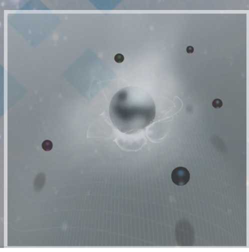
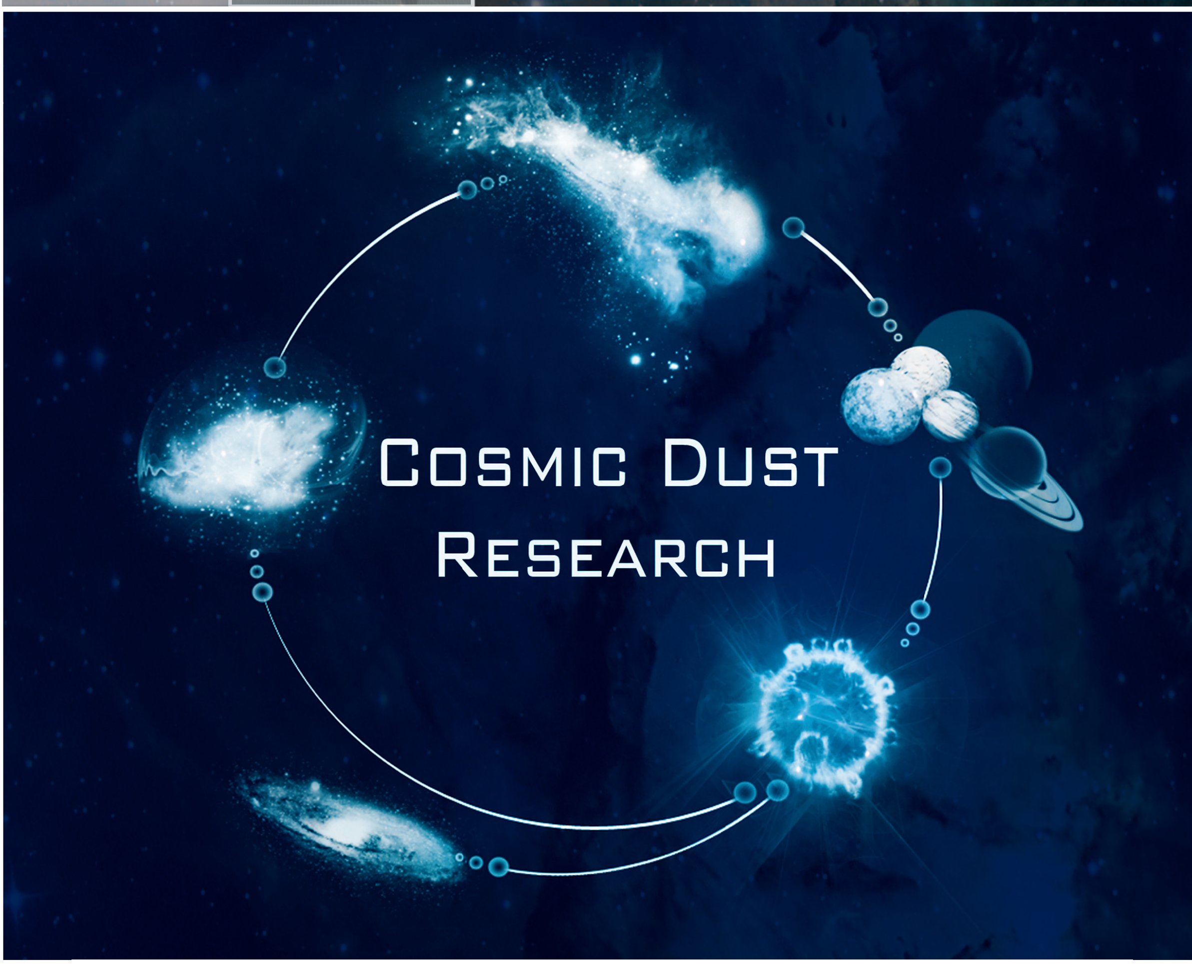
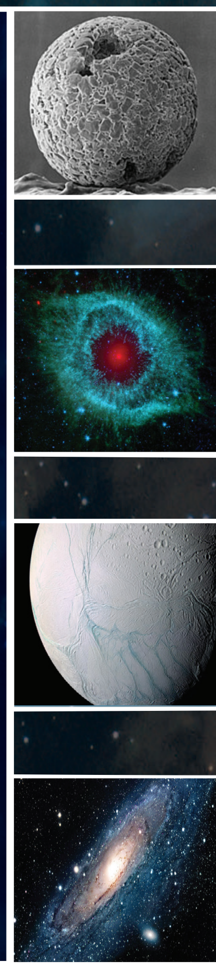
Universität Stuttgart

COSMIC DUST

Messenger from Distant Worlds







Contents

Dust transports information about the composition and evolution of distant realms over space and time. Dust sources may be in our local neighbourhood, such as the surfaces of moons, or further away, in the galactic environment. Dust grains are therefore like probes, giving us the opportunity to investigate these objects at a distance. Thus, a new field of activity has been born: Dust Astronomy. This uses different tools and techniques than those in optical astronomy. Traditional astronomy analyses the radiation emitted, reflected or absorbed by the observed astronomical objects, but dust instruments (so-called dust telescopes) actually make physical contact with the extraterrestrial material. When flown on a spacecraft, a dust telescope enables us to "touch" interstellar matter, the surfaces of atmosphereless bodies, comets and many other cosmic environments. Thus dust astronomy opens up a new, supplemental window for investigating astrophysical and planetological questions.

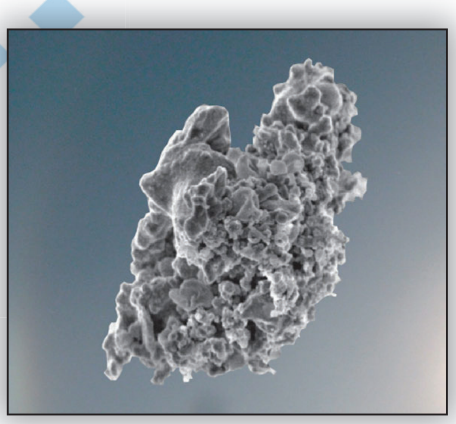


Figure 1: Interplanetary dust grain collected in the stratosphere

Cosmic dust is an important part of the space environment. It is comprised of particles that range from larger molecules or clusters with some thousands of atoms to small solid grains up to 0,1 millimetres in size. Cosmic dust is a link between the microscopic world of atoms and the macroscopic world we sense around us. During the last century cosmic dust was recognised as an important topic for study, as it brings together many scientific fields: astronomy, physics, fractal mathematics, chemistry, geology, mineralogy, and even aspects of biology. Modern dust telescopes have become sophisticated devices that analyse speeds, masses, charges, directions and compositions. Their development began with missions launched in the 1960s and major success has been achieved by Helios, Giotto, Ulysses, and Cassini. Their scientific achievements will be part of this brochure. Cosmic dust is distinguished by its composition or, more specifically, its origin: I.e. intergalactic dust, interstellar dust, interplanetary dust, and circumplanetary dust. The evolution of dust traces out paths in which the Universe recycles material. These processes are analogous to the recycling steps which are familiar to many people: production, storage, collection, consumption and disposal. In a similar way dust particles undertake growth, internal changes and destruction, meaning that they evolve chemically, physically, and dynamically. Observations and measurements of cosmic dust in various regions of space provide an important insights into these processes.

1. Activities of the Cosmic Dust Group

The Dust Research Group at the University of Stuttgart (formerly located at the Max-Planck-Institute for Nuclear Physics in Heidelberg) investigates cosmic dust phenomena via in situ measurements in space, by experiments in the laboratory and theoretical studies. The group has the scientific and engineering expertise to develop and operate sensors in space and is involved in the space missions Cassini, Rosetta, Stardust, Ulysses, Bepi Colombo and LADEE. The major ongoing space mission with an enormous science return for cosmic dust research is the Cassini spacecraft at Saturn. Science planning, operations and data analysis of the dust sensor onboard Cassini is performed by an international team of scientists under the leadership of the IRS at the University of Stuttgart. The instrument provides information about dust density distributions, particle charges, sizes and speeds. Dust grain elemental compositions are measured by the integrated time-of-flight spectrometer. Dust detection techniques and sensors are tested and calibrated at the Dust Accelerator Facility, a globally unique facility that is used by planetary scientists from the USA, Japan, France, Italy and the UK. Moreover the Dust Accelerator is also used to investigate the physical processes of hypervelocity impacts.

Four different instruments onboard interplanetary spacecraft unambiguously detected interstellar dust (Helios, Galileo, Ulysses, Cassini) in our Solar System at different locations and distances from the Sun. These findings led to the mission proposal of a dust telescope, a low-cost interplanetary mission to characterize the flux and composition of interplanetary dust and, in particular, interstellar dust. An interstellar dust sample return method was added to the concept of DuneXpress, leading to the mission concepts of SARIM and SARIM PLUS. Small dust telescopes with masses below 3 kg can be accommodated onboard spacecraft to investigate the surface composition of planetary moons (i.e., the lunar surface and the surfaces of the Galilean moons) by dust spectroscopy of their impact generated dust cloud.

2. Dust in Space

Generally, cosmic dust is viewed as an annoyance by astronomers, as it reddens and obscures the objects they wish to observe. Over the course of centuries mankind has realised that besides stars, gas, and plasma, dust is an important component of the visible Universe. Most importantly for us, our planetary system has evolved out of the protoplanetary gas and dust cloud. Some part of this pristine matter has remained in comets, asteroids, and meteorites. The diffuse glow of the zodiacal light which is concentrated along

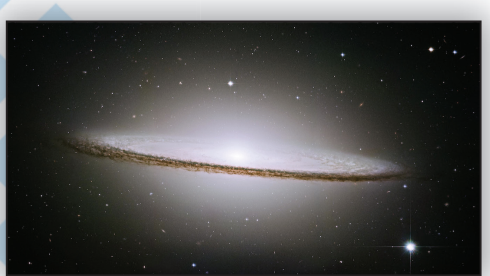


Figure 2: This image of the Sombrero Galaxy is a mosaic of six images taken by the Hubble Space Telescope in May and June 2003. The prominent dust lane and halo of stars give this galaxy its name. (HST/NASA)

the plane of the ecliptic is sunlight scattered by myriads of tiny particles that were released from these bigger objects by mutual collisions or cometary activity. Dust populations in our solar system can be divided into three large families: interstellar dust, interplanetary dust, and circumplanetary dust.

2.1 Interstellar Dust

The existence of interstellar dust was recognised by Robert Trumpler in the 1930s, while studying open star clusters. He found that the brightness of the more distant clusters is lower than expected, and they appeared reddened. He attributed these phenomena to dust particles along the line of sight, that absorb photons and re-emit them at longer wavelengths. The re-emission is in all directions, thus the original light is scattered and appears dimmed. Interstellar dust is very prominent in spiral galaxies. It surrounds their discs and is present in the spiral arms where much star formation occurs. A very conspicuous dust lane encircles the Sombrero Galaxy (M104, Fig. 2). This region contains most of the galaxy's molecular gas and dust, both of which are essential ingredients for star formation. While emitting continuous thermal radiation, dust cools the interstellar medium. With thermal pressure decreasing, a star forming cloud will be able to collapse under its own gravity and give birth to new stars. Then, after a star cluster is born, dust is pushed away by the energetic winds and strong UV-radiation from the stars. Shock waves from supernovae support star formation in two ways: they trigger instabilities in nearby molecular clouds that lead to collapse and new star formation, and also inject heavy elements into the surrounding interstellar medium which become seeds for dust grains that eventually may become planets. An intriguing example of a star forming region is the Rosette Nebula (Fig. 3). In its centre a cluster of new bright stars has formed and cleared out the dust and gas surrounding it. Usually, the particle densities vary in different regions. In the evacuated interstellar space the value ranges from 0.1 to 100 cm^{-3}; in HII regions from 100 to 1000 cm^{-3}; and in the dark molecular clouds up to $10^5 cm^{-3}$. Our Sun is currently passing through a low-density region of interstellar space. This local cavity extends few parsecs in diameter and consists of dusty plasma with an electron density of about 0.1 cm^{-3}. It is embedded in the hot medium of a "Local Bubble" with a temperature of $\approx 10^4$K (Fig. 4). Although interstellar dust has not been directly observed by astronomical means at

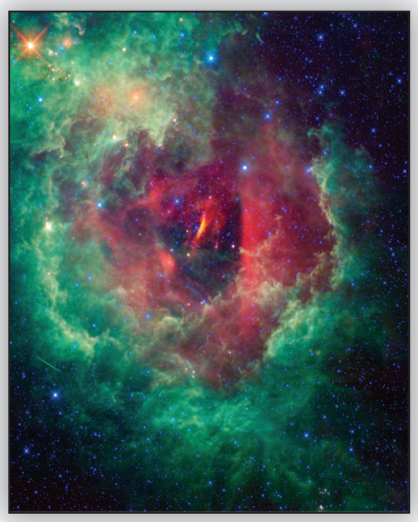


Figure 3: The Rosette Nebula is a prominent star formation region, glowing due to ultraviolet light from the young, hot, blue stars whose winds also cleared the central hole. The picture has a diameter of about 100 light years. (WISE/NASA)

visible wavelengths, dust particles which originated in the interstellar region have been detected in the Solar System. In 1993, the dust detector aboard the Ulysses spacecraft registered impacts from a direction that was opposite to the expected direction of interplanetary dust grains. Their impact velocities exceeded the Sun's escape velocity, even if radiation pressure effects were considered. The motion of the grains turned out to be almost parallel to the flow of neutral hydrogen gas that travels at a speed of 26 km s^{-1} with respect to the Sun. The dust flow persisted at high ecliptic latitudes when the spacecraft flew around the poles of the Sun. The particles seem to enter the Solar System from an ecliptic longitude of about 259° and a latitude of +8°. This amazing discovery of dust flow at 5 AU from the sun, by the Cosmic Dust Research Group, was followed by analyses of other spacecraft data which confirmed the detection of interstellar grains at many heliocentric distances. Both Cassini and Galileo recorded several hundred grains at between 0.7 and 3 AU from the Sun, and some interstellar grains were found in the Helios data that came from as close as 0.3 AU to the Sun. The sizes of those clearly identified interstellar dust particles depend on the heliocentric distance at which they were detected. Within 3 AU, grains that are bigger than 0.3 µm prevail, with increasing masses closer to the Sun. These bigger particles do not exhibit temporal variations due to the solar magnetic field. In contrast, small grains with sizes below 0.3 µm are depleted and show significant variations, because they are subject to electromagnetic interactions with the solar wind. Such facts indicate that the interstellar dust is filtered by both radiation pressure and electromagnetic forces.

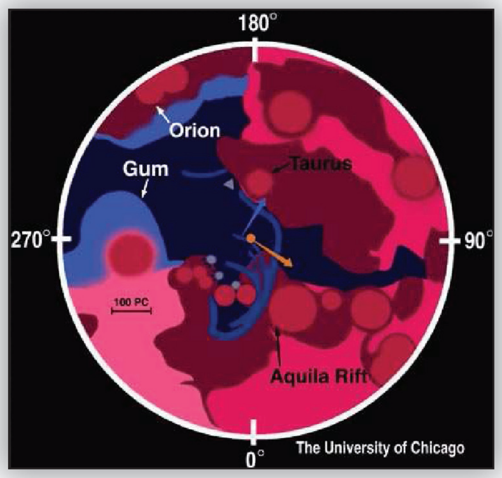


Figure 4: The orange dot in the above false-colour drawing represents the current location of the Sun among local gas clouds. Nearly spherical bubbles surround regions of recent star formation. The Sun has been moving between the spiral arms of this region for the past 5 million years (courtesy University of Chicago).

2.2 Interplanetary Dust

Dust plays a key role when a molecular cloud collapses and forms a protostar. The gaseous cloud contains a dust fraction of about 1 to 2 % of its total mass. While falling inwards, the heavier dust particles aggregate. The formation of planetesimals is triggered. This viscous stage lasts up to 1 million years. When the micron-sized dust has grown to objects of some metres or kilometres, they decouple from the chaotic motions in the nebula and move on Keplerian orbits around the central body. They also clear out their proximity by attracting the much lighter debris (Fig. 5). The planetesimals continue to grow and form protoplanets. Nevertheless, the interplanetary grains affect the internal composition of the objects they form. Close to the central star the grains are altered by the heat and shock waves. The growing

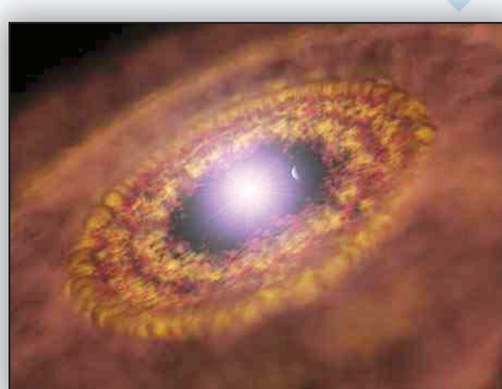


Figure 5: Artist's conception of a protoplanetary disk. Within 10 million years planets form out of the dust cloud while the gaseous surplus is blown away by the stellar wind (courtesey A. M. Quetz/ MPIA).

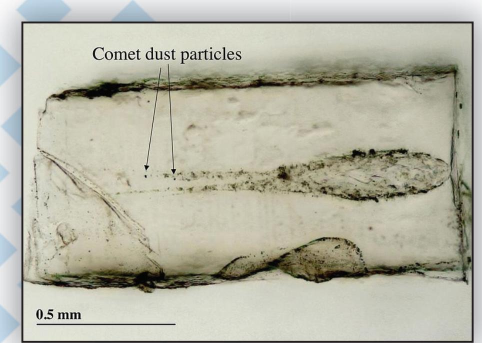


Figure 6: An aerogel slice removed with an ultrasonic blade showing particle tracks captured from a comets tail (NASA/JPL).

grains will melt, recondense, and the volatile components are more likely to vaporise and be depleted. In the outer parts of the protoplanetary disc, the grains will retain larger amounts of volatile material (such as ices) and show a different mixture of isotopes. Thus, the outer regions remain in a less processed state. It is believed that the volatile ices which survived the formation process are preserved in the outer regions of the Solar System. They might be incorporated in comets in the Oort Cloud that have not yet approached the inner Solar System. Thus, some comets may still reflect the original composition of the presolar cloud.

The interplanetary probes Giotto, VeGa1 and VeGa 2, ICE, Deep Space 1, Stardust, and Deep Impact investigated several different comets. They found that cometary material contains silicates of both crystalline and glassy structure. The Stardust mission returned, for the first time, material (Fig. 6) from comet Wild 2 to Earth. Surprisingly, some dust grains were found to contain highly refractory minerals similar to those found in chondritic meteorites. These chondrites have always been a puzzle because they contain minerals that formed at low temperatures as well as minerals that must have been formed at high temperatures. Other research indicates a very wide range of olivine and low-Calcium pyroxene compositions in the same comet. Such results imply different formation locations in the protoplanetary disk. Although comets are an obvious source of dust dating back to the formation phase of the Solar System, there are a variety of other sources that supply interplanetary space with tiny material: asteroids, meteoroids, moons and planets. The most prominent sources are comets and asteroids. Most interplanetary dust particles (IDPs) are born by impacts on their surfaces and distributed by planetary perturbations, solar radiation pressure, and electromagnetic drag from the solar wind.

Figure 7: The triangle-shaped bright cone near the Easter horizon is the zodiacal light. It is reflected from interplanetary dust particles orbiting in the same plane as the planets. The image was taken at the site of the Paranal Observatory in Chile in July 2007. (Credit: Y. Beletsky/ESO)

Several dynamically different sub-populations of interplanetary dust have been identified. Firstly, particles orbiting the Sun with low eccentricities, originating in the asteroid belt; secondly, particles with highly eccentric orbits that most likely derive from short-period comets; and thirdly, small β-meteoroids that arrive from a nearly solar direction and were generated by collisions among meteoroids close to the Sun. In addition to these main sources of dust in the Solar System there are the giant planets Jupiter and Saturn that expel tiny dust particles, so called dust streams, originating from planetary satellites and rings. An analysis of the physical and chemical properties of the the various dust populations improves our understanding of its origins. Obvious evidence of dust in interplanetary space is the Zodiacal light, visible as a faint glow along the ecliptic after sunset or before dawn (Fig. 7). It is due to the reflection of sunlight by dust particles. The glow is concentrated in the ecliptic plane, thus, the zodiacal light appears only in the constellations that lie on the Sun's apparent annual path. Although visible only in extremely dark areas away from moonlight and civil light pollution, its thermal emission is responsible for about 60% of the total sky brightness at infrared wavelengths. If seen from outside the Solar System, the dust cloud would appear to be lens-shaped and centred on the Sun.

Figure 8: The comet Hale-Bopp on April 2, 1997 from Blandford, MA. The bluish tail originates from ions that interact with the solar wind, while the white curved tail is caused by dust particles reflecting the sunlight. (Credit: J. Roberts)

Comets are icy bodies containing many mineral inclusions, often in the form of dust. Their chemistry includes silicates, sulfides, and organic material rich in oxygen and nitrogen. The dust grains are liberated from the comet when it approaches the Sun. When the surface material sublimates, due to the increasing temperature, the particles escape into space producing a tail of dust and volatiles. The gaseous components form the ionic tail of the comet (which may have a bluish hue depending on the gas composition, Fig. 8). The interplanetary magnetic field moves the charged ions outwards, directly away from the Sun. The dusty components are left behind along the trajectory of the comet and make up the curved white tail. These dust particles diffuse slowly in all directions, subject to a number of perturbations. Most important is the gravitation of planets and the Poynting-Robertson drag which brings them into orbits closer to the sun. Comets traverse the Solar System on eccentric orbits and a wide range of inclinations to the ecliptic. The Giotto mission was the first to investigate the amount of dust produced by the Comet Halley and Stardust collected dust grains from Comet Wild-2 and returned them to Earth for a detailed analysis.

Asteroids are believed to be relicts of planetary formation that did not result in significant growth. They are concentrated in the Asteroid Belt between the orbits of Mars and Jupiter. Beyond Neptune's orbit there is another belt of multi-kilometre-sized bodies: the "Kuiper belt" from which short period comets originate. In fact, dust from these objects exists anywhere in the Solar System, and its distinction to comet dust is rather blurred. Asteroids current contribution to the interplanetary dust population arises from both large scale physical collisions (Fig. 9) and small scale impact gardening by IDPs. They produce myriads of fragments that disperse. Sometimes the large scale impacts form a porous rubble pile asteroid, only weakly bound together. Their surfaces carry a metre-thick

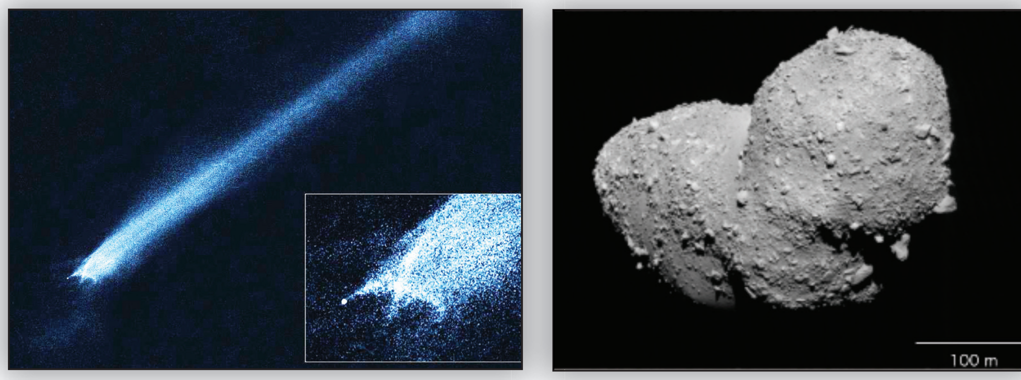


Figure 9: Left: The Hubble Space Telescope observed an unusual comet-like object. It suggests that it is not a comet but instead the product of a head-on collision between two asteroids travelling five times faster than a rifle bullet (5 km/s). Some of the filaments are swept back by radiation pressure from sunlight to create straight dust streaks. Right: The asteroid Itokawa as seen by Hayabusa (courtesy of JAXA).

layer of dust and debris, similar to that of the Moon.

Planetary Dust Streams are a newly detected phenomenon, discovered and characterised by our dust sensors onboard Ulysses, Galileo and Cassini. The satellite and ring systems of Jupiter and Saturn were identified as sources of streams of nanometre-sized dust, with speeds up to 400 km s^{-1}. The three spacecraft were able to measure the outflow of particles with a strong charge-to-mass ratio, even at a distance of 500 million kilometres away from their source region. The main sources of the dust streams are active moons, like Io or Enceladus, that distribute particles into the magnetospheres of their planets, where they become charged and accelerated by the rotating electromagnetic field. The streams are evidence of a strong coupling of dust particles to the magnetospheric environment of the source planet and the interplanetary magnetic field of the Sun.

2.3 Circumplanetary Dust

Another region for the detection or collection of dust is the direct environment of a planet or its satellites. This population of dust is bound to the gravity of the host. The most obvious examples are the planetary rings around the gas giants. Saturn possesses the most prominent rings, and also the most complex. They are divided into two classes: massive rings and dusty rings (Fig. 10). The massive rings are accessible to optical telescopes. Here, myriads of large grains and boulders lie on almost circular orbits around Saturn. Their sizes range from centimetres to tens of metres. The dynamics of the massive rings are solely governed by gravity and mutual collisions. Embedded moons and moonlets generate interesting structures in the rings, such as wavy edges,

Figure 10: Left: Saturn's blueish outer E ring along the orbit of the moon Enceladus. Cassini acquired this global view during a solar occultation of the planet. Right: In this false-colour image the moon Enceladus sends out jets of submicron-sized icy particles from the South Polar region. A part of the particle flux of several kg s^{-1} escapes the moon's gravitational domain replenishing the E-ring of Saturn. Beneath its ice crust liquid water was discovered to be the source of the jets. (NASA/JPL)

spirals, arcs and propellers. These depend on the local particle density and involved masses. Apart from these massive rings, Saturn has also "dusty rings" that exhibit different properties. The dust lifetime in the dusty rings is at most a few hundred or thousand years. The ring material must therefore be replenished. Secondary ejecta due to interplanetary meteoroid impacts onto a moon embedded within a dusty ring, can have escape speeds fast enough to leave the moon's gravity and become a ring particle. Alternatively, dust producing eruptions on an active moon can be a strong source of submicron-sized grains.

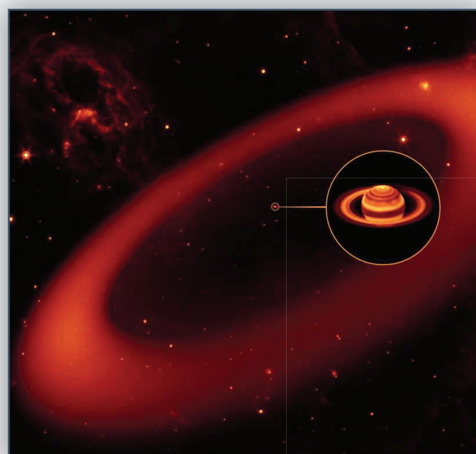


Figure 11: An artist's impression of the Phoebe ring. The Spitzer Space Telescope spotted it in the infrared. Saturn and the other rings would just appear as a tiny dot compared to the vast extent of the Phoebe ring. Dust grains originating from Phoebe with sizes bigger than 20 µm form this very faint retrograde ring. Can this ring be detected by the dust sensor onboard Cassini? (NASA/JPL/SSI)

In 2009, the Spitzer Telescope found another dust belt of completely different nature in the Saturn system: It exists at approximately the orbit of Phoebe, indicating its relationship to that satellite (Fig. 11). The ring is inclined by 27° with respect to Saturn's equatorial plane and the overall ring plane. The particles are presumed to have originated from micrometeoroid impacts on the surface of Phoebe.

A different type of short-lived planetary dust travels on ballistic trajectories close to many moons and planets. Discoveries by the dust instrument onboard the Galileo probe showed that such clouds are generated by the ejecta from impacts of interplanetary grains (micro-meteorites) onto the surfaces of the Galilean moons of Jupiter. These clouds are present around any essentially atmosphereless moons or planets (such as Mercury).

Figure 12: The Cassini-Huygens spacecraft in the clean room for Assembly Test and Launch Operations. The high gain antenna has a diameter of 4 m and the spacecraft has a wet (fuelled) mass of 5.6 tons. The CDA instrument with its white cover is mounted at the top left. Cassini was launched in October 1997 and reached Saturn in 2004 for orbit insertion. The end of the mission is planned for 2017.

3. Discoveries by Cassinis Dust Detector

Saturn with its huge system of rings and moons provides one oft the most interesting and intriguing environments in the solar system. After travelling for almost 7 years, the Cassini spacecraft (Fig. 12) entered into orbit around Saturn in 2004. The spacecraft carries a suite of more than 10 instruments, of which the Cosmic Dust Analyser (CDA, Fig. 13) is the only German instrument. This in situ detector was developed under the leadership of the Max Planck Institute for Nuclear Physics in Heidelberg, with the support of the DLR e.V., and it has been operated by the University of Stuttgart since 2011. It was designed to characterise the micron and sub-micron particles at (and on its way to) Saturn. Since Cassinis Orbit insertion in 2004, discoveries from CDA have led to publications in leading journals like Nature and Science every year.

CDA determines the speed (1 - 100 km s^{-1}), mass (10^{-15}-10^{-9} g), electric charge (1 fC - 1 pC) and elemental composition (m/Δm = 20 - 50) of individual dust particles and can measure dust spatial densities between 10^{-9} m^{-3} and 10 m^{-3}. An international team of scientists and engineers, led from the University of Stuttgart, performs science planning, operations (including commanding and instrument monitoring), data processing and science analysis. The instrument consists of an Impact Ionisation Detector (IID), a Chemical Analyser (CA) and a High Rate Detector (HRD). The CDA subsystems are based upon charge induction, impact ionisation, time-of-flight mass spectrometry and depolarisation of PVDF foils. The Cassini mission continues until September 2017 with excellent opportunities for CDA to gather information from Enceladus and other particle emitting moons, Saturn‘s ring system, and exogenous dust particles, such as interstellar dust. The following sections summarise some of the major findings of this instrument.

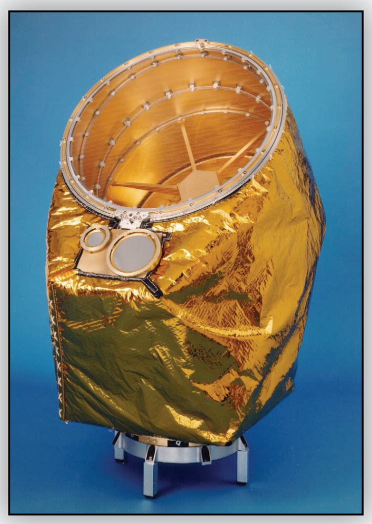


Figure 13: Flight unit of the Cosmic Dust Analyser for the Cassini mission. The instrument measures the speed, mass, electric charge and composition of individual submicron- and micron-sized dust impacts over a speed range of 1 to 100 km s^{-1}. The instrument has a mass of 17 kg and consumes 12 W.

3.1 Interstellar Dust in the Inner Solar System

In 1992, interstellar dust (ISD) was identified inside the Solar System by our dust detector onboard the Ulysses spacecraft. A flow of micrometre-sized interstellar grains was identified at a distance of about five AU from the Sun. The observed flux was $1.5 \cdot 10^{-4} m^{-2} s^{-1}$ of particles with a mean mass of $3 \cdot 10^{-13}$ g giving a mass flux of $5 \cdot 10^{-17}$ g m^{-2} s^{-1}. The results showed that interstellar dust of approx. 0.3 microns radius enters the Solar System at 26 km s^{-1} and its source direction, around 259° longitude and +8° latitude, was found to be compatible with the direction of the interstellar gas. This finding led to the integration of a special ISD observation period, at 1 AU solar distance, in the early cruise phase of Cassini in 1999. This high-risk observation with very limited spacecraft resources produced the first discovery of CDA: the in situ measurement of individual ISD grains in the inner solar system. An ISD flux of approximately $2.5 \cdot 10^{-5}$ m^{-2} s^{-1} was detected, at heliocentric distances of between 0.7 and 1.3 AU, of grains with masses compatible with values determined by Ulysses of $3 \cdot 10^{-16}$ kg (Fig. 14). The decrease of the ISD flux at small heliocentric distances can be explained by the radiation pressure filtering effect and by Lorentz forces due to the interplanetary magnetic field, preventing grains smaller than about 0.1 micron radius from reaching the innermost regions of the Solar System. Currently CDA measurements are in progress, in order to determine the interplanetary dust flux at Saturns solar distance (~10 AU).

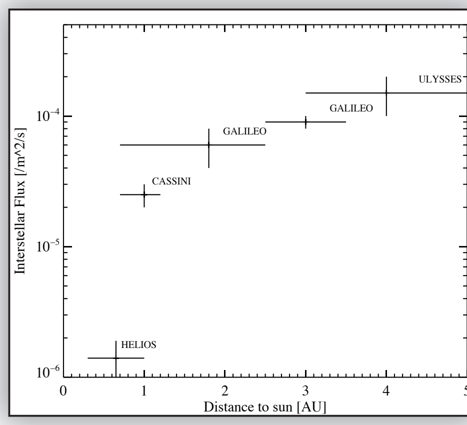


Figure 14: The ISD flux measured by various in situ dust detectors onboard the interplanetary spacecraft. The radiation pressure of the Sun , together with the interplanetary magnetic field, prevents the smallest particles (<0.1 microns in radius) from penetrating the heliosphere. However, interstellar dust particles reach the inner heliosphere and can be detected by dust instruments in Earth orbit, on the moon and in interplanetary space.

3.2 Charged Interplanetary Dust Particles

Cosmic dust particles are embedded in the heliosphere and interact with both ultraviolet light and solar wind particles from the Sun. They are affected by a variety of charging mechanisms which usually lead to an equilibrium potential at the grain surface of +5V. UV photoelectron emission dominates the charging process in regions with low plasma densities, such as interplanetary space. Other contributing charging processes are the sticking and penetration of plasma particles, and secondary electron emission due to the bombardment of highly energetic plasma particles. The CDA instrument can determine the electrical charge of incident dust grains with a sensitivity of approximately 1 fC. Between heliocentric distances of 1 and 2.1 AU, CDA registered six IDP impacts showing a clear charge signal (Fig. 15). This was the first unambiguous detection of the electrostatic charges carried by dust particles in interplanetary space. The trajectory detector geometry, with two inclined charge sensing grids, enables the accurate determination of particle speed, electrostatic charge, mass, and trajectory. The dust charges varied between 1.3 and 5.4 fC, corresponding to particle masses of between $1.3 \cdot 10^{-13}$ and $9.5 \cdot 10^{-12}$ kg. Here, for the first time, a reliable grain mass determination based on a surface potential of 5 V was derived.

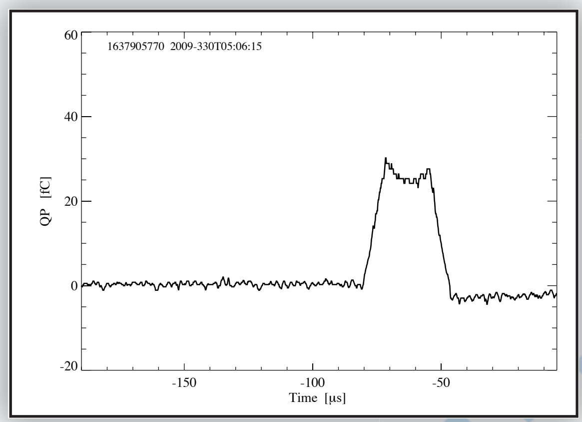


Figure 15: Induced charge signal of the CDA entrance grid channel (QP) due to a 40 μm particle carrying an electric charge of 30 fC. The impact speed onto CDA was 6 km s−1 and this particle was detected in the Saturnian system in 2009. The impact occurred in the ring plane at a distance of 36 Saturn radii from Saturn.

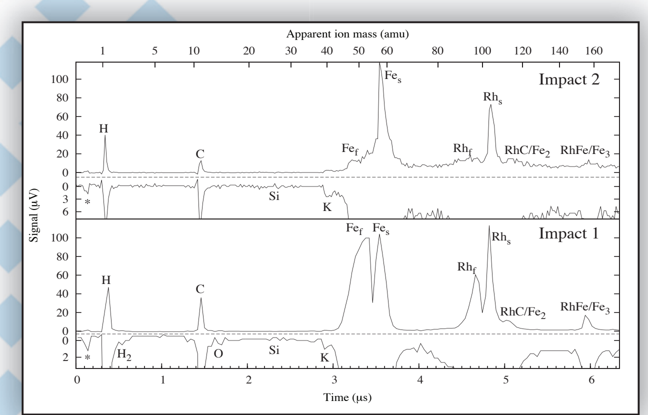


Figure 16: CDA Chemical Analyser time of flight mass spectra of two interplanetary dust particles. For clarity the spectra are shown inverted and magnified. The magnified view of the Impact 1 spectrum is magnified by a factor of 9, that of Impact 2 by a factor of 4.5. Carbon and Hydrogen are common contaminants of the Rhodium impact target but may also occur in the interplanetary dust particles

3.3 Composition of Interplanetary Dust Particles

Early in Cassini's interplanetary cruise phase, before the flyby of the Jovian system, CDA's Chemical Analyser subsystem detected two interplanetary dust particles. During this time the instrument was not in full science mode and serendipitous science data was returned with engineering and housekeeping data. The first IDP spectrum was recorded on 27th May 1999, when Cassini was 0.89 AU from the Sun. The second spectrum was recorded at a heliocentric distance of 1.87 AU, on the 10th November 1999. Laboratory calibration of the CDA flight spare using the Van de Graaff dust accelerator in Heidelberg indicates that the first particle had a mass of $9 \cdot 10^{-14}$ kg and struck CDA at a speed of approximately 18 km s^{-1}. The second particle had a mass of $1.4 \cdot 10^{-12}$ kg and impacted at a speed of approximately 7.7 km s^{-1}. The time of flight mass spectra for both impacts are shown in Fig. 16. Numerical ion modelling, comparison with laboratory calibration spectra and solar system elemental abundances indicate that the spectrum of impact one exhibits features of fast non-thermal (Fe_f and Rh_f) and slow thermal (Fes, Rhs) ions. Both grains were found to be similar in composition, predominantly Fe with surprisingly few traces of silicates. The apparent compositions of the particles, together with their detection locations and impact velocities indicates that they were in asteroidal-type orbits.

3.4 Composition of Stream Particles from Jupiter

Streams of nanometre-sized dust grains originating from Jupiter's moon Io were discovered and investigated by the dust instruments onboard the interplanetary space missions Ulysses and Galileo. These particles are released by Io's volcanoes, become charged in the plasma torus around Jupiter and are accelerated to speeds as high as 400 km s^{-1} in leaving the Jovian system before coupling to the magnetic field in interplanetary space (Fig. 17). As the Galileo and Ulysses detectors were not equipped with a spectrometer the Cassini flyby of Jupiter in 2000 provided a unique opportunity to investigate the composition of the Jovian dust stream phenomenon. Between day of year (DOY) 248 in 2000 and DOY 165 in 2001, corresponding to a Jovian distance of 1.1 AU at the inbound trajectory and about 2 AU on the outbound trajectory, the CDA sensor recorded 7283 stream particle impacts including 836 TOF mass spectra. Like Ulysses and Galileo, Cassini CDA observed bursts of high dust impact rates with durations between one and ten days. The time interval between the two

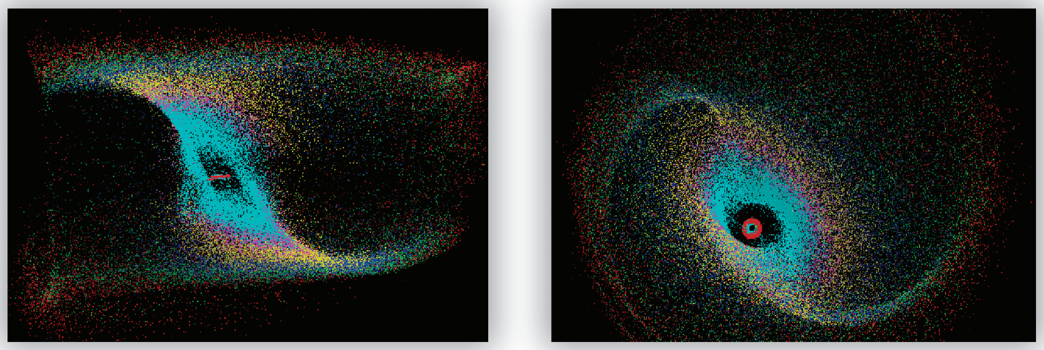


Figure 17: Escape of charged dust grains from the jovian magnetosphere (left: side view, right: top view). Each coloured point represents the position of a dust grain after 15 hours of travelling, launched at the orbit of Jupiter's moon Io. The colour represents the dust grain radius (red:5-7 nm, green 7-9 nm, dark blue 9-12 nm, orange 12-16 nm, purple 16-20 nm, light blue >20 nm). Bigger grains remain on bound orbits close to Jupiter in the centre (red ellipse). The 5 nm sized grains reach distances of 10 million km and speeds of 300 km s^{-1}. (Courtesy A. Graps)

strong impact bursts at DOY 251 and DOY 266 in 2000 is approximately 15 days, agreeing well with that expected for dust streams modulated by the IMF. A detailed analysis of more than 300 mass spectra were performed and nine distinct features were found (Fig. 18). By a clear quantitative correlation it appears NaCl is the parent molecule of the majority of the recorded Na^+ and Cl^+ ions. Silicates and sulfur or sulfurous components might be another constituent of the stream particles, which have masses equivalent to sizes of approximately 24 nm. From this chemical fingerprint, recorded approximately 100 million km away from Jupiter, Io's volcanoes are again identified as the source for the vast majority of stream particles detected. It is remarkable, that such an in situ analysis far away from its source enables us to learn about the thermodynamic and chemical properties of the volcanoes and their plumes and even to look inside a small planetary body.

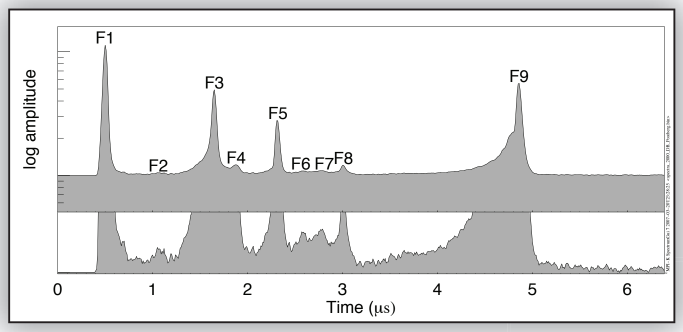


Figure 18: Dust spectrometry of Io's volcanic ash recorded more than 80 million km away from Jupiter. A sum spectrum of 30 TOF mass spectra of Jupiter's nanometre-sized stream particles show nine major peak features indicating a NaCl rich composition. The lower spectrum shows a stretched y-scale. The dominant spectral features are H^+ (F1), $C2^+$ (F2), C^+ (F3), O^+ (F4), Na^+ (F5), Si^+ (F6), S^+/Cl^+ (F7), K^+ (F8) and Rh^+ (F9). H^+ and C^+ are mainly attributed to contaminations and Rh^+ represents the target material such that sodium, chlorine, sulfur and potassium are the main particle components.

3.5 Discovery of Streams of Nanodust Escaping from Saturn

In order to escape from Saturn, positively charged grains have to be accelerated by the outward-pointing co-rotational electric field caused by Saturn's rotating magnetic field. Since the magnetic field of Saturn is more than 20 times weaker than that of Jupiter, the escaping grains are either slower or smaller than in the Jovian case. In order to search for such streams originating from Saturn, special observation campaigns were integrated in the approach phase to Saturn

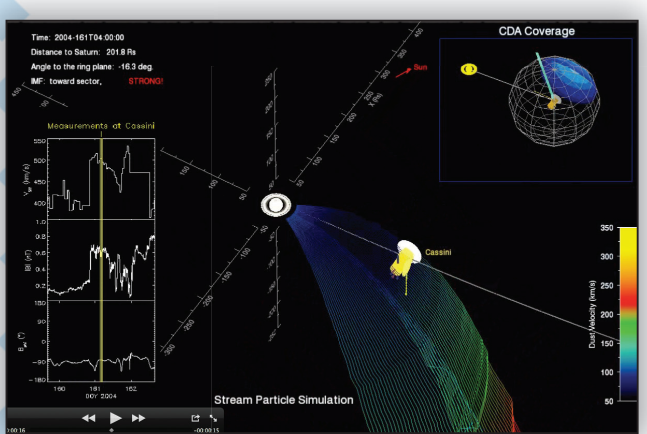


Figure 19: Snapshot of the dynamics of streams of nanodust escaping from Saturn's inner ring system and escaping to interplanetary space. The centre shows Saturn and coloured lines represent the tracks of sample particles influenced by the IMF structure. Increasing particle speeds are running from blue to red. Some grains reach speeds beyond 200 km s^{-1}.

starting in January 2004. The planning efforts were rewarded immediately by the detection of faint bursts of nanometre-sized stream particles starting at distances as far as 1200 RS (70 million km) away from Saturn (Figs. 19, 20). The burst intensities and impact rates seemed to grow with decreasing distance to Saturn implying an origin in the Saturnian system. Joining the Jovian system, Saturn with its ring system is now the second source of very tiny dust particles (masses below 10^{-21} kg) which move through the Solar System at speeds above 100 km s^{-1}.

3.6 Dynamics, Composition and Origin of Saturnian Stream Particles

The small size of stream particles generally leads to high charge-to-mass ratios such that electromagnetic forces significantly determine their dynamics. To overcome Saturn's gravity, the charge-to-mass ratio (Q/m) of the grain has to be sufficiently large. Only positively charged particles are accelerated outwards in Saturn's magnetosphere. Grain charges result from the competition between various charging processes such as collection of ions or electrons, emission of photoelectrons and emission of secondary electrons. There are two regions with a low plasma density where the dust surface potential is expected to be positive and which are considered as possible stream particle origins: The outskirts of the A ring and the region outside of approximately seven Saturn radii. Outside Saturn's magnetosphere, the dynamics of the grains are governed by their interaction with the Interplanetary Magnetic Field (IMF) convected by the solar wind (Fig. 19). As the Cassini spacecraft crosses the compression regions of the Co-rotation Interaction Regions (CIRs), not only the directionality of the impacts changes with the field direction, but also the impact signal and rate vary with an increase in field strength (bursts occur). At large solar distances the azimuthal component of the IMF dominates, and thus the out-of-ecliptic component of the dust velocity should be affected most. The monitoring of dust streams from Saturn's

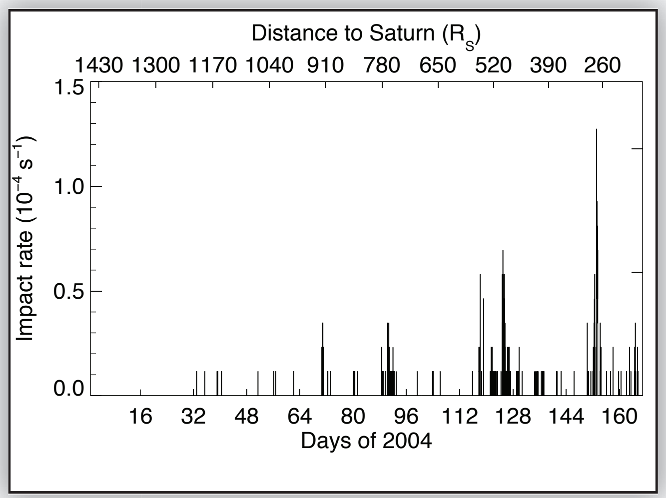


Figure 20: Discovery of streams of nanodust particles by CDA originating from the Saturnian system during the approach phase to Saturn between January 10 and September 6 in 2004. The upper scale gives Cassini's distance to Saturn in RS. In total, 1,409 impacts were detected.

magnetosphere is useful in identifying their source, and in understanding both the acceleration mechanism and the coupling between dust and the magnetic field and the plasma environment in the magnetosphere.

CDA also produced mass spectra from stream particle impacts.The preponderance of spectra with silicate lines suggest that the majority of the detected grains consists of silicate material, whereas solid ice grains are rare. Saturn's main ring is thought to be primarily made of water ice, possibly containing clathrate hydrates of ammonia or methane and a minor amount of impurities, such as iron-bearing silicate compounds. E ring particles mostly consist of pure water ice. These grains originating from Enceladus plumes are likely to also contain tiny silicate inclusions or organic compounds. Tiny silicate particle embedded in ice grains from Enceladus plumes might be an important source of Saturnian stream particles.

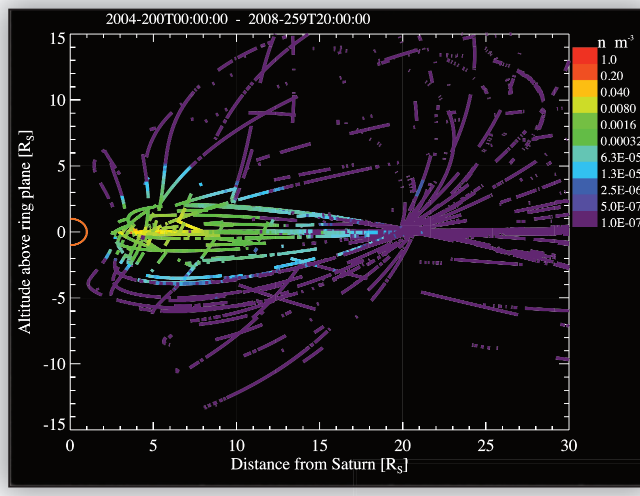


Figure 21: Global apparent dust density measured by CDA in the Saturnian system. The densities are colour coded along the Cassini trajectory in the time range of mid 2004 to mid 2008. Enhanced dust densities are found as far as 250.000 km away from the ring plane and extend to radial distances beyond 20 RS. Only an in situ instrument like CDA can measure the ring extension; the ring structure is too faint to be observed by optical instruments.

3.7 The E ring and Enceladus

Although mineral dust can be found in the Saturnian system too, it is particularly rich in icy dust particles. Saturn's outermost ring, the huge E ring, consists almost exclusively of micron and submicron-sized ice grains and its ring plane is crossed by Cassini in almost every orbit. The composition and dynamics of the tenuous E ring can therefore be efficiently investigated with an in situ instrument like CDA, providing information which can not be obtained with cameras or any other remote sensing technique. The E ring is one of the most exciting astronomical objects in our solar system, and it allows us to study the interaction of dust, plasma, moons and the magnetosphere (Fig. 10). In radial extend, the E ring is the largest planetary ring in the solar system, encompassing the icy satellites Mimas, Enceladus, Tethys, Dione, and Rhea. Optical observations of the ring reveal a bluish colour to the reflected light, typical for a narrow grain size distribution between. In situ investigations of the ring particles by the CDA detector helped to unveil some of the secrets of the E ring (Fig. 21). CDA found that the sizes of most E ring grains indeed range from 0.2 - 2 µm. The large ring thickness is caused by submicron-sized particles with inclined orbits. Simulating E ring dynamics remained a major challenge for the dynamical ring models. Extensive numerical simulations of the long-term evolution of E ring particles were performed, taking into account sputtering and dust particle erosion, which predicted a ring structure which could extend to distances as far as the orbit of Titan.

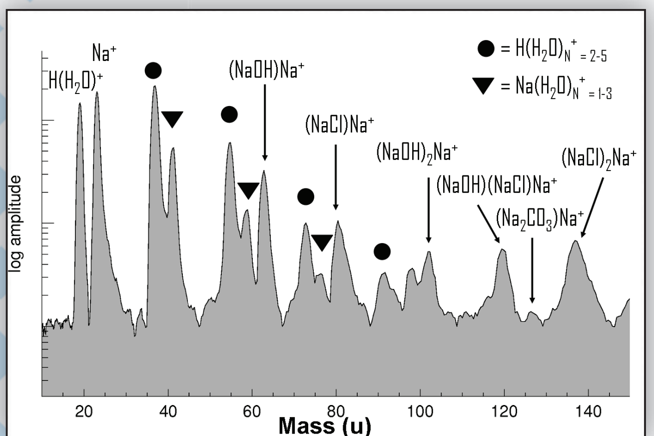


Figure 22: Proof for liquid water in the outer Solar System: TOF spectrum of a salt-rich water ice particle originating from the fountains on the surface of Enceladus. Below the icy crust of Enceladus, liquid water is in contact with the hot rocky core and salts and carbonates dissolve in the water. Fine droplets escape from the interior of Enceladus through surface cracks and form the outer E ring of Saturn.

Cassini, with its dust detector, discovered that the E ring is maintained by active ice jets on the surface of the moon Enceladus (Fig. 10). These jets, located at its south pole, provide an efficient source for injecting gas and dust into the outer Saturnian system. The total dust production rate is approximately 10 - 50 kg s^{-1}, ~10% of which escape from Enceladus' gravity to replenish the outer huge but faint ring of Saturn. Particle sputtering, electromagnetic forces, radiation pressure, gravity, Poynting-Robertson drag and plasma drag forces determine the fate of ring particles. Submicron grains may reach large distances or even escape from Saturn, bigger grains remain on almost circular orbits and migrate inwards. Cassini's dust detector CDA discovered that the radial extension of the E ring is more than 2 million kilometres, much larger than previously inferred from visual observations. Cassini's discovery in 2005 that Saturn's small ice moon Enceladus is cryo-volcanically active (Fig.11) was one of the major surprises in planetary science within the last decades. The small moon displays a huge plume from hundreds of high velocity jets of water vapour and ice particles that emerge from warm fractures in the surface near its southern pole. Some of the ice particles don't fall back, leave Enceladus' gravitational domain and form the E ring. Thus, the analysis of these grains provides the unique opportunity to gather information about subsurface processes below the moon's icy crust. Excitingly our compositional analysis of grains emitted from Enceladus show that they emerge from liquid water. The detection of significant quantities of salts and carbonates in the emitted ice grains was the major evidence for water close to Enceladus' icy surface which has been in contact with the moon's rocky core at much greater depth (Fig. 22).

4. Instrument Development: Dust Telescopes

When micrometeoroids encounter the Earth, they are heated during passage through the upper atmosphere and rarely reach the ground. Thus dust samples on Earth are few, and those grains that do reach the surface are processed and chemically altered during passage through the atmosphere. The only way to perform unbiased measurements and to separate natural meteoroids from space debris, is in situ measurements made in space. For this purpose, it is necessary to determine the grain trajectory and elemental composition accurately. One of the problems of the sensitive detection of space debris and micrometeoroids is the low flux, thus requiring a large sensitive area in order to obtain sufficient data on reasonable time scales. However, the accurate determination of a particle's properties such as speed, trajectory and composition is difficult with a big instrument.

What will be the future of dust detection technology? Are there new concepts for dust impact detection? The Cosmic Dust Analyser onboard Cassini is based upon induced charge detection and impact ionisation – is this still state of the art? The answer is yes. The basic principles of both induced charge detection and impact ionisation are still the most sensitive and most reliable methods. Both detection methods have been improved and led to the design of a Dust Telescope.

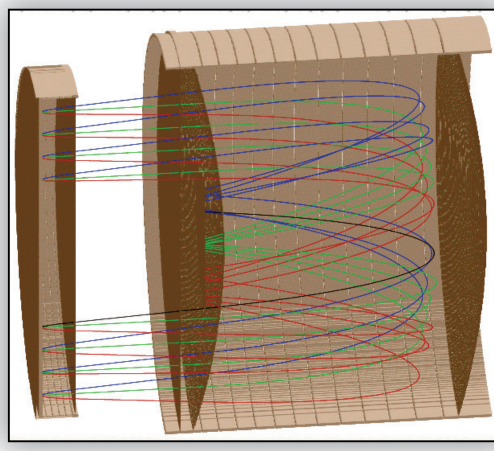


Figure 23: The time-of-flight Large Area Mass Analyser (LAMA) with simulated trajectories of ions starting at the ring-shaped target (left) and focused onto the central ion detector. The ion energy of the impact plasma was chosen to 50 eV and three different emission angles are shown (red, green, blue). The reflectron uses parabolic shaped grids.

A Dust Telescope is a combination of a trajectory sensor and a mass spectrometer. The trajectory sensor determines the speed, mass, primary charge and trajectory of micrometeoroids. The measurement is based on the amount of induced charge from the particle primary charge onto individual metal electrodes. For example, a particle with a radius of one micron and a surface potential of 1 volt, carries a charge of 700 electrons. Assuming an induction effciency of 50%, a signal of 350 electrons is expected. The amplifier noise of 100 electrons gives a signal-to-noise ratio of 3.5 which is sufficient under normal conditions. However, the grain's surface potential is low under the low energy plasma conditions encountered in Low Earth Orbit (-0.5 V) leading to a higher mass threshold of approximately 10^{-10} g. The high energy plasma conditions in Geostationary orbit lead to surface potentials between -30 V and +3 V. The measurement threshold of those particles is expected to be as low as 10^{-15} g (equivalent to a radius of 50 nm). In contrast, in interplanetary space photoemission dominates the grain charging process, leading to surface potentials of $\Phi \approx +5$ V. Here, a 0.1 micron particle would carry a charge of 350 electrons.

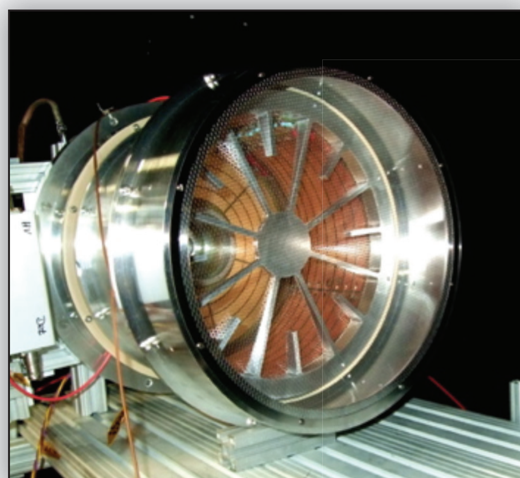


Figure 24: Laboratory model of the small dust telescope SUDA during tests at the dust accelerator. The ring-shaped target has a diameter of 20 cm and the instrument mass is below 3 kg. The integrated time-of-flight mass spectrometer uses a reflectron and has a mass resolution of around 150.

The low dust flux in interplanetary space (approximately $10^{-4}\,m^{-2}\,s^{-1}$) requires a dust analyser with a large (~0.1 m^2) sensitive area and a wide field-of-view (> 50°). This could not be achieved with previous dust analysers in space. Therefore a new Large Area Mass Analyser (LAMA) has been developed, that meets the requirements of a sensitive impact area and a mass resolution of Δm

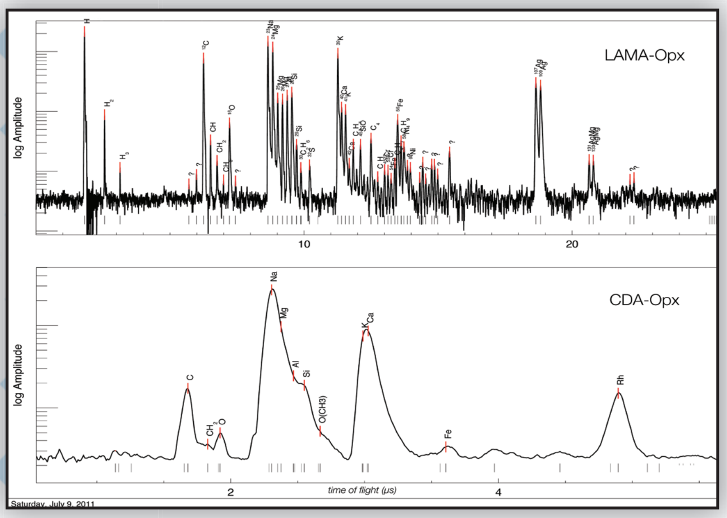


Figure 25: Comparison of the performance of the mass spectrometer CDA onboard Cassini (lower panel) and the new instrument LAMA (upper panel). The mass resolution of the new generation Dust Telescope is a factor of 10 higher.

>200. For LAMA, a configuration with cylindrical symmetry has been chosen, with a ring-shaped impact target held at a +5 kV acceleration potential. Potential rings provide a smooth electric field close to the cylindrical wall of the instrument housing (Fig. 23).

Figure 24 shows a compact spectrometer which is suited for smaller missions such as the Ganymede Orbiter, and Moon and Earth orbiting satellites (see section “Future Challenges“). A comparison of the spectral resolution between Cassini‘s CDA (built in 1996) and the Large Area Mass Analyser (LAMA, built in 2005) used for a Dust Telescope is shown in Fig. 25.

5. Laboratory Research

5.1 The Dust Accelerator

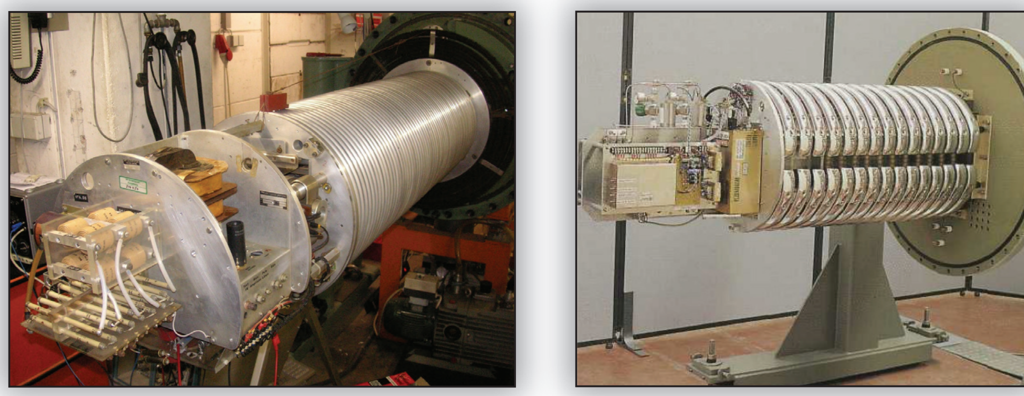


Figure 26: The Heidelberg 2 MV Van-de-Graaff accelerator (left) at the Max Planck Institute for Nuclear Physics, and the new 3.5 MV coaxial singletron accelerator (right) planned at the University of Stuttgart.

Impact processes play an important role in a variety of fields, such as the investigation of matter at extreme pressures and temperatures, shock waves in solid bodies, solar system research, planetology and cosmic dust research. The physical phenomena occurring during hypervelocity microparticle impacts include particle fragmentation, impact ionisation, impact flashes,

Figure 27: Concept of the new 3.5 MV Cockroft-Wolton Dust Accelerator providing micron and submicron dust grains with speeds between 1 and 100 kms^{-1}.

charge generation, charge induction, material ablation, electromagnetic pulse generation, and cratering. The investigation of these phenomena using the latest analysis techniques (such as high-speed cameras and high-resolution spectrometers) promises new instrument concepts and insights into the physics of short-lived, high-pressure states of matter. Impact studies are carried out using a dust accelerator and the results of these studies are relevant to planetology, astrobiology, re-entry physics, cosmochemistry, geophysics, chemistry, plasma physics and biology. The dust accelerator facility detailed herein (Fig. 26) is operated jointly by the University of Stuttgart and the Max Planck Institute for Nuclear Physics and currently located in Heidelberg, Germany. In 2013 it will be relocated in order to establish an upgraded facility at the University of Stuttgart, within the Institute for Space Systems (Fig. 27).

It is a unique facility which enables the investigation of hypervelocity dust impacts onto various materials. The main applications are to study the interaction of micro-grain impacts with target materials such as planetary analogues, metals or interplanetary dust collector materials as well as the development and calibration of dust sensor instrumentation for space-based applications. The current accelerator consists of a modified a 2 MV Van-de-Graaff ion accelerator which can accelerate micrometre and submicrometre-sized particles to velocities of up to 100 km s^{-1}. These particles are similar in terms of their dynamic properties to the main populations of cosmic dust particles found in the Solar System.

Phenomena currently being studied include dust charging, dust magnetosphere interactions, dust impact flashes and compositional measurements of impact generated plasma plumes. The results from the accelerator have been applied to multiple space missions including Galileo, Ulysses, Cassini, Rosetta, Stardust, and Bepi-Colombo. Future projects to the Moon and to the Jovian system will carry dust instrumentation which will be designed by applying the results of micrometeoroid impacts performed under controlled laboratory experiments. The test and calibration of dust collectors and dust detectors

Figure 28: The Flight Spare Unit of the Cosmic Dust Analyser in the thermal vacuum chamber for dust accelerator tests at the Heidelberg accelerator facility.

onboard interplanetary probes and terrestrial satellites iare major tasks of the accelerator facility (Fig. 28). For example, the recent Stardust mission returned samples of cometary, interplanetary and interstellar dust grains to Earth. Sample analyses and interpretation required the study of grain-collector analogue material interaction during hypervelocity impacts. The laboratory generation and analysis of mass spectra of the plasma cloud formed during high-speed micro-grain impacts of organic and inorganic cosmic dust analogues provides the basis for investigating the composition of interplanetary and interstellar micrometeoroids.

The latest advances in dust production and processing now allow solar system analogue dust particles (silicates and other minerals) to be coated with a thin conductive layer enabling them to be charged and accelerated. Recent refinements and upgrades to the beam line instrumentation and electronics facilitate the reliable selection of particles at velocities of 1 - 50 km s^{-1} and with diameters between 0.02 µm and 5 µm. This ability to select particles based on their charges, masses or velocities is provided by a Particle Selection Unit (PSU). The PSU contains a Field Programmable Gate Array (FPGA), capable of monitoring particle properties in real-time. The new control instrumentation and electronics, together with the wide range of accelerable particle types, allows the controlled investigation of hypervelocity impact phenomena across a hitherto unobtainable range of impact parameters.

5.2 History of the Heidelberg Dust Accelerator.

In the late 1960s and early 1970s the Apollo missions returned samples of lunar rock covered with craters caused by micrometeorite impacts. To obtain a better understanding of the cratering process, the impacts of micrometre-sized particles at velocities up to 50 km s^{-1} were investigated in the laboratory under controlled conditions. To this end the Heidelberg dust accelerator, initially designed and constructed as an ion accelerator, was modified and equipped with a dust source capable of charging and electrostatically accelerating micrometre-sized iron spheres to velocities comparable with those of cosmic dust particles in the Solar System. Dust sensors whose design was guided by the results of the experiments performed in Heidelberg have been flown on past and current space missions such as HEOS, Helios, Pioneer, Nozomi (MDC), Hiten, Giotto (PIA), Ulysses, Galileo, Cassini (CDA), Stardust (CIDA) and New Horizons (SDC). Furthermore, the Earth's space debris environment was investigated by Debie onboard PROBA and by the Long Duration Exposure Facility (LDEF).

Future missions with dust instrumentation, such as BepiColombo (MDM) and LADEE (LDEX), currently make use of the facility and, additionally, the Stardust Preliminary Examination team is performing in depth studies of dust penetration into low-density aerogel. Results from experiments carried out at the facility triggered the development of new collector materials (such as fluorescent aerogel) and new detector concepts like multi-array piezo detectors, trajectory sensors (ARMADILLO) and high-resolution, large area, mass spectrometers. Common to all these experiments is the necessity to relate the dynamical parameters, such as mass and velocity, of individual particle impacts to the properties of the resulting detector signal or the resulting impact structure.

5.3 Accelerator Subsystems

The main components of the facility are the dust source, the high-voltage generator, an acceleration section, a beam monitoring and deflection system, and the test chamber. The high-voltage generator (Fig. 26) is a modified Van de Graaff generator providing a potential up to 2 MV. In order to avoid discharges

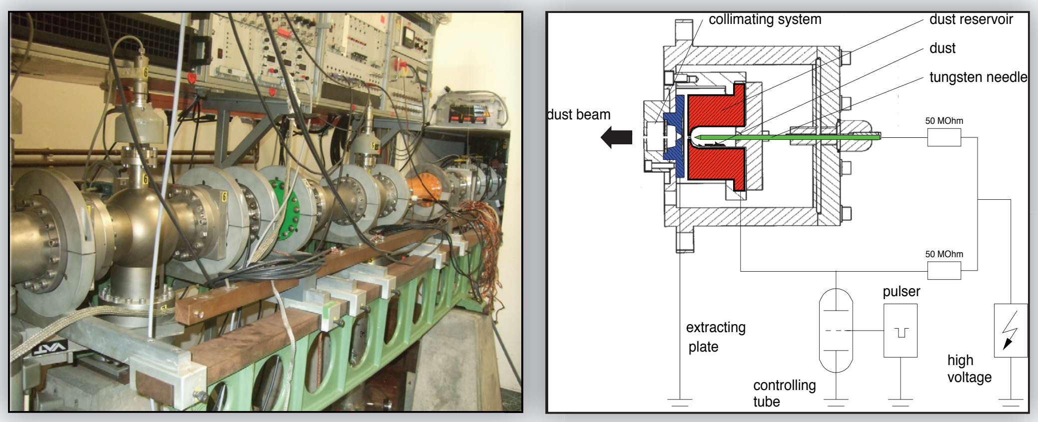


Figure 29: (left) Beam line of the dust accelerator with deflection electrode and electronics of the PSU. (right) Schematics of the dust source DS2001. A cavity is filled with submicron-sized grains and a pulsed high voltage of 20 kV between the reservoir and a needle lifts individual particles which leave the source through a central hole. This type of dust source is optimised for dust particles with low surface potentials, such as polypyrrole-coated silicates.

(sparking) between the terminal and the electrodes, the generator is immersed in a protective gas (SF_6 and CO_2) in a tank at a pressure of 16 bar. The dust grains are poured into a cavity in a reservoir (Fig. 29). A tungsten needle above the reservoir is pulsed at 20 kV and individual dust particles lift and become charged. Some positively charged individual particles leave the source through a small hole and are accelerated by the electrostatic field of the potential rings.

The kinetic energies of the accelerated particles arise from the conservation of energy, leading to particle velocities of:

$$v = \sqrt{2\,q\,U_{acc}/m}$$

with U_{acc} being the accelerator potential (V), q the particle charge (C) and m the mass (kg). Fig. 30 gives typical mass/velocity distributions for iron and orthopyroxene particles. The accelerated micro-grains pass focussing and

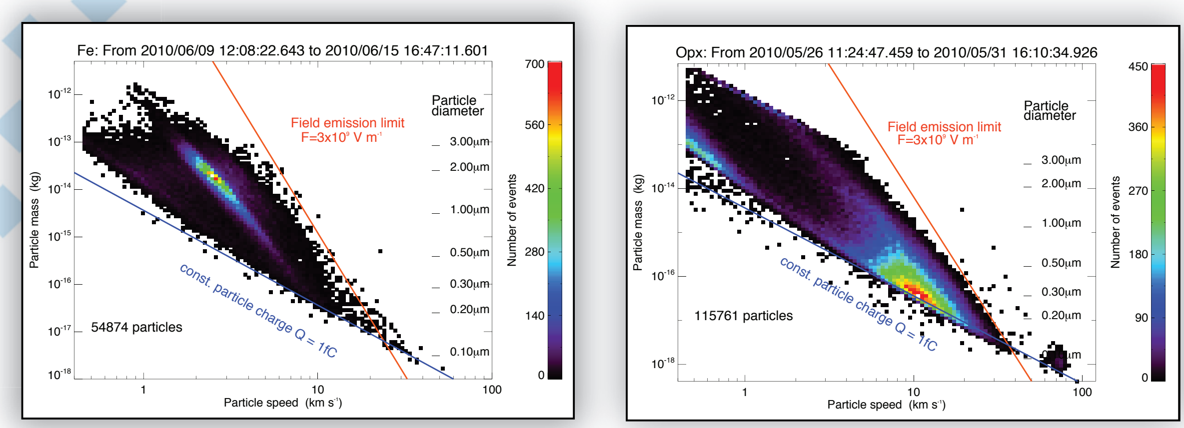


Figure 30: Velocity mass distribution for accelerated dust particles (left: iron, right: orthopyroxene).The blue line at the bottom determines the detection threshold of 0.1 fC and indicates particles with a constant charge. The upper red line represents a field emission limit of the grains of 1010V m−1 for grains with a constant field strength.

steering electrodes and their individual speeds and charges are determined by measuring the charge induced on sensitive detectors by the passing grains. Special control hardware and software determines the grains' speed and mass and selects individual dust grains on the basis of a speeds and masses window given by the experimenter. In the normal operating mode all particles are deflected by a 4 kV field. This field is switched off for fractions of a second to allow individual selected particles to reach the experiment chamber. A temperature controlled vacuum chamber with a diameter of 1.4 m enables the simulation of the space environment. The accelerator can also be operated in a single-shot mode and in a continuous mode. Dust materials include metal powders such as iron, coated microspheres - for example silicon dioxide, organic microspheres (polystyrene) and minerals (pyroxene (Fig. 31), anorthite, olivine).

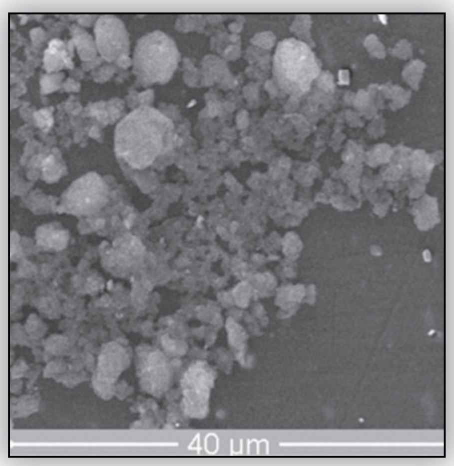


Figure 31: Electron microscope image of platinum-coated silica particles used at the dust accelerator.

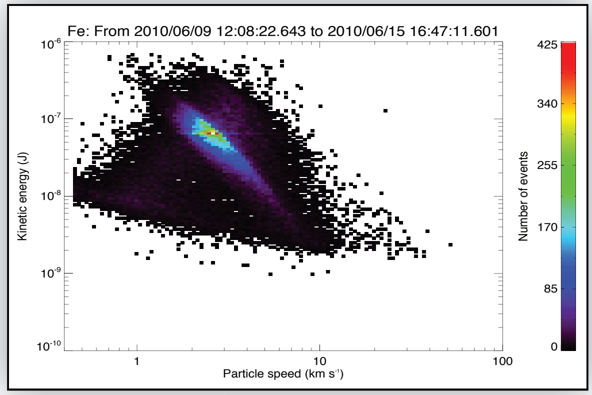


Figure 32: Velocity v and kinetic energy E_{kin} of accelerated iron micrograins to study impact effects at the dust accelerator.

The charge on a dust particle is given by

$$q = \Phi \cdot 4\pi\varepsilon_0 r$$

with Φ being the surface potential of the particle and *r* its radius. In order to reach high kinetic energies and thus high particle velocities, two requirements must be met. Both the accelerator potential and the charge-to-mass ratio (q/m) of the particles must be as high as possible. However, field emission limits the grain surface potential (Fig. 30). Figure 32 illustrates the relation between the particle velocity, v, and two impact parameters, $E_{kin} = 1/2mv^2$ and the energy density $D = E_{kin}/A$ upon impact, which is defined as the ratio of the particle's kinetic energy and the particle cross section, A (m^2).

5.4 Impact Studies

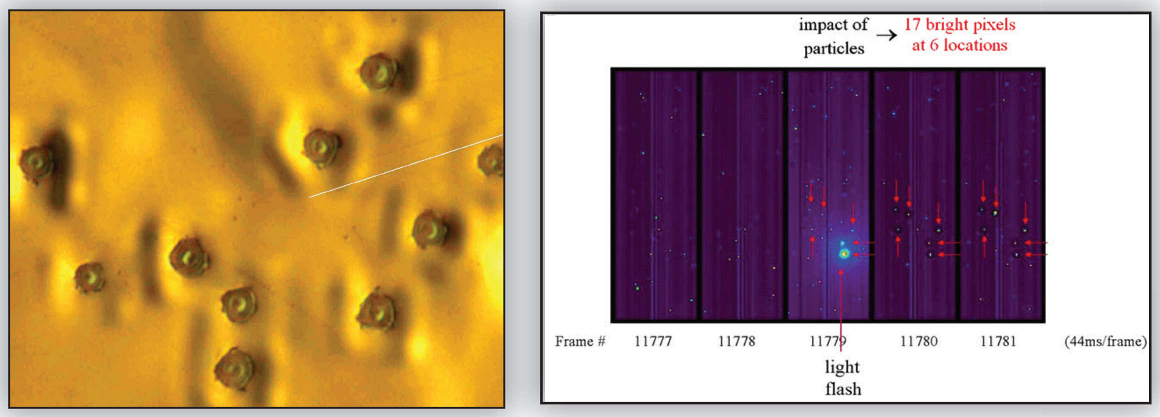


Figure 33: Left: Processed optical 3D image of a copper surface with features due to low-velocity iron sphere impacts. Illumination from the side (white line) makes the grey iron material in the craters visible. The magnification was 5000, giving to an image width of approximately 50 µm. Right: Impact on CCD of XMM-Newton telescope. Result of laboratory impact tests of micron sized particle under grazing incidence. Shown are five consecutive frames. A bright impact flash is seen on frame 11779. The subsequent frames show several permanently bright pixels which were damaged by the impact.

The interaction process of impacting high-velocity submicron or micron-sized projectiles with surfaces is highly complex process taking place within fractions of a nanosecond. The hypervelocity impact generates solid fragments, neutral and ionized gas, an impact flash and a crater with surrounding material defects (Fig. 33). Impact studies are performed in order to answer questions relating to crater sizes or ion yields, but due to the short interaction times and the extreme high pressures (GPa), no extensive description of the process has been achieved which is applicable to all size scales. The mechanics of cratering goes through several phases during the impact process, leading to various trajectories of the ejecta. Initially, a shock wave travels through the particle as well as the target. In this early state, the compressed material is limited to a small lens-shaped region directly below the area of impact. As the particle penetrates more deeply into the target, the shock waves travel through an increasing mass of the target and the projectile. There are rarefaction waves running across the target surface and along the sides of the projectile. This leads to a hydrodynamic ejection of mass at very high velocities, referred to as “jetting”.

The small number of available empirical data at micron scales and the fact that the existing data sets do not generally match in their range of parameters, such as projectile and target materials, impact speed etc., requires continued in-depth studies of the impact process. This will be achieved with state-of-the-art instrumentation such as streak cameras, sensitive charge amplifiers and high-resolution 3D microscopes.

6. Achievements and future challenges

Dust transports information across space and time – therefore it is an excellent medium for learning about the history of the Solar System, our interstellar neighbourhood and about the origin of life. Dust grains are charged and are thus influenced by planetary magnetospheres, the interplanetary magnetic field and the interstellar medium itself. The growing interest in the study of dust and its significance for astronomers, planetologists, geophysicists and astrobiologists led to a sequence of international mission proposals under the leadership of Germany (University of Stuttgart) and the USA (University of Colorado). These proposals were triggered by the knowledge gained by previous interplanetary missions such as Giotto, Ulysses, Galileo, Cassini and Stardust. Ulysses discovered and characterised interstellar dust, Cassini made excellent compositional measurements and detected for the first time grain charges, and Stardust brought cometary, interplanetary and possibly even interstellar dust samples back to Earth for study. This cosmic dust research has therefore explored micrometeoroids in the near Earth environment, interplanetary space, the vicinity of comets and in planetary rings. Exciting results have been achieved, with numerous discoveries of phenomena such as the fast nanometre-sized dust streams from the Jovian and Saturnian environments, dust clouds around small moons, detection of interstellar dust in the inner heliosphere and the detection of water in the outer Solar System. Do we now understand the origin, dynamics and composition of micrometeoroids in space? The answer is clearly no, progress has been made, but we have merely a few snapshots of our environment from a handful of instruments and missions. However, the available data from past missions have proven the significant scientific potential of Dust Astronomy.

A global scientific objective is the search for extant life and possible remnants of extinct life in our Solar System, outside of Earth. Two of the ingredients of life as we understand it are water and complex organic chemistry. Dust grains may have silicate cores with mantles of ice and complex organics, an ideal mixture to seed the basic components of life on the surface of planets. New dust spectrometer instruments enable us to investigate the composition of interstellar dust, Kuiper belt dust, dust from comets and asteroids, dust from planetary rings and dust from surfaces and the interiors of small moons. Dust contributes to the transport of water from the icy surfaces of moons to planetary rings and into planetary atmospheres, as well as from comets to interplanetary space and the Earth.

6.1 Dust Spectroscopy

The enormous potential of in situ compositional measurements was revealed recently by Cassini observations made with the Cosmic Dust Analyser. The CDA instrument determined the composition of Saturn's E ring particles, which originate primarily from the plumes of Enceladus' ice jets (Fig. 10, see chapter "Discoveries by Cassini's Dust Detector"). Scientists from our group reported the identification of a population of E ring grains that are rich in sodium salts, which can arise only if the plumes emanate from liquid water. This water source is, or was, in contact with rocky material, probably with the moon's rocky core at much greater depth. The evidence of liquid water in the outer Solar System has implications in the field of Astrobiology and the origin and formation of life.

This result clearly underlines the power of the remote detection and in situ method of dust detection by interplanetary spacecraft. Dust grains are formed at one location in space and are transported across space and time. Dust stream particles are formed in the inner Jovian and Saturnian systems, but they are detected outside of the magnetosphere of the planets, millions or even hundreds of millions of kilometres away from the original sources. For example, dust grains emitted by Jupiter's moon Io could enter the Earth's atmosphere and would be detectable using sensitive dust detection instrumentation. As a second example, dust grains from the interior of Enceladus are transported to the spatially extended E ring, and hence to a distance of between four to eight Saturnian radii, or possibly even further. More locally constrained dust grains in the clouds around small bodies preserve the compositional information of their parent surfaces and would comprise mostly of grains composed of a body's surface material. Compositional measurements thus allow for remote studies of a body's surface composition with a spatial resolution which is of the order of the dust grain altitude. Such measurements would enable in situ compositional studies of surfaces by orbiters without the need for a costly lander. Future targets for interplanetary missions to search for life tracers are the icy moons Europa, Ganymede and Enceladus. In situ dust spectrometry in the dust clouds around these small bodies would enable the remote investigation of their surface composition.

6.2. Astromineralogy

Interstellar Dust

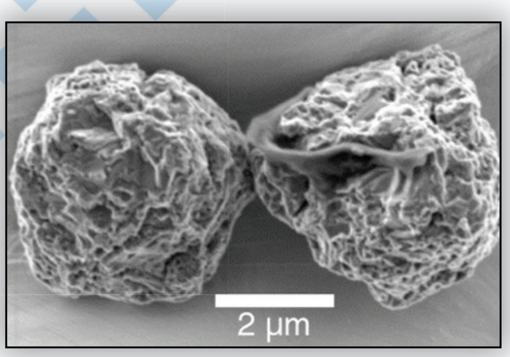


Figure 34: A pair of SiC stardust grains from the Murchison meteorite. (Credit: A. M. Davis)

Dust is formed in stellar environments and processed in the interstellar medium. It is formed in the ejected shells of gas that surround stars coming towards the end of their lives. Particles consist of both amorphous and crystalline materials. Crystalline magnesium-rich silicates, amorphous silicates, diopside, spinel and corundum are major components of the solid phase. Aromatic hydrocarbons and silicon carbide represent carbon-rich grains (Fig. 34). Primordial grains exist in the Kuiper belt and in comets. Studying dust grains thus plays a major role in understanding the formation and evolution of our Solar System; by studying dust we look into stars, planets, moons and rings.

The properties of interstellar dust are of significant astrophysical interest and scientists around the world are currently analysing the dust samples returned to Earth by the Stardust mission in 2006. Stardust collected cometary, interplanetary and interstellar dust grains during its interplanetary cruise phase and thousands of dust grains have been identified as originating comet Wild 2 during its encounter in 2004. However, to date, no interstellar dust grains have been positively identified in the aerogel collectors exposed to the interstellar dust direction. Why are they so hard to find? Interstellar particles have sizes of typically 0.5 µm, and with their high relative impact speeds (10 - 20 km s^{-1}) generate only a tiny, and hard to find, impact track in the low density aerogel matrix of the collector. The high impact speeds lead to particle fragmentation and evaporation and only a minor fraction of the presolar material remains unaltered in the collector matrix for analysis. In order to understand the physical processes of hypervelocity impacts of submicron-sized dust particles into aerogel materials, impact tests at the dust accelerator facility are performed as part of a joint project with the University of Heidelberg and the Max Planck Institute for Nuclear Physics. The investigation of the composition and size distribution of interstellar dust in the Solar System addresses several scientific key questions:

- Can we identify original stardust in the interstellar medium?
- What is the elemental composition of grains and its variability?
- What is the nature of carbonaceous dust?
- What is the composition of silicate grains?
- Can we identify SiC in ISD particles?
- Where does the iron originate?
- What are the sizes of compositionally different grains?

Interplanetary Dust

In contrast to ISDs, IDPs are formed in cometary comae, by asteroid collisions, by meteoroid impacts onto the surfaces of small bodies (asteroids, small planetary moons) and in planetary environments such as those which produce the Jovian and Saturnian dust streams. The most efficient sources for IDPs are within cometary tails as ice and silicate grains released by the cometary nucleus during the sublimation of volatile ices in the vicinity of the Sun. Larger dust particles preserve the orbital parameters of the comet and form the cometary tail. This tail can be studied directly when the Earth passes through it, leading to yearly meteor showers. However, our knowledge is primarily based on spacecraft data from the Giotto mission and its target, comet Halley. In situ dust experiments measured the size distribution of sub-micron to millimetre sized grains from the inner coma during the flyby in 1986. The results showed that large grains (mass $>10^{-6}$ g) were more numerous than expected and that these large grains dominated the ejected mass output of the comet.

The zodiacal cloud contains both fresh dust from cometary trails and asteroids and old cometary dust which has dispersed over time and can no longer be associated to a particular comet. To date the relative contributions of asteroidal and cometary dust to the zodiacal cloud are still unknown, and the past 40 years of space exploration by dust detectors onboard interplanetary spacecraft, as well as ground-based observations, have provided little insight into the cloud's dynamics. What is the ratio of cometary versus asteroidal particles at 1 AU? What are the orbital characteristics of different types of cometary and asteroidal particles at 1 AU? How does dust from comets differ chemically to dust from asteroids? Are there complex organic molecules in cometary and asteroidal dust that could be precursors of life? To gain a better understanding of the influence of the asteroidal and cometary dust sources, in situ studies of the dust populations by advanced dust detectors arre necessary.

Figure 35: Cosmic DUNE spacecraft in the vicinity of the Earth.

6.3 In situ analysis and sample return of Interstellar and Interplanetary Dust

Cosmic DUNE is a dust observatory for the study of interstellar and interplanetary dust in Earth orbit and provides a comparison between the composition of the interstellar medium and primitive planetary objects (Fig. 35). Hence Cosmic DUNE will provide insights into the physical conditions during planetary system formation. This comparison of interstellar and interplanetary dust is very important for both planetary science and astrophysics. The discoveries with respect to interstellar dust in the outer and inner solar system during the last decades suggest an innovative approach to the characterisation of cosmic dust. Cosmic DUNE establishes the next logical step beyond NASA's Stardust mission, with four major advancements in cosmic dust research:

- Analysis of the elemental and isotopic composition of individual cosmic dust grains
- Determination of the size distribution of interstellar dust
- Characterisation of the interstellar dust flow through the planetary system
- Analysis of interplanetary dust of cometary and asteroidal origin

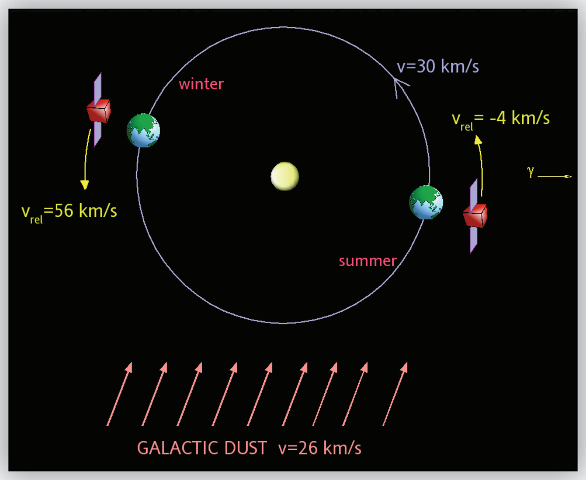


Figure 36: Mission scenario of DUNE at L2 of the Sun-Earth system. The interstellar dust flux direction, two positions of the Earth and the spacecraft are shown (right: late summer, and left: late winter). The orbital geometry leads to a yearly modulation of the interstellar flux. The corresponding fluxes are $F = 4.5 \cdot 10^{-4}\ m^{-2}\ s^{-1}$ in winter and $F = 6.6 \cdot 10^{-5}\ m^{-2}\ s^{-1}$ in summer.

An orbit about the collinear Lagrangian point L2 of the Sun-Earth system meets the requirement of being at a large distance from the Earth's orbital debris belts, and it provides a very stable thermal environment (Fig. 36). A Lissajous orbit about L2 was selected as the baseline orbit for Cosmic DUNE. The Lagrange point L2 is 1.5 million km away behind the Earth, pointing away from the sun. For most of the time a spacecraft in an orbit about L2 will be in the solar wind. The instrument subsystems form an integrated Dust Telescope with a shared pointing direction. About 1000 grains are expected to be recorded by this payload every year, with >10% of these providing elemental composition.

SARIM and SARIM PLUS are DUNE-like missions with additional sample return of interstellar and interplanetary dust grains. SARIM PLUS adds sample return of cometary dust grains. Sample return ensures state-of-the-art laboratory analysis of dust grain morphologies, grain size distributions and compositions. However, sensitive laboratory methods require unaltered and uncontaminated samples, therefore special precautions are necessary in collector handling, spacecraft integration and sample return. The Stardust mission focussed on the collection of cometary dust samples, but, to date, has not definitely identified any interstellar dust grains, although several candidate particles are currently undergoing analyses. For this reason, the SARIM missionwas proposed in the framework of the ESA Cosmic Vision program. The SARIM spacecraft (Fig. 37) could be launched into an halo orbit around the Sun-Earth Lagrange point L2. The scientific instruments would collect and measure ISD during a three year mission , after which dust samples would be returned to the Earth within a small reentry capsule. The in situ instruments will analyse the dust flux, size distribution, dust trajectories (dynamics and origin), and elemental composition. They will also study the time variability of the interstellar dust stream through the heliosphere and its coupling to the solar cycle. The preliminary payload consists of active dust collectors, a Dust Telescope, a nano-particle detector, a plasma monitor, and a Sample Return Capsule. This payload enables the sensitive and reliable determination of individual dust grain characteristics such as speed, mass, charge, trajectory and composition.

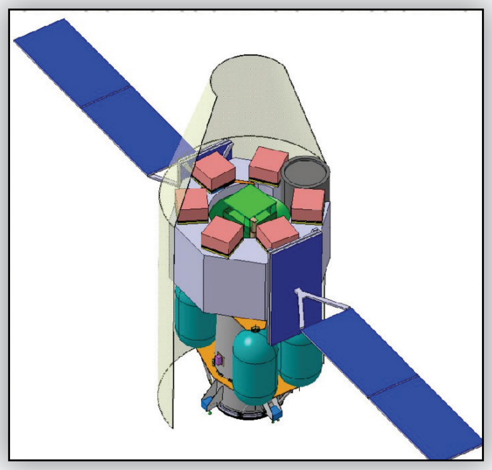


Figure 37: SARIM spacecraft in a VEGA payload fairing with extended solar sails (Astrium/EADS). Six Active Collectors (red cubes), one Dust Telescope (grey cylinder) and the collector sample stack (green) are mounted on the spacecraft body. The Sample Return Capsule encloses the collector samples in the centre (not shown).

The scientific success of SARIM is related to the quality of the subsequent laboratory analyses of dust samples extracted from the collectors. First analyses of the dust grains would focus on four major issues: isotopic composition, inorganic chemical composition, organic chemical composition and mineralogical/petrologic composition.

6.4 Lunar Dust

There are several outstanding issues, which must be addressed to ensure acceptable cost and risk for sustained human lunar programmes. Arguably, a high-priority issue, among others to be addressed, is that of lunar dust. In the near future this will be investigated by two missions equipped with dust detectors: a NASA orbiter (LADEE) and the proposed European Lunar Lander mission. Fine grains from the surface can be lofted due to human activities, but there is also evidence that a fraction of the fine lunar dust is electrostatically charged and transported by the influence of near-surface electric fields, as is believed to occur on asteroids(Fig. 38). Conjecture surrounding the transport phenomena range from the levitation of micron-sized dust grains at low altitudes (centimetre to metre height) to the lofting of sub-micron particles to tens of

Figure 38: Image of the surface of the asteroid Eros as an example for electrostatic dust, giving a global perspective on charging processes. Since the Moon is in the solar wind nightside, the lunar surface usually charges negative transport.

kilometres. Observations by the Apollo astronauts of the adhesion of sticky and fine grained lunar dust to their space suits and their equipment, even after short extravehicular activities, demonstrated the need to control dust contamination. Dust was also reported to reduce external visibility and cause difficulty to breathing and vision within the spacecraft. Eugene Cernan, commander of Apollo 17, stated ”... one of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and its restrictive friction-like action to everything it gets on” (Goodwin, 2002).

Simple instruments placed on the lunar surface monitored both natural and man-made dust coverage and cleansing effects that are still not fully understood. The interaction of the lunar surface with its radiation and plasma environment is expected to be similar to that of asteroids, Mercury, the Martian satellites, the Galilean satellites and Kuiper Belt Objects. Hence the lunar surface provides an excellent laboratory to study processes that could dominate the evolution of surfaces of airless planetary objects throughout the solar system that are directly exposed to plasma and radiation.

Each year the Moon is bombarded by approximately 10^6 kg of interplanetary micrometeoroids of cometary and asteroidal origin. Most of these projectiles range from 10 nm to approximately 1 mm in size and impact the Moon at speeds between 10 to 75 km s^{-1}. They excavate a mass of lunar soil of approximately 1000 times their own mass. These impacts leave a crater record on the surface from which the micrometeoroid size distribution has been inferred. Much of the excavated mass returns to the lunar surface and blankets the lunar crust with a highly pulverised and ”impact gardened” regolith several metres thick. Micron and sub-micron sized secondary particles which are ejected at speeds less than the lunar escape speed of 2300 ms^{-1} form a perpetual dust cloud around the Moon and, upon re-impact, also leave a record in the microcrater distribution on the surface. Such tenuous clouds have also been discovered by the dust sensor onboard the Galileo spacecraft around the Galilean satellites of Jupiter.

Another dust related phenomenon observed on the Moon is the electrostatic mobilisation of lunar dust. Images taken by the television cameras on Surveyors 5, 6, and 7 showed a distinct glow just above the lunar horizon, referred to as horizon glow. This light was interpreted to be forward-scattered sunlight from a cloud of dust particles above the surface near the terminator. The current knowledge is based on a rare set of observations and the lunar dust and plasma environment is not understood today. Different physical processes were proposed to explain the optical and in situ measurements and the major open questions are:

- Is the dust transport triggered by lit/unlit transitions?
- What does the ejecta distribution look like?
- What is the temporal and spatial variability of the properties of the transported grains?
- What is the size, charge and velocity of mobilised dust grains above the surface?

Answering above questions is fundamental for future robotic and human explorations of the Moon. However, a multitude of phenomena occurring in space remain unanswered as of yet and without a doubt has space science an enormous potential for future generations of scientists to work on unraveling the secrets of our wondrous and beautiful universe.

Cooperations

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Chiba Institute of Technology (J)
Deutsches Zentrum für Luft-und Raumfahrt e.V.
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