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A compact time-of-flight mass spectrometer for high-flux cosmic dust analysis

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[1] Time-of-flight mass spectrometers on spacecraft are the most direct method for determining chemical composition of cosmic dust grains. Miniaturization of these instruments presents many challenges. Larger space-charge effects, greater deviations from the paraxial approximation, and various ion-optical aberrations negatively affect mass resolution in small time-of-flight instruments. We report on the building and testing of an instrument design that may reduce these effects. In addition to a linear reflectron, ions pass through a ring aperture that transmits only those ions with transverse velocity components that fall within a specific range. This novel design focuses ions onto a detector with greatly reduced spherical aberration. Space-charge effects and the effects of impact plate cratering and grid scatter are also reduced using this design. Controlled impacts of iron microparticles at several km/s demonstrate instrument performance. This instrument is suited for characterization of cosmic dust in regions of very high dust flux, such as a comet flyby, and it may also have practical laboratory or field applications. *INDEX TERMS:* 2129 Interplanetary Physics: Interplanetary dust; 2194 Interplanetary Physics: Instruments and techniques; 5465 Planetology: Solid Surface Planets: Rings and dust; 6022 Planetology: Comets and Small Bodies: Impact phenomena; 6015 Planetology: Comets and Small Bodies: Dust; *KEYWORDS:* cometary dust, mass spectrometer, impact ionization, comet flyby, hypervelocity impact, interplanetary dust

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1. Introduction

[2] Objects in space are continually bombarded with micron-sized particulates known collectively as cosmic dust. Cosmic dust grains originate from a variety of astronomical sources including comet sublimation, asteroid impacts, supernovae, and carbon-rich stars. A dust grain contains chemical information about both its source of origin and the processes taking place throughout its history.

[3] An important segment of cosmic dust research is composition analysis by mass spectrometers on spacecraft. Spacecraft encounter dust grains at velocities ranging from a few to over a hundred km/s. At such speeds, the impacting dust grain and a portion of the surface it strikes are partially vaporized and ionized [*Hornung and Kissel*, 1994]. The ions are then extracted and analyzed using time-of-flight mass spectrometry. The resulting mass spectra consist primarily of singly charged atomic peaks, although in some cases molecular fragments may be observed [*Kissel and Krueger*, 1995; *Kissel et al.*, 1986].

[4] Several impact-ionization time-of-flight mass spectrometers have flown successfully through various dust environments in the solar system, and have been reviewed by *Auer* [2001]. The Vega 1 and Vega 2 spacecraft, which flew by Halley's comet in 1985, contained the identical PIA and PUMA dust mass spectrometers [*Kissel et al.*, 1986]. The Stardust Cometary and Interstellar Dust Analyzer (CIDA) uses the same design. Reflectrons in these instruments compensate for the initial kinetic energies of the impact-generated ions. The Cassini Cosmic Dust Analyzer (CDA) was designed with a large impact area for environments with sparse dust, but did not include a reflectron. Dust particle impacts produce ions with large initial kinetic energies—often over 50 eV—which can significantly reduce resolution if not corrected [*Ratcliff and Allahdadi*, 1996]. The PIA and PUMA instruments had a mass resolution ($m/\Delta m$) of around 200, while the CDA has resolution of around 20–50 (E. Grun, personal communication, 2002). All of these instruments had a mass of 16–17 kg and a volume of 0.02–0.03 m^3.

[5] The PIA, PUMA, and CIDA cosmic dust mass spectrometers were designed for environments with high concentrations of dust, such as the vicinity of a comet

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[*Kissel et al.*, 1986; *Ratcliff et al.*, 1992]. However, the large size and mass of these instruments makes them less compatible with NASA's current objectives of smaller, lighter spacecraft. Unfortunately, reducing the dimensions of time-of-flight mass spectrometers generally decreases mass resolution. Shortening the instrument can increase deviations from the paraxial approximation, and the resulting focused ions have greater spherical aberration. Related factors, such as astigmatism and grid scatter, are also adversely affected. The difference in flight times between ions of different mass is smaller, so better ion focusing is needed to maintain sufficient resolution. Space-charge effects present greater complications, both because of the need for narrower arrival time distributions, and also because the physical dimensions of the instrument (and the spacing between ions) are reduced.

[6] We have built and tested a smaller instrument design that addresses these limitations. This instrument includes both a reflectron and a novel ring aperture system to compensate for ion velocity distributions in all three dimensions. The design also reduces the adverse effects of spherical aberration, grid scatter, and impact plate cratering. The small impact area in this design, however, limits its usefulness to operation in a region of space with a very high concentration of dust, such as a close flyby of a comet or an impact-generated dust plume.

2. Instrument Design

[7] The cylindrically symmetric instrument is diagrammed in Figure 1. Dust grains enter through the grid and aperture at the left of the diagram and strike the impact plate. Ions produced upon impact are extracted into the reflectron region by a potential of 3000 V. The reflectron, originally described by *Mamyrin et al.* [1973], compensates for the spread in the initial kinetic energies of ions, or more precisely, for the spread in the velocity components parallel to the instrument axis. Ions with greater initial kinetic energy penetrate further into the reflectron and hence take a slightly longer path to the detector. In the reflectron region the ions spread out laterally due to space-charge and other effects discussed below. As ions leave the reflectron, a ring-like pupil blocks the transmission of ions whose velocity components perpendicular to the instrument axis fall outside a given range. Thus only a "ring" of ions is permitted into the drift region, corresponding to a specific, narrow distribution of radial kinetic energies. Ions are focused onto the electron multiplier detector. This ring aperture effectively reduces the spherical aberration of the ion beam to obtain the desired mass resolution. Of course, signal attenuation accompanies a narrow ion window, but dust impacts typically produce a sufficiently large number of ions that even a 10-fold reduction in ion transmission will still yield strong signal [*Austin et al.*, 2002; *Friichtenicht*, 1964; *Hansen*, 1968; *Roy*, 1975]. By allowing only a ring of ions to traverse the drift tube, space-charge effects are greatly reduced.

[8] In the reflectron region the ions spread out radially due to space-charge repulsion, scatter from the extraction grid, inhomogeneities in the extraction and reflectron fields, and velocity components arising from initial thermal energies of the ions. In a region of space with a high dust concentration the impact plate quickly becomes cratered. As more micro-craters are produced by impacts, the ion extraction field becomes less homogeneous. The magnitude of the field inhomogeneity and the resulting ion trajectory distortion is inversely dependent on the length of the extraction field, and for some large instruments might be negligible. In the PIA and PUMA instruments this cratering was an important issue affecting ion focusing and mass resolution. In the current instrument the ring aperture filters out lateral spread from any source, including field inhomogeneities. Thus cratering should not significantly affect instrument performance. An additional feature of this instrument design is that the ion detector is completely protected from stray particles and radiation that might otherwise cause detector damage.

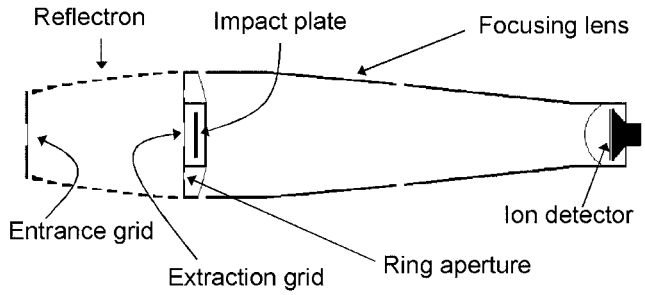

Figure 1. Schematic of time-of-flight mass spectrometer for high-flux cosmic dust analysis.

[9] As can be seen in Figure 1, the acceptance angle of this instrument is only a few degrees. Most cosmic dust analyzers maximize the acceptance angle in order to observe more dust grains. However, in a high flux environment the source of dust is presumably both known and localized, and the direction of dust flow is well defined. A narrow entrance can then be pointed in the direction of oncoming dust, while the small amounts of dust from other sources would not be accepted.

[10] Spherical aberration in ion optics systems is generally defined in terms of the spot size, Δr_2, of focused rays intersecting the image plane [*Moore et al.*, 2003]. In time-of-flight instruments it is more useful to consider spherical aberration as the difference in flight time between identical ions taking different paths through the ion optics system, Δt, as this latter effect more directly relates to mass resolution. The relationship between these definitions of spherical aberration is illustrated in simplified lens-ray form in Figure 2. Note that Δt is not defined by the points at which ion rays cross the optical axis, but rather by the amount of time taken to reach the detector by identical ions traveling on different spatial paths through the instrument. The dashed lines t_1 through t_4 show the locations of ions in four representative trajectories at the moment the first ions reach the image plane. The span of these ion positions at that moment is approximately equal to Δt. Note that Δt is defined by the difference in arrival times of ions at the plane of detection, which in Figure 2d does not coincide with the image plane. Figure 2 also shows the effect on spherical aberration of introducing both standard and ring apertures into the ion optical system. Although a standard pupil significantly reduces both Δr_2 and Δt, a ring aperture

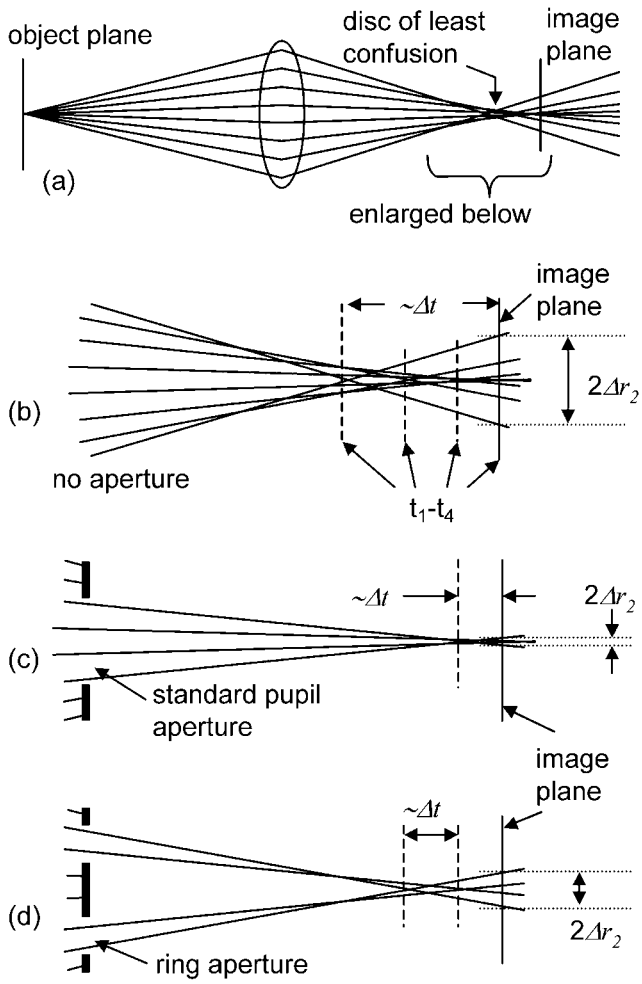

Figure 2. (a) Illustration of spherical aberration. (b) Spherical aberration defined as spatial spread in image plane, $2\Delta r_2$, and as spread in arrival time distribution, Δt. Dotted vertical lines ($t_1 - t_4$) show locations of given ions at the moment the first ion reaches image plane. Effect on apparent spherical aberration by (c) standard and (d) ring apertures.

produces a significant reduction in Δt but a smaller reduction in Δr_2. Similarly, the disc of least confusion is only somewhat reduced by the ring pupil. However, in a time-of-flight mass spectrometer application where the ion detector is larger than the circle of least confusion, only the spread in arrival times, Δt, is of concern.

[11] The instrument design was evaluated using SIMION 7.0 ion trajectory software [*Dahl*, 2000]. For simulations the instrument dimensions were as follows: length 28 cm, diameter 6 cm, sensitive area of impact plate 1 cm^2. Ions originated on the impact plate at the center, and at radii of 0.2, 0.4, and 0.55 cm. Groups of 500 ions at each location were defined to have mass of 100 Da, initial kinetic energy of 25 ± 15 eV, and a cos θ angular distribution about the normal. These values are typical of impact-generated ions [*Abramov et al.*, 1991; *Ratcliff and Allahdadi*, 1996]. Figure 3 shows simulated ion trajectories under these conditions. The ring aperture stops most ions, and those that are transmitted strike the ion detector. Mass resolution ($m/\Delta m$) of simulated ions was 350–400, sufficient to resolve isotopes of any element. Resolution was not reduced for ions originating away from the center of the impact plate, although the number of ions reaching the detector was reduced. Including a slight curvature to the impact plate improved this situation in simulations. In simulations 10–15% of ions reached the detector, assuming 70% transmission for the extraction grid and 90% transmission for all other grids. The duration of ion formation was not considered in these simulations, but is expected to be sufficiently rapid as to be ignored.

3. Experimental Procedure

[12] Hypervelocity impacts of iron microparticles simulated cosmic dust impacts in instrument performance evaluations. The prototype dust analyzer used in these experiments was the same size as that used in the simulations described above. The dust analyzer impact plate was made of tantalum. Microspheres were accelerated to several km/s using the 2 MV van de Graaff dust accelerator at Concordia College, Moorhead, Minnesota.

[13] The Concordia dust accelerator is essentially identical to Friichtenicht's dust accelerator [*Friichtenicht*, 1962]. Figure 4 shows the setup for microparticle impact studies, including the dust accelerator and the high-flux dust analyzer. The principal components of the dust accelerator include the dust reservoir and charging needle, the 2 MV van de Graaff ball, and charge-sensitive electrodes along the length of the flight tube.

[14] Iron particles with a size range of 0.1 to 3 microns (General Aniline and Film Corp.) were placed in the dust reservoir. The dust reservoir ball, chamber, and flight tube were then evacuated. On average, 1–10 particles per minute struck the energy analyzer impact plate.

[15] The dust reservoir, accelerator, and flight tube were evacuated using a diffusion pump. The dust analyzer was mounted inside a turbopumped vacuum chamber mounted at the end of the accelerator flight tube. The two vacuum systems were connected with a 1-cm circular aperture, through which the charged microparticles left the flight tube and entered the dust analyzer vacuum chamber. A flexible bellows allowed alignment of the particle beam

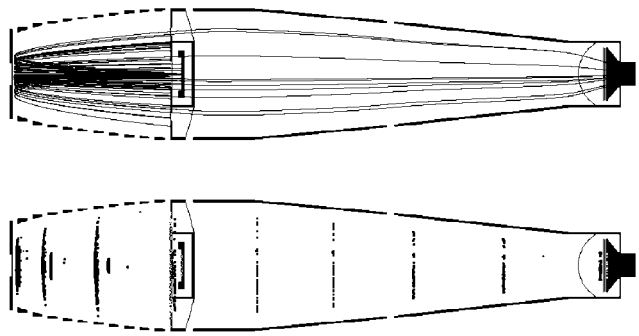

Figure 3. Simulated ion trajectories on dust analyzer. Lower diagram shows locations of ions (m/z = 100) at time intervals of 0.4 μs.

(which had a typical spread of 2 mm) with the dust analyzer impact plate.

[16] Image currents on three cylindrical electrodes within the flight tube measured the charges and velocities of the accelerated particles. Particle kinetic energies and masses were derived from these quantities. For accelerated microspheres charge is roughly proportional to surface area, and mass is proportional to volume, leading to a $v \propto r^{-1/2}$ relationship. As a result, smaller particles with less charge were accelerated to higher velocities than larger particles with more charge. Microparticles typically were accelerated to 2–5 km/s, although several particles above 10 km/s were observed.

[17] Spectra were recorded using a 150 MHz digital oscilloscope, triggered by the MCP signal. Several hundred impact spectra were recorded. During the experiments, a large number of particles struck the dust analyzer and triggered the recording electronics, but had too small a charge to be detected by the cylinder electrodes in the accelerator flight tube. Nonetheless, most of these particles generated interpretable mass spectra.

4. Results

[18] Figure 5 shows spectra typical of those acquired from microparticle impacts on the dust analyzer. Peaks frequently appearing included singly charged hydrogen, carbon, oxygen, sodium, potassium, and iron. Tantalum and tantalum oxide ions appeared in many spectra but not those included in Figure 5. Peaks of iron, tantalum, and tantalum oxide ions result from the microparticle and impact plate materials themselves. Sodium and potassium are expected as ubiquitous, readily ionized surface contaminants. The origins of hydrogen, carbon, and oxygen ions are not well understood, although such peaks have been frequently observed in impact ionization experiments by others [*Friichtenicht*, 1964; *Ratcliff and Allahdadi*, 1996; *Roy*, 1975]. It is believed that they result from pump oil or adsorbed gases ionized by electron emission immediately prior to impact [*Austin et al.*, 2003; *Novikov et al.*, 1988; *Sysoev et al.*, 1992, 1997]. The peak at m/z = 27 could be

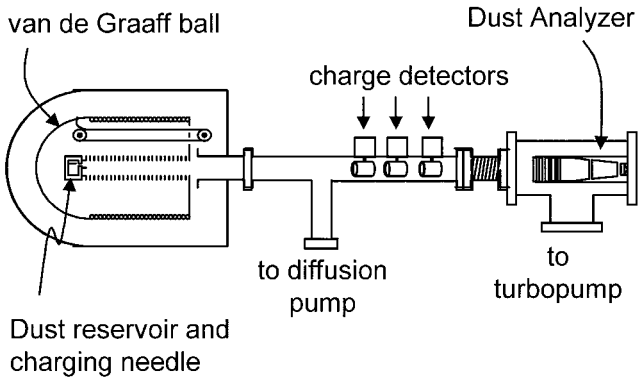

Figure 4. Experimental setup for dust analyzer experiments on the van de Graaff dust accelerator. Particles are charged within the van de Graaff ball, then accelerated onto the dust analyzer. Cylindrical charge detectors within the flight tube measure charge and velocity of accelerated particles.

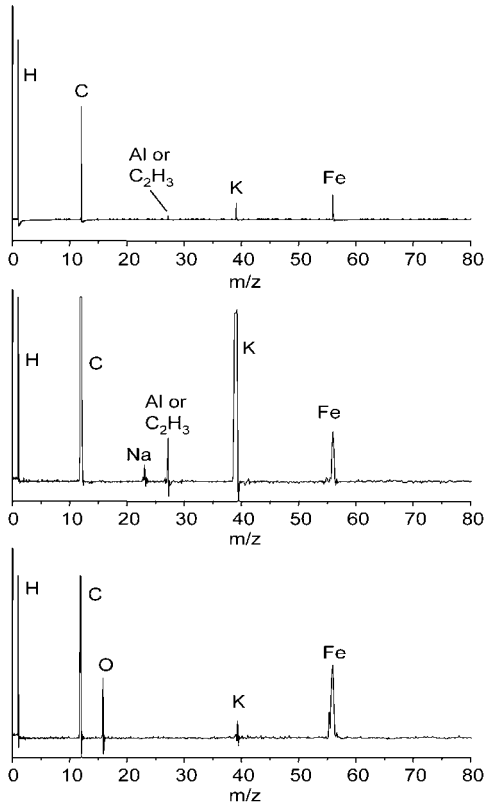

Figure 5. Typical spectra from impacts of accelerated iron particles on high-flux dust analyzer.

$C_2H_3^+$, as has been suggested from other impact experiments [*Ratcliff and Allahdadi*, 1996], but could also be aluminum, which was used in constructing several parts of the instrument. With previous dust mass spectrometers the composition of the dust grains is usually derived from the spectra by comparison with laboratory results rather than by comparison with theoretical models of impact ionization (J. Kissel, personal communication, 2002).

[19] Mass resolution ($m/\Delta m$) in the impact spectra from the dust analyzer is generally high compared with those of other impact ionization instruments. In most spectra, mass resolution exceeds unit resolution for all species, including tantalum and tantalum oxide. In some spectra, the more intense peaks are broadened and have lower resolution, although most broadened peaks are still within unit resolution. Mass resolution ranges from 300–500 for tantalum, 80–500 for iron, 30–300 for potassium and sodium, 30–200 for carbon, and 5–20 for hydrogen. The upper limit of resolution of lighter species (particularly hydrogen) is limited by the speed of the recording electronics. These impact results verify the results of computer simulations and demonstrate high-resolution mass spectra from impact-generated ions on a small time-of-flight instrument.

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