TOOLS FOR

DUST ASTRONOMY

CASSINI AND BEYOND

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Location

The Max-Planck-Institut für Kernphysik in Heidelberg, Germany
Der Beschleuniger
The Laboratory
<table>
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<tr>
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Figure 1: Different observation methods are necessary in order to cover the entire size range of micrometeoroids. Crater investigations of lunar rocks provided a broad overview of the entire dust mass range.
DUST ASTRONOMY ADVANCES

• You get dust dynamics (trajectories, orbital parameters)

• You measure local densities (not integrated along LOS)

• You measure dust charges

• You measure more sensitive (in threshold and number density)

• You measure dust composition (spatially resolved)

• You measure mass distribution

• You measure distant worlds by remote-in-situ analysis (look into moons and look into stars)
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- You get dust dynamics (trajectories, orbital parameters)
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EXAMPLES
(CASSINI CDA)
Cosmic Dust Analyser (CDA)

Dust detector on Cassini spacecraft:

- **dust mass/velocity**: impact ionisation detector
- **chemical composition**: time of flight mass spectrometer
- **dust charge/velocity/impact angle**: charge sensitive entrance grids
- **high rate detector (HRD)**
CDA measurement range

- Sensitive area: 0.1 m²
- Dust speed: 1-100 km s⁻¹
- Dust mass: $10^{-15}-10^{-9}$ g (@20 km s⁻¹)
- Dust charge: $10^{-15}$ - $10^{-13}$ C
- Dust composition: 20-50 mass resolution
- Impact counting rate: 1/week-10000/s
  1000 times more sensitive than optical measurements

CDA finds one particle within one km³
Raw data IID impact

13 Rs, 11° lat
Raw data CAT impact

2008-015T15.05.55

6Rs, 40° lat

QP

Q [pC]

-0.5
0.0
0.5
1.0

Time [μs]

0
-50
-100
-150
-200

QP

Q [pC]

-0.5
0.0
0.5
1.0

Time [μs]

0
-50
-100
-150
-200

QM

QM [μV]

-50
0
50
100
150

Time [μs]

0
2
4
6

QM

QM [μV]

-50
0
50
100
150

Time [μs]

0
2
4
6

Q [pC]

-0.5
0.0
0.5
1.0

Time [μs]

0
10
20
30
40
50

Q [pC]

-0.5
0.0
0.5
1.0

Time [μs]

0
10
20
30
40
50

Q [pC]

0
20
40
60

Time [μs]

0
50
100
150

Q [pC]

0
20
40
60

Time [μs]

0
50
100
150

Q [pC]
Compare: Model and CDA in-situ data

Angle between Dust sensor boresight and Dust RAM varies with time (S/C rocking mode)

Cassini distance to Saturn: ~ 8.2 Rs

Dust impact rate onto CDA: Modelled / observed
E ring dynamics

Dust eccentricity and semimajor axis for a given time (CDA pointing)
6 particles in interplanetary space (0.8 – 4 fC)

Apr. 2007
Recent impact with high primary charge

15 fC
21 Rs 5° lat

QP Signal

QP [fC]

Time [μs]
LOW DETECTION THRESHOLD (NANODUST)

Raw data stream particle

18Rs, 35° lat
Dust detection threshold

\[ T = b \cdot v^m \]

- \( b = 3.037 \times 10^{-13} \)
- \( m = -3.752 \)

Impact speed \( v \) [km/s]
- Mass threshold \( T \) [kg]
- Particle detection area
- No particle detection
- Stream particles
- E ring grains
- Particle diameter 2500 kg/m^3 [nm]
CASISNI/Huygens measures the volcanic ash of the Jupiter moon Io

Mass spectrum of a dust particle

speed approx. 300 km/s
radius approx. 10 nm

dust particles

Grain speeds ~ 300 km/s
Grain sizes ~ 10 nm
Composition: sulphur, sodium, silicates?

CASSINI

JUPITER

IO

volcano on Io

COSMIC DUST ANALYZER
CDA Science Highlights I (Cruise)

- Streams of nano-dust from Saturn: Discovery, composition and dynamics, coupling between CIRs/CMEs and dust stream dynamics (S. Kempf, Nature)

- Origin of particles detected during the approach to Saturn is the A ring

- Composition of these particles: silicates
SIMULATION OF ESCAPING DUST STREAMS FROM SATURN (M. HORANYI)
Where do the stream particles originate?
Modelling Stream Particles
Backward tracing of one stream particle impact

Possible Source Region

Origin?

Points show solution of one stream particle impact.
- color = speed
- size = inclination

Slower grains started either from regions with greater distances (10 Rs) or they are large.

Particles can be as small as 3 nm.
E ring particle composition

- dominated by water ice clusters
- water cluster ions \((H_2O)_xH^+\) with \(x\) up to 12
- Some Na, Si, C, Mg
- J. Hillier, F. Postberg
- Two populations:
  - pure water ice (source=moon surfaces)
  - water ice + silicate (source Enceladus interior?)

Time-of-Flight spectrum of the impact of an E ring particle
Example: Measure low number densities

Derived dust density in equatorial plane, 5 to 18 Rs
High uncertainty inside 6 Rs and outside 16 Rs
Comparison: Optical measurements

The E-Ring
NEW CALIBRATION ONSET
(MITIGATE ACCELERATOR BIAS)

• No law of $Q \sim m^a v^b$

• Use hyperplane fit to phase space of $v, Q, m$

• reduce order to ensure monotonic

• cover entire speed, charge, mass range
Figure 3.12: Overview of the speed and mass range of the dust grains used for calibration and provided by the dust accelerator. The data from M4 Stubig and R4 Srama were merged to total number of dust impact. Left: Dust charge and dust mass. Dashed lines indicate particles with a constant speed of $40$ km/s, $20$ km/s, $10$ km/s, $6$ km/s, and $2$ km/s. Right: Dust mass and dust speed. Dashed lines indicate the physical limits of a minimum dust charge which is detected by the accelerator electronics of approximately $0.7$ nC, and the maximum charge a grain can carry on its surface, which is limited due to field emission limit of $\approx 0.07\pm0.02$. In principle, $0.77$ nm sized grains would reach $0.77$ km/s or higher speeds, but such tiny grains cannot be extracted from the dust source due to clustering and their high adhesive forces. Only dust grains with a solid and hard surface, which are not too small, can be extracted and accelerated (Stubig et al., 2007). It is also obvious from Eq. 407 that faster grains are generally smaller than slower ones if their surface charge is identical. The mass range of dust grains given at a constant speed is determined by the amount of surface charge which is limited to the bottom by the sensitivity of the dust accelerator electronics and to the top by grain charging is limited due to field emission. Typical impact energies are only $0.7$ nJ and rather low, but already sufficient to generate enough impact charges for impact ionisation instruments. It has to be stated, that each of the points in the diagrams of Fig. 40 and Fig. 40 do produce a self-triggering signal at the CDA instrument. But this means, that the dust mass range offered by the accelerator is wider, specifically to lower speeds. There are of course low-speed grains which did not produce a sufficiently high signal on the CDA channels. The flight unit of CDA onboard Cassini, however, operates with a lower detection threshold than the flight spare unit in the laboratory. This behaviour was surprising and it was caused by the electrical noise in the dust accelerator laboratory. The electrical and electromagnetic noise onboard Cassini is better than in our accelerator.
3.3 Calibration Overview

Figure 3.12: Overview of the speed and mass range of the dust grains used for calibration and provided by the dust accelerator. The data from M4 Stubig and R4 Srama were merged to total number of -7/ dust impact. Left: Dust charge and dust mass. Dashed lines indicate particles with a constant speed of -7 km/s. Right: Dust mass and dust speed. Dashed lines indicate the physical limits of a minimum dust charge which is detected by the accelerator electronics of approximately 0 fC and the maximum charge a grain can carry on its surface (field emission limit of \( \approx 0 \cdot 07 \cdot 07 \cdot 07 \)) of the grain which is higher for small particles. In principle, 0.7 nm sized grains would reach 0.77 km/s or higher speeds, but such tiny grains cannot be extracted from the dust source due to clustering and their high adhesive forces. Only dust grains with a solid and hard surface (the extract limit as roughly at 0.7 nm) can be extracted and accelerated [Stubig et al., 2.770].

It is also obvious from Eq. 407 that faster grains are generally smaller than slower ones if their surface charge is identical. The mass range of dust grains given at a constant speed is determined by the amount of surface charge which is limited to the bottom (by the sensitivity of the dust accelerator electronics) and to the top (grain charging is limited due to field emission). Typical impact energies are only 0.7 nJ and rather low, but already sufficient to generate enough impact charges for impact ionisation instruments. It has to be stated that each of the points in the diagrams of Fig. 40 and Fig. 40 do produce a self-triggering signal at the CDA instrument. But this means that the dust mass range offered by the accelerator is wider, specifically to lower speeds. There are of course low-speed grains which did not produce a sufficiently high signal on the CDA channels. The flight unit of CDA onboard Cassini, however, operates with a lower detection threshold than the flight spare unit in the laboratory. This behaviour was surprising and it was caused by the electrical noise in the dust accelerator laboratory. The electrical and electromagnetic noise onboard Cassini is better than in our
Figure 3.13: Kinetic energy, mass, speed and particle diameter of the dust grains used for calibration. The dashed lines indicate constant impact speeds of 40, 20, 10, 6, 2 km/s.

The largest grains reached approximately 100 µm and were mainly out of aluminium. The symbol colors are black (iron), red (aluminium) and blue (latex). Only submicron grains were detected by CDA above 0.0 km/s.

For calibration the dust particle parameters speed, mass, charge, composition, impact angle and impact position on the target are important. These parameters are easily calculated or measured during tests in the accelerator laboratory. The aim in calibration is the determination of dust speed and mass, which depends on the impact location. Without the knowledge of the impact location on the target, no speed and mass determination is possible.

As described above, the instrument contains a large target (IIT), a small target (CAT) and further mechanical structure like the inner housing, the multiplier mounting made out of aluminium and the entrance grids (1 grids with a transmission of \(-\gamma\) each). The determination of the impact location from the impact signals alone is by far not trivial and extensive studies were performed in Srama [000b] to find conditions and constraints for a safe impact location determination, which is, in the first step, the separation of CAT impacts from IIT impacts, assuming already the recognition of wall and structure impacts. For a target impact both signals have to be present, the target signal (either QT or QC) and the ion grid signal (QI). For larger impacts a clear multiplier signal is also in coincidence (compare e.g. Fig. 8.8). The best criterion found to determine the impact target was the ratio between the target signals QT and QC. An impact on the large target (QT) should cause only a small signal at the adjacent target (QC) and vice versa (Fig. 8.8).

But even this simple consideration surprises with its physical nature. Even for an IIT impact, the signal of the adjacent target (QC) can be significant. The best criterion found to determine the impact target was the ratio between the target signals QT and QC. An impact on the large target (QT) should cause only a small signal at the adjacent target (QC) and vice versa. The best criterion found to determine the impact target was the ratio between the target signals QT and QC. An impact on the large target (QT) should cause only a small signal at the adjacent target (QC) and vice versa.
Figure 3.13: Kinetic energy, mass, speed, and particle diameter of the dust grains used for calibration. The dashed lines indicate constant impact speeds of 5, 10, 20, and 40 km/s. The largest grains reached approximately 3 μm and were mainly out of aluminium. For calibration, the dust particle parameters speed, mass, charge, composition, impact angle, and impact position on the target are important. These parameters are easily calculated or measured during tests in the accelerator laboratory. The aim in calibration is the determination of dust speed and mass, which depends on the impact location. Without the knowledge of the impact location on the target, no speed and mass determination is possible.

As described above, the instrument contains a large target (IT), a small target (CT), and further mechanical structure like the inner housing, the multiplier mounting made out of aluminium, and the entrance grids (up to grids with a transmission of -y each). The determination of the impact location from the impact signals alone is by far not trivial and extensive studies were performed to find conditions and constraints for a safe impact location determination, which is, in the first step, the separation of CT impacts from IT impacts assuming already the recognition of wall and structure impacts. For a target impact, both signals have to be present, the target signal (either QT or QC) and the ion grid signal (QI). For larger impacts, a clear multiplier signal is also in coincidence (compare e.g., Fig. 3.18).

The best criterion found to determine the impact target was the ratio between the target signals QT and QC. An impact on the large target (QT) should cause only a small signal at the adjacent target (QC) and vice versa (Fig. 3.18). But even this simple consideration surprises with its physical nature. Even for an IT impact, the signal of the adjacent target (QC) can be high (Fig. 3.18). Here is the problem.
Solve empirically: introduce artificial calibration points

Figure 3.15: Charge over mass ratios for CAT impacts (top) and IID impacts (bottom). The curve is biased by the selection rule of the dust accelerator and the used particle sizes in the dust source during the calibration tests. The fit by a linear function is not proposed, but individual tabulated values (blue). The dent in the middle of the lower two plots are attributed to a change of the impact ionisation process: Lower speeds produce impact ejecta, higher speeds do not generate impact ejecta. The blue symbols outside the clusters are speculative but are introduced to achieve monotony and continuity. The values shown are valid for iron projectiles only and are listed in Tab. A.1 and Tab. A.2 in chapter A.4.
3 Cosmic Dust Analyser Performance

The total ion yield is higher since the target ions contribute the majority of the ions. The different line colors and styles indicate different projectile materials, explained in the legend. The dotted black line is a theoretically calculated charge yield that takes into account the formation of cluster ions.

3.4 Impact Ionisation Detector Calibration

The voltages were carefully set to the lowest values providing the best results. The (35 V of the IID were selected based on former results of the Galileo detector design. This voltage was set to the lowest value which is enough to collect the entire impact plasma charge of a micron sized dust particle impact in the common speed range $\approx \, \text{km/s}$. However, very large grains or impact speeds of the stream particles of more than $\, \text{km/s}$ generate ions and electrons of higher energies, which can escape from the electric field and are not collected at the target or the ion grid.

The situation for CAT impacts is a bit different. Here the very strong field ensures the collection of all electrons as long as the field is effective. A dense impact plasma as obtained by, e.g.,...
In our case, fits with a maximum degree of two are sufficient to fit the data accurately and the function \( f(x, y) \) is nothing else than our dust mass. Since this method is new, some details will be given on how the data in the phase space was processed.

For the dust mass calculation, we need the impact speed \( v \), and mass \( m \) is used to fit the dimensional data set. The function determines a polynomial fit to a surface and returns a parameter array.

The hyperplane function is defined as:

\[
\sum_{i=0}^{n} a_i x^i y^j = 0
\]

This simple model is well established. The larger the dust grain, the more impact charge is generated directly with the dust mass, whereas the speed has a stronger dependency with exponents for higher impact speeds.

The relationship between the impact charge \( Q \) which exceeds the gain in kinetic energy. Since the default speed exponent is \( 3 \) and \( y \) is the impact charge

\[
\frac{Q_T}{v^{3.5}} = 4751 \cdot m^{1.30} \implies m = \frac{Q_T^{0.769}}{672 \cdot v^{2.69}}
\]
HOW TO SOLVE?

• Generated charge $Q$ is function of impact speed $v$

• Generated charge $Q$ is function of projectile mass $m$
of degree \( n \) to a surface and returns a parameter array \( k_x \). The hyperplane function is defined in Eq. 3.19:

\[
    f(x, y) = \sum_{i,j=0}^{n} k_{j,i} \cdot x^i \cdot y^j
\]

(3.19)

In our case, fits with a maximum degree of two are sufficient to fit the data accurately and the simplified formula uses only six parameters (Eq. 3.20):

\[
    f(x, y) = k_0 + k_1 \cdot y + k_2 \cdot y^2 + k_3 \cdot x + k_4 \cdot x \cdot y + k_5 \cdot x^2
\]

(3.20)

The function \( f(x,y) \) is nothing else than our dust mass \( m \) (in kg), whereas \( x \) is the impact speed \( v \) (in km s\(^{-1}\)) and \( y \) is the impact charge \( Q \) (in C). Before applying the fit formula, we have to take the logarithms of the values of \( v \) and \( m \). Then, the impact charge \( QT \) of IIT

\[
    \log(m_{QT}) = 10.02 + 2.943 \cdot \log(QT) + 0.0941 \cdot (\log(QT))^2 - 5.133 \cdot \log(v) - (3.21)
\]

\[
    0.135 \cdot \log(v) \cdot \log(QT) + 0.0614 \cdot (\log(v))^2
\]
3.4 Impact Ionisation Detector Calibration

Figure 3.21: Two views of the fitted hyperplane of QT calibration data of IIT impacts (red symbols). The axis $[x,y,z]$ are $v$, QT, $m$ and only iron particles were considered. The blue symbols are the projected data points onto the hyperplane.

$z = \log(\text{mass})$

$y = \log(Q)$

$x = \log(v)$

red lines : $v=\text{const.}$
3.4 Impact Ionisation Detector Calibration

Figure 3.21: Two views of the fitted hyperplane of QT calibration data of IIT impacts (red symbols). The axis $[x, y, z]$ are $v, QT, m$ and only iron particles were considered. The blue symbols are the projected data points onto the hyperplane.
Figure 3.22: Histogram of the ratio $f/y$ with $f = \text{calculated dust mass by fit-function}$ and $y = \text{m}$. The derived error factor is $1.75$ for iron impacts onto the IIT and the histogram belongs to the data shown in Fig. 3.21.

Figure 3.23: Low dimensional hyperplane approximation of the phase space $\{v, QT, m\}$. The plane slope for $v = \text{const.}$ is always positive as required. The error factor of this fit of $2.42$ is given by the histogram (right).

The same fitting procedure was applied to the ion grid signal and the result is shown in Fig. 3.24. The applied fit range was set to $v = 1.6 - 64 \text{ kms}$, $QI = 10^{15}$, ..., $10^{12} C$ and $m = 10^{-18}$, ..., $10^{-12}$ kg. This fit results in a hyperplane with the maximum degree $n = 2$ for each dimension and the function is given by Eq. 3.26:

$$\log(m QI) = 8.15 + 2.1 \cdot \log(QI) + 0.0439 \cdot \left(\log(v)\right)^2 - 10.24 \cdot \log(v) \cdot 0.497 \cdot \log(QI) + 0.215 \cdot \left(\log(v)\right)^2$$
NOW SOMETHING COMPLETELY DIFFERENT:

DEAD TIME CORRECTION OF EVENT RATES

\[ n = \frac{n'}{1 - n' \tau} \]

true event rate : \( n \)
mapped event rate : \( n' \)
dead time : \( \tau \)

\[ n = 8 \cdot \ln \left( \frac{0.125}{\frac{1}{n'} - 1} + 1 \right) \]

Real case for CDA
Dead time is 8 RTI
1 RTI = 0.125 s
but "RTI grid"
Figure 3.40: Stochastic data set (black histogram) with a maximum at 0.5 Hz and Poisson distribution function (red line). The coincidence verifies the data generation process.
PREPARE FOR DATA RECORDING

• CDA requires high operational efforts

• CDA has to set data rate and POINTING

• CDA has to take care of manoeuvers, telemetry modes, data rates, dead times, operational modes, ...
The Titan atmosphere is not the only danger in this regard. After the discovery of the Enceladus gas and dust plumes at the south pole region, a second hazardous region was found. Which dynamic pressures are now expected at Enceladus plume crossings?

Here a gas peak density of up to \(0.13 \pm 0.43 \times 10^{-44} \text{ kg m}^{-7}\) was measured by the neutral gas instrument and the Attitude Articulation Subsystem in 633, and the flyby speed was, due to the inclined orbit, 4. \(\text{km/s}^{-1}\). However, this provides a dynamic pressure of only 3.134. \(\text{Pa} \pm 0.43 \times 10^{-8} \text{mbar}\).

In contrast to the Titan flybys, the crossing of the Enceladus plumes takes only approximately 83 seconds. On November 633, Cassini goes deeper into the plume and orbit 463x, and higher densities are expected but with a rather low flyby speed of approximately 0.4 \(\text{km/s}^{-1}\). Nevertheless, the high voltage of the Chemical Analyser was reduced during the November 633 Enceladus flyby.

Many tools developed for science planning and operations.
REMINDER:
CDA CAN ARTICULATE
CDA POINTING PLATFORM
OPERATIONS

4.1 Dust Analyser Operations

and are named Science Analyser pointing analysis of directionality compatibility of the CDA boresight and the dust RAM directions. SASF Generator reading project file products and generate the CDA articulation and data rate commanding and SASF Editor comparing Fig. 4, and reading command sequences or project output files and edit or generate CDA command products overview of the CDA articulation profile and the dust RAM directions.

Figure 4.2: Overview of commanded CDA articulation profile in the sequence S54. The plot shows the required CDA articulation angle over time in order to point to various dust targets (small symbols for prograde, red, retrograde, blue, or interstellar dust grains, yellow). The pink line gives the commanded articulation profile. The analysis is based on the spacecraft C.Kernel and the top labels belong to the DOY, distance from Saturn in Saturn radii (yellow symbols) and distance from the ring plane in ktm (blue symbols and black dashed line).

A further important uplink software package is the java-based CDAcommandList tool which reads the command files and checks the project and CDA flight rules like the command timing, high voltage states, dead times and OTMs. In addition, a variety of smaller tools and scripts are used for file handling and information extraction.

The instrument monitoring occurs either in real time (project tools) or by transferring CDA housekeeping data from the project database and the consecutive analysis by self-developed 3 Spacecraft Activity Sequence File standard file format used in the uplink process.
FINALLY:
EVENT RATE MEASUREMENTS

301.0  301.5  302.0  302.5  303.0  303.5
-50    0      50    -50  0  50
CDA - RP

Distance from RP [tkm]

0.001  0.010  0.100  1.000  10.000
DA rate [1/s]

17.1  14.1  11.1  8.1  6.2  7.2  10.0  13.1  16.1
D Sat [R_s]

Figure 4.15: Pointing geometry and dust impact rates for the first inner ring plane crossing of Cassini at Saturn. The top panel shows the angle in degrees between the CDA boresight and the ring plane (black line) as well as the distance of Cassini from the ring plane in units of 0.000 km (dashed blue line). The symbols on the dashed line indicate crossings of different latitudes (circle: 0.0°, diamond: 0.6°, triangle: 1.2°, square: 1.8°). The middle panel shows the angle between the CDA boresight and the dust RAM direction assuming circular prograde orbits. The lower panel shows impact rates based on a flight software classification scheme: red line are class 1 events, blue line are class 2 events, and a black line for all events (see text for details). The red numbers at the top are Cassini's distance from Saturn in units of R_s. The vertical red line labelled 'PER' indicates the time of periapsis and the dashed red line labelled 'RPX' indicates the time of ring plane crossing. The lines labelled R, D, T, E, and M indicate the time of crossings of the orbits of the moons Rhea, Dione, Tethys, Enceladus, and Mimas respectively. The vertical bright blue bars indicate the time periods where CDA was not in a nominal measurement configuration (CDA did articulate, CDA was off or in a standby mode). The detection thresholds of the counters react to impact charges and the particle speed has a dominant influence on the impact charge. The separation between big and small impacts becomes only true by considering a constant impact speed. The measured rates after 00:00(7.0 are based on the classification and onboard processing with flight software version 0808. Here, we define the red curves as the sum of class 1 and class 2 events, which are true dust impacts with a mass threshold of (80^-0.0 - 0.2 kg). Class 1 events describe strong impacts and cover the counters 0, 1, 2, 3, 4, whereas class 2 events are used for medium sized dust impact charges and include the counters 5, 6, 7, 8, 9. The blue curve includes the counters 10, 11, 12, 13, 14 of class 2 which count small dust impacts.
ONE SOURCE FOR NOISE: THE ONBOARD BUS

**HRD rate M**

<table>
<thead>
<tr>
<th>DOY in 2008</th>
<th>0.00</th>
<th>0.02</th>
<th>0.04</th>
<th>0.06</th>
<th>0.08</th>
<th>0.10</th>
<th>0.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>r [1/s]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CDA rate N0**

<table>
<thead>
<tr>
<th>DOY in 2008</th>
<th>0.00</th>
<th>0.05</th>
<th>0.10</th>
<th>0.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>r [1/s]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.6: Correlation of the HRD M1 and CDA event rate with the onboard telemetry mode. The yellow marked areas represent modes of 8-times increased data pickup rates - 1 Hz instead of 0.125 Hz. The proofs, that the Bus Interface Unit of CDA disturbes the sensitive measurements of HRD and CDA.
Time: 2004-155T00:00:00
Distance to Saturn: 252.3 Rs
Angle to the ring plane: -0.3 deg.
Figure 4.16: CDA pointing and dust impact rates at the inner ring plane crossing in orbit B.
Three-dimensional dust density profile along Cassini's trajectory of the ring plane crossing and periapses of orbit 7. Two projections of the density profile are shown on the side panels (black and red curve). The vertical axis gives the dust density in units of \( \log(m^{-3}) \). The maximum dust density measured at this periapse was \( \approx -5 m^{-3} \). Due to dead time correction, the highest dust densities in the inner Saturnian region along Enceladus orbit at 4 Rs are a few particles per cubic metre and are consistent with former modelling work. Surprisingly, the high dust density inside Titan's orbit at 2.5 Rs with altitudes up to 4 Rs (25 km) from the ring plane in the outer region fluxes below \( \cdot m^{-3} \) are measured, interrupted by segments of higher densities of up to \( \cdot m^{-3} \) (green trajectory segments at distances beyond 3 Rs). However, it was shown by the occurrence of mass spectra in the raw signals of noise data that such impacts were caused by much faster grains of Saturnian stream particles with speeds above \( \cdot \text{km/s} \). By using the much lower relative impact speeds of a few \( \text{km/s} \) of bound prograde particles, these dust densities are overestimated by at least a factor of 2. Eliminating Saturnian dust stream particles from the data set (neglecting impacts with small impact charges) leads to another picture of the dust density around Saturn. Uncertainties: detection threshold, dust ram (sensitive area), mass distribution.
Figure 4.26: Dust density distribution around Saturn after the removal of dust stream particles and retrograde particles. The coordinate system used is a Saturn centered J2000 system with the x- and y-axis in the ring plane. Top: Top view; Bottom: Side view.
SATURN’S DUST ENVIRONMENT

Figure 4.26: Dust density distribution around Saturn after the removal of dust stream particles and retrograde particles. The coordinate system used is a Saturn centered J2000 system with the x- and y-axis in the ring plane. Top: Top view; Bottom: Side view.
3D DUST DENSITY
HEAR DUST IMPACTS!
NEW INSTRUMENTATION
NEW MISSION SCENARIOS
Figure 5.8: Design studies of three different Dust Telescopes. Top: TS5LAMA with a target diameter of 6 cm, von Hoerner and Sulger. Bottom left: LEOPARD with a Trajectory Sensor side length of & cm, G. Pahl. Bottom right: SODA with a target diameter of ), cm, V. Schlemmer.

The flight time of the ions in the spectrometer from the target to the MCP are described by Eq. 5.

\[ t = a \frac{m}{q} + b \]

In this equation, \( t \) is the flight time, \( a \) is the stretch parameter, \( m \) is the ion mass, \( q \) is the ion charge, and \( b \) is a constant.
5 New Dust Instrumentation

Figure 5.8: Design studies of three different Dust Telescopes. Top: TS5LAMA with a target diameter of 6 cm (von Hoerner & Sulger). Bottom left: LEOPARD with a Trajectory Sensor side length of 10 cm (G. Pahl). Bottom right: SODA with a target diameter of 39 cm (V. Schlemmer).

The flight time of the ions in the spectrometer from the target to the MCP are described by Eq. 5.6 using the stretch parameter $a$, the ion mass $m$, the ion charge $q$, and a constant $b$.

$$t = a \cdot \frac{m}{q} + b$$
### Table 5.4: Properties and measurement thresholds for three different Dust Telescopes DT (big), LEOP-ARD (medium size) and SODA (small).

<table>
<thead>
<tr>
<th>Property</th>
<th>DT</th>
<th>Leopard</th>
<th>SODA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [kg]</td>
<td>≈22</td>
<td>≈8</td>
<td>&lt;2.5</td>
</tr>
<tr>
<td>Power [W]</td>
<td>&lt;19</td>
<td>&lt;19</td>
<td>≈10</td>
</tr>
<tr>
<td>Area [cm²]</td>
<td>2200</td>
<td>750</td>
<td>240</td>
</tr>
<tr>
<td>FOV</td>
<td>±38°</td>
<td>±50°</td>
<td>±45°</td>
</tr>
<tr>
<td>Datarate [kbps]</td>
<td>1 - 10</td>
<td>0.5 - 10</td>
<td>0.5 - 4</td>
</tr>
<tr>
<td>Dimension m³</td>
<td>0.65×0.65×0.72</td>
<td>0.23×0.23×0.35</td>
<td>0.32×0.37×0.35</td>
</tr>
<tr>
<td>Dust speed [km s⁻¹]</td>
<td>1 - 50</td>
<td>1 - 50</td>
<td>1 - 50</td>
</tr>
<tr>
<td>Dust mass [kg]</td>
<td>1·10⁻¹⁸ - 1·10⁻⁸</td>
<td>1·10⁻¹⁸ - 1·10⁻⁸</td>
<td>1·10⁻¹⁸ - 1·10⁻⁸</td>
</tr>
<tr>
<td>Dust flux [m⁻²s⁻¹]</td>
<td>&lt;1·10⁻⁵</td>
<td>&lt;3·10⁻⁵</td>
<td>&lt;6·10⁻⁵</td>
</tr>
<tr>
<td>Dust charge [C]</td>
<td>3·10⁻¹⁶ - 1·10⁻¹³</td>
<td>3·10⁻¹⁶ - 1·10⁻¹³</td>
<td>5·10⁻¹⁶ - 1·10⁻¹³</td>
</tr>
<tr>
<td>Dust trajectory (1·10⁻¹⁵ C)</td>
<td>±1°</td>
<td>±1°</td>
<td>±10°</td>
</tr>
<tr>
<td>Dust composition $\frac{m}{\Delta m}$</td>
<td>yes, &gt;200</td>
<td>yes, ≈100</td>
<td>yes, ≈100</td>
</tr>
</tbody>
</table>
Figure 5.9: TOF spectra recorded in April 2008 with the small Dust Telescope SODA at the dust accelerator. The projectiles used were coated PMPV latex grains and the target was gold plated. The applied voltages were 2-5 kV (target), 2-7 kV (reflectron grid) and /1-5 kV (MCP) (top spectrum). The target voltage of the right spectrum was higher and 5 kV. The projectile properties were 17-7 km/s (top) and 7-8 km/s (bottom). The mass resolution of this compact spectrometer is $\approx 15$. 

Leopard

Intensity

Mass [amu]

0 20 40 60 80 100

0.0 0.2 0.4 0.6 0.8

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0

11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0

21.0 22.0 23.0 24.0 25.0 26.0 27.0 28.0 29.0 30.0

31.0 32.0 33.0 34.0 35.0 36.0 37.0 38.0 39.0 40.0

41.0 42.0 43.0 44.0 45.0 46.0 47.0 48.0 49.0 50.0

51.0 52.0 53.0 54.0 55.0 56.0 57.0 58.0 59.0 60.0

61.0 62.0 63.0 64.0 65.0 66.0 67.0 68.0 69.0 70.0

71.0 72.0 73.0 74.0 75.0 76.0 77.0 78.0 79.0 80.0

81.0 82.0 83.0 84.0 85.0 86.0 87.0 88.0 89.0 90.0

91.0 92.0 93.0 94.0 95.0 96.0 97.0 98.0 99.0 100.0

schlemmer

Mar1308,14-59-21_d_CH3_03h.wft_small_0-100_155_24_lin

schlemmer

Apr0108,08-30-41_d_CH3_03h.wft_small_0-100_38_10_lin

refmasses= 1 2 2
stretch factor = 1.0356325e-06

6.45E-17kg 0.456 micron

speed km/s= 17.64
• Analysis of the elemental and isotopic composition of individual cosmic dust grains

• Determination of the size distribution of interstellar dust

• Characterisation of the interstellar dust flow through the planetary system

• Analysis of interplanetary dust of cometary and asteroidal origin
• Measurement of dust charges down to $1 \cdot 10^{-16}$ C

• Determine dust trajectories with an accuracy of better than 3% in speed and 3° in direction in order to distinguish interstellar from interplanetary dust by their trajectories

• Analyse the elemental and isotopic composition of individual cosmic dust grains at a mass resolution of $m/dm > 100$

• Characterise the ambient plasma conditions
• Determine the physical properties of individual dust grains
DUNEEXPRESS SPACECRAFT

**Figure 6.5:** DuneXpress bus with two integrated Dust Telescopes (bright green) and three Dust Cameras (yellow boxes). The plasma monitor is mounted at a short boom (yellow box). (Dutch Space)
Table 6.2: Summary of the payload instruments onboard DuneXpress. Combinations of Trajectory Sensors with various impact stages (Dust Cameras, DC) are employed. Two types of Dust Telescopes (DT) provide trajectory and compositional information of impacting interstellar or interplanetary dust grains. Some instruments share a data processing unit (not shown). The total payload mass and power is 56 kg and 95 W, respectively. A further description is given in Grün et al. [2009].

<table>
<thead>
<tr>
<th>Instrument</th>
<th>DT1</th>
<th>DT2</th>
<th>DC1</th>
<th>DC2</th>
<th>DC3</th>
<th>AFIDDD</th>
<th>PLASMON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>LAMA1</td>
<td>LAMA2</td>
<td>PVDF</td>
<td>Piezo</td>
<td>Ionisation</td>
<td>Al film+MCP</td>
<td>Plasma</td>
</tr>
<tr>
<td>Area [m²]</td>
<td>0.05</td>
<td>0.05</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.004</td>
<td>NA</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>15</td>
<td>19</td>
<td>4.9</td>
<td>5.6</td>
<td>8</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>Power [W]</td>
<td>16</td>
<td>25</td>
<td>8</td>
<td>&lt;30</td>
<td>9</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>Size [cm]</td>
<td>44×49</td>
<td>48×48</td>
<td>30×30×34</td>
<td>36×36×29</td>
<td>50×50×23</td>
<td>13×13×2</td>
<td>15×15×15</td>
</tr>
</tbody>
</table>
SARIM

Sample Return of Interstellar Matter

Proposal for Cosmic Vision 2015-2025

May 2009, R. Srama
Future Dust Missions

The ConeXpress generic platform was developed under ESA by a European industrial team led by Dutch Space. The total mission cost was estimated to be below €99M.

This platform makes use of an Ariane 6 adaptor as a primary structure and uses electric propulsion to go within 99 days from GTO to a halo orbit around L.6 L. is preferred over L0 because the spacecraft configuration has the high-gain antenna pointing to the opposite direction than the dust instruments. During downlinks, the instruments point away from the Sun, which is required for thermal reasons.

The orbit geometry is shown in Figure 6.4, which presents the spacecraft bus with the integrated dust instrumentation.

Figure 6.4: Mission scenario of DuneXpress at L2 of the Sun-Earth system. The interstellar dust flux direction, two positions of the Earth and the spacecraft are shown (right: late summer, and left: late winter). The orbital geometry leads to a yearly modulation of the interstellar flux. The corresponding fluxes are $F = 4.5 \cdot 10^{-4} \text{m}^{-2} \text{s}^{-1}$ in winter and $F = 6.6 \cdot 10^{-5} \text{m}^{-2} \text{s}^{-1}$ in summer. Further information can be found in Grün et al. [2009] and Grün et al. [2003].

The S8C mass is 0.99 kg, with two drivable wings of three panels each generating a power output of 0.9 kW. Communication is provided by an omnidirectional S-band and an X-band system that will use a 96 m parabolic antenna reflector. DuneXpress will be 6-axis stabilised using star trackers as primary sensors and reaction wheels for actuation.

DuneXpress will be launched into GTO as an auxiliary payload of an Ariane 6 flight. From there, the perigee will be raised by electric propulsion to 9999 km, the apogee will be brought to 0.6 million km, and the spacecraft will be injected into a halo orbit around L.6 where scientific operation begins. The spacecraft provides pointing of the dust telescope to better than one degree and the measurements will be divided into observation segments of fixed duration from a few days to about 6 weeks. Within each observation segment, the spacecraft will maintain a fixed orientation, while all instruments collect data simultaneously starting 0.
HOW MUCH ISD DO WE GET?

Figure 6.8: Relative impact speeds, particle fluence and cumulated number of collected interstellar dust grains below a threshold speed $v_{thres}$ ($\beta = 1$).
WHAT IS THE EXPECTED RELATIVE IMPACT SPEED?

**Figure 6.6:** Flow of interstellar dust through the Solar System affected by gravity and radiation pressure. A dust mission on an Earth-like orbit observes a variation of the relative grain velocities $\vec{v}_{\text{red}}$, and the collector or Dust Telescope boresight has to be adjusted. Left: radiation pressure dominated grain trajectories $\beta = 1.20$; right: gravity dominated dust particle trajectories $\beta = 0.60$.

**Figure 6.7:** Relative impact speeds of ISD for a DuneXpress-like orbit for different angular distances from the point of periapsis (True anomaly $T$). The colours belong to particles with $\beta = 0.5$ (gravity dominated, big dust grains), $\beta = 1.0$ (radiation force and gravity are equal) and $\beta = 1.2$ (radiation force dominated, reflected by solar radiation pressure).
SARIM – Sample Return of Interstellar Matter

Figure 6.9: SARIM payload configuration with seven collector modules. Dust collectors are arranged in a stack mounted in a turn table housing within the front heat shield, which opens and thereby unseals simultaneously with the movement of the front heat shield. Seven dust collectors with a size of 0.00 mm × 0.00 mm × 0.00 mm and a total mass of 0 kg per collector plus supporting structure mechanism and a collector storage housing have to be accommodated within the MIRKA based return capsule. A collector handling system consisting of two linear actuators for vertical movement and a container bridge-like sliding mechanism picks up a single collector for delivery to each of the active collectors.

Nano-particle AFIDD detector and the plasma monitor PLASMON provide complementary information about the environment.

Most of the payload instruments were discussed in previous sections. DTS is explained in 6.6. The Dust Telescope is discussed in section 6.6, and the impact and plasma detectors are introduced in section 6.6.

How do the dust collectors look like and what are they made of?

For deep-space collection of interplanetary and interstellar particles dominated by silicate, sulfide, oxide minerals with very small grains including amorphous, non-crystalline materials, diamond, exotic carbides and nitrides, the ideal collector substrate must not contain...
Preparation of Active Collector development

- Aerogel (10 times cleaner than Stardust) density gradient (2…20 mg/ml ?)
- Foils of „soft“ and „clean“ metals (aluminium)
- 7 Modules, each module is articulated individually to expose the collector during phases of interstellar dust detection.
- Each module has a collective area of 40 cm x 40 cm
Trajectory Sensor developed

Measurement of induced charge of particle primary charge

- Dimension: 40 cm x 40 cm
- Depth: 20 cm
- Sensitive area: 0.14 m²
- FoV half cone: 45°
- Data rate: 1500 bps
- Mass: < 5 kg
- Power: 8 W
- Dust speed: 1 .. 100 km/s
- Dust charge: 0.1 fC .. 100 fC
- Dust mass: 10e-15 .. 10e-8 g
- Dust trajectory: 1°
- Dust composition: N/A
We have tested a Small Dust Telescope
- Combine trajectory sensor and TOF spectrometer
- Dust origin AND dust properties (mass, composition, charge,...)
New: Impact spectra of low-velocity impacts

Dust = Orthopyroxen, 2.5 km/s 0.6 μm
ToF Spectromter : LAMA

May 2009, R. Srama
New dust sample return mission - Increments on STARDUST

★ 10 times sensitive area (collector 0.1 to 1 m²)
★ 10 times sensitive area (spectrometer 0.01 to 0.1 m²)
★ Collection/detection of interstellar dust possible
★ Collection of dust grains in vicinity of small bodies (Hill sphere) – geyser or volcano activity provide a view below the surface
★ Dust grains rich in alkali metals: proof of subsurface-ocean
★ Determine impact time and location of individual impacts at the collector. Determine particle speed and mass of individual grains. We know where to look for particles in/at the collector.
★ Combine with in-situ package (spectrometer/trajectory sensor)
★ Separate interplanetary dust, interstellar dust, moon dust by trajectory analysis
Conclusion

* Targets: interstellar dust, interplanetary dust, dust from asteroid/moon surfaces, dust from moon interiors (detection of liquid water), cometary dust

* Combine dust collection with in-situ techniques, provides impact time and impact location (collector surface), grain mass, grain trajectory!

* Combine collector with in-situ compositional measurement (submicron or fast grains are problematic for collectors)
Univ. Colorado: Dune Mission Proposal (in-situ only)

A proposal submitted in response to NASA SMEX AO NNH07ZDA0030
Principal Investigator
Mihaly Horanyi
Laboratory for Atmospheric and Space Physics
University of Colorado
January 15, 2008

May 2009, R. Srama