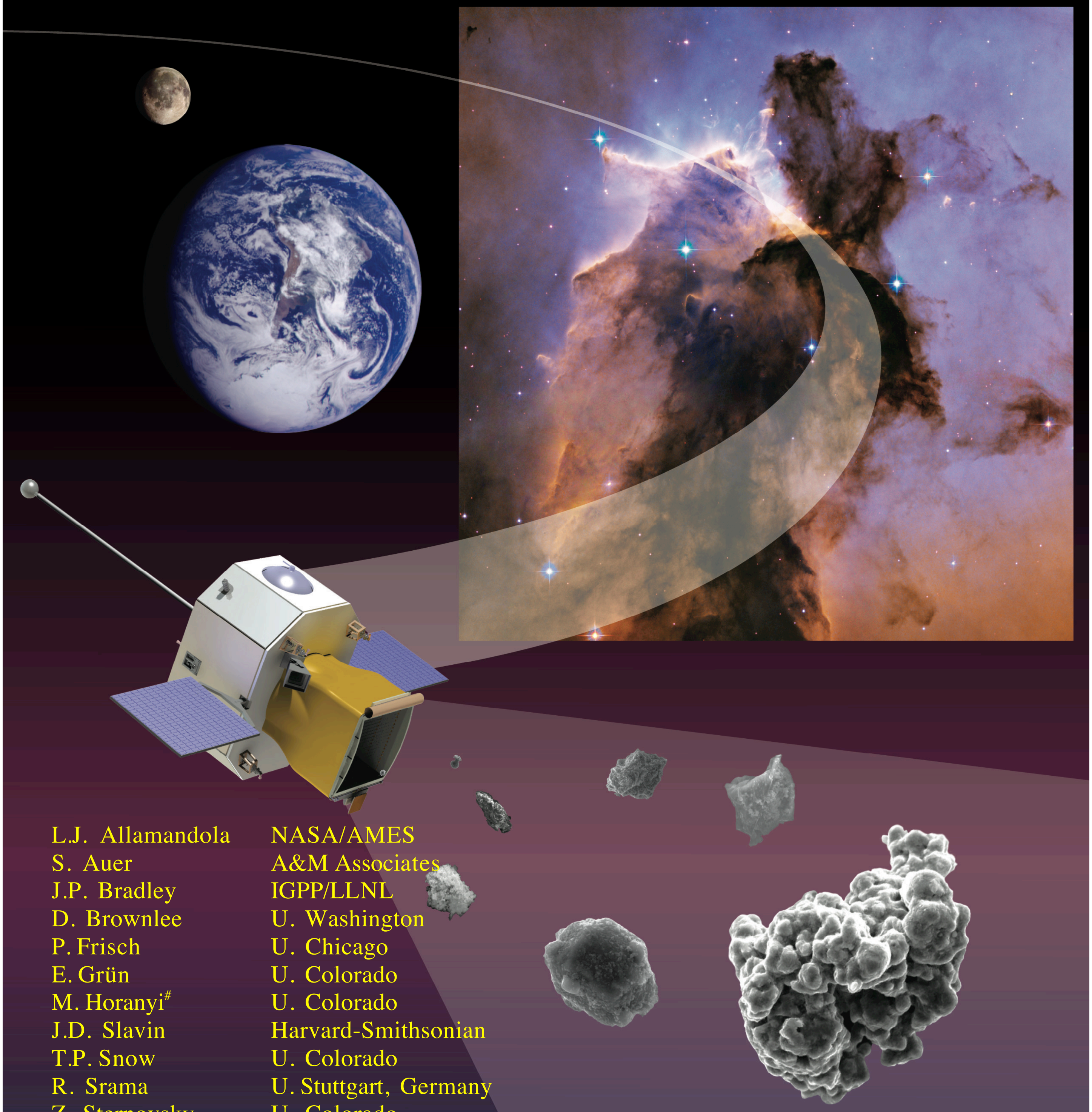
Dust Astronomy



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Executive Summary

Cosmic dust provides a link between the universe, the stars, the interstellar medium, our planetary system, the Earth, and our living world. A single grain is a world in its own right, consisting of millions of atoms, reflecting the conditions under which it was born and modified during its lifetime. By determining the origin, and analyzing the chemical and isotopic compositions of a single grain, we learn about the properties of its birthplace, and the processes responsible for its current state.

Most information about galactic interstellar dust is provided by astronomical observations. Present day observations of starlight extinction from IR to UV have been reproduced by Interstellar Dust (ISD) models with grain sizes ranging from a few nm to a few hundred nm. Based on model results, a range of chemical compositions have been predicted for ISD. However, as of yet we have not been able to directly sample interstellar matter.

Within the past few decades interstellar dust was positively identified within the planetary system by the dust detector onboard the Ulysses spacecraft. At the distance of Jupiter, the spacecaft picked up micron and submicron-sized particles originating from a direction that was opposite to the expected impact direction of interplanetary dust grains. The motion of the interstellar grains through the solar system was parallel to the flow of neutral interstellar hydrogen and helium gas, both traveling at a speed of 26 km/s. The ISD flow persisted even over the poles of the Sun, whereas interplanetary dust is strongly concentrated towards the ecliptic plane. Measurements by the Galileo and Cassini spacecraft confirmed Ulysses' ISD observations and extended them to within Earth's orbit.

Hence, interstellar matter is delivered within ‘arms-reach’; it can be identified and directly sampled from a spacecraft outside the Earth’s magnetosphere. Recent technology breakthroughs enable high-precision dust trajectory measurements in combination with *in-situ* chemical and isotopic analysis of ISD grains. This combination of measurements forms a unique ‘dust telescope’ that, by enabling the first direct dynamic and chemical analysis of ISD ever possible, opens a new window to the universe, ushering in the era of ***Dust Astronomy*** (Grün *et al*, 2005).

Dust trajectory sensors utilize the electric charge signals induced when charged dust grains fly through the detector. These sensors, in combination with state-of-the-art *in-situ* dust impact analyzers, are capable of determining mass, speed, physical properties and the chemical composition of individual dust grains in space.

This orbiting observatory will, for the first time, characterize interstellar and interplanetary dust *in-situ*, providing crucial information about our original, nascent molecular cloud that has not been, nor ever will be, accessible using remote astronomical methods. Galactic interstellar dust constitutes the solid phase of matter from which stars and planetary systems form. Interplanetary dust, from comets and asteroids, represents remnant material from bodies at different stages of early solar system evolution. Thus, studies of interstellar and interplanetary dust will provide a ground truth comparison between the composition of the interstellar medium and primitive planetary objects.

Scientific Motivation

Dust grains condense in the expanding and cooling stellar winds from asymptotic giant branch (AGB), post-AGB stars, and also in supernova explosions. This so-called 'stardust' provides the seeds for ISD grains that grow further in cool interstellar clouds by accretion of atoms and molecules, and by agglomeration. On the other hand, interstellar shocks can efficiently destroy ISD grains by sputtering and high-speed grain-grain collisions (resulting in shattering or vaporization) behind shock fronts. In diffuse interstellar clouds, the grains lose their volatile constituents (e.g., H_2O) due to UV irradiation (Greenberg et al., 1995). In denser regions, low-velocity grain-grain collisions results in coagulation. Ultimately, ISD grains can either be destroyed in newly-forming stars, or become part of a planetary system. The matter in ISD grains is repeatedly recycled through the galactic evolution process (Dorschner and Henning, 1995).

The chemical evolution of ISD in the Interstellar Medium (ISM) directly reflects the metallicity of the galaxy. ISD grains contain most of the mass of the refractory elements in the ISM (e.g., Fe, Mg, Si, Al, Ca). They also contain about half of the C, and 25% of the O (Jenkins, 2004). Fe is of particular interest because it is generally taken as a marker for the galaxy's metallicity. In the ISM, more than 90% of Fe is thought to be locked in ISD grains. The chemical form of the Fe is not known. Some of the Fe may be in magnesioferrosilicates, but Fe oxides (e.g., magnetite, Fe3O4) or even metallic Fe, may also be present. Although constituents of ISD grains are partially known, there are no direct measurements of the full grain composition nor is the intrinsic metallicity of the ISM well understood.

More than a decade ago, interstellar dust was positively identified inside the planetary system. After its fly-by of Jupiter, the dust detector onboard the *Ulysses* spacecraft detected impacts of particles in the mass range of $10^{-14} < m < 10^{-11}$ g, predominantly from a direction that was opposite to the expected impact direction of interplanetary dust particles (IDP), and the impact velocities exceeded the local solar system escape velocity (Grün *et al.,* 1993, 1994). Subsequent analysis showed that the motion of the ISD grains through the solar system was parallel to the flow of neutral interstellar hydrogen and helium gas (**Figure 1**) both traveling at a speed of 26 km/s. Measurements by Cassini and Galileo extended the range where interstellar dust was identified down to 0.7 AU (Altobelli et al., 2003, 2005). In 2005, the interstellar flux showed a 30° shift, the reason of which is presently unknown. A first dedicated attempt to analyze and collect interstellar dust grains was done with the Stardust mission. While the *in-situ* analysis interstellar dust by the Stardust mission suggested a large abundance of organic matter (Krueger et al., 2004). The identification and analysis of ISD collected by Stardust has not yet yielded results.

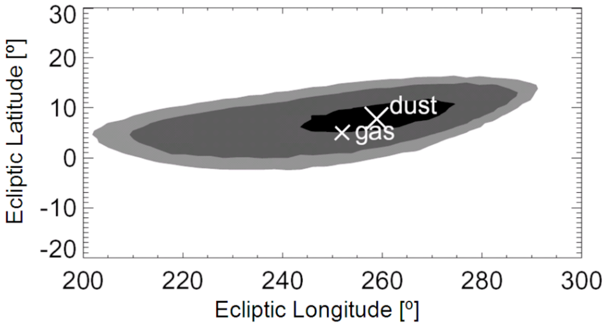

Figure 1. The interstellar solid matter is coupled to the interstellar gas flow through the heliosphere, delivering ISD grains to Earth. The upstream direction of the ISD flux observed by Ulysses is λ=259±20° and θ=8±10° ecliptic longitude and latitude, respectively. The contour plot shows 1σ, 2σ, and 3σ confidence levels as black, dark grey, and light grey color. The helium upstream direction is λ=254°, θ=5.6° (Frisch *et al.*, 1999; 2000).

The flux of particles with a mass of *m*$\approx 3\times10^{-13}$ g measured by *Ulysses* (**Figure 2**) is in good agreement with what is expected from conventional models for dust in diffuse interstellar clouds. Particles smaller than 2×10^{-13} g are expected to be 'filtered' out by the magnetic field in the interplanetary medium and in the heliosheath, and, hence, cannot penetrate our heliosphere. The unexpected result is that Ulysses measured a substantial flux of 'big' particles with masses in the range of $3\times10^{-13} < m < 5\times10^{-11}$ g. The reported abundance of these large particles with radii 0.3 - 1.5 µm is far higher than expected from conventional grain models (e.g., Weingartner and Draine, 2001; Zubko et al., 2004; Draine, 2008).

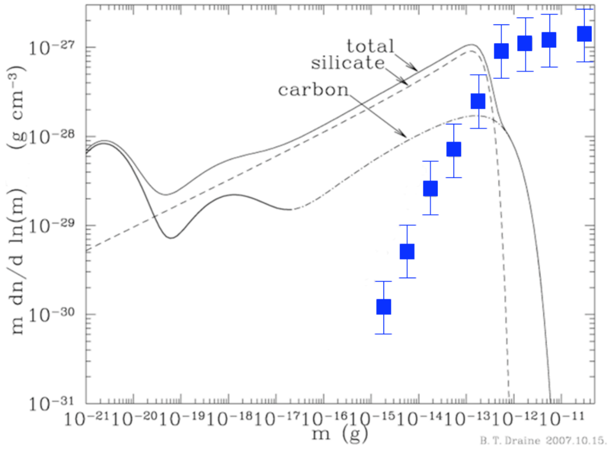

Figure 2. The mass density distribution per log mass interval measured by *Ulysses* (blue squares. Landgraf *et al*., 2000) shows an astonishing excess in large particles and drop-off of smaller particles that differ by many orders of magnitude over the predictions by models based on wavelength-dependent extinction observations (continuous lines). This is a serious challenge to our current understanding of the extinction measurements, as well as the chemistry of diffuse interstellar clouds (Draine, 2008).

This finding contradicts our current understanding of the nature of the ISM in general and the Local Interstellar Cloud (LIC) in particular. First, the addition of these very large grains to the ISD grain mixture would produce an extinction curve that is inconsistent with the average observed wavelength-dependent extinction in diffuse clouds. Second, conventional models of grain compositions and chemical abundances in the ISM fully consume the available refractory elements (Mg, Si, Fe) in grains with radii $r < 0.3$µm, and there simply isn't any material left to account for an additional component of $r > 0.3$ µm grains. It is therefore very important to confirm the Ulysses flux measurements and to determine the composition of these unexpected $r > 0.3$ µm particles. Third, the large grains increase the total local ISM grain mass, so that it violates the canonical gas-to-dust mass ratio of ~150-220 that is found to apply to the nearby ISM (Snow, 2000).

The observed reddening of starlight is attributed to the presence of dust in the interstellar space. Present-day observations of extinction from IR to UV can be reproduced by dust models with grain sizes ranging from a few nm to a few hundred nm. Small graphitic carbon particles are thought to account for the prominent extinction feature near 217.5 nm, and amorphous silicate grains reproduce absorption features near 10 and 20 µm. Infrared emission features at 3.3, 6.2, 7.7, 8.6, and 11.3 µm are interpreted as thermal emission following single-photon heating of small Polycyclic Aromatic Hydrocarbon (PAH) particles, while other features point to organic refractory materials in small dust grains (Pendleton and Allamandola, 2002). Absorption spectroscopy of dark clouds reveals an inventory of ice features of H_2O, CO, CO_2, CH_3OH and other molecules, but these ices are absent in diffuse interstellar clouds. Based on these observations, various models have been put forward for dust in diffuse clouds:

1) Mathis (1996) suggests three types of ISD particles: a) small graphite grains; b) silicate grains; and c) composite grains containing carbon (amorphous, hydrogenated, or graphitic), silicates, and oxides.

2) Li and Greenberg (1997) also proposed three grain types: a) large grains consisting of a silicate core and an organic refractory mantle; b) small carbonaceous grains; and c) very small grains (or large molecules) of PAHs.

3) According to Draine and Li (2007), ISD consists of separate amorphous silicate grains and carbonaceous grains, with PAHs as the smallest particles in the carbonaceous population.

The radiation pressure repulsion of ISD grains within 3 AU of the Sun is better described by composite grains than with bare silicate or graphite grains (Landgraf et al., 1999; Mann and Kimura, 2000). Grain model classes that include composite grains with ~ 0.7 μm radius provide acceptable fits to infrared to UV extinction curves (Zubko et al., 2004). The validity of these competing models can only be decided by directly sampling the chemical makeup of ISD grains.

During the formation of a protoplanetary system, dust particles undergo significant alterations. The accretion shock in a collapsing molecular cloud is likely to heat and vaporize much of the dust present in the pre-solar nebula. The subsequent re-condensation of this material explains the common isotopic composition found almost everywhere in our own solar system. However, dust in the outer parts of a proto-planetary disc is heated less, and there is evidence for surviving ISD grains in present day solar system materials: pre-solar grains in meteorites, and comets. For example, anomalies in the abundances of xenon isotopes have been suggested to indicate a Type II supernova origin of nano-diamonds found in meteorites. The different isotopic patterns of graphite grains recovered from meteorites suggest different sources for their origin, including AGB stars, WC stars, novae and supernovae. The *in-situ* isotopic analysis of ISD grains will reveal their origin.

Key scientific questions of that can be addressed by Dust Astronomy methods are:

- What is the elemental, isotopic, and mineralogical composition of interstellar grains and its variability?
- What is the size distribution and flux of interstellar grains passing through the planetary system?
- What is the metallicity of the local interstellar medium?
- Can destruction and formation processes (coagulation, condensation) be identified in the composition of ISD?
- Can we distinguish original stardust from grains that have been processed in the interstellar medium?
- What is the nature of carbonaceous and silicate dust?
- Are there multi-component grains? Are silicates mixed-in with carbonaceous material?
- How complete was the chemical homogenization in the protoplanetary nebula?
- Is today's interstellar material different from the ancient 4.6 Gyr old material incorporated meteorites and interplanetary dust?
- How important is size-dependent filtering of ISD in the heliosphere and at the heliospheric boundary?

Technological Readiness

a) Instrumentation

Dust particles in space are electrically charged. Measurements of the induced charges when a dust particle flies through an array of appropriately configured electrodes provide a contact-free means to analyse its trajectory (Auer and von Bun, 1994, Auer et al., 2008). Cassini's Cosmic Dust Analyser (CDA) unambiguously measured for the first time the electric charge on dust particles in interplanetary space and near Saturn before they impacted the detector (Kempf et al., 2004, 2006). Several micron-sized dust particles were recorded that carried positive charges of a few 10^{-15} C. Dust particles in interplanetary space are charged to an electrostatic potential of about $U \sim +5$ V mostly by the photoelectric effect from solar UV radiation (Horanyi, 1996). At a potential of +5 V, a dust particle of 0.2 µm in radius and 1000 kg/m^3 density has a mass of 8×10^{-17} kg and carries a charge of 10^{-16} C. Most of the interstellar grains observed in the planetary system were larger than 0.2 µm in radius; therefore, their charge will be accessible to dust instrumentation with 10^{-16} C sensitivity. Dust trajectory sensors have been developed that measure dust charges as low as 10^{-16} C and have an accuracy of better than 3 % in speed and 3° in direction (Srama et al., 2007). This is sufficient to distinguish interstellar from interplanetary dust by their trajectories.

First compositional analyses of cometary dust has been achieved by the dust analysers, PIA and PUMA onboard the Giotto and VeGa spaceprobes (Kissel, 1986). The instruments employed a time-of-flight mass spectrometer in order to derive the elemental composition of the plasma generated upon impact of fast cometary dust particles onto the sensor. A mass resolution of $M/\Delta M > 100$ was achieved by means of a reflectron that provided a focus of the energy. The data collected by PIA/PUMA demonstrate that each individual dust spectrum obtained contains a wealth of scientific information (Jessberger, 1991). The organic component of Halley dust consisted mainly of highly unsaturated hydrocarbon polymers containing C-H and C-N-H compounds (Kissel and Krüger, 1987). A later instrument of this type was the CIDA (Cometary and Interstellar Dust Analyser) instrument on the Stardust spacecraft. The spectra of presumably interstellar particles and the spectra obtained during the flyby of Comet 81P/Wild 2 confirm the predominance of organic matter (Kissel et al., 2004, Krüger et al., 2004).A medium-resolution impact mass spectrometer of 100 cm^2 sensitive area is part of the Cassini CDA instrument which totals a sensitive area of 0.1 m^2. Even at this low mass resolution ($M/\Delta M \sim 30$), significant compositional information was obtained on the Jovian (Postberg et al., 2006) and Saturnian stream particles (Kempf et al., 2005) and on particles populating Saturn's E ring (Postberg et al., 2007). Large-area (0.1 m^2 sensitive area) high-resolution ($M/\Delta M > 100$) mass analysers measuring both positive and negative ions have been developed in order to analyse the low fluxes of interstellar grains in interplanetary space (Sternovsky et al. 2007, Srama et al., 2007).

b) Mission Concept

A dust astronomy mission carries a dust telescope to space outside the Earth’s debris belt in a high elliptic Earth orbit or at the Earth’s libration points L1 or L2 (Fig. 3). Such a trajectory exploits the effect of the Earth's motion ($v_E \approx 30$ km/s) on the local interstellar dust velocity ($v_{ISD} \approx 26$ km/s) and flux. The interplanetary dust flux is constant throughout the year; only a long-term variation with the solar cycle is expected.

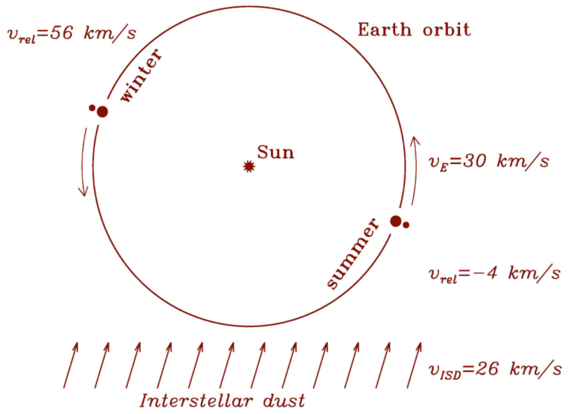

Figure 3. Dust Astronomy mission scenario. Earth's orbit around the Sun (v_E = 30 km/s), and the direction of the interstellar gas and dust flow at speed v_{ISD}= 26 km/s are shown. Two positions of the Earth and the satellite are displayed (left: late winter, and right: late summer). The corresponding fluxes of interstellar grains are about a factor 10 higher in winter than in summer.

In contrast to interplanetary dust flux, the interstellar dust flux varies strongly during the year: during the Earth's upwind motion, the velocities add up to ~56 km/s, and during the downwind motion, the relative velocity is a only few km/s. When the dust telescope points into this interstellar dust flow direction during the winter months, the flux of interstellar grains exceeds the flux of interplanetary grains at 10^{-13} g. The flux of submicron sized interstellar grains is about 1.5×10^{-4} m^{-2} s^{-1} which is of the same order of magnitude as the interplanetary dust flux at 1 AU. About 1000 impacts of interstellar grains per year will be recorded by a dust telescope that has a sensitive area of 0.5 m^2.

Summary

- Interstellar dust is accessible to *in-situ* analysis at 1 AU.
- Trajectories and composition of individual dust sub-micron sized particles can be measured simultaneously.
- A dust observatory will obtain unprecedented information on physical and chemical properties of interstellar dust grains.
- Studies of interstellar and interplanetary dust will provide a ground truth comparison between the composition of the interstellar medium and primitive planetary objects.
- Follow-on dedicated interstellar dust sample return missions will become attainable.

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