DUST ORBITRAP SENSOR (DOTS) FOR IN-SITU ANALYSIS OF AIRLESS PLANETARY BODIES

C. Briois[1], R. Thissen[2], C. Engrand[3], K. Altwegg[4], A. Bouabdellah[5], A. Boukrara[6], N. Carrasco[5], C. Chapuis[5], H. Cottin[6], E. Grün[7], N. Grand[6], H. Henkel[8], S. Kempf[9], J.P. Lebreton[1], A. Makarov[10], F. Postberg[11], R. Srama[11], J. Schmidt[12], C. Szopa[5], L. Thirkell[1], G. Tobie[13], P. Wurz[4], M. Zolotov[9].
[1]LPC2E, 45071 Orléans Cedex, France (Christelle.Briois@cnrs-orleans.fr), [2]IPAG, Univ. Grenoble, BP 53, 38041 Grenoble Cedex 9, France, [3]CSNSM, Batiment 104, 91405 Orsay Campus, France, [4]Univ. Bern, Physics Inst. Sidlerstrasse 5, 3012 Bern, Switzerland, [5]LATMOS, 11 Blvd d'Alembert 78280 Guyancourt, France, [6]LISA, 61 avenue du Général de Gaulle, 94010 Créteil Cedex, France, [7]Max Planck Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany, [8]vH&S GmbH, Schlossplatz, 68723 Schwetzingen, Germany, [9]LASP, Colorado University, Boulder CO 80303-7814, USA, [10]Thermo Fisher Scientific, Hanna-Kunath Str. 11, 28199 Bremen, Germany, [11]Univ. Stuttgart, Raumfahrtzentrum Baden Württemberg, Pfaffenwaldring 29, 70569 Stuttgart, Germany, [12]Univ. Oulu, Dpt Physics, PL 3000, 90014 Oulun yliopisto, Finland, [13]LPGN, Univ. Nantes, BP 92208, 4322 Nantes Cedex 03, France.

Introduction: Cosmic dust is abundant throughout the Universe. Dust astronomy [1] provides an unparalleled opportunity to learn about the conditions of the distant interstellar space, the planetary rings, as well as the surface and subsurface properties of airless planetary objects throughout the Solar System.

Our consortium of laboratories, in collaboration with Thermo Fischer Scientific, is currently developing a high-resolution Fourier Transform (FT)-Orbitrap based mass spectrometer optimized for in-situ analysis of dust from airless bodies of the Solar System. This new generation of dust mass spectrometer was studied in the framework of the Europa Jupiter System Mission (EJSM) instrument study in 2010-2011 and proposed in response to ESA's AO for the JUICE mission (Dust OrbiTrap Sensor - DOTS proposal, PI Roland Thissen, October 2012).

Dust science: The characteristics of grains in circumstellar dust, interstellar dust, interplanetary dust particles and in planetary rings are different in their chemical composition, morphology, structure (…) depending on their origin and history of interactions with the environment. In the solar nebula, dust grains could have encountered a variety of processes such as heating, collisions, irradiations, accretion, adsorption, desorption, condensation, and chondrule formation [2,3]. Some objects in our solar system, like chondritic meteorites, micrometeorites or interplanetary dust particles, are witnesses of these changes. Among them, primitive interplanetary dust particles (IDPs or micrometeorites [4,5]) are considered the most primitive materials in our solar system and thus keep the memory of the chemical and mineralogical characteristics of the dust in the protoplanetary disk before the formation of the first large objects (planetesimals, asteroids ...). However, their origin (asteroids versus comets) is only guessed by indirect methods, and a major goal of cosmic dust research is to identify the compositional differences between interplanetary micrometeoroids of cometary and asteroidal origin. Recent results from cometary samples returned by the Stardust mission have in fact shown that there exists a continuum between primitive asteroidal and cometary matter [6], and cosmic dust is thus a privileged tool to study this continuum. Cosmic dust also contains minute amounts of presolar material that can give insights into the astrophysical context of solar system formation [7,8].

The chemical analysis, from flybys or from orbit, of dust grains ejected from the surface of solar system airless bodies also provides a unique opportunity to remotely study the surface composition of those bodies, as well as to understand exchange processes with the subsurface. For instance, *in situ* measurements by the Cassini Dust Analyzer (CDA) of sodium salts in icy grains in the Saturn E-Ring have proven the presence of a subsurface liquid water reservoir in Enceladus [9,10]. Noticeably, this was not detected by other *in situ* or traditional remote sensing techniques. This implies that *in situ* measurements of dust particles emerging from the surface of a planetary body can reveal the nature of its geological activity.

Past and current dust mass spectrometry: The *in situ* analysis of cosmic dust composition is currently essentially performed by two methods depending upon the relative dust velocity with respect to the spacecraft. In the case of low relative velocity, typically below a few hundreds of m/s, the dust can be non-destructively collected on an optimized target and directly analysed via different techniques (e.g. COSIMA and GIADA on board the Rosetta Orbiter). Above one to a few km/s, the hypervelocity impact on the instrument target creates a plasma from which the ion cloud can be analyzed (CDA on Cassini, CIDA on Stardust, etc..). The cosmic dust detectors on board the Ulysses and Galileo spacecraft have also shown that the Galilean satellites are surrounded by clouds of sub-micrometer grains generated by impacts of interplanetary (micro)meteoroids [11,12]. The dust generation process is very efficient, as a micrometeoroid of ~ 200 µm in size may eject particles amounting to few thousand times the impactor's mass [13,14], which populate tenuous, approximately spherically symmetric clouds around the moons [15-17]. *In situ* analysis of these ballistic grains from orbit is a unique opportunity to directly assess the chemical composition of the Jovian moons surface and subsurface, and therefore bring crucial constraints on their potential as habitable worlds.

A new type of very high mass resolution dust mass spectrometer: DOTS (Dust OrbiTrap Sensor) directly samples dust in ballistic orbit by impact on a metallic target [18], and the resulting ion plume is analysed by a high mass-resolution FT-Orbitrap analyser [19, 20]. This mass analyser can provide very high mass resolution analysis (mass resolution M/ΔM at FWHM ~ 50 000 at m/z 50 Da). DOTS would allow identification of elemental and molecular species with good accuracy, in a mass range 20-1000 Da, with even no ambiguity from 20 to 100 Da.

The interpretation of *in situ* mass spectra obtained from interplanetary space missions has always been hampered by the lack of high mass-resolution. For instance, the presence of N_2 in cometary volatiles is still debated, as the resolution of the Giotto mass spectrometer could not differentiate CO from N_2 [21], and the carbon isotopic ratio in the upper atmosphere of Titan is poorly determined because models are needed to correct for mass interferences in order to assess the true isotopic ratio [22]. DOTS has the unique capability of very high mass-resolution that could characterize the organic and inorganic inventory in the dust grains originating from the bodies' surfaces. In the context of the JUICE mission, DOTS could provide information on the putative liquid oceans in the subsurface of Ganymede, Europa and Callisto. The characterization of both organic and dissolved inorganic compounds present in these oceans is necessary to assess the habitability of these locales, e.g. their ability to provide the chemical energy, stability and nutrients to sustain life. The nature of heavy molecular ions (like those observed in Titan ionosphere [23] or possibly in Io's particles [24), and complex organic compounds could be identified, based on their exact molecular masses.

The recently discovered outer rings of Uranus [25] present striking similarity with Saturn's E ring, which is now considered as the result of ice volcanic activity of Enceladus. This outer blue ring of Uranus also has a small embedded moon Mab, which is however probably too small to be internally active [26,27]. Meteoroid impacts continually blasting dust off the surface of Mab could spread it out into a ring around Uranus [26]. A DOTS-like instrument would be of great value to study the nature of these outer rings, in the context of a future mission to Uranus.

The high mass resolution capability of DOTS is especially beneficial for heavy species (for which the relative mass differences get smaller), as the mass resolving power (M/ΔM) of DOTS remains above 10 000 up to masses of 1 000 Da. Isotopic ratios could also be measured with DOTS, which would give insights into the origin and the processing of the parent molecules. Elemental ratios like H/C and O/C could then be calculated for organic entities that would give insights into the maturation of this organic matter, thus relating their composition to a relative age of the surface.

In this respect, DOTS is a science-enhancing add-on sensor to all surface remote sensing instruments on board an orbital mission, for which DOTS would provide ground truth information and reduce spectral confusion by high-resolution analysis.

The dual polarity of DOTS allows for the detection of both negative and positive ions, best suited for the detection of major rock forming elements (minerals, mostly cations) and organic compounds (preferentially anions in oxidizing medium).

Conclusions: This innovative concept of mass analyser for space is lightweight, uses DC voltages, and provides ultra high mass resolving power capabilities. A mass resolution of 280,000 at mass 56 has been recently achieved with our prototype at LPC2E. Therefore DOTS opens exciting new opportunities for molecular characterization, isotopic abundance evaluation, and more generally environmental characterization.

References: [1] Grün et al .(2009) *White Paper for Planetary Decadal Study.* [2] Brownlee D. (1993) *Workshop on the analysis of interplanetary dust particles,* May 15-17, 1993 at LPI, Houston TX. [3] Irvine W.M. and Lunine J.I. (2005) *Book Comet II,* 25-31. [4] Ishii H.A*., et al.* (2008) *Science* **319**, 447-450.[5] Duprat J*., et al.* (2010) *Science* **328**, 742-745. [6] Brownlee, D., *et al.* (2006) *Science* **314,** 1711-1716. [7] Yada T*., et al.* (2008) *MAPS* **43**, 1287-1298. [8] Messenger S*., et al.* (2003) *Science* **300**, 105-108. [9] Postberg F. et al. (2009) *Nature, 459*, 1098-1101. [10] Postberg F. et al. (2011) *Nature, 474*, 620-622. [11] Krüger H. et al. (1999). *Nature*, *399*, 558–560. [12] Krivov A.V. et al. (2003) *PSS* **51**, 251–269. [13] Koschny D. and Grün E. (2001) *Icarus* **154**, 402-411. [14] Kempf S. et al. (2012). *PSS* **65**, 10-20. [15] Krivov A.V. et al. (2003) PSS **51**, 251–269. [16] Sremcevic M. et al. (2003) *PSS* **51**, 455–471. [17] Sremcevic M. et al. (2005) *PSS* **53**, 625–641. [18] Kempf S. et al. (2012) *IPM,* Abstract# 1134. [19] Makarov A. (2000) *Anal. Chem., 72,* 1156-1162, [20] Hu Q. et al. (2005) *J. Mass Spectrom,. 40*, 430–443. [21] Eberhardt P.et al. (1987) *A&A* **187**, 481-484. [22] Mandt K.E. et al. (2012) *ApJ* **749**, 160. [23] Coates A.J. et al. (2007) *GRL* **34**, 22103. [24] Baklouti D. et al (2008) *Icarus, 194*, 647-659. [25] dePater I. et al. (2006) *Science* **392**, 92-94, [26] Showalter M.R. and Lissauer J.J. (2006) *Science* **311**, 973-977. [27] Murray C.D. (2006) *Science* **311**, 961-962.