Interplanetary Dust

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Abstract

Imagine a box filled with particles from hundreds of thousands of small bodies throughout the solar system, including asteroids, comets, Trojans, Centaurs, KBOs and even from other stars. Each particle contains information about the object from which it came and the space environment through which it has traveled. Largely collected near the Earth's orbit and on the Earth itself, this box of particles represents the most inexpensive sample return mission from a diversity of targets — some beyond the reach of any spacecraft. Linking particles to specific or classes of sources is a major challenge, but compositional and dynamical clues provide many of the insights needed to accomplish this.

I. Subdiscipline Overview

The interplanetary dust complex is a compositionally and dynamically diverse population stemming from a range of sources. This complex includes cometary dust, asteroidal dust, and Kuiper belt dust plus other smaller contributors. The dust is continually replenished by cometary sublimation, asteroid collisions and other production mechanisms), while evolving dynamically due to radiation forces and planetary perturbations, and is ultimately removed by inter-particle collisions, planetary accretion and scattering, evaporation, sputtering, and ejection from the solar system. Interstellar dust is also flowing through the solar system, offering a tangible, physical link between our planetary system and the stars. The presence of the dust is detected in many different ways; via in-situ detections and collections in space, as well as from remote sensing (thermal emission, optical scattering, radar echo), as meteors in the Earth's atmosphere, and as collections of interplanetary dust particles (IDPs) and micrometeorites at the Earth, extracted from the ocean floors to the upper atmosphere. The diverse nature of interplanetary dust makes its study both interesting and complex. It is a multi-faceted research topic that brings together many branches of physics, chemistry, geology, and astronomy.

Most of what we know about the composition of interplanetary dust comes from IDPs collected in the atmosphere, which likely originate from both asteroids and comets. However, the sources of IDPs (asteroidal vs. cometary) are inferred indirectly from their mineralogy and bulk composition, as well as determining densities of meteors. Many IDPs have bulk elemental abundances that closely match those of CI or CM carbonaceous chondrite meteorites (Rietmeijer et al., 1998). On the other hand, many IDPs are C-rich, fragile, fine-grained assemblages of anhydrous materials similar to comets. In-situ analyses of interplanetary dust are sparse. The Cassini and Stardust missions provided a handful of dust spectra in interplanetary space (Krüger et al., 2004; Hillier et al., 2007). Much more is needed in order to construct a compositional inventory of interplanetary dust and establish the link to its sources: comets, asteroids, Kuiper belt objects (KBOs), and interstellar space.

The source populations contributing to the interplanetary dust complex are dynamically quite different. It is generally considered that dust particles produced from comets are on orbits with high inclination and eccentricity, and those stemming from asteroids are on lower inclination, more circular orbits. However, it has been shown that the orbits of cometary particles can be circularized by injection into interior Jovian mean-motion resonances (e.g., Liou and Zook, 1996), while those of large asteroidal particles can be dynamically excited by passage through mean-motion and secular resonances (e.g., Kehoe et al., 2002). In contrast, interstellar dust has been identified in part by its consistent direction of motion and high velocity.

The orbits of dust particles from an asteroid or comet evolve due to the forces of Poynting-Roberston light drag and solar wind drag, which cause the orbits of the dust to decay in semimajor axis and eccentricity into the inner solar system. Particles smaller than a few microns are blown out of the system under the effect of radiation pressure and solar wind interactions and are observed as β-meteoroids or streams of nano-dust. Material from the Kuiper belt also migrates through the solar system. As the particles are dynamically evolving, they are also undergoing mutual collisions with background cloud particles and thus the size distribution of particles in the cloud is evolving with both time and heliocentric distance. Linking IDPs to their source bodies can therefore be problematic and requires detailed dynamical modeling.

The successes of previous missions have improved our understanding of the zodiacal cloud. LDEF returned samples of dust in the near-Earth environment to the laboratory for study (Zook, 1991; Horz et al., 1995), as Stardust did for the dust flowing from active comet 81P/Wild 2 (Brownlee et al., 2006). Deep Impact created and observed dust freshly released from a cometary source in a high-speed cratering event (A'Hearn et al., 2005). During their interplanetary cruise phase, Galileo and Ulysses explored the interplanetary dust cloud in three-dimensional space from Venus to Jupiter and from the ecliptic plane to the poles of the Sun (Grün et al., 1997; Krüger et al., 2007) and together with the old Pioneer 10, 11 and Helios data provided valuable input to modeling the dynamics of the zodiacal cloud (e.g. Divine, 1993; Staubach and Grün, 1995; Dikarev et al., 2005). Determining the detailed structure of the zodiacal cloud allows us to relate features of the cloud with sources and better understand dust production mechanisms. For example, the dust bands discovered by IRAS have been associated with asteroid families (Low et al., 1984), while the recent ejecta of comets create dust trails (Sykes et al., 1986) that evolve to produce meteor showers on the Earth (e.g., Jenniskens, 2008). The relative contributions of the different source populations to the interplanetary dust complex are still a matter of considerable debate. A better understanding of the origin and dynamics of the cloud is key to mitigating the hazards posed to spacecraft and satellites in near-Earth space. The zodiacal cloud also exhibits global structure such as a central offset, an inclined and warped plane of symmetry, and resonant rings that all result from planetary perturbations (e.g. Dermott et al., 2001). Information obtained by investigating the origin, structure, and evolution of the zodiacal cloud can also be exploited to gain a better understanding of debris disks and planetary systems around other stars.

II. Top-Level Scientific Questions

1. What is the detailed composition of interplanetary dust? Because IDPs come from all types of small bodies in the solar system, the determination of the range and detail of their makeup provides information on the sources of the particles and direct evidence of the source composition. This also yields information on the conditions in which IDPs were formed and the origin and evolution of their source bodies.

a. Identify the compositional differences between interplanetary dust particles of cometary, asteroidal, and Kuiper belt origin. How does the composition vary within each source population and region?
b. What is the composition of interstellar grains sweeping through the solar system? Are the sources of interstellar dust particles single stars or a galactic mixture?

2. How are interplanetary dust particles generated, how do they evolve dynamically, and what are the dominant loss mechanisms? The processes by which dust particles are generated by each source provides insight into the structure and physical properties of the parent body producing them. Understanding the life cycle of a dust particle allows us to link dust in a specific location with a source, and is therefore a key component in linking dust compositions to their source regions and parent bodies.

a. What is the collisional environment in the asteroid and Kuiper planetesimal belts?
b. How does the dynamical evolution of interplanetary dust particles affect their categorization into cometary- or asteroidal-type purely based on their orbits?
c. How important are inter-particle collisions, radiation pressure, and Poynting-Robertson drag, and what is their role in the production of β-meteoroids and nano-particles?
d. Which Near-Earth Objects (NEOs) are the parent bodies of our meteor showers? When were the meteoroid streams created? How did the meteoroid streams evolve to cause the meteor showers we now have at the Earth (and the Moon)? What are the differences and similarities between the characteristics of NEOs and meteoroids?

3. What are the relative contributions of dust particles from each source to the zodiacal cloud as a whole? The proportion of dust produced by different sources is reflected by the spatial distribution, particle size, heliocentric distance and latitude, and also provides information on the source body populations, such as their dynamical behavior or collisional environment. Understanding the sources of dust production informs us how we might expect the cloud to vary with time, characterizes the hazard posed to the near-Earth environment, and provides a model for understanding the observed production of dust in other planetary systems.

a. What is the orbital and velocity distribution of dust particles in the inner solar system and what implications does this have for the impact threat to artificial satellites and the exploration of the lunar environment?
b. Would the collisional breakup of a major asteroid result in a collisional cascade and cause a significant flare in the brightness of the zodiacal cloud? If so, how often does this occur?
c. How does the flux of interstellar dust through the solar system change over time as the Sun moves through the galaxy, the local hot bubble, and nearby molecular clouds?

4. What is the global structure of the cloud and how does it compare to exo-zodiacal clouds? Understanding the spatial and density distribution of the cloud allows us to produce models that can be constrained by comparison to observations. The study of the zodiacal cloud also provides a benchmark for comparison to the observed distribution of dust in debris disks around other stars and models for their production and evolution. This relates to the nature of small bodies elsewhere in the universe and the process of planetary formation.

a. Does the Kuiper belt produce a cloud of cold dust similar to that seen around most other main sequence stars (cf. Vega)? What is the structure of this outer zodiacal cloud?

III. Required Research and Research Facilities

The community needs continued R&A support of investigations into the nature of dust in the solar system. Specific areas to focus on are:

Continued collection experiments including airborne, ice fields, and sedimentary deposits.

An average of roughly 100 tonnes per day (Love and Brownlee, 1993) of interplanetary dust is accreted by the Earth (although not all of this material survives passage through the atmosphere unaltered). The Earth, therefore, acts a large-area collecting facility, sweeping up the particles, which can be collected by research aircraft that fly in the stratosphere, extracted from ice fields, or sedimentary core samples taken from the ocean floors. Support for continued retrieval of these particles is a relatively low-cost way to obtain samples of IDPs (Science Question 1).

Continued laboratory analysis of collected particles

Laboratory analysis provides the ground truth for the properties of IDPs. The mineralogy, chemistry, and isotopic compositions of IDPs provide direct constraints on the origins and histories of their parent bodies. Such studies can reveal the nature of the parent body source materials, thermal history, extent of water:rock interaction, chemical evolution, and even timescales for these processes. The sizes, densities, polarization and composition of these particles improves understanding of the formation and survival of the IRAS infrared dust bands, the zodiacal light, processes in comet tails, and space weathering effects on asteroids and other airless bodies (Jessberger et al., 2001). Laboratory analyses of these samples are both broad in scope and extreme in detail, including atomic-scale mineralogy by transmission electron microscopy; chemical bonding state by infrared, Raman, and beamline spectroscopy; and isotopic compositions by ion microprobe. Continued support of such facilities is essential. Some specific measurements of interests include:

a. Measurement of dust exposure times for particles using cosmogenic isotopes to determine the dynamical and collisional history of the particles (Science Question 2).
b. Analysis of the long-term evolution of the interplanetary dust flux (Science Question 3) through measurements of He^3 in recovered sedimentary deposits (e.g., Farley, 2006).
c. Identify the building blocks of the solar system – build a full mineralogical and organic inventory of nebular and presolar materials by isotopic, mineralogical, and chemical studies of IDPs.

Support for ground-based observation facilities and instruments

Support for ground-based spectrometers that can obtain Doppler shifts of scattered solar Fraunhofer lines in the zodiacal light. Such instruments provide a unique opportunity to explore and monitor the large-scale kinematics of interplanetary dust in the inner solar system by providing dust particle trajectory and speed over a broad range of particle sizes and with large sky coverage (e.g., Hicks et al., 1974; Reynolds et al., 2004; Madsen et al., 2007; May, 2007). (Science Questions 2 and 3).

Support for radar and optical facilities that monitor that monitor the meteor environment, including both sporadic background and shower meteor showers (Science Questions 2 and 3). This must also include support for modeling that allows one to correlate the observed properties of the meteor (i.e. signal strength and altitude) with properties of the meteoroid/dust particle (i.e. mass, radius and density).

Support for continuing ground-based characterization of comet and transition object dust production. Comets are one of the primary sources of interplanetary dust in the inner solar system (Kresak and Kresakova, 1987; Lisse, 2004). However, the details of their dust production over their orbits and as they age is only superficially known. Detailed synoptic studies of a large number of comets at visible and thermal infrared wavelengths are needed to better understand this process. The same studies should be applied to transition objects, which are known to experience intense outbursts (e.g., Centaurs: 29P), in order to better understand the dust production mechanism (Trigo-Rodríguez et al., 2008). (Science Questions 2 and 3).

Support for ground-based facilities to map and characterize (through modeling) the meteoroid streams throughout the year and establish meteor showers (Science Questions 2 and 3). There are 360 showers in the IAU Working List of Meteor Showers, only 64 of which are established. Each shower is an archeological record of past comet activity. When the parent body can be identified, it is possible to determine the epoch of ejection and today's three-dimensional distribution of the stream in the solar system. Complementary support is also needed for facilities that can increase the efficiency of recovery of meteorites from fresh falls.

Support for data archiving, distribution, and access

Recent spacecraft data important to the study of interplanetary dust (e.g., Galileo, Ulysses, Cassini, IRAS, COBE) is available in the NASA Planetary Data System or in astrophysics archives. However, compositional and morphologic data on IDPs curated at the Astromaterials Curation Facility at NASA Johnson Space Center are largely captured in pdf files and are not available in a searchable database. (Science Question 1).

Support for dynamical modeling

The orbital evolution of interplanetary dust requires a significant amount of modeling, due to the diverse nature of the dust sources, the different dust production mechanisms, and the complex dynamical and collision evolution of the dust particles. Continued research support is necessary for these ongoing efforts towards producing models that link particles to sources and reproduce the observed structure of the interplanetary dust complex. Creation of a global zodiacal cloud model is not only of intrinsic interest to those who study interplanetary dust, but is also important to researchers whose sole interest is to remove it as a foreground contaminant in observations of diffuse astronomical structure at wavelengths spanning the UV through the far-IR (e.g., Hauser and Dwek, 2001). (Science Questions 2, 3, and 4).

Support for spaceborne facilities and instruments

Spaceborne observations of meteors in the Earth's atmosphere make it possible to study the bulk carbon content of meteoroids. Ground-based observations of meteors provide data on their main element abundances via impact induced breakdown spectroscopy, but the more interesting bulk carbon content can only be measured by spaceborne sensors that can see the strong UV emissions of atomic carbon. (Science Question 1).

IV. Technology Needs

Trajectory Sensor

In order to test models of the evolution of dust particles and identify sources (Science Question 2), we need to be able to accurately determine their velocity vectors. There should be investment in dust trajectory sensors that make use of the electric charge that all particles in space carry (Srama et al., 2006; Auer et al., 2008). The utility of such a system has been demonstrated by the Cassini Comic Dust Analyzer (CDA) (Kempf et al., 2004), but needs to be explored for large area detectors.

Dust Mass Spectrometer/Collector

Spacecraft dust analyzers have been too small (< 0.01 $m^{2)}$ or less to accurately measure the low dust fluxes in interplanetary space. It is feasible to build a much larger area (> 0.1 m^2) mass analyzer based on a reflectron mass spectrometer design (e.g., Sternovsky et al., 2007; Srama et al., 2008). One method is to use a mass spectrometer. It has been determined that an instrument could obtain mass spectra with a resolution five times better ($M/\Delta M > 100$) than that of the Cassini CDA and that is also well suited to determine the composition of particles with impact velocities above 100 km/s.

Precision Capture Technologies

There should be research into combining the successfully demonstrated technologies of trajectory sensors (above) and aerogel capture (e.g., Brownlee et al., 2006). This would be of particular value for measurements of low fluence IDPs, allowing timing and pointing precision for captured particles. This would allow determining the orbital parameters of specific particles and thus constrain their sources.

Nano-Dust and β-Meteoroid Analyzer

β-meteoroids and interplanetary nano-dust have only been observed by impacts on simple detectors and on spacecraft skin. In order to obtain compositional information of this important loss mechanism of zodiacal dust a new type of dust mass spectrometer is needed. This instrument has to resist extended periods of Sun pointing with high thermal heat input and with interferences from solar UV and solar wind exposure. Methods used in space coronagraphs and solar wind instruments need to be employed to solve these problems.

Automated Meteoroid Orbit Surveys

Detection systems are needed that can measure the trajectories and speeds of bright (+6 to -6 magnitude) meteors in the Earth's atmosphere and determine large numbers of meteoroid orbits, in order to establish meteor showers and identify their parent bodies. Current radar-based systems have limited precision, leaving us with a blurry view of the directions and speed of incoming meteoroids. They also target relatively small meteoroids, which are dominated by sporadic meteoroids from which meteor showers are difficult to extract. To suppress this background and obtain more precise results in sufficient numbers, technologies need to be developed that efficiently target brighter meteors.

V. Major Mission Priorities

Leveraging Missions to the Outer Solar System

Missions to the outer solar system will necessarily be of the New Frontiers or Flagship classes. The infrequency and expense of such missions requires maximizing their science return, and including instrumentation capable of studying outer solar system dust is a high (Science Question 4a). The instrument suite considered should include particle detectors (sensitive to individual small particles and capable of determining orbital information), visible to far-infrared light detectors (capable of imaging the distribution of dust via the sunlight it scatters or the heat it radiates), as well as a spectrometer that can take advantage of the solar Fraunhofer lines to distinguish zodiacal from interstellar light and measure dust composition through near-infrared mineral bands (Science Question 1a). It is reasonable to expect dust in the Kuiper belt region to be structured in a way similar to the inner zodiacal cloud and evidence regions of collisional activity (Question 2a).

VI. Discovery Science Goals

Because of the accessibility of the full range of IDPs in the vicinity of the Earth's orbit, Discovery class missions can be designed capable of addressing the entire suite of top-level science questions for interplanetary dust. This is facilitated by the ability to deploy in near-Earth space remote observing facilities, in situ analysis technologies for dust studies, and sample return experiments that can target specific dynamical populations that may better constrain their source regions.

VII. Balancing Priorities

The study of interplanetary dust provides insights in to the nature and evolution of all small bodies in the solar system. In order to maintain the capability of conducting dust experiments on spacecraft to the outer solar system or benefit from a Discovery class dust mission, there needs to be an ongoing level of support for the study of dust production and dynamics, analysis of mission data pertaining to dust, the laboratory analysis of dust particles and their continued collection on the Earth using aircraft and via field work. This research should be ongoing whether or not space-based dust experiments or dust missions are in development or in-flight (though if in-flight, there may be additional research needed for specific mission support).

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