The Interactions of Interstellar Dust with our Heliosphere

A White Paper submitted to the 2024-2033 Decadal Survey for Solar and Space Physics

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Synopsis. Interstellar dust (ISD) continuously flows through our solar system as we orbit within the Milky Way galaxy, carrying information about the upstream local interstellar material (ISM). As ISD grains encounter the heliosphere, they experience gravitational, solar radiation pressure, and electromagnetic forces, perturbing their trajectories in a time-, charge-, and size-dependent fashion, leading to complex variability in the ISD flux throughout the heliosphere. Despite having been detected within our heliosphere via in-situ observations almost three decades ago, we still do not fully understand the nature of ISD, including its 'pristine' nature upstream of the heliosphere's influence or the details of its interaction with solar radiation and heliospheric electromagnetic fields. A deeper understanding of ISD grains and their interaction with the heliosphere offers an opportunity for insight into the conditions and forces driving the evolution of our global heliosphere and is thus deserving of sustained research in the next decade. In this white paper, we present compelling open scientific questions regarding interstellar dust and argue for multi-point measurements of ISD composition, flux, and variability throughout the heliosphere in the next decade.

Introduction and Open Science Questions. As our Sun orbits around the Milky Way Galaxy, it encounters a wide variety of interstellar environments that interact with and ultimately dictate the size and shape of the heliosphere. In addition to interstellar magnetic fields, plasma, and neutral gas populations, **interstellar dust** has long been recognized as a critical component in heliospheric physics. Identified in both remote-sensing [e.g., *Draine*, 2003; *Hensley and Draine*, 2021] and in-situ datasets [e.g., *Grün et al.*, 1993, 1994; *Frisch et al.,* 1999; *Altobelli et al*., 2004, 2005, 2016; *Krüger and Grün*, 2009; *Westphal et al*., 2014; *Krüger et al.,* 2015; *Strub et al.,* 2015], and also inferred via elemental depletions in the local interstellar cloud [e.g., *Slavin and Frisch*, 2008], interstellar dust provides key information about (i) the relative motion of our heliosphere through the local ISM, (ii) the physical nature of the ISM, including dust-grain size distributions and composition(s), and (iii) the physical coupling between the ISM and the outer boundaries of our heliosphere. Ultimately, an understanding of the heliosphere–and the role that our heliosphere plays in providing a habitable environment–requires a deep understanding of interstellar dust.

Despite decades of observations, many aspects of interstellar dust remain unexplored and/or poorly understood. Strong tension exists between the views of interstellar dust as determined from remote sensing versus those determined from in-situ detection, in particular with respect to large (radius > 1 μm) [e.g., *Weingartner and Draine, 2001*; *Landgraf et al., 2000*], a difference perhaps due to the very low-density "intercloud" interstellar environment of the heliosphere [*Frisch et al.,* 2011]. This suggests either that our local ISM material is distinct from the mean interstellar material found across the galaxy or that dynamic and/or chemical interactions at the outer heliospheric boundaries alter the otherwise "pristine" ISM material before it reaches in the inner heliosphere [e.g., *Kimura et al.,* 2020]. Additionally, we do not fully understand the kinematic and electrodynamic interactions of interstellar dust with the heliosphere and how such interactions both filter (and therefore bias) the flux of interstellar dust grains within the heliosphere [e.g., *Linde and Gombosi,* 2000; *Slavin et al.,* 2012]. Furthermore, much remains to be learned about how ISD grains exchange mass, charge, momentum, and energy with the outflowing solar wind and the outer heliospheric boundaries (e.g., the termination shock, heliosheath, and heliopause). Finally, a broader understanding of interstellar dust in our local ISM allows for comparative analysis and understanding of more extreme interstellar/astropheric interactions which may represent previous and/or future epochs for our own heliosphere as we pass through varying ISM conditions [e.g., *Zank and Frisch*, 1999; *Müller et al.*, 2006, 2008].

We call out three broad scientific questions regarding interstellar dust critical to heliophysics that should be answered in the next decade:

- **What are the physical characteristics of local interstellar dust, including their composition, morphology, size distribution, mass flux, and charge distribution?**
- **What are the dynamics of interstellar dust as a function of mass and charge as they interact with the heliosphere?**
- **What effects do interstellar dust grains have on the structure, dynamics, and composition of the heliosphere?**

Answers to these questions will further our understanding of and insight into both our heliosphere's place in the local galactic environment and the processes by which our heliosphere exchanges mass, charge, momentum, and energy with its surroundings.

Physical Characteristics of Interstellar Dust. A complete understanding of interstellar dust begins with a characterization of the physical properties of ISD, including their composition(s), physical structure, charge distribution, and size distribution. Knowledge of these various properties can be tied to our understanding of the local ISM and its interaction with our heliosphere.

ISD Composition. The composition of ISD grains reflects the nature of surrounding interstellar material and provides information on for the formative building blocks of our solar system and other exozodiacal systems. ISD grains also act as an important reservoir for interstellar material, exchanging atoms and/or molecules between the gas and solid phases [e.g., *O'Donnell and Mathis,* 1997; *Kimura et al.,* 2003]. The chemical makeup of interstellar gas is complemented by the condensable matter locked in solid macroscopic particles, the surfaces of ISD particles enable heterogenous catalytic chemistry, ISD emits and absorbs radiation, acts as sources and sinks of electrons and ions, and couples magnetic fields and radiation pressure to

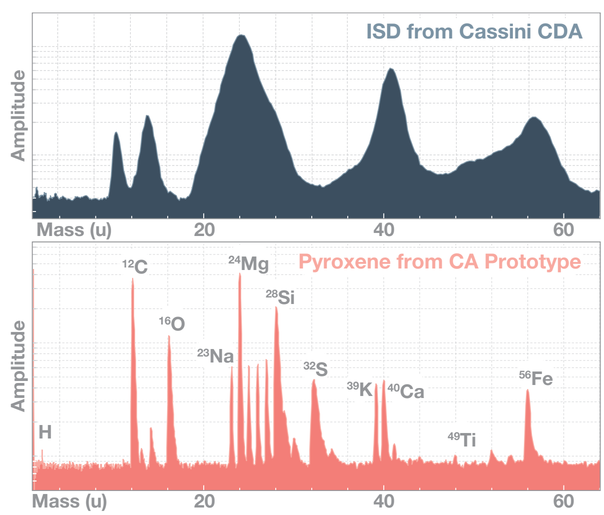

Figure 1: The best in-situ interstellar dust impact ionization mass spectra to date were recorded by the *Cassini* CDA (top; *Altobelli, et al., 2016*). Current dust impact analyzers enable more than 6x better mass resolution (bottom), and can reliably separate Fe, Mg, and Si from other elements present.

the interstellar gas. Despite its fundamental importance, we do not fully understand the composition of ISD grains, either remotely across the galaxy or nearby in the local ISM. The *Stardust* mission returned seven candidate ISD grains for laboratory analysis, revealing a population of grains diverse in elemental composition, crystal structure, and size. By implication, this suggests that individual ISD particles diverge from any one representative model inferred from astronomical observations and/or theory [*Westphal et al.,* 2014]. In comparison, the *Cassini* Cosmic Dust Analyzer obtained 36 ISD detections, all of which were Mg-rich grains of silicate and/or oxide composition with major rock-forming elements (Mg, Si, Fe, Ca) present with only small grain-to-grain variations [see **Figure 1**; *Altobelli et al.,* 2016]. Furthermore, grain composition may evolve both in time due to interactions with the ISM [e.g., interstellar shocks, UV radiation, sputtering, mutual collisions; *Draine and Salpeter, 1979*; *Tielens, 1998*; *Frisch and Slavin*, 2003; *Zhukovska et al.,* 2008; *Slavin et al.,* 2015] or in space as ISD grains pass from the 'pristine' interstellar environment into our heliosphere–thus biasing our in-situ measurements within the heliosphere [e.g., *Kimura, 2015*; *Kimura et al., 2020*]. Future measurements that enable high mass-resolution spectra of ISD grains (e.g., see Figure 1) both within and outside of the heliosphere are critical for both establishing the composition of the local ISM dust grain composition(s) and whether such compositions are altered–perhaps selectively so–as grains transit through the outer regions of the heliosphere.

ISD Size Distributions. The size distribution of ISD in the nanometer to micron range contains information about the origin(s) and subsequent processing of ISD grains in both the interstellar medium and our heliosphere. Both remote-sensing [e.g., *Weingartner and Draine,* 2001; WD2001] and in-situ [e.g., *Landgraf et al.,* 2000; *Krüger et al.,* 2015; *Sterken et al.,* 2015] observations have separately measured the ISD size distribution with distinctly conflicting results, **Figure 2**. The deficit in $m < 10^{-13}$ g grains in the Ulysses and Galileo observations is likely due to electromagnetic filtering of low-mass (or equivalently, high charge-to-mass ratio) grains by either outer heliospheric boundaries or internal heliospheric fields [e.g., *Linde and Gombosi*, 2000; *Slavin* et al., 2012; *Sterken et al.,* 2015]; however, the *excess* of in-situ observed grains for $m > 10^{-13}$ g relative to the WD2001 model is far more puzzling. *Draine* [2003] concluded that the in-situ observed grains cannot be representative of the general interstellar medium based on both the available abundance of material capable of being locked in the dust (as opposed to gas) phase and constraints from interstellar reddening spectra. Alternative scenarios for a local inhomogeneity in the ISD population that could explain the excess large grains, including turbulent ISM

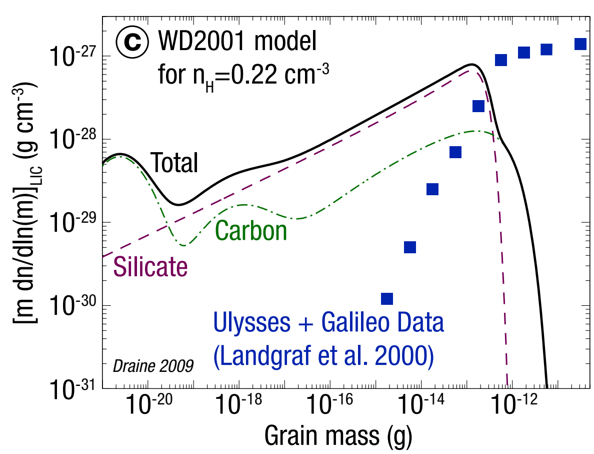

Figure 2: ISD mass distributions as determined from remote-sensing analysis [solid, dashed, and dash-dot curves; *Weingartner and Draine, 2001*] compared to in-situ measurements made by the Ulysses and Galileo spacecraft [squares; *Landgraf et al., 2000*].

mixing, dust injections from supernovae and/or cool AGB stars, or dynamical trapping via electromagnetic drifts all seem implausible to first order.

At larger sizes ($m > 10^{-9}$ g), reports of interstellar meteors detected by ground-based radar observations have raised the intriguing possibility of characterizing the ISD distribution in a manner similar to that used for interplanetary meteors [e.g., *Taylor et al.*, 1996; see also *Mann,* 2010]. The earliest reports of interstellar meteor observations suggested that interstellar meteors originated from distinct locations within the sky; however, such findings have been criticized and never fully reproduced [*Hajduk*, 2001]. Later observations have detected meteor head echoes potentially consistent with an interstellar origin (i.e., incident velocities greater than solar escape speed) [*Sato et al.*, 2000; *Janches and Chau*, 2005; *Szasz et al.*, 2008]; however, no statically significant grouping(s) of stellar radiants were found. Nevertheless, an analysis of Canadian Meteor Orbit Radar (CMOR) observations has shown that those meteor head echoes with a potential interstellar origin were compatible with an extrapolation of the ISD mass distribution as measured by *Ulysses* and *Galileo* up to $m \sim 10^{-11}$ g [*Weryk and Brown*, 2004].

Thus, future measurements that characterize the ISD size distribution both within the heliosphere (ideally at varying heliocentric distances) and outside the heliosphere are critical for understanding the nature of the local ISM and placing constraints on the mechanisms by which local ISD size distributions are altered via interactions with the heliosphere.

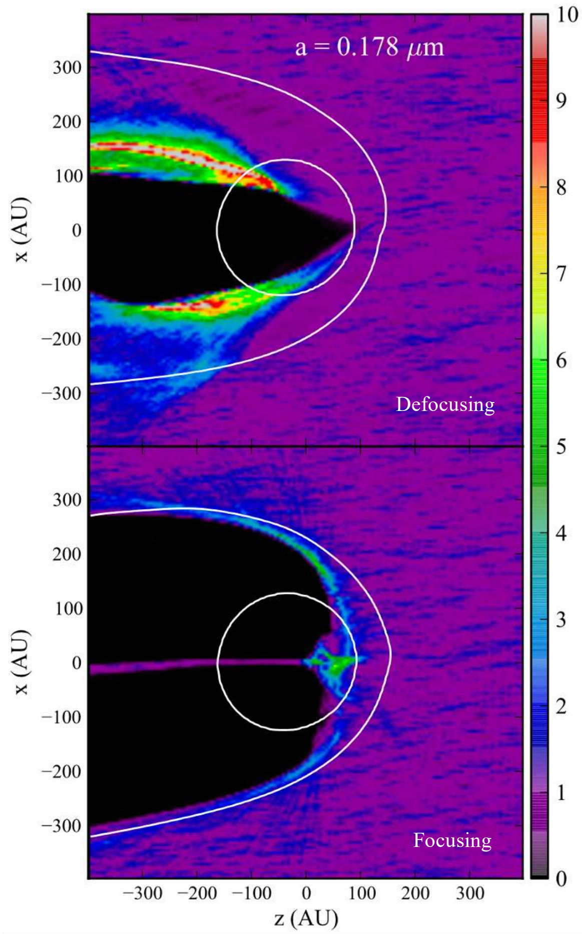

Figure 3: ISD density distributions for 0.178 μm grains interacting with the heliosphere under (top) defocusing and (bottom) focusing conditions [after *Slavin et al.,* 2012]. Solid white lines denote the boundaries of the termination shock and heliopause, respectively.

Interstellar Dust Dynamics in the Heliosphere. As the Sun transits through local interstellar space, interstellar dust grains stream towards the heliosphere at relative speeds of ~26 km/s. As ISD grains impinge upon the heliosphere, they are subject to gravity, radiation pressure, and electromagnetic Lorentz forces, all of which perturb their dynamics in a charge- and size-dependent fashion. At the outermost boundaries of the heliosphere, numerical modeling has shown that Lorentz forces strongly filter ISD grains [*Linde and Gombosi*, 2000; *Slavin et al.*, 2012]. The smallest grains (<~0.02 μm) are completely deflected at the heliopause and therefore entirely unable to penetrate the heliosphere, while progressively larger grains (~0.02 – 0.5 μm) can penetrate the heliosphere to varying degrees dependent on their charge-to-mass ratios and the polarity of the heliospheric magnetic field (HMF). The smallest deflected grains possibly account for the dust filament draped over the heliospheric nose and discovered through their effect on the polarization of background starlight [*Frisch et al.,* 2022]. Focusing periods, where the HMF is oriented such that the interplanetary electric field points into the ecliptic plane (thereby acting as a restoring force), allow ISD to penetrate deep into the heliosphere along the heliospheric current sheet, whereas defocusing periods, in which the HMF polarity is reversed, prevents charged ISD grains from penetrating the heliosphere, see **Figure 3**. Furthermore, even during focusing HMF periods or for grains with low charge-to-mass ratios that can penetrate through the outer heliospheric boundaries, ISD are still subject to the perturbing forces of solar gravity and radiation pressure. Here, previous work has shown numerous perturbative features in the ISD distribution based on their β value (i.e., the ratio of radiation pressure to gravity) [e.g., *Sterken et al.,* 2012, 2013, 2015]. For grains with $\beta>1$, solar radiation pressure will deflect their trajectories thereby preventing access into the inner heliosphere. In contrast, those grains with $\beta<1$ fully penetrate the heliosphere and undergo gravitational focusing with flux enhancements downstream of the Sun. Evidence for these interactions can be found in the analysis of in-situ ISD observations by the *Ulysses* spacecraft, which show solar cycle-era variations in the ISD flux within the inner heliosphere [*Landgraf et al.*, 2003; *Sterken et al.,* 2015; *Strub et al.*, 2015, 2019]. Considerable data have also been accumulated on ISD fluxes at 1 au based on the variation of impact rates with spacecraft position relative to the interstellar flux direction [*Belheouane et al.*, 2012, *Malaspina et al.*, 2016]. Nevertheless, significant uncertainty remains regarding the exact mechanisms and variability present in these interactions. Specifically, open questions regarding the dynamics of ISD include:

- *How does the process of heliospheric filtering operate on ISD in a time-dependent manner, both in terms of the solar-cycle variation and longer-term changes in ISM properties?*
- *Can changes in the ISD flux within the heliosphere inform us about the structure and strength of the outer heliospheric boundaries?*
- *Does the heliosphere act as a "compositional" filter for ISD by preferentially eroding certain grain compositions (e.g., via photodesorption or sublimation) more efficiently than others?*
- *Can we use knowledge of ISD dynamics within the heliosphere to connect ISD size distributions observed in-situ to the "pristine" ISD size distribution upstream of the heliosphere?*

In particular, accurate modeling of ISD grain dynamics requires improved knowledge of the structure of the heliosphere, which continues to rapidly evolve [e.g., *Kleimann et al.,* 2022, and refs. therein]. The upstream structure of the heliosphere–including, for example, the presence of a bow wave (or potentially a shock), the thickness of the heliosheath, and the temperature and density of the heliosheath (which control dust grain charging and sputtering)–are critical inputs to the initial dynamics of local ISD as the interact with the heliosphere and its upstream perturbations to the local ISM [e.g., *Czechowski and Mann,* 2003a,b; *Slavin et al.,* 2012].

Heliospheric Impacts of Interstellar Dust. In addition to the impacts that heliospheric structures and radiation have on interstellar dust, we can ask if the opposite may also be true–namely, do interstellar dust grains demonstrably impact the shape, size, structure, and/or composition of the heliosphere? Remote observations of astrospheres have demonstrated the existence of 'extreme' interactions of astrospheric structures with surrounding interstellar material (e.g., ζ Oph, λ Cep, LL Ori; see **Figure 4**) due to supersonic relative speeds between the stellar outflow and the local ISM. While these types of interactions are likely outliers, they nevertheless illustrate the breadth of stellar-ISM interactions that can exist and naturally lead to questions regarding the variability in our own heliosphere's interaction with changing ISM conditions. While several previous studies have explored the possibility that high-density neutral gas clouds in the ISM may significantly compress the heliosphere [e.g., *Zank and Frisch*, 1999; *Müller et al.*, 2006, 2008], the role of interstellar dust grains in such a process is far less understood. Theoretically speaking, dust within an interstellar cloud could alter the shape and structure of the outer heliospheric boundaries through mass and momentum exchange. Such an influx could also alter the composition of the heliosphere via ISD sputtering, sublimation, or other mass-loss processes. For example, high-density ISD flows through the heliosphere may alter the composition of anomalous cosmic rays via sputtered and/or sublimated material, similar to that hypothesized for the outer source of ACRs originating from the breakdown of Edgeworth-Kuiper Belt objects [*Schwadron et al.,* 2002; *Schwadron and Gloeckler*, 2007].

Figure 4: Astropause bowshock of LL Ori (K3e)'s stellar winds interacting with the thick dust clouds of the Orion nebula, as observed by Hubble (C.R. O'Dell, 1995, HST/WFPC2, 4-visible color [O III], Strömgren y, H-alpha, [N II]/502nm, 547nm).

To improve our understanding of the potential for ISD grains to affect the shape, structure, and physical mechanisms underpinning our heliosphere, it is critical that we measure the present-day interactions of ISD within the heliosphere, across the heliosheath, and out into the pristine local ISM. Key characteristics to measure include the overall abundance and composition of ISD at the heliospheric boundaries, changes in the ISD composition or size distribution as a function of heliocentric distance, and the gas-to-dust ratio both within and outside of the heliosphere. In comparison with variability in the local ISM conditions [e.g., *Frisch et al.,* 2011] and remotely observed astrospheres, we can then place our heliosphere and its interaction with the present-day ISM in proper context.

Recommendations for Future Observations. NASA's IMAP mission [*McComas et al.,* 2018] will make ISD composition measurements near 1 au beginning in 2024 and will significantly add to our current understanding of ISD properties. IMAP will carry the first ISD-dedicated impact ionization time-of-flight dust composition analyzer that will employ state-of-the-art dust detection methods. In turn, these observations will provide a comprehensive dataset that will allow studies of the heliospheric filtering of ISD grains, albeit only at a one heliocentric distance. Additionally, JAXA's DESTINY+ mission is planning to make ISD observations near 1 au [*Krüger et al.*, 2019b] and the Surface Dust Analyzer (SUDA) on NASA's Europa Clipper mission may make serendipitous measurements of ISD during either its cruise to or its science phase at Jupiter, allowing for multi-point ISD measurements that could help better separate spatial and temporal variations in ISD flux. However, understanding the ISD flux and directional variability remains an unfinished and challenging task [*Mann* 2010; *Krüger et al.* 2015, 2019a, 2019b; *Strub et al.* 2015, 2019; *Sterken et al.* 2015, 2019], given that the majority of ISD observations are very near to the Sun, where both heliospheric filtering and dynamical perturbations have already acted on these flows [e.g., *Slavin et al.*, 2012; *Sterken et al.* 2019]. Note that perturbations of pristine ISD trajectories in the outer heliosphere and heliosheath can *only* be derived from in situ measurements.

To propel our understanding of how ISD interacts with and is filtered by the heliosphere in the IMAP and post-IMAP era, scientific investigations aimed at making multi-point ISD measurements at various distances towards the upstream ISD flow direction are critical, specifically to characterize the heliosphere's ISD filtration effect [*Mann*, 2010; *Slavin et al.*, 2012; *Sterken et al.,* 2012, 2013, 2015]. Such measurements taken across a large range of heliocentric distances out to and beyond the heliopause are essential to fully understand and characterize the flux and composition of ISD, and how the heliosphere filters and interacts with this material. In a companion white paper (*Science Opportunities Enabled by In Situ Cosmic Dust Detection Technology for Heliophysics and Beyond*, Hsu et al.), we describe the detailed instrumentation and mission concepts that will enable next-generation studies of ISD. The *Interstellar Probe* (*ISP*) mission [*McNutt et al.,* 2022] is a promising concept that if equipped with a state-of-the-art dust detector, would provide revolutionary insight into the nature and dynamics of ISD. In addition to *ISP*, any heliospheric mission to regions beyond the immediate vicinity of the Earth at 1 au offers compelling opportunities to make in-situ measurements of ISD populations and their interactions with heliospheric structures and fields.

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