Solar System Debris Disk - S2D2

Image credit: NASA/JPL-Caltech

Proposal for Science Themes of ESA's L2 and L3 Missions

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Summary

Understanding the conditions for planet formation is the primary theme of ESA's Cosmic Vision plan. Planets and left-over small solar system bodies are witnesses and samples of the processing in different regions of the protoplanetary disk. Small bodies fill the whole solar system from the surface of the sun, to the fringes of the solar system, and to the neighboring stellar system. This is covered by the second theme of Cosmic Vision. Associated with the small bodies is a Debris Disk of dust and meteoroids that are constantly generated from the disintegration of their parent bodies due to a wide range of processes.

In recent years the solar system is no longer the only planetary system available to study. An ever-growing number of extra-solar planetary systems is being been discovered. Either the planets are seen directly, or the effects of the planet on their central star or on their environment are observed. Planets form in a protoplanetary disk from collapsing interstellar material which is mixed and heated and, finally, condensed and agglomerated into planetesimals that accreted into planets. Material not consumed in planets remains in a wide disk of planetesimals around the central star.

Debris disks have been identified around a significant fraction of main-sequence stars using the mid or far infrared excess in the spectral energy distribution of the stars. Debris disks are optically thin and mostly gas-free disks of 1 µm to 100 µm-sized dust grains. Such short-lived grains are continually replenished through mutual collisions in a ring of unseen km-sized and bigger planetesimals.

Most of the concepts required to explain extra-solar debris disks have been developed from observations of our own solar system debris disk. However, the detailed processes (the combination of planetary scattering and collisional shattering) and the resulting large-scale structure of this disk remain obscure. Indeed, our own solar system has inner and outer debris disks that are directly analogous to those in exoplanetary systems. Moreover, the best current models of the interplanetary dust environment are not in agreement.

Unlike extra-solar debris disks, knowledge of the solar system debris disk comes mostly from direct observations of the parent bodies. The sizes of these parent bodies range from Near Earth Asteroids with sizes of a few 10 m, to km-sized comet nuclei, to over 1000 km-sized Trans-Neptunian Objects. The inner zodiacal dust cloud has been probed by remote sensing instruments at visible and infrared wavelengths, micro crater counts, in situ dust analyzers, meteor observations and recent sample return missions. Nevertheless, the dynamical and compositional interrelations between dust, interplanetary meteoroids, and their parent objects are still largely unknown. No similar observations exist for the outer debris cloud.

An additional scientifically important population of dust is interstellar dust passing through the solar system. These grains are the present day version of the raw material that was collected in the protoplanetary disk, heated, mixed, and reassembled in planetesimals and planets.

To develop our understanding of exoplanetary systems, we thus need to study our own system. This requires two complementary missions:

- **S2**: for the first time, we will have a 'bird's eye view' of our inner debris disk in the infrared to examine the extent and fine structure of the 'warm' zodical cloud, and finally we may observe the 'cold' outer Trans-Neptunian disk.
- **D2**: an in-situ observations and sample return mission to probe the orbital and compositional connection between the dust in the inner interplanetary debris disk and its source bodies, mapping the sky in dust. This mission will provide a direct comparison of the composition of interstellar raw material with the more processed material from comets and asteroids.

The dynamical and compositional interrelations between dust, interplanetary meteoroids and their parent objects are still largely unknown. The outer debris cloud of our own solar system has not been observed in the infrared so far, and exodisks harbor unobserved planets or planetesimals, while their debris disks show clear features. By studying the interaction (compositionally and

dynamically) between dust and these parent bodies, we learn about the exodisks as well as about our own solar system. To date, no compositional and density “map” exists of the debris disk of the Sun and the existing meteoroid models do not provide reliable answers for meteoroid fluxes further away from the Sun as 1 AU.

If we want to understand exoplanetary systems, we must start at "home". S2D2 will shed light on all these questions by mapping our solar system in dust, using the unique combination of in-situ dust measurements, analyses of returned samples, and a bird’s eye view for infrared observations of our outer “home” debris disk and beyond. This will provide links between interplanetary meteoroids and their parent objects, teaching us about hidden planetesimals in exodisk debris clouds and much more. The wealth of science return of a mission like S2 and D2 is large: S2D2 therefore covers nearly all topics of the first and second cosmic vision themes, providing valuable information for astronomy, exoplanet sciences, solar system formation, planetary sciences, astrobiology and make human interplanetary spaceflight safer by better understanding the meteoroid environment.

Science goals

- **Determine the extent and fine structure of the solar system debris disk**
- **Establish the dynamical and compositional relationships between micrometeoroids and their parent bodies**
- **Characterize similarities and differences of micron to mm-sized meteoroids flux**
- **Determine compositional differences between interstellar, comet, and asteroid dust**
- **Link samples returned and analyzed to meteor streams and parent objects**

1. Introduction

1.1. Extra solar debris disks

Debris disks were first discovered by IRAS in 1984. Since then, a significant fraction of main-sequence stars have been found to harbor such disks. They are usually identified by the mid or far infrared excess in the spectral energy distribution of the stars (Wyatt 2008, Krivov 2010), which is interpreted as originating from cold dust located at tens to hundreds of AU from the central star. Debris disks consist largely of 100 µm to 1 mm-sized dust grains, and are optically thin and mostly gas-free.

Circumstellar dust is short-lived because it strongly interacts with the electromagnetic and corpuscular radiation of the central star. Therefore, the mere existence of these disks is evidence that dust-producing bigger objects are still present in mature stellar systems. Short-lived grains must be continually replenished by mutual collisions in a ring of unseen km-sized and bigger planetesimals. Hence, debris disks are believed to be the aftermath of planet formation, and to have formed within this process. Even after planet formation has long been completed, they continue to evolve collisionally and dynamically, are gravitationally sculptured by planets, and produce dust through ongoing collisional cascades. Therefore, debris disks can serve as indicators of directly invisible small bodies and planets, and are tracers of their formation and evolution. They are an important component of planetary systems.

The dust around almost all Vega-like stars is so cold that it must be orbiting with semi-major axes of 50 AU or more from the central star. Thus, the debris disks are mostly considered analogs of the Sun’s Kuiper Belt. The incidence rate of debris disks, about one-fifth for solar-type stars, is roughly comparable to the frequency of exoplanet detections with current techniques (Eiroa et al. 2013). Several tens of extrasolar systems are known to harbor both planets and debris disks. Spatially resolved images of about 70 debris disks have been obtained (Fig. 1); several of those possibly show the effects of planetary interactions. Gaps, clumps, warps, and sharp edges in the disks may indicate the existence of planets that sculpt these disks and are waiting to be discovered.

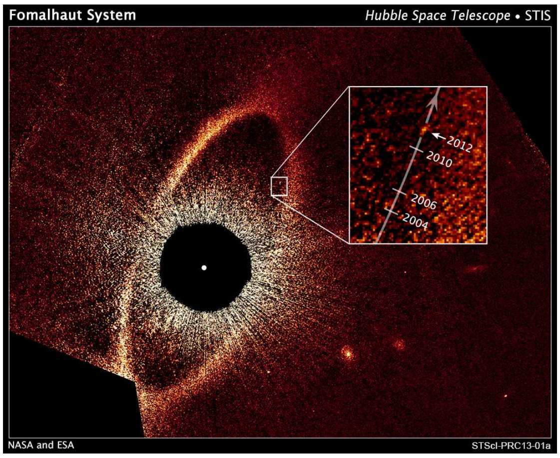

Figure 1. The Debris ring around Fomalhaut is located between about 130 and 160 AU from the star. The inset shows the location of planet Fomalhaut b imaged by Hubble Space Telescope's coronagraph. The interrelation of the planet with the debris disk is still unclear. (NASA, ESA, and P. Kalas, Univ. California, Berkeley)

A number of main sequence stars with far-IR excess also display the signature of warm micron-sized dust at distances of 1 to 10 AU from the star (Absil and Mawet, 2010). These warm inner 'exozodiacal' disks may originate from collisions in an inner planetesimal (asteroid belt analog) ring or from comet-type activity. In younger systems, they may signalize the ongoing terrestrial planet formation.

Debris disks can serve as tracers of planetesimals and planets and shed light on the planetesimal and planet formation processes that operated in these systems in the past. However, the 'visible' dust component in debris disks does not tell us directly about the dust parent bodies and dust production mechanisms. Therefore, many of the basic parameters of the debris disk remain obscure; for example, the bulk of a debris disk's mass is hidden in invisible parent bodies and cannot be directly constrained from analysis of the dust emission. Equally, the exact locations of the planetesimals remain unknown, although one expects that they orbit the star roughly where most of the dust is seen. Many properties of the planetesimals, such as their dynamical excitation, size distribution, mechanical strength and porosity, are completely unknown. For extra-solar systems we know everything from dust disks, but nothing about their parent bodies. In contrast, in the solar system we know the distribution of the source bodies, TNOs, comets and asteroids, but the link to their dust is still obscure (e.g., Vitense et al. 2012). Therefore, a deeper insight into the solar system debris disk and its interrelation with its parent objects will provide an important step towards the understanding of the formation of our own planetary system and of planetary systems in general.

1.2. Exploration of the solar system debris disk

Our own solar system debris disk must be observed using very different techniques. The major difference is we must observe the dust from a location within the disk. We do have observations that define the disk itself – such as zodiacal light and infrared observations. However, we also have measurements of individual particles, which are the constituent elements of the disk. We must combine these elements to put together an understanding of the properties of the overall debris disk.

Observations of the zodiacal light and the meteor phenomenon provided the first insights into the interplanetary dust cloud. Zodiacal light observations provided a spatial distribution of interplanetary dust, although the size distribution of the dust remained unknown. Triangulation of meteor trails in the atmosphere, especially during meteor showers, demonstrated the genetic relation of some meteor streams to comets. However, the sizes of the particles causing these phenomena remained unknown.

The earliest motivation to study dust in space came from the suspected hazard due to meteoroid impacts onto space vehicles. In 1965 NASA launched three Pegasus satellites (Fig.2) in rapid succession by the Saturn I rocket in support of the Apollo Program. They carried large-area (180 m^2) meteoroid detectors that reliably pinned down the flux of sub-mm meteoroids in near-Earth space and thus opened the door to extended manned exploration of space. These measurements (Naumann, 1966) ended the chaos caused by early unreliable dust measurements in near-Earth space that suggested a fictitious natural dust belt around the Earth. In the mean time an ominous man-made debris belt around the Earth has become reality.

Figure 2. Pegasus 1 satellite with 180 m^2 micrometeoroid detector (NASA).

In the years following these experiments dust measurements were conducted throughout the solar system by Helios (launch 1974) from 0.3 AU from the sun and by Pioneer 10 (1972) out to 18 AU. While the fluxes of micrometeoroids in narrow mass ranges decreased with increasing heliocentric distance, other properties of these meteoroids, in particular dynamical properties and the relation of these particles to their sources could not be established. Later, more sophisticated dust analyzers on interplanetary and planetary missions (Galileo, Ulysses, Cassini, and New Horizon) traversed the interplanetary dust cloud from South to North, and also in radial directions. These instruments obtained fluxes and limited dynamical information for the recorded meteoroids that helped to constrain models of the interplanetary dust cloud.

Analyses of microcraters on lunar samples returned by the Apollo astronauts finally made it possible to derive the size distribution of interplanetary meteoroids at 1 AU. These allowed the meteoroid flux and spatial density to be calculated at 1AU, using additionally careful crater size to projectile calibrations, determinations of the impact speed distribution from meteor observations, and flux measurements from early in situ instruments like Pegasus the meteoroid flux and spatial density at 1 AU was established. Later measurements of craters on the LDEF satellite and other exposed surfaces generally confirmed the lunar microcrater analyses. With an absence of relevant data outside of 1AU, this meteoroid mass distribution was extrapolated to other regions of the solar system.

Another milestone in the observations of the local debris disk was the first all-sky survey at infrared wavelengths, conducted by the Infrared Astronomical Satellite (IRAS) in 1983. It mapped the sky at 12, 25, 60 and 100 μm wavelengths, with resolutions ranging from 30 arcseconds at 12 microns wavelength to 2 arcminutes at 100 microns wavelength. Several hundred thousand sources were discovered including stars, galaxies, and solar system objects. Many stars with dust disks were identified through their infrared excess radiation; among them dust disks around Vega, Beta Pictoris, Fomalhaut, and Epsilon Eridani. A surprise was the observed structure in the zodiacal cloud: IRAS discovered a complex system of asteroid bands and many comet trails (Fig. 3). Because the Earth is located in the midst of the bright zodiacal cloud, weaker emissions from a presumed outer disk were not detected by IRAS or any follow-up infrared missions.

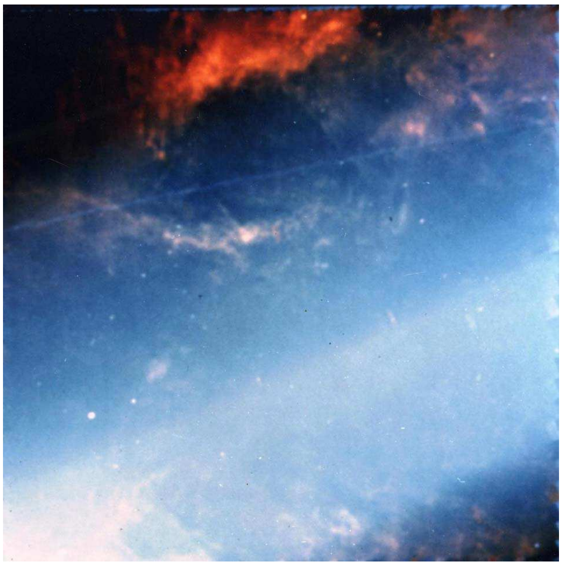

Figure 3. Composite view of a sky section by IRAS (Price, 2009, NASA). False color image with 12 μm intensity as blue and 100 μm as red. The fine streak across the upper part of the image is the dust trail of comet Temple 2 and the diagonal broad light blue band is emission from the zodiacal dust along the ecliptic plane with the asteroidal dust bands. The more complex white and red patches are emissions from interstellar cirrus and cool dust near the galactic plane.

The next break-through came from the Stardust mission that was launched in 2004. This mission returned samples from comet Wild 2 to Earth that revolutionized our understanding of early solar system processes.

Analysis of returned cometary grains demonstrated that the protoplanetary disk was a highly mixed environment that transported grains from the inner hot regions to the cold regions where comets formed. Earlier analyses of meteorites and interplanetary dust particles collected in the stratosphere always assumed that meteorites containing high-temperature mineral phases must have originated from asteroids that formed in the hot inner regions of the protoplanetary disk.

2. Parent bodies

Our planetary system contains a variety of highly interrelated objects. It extends from the F-corona (at ~0.02 AU) to beyond 50 AU from the sun and includes 8 planets, Trans-Neptunian objects (TNOs) and their relatives, Centaurs, and Jupiter family comets (JFCs), asteroids, meteoroids and dust. The eight known planets are arranged in two groups: four terrestrial planets and four giant planets. The main asteroid belt is located between these two groups of planets. It comprises planetesimals that failed to grow to planets because of strong perturbations from nearby Jupiter (e.g., Wetherill, 1980).

The most important dust sources in the solar system are the small solar system bodies. Fig. 4 shows the different populations of small bodies with distance to the Sun and their eccentricity. Understanding these sources allows us to build a picture of the generation of debris disks from the larger objects in planetary systems. In this section we describe the small body populations in our solar system and our present understanding of how they are related to the solar system debris disk. This relates both to an outer solar system dust disk associated with the TNO belt (analogous to the 'cold disks' around other stars), and an inner solar system dust disk interior of Jupiter (likely analogous to the 'warm disks' around other stars).

2.1. Trans-Neptunian Objects and Kuiper Belt Objects

The belt of Trans-Neptunian Objects (TNOs) outside the orbit of Neptune contains planetesimals that did not form planets because the density of the outer solar nebula was too low (e.g., Lissauer, 1987). Objects in this volume of space are normally divided between the Kuiper belt, the scattered disk, and the distant Oort cloud. The Oort cloud, located near the boundary of the solar system, is believed to be populated by objects scattered out by planetary interactions from the protoplanetary disk.

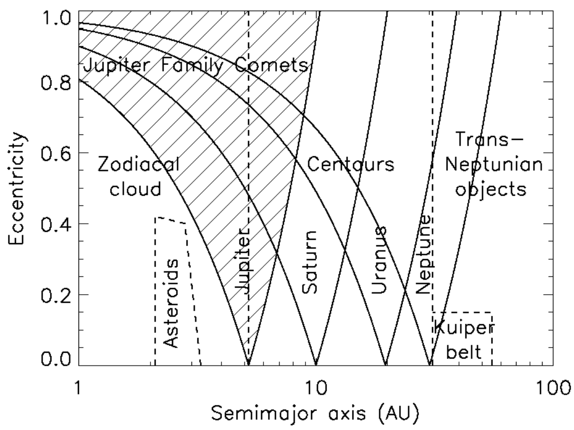

Figure 4. Small solar system bodies that are parents of the solar system debris disk. The triangular shaped regions at the semi-major axes of the giant planets delineate the scattering zones of the respective planet.

Pluto, discovered in 1930, was the first known Kuiper belt object. However, the belt itself was not identified until after the discovery of the next objects after 1992. At present, more than 1600 Kuiper belt objects are known to exist (Fornasier et al. 2013). At such large distances from the sun, these objects are very cold, hence produce black-body radiation at a wavelength of around 60 µm. The scattered disk objects are believed to be the main repository of the short periodic comets. Collisions among the TNOs (Stern, 1996) create fragments down to the size of dust grains: these generate a cold outer debris disk that has yet to be observed. Signatures of dust generated by TNOs have been found in the data from dust instruments on board the Pioneer 10 and 11, and recently the New Horizons spacecraft (Landgraf et al., 2002 and Poppe et al., 2010). While the dust concentrations detected between Jupiter and Saturn were mainly due to the cometary components, the dust outside Saturn's orbit is dominated by grains originating from the TNO belt either from collisional processes or cometary-like activity of TNOs (Altobelli et al., 2013). In order to account for the amount of dust found by Pioneer and New Horizon, a total of about 5x10 g s^{-1} of dust must be released by TNOs through collisional fragmentation and erosion by impacts of interstellar dust grains onto the objects' surfaces (Han et al., 2011). This makes the Kuiper disk the brightest extended feature of the Solar System when observed from outside the system. Nevertheless, the solar system's dust disk is orders of magnitude fainter than known debris disks around other stars. However, it is not yet clear why this is the case. Due to current observational limitations, it is not yet known if any other stars possess disks as tenuous as ours (Kuchner and Stark 2010).

TNOs are exposed to intense galactic cosmic radiation. For example, when high-velocity supernova shocks pass though the interstellar medium, the protective heliosphere is compressed allowing high fluxes of cosmic rays reach the Earth (Sonett et al. 1987). This radiation affects the upper meter of the surface layers of TNOs. Estimates of the composition of these objects come from observations of their colors and spectra. They range from very blue to very red. Typical models of the surface include water ice, amorphous carbon, silicates and the reddish tholins. Tholins are substances that are produced by the irradiation of gaseous mixtures of nitrogen or clathrates of water and methane or ethane.

2.2. Centaurs

Centaurs are small icy Solar System bodies with a semi-major axis between those of the giant planets Jupiter and Neptune (Fig. 4). They have unstable orbits that cross or have crossed the orbits of one or more of the giant planets, and have dynamic lifetimes of a few million years. Through a planetary scattering cascade (Quinn et al., 1990) some TNOs become Centaurs, Trojans, and Jupiter Family Comets (JFCs) that finally disintegrate and generate the inner warm Zodiacal debris disk. Because of its unstable nature, astronomers now consider the scattered disc to be the place of origin for most periodic comets observed in the Solar System, with the Centaurs, being the intermediate stage in an object's migration from the disc to the inner Solar System (Horner et al., 2004).

Examples of Centaurs that show cometary activity are 30 to 100 km objects like 95P/Chiron (at 13.7 AU), 39P/Oterma (7.2 AU), and 29P/Schwassmann-Wachmann 1 (5.9 AU). In these cases cometary activity is driven by CO_2 and other gases from even more volatile ices. The Trojans captured in a 1:1 resonance with Jupiter are a group of objects in between Centaurs and asteroids.

2.3. Comets

Comets have a wide range of orbital periods, ranging from a few years to hundreds of thousands of years. Short-period comets originate in the scattered disc. Longer-period comets are thought to originate in the Oort cloud. At the shorter extreme, Encke's Comet has an orbit that does not reach the orbit of Jupiter, and is known as an Encke-type comet. Most short-period comets (those with orbital periods shorter than 20 years and inclinations of 20-30 degrees or less) are called Jupiter Family Comets, JFCs. Those like Halley, with orbital periods of between 20 and 200 years and inclinations extending from zero to more than 90 degrees, are called Halley-type comets. As of 2012, only 64 Halley-type comets have been observed, compared to more than 500 identified Jupiter-family comets. It is useful to classify cometary orbits by the Tisserand parameter, T_J, which describes the interaction with Jupiter: Jupiter family comets have $2 < T_J < 3$, long period and Halley-type comets have $T_J < 2$. For most comets sublimation of water ices drives cometary activity inside 3 AU. But sometimes even JFCs like Hartley 2 show significant activity driven by volatile gases like CO_2. Besides emission of dust carried by cometary gases, comets frequently undergo fragmentation. A recent spectacular event of this type is the splitting 73P/Schwassmann-Wachmann (Fig. 5).

Instruments on the Halley missions (Giotto, VeGa 1 and 2) provided our first analyses of dust grains released from comets. The major goal of these dust measurements was to study the dust composition. Cometary dust particles were found to be mostly composed of by compounds of light elements H, C, N, O and of compounds of rock-forming elements such as Mg, Si, Ca, and Fe, respectively. Isotopic information was obtained only for a few among the most abundant elements in the mass spectra of the grains: C, Mg, Si, S, and Fe (Jessberger et al., 1988). The isotopic ratios - within large uncertainties - are generally similar to cosmic abundance. In January 2006 the Stardust sample capsule returned safely to Earth with thousands of particles from comet 81P/Wild 2 for laboratory study (e.g. Brownlee et al., 2006, Flynn et al., 2006, Hörz et al., 2006). The particles collected are chemically heterogeneous; however, the mean elemental composition of particles from comet Wild 2 is consistent with CI meteorite composition. The particles are weakly constructed mixtures of nanometer-scale grains with occasional much larger Fe-Mg silicates, Fe-Ni sulfides, Fe-Ni metal phases. The organics found in comet Wild 2 show a heterogeneous and unequilibrated distribution in abundance and composition. Hydrogen, carbon, nitrogen, and oxygen isotopic compositions are heterogeneous among particle fragments; however, extreme isotopic anomalies are rare, indicating that this comet is not a pristine aggregate of presolar materials. The abundance of high-temperature minerals such as forsterite and enstatite appears to have formed in the hot inner regions of the solar nebula.

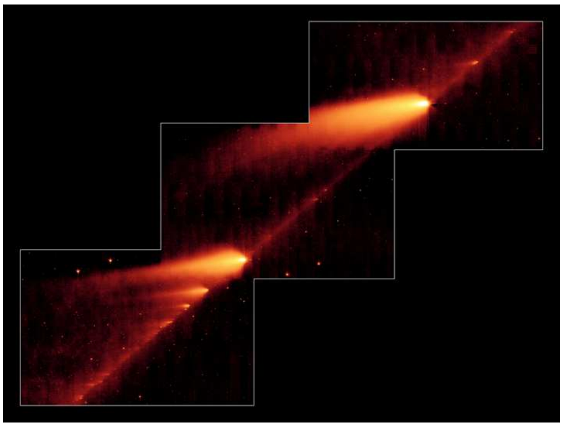

Figure 5. Breakup of 73P/Schwassmann-Wachmann and formation of a major new meteoroid stream (NASA, Spitzer). In 1995, 73P began to disintegrate; currently, the JPL data base identifies 66 individual fragments.

2.4. Asteroids

The large majority of known asteroids orbit in the asteroid belt between the orbits of Mars and Jupiter or co-orbital with Jupiter (the Jupiter Trojans). However, other orbital families exist with significant populations, including the near-Earth asteroids. Members of asteroid families are fragments of past asteroid collisions; e.g. the Karin asteroid family consisting of at least 90 main-belt asteroids. From orbital analysis it has been concluded that this family was created 5.8 ± 0.2 million years ago (Nesvorny et al., 2002) making it the most recent known asteroid collision. This family may also be the source of one of the interplanetary dust bands discovered by the IRAS satellite (Low et al., 1984).

Individual asteroids are classified by their characteristic spectra, with the majority falling into three main groups: C-type, S-type, and M-type. These were named after and are generally identified with carbon-rich, stony, and metallic compositions, respectively. The Japanese Hayabusa spacecraft picked-up from the surface of asteroid Itokawa some dust samples and returned them to the Earth by 2010. The composition was found to match that of an LL chondrite, i.e. the minerals olivine and pyroxene (Nakamura et al., 2011).

The relation of asteroid (3200) Phaethon to the Geminid meteor shower (in mid-December) demonstrates that asteroids are not just inert rocks that release dust when impacted by other objects. Recently discovered main-belt comets form a distinct class, orbiting in more circular orbits within the asteroid belt. On some of those (e.g. 24 Themis) water ice was found on the surface. These objects produce transient, comet-like comae and tails. However, other mechanisms like rotational instability, electrostatic repulsion, radiation pressure sweeping, dehydration stresses, and thermal fracture are considered as well (Jewitt, 2012).

3. Solar System Debris Disk

3.1. Meteoroids and Dust

The zodiacal meteoroid cloud is the inner part of the solar system debris disk. It extends from the F-corona (at ~0.02 AU) to Jupiter's orbit and exhibits global structure such as a central offset, an inclined and warped plane of symmetry, and resonant rings that all result from planetary perturbations (Dermott et al., 2001). At mid-infrared wavelengths (10 to 25 μm) thermal emission from the zodiacal cloud outshines any other diffuse astronomical object when observed from the Earth (Fig. 6).

The zodiacal cloud is a compositionally and dynamically diverse population stemming from a range of sources. Meteoroids are continually being replenished (via cometary sublimation and fragmentation, asteroid collisions and other production mechanisms), while evolving dynamically (due to radiation forces and planetary perturbations), and are ultimately removed (by inter-particle collisions, planetary accretion and scattering, evaporation, sputtering and ejection from the solar system).

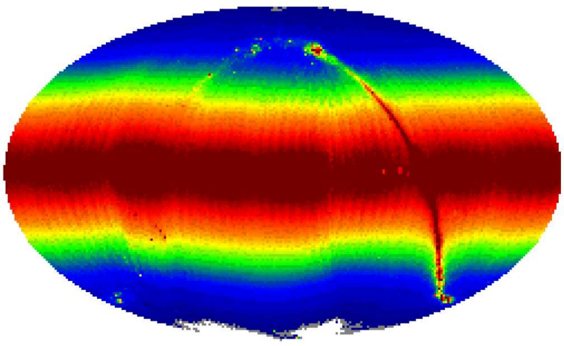

Figure 6. Sky map of zodiacal cloud at 25 microns (COBE DIRBE, Kelsall et al., 1998). Only radiation from the galactic plane is visible in the right part of the image.

Zodiacal dust particles originate in a collisional cascade from bigger interplanetary meteoroids or by direct injection from comets (Grün et al., 1985, Ishimoto 2000, Dikarev et al., 2005). The fate of freshly generated micrometeoroids strongly depends on the size of the particle. Sub-micron sized particles will mostly escape the solar system by the action of radiation pressure. Micron-sized dust is steadily transported by the Poynting-Robertson effect towards the sun, while 100 micron-sized and bigger particles remain on orbits similar to the parent object and rapidly expand into a dust trail: this forms a meteor stream if the Earth crosses its orbit. Cometary trails and meteor streams are a signs of fine structure in the zodiacal meteoroid cloud. On longer timescales (10^5 years), these big particles are randomly scattered through the solar system by the planets' gravitation. Infrared observations show that the majority of short-period comets display trails of big particles at high concentrations (Reach et al., 2007).

It is believed that at the present time comets produce most of the dust at 1 AU and asteroidal collisions contribute little to the zodiacal cloud (Nesvorny et al., 2010). However, this proportion may have changed with time: at the time of a major collision in the asteroid belt (e.g. at the time of the Karin event ca. 6 Mio years ago) the zodiacal light may have flared up by several orders of magnitude lasting for ~10^5 years until the optically most active particles have been removed by the Poynting Roberston effect (Durda and Dermott, 1997). Alternatively, when a new major comet enters the inner solar system the zodiacal cloud may be affected for similar time scales. Actually, there are indications that we are presently at the final stages of such an event: comet Encke is currently in a stable 3-year orbit from 0.3 to 4 AU and is still producing significant amounts of dust as evidenced by the associated tail and trail. Actually, the Taurid meteor streams and comet Encke are believed to be remnants of a much larger comet, which has disintegrated over the past 20,000 to 30,000 years (Whipple, 1940; Klačka, 1994). This meteoroid stream is the longest in the inner solar system and it contains a significant amount of big particles causing fireballs in the sky. The stream is rather spread out in space; Earth takes several months to pass through it, causing an extended period of meteor activity, compared with the much smaller periods of activity in other showers.

Spacecraft measurements have identified a significant presumably very fast flow of sub-micron sized dust grains arriving from the solar direction (Berg and Grün, 1973). These beta-meteoroids were probably generated as debris resulting from mutual collisions between larger meteoroids in the inner solar system and were driven out of the solar system by solar radiation pressure (Zook, 1975). Recently, the STEREO wave instrument has recorded a very large number of intense voltage pulses (Meyer-Vernet et al., 2009) that have been interpreted as nano-particles striking the spacecraft at a velocity of the order of magnitude of the solar wind speed. These particles may indicate significant sources of dust inside the Earth orbit.

Most of what we know about the composition of interplanetary dust comes from IDPs collected in the atmosphere. About half of the collected particles have elemental abundances that closely match the bulk abundances of CI or CM carbonaceous chondrite meteorites (Rietmeijer et al., 1998). However, the origin of these particles (cometary vs. asteroidal) is inferred by very indirect methods. In-situ analyses of interplanetary dust are sparse because of the small sensitive areas of dust mass analyzers. The Cassini and Stardust missions provided a handful of dust spectra in interplanetary space (Krueger et al., 2004; Hillier et al., 2007). Much more are needed in order to construct a compositional inventory of interplanetary dust and establish the link to its sources: comets, asteroids, Trans-Neptunian objects, and interstellar space.

The spatial and mass distribution of meteoroids everywhere in the solar system is determined by the competition between transport by (1) planetary scattering, (2) the Poynting-Robertson effect and (3) collisional balance (disruption of meteoroids and generation of fragments).

3.2. Models of the Inner Debris Disk

The best quantitative understanding of the meteoroid environment is summarized in the meteoroid environment models of the space agencies.

NASA's Meteoroid Environment Model (MEM) was developed by (Jones, 2004, McNamara et al., 2004) on the basis of sporadic meteor observations from the Canadian Meteor Orbit Radar (CMOR). This is combined with zodiacal light observations from Helios which provide the radial meteoroid density distribution. The mass distribution in the range from 10^{-6} to 10 g was derived from lunar crater statistics (Grün et al., 1985). Since the model heavily uses orbital element distributions from meteor data that must intersect the Earth, it can only be used at best for predictions of fluxes, speeds, and directions from 0.2 to 2.0 AU. This includes the environments of the planets Mercury (0.4 AU) to Mars (1.5 AU). Additionally, the model applies only to an observer moving near the ecliptic plane (McNamara et al., 2004).

ESA's Interplanetary Meteoroid Environment Model (IMEM) is a dynamical evolutionary model (Dikarev et al., 2005). Contrary to all earlier attempts, this model starts from the orbital elements of known sources of interplanetary dust: comets and asteroids. The model assumes that big meteoroids ($\geq 10^{-5}$ g) stay orbits like their parent objects, while the orbits of smaller meteoroids evolve under planetary gravity and the Poynting-Robertson effect. Thermal radiation measurements by the COBE DIRBE instrument (Kelsall et al., 1998), in situ data from the dust instruments onboard Galileo and Ulysses (Grün et al., 1997) and lunar microcrater distributions (Grün et al., 1985) are used to calibrate the contributions from the known sources. Attempts to include meteor orbits from the Advanced Meteor Orbit Radar AMOR (Galligan and Baggeley, 2004) in the model failed since the AMOR orbital distributions were incompatible with the COBE latitudinal density profile. The derivation of the meteoroid spatial distribution from the actual radar meteor measurements is quite complex and involves numerous assumptions; whereas the derivation of the infrared brightness along a line-of-sight is relatively straight-forward. Therefore, Dikarev et al. (2005) decided not to include meteor data in the IMEM model. A recent similar analysis (Nesvorny et al., 2010) confirms that comets are currently the main contributor to interplanetary dust at 1 AU confirmed that the radar meteor systems underestimate the contributions from slow meteoroids.

Both models describe the cratering flux at 1AU quite well; however, the flux of mm-sized meteoroids differs by a factor two due to the different assumed relative speeds. At other heliocentric distances from Mercury to Mars the predicted fluxes differ by up to 2 orders of magnitude between the two models (Grün et al., 2013). The current knowledge of the interplanetary meteoroid environment as exemplified by these meteoroid models is insufficient to provide reliable assessment of the risk of meteoroid impacts for human travel in interplanetary space (Grün et al., 2013).

The discrepancy between the models results from the lack of data that constrain these models. Most importantly needed are (1) dynamical data of both µm and mm-sized meteoroid populations, (2) the spatial distribution of the different populations and its time variation.

4. Interstellar dust in the solar system

Interstellar dust is the major ingredient for protoplanetary disks out of which planetesimals and planets form. From analyses of material we find a surprisingly homogeneous distribution of isotopes everywhere in our solar system. Therefore, by comparing the composition of interstellar dust and its variation with those of cometary, and asteroidal dust we will learn about the mixing processes in various parts of the protoplanetary disk.

Dust grains condense in the expanding and cooling stellar winds from asymptotic giant branch (AGB), post-AGB stars, and also in supernova explosions, which results in a wide range of elemental and isotopic compositions. 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 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 material in ISD grains is repeatedly recycled through the galactic evolution process (Dorschner and Henning, 1995).

The solar system currently passes through a shell of material that is located at the edge of the local bubble (Frisch et al., 1999). It emerged from the interior of this bubble within the past 10^2 - 10^5 years. Since entering the cluster of clouds that appear to have come from the Scorpius-Centaurus Assiciation, the Sun has encountered a new interstellar cloud at least every 10^4 years. It is clear that sampling of dust from our LIC would greatly help us to understand the nature and processing of dust in various galactic environments, and cast new light on the chemical composition and homogeneity of the ISM.

In 1992, after its Jupiter flyby, the Ulysses spacecraft unambiguously identified interstellar dust penetrating deep into the Solar System. The motion of the interstellar grains through the Solar System was approximately parallel to the flow of neutral interstellar hydrogen and helium gas, both traveling at a speed of 26 km/s (Baguhl et al 1995). Ulysses measured the interstellar dust stream at high ecliptic latitudes between 2 and 5 AU. The masses of interstellar grains range from 10^{-18} kg to about 10^{-13} kg with a maximum of the flux at about 10^{-16} kg (Landgraf et al., 2000). The in-situ dust detectors on board Cassini, Galileo and Helios, (Altobelli at al., 2003, 2005, 2006) detected interstellar dust in heliocentric distance range between 0.3 and 3 AU in the ecliptic plane. The interstellar dust stream is strongly filtered by electromagnetic interactions with the solar wind magnetic field and by solar radiation pressure and display a variation with the 22 years solar cycle (Landgraf et al., 1999, Sterken et al., 2012)

En route to the comet Wild 2, Stardust collected and returned interstellar dust particles to Earth for analysis. The CIDA instrument provided the first high mass-resolution spectra of a few tens of presumably interstellar grains. The spectra indicate that the main constituents of interstellar grains are organic with a high oxygen and low nitrogen content. It was suggested that polymers of derivatives of the quinine type are consistent with the impact spectra recorded (Krueger et al., 2004). Three candidate interstellar grains have been identified in the Stardust collections (Westphal et al., 2013) and await their detailed analysis.

5. Top-Level Scientific Questions and Required Observations

A better understanding of the solar system debris disk requires answers to the following questions:

- **What is the extent and fine structure of the solar system debris disk?**
  Infrared observations of the inner and outer debris disks.
- **What are the similarities and differences of the orbits and the fluxes of micron to mm-sized meteoroids in the mass range 10^{-15} - 10^{-3} g?**
  In situ measurements of fluxes of big and small dust particles and their spatial and temporal variations.
- **What are the orbital and compositional relationships between micrometeoroids and their parent bodies?**
  In situ measurements of trajectories and the composition of small dust particles and correlation of the composition of collected particles with their trajectories at the time of collection.
- **What is the composition of interstellar dust and its variation?**
  Identification of interstellar particles by their trajectories and measurement of their compositions both in situ and for collected particles.
- **What are the compositional differences between interstellar, cometary, and asteroidal dust and how do they relate to processes in the protoplanetary disk?**
  Identification of particles from different sources by their trajectories and comparison of their compositions both in situ and for collected particles
- **What are the objects and processes that generate nano dust in the inner solar system?**
  Determination of the temporal and spatial variation of the nano-particle flux and correlation with solar wind magnetic field conditions and the appearance of sun-grazing comets and other interplanetary phenomena.

6. Strawman Mission

This strawman mission concept to analyze the solar system debris disk comprises of the combination of two missions: **S2**, an infrared survey mission to determine the structure of the inner (zodiacal) and to identify the outer (trans-Neptunian) debris disk, and **D2**, an in situ dust analysis and sample return mission to establish the orbital and compositional relationships between meteoroids and their source bodies.

S2 - A bird's eye view on the solar system debris disk

S2 is a mission to characterize the **Spatial Structure of the Zodiacal Cloud**. Several infrared survey missions have been conducted previously from positions near the Earth (Tab. 1). S2 will be an IRAS-type mission that will characterize the inner (zodiacal) and outer (trans-Neptunian) debris disks from a position outside the densest part of the zodiacal cloud. This mission will reach 40° ecliptic latitude.

Table 1. Mid-infrared survey missions: mission characteristics, telescope diameter, wavelengths (between 10 and 100 µm)

Mission	Launch date	Mass (kg)	Diam. (m)	Wave lengths (µm)
IRAS	1983	1083	0.57	12, 25, 60, 100
COBE DIRBE	1989	2270	0.19	12, 25, 60, 100
AKARI	2006	955	0.68	65, 90
WISE	2009	750	0.4	12, 22

Taking into account a 4 year LHe lifetime (Herschel), Kawakatsu and Kawaguchi (2012) describe a method to achieve a high inclination orbit through Solar Electric Propulsion (SEP) combined with multiple Delta-V Earth Gravity Assists (EGA). It includes the following steps:

1. The spacecraft is injected into the earth synchronous orbit to re-encounter the earth after one year cruise.
2. During the cruise, SEP is used to maximize the spacecraft's v_{inf} to the Earth at the next earth encounter. The thrust does not necessarily increase the inclination by itself. To enhance the efficiency to increase v_{inf} , an elliptic orbit is used for the cruise orbit.
3. By EGA, the direction of v_{inf} is changed to contribute to the inclination increase.
4. By the repetitive use of the steps 2 and 3, the inclination is increased step by step.

The initial mass of the spacecraft was assumed to be 1200 kg, the launcher is capable of injecting the spacecraft into an Earth escape orbit with v_{inf} of 7.3km/s. The orbit eccentricity was constrained to be less than 0.3; that is the perihelion is above 0.7 and the aphelion is below 1.3AU. The specific impulse of the SEP was assumed to be 3800 s, and the maximum assumed thrust was 120mN; these values are about twice the values of the SMART-1 SEP. The SEP thrust is used to decelerate the spacecraft at aphelion and to accelerate the spacecraft at perihelion, which results in a build-up of eccentricity thus increasing the v_{inf} at the next Earth encounter. After 4 years and 4 gravity assists a final orbit inclination of almost 40° is reached. At such latitude the dust density will be reduced by 97% compared to 1 AU in the ecliptic and a view of the outer cold dust disk is possible that is not blurred by the foreground zodiacal emission (cf. Landgraf et al., 2001). This mission will conduct high-resolution partial sky surveys at 12, 25, 60, and 100 micron wavelengths (in order to resolve interplanetary meteoroid streams and comet trails), thereby investigating the structure of the warm inner debris disk and identifying and characterizing the cold outer solar system debris disk. The challenges of this mission are to find optimum strategies for 1. thrust periods, 2. observation periods, and 3. data downlink periods.

D2 - mapping the sky in dust

D2 is an interplanetary mission to characterize the **Dynamical and Compositional Distributions of Meteoroids**. D2 is a mission for the in situ analysis of nano to millimeter-sized meteoroids and for the collection and Earth return of micron-sized interplanetary and interstellar dust particles. This mission will cruise near the ecliptic between the orbits of Venus and Mars and have multiple orbit changes due to flybys of Venus, Earth, and/or Mars. These orbit changes are important in order to vary the relative speed of the spaceprobe with respect to the meteoroid cloud. This way, the recorded fluxes can be used to get statistical information on the orbit distribution of big meteoroids. During its multi-year cruise the spacecraft will pass through several meteoroid streams, e.g. the 73P/SW3 stream in order to record and analyze particles from the respective comet.

D2 will carry a two-sided 200 m^2 meteoroid detector (Pegasus-type) for mm-sized particles, two Dust Telescopes that will establish the orbital and compositional relationships between micrometeoroids and their source bodies: comets and asteroids. Nano-Dust Analyzers will characterize collisional and other dust sources in the inner solar system. The sample return part of D2 is similar to the SARIM-type mission (Srama et al., 2008, 2012). The capsule contains a mechanism to place the dust collectors individually below trajectory sensor modules and the collectors can be stored repeatedly during unfavorable collection conditions. The capsule provides a clean and sealed environment for the collectors and avoids contamination during non-active collection phases. Seven Active Dust Collectors have a total sensitive area of 1 m^2. The Active Dust Collector determines the time, trajectory, primary charge, speed and mass of micro-grains entering the aperture and impacting on the collector. This allows a characterization of the origin of individual grains and eases the process to find and locate the impact tracks in the collector surfaces after return to Earth.

The overall profile consists of the launch, in situ meteoroid analyses together with interstellar/interplanetary dust collection campaigns. The mission will include fly-throughs of several meteoroid streams and return of the sample capsule. The mission requires moderate relative impact velocities for interplanetary (~10 km/s) and interstellar grains (<20 km/s) and an overall collection phase of approximately three years. The mission will include fly-throughs of several meteoroid streams. A sample return capsule will approach the Earth with an off-targeting approach, in which the final decision to reenter allows to fulfill planetary protection requirements. This off-targeting puts the transfer stage with the in-situ instrumentation in a swing-by trajectory around Earth. The in-situ measurements will continue at least one year after the fly-by exploiting the characteristics of the new orbit.

7. Instrumentation

In the following sections key instruments are listed. They should be supplemented by environment monitors.

7.1. Infrared Telescope

An IRAS type telescope (Tab. 1) with a scanning detector system is capable of the required observations. A camera system similar to the WISE telescope is also a viable alternative. Partial sky surveys at 12, 25, 60 and 100 µm are to be performed from multiple positions within and above the ecliptic plane. The spatial resolution of the IRAS instrument is appropriate for surveys that range from 30 arcseconds at 12 micron wavelength to 2 arcminutes at 100 µm.

Observation mode: At various positions above and below the ecliptic plane the IR telescope will perform slow scans perpendicular to the spacecraft-sun line, thereby imaging a swath along a great circle from 60° to 120° solar elongation.

7.2. Pegasus-type meteoroid detector

A large-area (200 m^2) meteoroid detector (Pegasus-type) is needed in order to record statistically significant numbers of big ($m > 10^{-9}$ kg) particles. The Pegasus meteoroid detector (Naumann et al., 1966) consisted of parallel plate capacitor detectors (Fig. 7) arranged in 208 panels of 0.5×1 m^2 area. The deployed wing extended over 29 m and was 4.3 m in height. The instrument weighted 1450 kg total, with more than half of it being structural. Two capacitor detectors were bonded to either side of a 2.54 cm thick foam structural support core. The penetration depth of micrometeoroid detectors were measured by a double-sided detector consisting of 0.4 mm (total collection area of 171 m^2), 0.2 mm (16 m^2), and 0.04 mm (7.5 m^2) thick aluminum target sheets. The capacitor detector consisted of 12-micron thick Mylar sheets with a metallic (Cu) layer deposited on either side. The capacitor was maintained at a bias of 40 V and a penetrating impact caused a momentary short. The energy stored in the capacitor was discharged through this short and the Cu layers were evaporated, thus restoring the detectors back to operational condition.

A state-of-the-art version of a large-area detector system is envisioned for the D2 mission. Trajectories of big micrometeoroids would be measured with a DTS-type instruments (see below) that would covering ~10% of the sensitive area. The optimum pointing for such detectors is the apex ram/anti-apex direction. Electronics and detection methods now exist to operate these detectors very reliably with very low false detection rates (Auer et al., 2010).

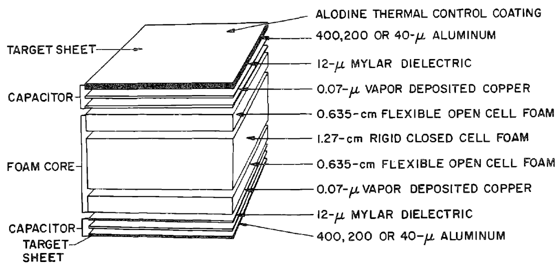

Figure 7. Pegasus meteoroid detector panel (Naumann et al., 1966).

7.3. Dust Trajectory Sensor

Micrometeoroids all acquire electric charge in space. It is possible to use this charge to accurately determine the velocity vector of these dust grains. This detection principle has been demonstrated by the Cassini Comic Dust Analyzer (CDA) (Kempf et al., 2004), where the trajectories are determined using the measurement of induced charge when the charged grains fly through a position-sensitive electrode system (Auer et al., 2008, 2010). The range of detectable particle charges is 10^{-16} to 10^{-13} C and the velocity is measurable up to

100 km/s. The newly developed Dust Trajectory Sensor (DTS) has much improved performance and sensitivity using four sensor planes with 20 wire electrodes in each (Auer et al., 2008; 2010, Xie et al., 2011). A charged dust grain flying through the instrument generates induced charges on the adjacent wires. Each electrode is connected to a separate Charge Sensitive Amplifier (CSA) and signals are digitized and recorded. The operation of a prototype DTS instrument with 40x40 cm^2 cross section has been demonstrated at the Heidelberg and Boulder dust accelerator facilities. The measurements are highly sensitive and accurate as a minimum 8 coincident signals from the closest wire electrodes are used for the analysis. The size of the DTS instrument is scalable to approximately 1 m^2.

7.4. Active Dust Collector

Novel active dust collectors are a combination of a Dust Trajectory Sensor, DTS, with a dust collector. In this way, not only are the trajectories of collected grains are determined (and hence their direction of origin is established), but in addition their impact positions into the collecting material can be determined to sub-millimeter precision.

Intact capture of hypervelocity projectiles in silica aerogel was successfully demonstrated (Tsou et al., 1990). For aerogels having densities about 10 kg/m^3 or less, intact projectiles were lodged at the end of track. This concept has been extremely successful during Stardust's fly-through of the coma of comet Wild2 at a speed of 6.1 km/s: many cometary particles were captured intact in aerogel that had a density of 10 to 50 kg/m^3 (Brownlee et al., 2006).

In an active dust collector all particles impacting the collector must pass through the dust trajectory sensor. To function properly the DTS requires a trigger signal that terminates the cyclic signal processing and starts the data read-out. In the case of a metal collector this will be used as the target of a simple impact ionization detector with a grid in front of it. It has been shown that even impacts into aerogel create impact charges that can provide the necessary trigger signals for DTS (Auer, 1998, 2010, Grün et al., 2012). The sensitivity of the DTS electronics is of the order of 10^{-16} C and thus the trajectory of cosmic dust particles as small as 0.4 µm size can be measured and collected.

7.5. Dust Telescope

A Dust Telescope is composed of two parts, a Dust Trajectory Sensor and a Mass Spectrometer subsystem. This sensor is an in-situ instrument designed to detect and analyze individual impacts of sub-micron and micron sized dust grains. First, the dust particles pass the DTS then the grains impact on the plane target of the mass analyzer at the bottom of the instrument (Fig. 9) generating electrons and ions that are analyzed in a time-of-flight spectrometer. Mass spectra are measured at high resolution ($M/\Delta M > 100$). Several versions of a Dust Telescope with sensitive area of 0.1 m^2 have been tested in the lab (Srama et al., 2005, Sternovsky et al., 2007, 2011).

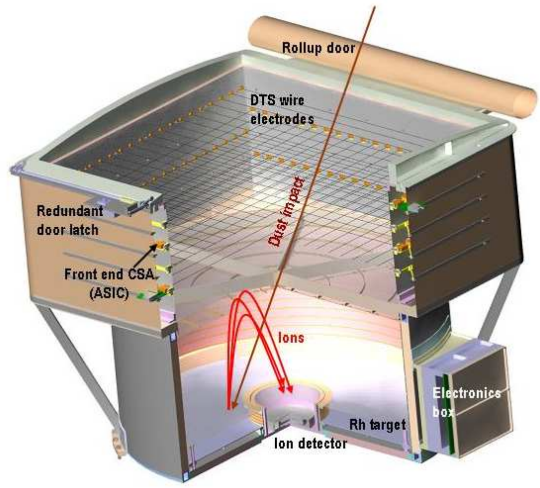

Figure 9. Dust Telescope with the four planes of wires of the Trajectory Sensor (top) and the time-of-flight mass-spectrometer (bottom). A particle impacting on the target generates electrons, ions, and charged cluster-molecules which are focused to the ion detector in the centre. Data acquisition is triggered by the electron signal collected at the target and by the ion signal.

7.6. Nano-Dust Analyzer

Beta-meteoroids and interplanetary nano-dust particles originating from the inner solar system have been detected, but only using simple impact detectors or through collisions with spacecraft. A special type of a dust mass spectrometer is needed to obtain compositional information of this important loss mechanism for zodiacal dust. This instrument has to be able 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 are employed to solve these problems.

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