Dustbuster: a compact impact-ionization time-of-flight mass spectrometer for *in situ* analysis of cosmic dust

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We report on the design and testing of a compact impact-ionization time-of-flight mass spectrometer for analysis of cosmic dust, suitable for use on deep space missions. The instrument, Dustbuster, incorporates a large target area with a reflectron, simultaneously optimizing mass resolution, particle detection, and ion collection. Dust particles hit the 65-cm^2 target plate and are partially ionized by the impact. The resulting ions, with broad energy and angular distributions, are accelerated through a modified reflectron, focusing ions of specific m/z in space and time to produce high-resolution mass spectra. The cylindrically symmetric instrument is 10 cm in diameter and 20 cm in length, considerably smaller than previous *in situ* dust analyzers, and can be easily scaled as needed for specific mission requirements. Laser desorption ionization of metal and mineral samples embedded in the impact plate simulated particle impacts for evaluations of instrument performance. Mass resolution in these experiments ranged from 60–180, permitting resolution of isotopes. The mass spectrometer can be combined with other instrument components to determine dust particle trajectories and sizes. [DOI: 10.1063/1.1427762]

I. BACKGROUND

Cosmic dust is an important component of the interplanetary and interstellar medium. An understanding of the composition, evolution, and dynamics of cosmic dust is essential to the understanding of stellar and planetary formation.[1] Methods for studying interplanetary and interstellar dust include remote sensing, collection and analysis of dust grains that have survived impact on the Earth, capture and return of dust samples to Earth for study, and *in situ* analysis using instruments on spacecraft. Remote sensing techniques, such as analysis of zodiacal light and thermal emissions,[2] are useful primarily for studying dynamics and distributions of dust populations. Dust grains collected from the Earth environment, including the upper atmosphere, polar ice, and deep-sea sediments, provide information about structure and composition, but these properties may have been altered by atmospheric heating, chemical reactions, or contamination.[3] Sample capture and return, such as that planned for the STARDUST comet fly-by,[4] allows in-depth analysis of dust grains by Earth-based laboratories, but is limited to studying dust relatively close to the Earth. Finally, dust may be studied directly by *in situ* instruments. Although limited by the low-power and low-mass requirements of space flight, *in situ* dust analyzers have proven useful for determining such properties as composition, mass, charge, distributions, and dynamics of dust at various locations within the solar system.[5–11]

Most *in situ* dust analyzers rely on the phenomenon of impact ionization.[12] Spacecraft typically encounter dust grains at velocities of 10–80 km/s.[13] At such velocities, the dust grain and a portion of the surface it hits are partially vaporized and ionized.[14,15] Figure 1 illustrates this phenomenon. The shock wave produced by the impact creates both positive ions and free electrons in a dense, expanding plasma.[16] The electrons, which are more mobile than the ions, escape the expanding plasma cloud first, resulting in a charge separation. The remaining atomic and/or molecular ions, expanding behind the electrons, emerge from a region of high positive space charge. High-velocity dust impacts produce ions with large and varied initial kinetic energies, typically several eV.[17,18]

In situ dust detectors generally make use of impact ionization either by measuring the current created on the target surface or a nearby grid,[10,11] or by time-of-flight mass spectrometric analysis of the resulting ions.[19] Only the latter method provides information about the composition of the dust grain. Previous impact ionization time-of-flight mass spectrometers for dust analysis include the Giotto Particulate Impact Analyzer (PIA) and the Vega dust impact mass analyzer (PUMA) used in the Halley comet fly-by, the Cassini Cosmic Dust Analyzer (CDA), and the STARDUST Cometary and Interstellar Dust Analyzer (CIDA).[1]

The PIA and PUMA dust analyzers and the STARDUST CIDA were based on similar designs. Because impact-generated ions exhibit a wide range of initial kinetic energies, these mass spectrometers used reflectrons, originally described by Mamyrin,[20] to compensate for the initial energy distribution of the ions. These dust mass spectrometers were large and heavy, each around 1 m in length and 17 kg in mass. Also, the target plate dimensions on these instruments were small in relation to the overall instrument size (5 cm^2 for PIA and PUMA, 50 cm^2 for CIDA).[1] Small target plates are useful for regions with high concentrations of dust, such as in the vicinity of a comet, but are less appropriate for regions with low concentrations of dust.[19]

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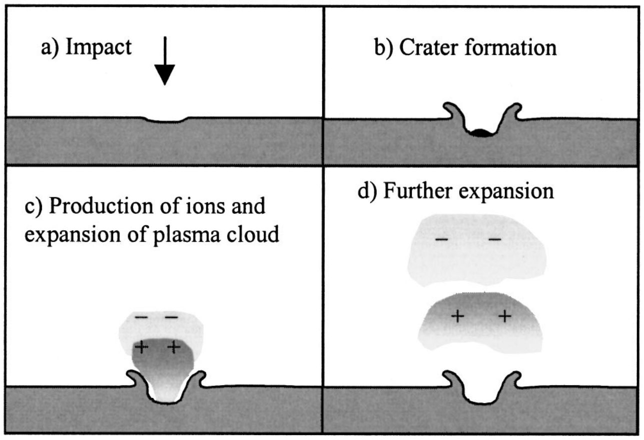

FIG. 1. Impact ionization of a high-velocity dust grain striking a surface.

In regions where cosmic dust is sparse, a large active target area is needed in order to get a statistically significant number of impact events. The Cassini CDA was designed for regions of the solar system with low and medium concentrations of dust. It has a large impact surface, of which 200 cm^2 is used for mass spectrometry on impinging dust grains.[21] A reflectron was not included in this 15-kg instrument because of the difficulty of combining a reflectron with a large target area and the simultaneous operation of the impact plasma sensor.[19]

Recently, NASA has placed emphasis on developing smaller, lighter, lower-power spacecraft and instruments. We have designed and built a compact impact-ionization time-of-flight mass spectrometer for *in situ* analysis of cosmic dust, suitable for use on future deep space missions. Christened "Dustbuster," this time-of-flight mass spectrometer combines the best aspects of previous dust analyzers in a more compact design. The Dustbuster includes a reflectron, modified so that it corrects for initial ion energies and also focuses the ions from a large target area onto the ion detector. This modified reflectron allows mass spectra to be obtained from dust grains hitting a 65-cm^2 target, with sufficient mass resolution to measure isotopic distributions of most elements. The active target area is large compared to the instrument size, and of sufficient size to be useful for regions of the solar system with low dust concentrations. The Dustbuster, measuring only 10 cm in diameter and 20 cm in length, and weighing approximately 0.5 kg, is much smaller and lighter than previous dust mass spectrometers. This article discusses the design of the instrument and its performance using laser desorption ionization to simulate hypervelocity dust impacts. A preliminary account of this investigation was presented at the October 2000 meeting of the Division of Planetary Sciences of the American Astronomical Society, held in Pasadena, California.[22]

II. INSTRUMENT DESCRIPTION

The cylindrically symmetric design of the Dustbuster is illustrated in Fig. 2. Dust grains, typically 0.1 to 10 μm, enter the instrument through the front grid, pass through the acceleration grid, and impact on the target plate, where they are partly vaporized and ionized. The ions are then accelerated into the reflectron region and focused through the drift tube onto a 5 cm^2 microchannel plate (MCP) detector. The following considers each component in detail.

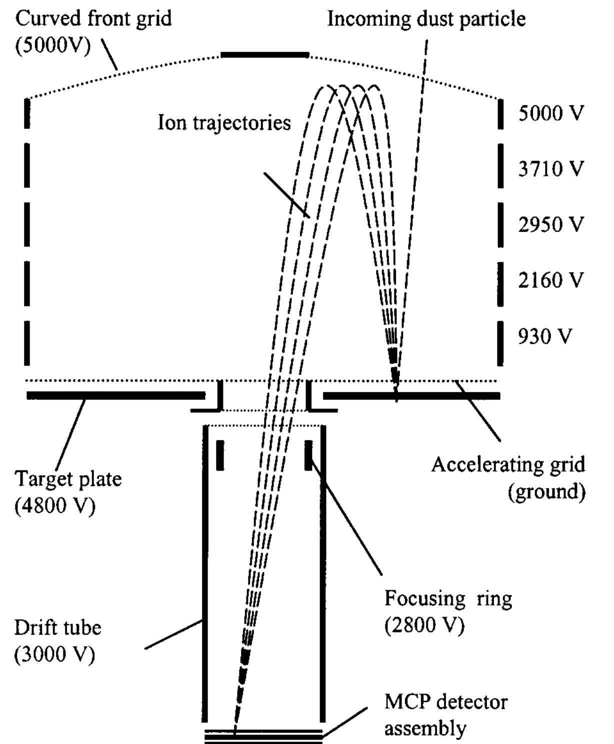

FIG. 2. Design of the Dustbuster mass spectrometer.

The target plate is a 75 cm^2 disk which has an active area of 65 cm^2 for dust analysis. A curved target plate has been explored and may also be suitable. The target must be made out of a material with a high density and high melting point in order to maximize the number of ions produced in a given dust impact event.[23,24] Because a portion of the target plate is also ionized when a dust grain impacts, the target plate must be made out of a material with low cosmic abundance to avoid interference with the dust composition. Rhodium and silver[1,19] have been used for target plates in previous instruments, and tantalum or gold would also likely work.[16] Our prototype instrument uses a copper target plate for laser desorption testing, where target composition does not matter. A tantalum plate for actual dust impact studies is planned for the future. A target containing two of these metals might work best for a flight instrument since the mass spectra could be calibrated using ions of both elements from the target plate.

Ions produced from an impact on the target plate are accelerated to 4800 V by the accelerator grid, located approximately 2 mm from the target plate. This grid must have high transmission and low field penetration. The Dustbuster accelerator grid is a 333 wire-per-inch (0.076 mm wire spacing) 70% transmission nickel grid manufactured by Buckbee–Mears St. Paul. Figure 2 indicates the voltages used to accelerate and detect positive ions. Hypervelocity impacts of microparticles typically do not produce a useful abundance of negative ions.[16,25]

The reflectron region consists of five ring electrodes with voltages (with respect to the accelerator grid) of 5000, 3710,

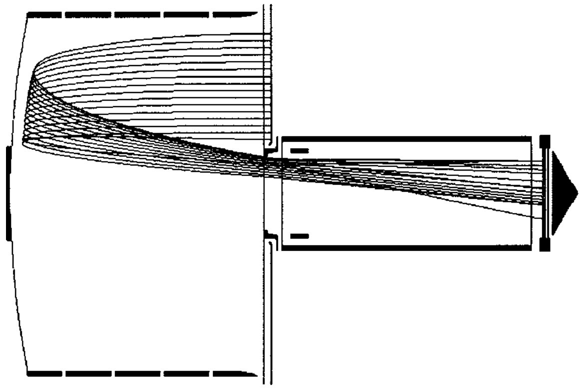

FIG. 3. Computer simulation (obtained using SIMION) showing trajectories for ions originating at points located at various radial distances along the target plate. These ions all have initial kinetic energy of 40 eV normal to the target plate.

2950, 2160, and 930 V, as shown in Fig. 2. These rings provide a longitudinal potential gradient, just as a standard reflectron does, in order to compensate for the initial kinetic energies of the ions. The rings also provide a small radial (transverse) gradient, pushing the ions toward the center of the instrument. Ions originating from approximately 65 cm^2 of the target plate will be focused into the drift tube and onto the MCP detector. The front grid is curved, providing additional spatial focusing to the ions. This modified reflectron design makes it possible simultaneously to optimize spatial focusing and energy focusing. In addition, any neutrals, liquid droplets, or solid ejecta fragments that might be produced[19] during the impact will not reach the detector, simplifying spectra, and preserving the life of the MCPs. Figure 3 shows typical trajectories of ions originating from various locations on the target plate. Ions of a given m/z from a single dust impact will all have the same flight time, but the time will be slightly different from the flight time of ions of the same m/z from a dust impact elsewhere on the target plate. This variation of flight times with location of dust impact will not present a problem because only one dust grain will strike the instrument at a time. However, the spectrum from each dust impact must be calibrated to compensate for this variation in flight time.

After the ions leave the reflectron region, they enter the drift tube. Although drift tubes are normally grounded, the Dustbuster drift tube is kept at a fairly high potential (3000 V). In general, when a time-of-flight mass spectrometer uses a reflectron, ions with different initial kinetic energies will reach the same plane or focal point after the ions have spent approximately equal amounts of time inside and out of the reflectron.[26] In this case, a grounded drift tube would need to be quite long. The high-potential drift tube considerably shortens and lightens the instrument, while sacrificing resolution only minimally. The drift tube is not completely field free. A small ring electrode (2800 V) at the entrance of the drift tube aids in directing the ions toward the detector. As ions leave the drift tube they are detected using the MCP detector. The MCP signal is then amplified and recorded.

Several instrument components are not shown in Fig. 2. First, in order to protect the MCP plates from direct sunlight or other damaging particles, an iris-type aperture is located at the rear of the drift tube. This aperture can be opened or closed as needed. Second, although the current prototype Dustbuster uses an external signal acquisition trigger, an internal trigger is needed, either based on charge detection, such as has been used on previous instruments,[16] or a photodiode trigger which would respond to the flash of light that accompanies hypervelocity impacts.[27,28] The Dustbuster also includes high voltage supplies and voltage dividers to provide power to the electrodes and the MCP assembly.

Although the Dustbuster could be used as a standalone instrument, it is designed to be combined with other instrument subsystems that would measure the charge, mass, and/or trajectory of the incoming dust grains. For instance, a series of entrance grids, such as those used on the Cassini CDA,[19] or an optical system, based on the detection of light scattered by incoming dust grains,[29] could be used to determine the velocities and trajectories of dust grains as they enter the Dustbuster. We are also exploring the use of an optical spectrometer to determine composition and mineralogy from an analysis of the impact flash. The design of the Dustbuster is easily scaled to meet the needs of specific missions.

III. PERFORMANCE EVALUATIONS

Using SIMION ion trajectory software,[30] numerous computer simulations were performed, both to optimize the design and simulate the performance of the Dustbuster. For most performance simulations, ion groups were defined to have initial kinetic energies with a Gaussian distribution centered at 40 eV, and a spatial distribution of $\cos\theta$ or $\cos^2\theta$ about the normal to the target plate. These represent the energy and angular distributions of ions reported by Ratcliff and Alladhadi[17] for a 94 km/s impact, and have been used for simulations by other researchers in this field.[31] Impacts at lower velocities will produce ions with lower energies.[18] Some Dustbuster simulations used ions with energies of 5–20 eV. A variety of ion mass-to-charge ratios were used. In simulations with 40 eV ions, mass resolution $(m/\Delta m)$ ranged from 100–400, with higher resolution for impacts closer to the axis of the instrument. Ion collection efficiency ranged from 20%–40%, with most ion losses caused by the grids through which the ions passed. Figure 4 shows a typical scenario of ions produced by a single impact. In this case, the position of singly charged ^{56}Fe ions, with initial kinetic energy of 10 ± 4 eV (typical of a 10–20 km/s impact)[18] and $\cos\theta$ angular distribution is shown at intervals of 0.5 μs from the point of impact to the MCP detector. Note that SIMION treats grids as having 100% transmission.

The Dustbuster was subsequently tested using laser-desorption ionization (LDI) to simulate dust impacts. A photograph of the prototype is shown in Fig. 5. A 337-nm nitrogen laser with a pulsewidth of 4 ns was attenuated from 300 to approximately 60 μJ using a neutral density filter, although precise laser intensity measurements were not made. Using a biconvex lens with a focal length of 40 cm, the laser beam was focused to a spot size of approximately 40 μm, resulting in a power density of approximately 10^9 W/cm^2. The Dustbuster was inside a vacuum chamber, which was

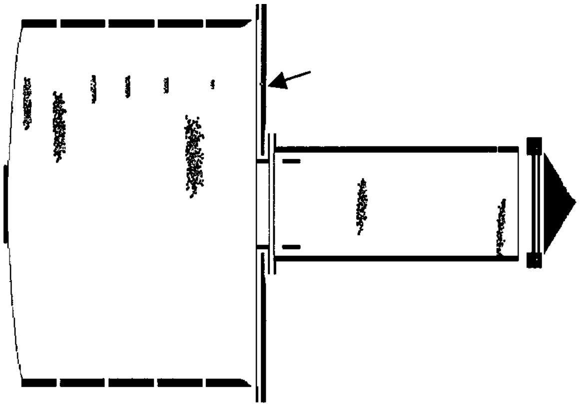

FIG. 4. SIMION simulation showing locations of ions originating at a given point (a single impact) at 0.5 μs intervals after the impact. Point of dust impact is indicated with an arrow. Ions from some time intervals are omitted for clarity, and shorter intervals are shown for the first microsecond in order to emphasize the point of origin.

evacuated by turbopump to below 10^{-7} Torr. The MCP detector for these experiments comprised two stacked plates. After amplification and differentiation by an EG&G Ortec fast preamp (model VT120C), the MCP signal was recorded by a 200 MHz digital oscilloscope.

The properties of ions produced using laser desorption are somewhat different than those produced in a high-velocity impact, but there are sufficient similarities to make laser desorption a useful method for evaluating instrument performance.[32,33] For instance, the ionizing ability of light is much greater than that of an impacting particle, while the cratering and vaporizing efficiency is similar. As a result, the ratio of ions to neutrals in the vapor may be different between the two ionization methods. This may result in different space-charge or shielding effects. However, the initial kinetic energies of the ions are roughly the same (approximately 10–30 eV for laser desorption),[34] and the duration of the laser pulse is similar to the duration of an impact ionization event, estimated to be a few nanoseconds.[16,35]

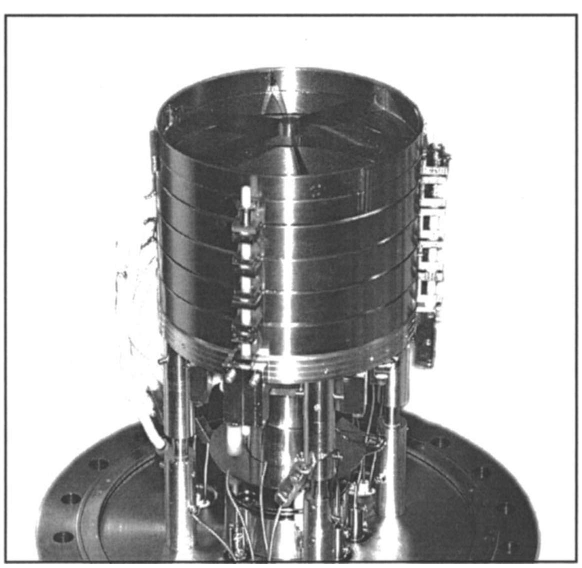

FIG. 5. Photograph of the prototype Dustbuster instrument mounted on an 8 in. vacuum flange.

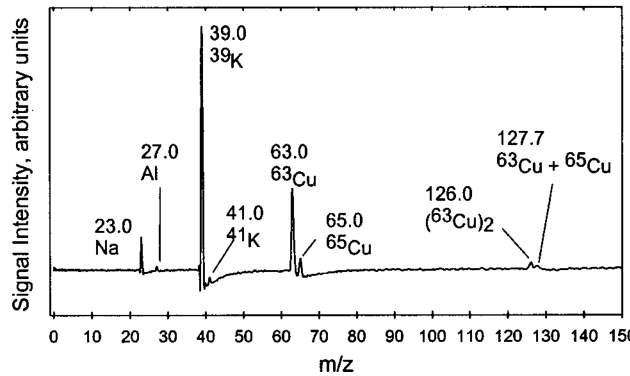

FIG. 6. Laser-desorption spectrum of the copper target plate. Spectrum shows sum of 12 single-laser-shot spectra.

Figure 6 shows a laser-desorption time-of-flight mass spectrum of the copper target plate. This spectrum is the average of 12 individually calibrated, single-shot spectra. Ions of sodium and potassium, common contaminants both in laser- and impact-generated ions,[16,36] are observed. Also present is a small but reproducible aluminum ion peak, the source of which is unknown. Both isotopes of copper are present and completely resolved. Copper clusters were also detected in low abundance. In this averaged spectrum shown in Fig. 6, the ^{63}Cu peak has a mass resolution $(m/\Delta m)$ of 100. The mass resolution of copper peaks in the individual (single-shot) spectra ranged from 85–180. The differences in resolution between shots may be caused by inhomogeneities in the laser beam or the copper surface, or by space-charge or other effects.

Because mineral grains are important components of cosmic dust, Dustbuster performance studies included LDI of several mineral samples. Chalcopyrite, a copper–iron sulfide, worked best for these tests because it conducts electricity, cleaves into thin flakes, and was easily ionized by the nitrogen laser employed in this study. The first two of these properties were useful to prevent charge buildup and large deviations of the electric field in the accelerating region. Figure 7 shows an averaged spectrum taken using a piece of chalcopyrite embedded in the target plate at a point 2.5 cm away from the center. The iron and copper isotope peaks are completely resolved. Mass resolution of the copper and iron

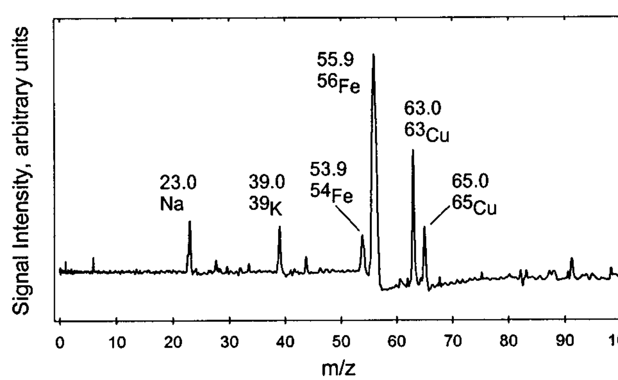

FIG. 7. Laser-desorption spectrum of chalcopyrite, a copper–iron sulfide, embedded in the Dustbuster target plate. Spectrum shows sum of nine single-shot spectra.

isotope peaks in this averaged spectrum ranged from 60–180.

These LDI results confirm the performance predicted by computer simulations and show that the Dustbuster successfully yields mass spectra of a sufficiently high resolution for elemental and isotopic analysis of cosmic dust.

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