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Dust Astronomy: New Venues in Interplanetary and Interstellar Dust Research

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Abstract. Dust Astronomy is a new research area which investigates the properties of and the link between the interplanetary and interstellar dust. Both, in-situ methods as well as remote sensing methods like optical and infrared observations are used to study the physical and chemical properties of the dust. These measurements need to be complemented by ground-based meteor studies and the analysis of collected dust samples. Major goals for the next decade are to characterize the Kuiper belt dust, the zodiacal and interstellar dust complex. It is recommended that (1) all missions to the outer solar system carry an in-situ dust detector, (2) a Cosmic Dust Observatory should be launched into heliocentric orbit,

and (3) a Heliocentric High-Inclination Explorer infrared mission should be realized.

EXECUTIVE SUMMARY

Dust particles, like photons, are born at remote sites in space and time. From knowledge of the dust particles' birthplace and the particles' bulk properties, we can learn about the remote environment out of which the particles were formed and how those particles have evolved physically and dynamically. Moreover, dust dominates the thermal emission of our planetary system and other planetary systems, therefore studying interplanetary dust teaches us how the solar system appears from space, and it helps us to interpret observations of other planetary systems.

The study of dust in the planetary system has been, and will be, a prime goal of many NASA missions. Missions to the dust rich environments of comets and planetary rings carried, and will carry, one or several dust instruments. In addition, interplanetary missions, like Pioneer 10 and 11, Helios, and Ulysses performed studies of the interplanetary dust environment among their primary objectives. Future missions to the unexplored regions on the solar system map, such as the Solar Probe missions, missions to study long-period comets, orbiter missions to Uranus, Neptune, and Pluto, and missions to the Kuiper belt and beyond, will carry dust instrumentation. Small dedicated missions to study the dust environment at 1 AU and in near-Earth space will also carry sophisticated dust detectors. In addition to in-situ methods, optical and infra red remote sensing methods of observing dust will allow us to make a global assessment of dust origin and production in our solar system and its context within the local interstellar environment, and will provide insights into basic processes within our solar system that are directly applicable to planetary systems around other stars. Because of the complex nature of dust particles, the study of space dust requires a multi-disciplinary approach: space measurements, both by in-situ and remote sensing methods need to be complemented by ground-based meteor studies, analyses of collected samples, simulation experiments and theory. Priority questions for the next decade are:

- Is there dust in the Kuiper belt and what is its distribution and density?
- What are the compositions of the components of the zodiacal dust complex and how do they vary spatially and temporally?

Recommendations for the next decade are, in order of importance:

- All missions to the outer solar system, in particular missions to Pluto and beyond, should include an in-situ dust experiment for detecting and determining the properties of local dust
- A "Cosmic Dust Observatory" should be launched into heliocentric orbit near 1 AU to measure compositional, physical, and dynamical properties of interplanetary dust particles (which should include dust from identified comets). There should be coordination between this observatory and collection experiments from the Earth's upper atmosphere.

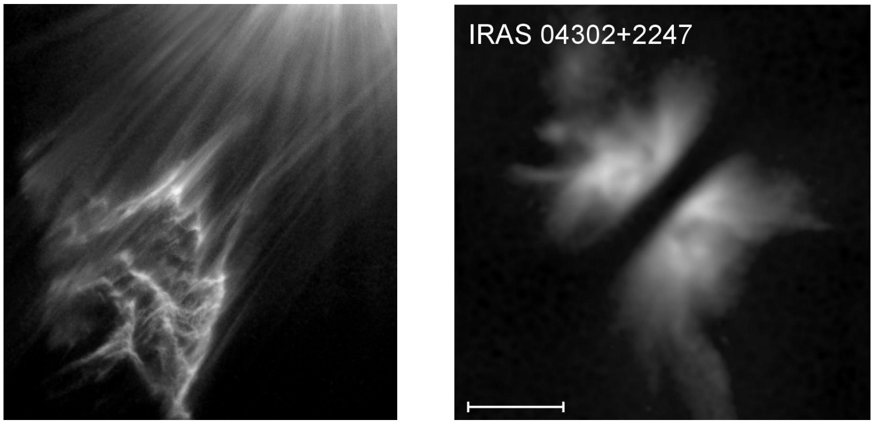

Figure 1. Reflection nebula in the Pleiades (left). An interstellar dust cloud is illuminated by a near-by star (above the top). Right: Young stellar disk around IRAS 4302-2247. The dark dust band obscures the central star and is probably the birth place of planets (HST images).

- A Heliocentric High-Inclination Explorer mission consisting of a cryogenically cooled thermal infrared telescope that 'looks over' the inner zodiacal cloud to study dust in the outer solar system and investigate the structure, sources, and sinks of the inner zodiacal cloud.

All recommendations require support for continuing theoretical studies of dust dynamics, modeling of past observations, and laboratory studies to characterize the composition and physical properties of dust.

REPORT

1. Current State of Knowledge

Cosmic dust particles evolve chemically, physically and dynamically. The evolution of dust traces out paths in which the universe recycles material: production, storage, processing, collection, consumption, and discarding. In stellar winds of evolved stars, new dust is formed and is injected into interstellar space. Young stardust is mixed with old heavily-processed diffuse interstellar dust, and is subject to passing supernova shocks and ultraviolet radiation. Dusty clouds form (Figure 1). Star formation in cool molecular clouds becomes both a sink of old dust, as well as a source of new dust. A typical dust grain anywhere in space will have undergone several cycles.

Dust in a planetary system is the most processed (being formed, destroyed, and/or locked into a near-pristine state) of the different populations of cosmic dust. Interplanetary dust is permanently replenished by dust ejected from cometary nuclei, the most pristine bodies in the solar system, and released from collisions in the asteroid and Kuiper belts. In our solar system, interplanetary dust exists alongside interstellar dust, which is flowing through the solar system, offering a tangible, physical link between our planetary system and the stars.

The planetary system hosts a variety of dusty phenomena, such as scattered light, thermal emission, impacts on solid bodies and on atmospheres. Cosmic dust can be found in cometary comae and tails, in planetary rings, on asteroidal regolith, in the Earth's stratosphere, in polar ices, and in the interplanetary dust cloud, which is permanently replenished by interstellar, cometary and asteroidal dust.

One of the source mechanisms for dust is hypervelocity impacts of micrometeoroids, interstellar grains, or ring particles onto the surfaces of solar system bodies (planetary satellites, asteroids, atmosphereless planets Mercury and Pluto, KBOs etc.). For example, Mercury, an atmosphereless planet orbiting the Sun in the densest part of the interplanetary dust complex, must experience intensive meteoroidal bombardment and should be surrounded by a pronounced ejecta cloud. Recent in-situ detections of ejecta clouds around Galilean satellites of Jupiter and future measurements of dust swarms around other bodies (e.g., outer Saturnian moons by Cassini) can be considered as a natural impact experiment. Such studies will allow us to get more insight into impact physics in space and to extend the lab impact experiments to a broader range of masses and speeds, astrophysically relevant materials and morphologies of targets and projectiles, and microgravity conditions.

Once produced, dust grains are moving through complex gravitational, radiation, and magnetic fields and plasma environments. Studying the dust dynamics and comparing the results with remote and direct observations allow one to indirectly probe the properties of these fields and environments and in such a way, to complement direct measurements.

Planets and extrasolar dust disks (Figure 2) are manifestations of the same phenomenon called a planetary system. Circumstellar dust is the material from which, and in which, planets are formed. Dust is an excellent indicator of physical processes and larger bodies in a circumstellar disk - comets and planetesimals (that continuously replenish the dust cloud) and planets (that perturb dust disks directly as well as indirectly, through dynamical sculpturing of the dust parent body populations). Dust, however, is much easier to observe than the planets. The masses of the observable disks in Vega-type systems are estimated to be less than the Earth's mass, whereas planets of such masses are far beyond the detection limits. The properties of dust and their change with time fully reflect the evolution of a planetary system and may serve as a measure of the evolutionary stage of an evolving planetary system.

An early motivation for the study of dust in space was the risk imposed by impacts of meteoroids onto man-made satellites. From that early motivation a large number of primitive dust detectors were launched into near-Earth space. After it was recognized that the natural meteoroid flux is low and that the risk can be mitigated by simple technical means, the early motivation ceased to exist. Subsequently, the motivation for the study of dust in space shifted to astrophysical questions about the physical and chemical properties of the grains, their contemporary sources and sinks, and their significance as probes of the conditions during the formation of the planetary system. This is documented by dust measurements in the inner planetary system (Helios), at comets (Giotto,

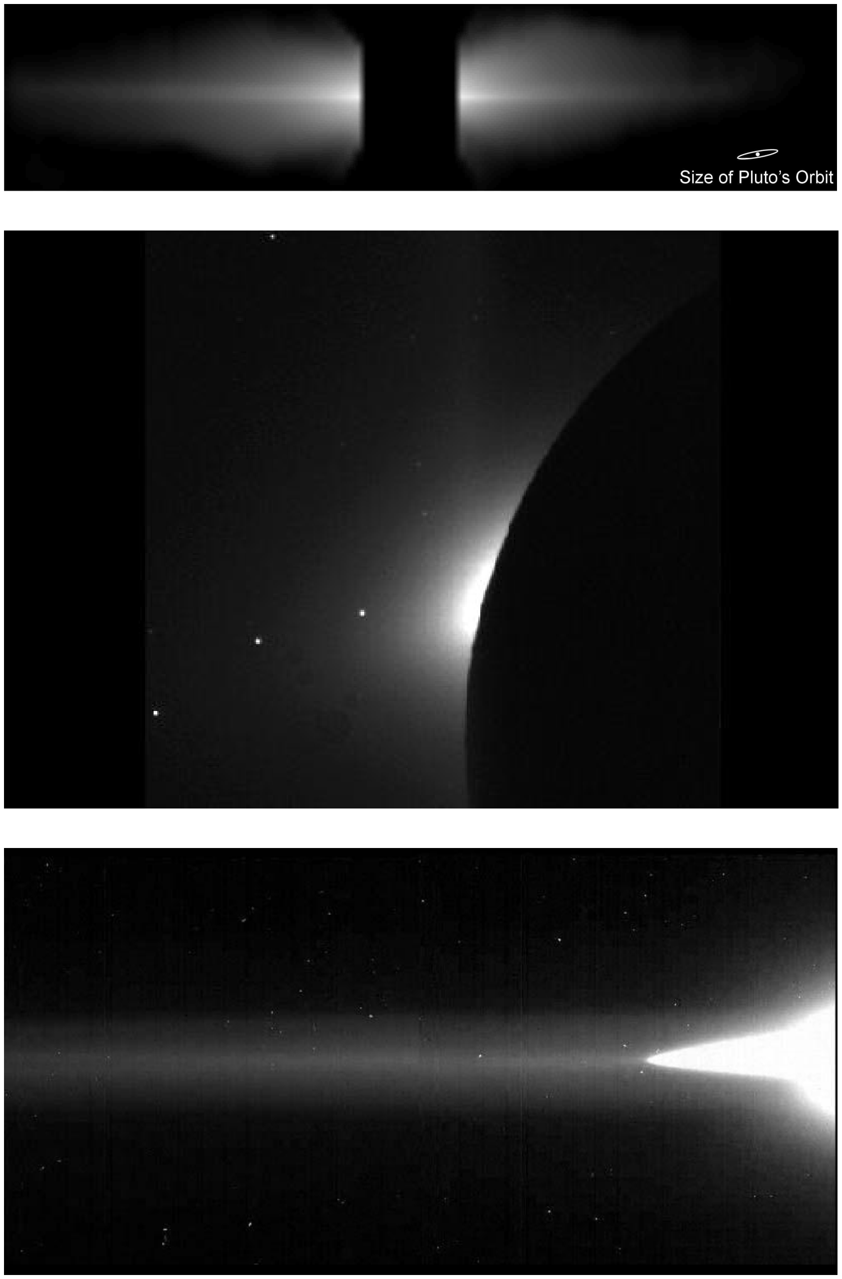

Figure 2. Dust disks. Top: Edge-on view of the dust disk around the star beta Pictoris (HST image). This disk is a model for the suspected Kuiper belt dust ring of our solar system. Middle: Inner zodiacal dust cloud, partially obscured by the moon (NASA Clementine image). Bottom: Jupiter dust ring. Outside the bright central ring is the faint gossamer ring that derives from the Jovian satellites Amalthea and Thebe. (NASA Galileo image)

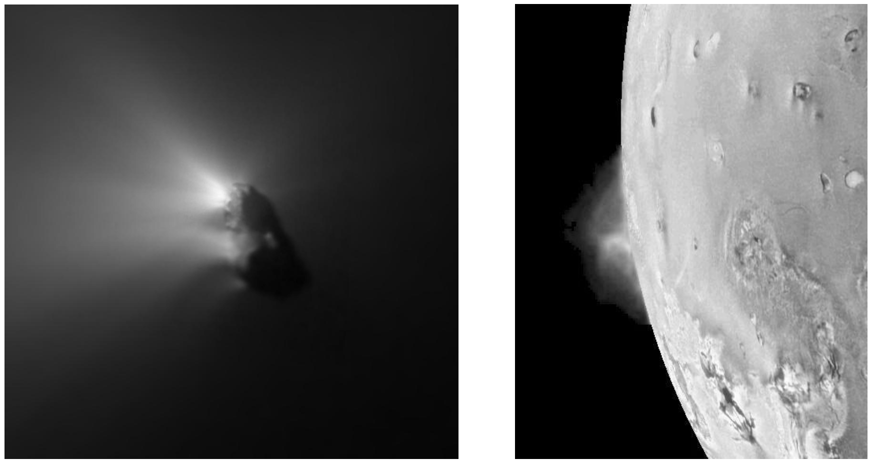

Figure 3. Dust formation. Dust emission from Comet Halley (Giotto image, courtesy H.U. Keller). Right: Volcanic plume on Jupiter's moon Io. Nanometer-sized dust escapes Io and is ejected by Jupiter's magnetic field (NASA Galileo image).

VeGa, Stardust), in the vicinity of Mars, Jupiter, and Saturn (Nozomi, Galileo, Cassini) and above the poles of the Sun (Ulysses) (Figure 3). The recognition that manned activity in near-Earth space left a growing amount of space debris lead to the deployment of an increasing number of small dust impact detectors in low Earth orbit, like Spadus and Debie. However, within the Earth debris belts, the natural meteoroid background is obscured.

The dust detectors on the Galileo, Ulysses and Cassini missions have a high sensitivity (0.1 μm particles) together with a large sensitive area (0.1 m^2) and enable the study of difficult-to-detect effects, such as the passage of interstellar grains through the planetary system (which cannot be identified by smaller detectors because of a too low number of recorded dust impacts). The combination of an impact ionization detector with a time-of-flight mass spectrometer provides the capability of a chemical analysis of the recorded dust grains. Such instruments have been used in the Halley missions and an upgraded version flies on the Stardust mission to comet Wild 2. The Cosmic Dust Analyzer, CDA on the Cassini mission, is the most versatile dust detector. It combines a large impact area with a mass spectrometer. In addition, it measures the electrical charge of dust particles, which provides a refined measurement of the dust speed and trajectory. A smaller impact ionization detector, the Mars Dust Counter, MDC on the Nozomi mission, is currently en route to Mars, where it will characterize the Martian dust environment.

There are other methods to collect and analyze cosmic dust at Earth: Interplanetary dust particles can be collected in the stratosphere by aircraft or micrometeoroids can be extracted from the Antarctic ice (Figure 4). From analyses of these particles, compositional, mineralogical, and structural information is obtained. The composition, shape, and density of the particle affects all physical processes acting on the particle, such as the Poynting-Robertson drag force and the charging currents. One result from particle density measurements is

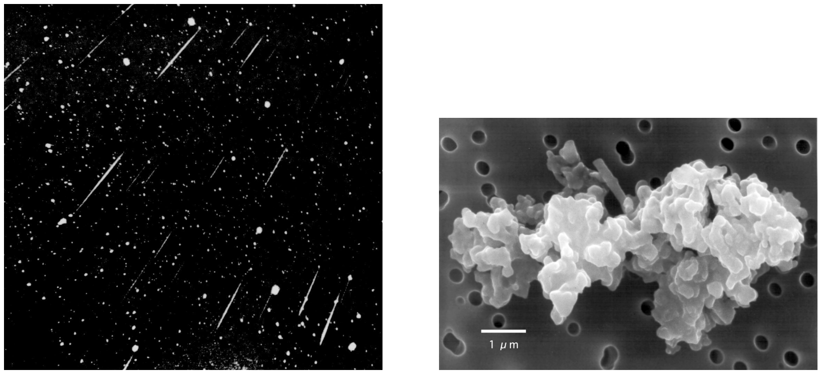

Figure 4. Dust reaching the Earth. Left: Leonid meteor storm as observed in 1966. Centimeter-sized particles enter the Earth's atmosphere. Right: Interplanetary Dust particle collected by high-flying airplane (NASA image).

that common IDPs are much more porous than meteorites, with a typical density of ca. 2 g/cm^3 corresponding to a porosity near 40%. Particles with a density below 1 g/cm^3 do exist, but they are rare. Microcraters on satellite surfaces (e.g., LDEF or on lunar rocks) provide knowledge of the overall dust flux over a wide size range from micrometer to millimeter sizes. On the basis of this information, an interplanetary dust flux model at 1 AU distance from the sun has been formulated. The model covers a mass range from 10^{-18} to 10^2 g.

Zodiacal light observations have been performed from the ground, from Earth satellites and from deep spaceprobes. With the photometers on board Helios, a radial brightness profile of zodiacal light was determined between 0.3 and 1 AU. Outside the Earth's orbit, zodiacal light was observed by photometers on board Pioneer 10 and 11. The zodiacal light brightness was found to exceed the background out to 3.3 AU distance from the Sun.

Once the technology for spacebased infrared observations was developed in 1984, the IRAS satellite and, later, the COBE satellite, obtained unprecedented information on the overall structure of the zodiacal cloud. Besides the large-scale structure of the zodiacal cloud, broad asteroidal bands, as well as narrow comet trails, were discovered that directly relate to asteroidal and cometary sources of the zodiacal cloud. Models have been derived that describe the infrared brightness of these phenomena as observed by COBE with an accuracy of better than 3%.

In the mass range $m > 10^{-7}$ g, radar and photographic meteor observations provide independent information on the orbits of these particles. The Arecibo radio telescope in radar mode can detect meteors from grains of masses $m > 10^{-11}$ g.

Dynamical models have been constructed on the basis of meteor data, zodiacal light observations, and spacecraft measurements that predict the distributions in mass and orbital elements of interplanetary dust grains. While these models describe the current state of the meteoroid population, the origin of these particles is generally unknown. No evolutionary models have been constructed that reliably describe the relative contributions from asteroidal, cometary, Kuiper belt and other sources to the solar system dust cloud.

2. Key Science Questions

The field of space dust research is far from complete. Despite the great advances made in the last years of the understanding of the interplanetary and planetary dust environments, there remain many important questions to be answered. Starting close to the Sun, nature separates meteoroid material according to its volatility. Analysis of the spatial distribution of matter close to the Sun will immediately give us information on the volatility of its constituents.

Closer to home, the dust environment of the Earth is of interest, because mankind is affecting this environment due to its space activities. However, the natural dust environment is also of technological and scientific interest. Hazards from meteor streams (like the Leonids) will require continuous attention. Meteoroids that pass the Earth are of scientific interest because they are messengers from distant worlds, like asteroids, comets and even interstellar space. Once we know from where dust grains originate, compositional analysis of grains can tell us many things about these worlds. Therefore, the goal of such dust studies is to identify the sources of dust particles together with their in-depth analysis. The future of dust measurements in Earth orbit lies in three areas: (1) environmental monitoring, (2) use of dust telescopes to separate and analyze dust populations of different origin, and (3) collection and sample return of dust from various sources for in-depth analysis in laboratories.

Analysis of particulates from comet Halley brought us new and important information that has relevance to the understanding of the formation of our planetary system. Currently, the Stardust mission is on its way to analyze, collect and return dust from comet Wild 2. This will give us a second example from the large variety of comets. Analyzing different comets will tell us about the spatial and compositional variations in the protoplanetary nebula through the comets, which may have sampled different regions of this nebula.

Enhanced dust densities in the Martian planetosphere have long been suspected. The comparison of future dust observations at Mars with those in the dusty rings of Saturn and the other giant planets will tell us the effects of solar radiation pressure (strongest at Mars) and planetary magnetospheres (negligible at Mars).

All giant planets have ring systems which display a variety of different "dusty" phenomena. While Saturn's ring system is of high complexity, the rings of Jupiter, Uranus and Neptune show other features that have not yet been found elsewhere. The Pluto-Charon system may have rings with yet other features. To understand the common characteristics of all these rings, and the reasons why they are so different, requires detailed measurements of the rings and their environments.

Detection of Kuiper belt objects (KBOs) of up to a few 100 km diameter confirmed the existence of objects beyond the orbits of the planets. Mutual collisions among KBOs, as well as impacts of interstellar grains, generate dust locally. The action of the Poynting-Robertson effect, together with resonances with the outer giant planets, interaction with the solar wind and neutral interstellar gas, may have lead to radial and azimuthal structure of the distribution of dust at the edge of the planetary system. The detection of infrared excesses in main sequence stars began a renewed interest in the outer extensions of our own solar system dust cloud. The observation of dust disks around beta Pictoris and epsilon Eridani stimulated this interest. Observations of the Kuiper dust belt in our solar system can, therefore, be used as a model for extra-solar dust clouds and can help to reveal information about other planetary systems.

Effects of the solar cycle-dependent heliosphere reach into interstellar space out to about 300 AU from the Sun, where it interacts with the small (<0.1 micron) particles entering the heliosphere and modulates their flow. The tiny particles' origin, however, may be different from that of bigger grains that are accessible in Earth orbit. We know that evolved stars continuously lose mass. This "stardust" provides the seeds for ISD grains, that grow in cool interstellar clouds by accretion of atoms and molecules and by agglomeration. An unbiased look into this interstellar dust factory will provide us with information on processes that are difficult to quantify by astronomical observations alone. Therefore, in-situ dust measurements will be an important analysis tool when automated probes will leave our solar system.

Dust studies may be broken down into the following key areas:

- Dust inventory in the solar system
  - What are the spatial, size, and temporal distributions of dust in the solar system?
  - How important are comets, asteroids, and Kuiper belt objects as sources of the solar system dust cloud?
- Structure of the solar system dust cloud
  - What are the radial and latitudinal distributions of the solar system dust cloud?
  - What is the configuration of the symmetry plane dust of solar system dust cloud?
  - What is the fine structure dust of solar system dust cloud (comet trails, asteroidal bands, planet shepherding rings, and other local phenomena)?
- Specific dusty environments in interplanetary space
  - How is dust of different volatilities separated in the F-corona?
  - What is the chemical, isotopic, and mineralogical composition of dust from short-period and long-period comets?
  - What is the dust environment in the asteroid belt?
  - What are the processes of dust generation and dispersion in the Kuiper belt?
  - What is the temporal and spatial evolution of meteor stream dust, e.g., in the Leonids?
- Dust in planetary environments

- What are the characteristics of the Mercury ejecta cloud?
- How do natural and man-made debris evolve in near-Earth space?
- What is the dust mobility on the lunar surface?
- What is the dust environment of Mars?
- How different are the rings and dust environments of Jupiter, Saturn, Uranus and Neptune?
- How much dust is in the Pluto-Charon system?
- What role does dust play as a medium for material transport in planetary environments?

• Interstellar dust inside and outside the heliosphere

- What is the flow of ISD through the heliosphere?
- How important is size-dependent filtering of ISD in the heliosphere and at the heliospheric boundary?
- What is the chemical and isotopic composition of interstellar dust grains in the heliosphere?
- How do dust grains evolve in interstellar space?
- What is the interstellar dust size distribution and how significant are large interstellar dust grains contributing to the total dust content of the local interstellar cloud?
- How significant are spatial and compositional variations of the local interstellar dust cloud?
- How strongly is the chemical evolution of the local interstellar cloud coupled to the overall chemical evolution of the Galaxy?
- What are the key ejection mechanisms for ejection of dust from a planetary system into interstellar space?

• What do dust observations tell us about the space environment and about basic planetary processes?

- Dust ejecta clouds as natural impact experiments
- Dust as probes of remote plasma and fields environments
- Dust as monitors of volcanoes (Io) and geysers (Triton)
- Dust processes in the Kuiper belt as a model for extra-solar dust clouds
- Dust-magnetosphere interactions, dusty plasmas in space
- Levitation and dust transport on planetary and asteroidal surfaces

3. How Do We Address Key Science Questions?

3.1. From space

- Determine the large- and fine-scale structure of interplanetary and planetary dust clouds.

  This requires remote sensing observations of the dust distribution using scattered sunlight and thermal radiation throughout the solar system. Dedicated instrumentation may be needed to provide successful measurements.

- Characterize the dust environment throughout the solar system

  Perform in-situ measurements of dust distribution and of dust properties, and fly dust instrumentation on missions to unknown territory, e.g., the F-corona, the Kuiper belt and the planetospheres of Uranus, Neptune, and Pluto. Appropriate dust instrumentation should determine the radial profile of dust density, the orbital distribution, physical, and chemical properties of dust.

- Analyze the orbital characteristics and chemical composition of various dust components in interplanetary space: interstellar dust and interplanetary dust of cometary and asteroidal origins.

  These types of measurements require a spacebased "Dust Telescope". Such a dust telescope is capable of providing mass, speed, physical and chemical information of dust grains in space. Particle origins are identified by their trajectories, which need to be determined with sufficient accuracy. Information on the physical and chemical composition is obtained from impact signals when dust particles hit versatile dust detectors. Targets for such telescopes are: dust from meteor streams, comets, asteroids, the Moon, and interstellar space (passing dust through the solar system). It provides a cost-effective means of geochemically sampling targets which are otherwise inaccessible by spacecraft. Even though a dust telescope should first be employed in near Earth space (outside the dense debris belts), it is foreseen that this kind of telescope will provide valuable information also in planetary environments and in the outer regions of the solar system.

- Collect and return samples of dust from various sources (comets, asteroids, interstellar dust) at 1 AU and beyond.

  Interplanetary grains collected by high-flying aircraft have been successfully analyzed in many laboratories. Stardust is the first mission planned to provide dust samples from a short-period comet, and, perhaps, a few interstellar grains. Future missions in interplanetary space at 1 AU and beyond will be able to return dust samples from asteroids, long-period comets and interstellar grains.

3.2. From the ground

- Extend the trajectory studies of meteoroids to larger masses by performing optical and radar meteor studies.

  Optical and radar meteor studies will expand the dynamic studies of meteoroid orbits to larger masses than those obtained by space measurements.

- Establish a "Dust Laboratory" which provides the infrastructure for the development and calibration of advanced dust instruments

  A Dust Laboratory should serve the scientific community with state-of-the-art simulation facilities for the study of dusty phenomena. Key facilities should be dust accelerators that extend the capabilities of the only operational dust accelerator facility in Germany. A dust accelerator serves for instrument development and calibration and for studies of effects of hypervelocity impacts on space systems. Besides studying impact processes, it provides a means for characterizing detrimental effects on sensitive space instrumentations, e.g., optical surfaces, x-ray detectors, and neutral particle detectors.

- Develop advanced in-situ and remote sensing space dust instrumentation

  A dust telescope requires new advanced analyzers for trajectory and composition measurements. These analyzers should have large (0.1 to 1 m^2) sensitive areas in order to provide statistically meaningful numbers of impacts in interplanetary space. Light weight detectors of even larger impact areas require novel design of sensors and signal processors. Dedicated infrared instruments that work in the 10 to 200 micron wavelength range without requiring active cooling could provide key information on the structure of and the dust production in the outer zodiacal cloud and Kuiper belt.

- Maintain and extend the laboratory facilities to analyze dust particles

  A wide range of micro-analytic tools is being used for elemental, isotopic, mineralogical, and morphological analysis of extraterrestrial dust particles: electron microscopy in conjunction with energy-dispersive X-ray analysis, X-ray fluorescence, neutron activation, and proton as well as synchrotron induced X-ray emission, and secondary ion mass spectrometry. These and even more powerful methods need to be developed in the future in order to make the best use out of samples returned from planetary bodies. Some methods require major facilities, such as the synchrotron light facility at the Brookhaven National Laboratory, which should be available for future cosmic dust studies.

- Perform theoretical studies of dust origin and evolution

  Further development of evolutionary models of the interplanetary dust cloud and of the dusty planetary environments. The current empirical dynamic models of the interplanetary dust cloud do not provide reliable extrapolations to regions were no previous measurements were taken.

4. Priority Issues for the Next Decade

A. Is there dust in the Kuiper belt and what is its distribution and density?

The dust population in the outer solar system is the largest single unknown in our understanding of the dust inventory of the solar system and its structure. Determination of dust densities in that region would provide an important constraint to the level of past and ongoing collisional activity.

B. What are the compositions of the components of the zodiacal dust complex and how do they vary spatially and temporally?

Through impact detection and remote observations, we have identified the general morphology of the interplanetary dust cloud within Jupiter's orbit, as well as identified significant sources of dust production in some asteroid families and comets. Knowledge of the relative and specific contributions from sources (which are presently very uncertain) would reveal structures (otherwise degenerate along our line of site) and allow us to better model the evolution of the cloud.

5. Recommendations

In order of importance:

- All missions to the outer solar system, in particular, missions to Pluto and beyond, should include an in-situ dust experiment for detecting and determining the properties of local dust

  This directly addresses priority issue A and is a low cost alternative to a stand alone mission.

- A "Cosmic Dust Observatory" should be launched into heliocentric orbit near 1 AU to measure compositional, physical, and dynamical properties of interplanetary dust particles (which should include dust from identified comets). Such a facility could be constructed, making use of the Cassini Composition Dust Analyser design. There should be coordination between this observatory and collection experiments from the Earth's upper atmosphere.

  This directly addresses priority issue B.

- A "High-Inclination Explorer" mission consisting of a cryogenically cooled thermal infrared telescope that "looks over" the inner zodiacal cloud to study dust in the outer solar system.

  This directly addresses both priority issues A and B.

NOTE: All recommendations require support for continuing theoretical studies of dust dynamics, modeling of past observations, and laboratory studies to characterize the composition and physical properties of dust.