SUDA: A DUST MASS SPECTROMETER FOR COMPOSITIONAL SURFACE MAPPING FOR THE JUICE MISSION TO THE GALILEAN MOONS.

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Introduction: We developed a dust mass spectrometer to measure the composition of ballistic dust particles populating the thin exospheres that were detected around each of the Galilean moons. Since these grains are direct samples from the moons' icy surfaces, unique composition data will be obtained that will help to define and constrain the geological activities on and below the moons' surface. The proposed instrument will make a vital contribution to ESA's planned JUICE mission and provide key answers to its main scientific questions about the surface composition, habitability, the icy crust, and exchange processes with the deeper interior of the Jovian icy moons Europa, Ganymede, and Callisto.

The SUrface Dust Aanalyser (SUDA) is a time-of-flight, reflectron-type impact mass spectrometer, optimised for a high mass resolution which only weakly depends on the impact location. The small size (268×250×171 mm^3), low mass (< 4 kg) and large sensitive area (220 cm^2) makes the instrument well suited for the challenging demands of the JUICE mission to the Galilean moons Europa, Ganymede, and Callisto. A full-size prototype SUDA instrument was built in order to demonstrate its performance through calibration experiments at the Heidelberg dust accelerator with a variety of cosmo-chemically relevant dust analogues. The effective mass resolution of $m/\Delta m$ of 150-200 is achieved for mass range of interest m = 1-150.

Dust Exoclouds: The basic idea of compositional mapping [1], [2] is that moons without an atmosphere are ensgulfed in clouds of dust particles released from their surfaces by meteoroid bombardment. The ejecta cloud particles can be detected and their composition analyzed from orbit or during a spacecraft flyby. The ejecta production process is very efficient: a typical interplanetary 10^{-8} kg micrometeoroid impact on a Jovian moon produces a large number of ejecta particles whith a total mass on the order of a few thousand times of that of the impactor [3]. These ejecta particles move on ballistic trajectories and most of them re-collide with the satellite due to the lower initial speed. As a consequence, an almost isotropic dust exosphere is present around the moon [4] [5].

Moon	Yield (kg/s)	Impact Rate (1/min)	
		200 km	400 km
Europa	17000	35	11
Ganymede	3900	28	10
Callisto	670	10	4

Tab. 1 Parameters of dust exospheres of the JUICE target moons Europa, Ganymede, and Callisto. The table shows the ejecta mass yield Y and the impact rates of grains >200 nm expected to be detected by SUDA at 2 typical orbiter altitudes. The calculations have been performed using the full cloud theory by Krivov et al. [4].

In 1999, the Galileo dust instrument measured the density profiles of the tenuous dust exospheres around the Galilean satellites Callisto, Ganymede, and Europa [6]. The cloud density decreases asymptotically with radial distance as $r^{-5/2}$, i.e. the cloud extent is only of a few moon radii. However, a spacecraft in close orbit around a Galilean satellite will detect a substantial number of ejecta particles (Tab. 1). The initial speed of most ejecta particles is smaller than the escape velocity, which in turn is much smaller than the speed of an orbiting spacecraft. The ejecta particles thus hit the dust detector with the velocity of the spacecraft and arrive from the apex direction. The dynamic properties of the particles forming the ejecta cloud are unique and can be clearly distinguished from any other kind of cosmic dust likely to be detected in the vicinity of the satellite.

Surface Composition of the Galilean satellites: For planetary scientists, the Galilean moons satellites Europa, Ganymede, and Callisto are amongst the most interesting bodies in the solar system. Their surface composition is revealing the past and recent geophysical processes both on and below the surface, and a dust mass analyzer onboard the JUICE mission will allow us to acquire this invaluable knowledge. In particular, hydrated forms of minerals such as sodium carbonates and magnesium sulfates present in the ice surface probably represent deposits of materials from below the ice crust [8].

Ejecta particles from Europa, Ganymede, and Callisto will mostly consist of water ice with traces of

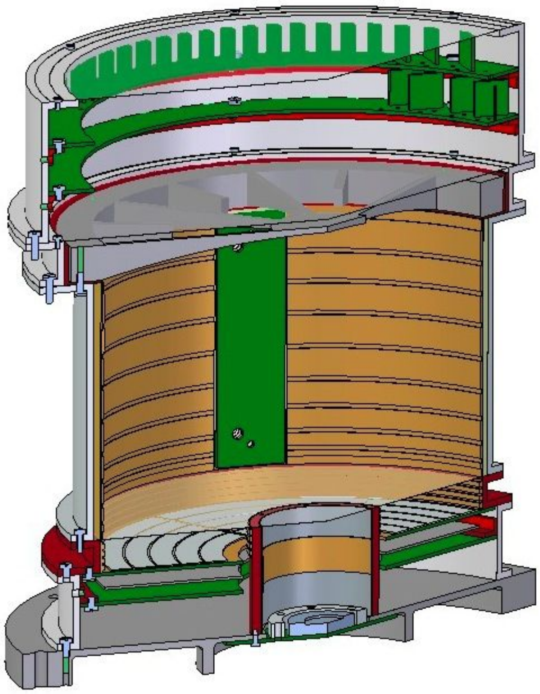

Fig. 1 Cut through the SUDA impact mass spectrometer.

hydrated minerals such as sodium carbonates and magnesium sulphates, hydrated sodium chloride, and of organic materials. The spectra of Enceladus plume particles and E ring grains obtained by the Cassini dust detector CDA [8], [9], [10] detected at low impact speeds are, thus, be similar to mass spectra of cloud particles of Galilean moons. Impact spectra of slow water ice particles are dominated by positive water cluster ions $(H_2O)_nH^+$. Traces of hydrated minerals embedded in the grains' ice matrix will manifest themselves as positive cluster ions formed from their metallic component and water such as $(H2O)_n(MgOH)^+$ [11]. A dust mass spectrometer in orbit around a Galilean satellite will mostly record mass spectra with the mass range up to 150 amu densely filled with mass lines. Thus, a surface composition analyzer for the Galilean satellites must be able to resolve adjacent mass lines in this range, i.e. its resolving powers should be beyond 150.

It is important to note that the interpretation of impact mass spectra of surface ice ejecta particles is a well-developed technique aided by laboratory calibration measurements and yields clear composition analysis, at least when compared to the more ambiguous IR spectrometry.of ejected surface ice is less ambiguous than by IR spectrometry. This is because the high mass resolution allows to constrain the nature of the molecule by its mass.

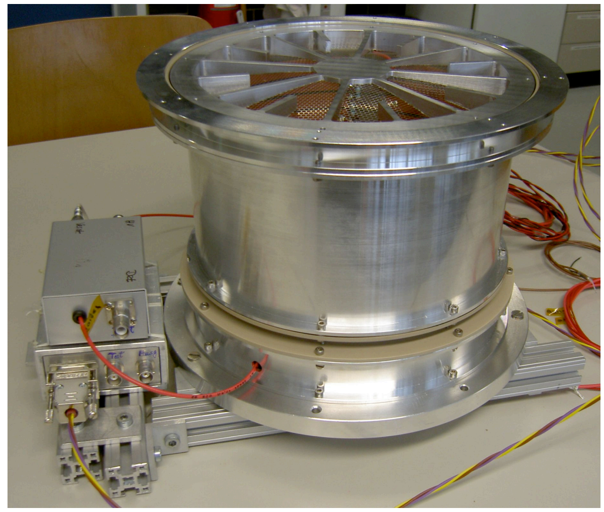

Fig. 2 SUDA laboratory model before integration into the test chamber of the Heidelberg dust accelerator.

Instrument description: The SUrface Dust Analyser (SUDA) is a reflectron-type, time-of-flight impact mass spectrometer, which has heritage from the Cassini CDA and the Stardust CIDA instruments. The main challenge for the design of a dust mass spectrometer is to achieve simultaneously a high mass resolution, a sufficiently large sensitive area, and a compact design. The plasma ions produced by the hypervelocity impact may have a broad energy distributions of up to 100 eV, which limits the mass resolution of linear TOF dust spectrometer of reasonable size to about $m/\Delta m = 50$. The effect of the initial energy spread on the mass resolution is significantly reduced by employing a so-called reflectron acting as an electrostatic mirror [12]. The ion optics of large area reflectron mass spectrometers can be designed using optimization methods to ensure simultaneously the good spatial and time focusing of ions. The combination of a plane target, a set of ring electrodes and an hemispherical reflectron grid yields a good performance instruments (Fig. 1, 2).

The SUDA mass spectrometer is a scaled-down version of the Large Area Mass Analyser LAMA [13]. However, there are significant differences between the design of LAMA and SUDA, which does not have a field-free drift region between the acceleration grid and the reflectron unit and employes a larger number of ring electrodes (see Fig. 1). The instrument size is $268\times250\times171$ mm^3 and the weight of the laboratory prototype is 5 kg.

Dust particles enter the aperture and fly through a set of shielding grids and reflectron grid before impacting on the planar, ring shaped target (Fig. 1). Even a relatively slow dust impact of typically 1.6 km/s generates a sufficient amount amount of atomic and molecular ions for the in-situ mass analysis of the grain's material. A strong electric field generated by the 2.5

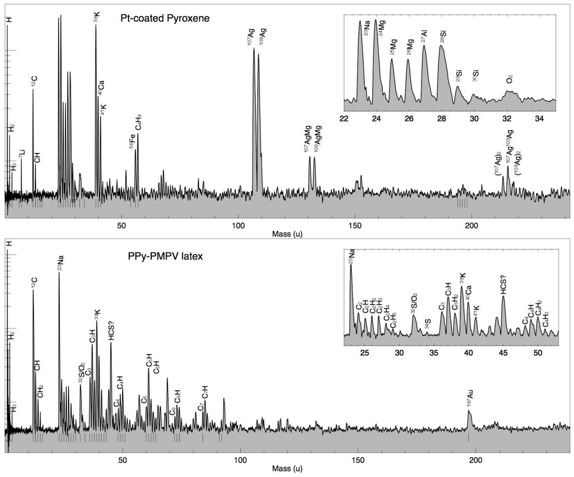

Fig. 3 Example spectra of a pyroxene particle impact on a silver target and of a latex particle on a gold target recorded with SUDA.

kV bias potential on the target accelerates the ions toward the ions detector, where they are detected in a time-of-flight fashion focusing by the reflectron. The acquisiton of the mass spectra is triggered by the impact generated charge pulse detected by the charge sensitive electronics connected to the target. The retarding field of the reflectron was optimized to achieve the best spatial and time focusing at the ion detector area in the center of the instrument.

An Add-on instrument, called Dust OrbiTrap Sensor (DOTS) is proposed as an option of SUDA. This sensor will be able to perform parallel measurements of dust particles with the objective to collect the produced ions into a Fourier Transform-Orbitrap high-resolution mass analyser. This sensor will have a reduced sensitive area of 20 cm², and will be optimized to analyse ions resulting from the dust impact with a mass-resolving power better than 7 000 at 50 amu. This mass resolution will allow to provide a molecular formula for all ions, including organics containing H, C, N, O and S up to 75 amu. The main objective of DOTS is therefore to describe the organic content of the dust ejected from the Galilean moons. The orbitrap mass analyser was first described in 2000 [14]. It is small size (4x3x3cm) and consists in three carefully shaped electrodes trapping the ions in a quadro-logartithmic electric field in which they oscillate. The FT analysis of the signal induced by the coherent oscillation of ions leads to a frequency spectrum, directly related to the intensity and exact mass of trapped ions. Extreme resolving power up to 250 000 at 400 amu are commonly obtained in the commercial instrument. Since 2009, CNES has funded an R&T program in order to study the space applications of the concept. A consortium of 4 laboratories located in France:

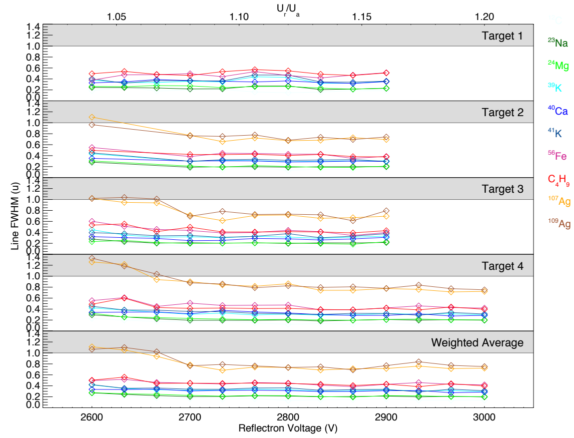

Fig. 4 Dependence of the width of typical mass lines on the impact location and on the reflectron voltage U_r. For U_r>2700V adjacent mass lines are resolved.

LATMOS, LPC2E, LISA, coordinated by IPAG in collaboration with thermoelectron company which commercialize the concept since 2005, was organized [15]. A prototype instrument relying on laser desorption ionization recently reached high mass resolving power of 280 000 at 56 amu.

Instrument performance: SUDA was tested using the Heidelberg 2 MV Van de Graaff dust accelerator [16] to simulate hyper-velocity impacts of cosmic dust particles. We performed calibration experiments with powders of submicron-sized Fe/Ni, orthopyroxene, pyrrhotite, and latex particles. This choice of test particles covers a broad variety of materials representive for cosmic dust grains of planetary, interplanetary, and interstellar origin. The vast majority of the dust impacts were slower than 4 km/s, which is similar to the typical ejecta impact speeds onto a detector orbiting one of the JUICE target moons. The grain sizes ranged between 200 nm and 1 µm, which are typical for surface ejecta. Fig. 3 shows two typical examples of SUDA impact spectra.

We determined the mass resolution of prominent mass lines by measuring the line width at half of the line's amplitude (full width at half maximum- FWHM). Fig. 4 shows the dependence of the resolution on the impact location and on the reflectron voltage.

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