Chapter 1

Cosmic Dust and Impact-Ionization Mass Spectrometry

1.1 Cosmic dust

Scattered throughout the observable universe is a great diversity of microscopic particles, known collectively as cosmic dust. Cosmic dust is responsible for such phenomena as zodiacal light, comet tails, extinction of light from distant stars, the transfer of heavy elements from supernovae to emerging star systems, and perhaps even the abiotic synthesis of complex organic molecules [1, 2]. Cosmic dust grains fall into two classifications: interstellar dust and interplanetary dust.

Interstellar dust is generally defined as particulate matter that originates outside of the solar system. Interstellar dust grains are created during a variety of stellar phenomena including supernovae, red giants, and carbon-rich stars [3]. The chemical and isotopic properties of dust grains provide important information about the stellar processes taking place in the environments in which the grains were formed. Because the material making up the Earth and other planets was, at one time, interstellar dust, the chemical and isotopic properties of dust grains provide information about planetary formation processes. Interstellar dust may make up the difference between the observed abundances of elements heavier than helium in the interstellar gas and the assumed cosmic abundances of the elements [4]. A significant fraction of the total galactic mass may be hidden in these optically invisible grains. Interstellar dust flows through the solar system with a speed of 26 km/s coming from the direction of 253° ecliptic longitude and 5° ecliptic latitude [3, 5]. Because cosmic dust grains are electrically charged by photoelectron emission, grains smaller than about 0.1 μm are deflected by the sun's magnetic field, and do not frequently penetrate the solar system [6-9]. Larger grains are frequently seen even as close to the sun as 1 AU [10]. In fact, about 30% of the micron-sized dust reaching the Earth is of interstellar origin [3]. A variety of pre-solar grains have been discovered and characterized from meteorites that have survived impact on the Earth [11], but the bulk composition of the interstellar dust remains unknown.

Interplanetary dust is defined as particulate matter originating within the solar system. This includes cometary debris, planetary rings, man-made debris (frequently encountered in Earth orbit), particles created during asteroid and meteor impacts, and various other local sources. Particles in the size range of 10-100 μm account for most of the light scattering in the zodiac [12]. Most interplanetary dust grains eventually assume quasi-stable orbits around the sun, although radiation pressure, charge and magnetic interactions, and gravitational resonances all complicate their trajectories and lifetimes. The dynamics, distributions, and possible sources of various dust populations within the solar system have been extensively studied [13, 14]. The elemental composition of most solar system dust grains is approximately chondritic, although individual particles may have disproportionate contributions from specific minerals such as magnesium silicates, iron-nickel metal, sulfides, phosphides, or carbonates [15]. For a thorough review of cosmic dust see reference [16].

1.2 Methods for studying cosmic dust

Methods for studying interplanetary and interstellar dust include remote sensing, collection and analysis of dust grains that have survived impact on the Earth, capture and return of dust samples to Earth for study, and *in situ* analysis using instruments on spacecraft. Remote sensing techniques, such as analysis of zodiacal light [16], extinction of stellar emissions [17], and thermal emissions [18], are useful primarily for studying dynamics and distributions of dust populations. Dust grains collected from the Earth environment, including the upper atmosphere, polar ice, and deep-sea sediments, provide information about structure and composition, but these properties may have been altered by atmospheric heating, chemical reactions, or contamination [15]. Sample capture and return, such as that planned for the STARDUST comet fly-by [19], allows in-depth analysis of dust grains by Earth-based laboratories. However, sample return is limited to studying dust relatively close to the Earth, and the collection and delivery of samples poses numerous risks and uncertainties. Finally, dust may be studied directly by *in situ* instruments. Although limited by the low-power and low-mass requirements of space flight, *in situ* dust analyzers have proven useful for determining such properties as composition, mass, charge, distributions, and dynamics of dust at various locations within the solar system. The principal goals of *in situ* analysis are determination of the elemental and isotopic compositions of individual grains, and determination of the size distributions of grains. These properties cannot be measured by astronomical observations, but they are essential to understanding the sources and evolution of any type of dust [3].

Dust grains, typically 0.1 to 10 μm, encounter spacecraft and *in situ* instruments at relative velocities of up to 80 km/s [20]. At such high velocities, the dust grain and a portion of the surface it hits are partially vaporized and ionized [21, 22]. The impact ionization process is illustrated in Figure 1.1. The shock wave produced by the impact creates both positive ions and free electrons in a dense, expanding plasma [23]. The electrons, which are more mobile than the ions, escape the expanding plasma cloud faster, resulting in a charge separation. The remaining cloud of atomic and/or molecular ions emerges from a region of high positive space charge. High-velocity dust impacts produce ions with large and varied initial kinetic energies, typically several eV [24, 25]. For a given element, the quantity of ions produced depends on the impact velocity, the density of the materials involved in the impact, and other factors. Impact ionization was originally observed by Friichtenicht [26]. Subsequent studies have evaluated the possibility of using the ions produced in a hypervelocity impact to measure the properties of cosmic dust grains [27, 28]. Chapter 4 contains a more detailed description of impact ionization, including the results of experiments, theoretical treatments, and other considerations.

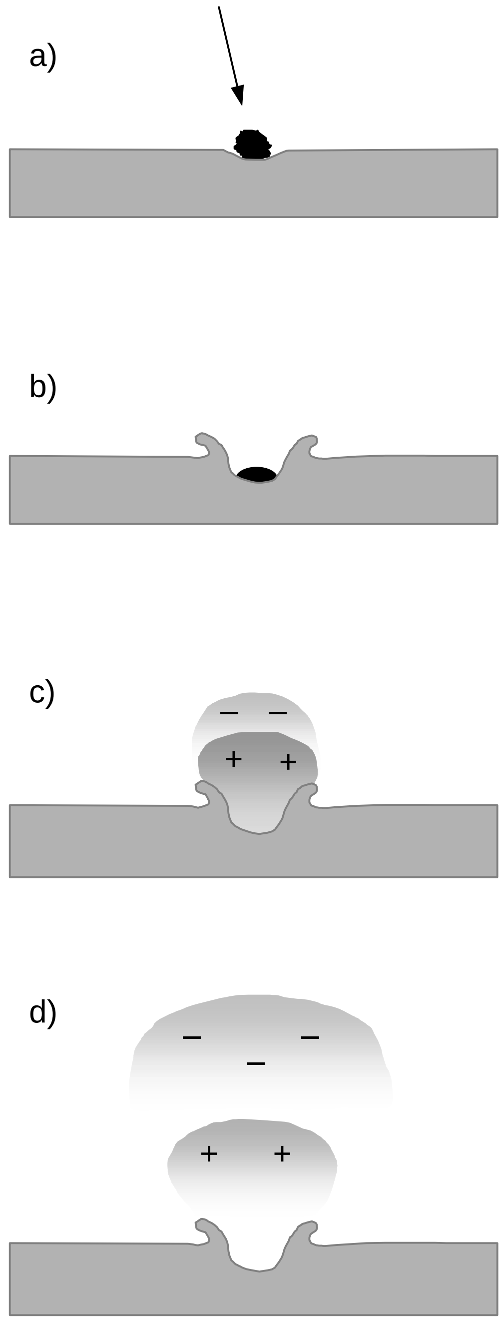


Figure 1.1. Impact ionization scenario: a) particle impacts, b) melting and formation of crater, c) formation of vapor and ions, and d) expansion of ion clouds (electrons and positive ions). Electrons leave more quickly due to higher mobility. Neutral species are also formed, but are not shown in this illustration.

1.3 Instrumentation for *in situ* analysis of cosmic dust

In situ dust detectors utilize impact ionization either by measuring the electrical current created on the target surface or on a nearby grid, or by time-of-flight mass spectrometric analysis of the resulting ions. Only the latter method provides information about the composition of the dust grain. Previous dust analyzers that measured the charge produced from impact include the Ulysses [29] and Galileo [30] dust detectors, and the GORID [14] dust detector. Previous impact ionization time-of-flight mass spectrometers for dust analysis include the Particulate Impact Analyzer (PIA) and the Dust Impact Mass Analyzer (PUMA) instruments used in the Halley comet fly-by [31], the Cassini Cosmic Dust Analyzer (CDA) [32], and the STARDUST Cometary and Interstellar Dust Analyzer (CIDA) [19].

The PIA and PUMA dust analyzers and the STARDUST CIDA were based on the same design, which is shown in Figure 1.2. Because impact-generated ions exhibit a wide range of initial kinetic energies, these mass spectrometers used reflectrons, originally described by Mamyrin [33], to compensate for the initial energy distribution of the ions. Figure 1.3 shows a diagram of a basic reflectron. Ions with greater initial kinetic energy penetrate farther into the reflectron, thus taking a longer path to the detector. The detector is located at the point where faster and slower ions meet (the space-focus plane). The use of a reflectron allowed mass resolution of around 200 for most spectra obtained with these instruments.

The PIA, PUMA, and CIDA mass spectrometers were each approximately 1 meter in length and 17 kilograms in mass. Also, the target plate dimensions on these

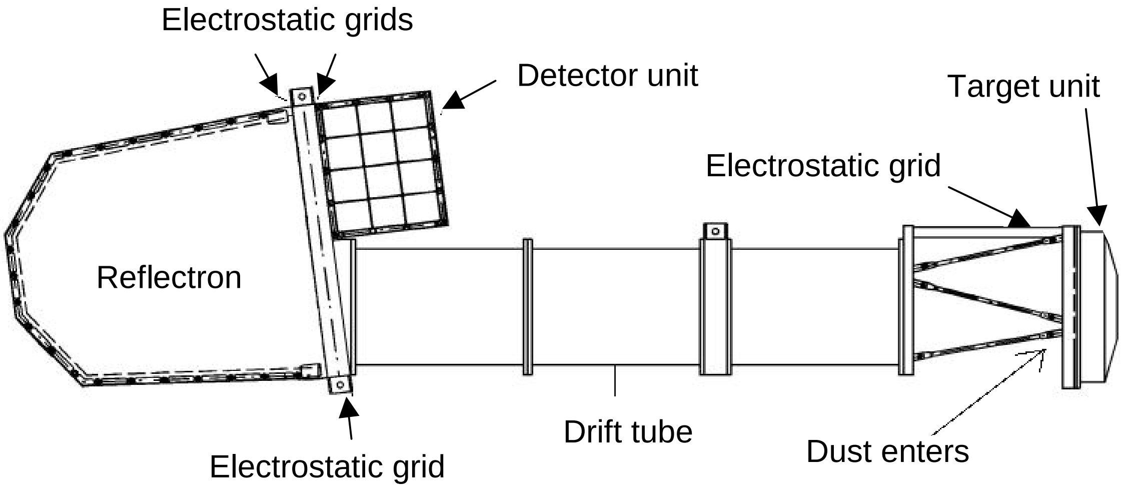
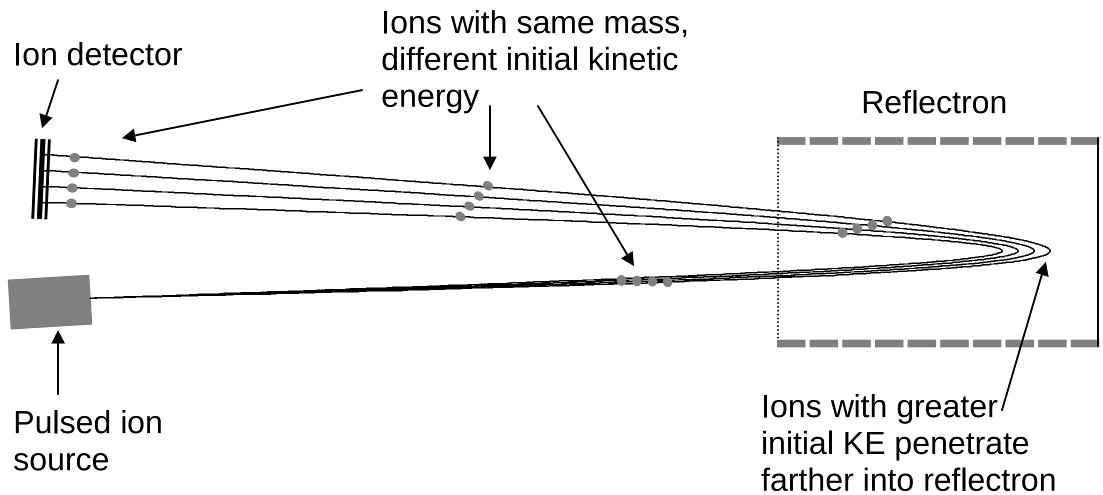


Figure 1.2. Design of PIA and PUMA dust analyzers. Instrument is approximately 120 cm long. STARDUST CIDA is nearly identical, but with larger impact target. Dust grains impact a rhodium target plate. Resulting ions are electrostatically extracted and accelerated through drift tube. Reflectron directs ions to detector and compensates for variations in initial kinetic energies of ions.



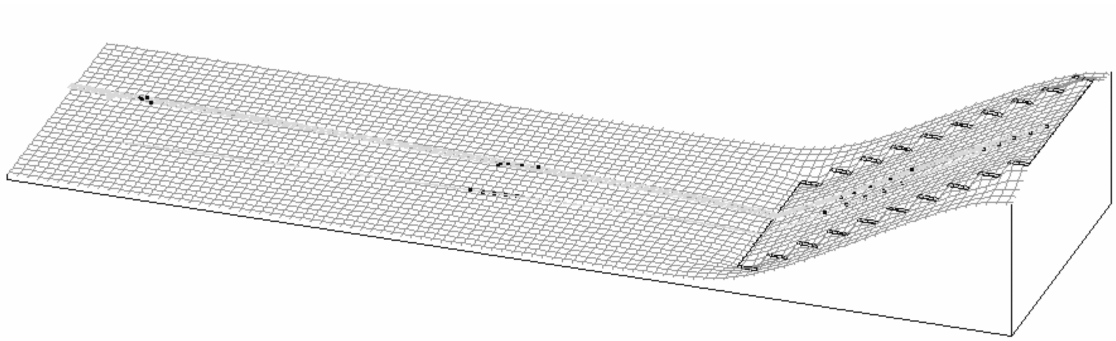


Figure 1.3. A typical reflectron. Ions of a given m/z are produced simultaneously by a source and accelerated to some voltage. Differences in the initial kinetic energies of ions result in spreading. Ions enter the reflectron. Ions with greater initial kinetic energy penetrate farther into the reflectron, resulting in a longer flight path to the ion detector. Detector is positioned at the space-focus plane, where ions arrive nearly simultaneously. The lower illustration shows the electrostatic potential surface of the reflectron setup.

instruments were small in relation to the overall instrument size (5 cm^2 for PIA and PUMA, 50 cm^2 for CIDA). Small target plates are useful for regions with high concentrations of dust, such as in the vicinity of a comet, but are less appropriate for regions with low concentrations of dust [32].

In regions where cosmic dust is sparse, a large active target area is needed in order to record a statistically significant number of impact events. The Cassini Cosmic Dust Analyzer, or CDA, was designed for regions of the solar system with low and medium concentrations of dust. Figure 1.4 shows a diagram of the CDA. It has a large impact surface, of which 200 cm^2 is used for mass spectrometry on impinging dust grains [34]. A reflectron was not included in this 17-kg instrument because of the difficulty of combining a reflectron with a large target area and the simultaneous operation of the impact plasma sensor [32]. Due to the lack of a reflectron, or other energy compensating device, mass resolution in the CDA is low (5-20 in many cases). Peak identification in some spectra is not possible.

Recently NASA has placed emphasis on developing smaller, lighter, lower-power spacecraft and instruments. Considering the limitations of previous instruments I have designed and built a compact impact-ionization time-of-flight mass spectrometer for *in situ* analysis of cosmic dust, suitable for use on future deep space missions. Named the Dustbuster, this time-of-flight mass spectrometer combines the best aspects of previous dust analyzers in a more compact design. The Dustbuster includes a reflectron, modified so that it corrects for initial ion energies and also focuses the ions from a large target area onto the ion detector. This modified reflectron allows mass spectra to be obtained from dust grains hitting a 65-cm^2 target, with sufficient mass

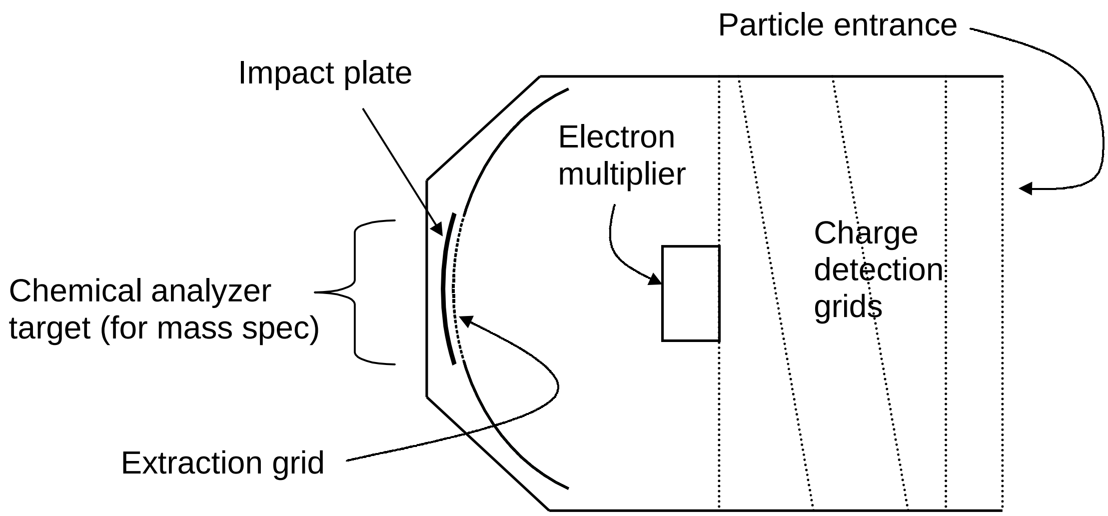


Figure 1.4. The Cassini Cosmic Dust Analyzer (CDA). Instrument is 0.4 m in diameter and has a mass of 17 kg. Charge detection grids measure charge, velocity, and direction of incoming dust. Time-of-flight mass spectrometer measurements are made only for those particles impacting the chemical analyzer target, located in the center of the impact plate.

resolution to measure isotopic distributions of most elements. The active target area is large compared to the instrument size, and of sufficient size to be useful for regions of the solar system with low dust concentrations. The Dustbuster, measuring only 10 cm in diameter and 20 cm in length, and weighing approximately 0.5 kg, is much smaller and lighter than previous dust mass spectrometers. The design of the Dustbuster is described in detail in Chapter 2.

1.4 References

1. Blake, G., *Class notes from Ch/Ge 128, Cosmochemistry, Caltech*. 2000.
2. Greenberg, J. M. and Caro, G. M. M., *Organics in space: from interstellar dust to comets.* Astrochemistry: from molecular clouds to planetary systems IAU symposia, 2000. **197**: p. 331-342.
3. Grun, E.; Landgraf, M.; Horanyi, M.; Kissel, J.; Krüger, H.; Srama, R.; Svedhem, H.; Withnell, P., *Techniques for galactic dust measurements in the heliosphere.* Journal of Geophysical Research, 2000. **105**(A5): p. 10403-10410.
4. Frisch, P. C., *The nearby interstellar medium.* Nature (London), 1981. **293**: p. 377-379.
5. Witte, M.; Rosenbauer, H.; Banaskiewicz, M.; Fahr, H., *The Ulysses neutral gas experiment: determination of the velocity and temperature of the neutral interstellar helium.* Advances in Space Research, 1993. **13**(6): p. 121-130.
6. Frisch, P. C., *Dust in the local interstellar wind.* Astrophysical Journal, 1999. **525**(1): p. 492-516.
7. Landgraf, M.; Baggaley, W. J.; Grun, E.; Krüger, H.; Linkert, G., *Aspects of the mass distribution of interstellar dust grains in the solar system from in situ measurements.* Journal of Geophysical Research, 2000. **105**(A5): p. 10343-10352.

8. Kimura, H. and Mann, I., *The electric charging of interstellar dust in the solar system and consequences for its dynamics.* Astrophysical Journal, 1998. **499**(454-462).

9. Landgraf, M.; Augustsson, K.; Grun, E.; Gustafson, B. A. S., *Deflection of the local interstellar dust flow by solar radiation pressure.* Science, 1999. **286**(5448): p. 2319-2322.

10. Grun, E.; Staubach, P.; Baguhl, M.; Hamilton, D. P.; Zook, H. A.; Dermott, S.; Gustafson, B. A.; Fechtig, H.; Kissel, J.; Linkert, D.; Linkert, G.; Srama, R.; Hanner, M. S.; Polanskey, C.; Horanyi, M.; Lindblad, B. A.; Mann, I.; McDonnell, J. A. M.; Morfill, G. E.; Schwehm, G., *South-north and radial traverses through the interplanetary dust cloud.* Icarus, 1997. **129**(2): p. 270-288.

11. Zinner, E., *Stellar nucleosynthesis and the isotopic composition of presolar grains from primitive meteorites.* Annual Review of Earth and Planetary Sciences, 1998. **26**: p. 147-188.

12. Grun, E., *Dust measurements in the outer solar system.* Asteroids, Comets, Meteors 1993 IAU Symposia, 1994. **160**: p. 367-380.

13. Mann, I. and Grun, E., *Dust particles beyond the asteroid belt—a study based on recent results of the Ulysses dust experiment.* Planetary and Space Science, 1995. **43**(6): p. 827-832.

14. Drolshagen, G.; Svedhem, H.; Grun, E.; Bunte, K. D., *Measurements of cosmic dust and micro-debris in GEO.* Advances in Space Research, 2001. **28**(9): p. 1325-1333.

15. Brownlee, D. E. *The elemental composition of interplanetary dust*. in *Physics, Chemistry, and Dynamics of Interplanetary Dust, 150th Colloquium of the International Astronomical Union*. 1995. Gainesville, Florida: Astronomical Society of the Pacific Conference Series, San Francisco.

16. Grun, E.; Gustafson, B. A.; Dermott, S.; Fechtig, H., eds. *Interplanetary Dust*. 2001, Springer: New York.

17. Mathis, J. S., *Interstellar dust and extinction.* Annual Reviews of Astronomy and Astrophysics, 1990. **28**: p. 37-70.

18. Mann, I. *Dust near the sun*. in *Physics, Chemistry, and Dynamics of Interplanetary Dust, 150th Colloquium of the International Astronomical Union*. 1995. Gainesville, Florida: Astronomical Society of the Pacific Conference Series, San Francisco.

19. Brownlee, D. E.; Burnett, D.; Clark, B.; Hanner, M. S.; Horz, F.; Kissel, J.; Newburn, R.; Sandford, S.; Sekanina, Z.; Tsou, P.; Zolensky, M. *STARDUST: comet and interstellar dust sample return mission*. in *Physics, Chemistry, and Dynamics of Interplanetary Dust,150th Colloquium of the International Astronomical Union*. 1995. Gainesville, Florida: Astronomical Society of the Pacific Conference Series, San Francisco.

20. Hornung, K.; Malama, Y. G.; Kestenboim, K. S., *Impact vaporization and ionization of cosmic dust particles.* Astrophysics and Space Science, 2000. **274**: p. 355-363.

21. Hornung, K.; Malama, Y. G.; Thoma, K., *Modeling of the very high velocity impact process with respect to in situ ionization measurements.* Advances in Space Research, 1996. **17**(12): p. (12)77-(12)86.

22. Hornung, K. and Kissel, J., *On shock wave impact ionization of dust particles.* Astronomy and Astrophysics, 1994. **291**: p. 324-336.

23. Hansen, D. O., *Mass analysis of ions produced by hypervelocity impact.* Applied Physics Letters, 1968. **13**(3): p. 89-91.

24. Ratcliff, P. R. and Allahdadi, F., *Characteristics of the plasma from a 94 km/s microparticle impact.* Advances in Space Research, 1996. **17**(12): p. (12)87-(12)91.

25. Abramov, V. I.; Bandura, D. R.; Ivanov, V. P.; Sysoev, A. A., *Energy and angular characteristics of ions emitted in the impact of accelerated dust particles on a target.* Sov. Tech. Phys. Lett., 1991. **17**(3): p. 194-195.

26. Friichtenicht, J. F., *Micrometeoroid simulation using nuclear accelerator techniques.* Nuclear Instruments and Methods, 1964. **28**: p. 70-78.

27. Friichtenicht, J. F.; Roy, N. L.; Becker, D. G. *The Cosmic Dust Analyzer: experimental evaluation of an impact ionization model*. in *International Astronomical Union Colloquium #13*. 1971. State University of New York, Albany, NY: Scientific and Technical Information Office, NASA, Washington, D.C.

28. Auer, S. and Sitte, K., *Detection technique for micrometeoroids using impact ionization.* Earth and Planetary Science Letters, 1968. **4**: p. 178-183.

29. Grun, E.; Fechtig, H.; Giese, R. H.; Kissel, J.; Linkert, D.; Maas, D.; McDonnell, J. A. M.; Morfill, G. E.; Schwehm, G.; Zook, H. A., *The Ulysses dust experiment.* Astronomy & Astrophysics, Supplement Series, 1992. **92**: p. 411-423.

30. Grun, E.; Fechtig, H.; Hanner, M. S.; Kissel, J.; Lindblad, B.-A.; Linkert, D.; Maas, D.; Morfill, G. E.; Zook, H. A., *The Galileo dust detector.* Space Science Reviews, 1992. **60**: p. 317-340.

31. Kissel, J.; Sagdeev, R. Z.; Bertaux, J. L.; Angarov, V. N.; Audouze, J.; Blamont, J. E.; Buchler, K.; Evlanov, E. N.; Fechtig, H.; Fomenkova, M. N.; von Hoerner, H.; Inogamov, N. A.; Khromov, V. N.; Knabe, W.; Krueger, F. R.; Langevin, Y.; Leonas, V. B.; Levasseur-Regourd, A. C.; Managadze, G. G.; Podkolzin, S. N.; Shapiro, V. D.; Tabaldyev, S. R.; Zubkov, B. V., *Composition of Comet Halley dust particles from Vega observations.* Nature (London), 1986. **321**: p. 280-282.

32. Ratcliff, P. R.; McDonnell, J. A. M.; Firth, J. G.; Grun, E., *The Cosmic Dust Analyzer.* J. British Interplanetary Soc., 1992. **45**(9): p. 375-380.

33. Mamyrin, B. A.; Karataev, V. I.; Shmikk, D. V.; Zagulin, V. A., *The mass-reflectron, a new nonmagnetic time-of-flight mass spectrometer with high resolution.* Sov. Phys. JETP, 1973. **37**: p. 45-47.

34. Srama, R. and Grun, E., *The dust sensor for Cassini.* Advances in Space Research, 1997. **20**(8): p. 1467-1470.