# In-Situ Mass Spectrometry of Atmosphereless Planetary Objects

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## *Science Goals*

Dust particles, like photons, carry information from remote sites in space and time. From knowledge of the dust particles' birthplace and their composition, we can learn about the remote environment out of which the particles were formed. This approach is called "Dust Astronomy" which is carried out by means of a dust telescope in space. Dust Astronomy provides a novel method to directly analyze surface composition of atmosphereless planetary objects.

All atmosphereless objects are exposed to the ambient meteoroid bombardment that erodes the surface and generates ejecta particles at a wide range of ejection speeds. Objects with radii bigger than 1000 km keep all particles with ejection speeds lower than ~1000 m/s. Therefore, such objects are enshrouded in clouds of dust particles that have been lifted by meteoroid impacts from the bodies' surfaces. These particles move on ballistic trajectories, most of which re-collide with their parent object. In-situ mass spectrometric analysis of these particles from an orbiting spacecraft provides spatially resolved mapping of the surface composition of the object. Particulates ejected from the surface of objects with a size above ~ 1500 km can be directly analyzed with an in-situ impact ionization mass spectrometer in orbit around the body (the method works at orbital speeds down to about 1 km/s). The composition of smaller objects (planetary satellites, asteroids, KBOs, and cometary nuclei) can be explored by fast fly-bys through their ejecta clouds. Even trace amounts of endogenic and exogenic minerals (e.g. salts), cyanogen, sulfur, and organic compounds which are embedded in ejected grains can be quantified with high accuracy. In some cases (e.g., on Europa), the achieved knowledge about surface-interior exchange processes may provide information about the internal composition of the satellite. This is also possible at moons that display active venting, e.g., Io, Enceladus.

The composition of the source moons of dusty rings is imprinted in the ring particles themselves. Likewise, the composition of asteroids, comets, and KBOs is conserved in particles of the zodiacal cloud and the Kuiper belt dust ring. Even the composition of our galactic neighborhood and nearby star forming regions can be probed by analyzing interstellar grains sweeping through the planetary system.
The proposed investigation addresses the following scientific objectives:

- Map the surface composition of Mercury, the Moon, the Galilean satellites, and Triton by analyzing their ejecta clouds. What provinces of different composition can be identified? What surface-interior exchange processes are in action?
- Study the interior composition of satellites that display volcanism.
- Determine the compositions of the outer planets' dust rings and their satellite origin.
- Study the composition of Phobos and Deimos by analyzing dust grains in their environment and search for the putative dust rings of Mars.
- Determine the composition of asteroids, comets, and KBOs by analyzing dust grains in its vicinity.
- What is the composition and what are the sources of interstellar grains sweeping through the solar system?

# Scientific Motivation

## Mapping the Surface Composition of Planetary Objects

Classical methods to analyze atmosphereless planetary objects are IR spectroscopy and gamma ray spectroscopy. Recently, a new method has been proposed to analyze dust particles as samples of planetary objects from which they were released. Dust Astronomy uses the information that dust particles carry from their sites of origin. This approach is carried out by means of a dust telescope on a Dust Observatory in space (Grün et al., 2005).

During its orbit tour about Jupiter, the Galileo spacecraft discovered impact-generated dust clouds surrounding all Galilean satellites. These dust clouds are a general phenomenon in the solar system which has been predicted by modeling and proved by observation (Krüger et al., 1999; Spahn et al. 2006). Detailed geological and geochemical information of the source objects can be obtained by dust astronomical methods: The observations are carried out by measuring the trajectory and chemical composition of individual ejected dust particles from low altitude orbits (Fig. 1). They establish a direct link to the grain's origin on the surface (compositional mapping) and can provide key chemical constraints for revealing the satellite's composition, history, and geological evolution.

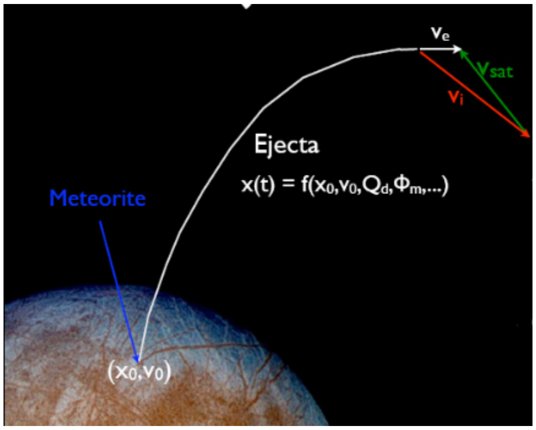

***Figure 1. Schematics of the proposed investigation. Ejecta particles lifted by meteoroid impacts from the satellites' surface are analyzed by a dust trajectory sensor in combination with a high-resolution dust mass spectrometer. By tracing back the trajectory to the surface compositional maps of the surface are generated.***

The speed of a spacecraft orbiting a planetary object with radius > 1500 km is > 1 km/s. This is sufficient to get chemical information from a highly resolved impact ionization mass spectrum. Objects of this size include planets like Mercury and Pluto, the Moon, all Galilean satellites, and Neptune's moon Triton. At lower orbital speeds, i.e. at smaller planetary objects, dust collection and in-situ analysis by, e.g., a secondary ion mass-spectrometer, like the COSIMA instrument (Kissel et al., 2007) is the method of choice. Sample collection and return to Earth is possible, e.g. in aerogel (Tsou et al., 2003, Brownlee et al. 2006) at all speeds up to about 20 km/s.

Mass analysis of ejected particulates by a dust telescope is complementary to studies by remote sensing methods (e.g., by infrared spectroscopy) and analysis of the gas phase (by an ion and neutral mass spectrometer). A dust telescope onboard an orbiter about any atmosphereless planetary object could analyze provinces of different chemical surface composition and, hence, could complement previous measurements by other methods. In the following, some key targets are described in more detail.

**Mercury** is the smallest, the densest, and the planet with the oldest surface. It has a tenuous surface-bounded exosphere containing hydrogen, helium, oxygen, sodium, calcium, and potassium. Hydrogen and helium atoms probably come from the solar wind. Water vapor is present, being released by a combination of processes such as comets striking its surface. Sodium and potassium are believed to result primarily from the vaporization of surface rock struck by micrometeorite impacts. The meteoroid flux is ten times higher than at Earth and hence the ejecta cloud is enhanced accordingly.

**The Moon**'s crust is blanketed by a highly comminuted and "impact gardened" about 10 m thick surface layer called regolith. Beneath the finely comminuted regolith layer is what is generally referred to as the megaregolith. This layer is much thicker (on the order of tens of kilometers) and comprises highly fractured bedrock. Geochemical maps were obtained from the Lunar Prospector gamma-ray spectrometer (GRS). GRS has identified several regions with high iron concentrations. The most important elements detectable by the GRS were uranium, thorium, potassium, iron, titanium, oxygen, silicon, aluminum, magnesium, and calcium.

The lunar dust environment is expected to be dominated by submicron sized dust particles released from the Moon due to: a) the continuously ongoing bombardment by interplanetary meteoroids and b) due to plasma effects that induced large transient electric fields. To a good approximation, the impact produced ejecta is expected to form a spherically symmetric, continuously present cloud, while the electrically lofted population is expected to be concentrated over the terminators, and remain highly temporarily and spatially variable. Based on photometry, this second population has been suggested to have a characteristic radius of about 0.1 µm.

**Europas'** surface is composed of ice and exhibits one of the smoothest surfaces in the Solar System. This young terrain is striated by cracks and streaks, while craters are relatively infrequent. The apparent youth and smoothness of the surface have led to the hypothesis that a water ocean may exist beneath it. Heat energy from tidal flexing ensures that the ocean remains liquid and drives geological activity. All these surface features indicate that an exchange between the interior and the surface has occurred in the recent past on Europa and is maybe still ongoing. The presence of sulfate in endogenic surface areas may be an indication of oceanic constituents that were delivered to the surface through cracks or fractures in the ice shell. Theoretical models of the oceanic composition (Zolotov and Kargel, 2009) predict sulfate together with Na, K, Mg, Cl, and carbonate/bicarbonate solutes.

Interpretation of optical spectroscopy data is often not unique. This is of particular relevance for the hydrated salts exposed on Europa’s and Ganymede’s surfaces which probably come from the internal ocean. An impact mass analyzer like a dust telescope is very sensitive to different types of salts (e.g., NaCl or $MgSO_4$) and carbonaceous material. Only direct sampling will provide unambiguous evidence for the origin of the surface materials and it is important that both solid and gas phases be measured.

**Ganymede**'s surface is heavily cratered but some bright terrain is being interpreted as caused by resurfacing by cryo- or liquid-water volcanism. Impact cratering by km-sized objects also likely contributes significantly to exchange processes between the moon’s interior and the surface. The existence of a subsurface ocean is implied by Galileo magnetometer data and is also consistent with surface geological features. On Ganymede, the determination of particle composition in the vicinity of relatively young impact craters should give information about its subsurface composition, which is fundamental for understanding its evolution.

## Studying the Interior of Satellites that Display Active Venting

In case active venting is present at the visited object (like at Io, Enceladus, Triton, and all active comets), the analysis of ejected particles provides even information on sub-surface processes as has been demonstrated in the case of Enceladus (Postberg et al., 2009).

During the flyby of **Enceladus'** South Pole in 2005 the Cassini Cosmic Dust Analyzer (CDA) and other Cassini Instruments discovered a source of ice particles and vapor (Spahn et al., 2006, Waite et al., 2006) expelled from a region of enhanced temperature. Some of the tiny ice grains escape the moon’s gravity, replenishing Saturn’s outermost E ring. Analysis of the icy dust from Enceladus revealed frozen salt water containing sodium salts (Fig. 2). It was the combination of the sodium found in the dust particles and the analysis of the gas phase that led to the inference of a liquid water reservoir beneath Enceladus' surface that is (or has been) in contact with the moon's rocky core (Postberg et al., 2008, 2009; Waite et al., 2009).

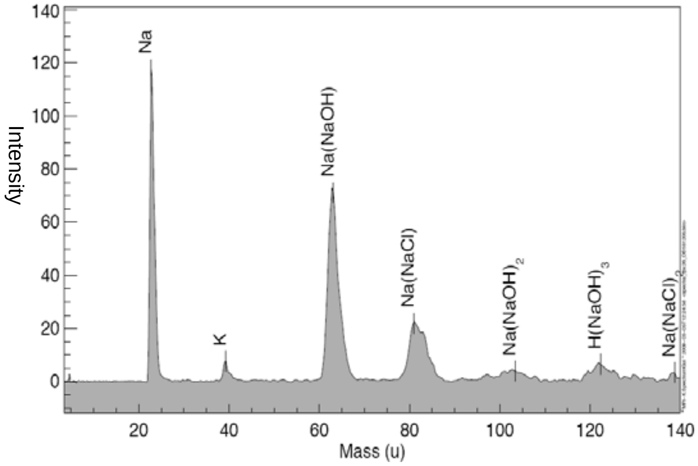

***Figure 2. CDA Spectrum of an ice grain which hit the detector with v ~ 6 km $s^{-1}$ near Enceladus. The spectrum shows pronounced signatures of sodium and potassium salts in a water matrix. NaCl and NaHCO3 could be identified as constituents of the salt- ice particles on a percent level (Postberg et al. 2009).***

It has been suggested that active venting may be present even on the Galilean moon **Europa** and perhaps on **Ganymede**: There, venting might be too tenuous to be observable by optical instruments, but some of the ejecta particles observed near the satellites by the Galileo dust detector (which was not equipped with a mass spectrometer) may have been released in such vents.

The analysis of ice grains expelled from bodies with subsurface liquid water would not only be of geochemical and geophysical relevance, but also of high astrobiological potential. With a high resolution mass spectrometer, even the chemical investigation of life precursor molecules and biomarkers would be possible. Complex molecules are protected when hidden and embedded in an ice matrix. After the ice grains are ejected from the moons' surfaces (either by micrometeoroid impact or active venting) detection with an in-situ dust instrument provides the best chance to detect intact large organic molecules.

With over 400 active volcanoes, **Io** is the most geologically active object in the Solar System. This extreme geologic activity is the result of tidal heating from friction generated within Io's interior by Jupiter's varying pull. Several volcanoes produce plumes of that reach heights of 500 km. Sulfur, sulfur dioxide, and alkali salts are the main constituents of this matter which is partly expelled into Io’s exosphere. Io is also the main emitter of gas, plasma, and dust into the Jovian magnetosphere shedding its material onto the neighboring satellites. Nanometer-sized charged dust particles are accelerated by the giant Jovian magnetic field to high speeds (> 200km/s) and dispersed into interplanetary space. Analysis by the Ulysses and Galileo spacecraft implied that the tiny dust particles were released into the magnetosphere from the volcanic plumes on Io (Graps et al., 2000, Krüger et al., 2003). In 2000 the Cassini spacecraft flew by Jupiter and provided the first compositional analysis of the stream particles which were found to consist mainly of alkali salts. This finding confirmed their origin in Io’s volcanoes and gave insight into condensation processes within the plumes (Postberg et al., 2006).

**Triton** is by far the largest moon of Neptune and has a tenuous nitrogen atmosphere. It has a retrograde orbit, indicating that it was captured from the Kuiper belt. Its crust is dotted with geysers believed to emit particles probably composed of solid nitrogen. As a consequence, its surface is relatively young with a complex geological history revealed in intricate and mysterious tectonic terrains.

## Studying Source Objects of Dust Rings

**Jupiter's ring system** was investigated with remote imaging from the Earth and from Voyager, Galileo, Cassini, and New Horizons spacecraft, revealing significant structure in the ring (Krueger et al., 2009). Galileo in-situ dust measurements revealed previously unknown structures in the gossamer ring, clearly emphasizing the significance of electromagnetic forces in shaping this tenuous dust ring (Hamilton and Krüger, 2008). The small moons Metis, Adrastea, Amalthea, and Thebe are embedded in the ring system and act as sources of ring dust via meteoroid impact erosion of their surfaces. The faint gossamer rings appear to extend primarily inward from the orbits of Amalthea and Thebe. Even in the region between the Galilean satellites the Galileo dust detector discovered a tenuous dust ring with a peak number density of $5\times10^{-7}$ $m^{-3}$ at Europa's orbit. Furthermore, the data indicated an increase in the number density between Europa and Io (Krivov et al., 2002).

At **Saturn,** numerous icy satellites have been found shaping the main rings and the extended dusty E ring. The enigmatic satellite Enceladus is located in the densest part of the E ring and constitutes the main source of this huge dust ring. The icy moon Rhea  the second largest moon of Saturn after Titan  is located at the outer edge of the visible part of the E ring about twice as far as form Saturn as Enceladus. Observations by Cassini suggest an enhancement of particulates close to Rhea and the other embedded moons (Mimas, Tethis, Dione).

**Uranus** and **Neptune** both show extended ring systems. Uranus has five main satellites (Miranda, Ariel, Umbriel, Titania, and Oberon) and 22 small moons. Some moons, probably ice-rock conglomerates, interact with the rings that are composed of extremely dark particles, which vary in size from micrometers to a fraction of a meter. Neptune's rings structure might be due to gravitational interactions with small moons in orbit near them. The outermost ring contains five prominent arcs, which are believed to be corralled by the gravitational effects of Galatea, a moon just inward from the ring. The plasma wave experiments on Voyager 2 detected impacts of dust particles in the vicinity of Uranus and Neptune.

Dust released by meteoroid impacts onto the **Martian moons Phobos and Deimos** should orbit Mars for some significant time giving rise to faint dust rings (Krivov and Hamilton, 1997). Observations by the ill-fated Phobos mission provided indirect evidences for a gas/dust torus along the Phobos orbit. An in-situ dust analyzer is several orders of magnitude more sensitive to low spatial dust densities than remote sensing methods and should provide a clear signature of the Phobos and Deimos dust rings with information about surface composition of both moons.

## Studying Dust Sources from the Outer Solar System and Beyond

It has been suggested that **Pluto and Charon** are immersed in a tenuous dust cloud. The cloud consists of ejecta from Pluto and Charon, released from their surfaces by impacts of micrometeoroids originating from Edgeworth–Kuiper belt objects (Thiessenhusen et al., 2002). The dust cloud may be dense enough to be detected by the New Horizons mission, which is en-route to Pluto and the Kuiper Belt. More than 1000 **Kuiper Belt Objects** (KBOs) have been discovered outside about 30 AU. The outer Kuiper belt is assumed to be the main repository of the short periodic comets. Collisions among the KBOs lead to fragments down to the size of dust grains. Measurements of the dust instruments on board the Pioneer 10 and 11 spacecraft found the signature of dust generated by Edgeworth-Kuiper Belt objects (Landgraf et al., 2002), which makes the Kuiper disk the brightest extended feature of the Solar System when observed from afar.

High-resolution dust mass analyzers were employed by the Halley missions (Giotto, VeGa 1 and 2) in order to study the **cometary dust** composition. The average bulk mineral component is in agreement with solar elemental abundance (CI chondrite) except for an excess of light elements H, C, N. The mineralogical composition of Halley dust resembles that of stony and iron meteorites. In January 2006, the Stardust sample capsule returned safely to Earth with thousands of particles from comet 81P/Wild 2 for laboratory study, providing new insights into the nature of cometary material. However, the composition of the ice fraction of cometary dust is currently unknown but could be analyzed by a modern dust detector.

The Solar system passes currently through a shell of **interstellar material,** which is located at the edge of the local bubble. Interstellar dust grains condense in the expanding and cooling stellar winds from stars and in supernova explosions. This so-called ‘stardust’ provides the seeds for interstellar grains that grow further in cool interstellar clouds by accretion of atoms and molecules, and by agglomeration. In 1992, after its Jupiter flyby, the Ulysses spacecraft positively 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. Ulysses, Cassini, Galileo and Helios detected interstellar dust in heliocentric distance range between 0.3 and 5 AU. However, a detailed compositional analysis has not been accomplished yet, but could be achieved by a modern dust telescope.

## *Enabling Technologies*

In order to address the above scientific questions, it is essential to a) reliably distinguish dust particles from different sources, b) measure the grain trajectories accurately enough so that their individual source object can be determined, and c) determine the launch position on the source object. Finally, one has to measure the composition of the particle with sufficient accuracy to derive the desired cosmochemical information.

## Dust Telescope

In-situ analysis of dust particles with speeds in excess of 1 km/s requires a Dust Telescope that is composed of two parts, a *Dust Trajectory Sensor (DTS)*, and a *Dust Mass Spectrometer (DMS)* subsystem. The Dust Telescope is an in-situ instrument detecting and analyzing individual impacts of sub-micron and micron sized dust grains. First, the dust particles pass the Trajectory Sensor measuring the induced electrical charge of the grains to derive their trajectory information (Fig. 3). Then the grains impact on the target of the mass analyzer at the bottom of the instrument, generating electrons and ions which are analyzed in a time-of-flight spectrometer. The instrument measures the chemical composition of submicron to micron-sized dust particles between 1 and ~500 amu at a mass resolution M/ΔM of ~200 and it determines the particles' trajectories with an accuracy of 1% in speed and 1 deg in direction. Several versions of a Dust Telescope have been studied in the past (Sternovsky et al., 2007; Srama et al., 2008), and their two major subsystems are discussed below.

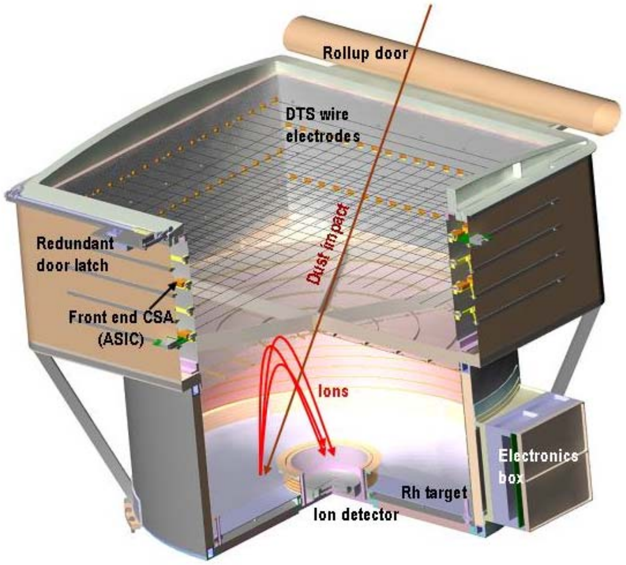

***Figure 3. Dust Telescope (DUNE-SMEX version) with the four planes of wires of the Trajectory Sensor (top) and the time-of-flight mass-spectrometer (bottom). A particle impacting on the target generates electrons, ions, and charged cluster-molecules, which are focused to the ion detector in the centre. Data acquisition is triggered by the electron signal collected at the target and by the ion signal.***

## Dust Trajectory Sensor

The Dust Trajectory Sensor makes use of the electric charge that all particles in space carry (Srama et al., 2006, Auer et al., 2008). A DTS has four sensor planes consisting of 16 wire electrodes each. When a charged grain flies through this position sensitive electrode system, its trajectory is determined by the measurement of the induced electric signals. The charge is induced on the most adjacent wires. Each wire is connected to a Charge Sensitive Amplifier and the 16 wires of each plane are routed to a single multi-channel transient recorder (TR) digitizing the signals. The ASIC electronics were integrated in the laboratory model, and induced signals of dust grains have been recorded at the Heidelberg dust accelerator facility. Dust charges are measured in the range $10^{-16}$ to $10^{-13}$ C and dust speeds up to 100 km/s, with 1% accuracy.

The attainability of dust trajectory analysis in space was demonstrated by the measurement of dust charges with the Cassini Cosmic Dust Analyzer (CDA). CDA reliably determined electrical charges of several interplanetary dust grains (Kempf et al., 2004).

## Dust Mass Spectrometer

Previous dust analyzers flown in space had sensitive areas of 0.01 $m^2$ or less. In order to cope with the low dust fluxes expected in interplanetary space and in the ejecta cloud of a planet or satellite a new high-resolution large-area mass analyzer of 0.1 $m^2$ sensitive area has been developed (Sternovsky et al., 2007, Srama et al., 2008). The dust particle enters the instrument through annular disk electrodes made of highly transparent grid material. After passing another (grounded) grid it impacts the target surface. The target has an opening in the center for the ion detector. Positive ions generated from the high velocity impact are accelerated away from the target by an applied +5 kV bias. By a positively biased grid the ions are reflected and directed towards the ion collector in the center. By the action of this reflectron a high mass resolution spectrum (M/ΔM ~200) of the ions is obtained.

Figure 4 shows examples of mass spectra with a resolution five times better than that of the Cassini CDA. It displays the major elements of the orthopyroxene projectile used in this experiment. The detection threshold is given by the charge threshold of approx. $10^{-15}$ C corresponding to a grain size of 0.4 µm for Europa (average rel. impact speed 1.4 km $s^{-1}$) and 0.3 µm for Ganymede (average rel. impact speed 1.9 km $s^{-1}$), respectively.

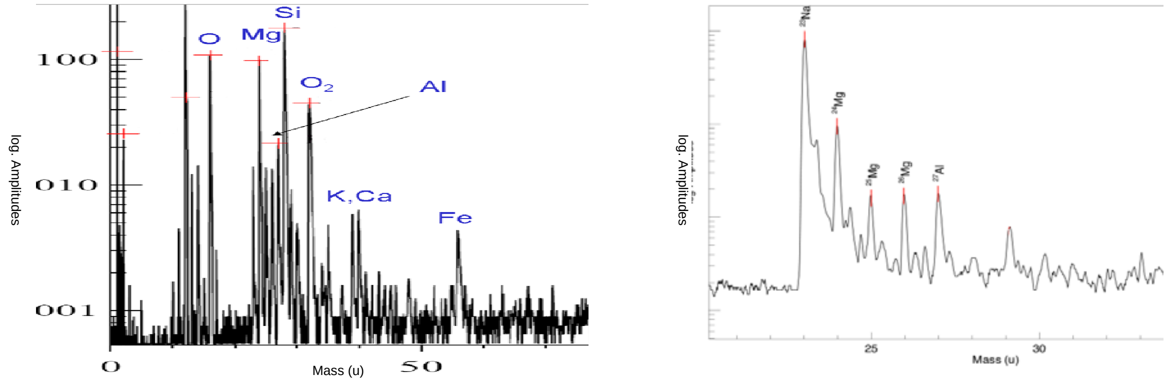

***Figure 4. Mass spectra of orthopyroxene grains obtained by a dust telescope in the lab at 20 and 2 km/s impact speed, respectively. Particle constituents like, e.g., magnesium isotopes and aluminum can be quantified.***

Accelerator experiments with a dust telescope demonstrated that dust impacts at 13 km/s yield high quality mass spectra (Figure 4, right).

Recent progress in the investigation of low energy ionization processes in a water matrix led to a greatly improved understanding of impact ionization spectra at impacts speed expected in an orbit around e.g. the Galilean moons (12.5 km/s, corresponding to less than 0.2 eV per water molecule). It has been shown that neutral molecular clusters and particles with kinetic energies much less than the ionization energy of atoms and molecules fragment upon target or laser impact and display ion/charge separation in the fragments (Gebhardt et al., 1999; Abel et al., 2009). This effect works particularly well in a water matrix and is due to preformed ions in the particles that are simply separated from their counterions on a fast timescale. These ions form clusters with any neutral water molecules but also with any impurity embedded in the ice matrix. The presence of species which are easily charged (e.g., Na or Mg salts) drastically enhance the ion yield and the 'visibility' of such species.

For a particle impact a combination of two processes of ion formation occurs. While for large kinetic energy impacts (> 15 km/s) the plasma generation mechanism is dominating, the dispersion and charge separation mechanism (DCS-mechanism) is dominating at low kinetic energies (15 km/s) and exclusively operating in cases in which no plasma is formed anymore (Gebhardt et al., 1999). Mass spectra from impacts at lower energies display a series of positively and negatively charged clusters and aggregates with minor intensities in ionized atomic species. The yield for charged species in the DCS-mechanism is slightly lower than in the plasma ionization case but still of the same order of magnitude (Charvat and Abel, 2007). Therefore, a dust telescope is well suited to determine the composition of particles with the impact velocities above 1 km/s.

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