***Dust Measurements from Interstellar Probe:
Exploring the Zodiacal Cloud and the Interstellar Dust Environment***

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Cover image: Simulated thermal emission brightness from interplanetary dust grains in the solar system at six wavelengths (5 – 500 μm) [Poppe et al., 2019].

Introduction and Open Science Questions. Sub-millimeter sized dust grains are present throughout the solar system as both interplanetary dust (IDP) and interstellar dust particles (ISD). IDPs within the inner solar system are sourced primarily from the Jupiter-Family Comets (JFC), with smaller contributions from asteroids and Oort Cloud comets [e.g., Kelsall et al., 1998; Nesvorný et al. 2010, 2011; Pokorný et al., 2014]. In the outer solar system, roughly beyond the orbit of Jupiter, models suggest that IDPs are most likely dominated by sources in the Edgeworth-Kuiper Belt with additional minor contributions from Oort Cloud comets and active Centaurs [Liou and Zook, 1999; Han et al., 2011; Szalay et al., 2013; Piquette et al., 2019; Poppe et al., 2019; Poppe, 2016, 2019]. Finally, interstellar dust (ISD) flows through the solar system due to the solar system's relative motion through the local interstellar medium [e.g., Grün et al., 1994; Krüger et al., 2007; Krüger and Grün, 2009]. ISD carry vital information about the galactic kinematics of our solar system, the electromagnetic structure of the outer heliosphere, and the characteristics of our local interstellar and galactic environment. ISD connect the history of our solar system to planetary systems forming around other stars [e.g., Sterken et al., 2013; Westphal et al., 2014; Altobelli et al., 2016].

Knowledge of the interplanetary and interstellar grain distributions is critical for understanding a multitude of processes throughout the solar system. The flux of interplanetary dust grains to planetary systems is responsible for the formation of tenuous rings [e.g., Verbiscer et al., 2009], impact ejecta clouds [e.g., Krüger et al., 1999; Horányi et al., 2015], and tenuous neutral exospheres around airless planetary bodies [e.g., Colaprete et al., 2016; Szalay et al., 2016; Pokorný et al., 2017, 2019]. Interplanetary dust flux contributes to the spatial and compositional evolution of the main ring system of Saturn [e.g., Cuzzi and Estrada, 1998; Estrada et al., 2015], the injection of meteoric material into planetary magnetospheres [e.g., Christon et al., 2015, 2020], and the alteration of neutral and ionospheric chemistry in planetary atmospheres [e.g., Moses et al., 2000; Carrillo-Sánchez et al., 2016; Moses and Poppe, 2017]. Determination of the production rates of interplanetary dust grains can inform us about the physical evolution of their parent bodies, including, for example, the fading times of Jupiter family comets [e.g., Nesvorný et al., 2010] or the current-day collisional state of the Edgeworth-Kuiper Belt [e.g., Stern, 1995, 1996; Singer et al., 2019; Abedin and Kavelaars, 2019]. Finally, our solar system's debris disk provides "ground-truth" comparison to the multitude of observations of exozodiacal debris disks around other stars [e.g., Trilling et al., 2008; Bryden et al., 2006, 2009; Koerner et al., 2010; Millan-Gabet et al., 2011; Montesinos et al., 2013; Eiroa et al., 2013; Chen et al., 2014; Kral et al., 2017; Hughes et al., 2018; Ertel et al., 2018], where hidden planets may warp and/or perturb their debris disks in manners similar to how Neptune and/or Jupiter may affect the equilibrium distribution of interplanetary dust in our solar system [e.g., Liou and Zook, 1999; Moro-Martín and Malhotra, 2002; Holmes et al., 2003]. *Despite these broad, crosscutting implications for planetary science, we still do not fully understand the dust grain spatial and velocity distributions sourced from various parent bodies, or the variability of the chemical compositions of interplanetary and interstellar dust grains throughout our solar system.*

Composition and Structure of the Inner Zodiacal Dust Cloud.

IRAS and COBE scans, ISO and Spitzer spectroscopy, and visible data on scattered zodiacal light have constrained many theoretical models for the spatial distribution, origin, and composition of zodiacal dust in the inner solar [e.g., *Hauser et al., 1984; Kelsall et al., 1998; Hahn et al., 2002; Nesvorný et al., 2010; Rowan-Robinson and May, 2013; Planck Collaboration et al., 2014*]. These models have to explain the various band and tail structures associated with asteroid collisional families and comets [e.g., *Nesvorný et al., 2006; Arendt, 2014; Espy Kehoe et al., 2015*], the strong ecliptic plane-to-pole surface brightness decrease, and the asteroid-like spectrum for the zodiacal cloud found in the near-infrared that shifts to a comet-like dust thermal emission spectrum in the mid-infrared [e.g., *Tsumura et al. 2010, 2013*]. Typically, these models incorporate a “fan”-like structure with dust density following both a radial power law and an exponential vertical distribution with scale heights increasing with radial distance from the Sun. Grain properties include a distribution of sizes ($0.5\text{--}500\ \mu\text{m}$) and a variety of compositions (predominately silicates; e.g., *Reach et al., 2003*); however, numerous questions remain. These “fan” models show that the cloud consists of a combination of cometary dust (primarily from Jupiter family comets), dust originating in the asteroid belt, and dust entering the solar system from the interstellar medium (ISM). *Rowan-Robinson and May [2013]* found a ratio of 70%:22%:7.5%, respectively for these three components. In contrast, *Nesvorný et al., [2010]* found 85-95% of the cloud originates from Jupiter family comets with the remainder from main belt asteroids. More importantly, little is known about how these contributions vary with distance from the sun, particularly on the far side of the asteroid belt. Indeed, at 4 au the *Rowan-Robinson and May (2013)* model is inconsistent with direct measurements of dust fluxes from the *Ulysses* spacecraft by a factor of ten. *Thus, despite decades of measurements, we still do not fully understand the spatial and compositional distribution of zodiacal dust grains in the inner solar system.*

Figure 1: The total optical depth of $0.5 - 500\ \mu\text{m}$ interplanetary dust grains in the solar system from the model of *Poppe et al. [2019]*, viewed from (a) above the ecliptic plane and (b) through the ecliptic plane.

Structure of the Outer Solar System Debris Disk.

Despite previous observations, the full shape and structure of the solar system's outer debris disk beyond Jupiter is poorly understood because we live inside of it. We do not fully understand how much dust is produced from the EKB nor how that dust migrates through the outer solar system since near-Sun cometary contributions dominate near-Earth space and only one spacecraft, *New Horizons*, has ever flown a dedicated dust detector through the EKB [e.g., *Piquette et al., 2019*]. Models such as those shown in **Figure 1** [*Poppe et al., 2019*; see also, e.g., *Kuchner and Stark, 2010*; *Vitense et al., 2012*] are needed to connect the in-situ dust density measurements from *New Horizons* to a global, solar-system wide picture of the interplanetary dust density distribution. Based on *New Horizons* measurements, this recent modeling has in fact suggested that dust generated outside of 30 au from EKB objects and Oort Cloud comets accounts for ~99% of the total mass of all dust grains in the solar system [*Poppe et al., 2019*]. In other words, the zodiacal light seen from Earth, which is dominated by Jupiter-family comets, comprises only ~1% of the picture! Further validation of this claim requires next-generation follow-up instrumentation capable of extending the in-situ measurements made by *New Horizons*, which mainly focused on grains with radii $< \sim 5 \mu\text{m}$, whereas the dominant grain size is thought to be $\sim 100 \mu\text{m}$.

Compositional information on the makeup of interplanetary dust grains in the outer solar system is also extremely sparse, for the simple reason that when viewed from near 1 au, inner solar system grains obscure much of the signal from outer solar system dust. Analysis of sample returns by the *Stardust* mission from comet 81P/Wild 2, which is thought to originate from the EKB, provided evidence of large-scale radial mixing of material in the early solar nebula [e.g., *Ishii et al., 2008*]. On its interplanetary cruise to Saturn, the *Cassini* Cosmic Dust Analyzer (CDA) recorded time-of-flight mass compositional spectra of only two interplanetary dust grains, both iron-rich and surprisingly silicate-poor [*Hillier et al., 2007*]; however, both grains most likely originated from inside 2.5 au and thus, are not necessarily representative of outer solar system grain compositions. Further analyses of potential interplanetary dust grain compositions detected by *Cassini* CDA while in orbit around Saturn continue [e.g., *Kempf et al., 2017*], yet questions remain about the dominant composition of outer solar system interplanetary dust. *The ability to map the radial gradient of interplanetary dust grain composition(s) could provide strong constraints on the chemical and isotopic compositions of their parent bodies and in turn, on the formation and evolution of the solar system.*

Interstellar Dust.

Interstellar dust grains (ISD) from the local galactic environment continuously flow through our solar system. ISDs erode the surfaces of airless bodies at the outer reaches of our solar system, such as Oort Cloud Comets and Kuiper Belt Objects, thereby contributing to the production of the outer interplanetary dust disk [*Yamamoto and Mukai, 1998*]. Each ISD grain also carries critical compositional information, delivering matter that may resemble the original solid building blocks of our solar system

Figure 2: a. ISD flux as a function of heliocentric distance, as detected by missions to date [Landgraf et al., 2000]. b. Representative ISD trajectories showing how solar radiation pressure can exclude ISDs from the inner solar system [Sterken et al., 2012]. c. Discrepancies in the ISD mass distribution between remote sensing observations in black [Draine, 2009] and in-situ observations in blue [Landgraf et al., 2000].

[Horányi et al., 2019]. Our solar system alters the flow of ISDs, primarily through solar radiation pressure and electromagnetic forces over long timescales [e.g., Landgraf et al. 2002; Sterken et al. 2012, 2013]. Radiation pressure alone prevents much of the flux of the smallest ISD grains from reaching the innermost solar system (Figure 2b). The filtering mechanisms may be sensitive to ISD composition(s), hence ISD fluxes in the inner solar system may not be representative of the unperturbed, pristine upstream flow. Figure 2a shows the ISD flux observations to date [Altobelli et al., 2003, 2005, 2006; Krüger et al. 2015], which have led to an improved understanding of its motion through the heliosphere.

Despite these previous observations and modeling efforts, understanding the ISD flux and its directional variability remains an unfinished and challenging task [e.g., Krüger et al., 2015, 2019; Strub et al., 2015; Sterken et al., 2015], given that the majority of ISD observations are relatively near to the Sun ($< \sim 5$ au), where large perturbations have already acted on these flows. Additionally, the size distribution of ISD entering the heliosphere measured by Ulysses contradicts both optical observations and expectations of the required abundance of elements based on current models, Figure 2c [e.g., Weingartner and Draine, 2001; Draine, 2009, 2011]. In addition, the *Stardust* samples of captured ISD particles showed a wide range of elemental compositions, crystal structures, and sizes [Westphal, et al., 2014], contradicting the *Cassini*-identified ISD with primarily Mg-rich silicates [Altobelli et al., 2016]. In-situ measurements of ISD grains taken across a large range of heliocentric distances out past the Kuiper Belt are critical to fully understand and characterize the flux and composition of ISD, and how the solar system filters and interacts with this material. *Despite this, a comprehensive experimental effort to explore the composition and dynamics of interstellar dust particles flowing through our solar system has not yet been accomplished.*

Exploration of Interplanetary and Interstellar Dust with *Interstellar Probe*

Interstellar Probe (ISP) is a mission concept to fly through the solar system, the outer heliosphere, and into the nearby “Very Local” interstellar medium (VLISM) [McNutt et al., 2019]. By escaping beyond the solar system’s boundaries with modern

observational techniques, *Interstellar Probe* would be a bold move in space exploration, enabling new and detailed understanding of the global heliosphere in the context of other astrospheres, further discoveries of unexplored Kuiper Belt Objects, and the first externally-based, global observations of our interplanetary dust disk. Taken together, *Interstellar Probe* would provide groundbreaking insight into the evolution of the solar system, the nature of our galactic neighborhood, and our understanding of exoplanetary systems.

Remote Sensing Dust Measurements with *Interstellar Probe*.

Information about the large-scale structure of the circumsolar dust disk can be obtained via remote sensing instrumentation onboard *Interstellar Probe* in two ways: by visible, near-infrared, and far-infrared line-of-sight measurements during the outbound trajectory or by pointed look-back measurements once the spacecraft is far outside the zodiacal cloud. The former technique would provide brightness measurements of the cloud from continually changing vantage points, until the signal ultimately vanishes as ISP fully exits the zodiacal dust cloud. With appropriate design and inversion techniques, such as the Radon transform [Radon, 1986], one can extract unprecedented three-dimensional maps of the zodiacal dust distribution, and produce revolutionary new constraints on current physical models of the cloud, particularly beyond 5 au. The latter method could provide global imaging of the zodiacal dust cloud similar to that modeled in Figure 1(b).

Figure 3: Model predictions of the 50 μm thermal emission surface brightness from interplanetary dust grains as a function of heliocentric distance. Two viewing directions from a hypothetical observer are shown: $\theta=0^\circ$, in-ecliptic, and $\theta=90^\circ$, towards the ecliptic poles, both from a radially outwards trajectory. Colors correspond to the contributions from individual populations of dust grains (EKB=Edgeworth-Kuiper Belt; OCC=Oort Cloud comets; JFC=Jupiter Family Comets), while black is the summed thermal emission.

Based on current models [Pope *et al.*, 2019], the dust cloud should diminish in brightness by a factor of ~ 100 between 1 and 10 au at visible and IR wavelengths due to simultaneous declines in the dust density, solar irradiance, and grain temperature (from ~ 270 K at 1 au down to ~ 85 K at 10 au to ~ 30 K at 100 au), see Figure 3. Within ~ 10 au, it would be straightforward to survey the zodiacal cloud in both reflection and thermal emission. A modest spectrophotometric capability using selected medium or narrow band filters could also remotely probe composition as a function of distance. Beyond ~ 10 au, solar illumination becomes too faint for mapping in reflected light, yet direct thermal emission in the mid- to far-IR should plateau until well into the EKB. For example, a suitably designed ISP instrument could measure the falloff in zodiacal thermal emission brightness at wavelengths of $\sim 50 \mu\text{m}$ as ISP voyages outward (Figure 3) and would thereby quantify the contributions of different dust components (cometary, asteroid, EKB, etc.). Determining the ratios between different dust sources (asteroids,

JFC comets, EKB objects, Oort Cloud comets, and interstellar dust) and their variation with distance would provide important constraints on the composition of the parent bodies and by extension, the evolution of the solar system.

In-situ Dust Measurements with *Interstellar Probe*.

Complementary to remote sensing measurements, in-situ observations of dust densities and compositions along the out-going trajectory of ISP would provide invaluable information on the nature of both interplanetary and interstellar dust grains in the solar system. Based on the SUDA instrument currently in the build phase for the *Europa Clipper* mission [Kempf et al., 2019] and the IDEX instrument in development for the *IMAP* mission [McComas et al., 2018], an impact-ionization, time-of-flight dust impact instrument, similar to that shown in Figure 4, would measure the both the impact rate and the chemical composition of dust grains. This “next-generation” dust instrument would yield vast improvements in our knowledge of the density, velocity distributions, and chemical compositions of both interplanetary and interstellar dust grains.

Figure 4: A cutaway diagram of the Interstellar Dust Experiment (IDEX) on the IMAP mission [McComas et al., 2018]. IDEX detects dust impacts via impact ionization-produced charge (left; upper right) and concurrently produces high mass resolution compositional spectra (lower right).

Recommendations

Answering the following scientific questions is critical to advancing our understanding of interplanetary and interstellar dust throughout the solar system:

- ***What are the spatial distributions of interplanetary and interstellar dust fluxes throughout the solar system?***
- ***How do forces such as planetary gravitation and electromagnetism affect these dust fluxes throughout the solar system?***
- ***What are the various compositions of interplanetary and interstellar dust grains and how do they constrain planetary formation models?***

While both remote sensing and in-situ instruments can provide significant insight into dust dynamics and compositions in their own right, co-manifesting both types of instruments onboard a common spacecraft will enable detailed cross-correlations between both datasets, thereby ensuring a deeper and more robust understanding of interplanetary and interstellar dust. The once-in-a-generation *Interstellar Probe* mission concept provides an unparalleled opportunity to advance the state of knowledge of the interplanetary and interstellar dust populations present in our solar system. Finally, we recommend close cooperation across the Heliophysics and Planetary Science Divisions with regards to *Interstellar Probe*, so that this opportunity for groundbreaking advances in planetary science is fully capitalized upon.

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