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Cometary and Interstellar Dust Analyzer for comet Wild 2

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[1] The Cometary and Interstellar Dust Analyzer (CIDA) instrument analyzes the composition of individual grains in the cometary coma. As each particle impacts a silver plate, the high-impact energy due to the relative velocity of the spacecraft as it flies through the coma causes the elements and molecular compounds in the particle to become ionized. Using a fast time-of-flight mass spectrometer, a complete set of ions are detected for each impact, from a mass range of 1 (atomic hydrogen) up to a few thousand atomic mass units, encompassing all elements in the periodic table and many molecules, such as organic compounds. This experimental technique has already been applied with excellent success at Halley's comet, and the CIDA derivative instrument is flying on the Stardust mission, which will encounter comet Wild 2 in January of 2004. The data returned will give clues to the elemental and chemical composition of the dust component of this comet. *INDEX TERMS:* 2129 Interplanetary Physics: Interplanetary dust; 2194 Interplanetary Physics: Instruments and techniques; 2199 Interplanetary Physics: General or miscellaneous; *KEYWORDS:* dust mass spectrometer, interstellar and cometary dust, composition, positive and negative ions, instrument description

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1. Introduction

[2] Cosmic grains have been of great interest since the onset of space research, for what they can tell us about the objects which create them. Even small particles can cause considerable damage to spacecraft if they impact at the hypervelocity speeds common in the solar system. From the science standpoint the in situ analysis of the chemical, molecular and in cases the isotopic composition of individual dust particles is of great fundamental relevance to the challenge of elucidating the origins and possible evolution of materials in the solar system.

[3] To date, mass spectrometric data are available for comet p/Halley only, which were obtained from the PUMA 1 + 2 and PIA instruments on the Vega 1 and 2 and Giotto missions, respectively, in 1986. Those flybys occurred at speeds of 68–80 km/s, a regime where atomic ions are predominantly formed upon impact.

[4] Instrumentation to detect the flux, size distribution, velocity and direction of interplanetary (and even interstellar) dust particles is therefore of considerable importance. Since *Friichtenicht and Slattery* [1963] first described impact ionization, instruments for the in situ particle analysis have been implemented in the Helios mission [*Dietzel et al.*, 1973; *Grün et al.*, 1977] and with great success in the missions to comet Halley [*Kissel et al.*, 1986a, 1986b]. Comets are major suppliers of dust to the inner solar system. They may be chemically diverse, not just from comet to comet, but even between different zones of emission on the same cometary nucleus [*Clark et al.*, 1987]. For these reasons, missions to comets should carry dust analyzers wherever practical. The recently detected interstellar component of the dust in the

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solar system is another driving motivation for such instruments. Knowledge of the composition of the dust is an important clue to the source(s) of dust in planetary systems, a strong reason for the addition of a mass spectrometer capability to the successful type of dust detector that is already onboard the Cassini mission [*Srama et al.*, 2003] to explore the Saturnian system. The CIDA instrument on the Stardust spacecraft is a direct derivative of the Particle Impact Analyzer (PIA) instrument flown previously on Giotto [*Kissel*, 1981]. The main objective of CIDA is the analysis of particulates, with emphasis on the organic component. Important ancillary data is expected on dust flux rate, particle size distribution and possibly particle mass densities.

[5] Cometary nuclei are small bodies of ices and mineral grains. They are considered to be least thermally altered since the formation of the solar system. They probably provide the most direct information on the original material from which once the Solar System formed [cf. *Sekanina et al.*, 1998; *Jessberger et al.*, 1999]. This is the main motivation to measure their physical and chemical properties and states as accurately as possible. It is already known that comets contain silicate grains and are rich in smaller organic molecules, but it was not until the Halley missions that it was discovered, using earlier versions of the CIDA instrument, that the particulates contain not only the elements expected in rock-like matter (Mg, Al, Si, Ca, Fe and oxygen) but also an abundance of sulfur, carbon and nitrogen. Complex organics and probably sulfides are present in cometary solid matter at high levels of abundance [*Kissel and Krueger*, 1987b, 1987c]. It is an unanswered question whether all comets are similar, or the same, with respect to their non-volatile dusty components. It is clear that the volatile icy materials can vary significantly. These chemical compositional data are clues to the origin and history of the various cometary bodies, and may help us understand the differences between Oort cloud comets and those from the Kuiper belt. Some scientists are especially interested in the organic materials because the early Earth may have been impoverished in these compounds, yet life somehow became entrenched in that environment. An impact of a comet with a planet could have been the source of key materials needed for the beginnings of life.

[6] As a result of previous experiments of this type, it is clear that comets are highly heterogeneous down to the level of submicron-sized individual dust particles [*Schulze et al.*, 1997]. The goals of CIDA are therefore the analysis of individual particles for (a) overall elemental composition, (b) characterization of the organic component, (c) characterization of the mineralogy, (d) range of elemental ratios, (e) mass and density, (f) volatile element abundance relative to that in the Sun and in CI chondrites, (g) and isotopically light carbon [cf. *Jessberger and Kissel*, 1991] and other major isotopic anomalies. From these measurements we have the potential to draw conclusions on such diverse and important topics as the light element distributions within the coma, the mass loss from ice and CHON particles as a function of distance from the nucleus, and eventually find clues to the existence and nature of very small particles, the so-called "attodust" [*Sagdeev et al.*, 1989; *Utterback and Kissel*, 1989]. The Stardust mission also provides a unique opportunity for long periods of undisturbed measurements ("on-time") it provides an excellent opportunity for the search for and analysis of interstellar dust. For these particles there are the same fundamental scientific objectives as for cometary dust: overall elemental composition characterization of the organic component characterization of the mineralogy; range of elemental ratios mass and density; light element abundance relative to CI chondrites light carbon and other gross isotopic anomalies. A comparison will be possible between interstellar material found in meteorites and comets that formed 4.5 Gyr ago to material that is currently streaming into our solar system.

2. Principle of Operation of CIDA

[7] When a dust particle impacts a solid target at speeds well above 1 km/s, inelastic mechanical deformation of both the target and the projectile occurs. With increasing speed more and more of the particle is vaporized (depending on the target-projectile combination) and above some 15 km/s it is usually completely destroyed. During the impact process, secondary debris (i.e., solid particulates), neutral and ionized molecules, atoms, electrons, and IR and visible light from the target and the projectile are emitted. While the light might be accessible to an optical spectrometer, the charged particles (positive and negative ions) can be influenced by electromagnetic fields and hence be analyzed with an ion mass spectrometer. A charge-sensitive preamplifier is connected to the voltage-biased part of the target to detect transients induced by the charge separation. Its output is compressed in order to accommodate a wide dynamic range, and it works for both polarities, i.e., positive ions, or negative ions and electrons. Figure 1 shows a schematic cross-section of the CIDA instrument.

[8] Accelerated by the electric field in front of the target, the ions travel into the inlet drift tube of a time-of-flight (TOF) mass spectrometer. The accelerated ions pass through an electrostatic reflector which deflects the ions onto an electron multiplier, and at the same time compensates for flight time dispersions due to the intrinsic distribution in initial starting energies of the ions. Amplifiers connected to the multiplier allow the measurement of the time-of-flight spectrum. Biases at the target and multiplier entrance are 1 kV and 1.3 kV, respectively, with the appropriate polarity for either positive or negative ions. The operating voltage for the multiplier is added to this bias.

3. Instrument Layout

[9] CIDA is a space qualified time-of-flight mass-spectrometer. Each impacting particle provides a TOF spectrum which can easily be transformed into a mass spectrum once at least two peaks are found to which well known mass numbers can be assigned. The layout of the device is determined by the size of the target and the desired mass resolution and hence time resolution. While the target size is limited by the size of the ion detector, the time resolution is mostly limited by the instrument electronics. For CIDA we chose a single stage ion reflector, followed by an open electron multiplier, also sensitive to ions, of 30 mm diameter sensitive surface area. The mass resolution of m/dm = 250, or t/dt = 500, that - combined with the requirement of more than 5 samples per mass line - required a frequency of digitization of 80 MHz, which is

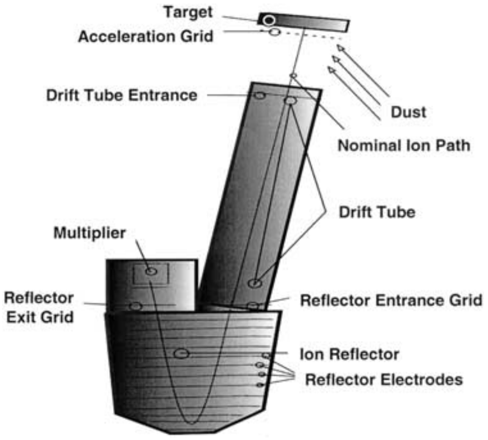

Figure 1. A schematic cross section of the CIDA sensor. Dust particles can enter through the open gap between the target and the first drift tube. On Stardust this gap is covered with a thermal blanket in the area, where access would otherwise be blocked by the spacecraft or the solar arrays. For more explanation see the main text.

split into two interleaved channels of 40 MHz each. The maximum mass to be detected was chosen as 330 Da. With t = a * sqrt(m) and a = 4.457 (where t is in μs, m in Da), it acquires 3060 samples over the range of m = 1 to m = 330 Da. The highest sensitivity is obtained if most ions generated upon impact can be transferred to the ion detector, irrespective of the location of the impact on the target and independent of the distribution of initial energies and angles of the ions. The ion optics of this instrument was designed with the aid of SIMION 6 software by D. Dahl, which allowed us to calculate for each part of the instrument the electric field patterns and then to combine all segments together into one entity. We started with the simulation of the PIA instrument flown on Giotto to comet Halley and then adapted the model to the CIDA case. A significant difference between them is that PUMA and PIA were exposed to 70–85 km/s impacts onto a fairly small target (5 cm^2), while CIDA has to handle two cases, namely 25–55 km/s for interstellar material (ISM) in the form of dust on a rather large target (about 100 cm^2), down to 28, 14, or 6 km/s cometary dust on a smaller target of a few cm^2. While the imaging of an individual impact onto the detector requires a strong lens, the imaging of the whole target area onto the same detector would require a series of lenses. Within the given geometrical, mechanical, and time constraints, we decided not to implement any lenses at all, which in turn led to a quite homogeneous sensitivity over the full target area. Another method converging the ion beam at the reflector output onto the detector was found too late to be implemented. The angle of the detector entrance relative to the ion beam from the reflector was optimized, however, resulting in a considerable improvement of the time (= mass) resolution.

4. Target Design

[10] In optimizing for the two dust populations, interstellar and cometary, the target size had to be chosen as large as feasible to allow for a significant number of detected interstellar particles. A much smaller size is desired to avoid pulse pile-up due to excessive counting rates in the phase of closest approach during comet flybys. For technical reasons a maximum target of 130 mm diameter was chosen. Due to fringe effects of the accelerating electrical field, about 120 mm is useful. The target effective surface area is 86.6 cm^2, projected onto a plane orthogonal to the velocity vector of the S/C. The geometry of the target provides a flat center of 50 mm diameter, while the outer area is inclined by 3 degrees toward the time-of-flight section of the instrument. In order to prevent electrical fields from fringing outside the instrument, the target has been biased while the acceleration grid and the time-of-flight section are electrically grounded with respect to the mounting structure.

[11] When operated during cruise, an interplanetary dust impact rate of the order of 1 particle per week is expected [*Landgraf et al.*, 1999], while the impact rate at comets could reach several thousand per second. In order to cover this wide range of impact rates the size of the active target should be varied by a large ratio. A circle of 30 mm diameter was cut in the center of the target. Accounting for a fringe field region, this results in an effective projected area of about 3 cm^2, allowing us to selectively set the target area by a factor of about 30. The material the target is made of determines the yield of ions released upon particle impact [*Kissel and Krueger*, 1987a]. The ratio of the mass density of the particle to the density of the target material and the impact speeds are critical parameters. From previous results, we have chosen silver (Ag) as a reasonable compromise between the case of the high-speed interstellar particles and the case of the relatively low encounter speed for cometary particles, especially for the Stardust flyby.

5. Impact Detection

[12] The impact of a particle can be detected by the signals caused by the emission of light and charged entities. In the instruments sent to Halley, impact events were detected by both these signals as they occurred at the target. This method could not be used for CIDA because the main body of the instrument is located behind the meteoroid protection shield and the target must be fully exposed in order to efficiently collect interstellar flux. Due to its large size and wide field of view, it could not be shielded from the Sun's stray light by a baffle. Therefore the ion detector signal is used to identify an event. This signal is constantly digitized and the data are shifted through a 16 kByte FIFO (first-in, first-out) memory. Two trigger generators with adjustable levels monitor the signal in parallel, one having a fast response, the other responding in a time period equivalent to several mass lines. Once triggered, the data flow is stopped such that one-half of the memory retains that data collected before the trigger and the remainder the data that occur after it, 2 * 8192 * 12.5 ns = 2 ms in total. This is sufficient for the entire mass range even if the spectrum is triggered by H+ ions. The signals generated by cometary dust particles with a size distribution like those at comet Halley [cf. *Mazets et al.*, 1987; *McDonnell et al.*, 1989] require a dynamic range many orders of magnitude, which cannot be dealt with in one single channel. Ions reaching the electron multiplier (Becton Dickinson MM1) release a few electrons. Their number is multiplied by

roughly a factor of two at each dynode. Amplifiers are therefore connected to dynodes # 13, 15, and 20, and provide a fully redundant system. Each channel has a quasi-logarithmic characteristic over 3 decades. The amplifiers at dynodes 13 and 15 serve the low-sensitivity channels. The signal is nominally a factor of 100 smaller than for the dynode 20 or the anode, the exact value of which is determined by the actual high voltage applied to the multiplier. System 1 is formed by the amplifiers at dynode 15 and at the anode; those at dynode 13 and 20 form system 2. Only one system is active at any time, providing low- and high-sensitivity modes for the instrument.

6. Onboard Data Handling

[13] For each event a total of 4 * 8192 bytes is recorded in the high- and low-sensitivity channels. The transmission of the full set of information is possible only during times of low event rates. As the spacecraft penetrates deeper into the coma, the rate of data generation eventually exceeds the telemetry or storage rate, and increasing steps of data selection and/or data compression will be applied. For reasons discussed above, an event is detected in the high-sensitivity channel of the multiplier output. In order to get information on the target signal which is associated with the event, one of the interleaved low-sensitivity channels stores the target signal until the event is triggered.

[14] In addition to this time-of-flight ion data, a complete set of housekeeping data, describing the status of the instrument, is collected. These two data sets are merged into an experiment data frame (EDF). For technical reasons some of the housekeeping data is spread out over several EDFs by multiplexing slowly varying data into adjacent data frames. The assembled EDFs are then either passed directly to the telemetry buffer of the instrument computer or are first compressed and then placed in the buffer. The buffer is asynchronously passed on to the spacecraft data handling system.

[15] The onboard data handling system has been optimized for two separate operation modes: the cruise mode and the encounter mode. In the cruise mode, the expected event rates are so low that complete sets of data may easily be transferred to ground. In the encounter mode, to be used during comet flybys, the impact-driven data rate would essentially saturate the instrument and the spacecraft's allocated data storage for CIDA of 200 Megabits on Stardust. Therefore, in this mode the instrument data handling optimizes the size of the data passed to the spacecraft and attempts to discard all events obviously not containing meaningful data. In order to check the performance of the selection process, every 16th triggered event is transmitted unaltered, regardless of its contents. Every triggering event is counted, but only a subset of data can be transferred to the spacecraft.

[16] Identifying a particle impact is a complex task containing several sub-tasks. When the instrument is turned on, the outputs of the high- and low-sensitivity channels are continuously digitized at 80 Mega-samples/s and written to the 8 kByte FIFO memory. Whenever the signal exceeds the values put into either one of two hardware registers by the processor, the hardware freezes the data in the FIFO after 4096 more samples, injects a set of calibration signals directly into the amplifiers and alerts the instrument computer. One of the two trigger levels compares directly with the high-sensitivity channel output, while the other has a 10 μs integration time constant, intended to react to the signature of several mass lines only. In order to check out the instrument, the calibration signals can also be triggered deliberately, and this way serve as test pulses. Once alerted, the processor transfers these data into its working memory and enables data acquisition again. The processor scans the data and computes a "feature vector" representing a very crude spectrum by essentially low-passing and resampling the data into a 14 element vector. This vector is then compared to the level of the spectrum background, to positions and sizes of the peaks. On this basis it is determined if the event is accepted for transmission to ground. Once accepted, the data are transferred to the telemetry buffer of the instrument either directly or after compression by a wavelet or Rice algorithms.

[17] The telemetry buffer is asynchronously read by the spacecraft in packets. During comet encounters, when the data rate is too high for direct transmission to the ground, and its time-profile is unpredictable, the instrument, on the basis of the comparison of the actual event fluence and a predetermined profile, instructs the spacecraft to store its data at the beginning of one of 8 memory segments. With this method the goal is to achieve a more statistically even coverage by dust-samples of the entire comet flyby. After a timemark for closest approach, the measurement of negative ions is enabled.

7. Instrument Control

[18] The instrument is controlled by a microprocessor and its software. This is necessary as during the comet flyby the signal round trip time would not allow control from the ground. The software of CIDA has been programmed in C and where necessary in Assembler language for critical routines in order to achieve the efficiency and throughput needed. See Figure 2 for a block diagram.

[19] The software has one main loop which takes care of instrument control, data generation and Experiment Data Frame (EDF) assembly. This loop can be interrupted by new events (e.g., incoming dust particles), and by spacecraft communication cycles. All data generated are placed in a buffer, which then is read by the spacecraft during spacecraft communication cycles. When an event has been detected a flag is set, indicating the availability and amount of new data. Next, control is returned to the main loop to read the FIFO. After reading the data out to the spacecraft, the flag is cleared and the instrument is ready to receive new data.

[20] The FIFO is organized in four parallel channels: for the high- and low-sensitivity dynode outputs of the ion detector, each of which is actually split into two time-interleaved channels. The four data streams are high sensitivity, high sensitivity delayed, low sensitivity, and low sensitivity delayed. These data sets can be saved entirely, or the actual spectrum can be located within them. The actual spectrum may require only about a quarter of the space available in the FIFO. During the comet encounter, every 16th FIFO readout is saved entirely unaltered, and the rest of the readouts are searched for meaningful spectra.

[21] A spectrum is found in the following way: 14 sums of 512 points each are calculated from the high-sensitivity

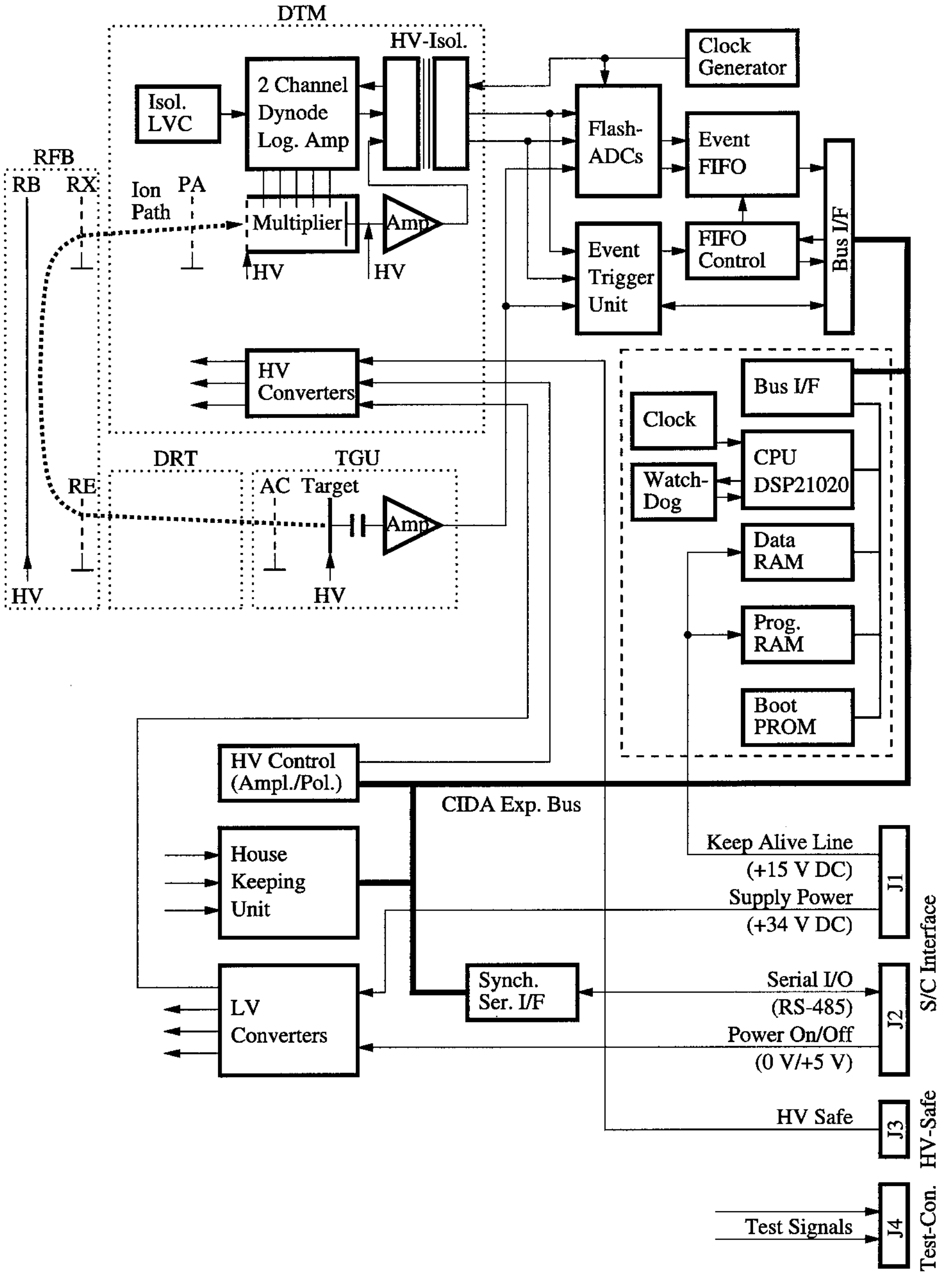

Figure 2. Block diagram of the CIDA electronics. During normal operation the instrument is continuously running and passing data from the flash ADCs through the "first-in-first-out" memory until this process is stopped by the event trigger. After triggering, the data are checked, compressed, formatted and sent to telemetry. For more explanation see main text.

channel. The value of the lowest result in a bin is subtracted from all the other bins. Those bins then above a certain threshold are considered to be above noise level. At least three of them in a row (111 rule) or at least two in a row and one apart to the left (1011 rule) or to the right (1101 rule) are considered to indicate a valid spectrum. If a spectrum is found in the high-sensitivity channel, the corresponding range is also extracted from the other high channel. Within this range, the subrange between the leftmost and the rightmost peaks exceeding a certain threshold are extracted from the low-sensitivity data. After the extraction of the spectrum the channels are packed separately with a modified Rice compression. Next, the EDF is assembled by adding the header containing the instrument status and housekeeping data, the spectrum, and a checksum. The readied EDF is then transferred to the telemetry buffer and eventually to the spacecraft memory.

8. Laboratory Results

[22] The CIDA instrument has been extensively tested in the laboratory. The goal of these tests was to ensure that the instrument performs as well as expected, with the mass resolution and sensitivity as the main objectives. In addi-

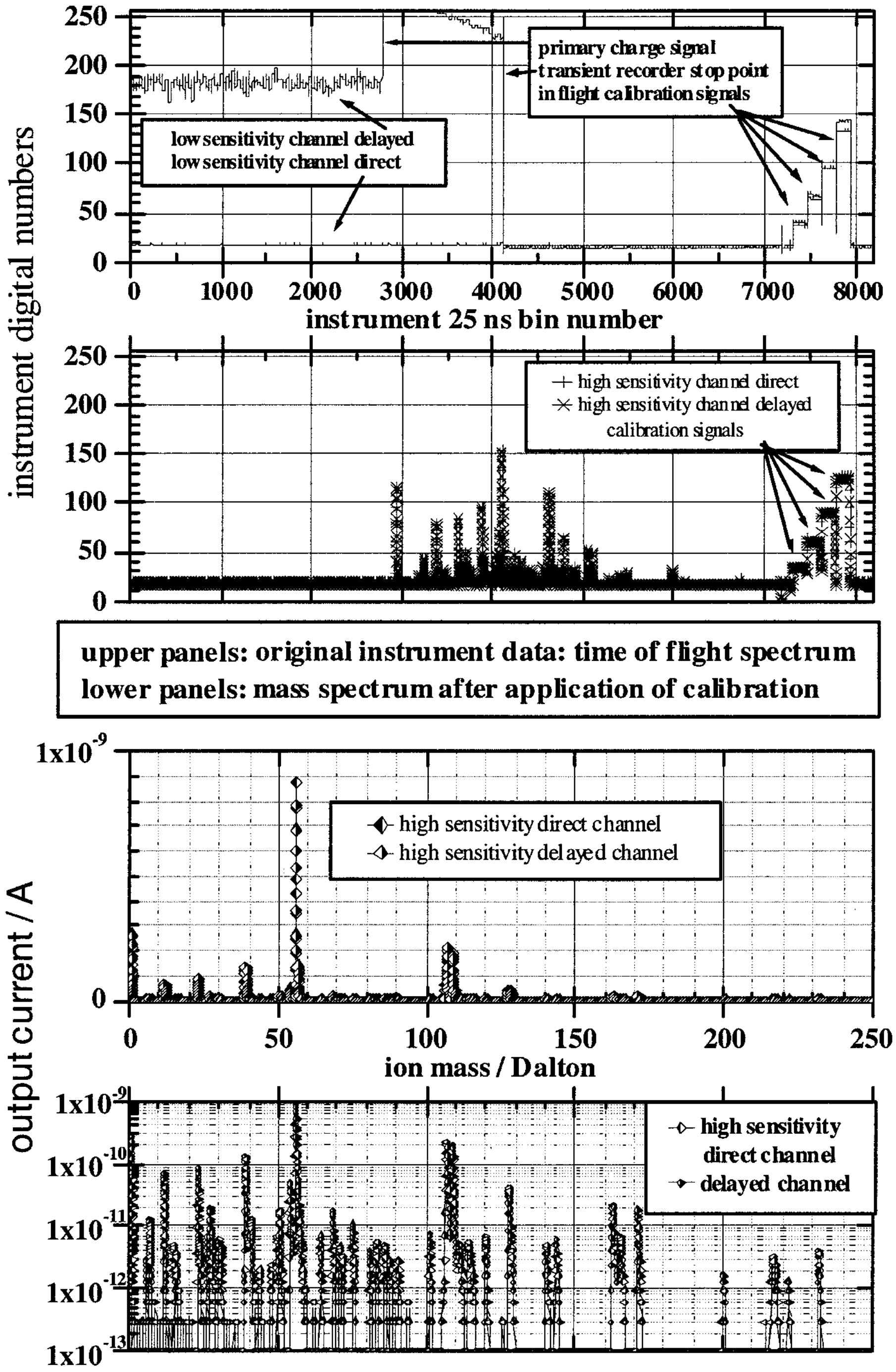

Figure 3. Data for one single iron particle impact at about 10 km/s in the Heidelberg dust accelerator laboratory: The top two panels show original CIDA output data. The lower two panels show the same data after amplitude conversion into physical units using calibration data, and the calculation of the mass scale. For more details see the main text.

tion, software functionality was tested and refined. The main experimental limitation was that due to technical reasons (requirement for smooth, small conductive particles to be electrically charged) only iron particles could be used.

[23] The instrument was mounted in a vacuum chamber of the dust accelerator at the MPK/Heidelberg. A wide range of dust speeds were used (4–40 km/s). For a number of spectra, very accurate records were kept of the charge and speed of the individual particles. For other cases spectra were recorded without these details, in order to obtain a statistically significant sampling of spectra. The instrument was mounted in such a way that it could be slightly moved and tilted. This made it possible to calibrate the entire target area.

[24] Some 20,000 events (spectra, test triggerings, spurious triggerings, etc.) and about 13,000 real spectra have

been recorded during these tests. Spectra are designated using a naming convention which unambiguously gives the event time as the file name. The recorded data are time-of-flight spectra, i.e., a record of ion intensity versus time. Signal strength is quasi-logarithmic because of the electron multiplier behavior and the design of the amplifiers.

[25] Each recorded TOF spectrum contains essentially 4 independent measurements of the TOF signal. Additionally one of the channels has been multiplexed so that a target signature has been inserted, seen as the high-amplitude signal top left in Figure 3. The time of incidence on the silver target can be directly identified as a step in the target signal. This signature is quite variable and cannot as a routine be used as a triggering time indicator. Instead the spectral features have to be analyzed by, e.g., a cross-correlation technique like the one in panel 2 of Figure 3. The cross-correlation between a simple model spectrum and the measured spectrum shows up as a significant single maximum, indicating directly the delay time between the nominal triggering position at channel 4096 and the actual event.

[26] At the end of the recording, a calibration signal is injected. This stair-case signal has been calibrated by measuring actual current pulses from a signal generator connected to the instrument input. Knowing these current pulse values, the spectrum amplitude readings may be converted into a physical ionic charge value.

[27] In the 3rd and 4th panels of Figure 3, the calibrated mass spectrum is shown for one particular particle as a linear (panel 3) and as a logarithmic plot. Only one signal channel is used to show as clearly as possible the basic performance of the instrument. The mass resolution dm/m at mass 12 exceeds 100, but is not representative because of the small amplitude. The Ag-isotopes at 107 and 109 Da are well resolved. During the calibration experiments, it has been noted that spurious peaks in some cases are observed in the mass range between 1 and 12 Da. These can be interpreted as consequences of fragmentation of molecular ions near the target. [cf. *Standing et al.*, 1989].

[28] The tests were performed at the dust accelerator facility at the MPI in Heidelberg. The Instrument itself was mounted in a vacuum chamber, which was then evacuated and opened to the dust accelerator, simulating the correct impact angle of particles on the target. First, signals of the impacting particles were seen from the target-amplifier. For the subsequent tests, two kinds of particles were selected: particles with speeds of 5 km/s, simulating cometary dust; and particles with more than 15 km/s, simulating interstellar dust. Iron microspheres were used because the electrostatic accelerator requires electrically conductive material. The spectra of the two different particle speeds also differed significantly. A typical spectrum of a particle with 5 km/s showed mainly the elements Na, K, Fe, and Ag, whereas a spectrum obtained by higher particle velocity showed H, C, O, Cr, Fe and Ag. This difference can be explained by the much higher velocity of the second kind of particles, where the much higher impact energy ionizes even light elements like C. With lower speeds the ions found are easily ionizable elements like Na, as well as both Fe from the particles and Ag from the target. For details, see *Kissel and Krueger* [1987a]. During the second session of function tests, the ability to detect negative ions was tested. The instrument performed well at both velocities. Main peaks found in the spectra where first the electron peak and then elements like O and Cl. For first results, see *Kissel and Krueger* [2001].

9. Discussion

[29] The CIDA instrument on the Stardust comet mission will provide new data sets that can be compared with earlier measurements at p/Halley, greatly expanding our knowledge of the compositional nature of cometary particulates. A copy of this instrument, CIDA II, was hosted on the CONTOUR mission spacecraft which, up until it was lost in August 2002, was on a planned flyby encounter with two comets, Encke in November of 2003 and Schwassmann-Wachmann III in June of 2006. The ground truth measurements that will be available from post-flight analyses on grains recovered by the Stardust sample return mission will allow a correlation with results obtained in situ by TOF-MS in CIDA at the flyby velocity of 6.1 km/s, and was to have been further used to cross-calibrate results from the CONTOUR flybys of two of more other comets.

[30] **Acknowledgments.** The two CIDA instruments were developed, built, flight qualified and delivered by the company von Hoerner & SulgeR GmbH, (vH&S), Schwetzingen, Germany, with the following contributions: part of the mechanical hardware, calibration, science support and environmental testing from MPE and MPK, Germany; part of the low voltage converters from IAS/CNES, France; some electronic parts from JPL, USA; some design support by a US Co-I funded by NASA, USA. The prime contracts to vH&S came from DARA, Germany with additional funding from MPE, Germany (Stardust project) and from APL, USA (Contour project). Software, GSE, and operational support was performed for both projects by the FMI, Helsinki, Finland and development of the data acquisition unit by LMT, Wuppertal, Germany, under subcontracts to vH&S. Spacecraft, operations, instrument accommodation and software for real-time data updates were performed by Lockheed Martin Astronautics for the Stardust S/C and by the Applied Physics Laboratory for the CONTOUR S/C. Without the personal efforts, overtime, and support of many individuals these two projects could not have been completed.

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