, in particular, because this has never been done before. We, therefore, need *in-situ* measurements of dust and plasma parameters in interplanetary space, at the termination shock, in the heliosheath, at the heliopause and – especially – beyond the heliopause, over the solar cycle, from a future ISP.

*In situ* ISD measurements with *Ulysses* up to 5.4 AU indeed contained a signature of the dynamic heliosphere (Landgraf et al. 2003; Sterken et al. 2015; Strub, Krüger & Sterken 2015). These particles were measured for the first time in 1993, using an impact ionization dust detector (Grün et al. 1993). *Ulysses* monitored the ISD throughout the solar cycle for 16 yr, giving us an impression of the fluxes and roughly the flow directionality of the dust. The dust flow direction changed, in particular, in the latitudinal direction around 2006 (Krüger et al. 2007), which may have been caused by the Lorentz force (Sterken et al. 2015). Simulations of ISD dynamics in the solar system (without heliospheric boundaries) would be piecewise compatible with the data if the larger dust particles are porous, or aggregates (hence, if they have a higher charge-to-mass ratio; Sterken et al. 2015). A second time-dependent mechanism of filtering in the heliosheath was suggested to be needed in order to explain the Ulysses data (Sterken et al. 2015). Time-dependent models of the heliosphere–dust interaction including a heliosheath are currently under development.

### 1.4 Compositional measurements of interstellar and interplanetary dust grains

#### *1.4.1 Circumstellar grains versus ISM dust versus solar system dust*

Both model predictions (Zhukovska et al. 2016) and analysis of presolar dust grains from primitive meteorites (Hoppe, Leitner & Kodolányi 2017) indicate that only about ∼3 per cent of the ISM and parent interstellar cloud dust of our Sun is circumstellar dust. Measurements of contemporary ISD offer the opportunity to compare the inferred ratios at the time of formation of the Solar System with present-day data. However, this would require a sufficiently large number of investigated particles. Assuming a similar circumstellar dust/ISM dust ratio as obtained from modelling and at the time of Solar System formation, we would expect one circumstellar grain among ∼33 ISM grains, on average.

From an astrophysical point of view, oxygen isotopes are best-suited to identify circumstellar oxygen-rich grains (silicates and refractory oxides), while carbon isotopes are diagnostic for most C-rich species (Zinner 2014). The oxygen and carbon isotopic compositions of the local ISM are not well constrained; there is information on the $^{18}O/^{17}O$ ratio (e.g. Wouterloot et al. 2008), which differs from the Solar System value. Analysing the oxygen and carbon isotopic compositions of a large number of ISD particles would help closing this knowledge gap.

Laboratory isotope measurements of extraterrestrial samples with high-spatial resolution secondary ion mass spectrometry (SIMS), like NanoSIMS (Hoppe, Cohen & Meibom 2013) or TOF-SIMS (Stephan 2001), have to deal with a multitude of mass interferences, which often require high mass resolutions m/Δm of several thousand to be resolved. Spacecraft-mounted impact-ionization TOF-MS instruments, on the other hand, achieve mass resolutions ≤200, which is sufficient to resolve different isotopes of C, O, Mg, Al, Si, and Ca but not sufficient to resolve the isotopes from interfering compound ions. Nevertheless, due to the different ionization process, many compound ions responsible for hydride or oxide mass interferences (e.g. $^{24}Mg^{1}H^{+}$, $^{28}Si^{16}O^{+}$) do not occur in relevant numbers, allowing the measurement of diagnostic isotopic ratios, when the detection sensitivity of the element in question is sufficient. Limiting factors would be the concentration of the respective element in a given dust grain, and the impact velocity/energy, governing the ionization yield. The required impact velocities for different species are listed in Table 2.

Besides oxygen and carbon (which are detected as O- and C-), further elements of interest would be Mg, Al, Si, and perhaps Ca, all forming positive ions, and present in the vast majority of O-rich circumstellar grains (silicates and refractory oxides). Mg and Si in circumstellar grains can also display isotopic anomalies, although not as pronounced as O and C. However, the Mg-, Si-, and Ca-isotopic compositions of ISD are unknown, making such measurements even more valuable. Another electronegative element of interest would be

Sulphur, which is present in C-rich pre-solar grains (Hoppe, Fujiya & Zinner 2012). Sulphides have been identified around evolved stars (Hony, Waters & Tielens 2002). No pre-solar/circumstellar sulphides have been unambiguously identified so far, except for one signature in an impact crater on Stardust Al foils (Heck, Hoppe & Huth 2012). None of the *Cassini in situ* measurements of 36 ISD particles (Altobelli et al. 2016) show evidence for sulphides, despite evidence that S is depleted from the gas phase in the ISM where an abundance of ∼100 ppm has been inferred for primitive Solar System materials (Keller & Rahman 2011). Thus, we would expect a certain amount of circumstellar sulphides in the ISD population, if sulphides are able to escape destruction in the ISM – an important question that could be addressed by *in situ* dust measurements. The mass of S coincides with that of $O_2$ and sulphur measurements, therefore, require a higher mass resolution than 200.

### *1.4.2 Galactic chemical evolution*

Elemental – and especially isotopic – ratios of contemporary circumstellar and ISD would greatly complement and enhance our knowledge on galactic chemical evolution (GCE), i.e. the enrichment of the ISM and stars with heavier elements and heavier isotopic compositions over time. For certain elements, like Si and Mg, GCE-related correlations have been observed in pre-solar dust grains (e.g. Zinner et al. 2006; Hoppe et al. 2021), and general predictions have been made for these and other elements from model calculations (e.g. Timmes, Woosley & Weaver 1995; Kobayashi, Karakas & Lugaro 2020). However, models and measured grain data do not always show good correlations, thus, information on isotopic ratios like $^{25}Mg/^{24}Mg$, $^{26}Mg/^{24}Mg$, $^{29}Si/^{28}Si$, and $^{44}Ca/^{40}Ca$ would establish another baseline and allow the study of potential heterogeneities of these isotopic systems in the local ISM, which is typically not covered by the models. Similarly, $^{13}C/^{12}C$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{33}S/^{32}S$, and $^{34}S/^{32}S$ would yield important information, if electronegative elements can be measured by the respective instruments and if the ratios can be determined with sufficient precision.

### *1.4.3 Interplanetary dust composition and diversity*

Interplanetary dust particles (IDPs) collected in the stratosphere and subsequently analysed at laboratories on Earth sample a mix of particles from dust-producing bodies. Dust from Jupiter Family Comets is likely dominating (Nesvorný et al. 2010) while dust from the asteroid belt (Rietmeijer 1996) and even the Kuiper belt have also been observed (Keller & Flynn 2022). However, stratospheric IDPs are not an unbiased sample of the dust population as their survival during atmospheric entry depends on entry speed and angle (Love & Brownlee 1991). Measurements of the elemental compositions of IDPs in space would not suffer from this bias and therefore give an average composition of the zodiacal cloud. Further, compositional mapping over different orbital distances could potentially detect differences between Jupiter Family Comets and Kuiper Belt Objects. The major element composition (e.g. Mg/Si, Ca/Si, Fe/Si) of IDP particles is variable and it is unclear if the heterogeneity occurs within or between parent bodies since the origin of individual IDPs collected in the stratosphere is unknown (Bradley 2014). Compositional mapping of IDPs in the solar system and targeted analyses of individual dust-producing bodies would answer that question. ISP may cross cometary dust streams on its path towards interstellar space. Modelling of these streams (Soja et al. 2014) and suitable instrumentation to determine dust compositions and to constrain the dust dynamical properties may provide a statistically relevant data set for a number of comets and for the sporadic dust background, with increasing distance to the Sun. In particular supporting missions in the solar system may – with the current and near-future generation of instrumentation – be able to analyse IDPs from different well-known sources (e.g. Krüger et al. 2020; Sterken, in preparation).

The Poppe (2016) model predicts that Jupiter-family comet grains dominate the interplanetary dust grain mass flux inside approximately 10 AU, Oort-Cloud cometary grains may dominate between 10 and 25 AU, and Edgeworth-Kuiper Belt grains are dominant outside 25 AU. Mapping the composition of dust over those regions with an ISP, and if possible measuring oxygen isotopes (and other isotopic data) would be very valuable for gaining knowledge on the history of the solar system.

## **1.5 Inner and outer source of pickup ions**

Pickup ions (PUIs) were originally assumed to be formerly neutral (mainly H and He) particles of interstellar origin that were ionized in the heliosphere and picked up by the solar wind, where they accelerate to higher energies, presenting a cut-off at roughly twice the solar wind bulk speed. These interstellar PUIs enter the heliosphere in the same manner as ISD does (see Section 1.1 and Kallenbach et al. 2000 and references therein). For a review of *in-situ* detections of PUIs, see Zirnstein et al. (2022).

Measurements from the solar wind ion composition spectrometer (SWICS) on *Ulysses* (Geiss et al. 1995) discovered other species of PUIs (in particular C+, and O+, N+, etc.) from an 'inner source' near the Sun that had previously been hypothesized by Banks (1971). Two competing mechanisms of generation of these inner source PUIs were proposed: (1) solar wind particles are first embedded in and later released from dust grains close to the Sun (Gloeckler et al. 2000), and (2) energetic neutral atoms (ENAs) are created in the heliosheath and propagate close to the Sun, where they are ionized and picked up by the solar wind (Gruntman & Izmodenov 2004). Schwadron & Gloeckler (2007) showed that the second mechanism is dominant for inner source PUIs. Szalay et al. (2021) confirmed from measurements by Parker solar probe that submicron-sized dust grains do not have sufficient cross-sections to produce all inner source PUIs; however, because nanograins can become trapped close to the Sun, they may account for inner source PUIs via mechanism (1).

Neither interstellar nor inner source PUIs can explain the presence of easily ionized atoms among the measured composition of anomalous cosmic rays in the outer solar system (Cummings, Stone & Steenberg 2002; Schwadron & Gloeckler 2007). Therefore, an additional 'outer source' of PUIs was proposed: sputtered atoms from dust grains originating in the Edgewort–Kuiper belt are ionized and picked up by the solar wind (Schwadron et al. 2002).

The dynamics of nanodust is expected to be similar to that of PUIs but the contribution of nanodust (heavy charged particles that may be multiply charged) to the physics and boundaries of our solar bubble has not currently been quantified. To date, we only have limited knowledge about the PUI distribution in interplanetary space from the New Horizons mission, from older missions/instruments like Ulysses/SWICS, and (in the heliosheath) from indirect measurements of PUIs by *Cassini* and IBEX that measure remotely sensed ENAs from 10 and 1 AU, respectively. Measurements from the Solar Wind Around Pluto (SWAP) by the (McComas et al. 2008) instrument on the New Horizons mission showed that the interstellar PUIs are heated in the frame of the solar wind, before reaching the termination shock (McComas et al. 2021). Notably, once the *Voyager* missions crossed the termination shock (Decker et al. 2005, 2008; Stone et al. 2005, 2008) they identified that the majority of the shocked solar wind energy density went into heating the PUIs, whereas >15 per cent was transferred to energetic ions, showing an unexpected charged particle spectrum inside the heliosheath (e.g. Dialynas et al. 2019, 2020). Only ∼20 per cent of the shocked solar wind energy density went into heating the downstream thermal plasma (Richardson et al. 2008). Consequently, PUIs are expected to play a substantial role in the pressure balance between the heliosheath and the VLISM, but the *Voyager* missions could not measure PUIs. The analysis of a unique combination of all available *in situ* ion and remotely sensed ENA measurements (Dialynas et al. 2020) over ∼10 eV to ∼344 MeV energies, showed that the heliosheath is a high plasma-$\beta$ region ($\beta$ is here the particle over the magnetic field pressure), where PUIs (primarily) and suprathermal particles (secondarily) dominate the pressure (see also review article by Dialynas et al. 2022). Understanding both the nanodust and PUI populations through direct *in situ* measurements from a future ISP mission will be instrumental for understanding the heliosphere's interactions with the VLISM.

## 2 AN INTERDISCIPLINARY SCIENCE CASE AND ITS IMPORTANCE FOR A WIDER FIELD

Here we summarize the most pressing science questions covering the fields of heliospheric (H) and dust science (D), and questions related to the heliosphere–dust interaction (HD). Addressing in depth this broad spectrum of questions is also important for the astrospheric community and for understanding our local interstellar neighbourhood. In the following, we divided the questions according to the dust size, so that they can be linked more easily to the type of measurements and instrumentation that are needed. Apart from ISD, interplanetary (nano)dust may also play a role in these questions.

### 2.1 Micron-sized ISD

What is the gas-to-dust mass ratio in the ISM, and hence, what is the biggest size of ISD residing in the ISM?$^{(D)}$ Do large grains detected at Earth as (interstellar) meteors exist in the ISM?$^{(D)}$ Is any of the dust coming from a direction other than the heliosphere nose and what does it imply for our current interstellar environment near the interface between LIC and G-cloud?$^{(D)}$ What is the composition and morphology of micron-sized ISD (porous, aggregate, compact?) and what implications are there for the formation of the dust and processes in the VLISM?$^{(HD)}$ What are the characteristics of Oort cloud dust, and what will the Kuiper belt dust reveal about its sources?$^{(D)}$.

### 2.2 Submicron-sized ISD

How do ISD dynamics depend on the heliosphere, and specifically how does the heliosheath filter out these particles?$^{(HD)}$ What is the time-variable size and structure of the heliosphere (using dust measurements as additional boundary conditions for the heliosphere models)?$^{(H)}$ From which distance to the Sun can we measure carbonaceous ISD, and why has there been little evidence in detections so far?

### 2.3 Nanodust ISD

How much nanodust is filtered (time-dependent or permanently) at the heliopause and heliosheath?$^{(HD)}$ What role does the nanodust inside and outside of the heliopause/heliosheath play in heliospheric physics?$^{(HD)}$ Does nanodust pile-up near the heliopause?$^{(HD)}$ Where does 'outgoing' (interplanetary) nanodust from the solar system and the ISD reside in the heliosphere; i.e. will they flow to the heliosphere flanks?$^{(HD)}$ Can it affect the heliosphere size and structure throughout the solar cycle?$^{(HD)}$ What are carbon nanodust species made of and will we measure PAH clusters outside of the heliopause?$^{(D)}$.

### 2.4 All dust sizes

How much charging does ISD acquire in different regions of the heliosphere, in particular in the heliosheath, and how does this charging depend on dust size, composition, and local environment properties?$^{(HD)}$ Does dust – and what sizes of the dust – play a role in the pressure balance of the heliosphere?$^{(HD)}$ How does dust affect the production of PUIs, and how does it depend on the solar cycle? Do ISD or IDPs contribute to mass-loading of the solar wind?$^{(HD)}$ What are the different dust populations in the ISM, and what are their compositions, particle morphologies, and bulk densities?$^{(D)}$ How do they compare with astronomical measurements and cosmic abundances?$^{(D)}$ How much do they affect the plasma / heliosphere physics, and at which spatial scales?$^{(HD)}$ What species of carbonaceous ISD exist and for which dust sizes and abundances?$^{(D)}$ How much of the ISD is likely recondensed or pristine stardust?$^{(D)}$ How accurately does our current knowledge of elemental and isotopic composition, mostly derived from measurements of the solar nebula and GCRs, reflect that of the galaxy/universe?$^{(D)}$ What is the role of the dust for astrospheres?$^{(HD)}$ What is the role of the dust in the history and habitability of the heliosphere?$^{(HD)}$.

### 2.5 Importance

Probing the heliosphere–dust interaction using modelling and *in situ* measurements is essential for understanding our own immediate interplanetary and interstellar environment. It is also a test-bed to understand how other astrospheres work, as well as to unravel the history of our own solar system and its interaction with various environments during its journey through the Galaxy. Tracers of this journey can now be found in deep-sea sediments (e.g. from supernovae (Miller et al. 2022) or perhaps from passing through denser clouds; Opher & Loeb 2022). Dust from the VLISM is of particular astrophysical interest in light of recent near-Earth supernovae from which debris is still falling on Earth today (Koll et al. 2019) and must arrive in the form of dust (Miller et al. 2022). Studying this dust is also important for galaxy evolution and physics of the ISM (see Section 1.4).

## 3 ASSESSMENT OF INFRASTRUCTURE, RESEARCH STRATEGY TO ANSWER THESE SCIENCE QUESTIONS, AND TECHNOLOGICAL DEVELOPMENT NEEDS

### 3.1 Dust measurements on an interstellar probe

First and foremost, a mission into interstellar space like the ISP (Brandt et al. 2022; McNutt et al. 2022) with a dedicated dust detection suite on board would be optimal for compelling ISD and heliosphere research. Such an ISP would – for the first time – be able to measure the smallest ISD particles beyond the heliopause that are blocked from entering the solar system. With such measurements, ISP would be entering unexplored scientific territory. Also, these dust particles of a few to tens of nanometres are orders of magnitude more numerous than the particles *Ulysses* could measure (see Fig. 1). In addition, ISP could detect whether there is really a pile-up of particles near the heliopause. For the first time, we would be able to measure how and until what size the particles follow the flow of the VLISM, which sizes can cross the heliopause (heliopause permeability), and how far some particles can travel through the heliosheath. Such measurements in combination with measurements of the local magnetic field, plasma properties, PUIs, and the surface charge for dust particles larger than a few hundred nanometres, will help tremendously in understanding the heliosphere–dust interaction and the potential role of dust in heliosphere physics. Also, ISPs move fast (ca. 7–8 AU per year outwards) into the stream of ISD (coming at 5.5 AU per year inwards). The high speed results in higher fluxes (cf. detection rates) and enhanced detector sensitivity for the dust impacts, making the detection of tiny particles easier as well as allowing particles to be fully ionized for all compositional elements. Last but not least, ISP will fly throughout approximately 16 yr, more than a solar cycle, while passing through interplanetary space, the termination shock, the heliosheath, up to the heliopause and beyond, making it an optimal mission for studying the heliosphere–dust coupling and using this knowledge for other astrospheres. Beyond the heliopause, the tiny dust with gyroradii of only a few to 100 AU (for dust radii $< 0.1$ µm, see also Table 3), will help study the interstellar environment (magnetic field, plasma) and may detect local enhancements of smaller as well as bigger ISD. The strength of the mission lies in flying through all of these diverse regions with simultaneous magnetic field, dust, plasma, and pickup ion measurements. No mission so far has flown a dedicated dust dynamics and composition suite into the heliosheath and the vast space beyond.

### 3.2 Continuous observations and observations from different vantage points in space

The optimal way to disentangle the spatially and temporally variable dust dynamics in the heliosphere is by ensuring long-term monitoring of the dust flux ($>$22 yr) and by combining measurements from different vantage points in space. Hence, the science yield of an ISP mission would be greatly enhanced by simultaneous measurements inside the solar system by another mission, with a dust suite tailored to measuring dust dynamics (and composition) over an extended period of time. One example of such an observing capability in the ecliptic plane is a long-term dust suite on the Lunar Gateway (Wozniakiewicz et al. 2021; Sterken, in preparation), with the continuation of complementary dust measurements by IMAP (McComas et al. 2018). Examples of such missions out of the ecliptic could be the DOLPHIN(+) mission concept that was proposed to ESA 2022 (Sterken, in preparation), the SunCHASER mission concept that includes a dust detection suite in its baseline (Posner et al. 2021), or a mission with a *Ulysses*-type orbit that is out of the ecliptic and perpendicular to the ISD stream. Missions with inclined orbits can in addition investigate the IDP–heliosphere interactions, and the solar-cycle dependent vertical structure of the zodiacal dust cloud. Such a dust suite could contain a large area mass spectrometer (Srama et al. 2007; Sternovsky et al. 2007) (or a combination with an impact ionization detector), equipped with one or several charge grids / a trajectory sensor, eventually augmented by a large-area polyvinylidene fluoride (PVDF) detector. An in depth overview and discussion of possible ISP instrumentation is given in Section 4, while an overview table of the main goals of the above mentioned supporting missions is given in Table A1.

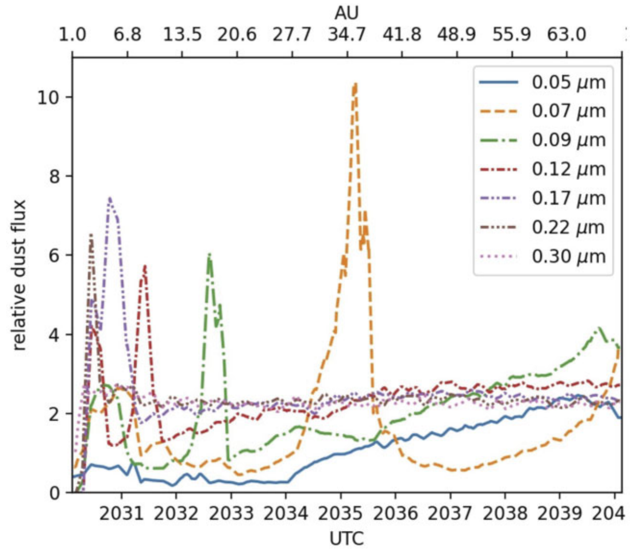


**Figure 5.** An example of how computer simulations of relative dust fluxes can teach us about the filtering at the heliosheath, when compared to spacecraft data for the respective dust sizes, from Hunziker et al. (in preparation).

### 3.3 Synergies between heliosphere and dust measurements, inclusion of 'serendipity instruments', and modelling

Simultaneous measurements with complementary instruments, i.e. for plasma and magnetic field properties and pickup ion detections, together with dust fluxes, velocities, directions and – if possible – dust surface charge will yield particularly strong synergies between dust and heliospheric science. The inclusion of 'serendipity dust instruments' that collect information on dust impacts, but were not originally designed for this work, will enlarge the pool of data to be used from different vantage points in space. Plasma wave instruments on various satellites, which pick up a sharp signal when a dust particle impacts the spacecraft, are very good examples of this. The Wind mission yielded a yearly recurring ISD signature in the more than 25 yr of plasma wave dust data, including a solar cycle variability (Malaspina et al. 2014; Malaspina & Wilson 2016; Hervig et al. 2022). Also *Voyager* has detected a few impacts (Gurnett et al. 1983). A challenge is that the operations and observations were not tailored to dust impacts; hence, retrieving the dust flux and direction is a challenging task. Also, information such as impact velocity, particle mass, or particle charge is missing. Therefore, it is difficult in the solar system to distinguish between IDPs and ISD impacts with these types of instruments.

A long-term dust monitoring mission, with sufficiently large detector surfaces, dust trajectory, surface charge, and velocity sensing capabilities (and composition) would be a tremendous leap forward and a significant increment to this pool of data. In any case, Wind has fuel for another 50 yr (Darling 2019), IMAP (with dust compositional analyser, without grid) could keep monitoring the compositions and fluxes of incoming ISD on a statistical basis, and the Gateway may be a good platform for long-term monitoring during the flight time of an ISP. When such a data set (multiple places and long-term) is combined with state-of-the-art computer modelling of the heliosphere-dust flow, then the particle properties (e.g. size distribution in the LIC) and the dynamical structure of the heliosphere can be retrieved by fitting a model of the heliosphere, including time-variable heliosheath, to the pool of data. Fig. 5 illustrates that even a simple model with only dust filtering in the solar system can already yield valuable information about filtering at the heliosheath if sufficient data are available. The model used is the IMEX model (Strub et al. 2019) and the predictions shown are for an ISP. The ISD waves 'rolling' in can be seen as sharp increases in relative flux at different times for different particle sizes. An additional filtering at the heliosphere boundaries would alter this pattern. These fluxes are predicted along an ISP trajectory with launch date in 2030, during the focusing phase of the solar cycle. Dust observations along the path of ISP at high impact velocities may be able to shed light on heliospheric filtering, through monitoring whether such patterns are present inside of the heliosphere, in addition to the direct measurements in the heliosheath. Similar investigations can be undertaken in the solar system.

### 3.4 Ground-based facilities

An on-going calibration effort of different dust detectors with a dust accelerator is crucial for success. Since ISP moves very fast, calibrations with a dust accelerator are needed with high velocities and for dust particle analogues with different properties (e.g. lower bulk density dust analogues are important for measurements of μm-sized ISD; Hunziker et al. 2022). New dust analogues need to be further developed, measurements with plasma wave instruments need to be further understood (e.g. Shen et al. 2021), and high-level computing facilities are needed for the modelling. The dust accelerator at LASP, Univ. Colorado Boulder and at IRS, Univ. Stuttgart, are indispensable tools for any space mission with a dust detector on board. Developments are underway at the University of Stuttgart for a linear staged accelerator (faster velocities), and at ETH Zürich and FU Berlin for the next generation of dust analogues. High-precision and high-power (>100 kW pulse) ground-based radars are needed for interstellar meteor research (Hajdukova et al. 2020).

The technological risk for these types of missions, instruments, and ground-based facilities is relatively low, since most have been developed already or are based on heritage.

## 4 AVAILABLE INSTRUMENTATION AND HOW THEY ADDRESS THE SCIENCE OBJECTIVES AND QUESTIONS

This paper does not propose a mission or an in-depth Science Traceability Matrix, but we discuss instrumentation that is available today or in the near future, its strengths and weaknesses with respect to different types of measurements, and how it can contribute to the science questions and science goals for an ISP and support missions. We focus mostly on science questions related to ISD- (or IDP-) heliosphere interactions. Questions focusing on other fundamental physics aspects of the heliosphere, in part as a result of the *Voyager* 1, *Voyager* 2, *Cassini*, *IBEX*, and *New Horizons* missions, are reviewed in Dialynas et al. (2023) and particularly in Brandt et al. (2022, 2023) and McNutt et al. (2022).

The science questions in Section 2 can be summarized in the following science objectives (SO) (see also Table 1):

1) Nature of our local insterstellar medium environment
2) Origins and processes of dust in the local ISM
3) Origins and processes of dust in or nearby the heliosphere
4) Heliosphere structure, physics and dynamics.

### 4.1 PVDF detectors

PVDF detectors employ a permanently polarized polymer film that generates a charge pulse upon particle impact. The penetration of the film causes a depolarization of the material, ensuing a measurable relocation of charge (see e.g. Simpson & Tuzzolino 1985). The shape and amplitude of this signal depend on the mass and impact speed of the dust particle. PVDF sensors are foil-type detectors, named after the material used as the polymer (polyvinylidene flouride).

PVDF detectors have the advantage of being low-cost, low-resource, and fairly simple. They can be used to cover large areas (e.g. 0.54 $m^2$ onboard IKAROS; Hirai et al. 2014) and may even be integrated with a spacecraft's thermal insulation (e.g. onboard EQUULEUS; Funase et al. 2020). A student-project PVDF detector currently flies on the *New Horizons* mission, providing measurements from beyond 55 AU (Horányi et al. 2008; Bernardoni et al. 2022). PVDF detectors are particularly useful for the micron-sized part of the dust size distribution. However, they lack the possibility to distinguish impact mass and impact speed, and contain no information about impactor directionality except for the pointing of the instrument with a field of view of 180°. Due to their piezo- and pyroelectric properties, PVDF sensors can generate noise events induced by mechanical vibrations or thermal variations (Simpson & Tuzzolino 1985; James, Hoxie & Horanyi 2010). These can be mitigated to some degree by correlation of events with spacecraft operational activities or by use of shielded reference sensors to adjust the trigger threshold (Piquette et al. 2019).

PVDF can contribute to the science questions (Section 2) related to large ISD particles and (towards) interstellar (micro)meteoroids (Hajduková, Sterken & Wiegert 2019; Gregg & Wiegert 2023), provided that the spacecraft is outside of the solar system. For a spacecraft in orbit around the Sun, e.g. at Earth distance, the yearly modulation of the dust fluxes – due to the fact that ISD from the LIC comes mostly from one direction – provides some information about the ISD flux as well (e.g. Malaspina et al. 2014; Hervig et al. 2022). The inability to discriminate between ISD and IDP with PVDF makes it less useful for studies of ISD inside the solar system. Because PVDF is suitable for micron-sized ISD detections, owing large surface areas, it can contribute to a certain extent to the science questions concerning the gas-to-dust mass ratio in the ISM, finding 'big' dust grain populations, and to support astronomical observations of ISD in the micron-sized regime and above.

### 4.2 Impact ionization detector

When a dust particle impacts the target of an impact ionization detector (IID) at hypervelocity speeds, particle as well as target material are vapourized and partially or fully ionized (depending on speed). The charge of the generated ions and electrons is measured, and the impact speed and mass of the dust particle are estimated through calibrated signal rise times (e.g. Grün et al. 1992) and charge signal amplitudes (see e.g. Friichtenicht & Slattery 1963; Grün et al. 1992), respectively.

IIDs achieve a high degree of reliability and sensitivity, with the ability to detect impactors of only tens of nanometres in size (or below for fast speeds, see also Section 4.11). Considerable surface areas in the order of 0.1 $m^2$ can be accomplished (e.g. onboard *Ulysses*) despite relatively simple and lightweight designs. However, they only obtain limited information about the dynamics of the impactors. The directional constraint comes solely from the aperture design (consider e.g. the FOV half angle of the Cosmic Dust Analyzer (CDA[2]) onboard Cassini of ∼45°; Srama et al. 2004a). Impact velocity estimates based on the charge signal shape involve large uncertainties in the order of a factor of 1.6–2 (Göller & Grün 1989),

[2]Note that CDA was a combined TOF-MS and IID with two charge-sensing grids.

**Table 1.** Summary of science objectives and types of science questions considered in this publication with strong dust-heliosphere synergies.

| Dust size regime | Science objectives | Main type of questions |
|---|---|---|
| μm-sized dust from the ISM | SO1, SO2 | ISM exploration, sources, processes, populations |
| Electromagnetically dominated (sub-micron) sizes | SO3, SO4 | Heliosphere–dust dynamics, dust as a tracer, heliosphere–dust interactions and processes, ISM dust dynamics |
| Nanodust sizes / macromolecules | SO4 | Influence of dust on heliosphere plasma, dust as a tracer in the heliosphere and the ISM, PAH in the ISM |

**Table 2.** Minimum impact velocities for measuring the composition of the tabulated species with impact ionization time-of-flight mass spectrometry (in positive ion mode). The Mg-peak can also appear even at lower speeds around 3 km s$^{-1}$ but is then very small. The Si-peak can also appear at 7 to 10 km s$^{-1}$, albeit also very small. The peaks of S and $O_2$ are difficult to distinguish.

| Species | $V_{\mathrm{min}}$ (km s$^{-1}$) |
|---|---|
| H | 8–10 |
| C | 10–12 |
| O | 14–16 |
| Na | 2–5 |
| K | 2–5 |
| Mg | 5–10 |
| Al | 5–10 |
| Si | 10–15 |
| Ca | 5–10 |
| Fe | 10–15 |
| Rh | 8 |
| S or $O_2$ | 15–20 |

which may be even higher for fluffy particles (Hunziker et al. 2022). Since the mass of the impactor is derived from the relation $Q \sim \mathrm{m}\,\mathrm{v}^{\alpha}$ (with $Q$ the measured charge after impact, $m$ the impactor mass, and $v$ the impact velocity), the particle mass uncertainties typically are in the order of a factor of 10 (Göller & Grün 1989). This is why reliable velocity information is of crucial importance for impact ionization instruments, in order to distinguish interstellar from interplanetary dust in the solar system, and for estimating the mass–frequency distribution of the ISD in the ISM. Large statistics may nevertheless yield useful information about the dynamics of the dust (e.g. Sterken et al. 2015; Strub et al. 2015). Adding a (segmented) charge-sensing grid or trajectory sensor, however, greatly enhances the science return (see Section 4.6).

Due to their sensitivity, IIDs have been instrumental in the exploration of the smallest meteoroids, such as $\beta$-meteoroids (Wehry, Krüger & Grün 2004), nanodust (Section 4.11), and submicron ISD, particularly with regard to their abundance, but also their dynamics (Landgraf et al. 2003; Sterken et al. 2015; Strub et al. 2015). Since these detectors can detect dust from the few-nanometres to micrometre size range, they also are powerful for a larger number of science questions related to the ISD size distribution inside and outside of the heliosphere, the modulation of the ISD dynamics by the heliosphere, the gas-to-dust mass ratio, etc. comparable to the work done with the *Ulysses* mission dust data, if there is a sufficiently large surface area. The fact that the instrument is sensitive to dust impacts of a few nanometres at relative speeds typical for ISP (ca. 55 km s$^{-1}$; Hunziker et al., in preparation) makes it useful for nanodust studies as well (see also Section 4.11). Therefore, such instruments can contribute to questions of the dust distributions in and around the heliosphere, including a possible pile-up of ISD outside the heliopause, and consequences for the physics of the heliospheric boundary regions. These dust measurements throughout the solar system may be used as an extra boundary condition for the heliospheric model, but inside of the heliosphere, it is challenging to discriminate ISD from IDP.

Adding a segmented grid (see Sections 4.4 and 4.6) for better velocity determination would greatly augment the science return both from the point of view of distinguishing populations as well as for having more precise estimates of the particle masses. Since the instrument is more sensitive than PVDF, it would also augment our current knowledge on dust in the Kuiper belt region (in particular if combined with a grid), after the first crude dust measurements in the region were taken by the *Voyager* mission using plasma wave antennas (Jaynes, personal communication), and by the *New Horizons* mission using a PVDF detector (Bernardoni et al. 2022). Although this type of fairly simple and well established instruments can contribute to many science questions concerning populations, dynamics, and in particular dust–heliosphere interaction and physics, it still lacks compositional information for many of the origins, processes, and populations related science questions. Compositional information can also help discriminate ISD from IDP. A combination with a time-of-flight mass spectrometer (Section 4.3) and/or (segmented) grid can be flown (e.g. *Cassini* CDA).

### 4.3 Time-of-flight mass spectrometer (TOF-MS)

Dust particles impacting at hypervelocity speeds on a time-of-flight (ToF) mass spectrometer ionize by the impact ionization process. The plasma's ions are then accelerated by an electric field (e.g. 1000 V for Cassini CDA) that separates them according to their charge-to-mass ratios. The recording of their traveltimes from the impact target to an ion detector then yields the abundance of species with different charge-to-mass ratio within the impact plasma, from which the information about the impactor composition can be derived.

The key benefits of the TOF-MS are: (1) its ability to analyse the grain composition, and (2) that the recording of a mass spectrum functions as unequivocal proof of a true particle impact (as opposed to a noise event). Higher mass resolutions can be obtained with more sophisticated mass analyser concepts ('ion-optics') than for the linear TOF-MS:

1. linear; $m/dm \approx 30$; e.g. CDA, (Srama et al. 2004a)
2. reflectron; $m/dm \approx 100-300$; e.g. DDA, SUDA (Kempf 2018; Krüger et al. 2019)
3. orbitrap; $m/dm > 10\,000$; e.g. onboard SLAVIA (Zymak et al. 2023) yet to be tested in space

One limitation of the TOF-MS is that only either the plasma's cations or the anions can be fed into the mass analyser, depending on the polarity of the ion optics. So far only cation mass analysers have been used in space missions, as cations are readily formed by most elements and molecules (Srama et al. 2009). Certain organic molecules, however, form anions rather than cations during impact ionization (Hillier et al. 2014, 2018), suggesting the use of (switchable) dual polarity ion optics in future instruments (as first

**Table 3.** Approximate size, mass, charge, surface potential, and gyroradius, adapted from Grün & Svestka (1996), assuming spherical particles, a magnetic field strength of 1 nT in the interplanetary medium, 0.1 nT in the heliosheath, and 0.5 nT in the LISM, and a relative particle speed of 400 km s$^{-1}$ in the interplanetary medium, 100 km s$^{-1}$ in the heliosheath, and 5 km s$^{-1}$ in the undisturbed LISM. Gyroradii are upper limits for particle motions perpendicular to the magnetic field. Surface potentials for 0.1 μm do not take into account the small particle effect and may be larger in reality; for micron-sized particles a compactness of 33 per cent was assumed, which increases the surface potential by a factor of about 4 (Ma et al. 2013). The instrument threshold is indicated in yellow.

| Radius (μm) | Density (g cm$^{-3}$) | Mass (kg) | Surface potential (V) | Charge (fC) | Gyroradius (kAU) |
|---|---|---|---|---|---|
| | | Interplanetary conditions | | | |
| 0.1 | 2.5 | $1 \times 10^{-17}$ | +5 | 0.06 | 0.5 |
| 0.2 | 2.5 | $8 \times 10^{-17}$ | +5 | 0.1 | 2 |
| 0.5 | 2.5 | $1 \times 10^{-15}$ | +5 | 0.3 | 9 |
| 1 | 0.8 | $3 \times 10^{-15}$ | +20 | 2 | 4 |
| 5 | 0.8 | $4 \times 10^{-13}$ | +20 | 11 | 97 |
| | | Heliosheath conditions | | | |
| 0.1 | 2.5 | $1 \times 10^{-17}$ | +8 | 0.09 | 0.7 |
| 0.2 | 2.5 | $8 \times 10^{-17}$ | +8 | 0.2 | 3 |
| 0.5 | 2.5 | $1 \times 10^{-15}$ | +8 | 0.4 | 17 |
| 1 | 0.8 | $3 \times 10^{-15}$ | +32 | 4 | 5 |
| 5 | 0.8 | $4 \times 10^{-13}$ | +32 | 18 | 150 |
| | | Local interstellar conditions | | | |
| 0.1 | 2.5 | $1 \times 10^{-17}$ | +0.5 | 0.006 | 0.1 |
| 0.2 | 2.5 | $8 \times 10^{-17}$ | +0.5 | 0.01 | 0.5 |
| 0.5 | 2.5 | $1 \times 10^{-15}$ | +0.5 | 0.03 | 2 |
| 1 | 0.8 | $3 \times 10^{-15}$ | +2 | 0.2 | 1 |
| 5 | 0.8 | $4 \times 10^{-13}$ | +2 | 1 | 27 |

employed in the upcoming SUDA instrument; Napoleoni et al. 2023). Two arguments especially support an anion analysis of impact plasma of a dust particle: (1) oxygen can be measured with a much higher sensitivity (up to factor $10^5$) which would allow the determination of isotopic ratios. This is important for the sensitive detection of water ice, hydroxides, silicates, and oxides. However, its yield for cations is strongly impact speed dependent. (2) A negative anion mode would also allow a sensitive study of Halogens, Carbon, and minerals like S, P, $SO_4$, and $PO_4$. This complements the sensitive detection of metals in the cation mode. In summary, using the combination of cation and anion modes in TOF-MS impacts with speeds above 30 km s$^{-1}$ allows the sensitive detection of all elemental ions between 1 and 200 amu.

Isotopes help us to identify elemental species, but are not trivial to measure. Measurements of isotopes at mass M require both a mass resolution higher than M and a high dynamic range in order to quantify small peaks in the vicinity of larger peaks. When the dynamic range reaches 1000 or better, the identification of isotopically anomalous ISD grains of circumstellar origin is achievable, provided extensive calibration data is available. The current and former generations of impact ionization TOF-MS were not optimized for simultaneous high-dynamic range and high mass resolution. Future instruments will employ improved electronics in order to extend the dynamic range.

Impact velocities also play a major role in TOF impact ionization spectrum analysis. At lower velocities, not all of the impactor constituents may become ionized. Table 2 shows the minimum impact velocities that are needed for the detection of the ion species (for the positive ion mode). Considering the flow speed of ISD of about 25 km s$^{-1}$, such velocities are met in most conceivable cases. In particular for ISP, moving into the nose direction of the heliosphere, all particles are expected to be fully ionized at relative speeds of ca. 55 km s$^{-1}$. However, for spacecraft in the solar system moving in the down-wind direction (along their heliocentric orbit or on a down-wind escape trajectory), the relative velocities of ISD may be insufficient for complete ionization of certain species.

Compositional information is crucial for many of the science questions related to the origins and processes of ISD in the VLISM, dust origins, and processes in the solar system (e.g. Kuiper belt, various comets), charging mechanisms, generation of PUI, etc. (see also Section 1.4), but it can also help us to discriminate between different dust populations. Also, for such instruments statistics are vital for the science results and hence, the need for large surface area. Large area mass spectrometers have been developed with surface areas of 0.1 m$^2$ (Srama et al. 2007; Sternovsky et al. 2007). Speed information can be constrained within boundaries from the shapes of the peaks, and from the occurrence of the peaks or from molecular clusters. Particle masses can be constrained from the impact charge together with simulations of the ion optics and calibration data. However, a (segmented) grid or trajectory sensor would be of great added value.

#### *4.3.1 Plasma wave antennas*

When a dust particle impacts the body of a spacecraft at hypervelocity speeds, it vapourizes both itself and a fraction of the spacecraft surface. The recollected electrons and the induced charges of the escaping electrons and ions measured by the plasma wave antennas produce a distinct amplitude signal. Whether the impact speed and mass of the dust particle can be reconstructed from that signal is currently a topic of investigation (see e.g. Shen, Sternovsky & Malaspina 2023, and references therein).

The advantage of the plasma wave antennas is the large surface area (basically, the spacecraft body), and the science-at-no-extra-cost if a plasma wave antenna is on board. However, it comes with the caveat that only limited directionality information can be derived (e.g. Malaspina et al. 2014; Pusack et al. 2021). Also, the signal is a function of mass, impact velocity, distance to the antenna (depending on configuration), and spacecraft surface material. As a consequence,

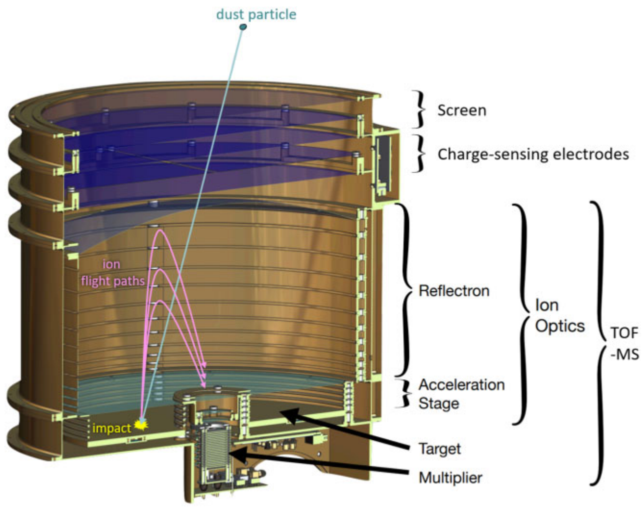


**Figure 6.** Schematic of the DDA instrument. Image credit: IRS/Univ. Stuttgart.

it is not yet possible to uniquely determine the mass, velocity, and/or distance to the antenna of the impact. A plasma wave antenna can detect many dust impacts per time period compared to other dust instruments. This information can be heavily compressed into a low-bandwidth data product via on-board dust detection algorithms.

Outside of the heliosphere, the plasma wave antennas can be especially useful because large counting statistics (due to the large surface area of the spacecraft body) may yield important information on the distribution and populations of ISD in the ISM. Large counting statistics are especially useful for detecting larger, more sporadic dust grains. However, just like PVDF detectors, only limited information on mass and velocity can be derived. Inside of the heliosphere, at e.g. Earth orbit, the plasma wave antennas can infer information about the ISD variability with time through the modulation of the flux throughout the year and throughout the solar cycle (Malaspina et al. 2014; Hervig et al. 2022). Plasma wave and PVDF results could be compared with each other.

### 4.4 Charge-sensing grid

Charge-sensing grids are grid electrodes that sense charged dust particles passing through, via the charge they induce in the electrode (e.g. see upper elements in Fig. 6). In addition to measuring the particle charge, dynamical information such as entrance angles and speed may be estimated from the signal shape of the induced charge.

Different configurations of charge-sensing entrance grids have been proposed. The CDA used a serial electrode design with two canted grids that could yield speeds as well as incident angles (Auer et al. 2002). However, the large capacity of the two grids restricted this design to relatively large grains with charges > 1 fC. A design employing segmented, lower capacity grids has been proposed by Li et al. (2014, 2015, 2017). Such a segmented design is awaiting in-flight demonstration on-board of the Destiny+ mission[3] (Arai et al. 2018) as part of the Destiny+Dust Analyzer (DDA) (Simolka et al. 2022) with an anticipated detection threshold of 0.2 fC. This corresponds to a dust particle with radius of 0.35 μm (in the solar system). Segmented charge sensing grids are a good compromise between increased science output and instrument complexity. Since they are non-destructive, they are especially suited to be combined with destructive detector stages, so that even a single-plane charge-sensing grid can be used for time-of-flight impactor speed measurements (as done in DDA). The DDA system can determine the speed with a ca. 15 per cent and the mass with approximately a 20 per cent accuracy.

Charge-sensing grids are well suited to study the abundance and dynamics of bigger (>1 μm diameter) particles in the solar system. These particles are on the larger end of the dust particle size range that is still affected by electromagnetic forces in the solar system. Measuring or constraining their speed would increase the accuracy of the mass determination ($Q \sim m \cdot v^{\alpha}$), and constraining the speed and velocity vector to a certain extent would allow for a better discrimination between the sources of the dust particles (in particular ISD versus IDP) in the solar system. Measuring their surface charge (with the grid), their mass (through an IID or TOF-MS) and plasma parameters (plasma instrument) may even yield constraints on their bulk densities. In the heliosheath, the dust is expected to reach higher equilibrium potentials of ca. +6 to +12V (Kimura & Mann 1998) or +8 V (Slavin et al. 2012), as opposed to ca. +5V for the solar system (see Table 3). These are equivalent to dust particle radii of ca. 0.3, 0.15, and 0.2 μm, respectively, which is well within the range of electromagnetically affected dust that reacts dynamically to the solar cycle through the time-variable heliospheric magnetic fields. In interstellar space, the dust particles are expected to have lower charges, corresponding to ca. +0.5V (Grün & Svestka 1996) equilibrium surface potential (equivalent dust radii ca. 3.5 μm). However, it can be expected that micron-sized ISD may be porous (Westphal et al. 2014; Sterken et al. 2015). Assuming a compactness factor of ca. 1/3rd, they can be ca. three to four times more charged (Ma et al. 2013), i.e. they would be detectable by the grid from a radius of ca. 2 μm (detection threshold 0.2 fC). Adding a charge grid to the design of an IID or TOF-MS (Section 4.6) may thus yield important information on the dynamics of the mid-sized (sub-micron) particles in the heliosphere and, in particular, in the heliosheath, as well as help constrain the direction of motion of very large grains or micrometeoroids that may exist in the ISM, in addition to possibly constraining their bulk material densities. Science questions inside the heliosphere (in particular the heliosheath) related to the dynamics and mass distribution of submicron ISD would be easier to tackle if an IID or TOF-MS instrument includes a (segmented) grid, with limited add-on complexity. Such instruments provide higher constraints on dust directionality, velocity (hence, ISD-IDP discrimination), better mass constraints (using the velocity constraints) and useful information on the dust surface charge.

### 4.5 Trajectory sensor

The concept of the trajectory sensor involves two planes of position-sensitive charge sensors, from which the flight path of a particle may be accurately reconstructed. These position-sensitive charge sensors can be realized through a set of crisscrossed wire electrodes (Auer 1975; Auer et al. 2008) or through a finely segmented grid (Li et al. 2014).

The key advantage of a trajectory sensor is its accuracy. For instance, uncertainties of <1° are reached the design of Auer et al. (2008). The difficulty of this design lies in its complexity, as one charge-sensitive amplifier (CSA) is required for each wire or grid segment (e.g. 64 CSAs in the design of Auer et al. 2008). So far, such designs (see e.g. Fig. 7) have only been demonstrated in the laboratory (Xie et al. 2011).

[3]Demonstration and Experiment of Space Technology for INterplanetary voYage Phaethon fLyby and dUst Science, to be launched in 2024.

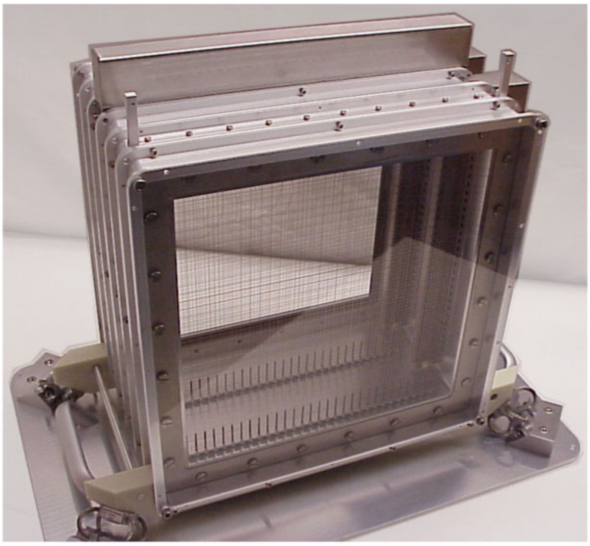

**Figure 7.** Photo of a trajectory sensor. Image credit: MPI-K/Univ. Stuttgart.

One of the major motivations for using trajectory sensors, apart from dust surface charge measurements, would be the dynamic differentiation between dust types (e.g. between interstellar and interplanetary dust, or cometary dust streams). Their use together with IID or TOF-MS detectors (see Section 4.6) would yield an improved mass determination through an accurate velocity determination (see also the discussion above for the grids).

### 4.6 The dust telescope

The combination of a non-destructive trajectory sensor with an impact plasma mass spectrometer allows for the simultaneous analysis of dust particles' physical, chemical, and dynamical properties. This type of instrument as been nicknamed 'dust telescope' (Srama et al. 2004b; Grün et al. 2005). A simplified version of a dust telescope could consist of instruments such as CDA and DDA with their less accurate, charge grid-type dynamics-sensing detector stages. A laboratory model of a true dust telescope (i.e. with high-accuracy trajectory sensor) has been implemented by Horányi et al. (2019).

### 4.7 Plasma instrument

The purpose of a plasma instrument (Plasma Subsystem-PLS; see also Table 5) is to measure the low energy (eV to keV) particle distributions throughout the heliosphere with the sensitivity to detect the very cold plasma populations in the VLISM and the dynamic range to measure the solar wind. The physics of the boundaries of our solar bubble, namely the termination shock (TS), the heliopause (HP), and the heliosheath, including the VLISM (e.g. Dialynas et al. 2022; Kleimann et al. 2022) requires the determination of the composition of ions (and electrons) that are 'frozen in' to the magnetic field along with an accurate determination of their energy distributions and moments (temperatures, densities, velocities, and pressure). Dust in the Solar System is embedded in the solar wind plasma and the relative abundance of dust populations throughout the heliosphere affects the interplay of outflowing solar wind plasma and inflowing interstellar material. Also, measuring plasma parameters along with the dust allows calculating and studying the dust charging process, and constraining the dust bulk densities (morphology) via its surface charges and mass measurements. Direct measurements of the distribution functions of both the interstellar cloud and dust cloud PUIs up to energies of a few keV $e^{-1}$ would be possible with a plasma detector with a geometry factor of $\sim 10^{-3}$ $cm^2$ ·sr and a signal-to-noise ratio of >10 (McNutt et al. 2021).

### 4.8 Pickup ion instrument

As explained in Section 1.5 and throughout this manuscript, PUIs play a substantial role in the dynamics of our solar bubble, are very important indicators of the plasma processes throughout the heliosphere, i.e. from interplanetary space out to the heliopause (e.g. Dialynas et al. 2022; Zirnstein et al. 2022), and may be related to dust populations (Schwadron et al. 2002). Despite the SWAP (McComas et al. 2008) and PEPPSI (McNutt et al. 2008) instruments on *New Horizons* being operational for many years, this spacecraft is not expected to make measurements at distances far beyond the termination shock. Also, its instruments were not designed to measure multiple and heavier species of PUIs (only limited to hydrogen and helium) and there is limited directional information. Furthermore, the limited scientific payload of *New Horizons* (e.g. it does not carry a magnetometer) indicates that those PUI measurements it obtains cannot be set in context with simultaneous fields or wave measurements. To understand the important physics of our heliosphere through the PUIs and their possible link to dust, a future ISP mission should include a detector with a fairly large geometrical factor ($>10^{-3}$$cm^2$ sr), a high dynamic range ($10^{-1}$ to $10^4$ ($cm^2$ sr s keV)$^{-1}$), and a combination of high time and energy resolution (of $\Delta E/E \leq 10$ per cent) that would resolve light and heavy ions and their charge states within the energy range of ∼0.5–78 keV $e^{-1}$ (see McNutt et al. 2021).

### 4.9 Magnetic field instrument

The *Voyager* mission survey through the heliosphere showed that taking accurate magnetic field measurements from interplanetary space all the way to the VLISM is of paramount importance for addressing timeless questions concerning the shape of the global heliosphere, its nature, dynamics, and interactions with the VLISM. The relatively low resolution of the MAG experiments on the *Voyagers* demonstrated the necessity of obtaining magnetic field observations from a future ISP mission in the nT range with pT resolution (see McNutt et al. 2021, and Table 5) to address questions concerning the role of plasma turbulence and magnetic reconnection throughout the heliosphere. A high dynamic range (ca. ∼0.01–100 nT) would provide invaluable aid in determining the interaction of small dust grains with particles and fields throughout the heliosphere (e.g. CMEs) and, in particular, in the heliosheath.

### 4.10 Neutral mass spectrometer

The primary science goal of the Neutral Mass Spectrometer (NMS) is to measure the chemical composition of neutral gas along the spacecraft trajectory, employing two measurement techniques: an antechamber and a collection foil. The latter provides a higher sensitivity than the antechamber, but less frequent measurements. The technology readiness level and the longevity of NMS are backed up by e.g. the Neutral Ion Mass Spectrometer NIM (Föhn et al. 2021) on the *Jupiter Icy Moons Explorer* (launched in 2023, nominal end of mission 2035). NMS may detect dust grains that happen to enter the antechamber or hit the collection foil. However, the collection area is rather small (on the order of $cm^2$) compared to dedicated dust

**Table 4.** Technical data of state-of-the-art dust instrumentation. The mass and velocity range of TOF-MS, grid, and trajectory sensors can shift towards larger values depending on gain settings and some instrument adaptations.

| Dust parameter | Instrument | | | | | |
|---|---|---|---|---|---|---|
| | PVDF | IID | TOF-MS | Grid | Traj.-Sens. | Plasma wave |
| Mass, kg (at $10\,\mathrm{km\,s^{-1}}$) | $>10^{-14}$ | $>10^{-17}$ | $10^{-18}$ to $10^{-15}$ | $>5\times10^{-15}$ | $>10^{-15}$ | $>10^{-14}$ |
| Mass, kg (at $50\,\mathrm{km\,s^{-1}}$) | $>10^{-14}$ | $>10^{-21}$ | $10^{-22}$ to $10^{-17}$ | $>5\times10^{-14}$ | $>10^{-15}$ | $>10^{-19}$ |
| Speed, $\mathrm{km\,s^{-1}}$ | 1–100 | 2–100 | 2–100 | 2–50 | 2–50 | 4–100 |
| FOV, sr | $2\pi$ | $1\pi$ | $0.2\pi$ | $1.5\pi$ | $0.5\pi$ | $4\pi$ |
| Sens. area, $\mathrm{m^2}$ | Variable 0.005 – 0.1 | Variable 0.05 – 0.1 | variable 0.05 – 0.03 | Variable 0.005 – 0.1 | Variable 0.01 – 0.1 | (0.25–1) |
| Observables | $E_{\mathrm{kin}}$ | $v,\ m$ | $v,\ m$, comp. | $v,\ m,\ q$ | $v,\ m,\ q$, direc. | $E_{\mathrm{kin}}$ |
| Advantages | Low mass, low power, robust | Reliable, sensitive, nano-grain detection, high dynamic range | Composition, high reliablility, nano-grain detection | Get $v$, $m$ and $q$ with small errors | Get $\vec{v},\ m,\ q$ with small errors | 2in1 instrument, large FOV |
| Disadvantages | Calibration, not suited for inner solar system | Errors in $v,\ m$ | Complex instrument, HV needed, limited sens. area, FOV limited, errors in $v,\ m$ | Sensitive to plasma, SNR for submicron grains | Sensitive to plasma, many signal channels, power | Calibration, no composition, no directionality |
| Mass, kg | 1–2.5 | 2–8 | 4–12 | 2–5 | 2–8 | 37 (RPWS) |
| Power, W | 1–2.5 | 3–7 | 5–15 | 3–6 | 5–10 | 16 (RPWS) |
| Data vol., MB/d | <1 | <1 | 1–100 | 1–2 | 1–100 | 2–1000 |
| TRL | 9 | 9 | 9 | 9 | 4–9 | 9 |
| Cost, M€ | 5 | 5 | 10 | 5 | 6 | (12) |

**Table 5.** NMS, PLS, MAG and PUI specifications according to McNutt et al. (2021).

| | NMS | PLS | MAG | PUI |
|---|---|---|---|---|
| Measurement range | 1–1000 amu (molecules) | <3 eV $\mathrm{e^{-1}}$ to 20 keV $\mathrm{e^{-1}}$ ($\Delta E/E \leq 10$ per cent) | 0.01–100 nT (three components) | ~0.5–78 keV $\mathrm{e^{-1}}$ |
| Power consumption | 11 W | 10 W | 5.7 W, including two survival heaters | 7 W |
| Mass | 10 kg | 8 kg | 0.6 kg for two fluxgates, 4.2 kg for 10-m boom | 5.5 kg |
| Volume | $40\times15\times15\ \mathrm{cm^{-3}}$ | – | – | – |

detectors, which implies low detection rates. The volatile component of any dust particle entering the antechamber can be measured by the NMS. When nanograins impact the collection foil, both their volatile and refractory species can be analysed. Additional on-ground calibration at impact speeds representative for the ISP will be needed (McNutt et al. 2021). Although NMS can be very valuable for the compositional analysis of nanodust and macromolecules in the VLISM, it does not provide impact rates, sizes, or dynamical information about the nanodust that would be useful for further exploring the dust–heliosphere physics and the smallest populations of condensed matter in the VLISM.

Tables 4 and 5 show an overview of the instrumentation discussed, with typical values for measurement ranges, power consumption, instrument mass, and volume.

### 4.11 Discussion on nanodust measurements

A fundamental question for *in-situ* instrumentation is what the lower detection limit in particle size is. Fortunately, the detection method of impact ionization is extremely sensitive to small particles as long as the impact speed exceeds a certain limit. Above impact speeds of approximately $30\,\mathrm{km\,s^{-1}}$, the particle becomes fully ionized, providing enough ions to be detected with sensitive ion detectors.

The measurement of nanodust with sensitive non-TOF detectors (*Galileo*, *Ulysses*; Grün 1993) and with TOF-MS instruments (*Cassini*, GIOTTO) is well known and published. Utterback & Kissel (1990) identified particles of only $5\times10^{-22}$ kg during the flyby of comet Halley in 1986 with the mass spectrometer PIA/PUMA. The relative flyby speed was $78\,\mathrm{km\,s^{-1}}$ and the smallest signals contained only 75 ions from the generated impact plasma.

The instruments onboard *Galileo* and *Ulysses* detected the Jovian dust streams. Models have shown that these particles reach $400\,\mathrm{km\,s^{-1}}$ with typical particle sizes between 10 and 20 nm (Zook et al. 1996). These detectors used large target areas of up to $0.1\,\mathrm{m^2}$, although their large targets and related large electrode capacitances led to a low sensitivity. Later, *Cassini* characterized the Jovian and Saturnian dust stream particles, measuring the composition of fast and tiny grains: Saturnian stream particles typically have speeds between 100 and $200\,\mathrm{km\,s^{-1}}$ and are usually smaller than Jovian stream particles (Horányi 2000; Kempf et al. 2005; Hsu et al. 2011). Another good example of measuring the composition of individual grains smaller than 50 nm at moderate impact speeds of approximately 30 km s$^{-1}$ is the *Cassini* CDA proximal orbit campaign with its inner ring plane crossings in 2017 (Hsu et al. 2018). This demonstrated a high sensitivity for simple TOF-MS instruments using impact ionization.

Not only dust spectrometers were able to detect nano-sized grains, Carpenter et al. (2007) demonstrated the measurement of nanometer-sized dust impacts with an instrument combining a thin foil and a multichannel plate (MCP) in Earth orbit onboard the ISS.

In order to determine the lower mass threshold in dependence of the impact speed, one can use calibration equations by Grün (1984) of $Q = 6.3 \times 10^{-4} \cdot m \cdot v^{5.6}$, or Burchell et al. (1999) with $Q = 0.096 \cdot m \cdot v^{4.01}$. Using the Burchell equation gives a total impact plasma charge of $Q = 6.2 \times 10^{-16}$ C for a 50 km s$^{-1}$ and $10^{-21}$ kg particle (4.6 nm radius, silicate). However, at such high speeds, it is a good approximation to assume full ionization of the projectile material. Furthermore, the plasma is dominated by ions from the target material (with or without surface contaminations). If the goal is not the detection of a particle but a careful compositional analysis or mass determination of the nano-meteoroid, one should consider only the dust particle material, and the typical equations giving *Q*/*m* for a given size and speed are not applicable. An estimate of the number of dust particle atoms gives, therefore, a more precise quantity of the relevant impact charge.

We consider the sensitivity for an IID with ion optics that focuses all generated ions towards an ion detector that could be either an MCP or a multiplier. The target is normally a polished metal surface (gold, rhodium, iridium, palladium) onboard dust telescopes like SUDA (*Europa Clipper*) or DDA (DESTINY$^{+}$). The loss factor from the target to the ion detector is assumed to be 50 per cent. An MCP and multiplier is sensitive enough to measure even single ions. But such high detector gains are not practical in space due to the high sensitivity to radiation. Therefore, the ion detector should operate with a reduced gain (determined empirically). We consider 100 ions within one peak of a mass spectrum as a good number. We also assume five elements within the particle with equal ionization yield, and each element contributes at least 100 ions to a mass line in the spectrum. This means that we can detect as a lower mass threshold particles providing 500 ions at the ion detector, which corresponds to a particle with at least 1000 atoms. This marks a useful lower particle size and mass detection limit. For a bonding length of approximately 2 Å, such a particle would be not larger than 2 or 3 nm in diameter. However, if a particle contains less than five species, the detection of even smaller particles is not excluded.

On the other hand, an IID using a multiplier for ion detection can be adjusted to measure larger grains by reducing the detector gain by a factor of 100 or even 1000 by lowering the operating high voltage. This ensures a wide dynamic range to measure mass spectra of nanodust as well as of micron-sized particles with the same instrument electronics. Changes in instrument gain every hour, day, or just a month can be foreseen for this reason. This procedure was tested in-flight with *Cassini* CDA.

## 5 CONCLUSIONS

Many compelling science questions exist concerning the interaction of ISD (and IDP) with the heliosphere. We highlight the synergies between the two sciences, and what tremendous progress we could make if a dedicated dust suite would fly on an ISP to measure dust properties together with the plasma, magnetic field, and PUIs, during its journey through all regions inside and outside of the heliosphere. The science yield would be increased even more by simultaneous measurements from other missions inside the solar system while ISP is on its journey. The science results may be crucial for understanding the physics and pressure balance of the heliosphere, and the pool of new dust measurements can be used as an extra boundary condition for heliosphere models to help reveal the time-dependent structure and size of the heliosphere. We describe the major advantages for the dust measurements on ISP, including being outside of the heliopause where highly abundant nano-ISD resides, and flying at very high speeds against the flow of ISD – good for detecting dust. From a programmatic point of view, a mission like ISP with a dust detector is crucial, but there is also a need for an optimized long-term monitoring of ISD dynamics parameters (and composition) with broad temporal and spatial coverage in the solar system. The currently existing dust and dust–heliosphere-related instruments each have their advantages and disadvantages for certain types of measurements to help answer the science questions currently posed. With these instruments, we can push forward the boundaries of our knowledge as described here. The topic of dust-heliosphere science is gaining a lot of traction in the community, and collaborations between the continents are important. The 'new space' launcher industry is expected to allow for instruments with larger detection surfaces in optimized orbits. Finally, solving the science questions presented here will not only benefit dust science and heliosphere science; it will also foster broader synergistic cross-divisional science between heliophysics, astronomy, planetary science, and astrobiology, addressing for instance the role of astrospheres in habitability of planetary systems. Such cross-divisional science not only 'crosses' the borders of divisions, but also augments science in each of them, thus meeting the exact definition of a true 'synergy'.

## ACKNOWLEDGEMENTS

VJS, LRB, and SH received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 851544 - ASTRODUST. This work has been carried out within the framework of the NCCR PlanetS supported by the Swiss National Science Foundation under grants 51NF40_182901 and 51NF40_205606. Konstantin Herbst acknowledges support from the German Research Foundation priority program SPP 1992 'Exploring the Diversity of Extrasolar Planets' through the project HE 8392/1-1. The authors would like to thank the anonymous referees for their helpful comments to improve the manuscript.

## DATA AVAILABILITY

Data in this paper can be made available upon request.

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## SUPPORTING INFORMATION

Supplementary data are available at RASTAI online.

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## APPENDIX A: SUPPORTING MISSIONS AND MISSION CONCEPTS

**Table A1.** Summary of the missions and mission concepts considered in this publication with strong dust–heliosphere synergies.

| Mission / Concept | Version | Period of flight | Orbit | Primary science goals |
|---|---|---|---|---|
| IMAP | McComas et al. (2018) | 2025– | Sun-Earth $L_1$ | Composition and properties of the LISM (incl. dust); dynamics/evolution of the heliosheath; interaction of solar wind magnetic field and interstellar magnetic field; particle injection and acceleration processes |
| ISP | Brandt et al. (2022); ISP (2023) | 2036–2086+ | Escape trajectory | Global nature of the heliosphere: dynamics & evolution, evolutionary history; properties of the ism: gas, dust, magnetic field, low-energy cosmic rays; exploration of the large-scale circumsolar dust debris disk; flyby observations of Kuiper Belt objets and planetesimals; unobscured mapping of the cosmic infrared background |
| DOLPHIN (2022) | Sterken (in preparation) | 2031–2035+ | incl. 23° at 1 AU | ISD: composition, abundances, size distribution and its modulation by the heliosphere, dust-heliosphere interaction and physics (incl. PUI), role of dust/PUI in heliosphere-LISM pressure balance; structure and time-variable properties of the zodiacal dust cloud; composition of cometary dust |
| SunCHASER | Posner et al. (2021) | tbd | incl. 14° at Sun-Earth $L_4$, potentially also at $L_5$ and $L_1$ | Solar energetic particle forecasting; improve model of inner heliosphere solar wind and magnetic field; long-term forecasting of solar activity; dust populations in near-Sun environment |
| Lunar Gateway | Sterken (in preparation), Wozniakiewicz et al. (2021) | tbd | lunar halo orbit | presence/absence of human-made debris in lunar orbit; composition and fluxes of asteroidal and cometary dust, separately; ISD: composition, species abundances, size distribution, morphology, directionality; organic component of dust grains; shape, dynamics and physics of heliosphere |

[1]*Institute for Particle Physics and Astrophysics, Physics Department, ETH Zürich, Wolfgang-Pauli Strasse 27, Zürich 8093, Switzerland*
[2]*Center of Space Research and Technology, Academy of Athens, 4, Soranou Efesiou str., 11527 Papagos, Athens, Greece*
[3]*Institute of Earth Sciences, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 234-236, D-69120 Heidelberg, Germany*
[4]*Institute Space Systems (IRS), University Stuttgart, Pfaffenwaldring 29, D-69168 Stuttgart, Germany*
[5]*Department of Physics and Astronomy, University of Missouri, Columbia, MO 65211, USA*
[6]*Institute of Experimental and Applied Physics (IEAP), Faculty of Mathematics and Natural Sciences, Christian-Albrechts-University of Kiel, Leibnizstrasse 11-19, D-24118 Kiel, Germany*
[7]*Physics Institute, University of Bern, CH-3012 Bern, Switzerland*
[8]*Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD 20723, USA*
[9]*Institute of Geochemistry and Petrology, Department of Earth Sciences, ETH Zürich, Clausiusstrasse 25, CH-8092 Zürich, Switzerland*
[10]*Department of Physics and Astronomy, University of Canterbury, Christchurch, 8020, New Zealand*
[11]*Institut de Recherche en Astrophysique et Planétologie (IRAP), 9 Av. du Colonel Roche, F-31400 Toulouse, France*
[12]*Space Research Centre, Polish Academy of Sciences, Warsaw 00-716, Poland*
[13]*Institute for Theoretical Physics IV, Chair for Space and Astrophysics, Ruhr-Universität Bochum, D-44780 Bochum, Germany*
[14]*Bay Area Environmental Research Institute, NASA Research Park, Moffett Field, CA 94035, USA*
[15]*Center for Theoretical Astrophysics, Departments of Astronomy and Physics, University of Illinois, Urbana, IL 61801, USA*
[16]*University of Chicago, Astronomy and Astrophysics Center, 5640 S Ellis Ave, Chicago, IL 60637, USA*
[17]*Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303, USA*
[18]*Institute of Geological Sciences, Freie Universität Berlin, D-12249 Berlin, Germany*
[19]*Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, D-37077 Göttingen, Germany*
[20]*Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, IA 52242, USA*
[21]*JILA, University of Colorado, Boulder, CO 80305-0440, USA*
[22]*Astrophysical and Planetary Sciences Department, University of Colorado Boulder, CO 80305, USA*
[23]*Astronomy Department, Boston University, Cambridge, Massachusetts, MA 02215, USA*
[24]*Space Sciences Laboratory, University of California at Berkeley, Berkeley, CA 94720, USA*
[25]*Astronomy Department, Van Vleck Observatory 101, Wesleyan University, 96 Foss Hill Drive, Middletown, CT 06459, USA*
[26]*MIT Kavli Inst. for Astroph. and Sp. Res., 77 Massachusetts Avenue, McNair Building (MIT Building 37), Cambridge, MA 02139, USA*
[27]*Astrophysics Group, Imperial College London, Prince Consort Rd, London SW7 2BZ, UK*
[28]*Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*
[29]*Center for Astrophysics, High Energy Astrophysics Division, Harvard and Smithsonian, 60 Garden Street, MS 04, Cambridge, MA 02138-1516, USA*
[30]*Institute of Applied Physics, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland*
[31]*Oeschger Center for Climate Change Research, University of Bern, Hochschulstrasse 4, 3012 Bern, Switzerland*

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