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INTERPLANETARY AND INTERSTELLAR DUST AS WINDOWS INTO SOLAR SYSTEM ORIGINS AND EVOLUTION



We can explore *in situ* the building blocks of the planets by measuring the trajectories and compositions of thousands of dust particles from comets and our interstellar neighborhood, a full survey of our “dust sky.”

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Introduction Among solar system objects visible to the unaided eye, the only one not yet targeted by a dedicated space exploration mission is our zodiacal cloud, comprised of interplanetary and interstellar dust. We see it near the horizon at dark-sky sites after dusk and before dawn, when sunlight scatters off the dust grains shed by thousands of comets and asteroids. Every manned or unmanned mission was and will be subject to impacts of interplanetary and interstellar dust. Fundamental science questions about the origins of our solar system and our connection with the universe can be addressed by visiting the zodiacal cloud to measure fresh samples from both ancient solar system objects and our galactic neighborhood. In our ongoing quest to learn about our cosmic roots, interstellar and interplanetary dust offer vital clues to the origin and evolution of the solar system. Each speck of dust is a tiny time capsule of the original building blocks of our planets. Interstellar dust from our galactic neighborhood is the closest available relative of the raw material of the solar system, while interplanetary dust shed by comets carries information on processes that occurred during solar system formation. This dust provides a unique opportunity to sample from hundreds of asteroids and comets and interstellar space, dramatically differing from the traditional strategy of single-destination missions. Sampling from these reservoirs uncovers the identities of the typical feedstock of the planets, revealing our cosmic roots. Characterizing interstellar dust enables determination of the raw materials present during the formation of the solar system and resolves conflicting information about its makeup and size distribution from optical starlight observations, *Ulysses* and *Cassini in situ* measurements, and laboratory analysis of Stardust samples. Interplanetary dust samples can be used to determine the degree to which the material in comets was processed by heat and water in the early solar system and to characterize organics delivered by comets to the planets.

Interstellar dust (ISD) is critical to the formation of stars and their planets, and its compositional information yield clues into these processes. ISD also governs the chemistry and dynamics of interstellar matter (Draine, 2011). Dust travels from old stars to young ones, seeding the next generation with its cargo of various elements. For most of modern history, our understanding of the interstellar medium (ISM) was limited to telescopic observations (Messier, 1781; Hartmann, 1904; Barnard, 1919), leaving several open questions about the makeup and size distribution of interstellar dust. The *Ulysses* mission was the first to recognize that interstellar dust is entrained in the interstellar gas flowing through the solar system (Grün, et al., 1993). These *in situ* measurements conflict with decades of optical observations of the attenuation and polarization of the light from nearby stars. It is also important to understand the nature and mass distribution of ISD in order to prepare for interstellar missions.

Interplanetary dust particles (IDP) provide a fast and efficient way to sample large numbers of comets since they originate mostly from particles shed by the >500 (Fernandez, 2020) short-period Jupiter Family Comets (JFC), which originate from the Kuiper Belt (Levison & Duncan, 1997), delivering samples from the earliest epochs and farthest reaches of the solar system. The JFC particles preserve the refractory component of their parent bodies over their ~1,000-year lifetime in the cloud (Burns, et al., 1979, Gustafson, 1994). Less than 10% of the flux at Earth is believed to have come from asteroids and even less from highly inclined Halley-type and Oort Cloud comets (Nesvorný, et al., 2011; Carrillo-Sánchez, et al., 2016).

Our current state of knowledge and open questions

Raw materials of our early solar system Interstellar dust from our galactic neighborhood is a very close relative of the raw material of the early solar system due to the expected slow chemical evolution of the galaxy at late times (see, e.g., Casagrande et al. 2011), yet we lack critical information about its composition and size distribution. Both of these are needed to understand the content of the nearby interstellar medium.

The mass distribution of interstellar dust passing through the heliosphere measured *in situ* by Ulysses contradicts expectations because there were more large particles ($>0.4 \mu\text{m}$ radius) than indicated by optical starlight measurements (Draine, 2009). Resolving this conflict in favor of Ulysses results would trigger a reevaluation of our understanding of the evolution of the interstellar medium and the formation of stars and planets. Rare, individual interstellar particles are identified in meteorites by their unusual elemental and/or isotopic ratios, reflecting condensation in the envelopes of particular giant stars and supernovae (Clayton & Nittler, 2004, McSween & Huss, 2010). However, modeling suggests that $\sim 95\%$ of interstellar dust particles are difficult to distinguish from other solar system materials by elemental and isotopic composition alone, having been broken up and reassembled multiple times since ejection from their parent stars (Draine, 2011). Thus, definitive composition measurements of the major constituents are critical in establishing the raw materials present in the early solar system.

This need motivated two direct measurements of interstellar dust composition, leading to contradictory results. The Stardust mission identified seven candidate particles, with three returned to Earth intact in aerogel; the remaining four were observed as residues left behind in their impact craters in returned instrument foils (Westphal, et al., 2014). Cassini measured the compositions of three dozen interstellar particles (Fig. 1) while orbiting Saturn (Altobelli, et al., 2016). The Stardust samples show a wide range of elemental compositions, crystal structures, and sizes (Westphal, et al., 2014), while the Cassini samples are all Mg-rich silicates. These already-conflicting observations are further contradicted by optical starlight data indicating either: (1) separate silicate- and C-rich populations, (Weingartner & Draine, 2001), or (2) that the two kinds of materials are combined in individual grains. Measuring how the elements are distributed across the population of particles is necessary to resolve these conflicts.

The abundances of the refractory elements in a rare meteorite type known as CI carbonaceous chondrites closely follow those found in the Sun's atmosphere and are used to trace back to what was present early in our solar system (Lodders, 2003). Whether the local interstellar dust population is chondritic remains unknown; even $\sim 10\%$ departures

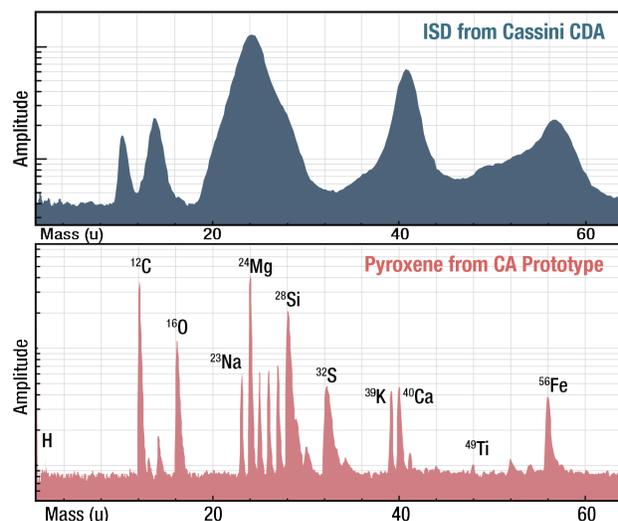


Fig. 1 The best *in situ* interstellar dust impact ionization mass spectra (top) to date were recorded by Cassini CDA (Altobelli, et al., 2016). Current dust impact analyzers can give more than 6 times better mass resolution (bottom; lab spectrum), and can reliably separate Fe, Mg, and Si from other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

from chondritic content would be revealing. For example, Si/Mg and Fe/Mg ratios are set by the balance between their exploding sources: (a) massive stars and (b) white dwarfs (Johnson, 2019, Leitner & Hoppe, 2019). Departures in these specific element abundances would point to a change in the stellar demographics of the solar neighborhood or indicate unexpectedly swift chemical evolution in the local ISM (Lugaro, 2005). Deviations from chondritic elemental ratios favoring lower temperature condensates would imply that differential loss processes operated as our Sun and planets were forming. This compositional information would reveal initial conditions and available materials in our early solar system.

Solar System history recorded in cometary minerals Interplanetary dust shed by comets and asteroids contains chemical and physical traces of processes that occurred during solar system formation. The most detailed information we have about the rocky and carbonaceous components of comets comes from just two missions. Stardust returned samples from 81P/Wild 2 in 2006 and Rosetta studied comet 67P/Churyumov–Gerasimenko up close in 2014–2015. Neither mission was able to reach conclusions on fine-grained sub-micron sized particles. Stardust encountered challenges extracting and analyzing sub-micron particles from aerogel collectors (Leroux & Jacob, 2013), but found *“indications that the fine-grained, sub-micron sized components of Wild 2 particles could be systematically different from the coarse-grained components. This may not be unexpected, if the coarse-grained components are ‘xenoliths’ derived from the inner solar-system, and the fine-grained components are the relatively unprocessed solids that were present in the Kuiper Belt at the time of comet formation”* (Westphal, et al., 2017).

The primordial interstellar material could have been processed in the solar nebula by: (1) sublimation in hotter regions, followed by condensation, transport to the comet-forming region, and incorporation into the bodies present today and/or (2) aqueous alteration due to warming in the presence of water. There is controversial evidence for aqueous alteration in comets (Westphal, et al., 2017). High-temperature condensates are known to be present in large 81P cometary particles ($> 5 \mu\text{m}$) thanks to the samples from the Stardust mission. The presence of high-temperature condensates in fine-grained materials implies efficient long-range transport in the early solar system. Widespread aqueous alteration would suggest either liquid water in a previous generation of bodies that were broken up and dispersed or exposure to concentrated water vapor in the nebula (Wooden, 2008; Nakamura-Messenger, et al., 2011).

Heterogeneous aggregates called chondritic porous interplanetary dust particles (CP-IDPs), collected in Earth’s stratosphere, are made of individual grains with characteristic sub-micron sizes. These aggregates are thought to be cometary in origin (Bradley, 2014). Detecting cometary grains above the atmosphere, before they are exposed to ablation and heating processes, would simplify the recognition of aqueously-altered and high-temperature condensate minerals among zodiacal cloud particles.

Primordial sources of organic material Since the *Vega* and *Giotto* encounters with comet Halley, comets have been recognized as carriers of the remnants of primordial organic material (Kissel, et al., 1986a,b; Kissel & Krueger, 1987). More recently, organic matter was also detected in comets 81P and 67P (Sandford, et al., 2006; Fray, et al., 2016; Altwegg, et al., 2017). However, there is still no comprehensive characterization of organic materials across the cometary population.

Organic material enters Earth's atmosphere continually as a component of the zodiacal dust. Some of the particles are collected in the stratosphere by high-flying aircraft, but their compositions are altered by heating as the particle enters the atmosphere. High temperatures irreversibly change the elemental composition and chemical bonding (Komiya & Shimoyama, 1996; Matrajt, et al., 2006; Okumura & Mimura, 2011), while volatile organic molecules evaporate even at lower temperatures.

If cometary organics above the atmosphere are relatively unprocessed, they may have H/C ratios >1 . This would be greater than any known carbonaceous chondrite organic matter and even comet 67P, based on measurements from the secondary-ion mass spectrometer on Rosetta (Fray, et al., 2016; Isnard, et al., 2018). This hypothesis of high H/C ratios remains untested for the comet population as a whole.

Meanwhile, N/C ratios tell us about the origins of particles, indicating either volatile chemistry during organic synthesis or, more likely, thermal and/or radiation processing. For example, N-rich, O-poor organics indicate formation under very specific conditions found only in the distant solar system or ISM (Dartois, et al., 2013). Also, an especially primitive origin for N-rich organics is supported by their discovery embedded within glassy silicate cometary particles (Ishii, et al., 2018). The existence of a N-rich reservoir would be confirmed or ruled out by determining the distribution of N/C ratios across the comet population. The O-abundance in C-rich particles is another marker of thermal history since carboxyl-bearing molecules are unstable at temperatures as low as 450K (Fray, et al., 2004; He & Smith, 2014). Thus, finding particles with both low O/C and H/C ratios would be strong evidence for thermal processing.

Cometary particles, absent atmospheric entry, are thought to preserve their primordial semi-volatile content better than the carbonaceous chondrite meteorites and CP-IDPs collected on Earth. Cometary dust's average Si/C ratio should then be closer to solar than those of the meteorites and chondritic porous dust. While individual particles from comet 67P span wide ranges in Si/C, on average they are twice as C-rich as the CP-IDPs (Bardyn, et al., 2017). Knowing the broader compositional context is vital for the interpretation of Rosetta and future cometary missions. Organic molecules are also characterized by combinations of structural and functional groups. Of particular interest are the aromatic groups produced by solar nebula processing through heating and irradiation (Pascucci, et al., 2009; Bergin, et al., 2014; Kuga, et al., 2015). The information carried by interplanetary dust tests chemical kinetics models and laboratory analogs for processes that occurred in the proto-solar disk (Öberg et al., 2009; Walsh, et al., 2014; Henderson & Gudipati, 2015; Eistrup, et al., 2018).

Measurement approaches and instrumentation

Meteorites yield invaluable composition information, especially for certain asteroid families, but trajectories are known only for a subset. Tracking meteors yields orbits but limited composition information. Zodiacal light imaging and optical-infrared spectroscopy constrain particles' orbits but similarly offer only broad constraints on composition. None of these techniques tells us about the contemporary interstellar dust. Recently developed Dust Telescopes (DTs) are capable of measuring the trajectories and composition of interstellar and interplanetary dust particles, confidently distinguishing them from each other. DTs measure the particles' velocity vectors, masses, and compositions using techniques demonstrated by several instruments, including the Cosmic Dust An-

alyzer (CDA) on Cassini, the Lunar Dust EXperiment (LDEX) on LADEE, and the SURface Dust Analyzer (SUDA), under development for the Europa Clipper mission (Auer, et al., 2002; Srama, et al., 2004; Horányi, et al., 2014; Altobelli, et al., 2016). After the non-destructive velocity vector measurement, the particle impacts a target. In a process known as impact ionization, the particle is partially vaporized and ionized. The mix of impact ions generated is a function of the dust particle composition and speed (e.g., Göller & Grün, 1989; Auer, 2001). The setup utilizes time-of-flight (TOF) mass spectrometry (Fig.1) to identify the ions, achieving a high mass-resolution ($\text{FWHM} \leq 1 \text{ u}$ over mass range 1–200 u) (Srama, et al., 2005; Rachev, et al., 2004; Sternovsky, et al., 2007).

Recommendation

Advances in instrument capabilities now allow for the *in situ* identification of interplanetary and interstellar dust particles and the measurement of their composition. These measurements could bring closure to several open questions about the origins and evolutions of our solar system, and planetary systems around other stars. Hence, our recommendation is to complete a survey of our “dust sky” at 1 AU, but outside the Earth’s atmosphere, to sample a large number of bodies, complementary to traditional missions with single or few targets. These new measurements would:

- (1) discover whether today’s local interstellar dust matches the composition of the feedstock from which the solar system formed;
- (2) determine whether comets’ fine-grained component preserves unprocessed pre-solar dust or shows signs of processing in the early solar system;
- (3) learn whether cometary and asteroidal organic material share a common source or formed from distinct reservoirs.

We also recommend the development of extended laboratory dust impact TOF mass spectral libraries to prepare for the analysis and interpretation of data from future missions with *in situ* dust composition measurements.

Beyond Planetary Science, the three objectives above crosscut all Divisions of NASA’s Science Mission Directorate. Astrophysics interests lie in understanding the interstellar matter and the only debris disk accessible *in situ*, our own zodiacal dust cloud. Heliophysics interest is in the verification of large-scale heliospheric magnetic field models by the measured effects on the motion of electrically charged interstellar dust (STS, 2013). Reporting the makeup of interplanetary minerals and organics that ablate in our atmosphere is valuable to the Earth Science Division (ES&A, 2007). The characterization of the micrometeoroid population is of interest to NASA’s Human Exploration and Operations Missions Directorate to improve dust hazard modeling (Moorhead, 2018). A mission dedicated to surveying the content of our zodiacal dust cloud would deliver perhaps the lowest-hanging fruits remaining in planetary science.

Connections to other white papers for the decadal survey

- (1) *In situ* measurements taken across a large range of heliocentric distances out past the Kuiper Belt are key to fully understanding and characterizing the flux and composition of ISD, and how the solar system filters and interacts with this material

(Poppe et al., *Dust Measurements from an Interstellar Probe: Exploring the Zodiacal Cloud and the Interstellar Dust Environment*).

- (2) Dust observations are critical for understanding its effects upon the martian system, including the carbonaceous input into the regolith of Mars and its moons, and the chemical input into the atmosphere (Fries et al., *The Scientific Need for a Dedicated Interplanetary Dust Instrument at Mars*).
- (3) Continuing and expanding terrestrial recovery of extraterrestrial samples remain an integral and critical support to small body and planetary missions, and require the development of high level of capability for sample curation and sample-analysis (Ishii et al., *Terrestrial Recovery of Extraterrestrial Materials: Providing Continued, Long-Term Sample Analysis, Opportunities for Research and Mission Support*, and Stroud et al., *Strategic Investment in Laboratory Analysis of Planetary Materials as Ground Truth for Solar System Exploration*)

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