MASS SPECTROMETER CALIBRATION OF HIGH VELOCITY IMPACT IONIZATION BASED COSMIC DUST ANALYZER

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Summary — We are calibrating the time of flight mass spectrometer of the Cosmic Dust Analyzer (CDA) instrument aboard the Cassini spacecraft. The CDA measures the flux of particles in the $10^{-15}$ to $10^{-9}$ g range at intersection velocities of up to 100 km/s. Of special interest are the chemical composition of the particles in orbit about Saturn and/or its satellites that are expected to be captured by CDA during ring plane crossings and upon close encounter with the satellites. Upon impacting a rhodium plate, particles are expected to partially ionize and their chemical composition is expected to be determined from mass analysis of the positive ions. In order to optimize impact ionization calibration experiments using a light gas-gun launched microspheric particles, we have done initial testing with a short duration pulsed laser (4 ns duration nitrogen laser (337 nm)). The beam is focused to deliver the 300µJ energy per laser pulse onto a 33 µm². The laser power density (~10$^{10}$ W/cm$^2$) simulates the impact of particles with various combinations of density and velocities, e.g., 8 g/cm$^3$ (Fe) projectile at 23 km/s or 1 g/cm$^3$ projectile at 65 km/s. The CDA spectrometer will operate in the near vacuum of Saturnian zone environment is housed in a laboratory chamber at 10$^{-6}$ mbar. The ions and electrons are separated by 680 V between target and grid. The laser ionization produces charge of 4.6pC (mostly Al$^{1+}$) in aluminum and 2.8pC (Fe$^{1+}$) in stainless steel. Estimating that each Al$^{1+}$ and Fe$^{1+}$ ion requires an energy of 5.98 and 7.90 eV/ion implies that ~10$^{-5}$ % of the laser pulse energy produces ions and the present system has a 10% detection efficiency. Using multi-channel plate detector to detect ions from aluminum alloy and kamacite yields well defined peaks at 24(Mg$^{+1}$), 27(Al$^{1+}$) and 64 (Cu$^{+1}$), and, 56(Fe$^{1+}$), 58(Ni$^{1+}$) and 60(Ni$^{1+}$) amu, respectively. Also contaminant ions at 23 (Na$^{+1}$) and 39(K$^{1+}$) amu are detected.

INTRODUCTION

One of the objectives of the Saturn orbiter, Cassini spacecraft is to characterize the dust/meteoroid environment of the Saturnian ring and satellite system. For this purpose the orbiter is equipped with a Cosmic Dust Analyzer (CDA) instrument[1]. The CDA measures the charge, the impact speeds, the mass and composition of these dust particles. The micrometeoroid mass measurement range is $10^{-15}$ to $10^{-9}$ g and the speed measurement range is 1 to 100 km/s. The initial (usually positive) charge on the particles is measured upon their passage through the two inclined grids at the entrance of the sensor housing, Fig.1a. The speed and the mass of the particles is determined from the rise time and the amplitude of the integrated charge pulse upon impact on the impact ionization detector (IID), Fig.1a. Upon impact single and multiple ionization occur depending upon particle material and velocity. Electrons are
collected on the impact plate of the detector. An integrated time-of-flight impact ionization mass spectrometer provides constraints on the particle chemical composition. Particles impacting onto the Rh target plate (Fig 1a), and a lesser mass of the Rh target, get vaporized and partially ionized. The positive ions (mostly singly charged) so produced get accelerated to $10^3$ eV energy. Providing no equi-dalton interference exists, the time of arrival of ions provides mass spectra for each dust particle in the above mass range.

![Schema of the CDA instrument](image)

Fig 1. Schematics of (a) the CDA instrument aboard Cassini mission which is simulated by the (b) laser ionization time of flight mass spectrometer at our laboratory.

The dust analyzer has two types of ion detection systems, one is a charge sensitive amplifier (CSA) that measures the ions collected at the ion collector and the other is an electron multiplier[2]. The multiplier (Johnston, type MM1) consists of stacked dynodes that provides upon electrostatic capture of positive ions, a high electron current gain and time resolutions of $10^{-8}$ s.

The output of the CSA is in the form of an integrated charge pulse. The pulse has steps that correspond to the arrival time of different ionic species, whereas the output signal of the electron multiplier is in the form of separate (differentiated) peaks.

**BACKGROUND**

Impact ionization experiments that determine the species type have been carried out previously with dust particles with diameters in the range 0.2 µm to 20 µm that have been
electrostatically accelerated[3] to velocities in the range of 1 to 70 km/s and in the mass range $10^{-15}$ to $10^{-10}$ g. The particles normally used were iron, or metal coated carbon and silicate spheres. These experiments were limited by the commercial availability of conducting particles. For larger particles having diameters of the order of 100 µm, we expect to employ a light gas gun for launching a wide range of projectiles of cosmochemical importance. Particles with velocities of the order of 6 km/sec are expected to be launched. These velocities are comparable to the circular orbit speeds around Saturn, the larger Saturnian satellites, and ring-plane particles (5-10 km/s). The CDA is expected to characterize the environment at each object for which a close encounter is conducted during this part of the Cassini tour.

Because of the difficulty in launching a single microspheric projectile with a light gas gun, and also to provide the pulsed ion source for setting up the calibration electronics, a crucial calibration program was initiated using a commercial pulsed laser. Fig.1 shows the correspondence between the laser ionization time of flight mass spectrometer (on mock-up instrument) in our laboratory and the CDA instrument now aboard the Cassini spacecraft. Detection methods for the micro-particle impact experiments to be conducted at F. Hörz’s 4 mm diameter, two stage light gas gun (NASA/ Johnson Space Center), are now being developed using the laser source as a proxy for the impact of a dust particle. Since the particle-target interaction occurs over a short interval (~10 nanoseconds) and the impact energies of dust particles are comparable to the duration and energy deposition achievable with commercial pulsed lasers[4], laboratory laser ionization experiments are useful to optimize the instrumentation for impact experiments.

We employ a 4 ns pulsed nitrogen laser with an energy of 300 µJ, a power density of $~2.25 \times 10^{11}$ W/cm² and a laser focal spot diameter of ~6.5 µm. The incident laser energy density simulates the impact of particles with various combinations of density and velocity. For example, it simulates an Fe-Ni projectile having a density of ~8 g/cm³, impacting at 23 km/s (the projectile footprint is taken to be 6.5 µm). The particle velocities as a function of various particle densities in the range 1.0 to 10 g/cm³, so as to produce the energy density of our laser

![Fig. 2 Velocity of the 300 µJ kinetic energy, 6.5 µm diameter impacting particle as a function of particle density.](image-url)
The velocities, $V$, are calculated using $E = 0.5 \rho_p v_p V^2$ where $\rho_p, v_p$ are the particle density and total volume, respectively, and $E = 300 \mu J$. Normally, particles having initial densities in the $\sim 0.01$ to $5 \text{ g/cm}^3$ range are expected to be encountered in space. They could range in composition from those similar to carbonaceous chondrites that are of low density and possibly correspond to the Brownlee particles\cite{5} collected in the Earth's atmosphere to differentiated metal silicate asteroid fragments.

**EXPERIMENTAL METHOD**

The schematic of the experiments carried out with a nitrogen laser (Laser Science, VSL337ND-S model #337201) on a mock-up instrument of the CDA is shown in Fig. 3. The 337 nm, 300 $\mu$J energy laser beam enters the chamber through a quartz window (MDC, quartz Viewport no. 450020). The beam is directed into the chamber by two beam steers (Newport, model BSD-1). The mirrors used in these beam steers have a dielectric coating to give 99% reflectivity in the UV region. The laser is focused onto the target with a 2.54 cm diameter plano-convex fused silica lens (Newport, SPX022AR10) having anti-reflection coating in the UV region. The focal length of the lens is 10 cm. The ions are formed in the short source region between the target plate and the grid. The target plate, here, is $\sim 17.5 \text{ cm}$ in diameter, made of commercial aluminum alloy on which samples of a few mm diameter and 0.10 to 0.15 mm in thickness are mounted. The grid parallel to and in front of the target is made of copper.

This grid has a transmission of 66%. The nominal distance between the grid and the target plate was kept at 6 mm. A voltage (680 V) impressed on the target accelerates the positive ions towards the detector which is at ground potential. The distance between the target and the detection system can be varied between 20 to 30 cm. The chamber pressure was maintained
below 1.0×10^-6 mbar with a 1500 l/s diffusion pump. We have also employed two kinds of ion detection systems in two series of experiments described below. In Experiment Run #1, the detector consists of a copper collector plate (at ground potential), shielded in an aluminum enclosure to suppress electromagnetic noise. The side of the detector facing the target is constructed of 78% transmission aluminum mesh. The collection area was limited to a central zone (~6.8 cm diameter) of the 15 cm diameter copper collection plate. The charge on the copper electrode is monitored by a charge sensitive amplifier (CSA, EG &G, ORTEC model 142A) and a 500MHz, HP54540 digital storage oscilloscope. The laser is triggered externally. The oscilloscope is triggered by the optosynchronous signal provided by the laser (Fig. 4).

![Experimental set-up for the signal recording system.](image)

For Experiment Run #2, the collector plate is replaced by a multichannel plate detector (MCP) (Galileo Corp., part no. 1397-0050). The MCP consists of an array of miniature high-gain electron multipliers oriented parallel to one another. The time resolution of the MCP is comparable to the MM1 multiplier used in the CDA (Fig. 1). The active detection diameter of the MCP used here is 18mm and its operating voltage is kept at -1800V. A preamplifier (EG&G, ORTEC model VT120C) is used to couple the MCP signal to the oscilloscope.

**RESULTS**
Charge Sensitive Amplifier

For Run #1A experiments, where charge is measured by a CSA, the first sample material was an aluminum alloy target plate. Here, initially at low laser power densities, we observed a two-step pulse corresponding to Na$^+$ and K$^+$ each with an approximately 350 ns rise time. The presence of contaminant alkali salts on material/sample surfaces is well known in laser desorption mass spectrometry. Although impurities, the known mass of the Na$^+$ and K$^+$ ions is advantageously used for calibrating the instrument. With higher laser power density, we observed a high-amplitude, long duration (~ 800 ns) pulse at the times corresponding to arrival of $^{23}\text{Na}^+$ and $^{27}\text{Al}^+$ (Fig. 5a). No further steps were observed.

For Run #1B, stainless steel was used, and we found Fe, Cr and Ni at 56, 52 and 58 amu to be merged into a single pulse, Fig. 5b. The electron charge collected (at the target end) is estimated to be around 4.7 pC and 2.8 pC for the aluminum alloy and stainless-steel samples, respectively. The ion charge collected at the collector plate was estimated to be 0.23 pC and 0.15 pC for these two samples. This corresponds to an ion detection efficiency of 4-5% over a ~0.09 sr collection solid angle.
Fig. 5. Single shot time of flight spectra recorded using charged sensitive amplifier: (a) from Al sample, (b) from stainless steel sample, (c1 is the optosynchronous output due to laser trigger (5V/div), c2 is the integrated electron charge signal at the target end (200m V/div), c3 is the ion signal at the collector plate (75mV/div)).
Figure 6. Single N\textsubscript{2} laser pulse, time-of-flight spectra recorded using multi-channel plate detector: (a) from Al sample (b) from kamacite, at laser power density of $3.45 \times 10^9$ W/cm\textsuperscript{2} (c) from kamacite, at laser power density of $4.5 \times 10^9$ W/cm\textsuperscript{2}.
Multichannel Plate Detector

In the second category of experiments, we employed a MCP. Experiments were repeated, first on the aluminum alloy target plate and on the mineral, kamacite. Kamacite[6] (94.5% Fe and 5.5% Ni) is the principal mineral in Fe-Ni meteorites. The Gibeon meteorite was the source of our sample. Fig. 6a displays the spectrum recorded with the Al target. It shows a well-defined singly charged aluminum peak. The Na⁺ and K⁺ peaks observed from the surface impurities are used to calibrate the mass spectra. Peaks corresponding to Cu⁺¹ and Mg⁺¹ present at low levels are aluminum alloying elements. Fig. 6b shows the spectrum recorded for kamacite. Here too, apart from well-separated Na⁺ and K⁺ peaks, we observe well-resolved peaks for ⁵⁶Fe²⁺ and ⁵⁸Ni⁺. Yet another spectrum from this mineral at slightly higher laser density (laser density was varied with the help of neutral density filters) is shown in Fig. 6c. Here, we see an additional peak corresponding to ⁶⁰Ni. Further systematic study with varying laser energy density from 1.0 × 10² W/cm² to 9.0 × 10² W/cm² is in progress.

SUMMARY AND CONCLUSIONS

In our first set of experiments using a 300 µJ, 4 ns, 337 nm laser pulse and a charge sensitive amplifier as a detector, the elements with masses differing by 4 amu (e.g. ²³Na and ²⁷Al) could not be distinguished. In the second set of experiments with the multi-channel plate detector (similar to the multiplier on CDA), we observed well-defined peaks of Fe and isotopes of Ni. We also could observe ion signals from several elements that are present at low levels in the sample, e.g. Cu and Mg in case of commercial aluminum sample. We are now conducting additional pulsed laser experiments on pyrrhotite (FeS), olivine (Mg₂SiO₄), serpentine (Mg₃Si₂O₇·2H₂O) and Murchison meteorite prior to studying ionic spectra on these same materials at the light gas-gun facility at the NASA/Johnson Space Centre (operated by Dr. F. Hörz). In addition we expect to study ¹³C/¹²C ratio in a series of terrestrial coal, petroleum, the tissue of plant eating bovine and other carbon bearing meteorites besides Murchison to verify that we can detect a wide range in ¹³C/¹²C ratio, previously reported. We also expect to determine the ratio of D/H for ices. Because of the enhancement of D/H in comets, these data can be applied in measurement of D/H for ring particle ices. Finally, we expect to obtain mass spectra of volatized ilmenite FeTiO₃ and GeO₂ in order to attempt to verify the occurrence of Ti⁺¹ and Ge⁺¹ observed in spectra shown in Fig. 6a.

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