

IMPACT-IONIZATION MASS SPECTROMETRY OF COSMIC DUST

Thesis by

Daniel E. Austin

Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

California Institute of Technology

Pasadena, California

2003

(Defended November 5, 2002)

© 2003

Daniel E. Austin

All Rights Reserved

Acknowledgements

First of all, I thank Dave Dearden, Professor of Chemistry at Brigham Young University, and a former Caltech graduate student, for encouraging me to pursue graduate work at Caltech. The experiences I gained working with him, both as a research assistant and as a teaching assistant, proved invaluable during my stay here.

Numerous people at Caltech have contributed in some way to my research efforts. Foremost among these is my advisor, Jack Beauchamp, who successfully balances providing advice and supervision with the hands-off approach that is essential to developing creativity, resourcefulness, and drive in students. I also thank all the other Beauchamp group members who have helped me in so many ways: Dmitri Kossakovski, Sang-Won Lee, Jim Smith, Heather Cox, Ron Grimm, Ryan Julian, and Rob Hodyss. I joined Jack's group in part because of the very high caliber of students at that time. It seems I am leaving a group equally outstanding. There could be no finer collection of colleagues than this.

Minta Akin, an undergraduate Caltech student, has helped tremendously with the ice accelerator, and I thank her for all her work. Mike Roy, Guy Duremberg, and Ray Garcia, the chemistry department machinists, have been both helpful and patient with me as I've built numerous instrument parts. I hope I returned everything I borrowed from them. Thanks, gentlemen, for all your instruction and assistance. I also thank Priscilla Boon, the group secretary, and Dian Buchness, the graduate secretary, and the other support staff for taking care of so many small but necessary things over the years. I am also grateful for the many other people who have listened to me, told me what to

do, told me what not to do, reminded me of conferences, proofread papers, and put up with me in general.

Much of my work was done in collaboration with Tom Ahrens and his geophysics group. I am grateful to all of them, including Joe Atkins, Andy Shen, Ingrid Mann, Mike Long, and Sue Yamada.

A primary segment of my thesis research was conducted on the van de Graaff dust accelerator at Concordia College, Moorhead, Minnesota. While many other microparticle accelerators from the 1960's have long since been disassembled, the faculty at Concordia have carefully maintained this instrument in working condition. It is the only functional dust accelerator in the Western Hemisphere, and my research would have been much more complicated had it been necessary to go overseas for fast dust. I am grateful to Carl Bailey and Heidi Manning, both of the Concordia Physics faculty, for hosting my research visit, running the accelerator, and helping solve every problem that arose. I also thank Jim Farnsworth, an undergraduate physics student, who spent many days and evenings recording particle velocities in my lab notebook.

I am grateful to all who have contributed financially to my graduate work. NASA and NSF have supported the research. An NSF Graduate Research Fellowship and an ARCS Fellowship have contributed to my personal support.

Finally, I am eternally grateful for the greatest friends of all, my family. My grandfathers both attended Caltech; they and other relatives have been very supportive of all my efforts. My parents and sisters in particular have always encouraged me to do my best. I thank my wife, Lisa, who spent many nights putting the kids to bed alone

while I was having fun in the lab shooting lasers or small projectiles at things and calling it “work.”

Abstract

In situ characterization of cosmic dust grains typically involves impact-ionization time-of-flight mass spectrometry. Considering the performance and limitations of previous instruments, I designed and tested a novel, compact time-of-flight mass spectrometer for cosmic dust analysis. The instrument, Dustbuster, incorporates a large target area with a reflectron, simultaneously optimizing mass resolution, particle detection, and ion collection. Dust particles hit the 65-cm² target plate and are partially ionized by the impact. The resulting ions, with broad energy and angular distributions, are accelerated through the modified reflectron, focusing ions spatially and temporally to produce high-resolution spectra.

Initial performance tests of the Dustbuster used laser desorption ionization of embedded metal and mineral samples to simulate particle impacts. Mass resolution (mass/peakwidth) in these experiments ranged from 60 to 180, permitting resolution of isotopes. Subsequent experiments included hypervelocity microparticle impacts. Charged iron and copper microparticles, accelerated to 2-20 km/s in a 2 MV van de Graaff accelerator, impacted the Dustbuster. Mass resolution in these experiments ranged from 150 to 300 for iron and copper. Hydrogen, carbon, and oxygen ions appeared in many spectra. Field-induced emission of electrons immediately before impact is a possible cause of ion formation from species with high ionization potentials. The implications of this ionization effect are discussed in relation to interpretation of mass spectra from other *in situ* dust analyzers.

Another time-of-flight instrument, originally designed as an energy analyzer, shows promise as a high-resolution mass spectrometer for high-flux cosmic dust environments.

Ice is an important component of particulates ejected from comets and other icy bodies in the solar system. Due to limited experimental data on ice particle impacts, I built an ice particle source based on a vibrating orifice aerosol generator connected directly to vacuum. Ice particles produced in this manner can be electrostatically accelerated for impact ionization studies.

Hypervelocity impact vaporization may have played a key role in the mass extinction that occurred at the Cretaceous-Tertiary (K-T) boundary. In order to study the speciation of gases that may have been produced in such an asteroid impact, I designed a specialized orthogonal extraction mass spectrometer for future laboratory impact experiments.

Contents

Chapter 1: Cosmic Dust and Impact-Ionization Mass Spectrometry

1.1	Cosmic dust	1
1.2	Methods for studying cosmic dust	3
1.3	Instrumentation for <i>in situ</i> analysis of cosmic dust	6
1.4	References	11

Chapter 2: The Dustbuster: A Compact, Time-of-Flight Mass Spectrometer for Cosmic Dust Analysis

2.1	Objectives in designing an improved cosmic dust mass spectrometer	15
2.2	Early designs and obstacles	16
2.3	Working design	21
2.4	Computer simulations of Dustbuster performance	27
2.5	Other instrument issues	29
2.6	Suitability for various missions	35
2.7	Future design improvements	36
2.8	References	41

Chapter 3: Laser Desorption Ionization Experiments

3.1	Introduction	44
3.2	Experimental setup	45
3.3	Results and discussion	51
3.4	References	71

Chapter 4: Hypervelocity Microparticle Impact Experiments		
4.1	Simulating cosmic dust impacts in the lab: accelerating microparticles	73
4.2	Impact ionization theory, models, and experiments	75
4.3	The dust accelerator at Concordia College, Moorhead, Minnesota	80
4.4	Characterization of microparticle impacts using energy analyzer	85
4.5	Results of pulsed ion energy analyzer experiments	92
4.6	Experimental setup for Dustbuster testing	101
4.7	Results of microparticle impact experiments on the Dustbuster	104
4.8	Charge transfer and the impact ionization mechanism	123
4.9	Simulating cometary dust: ice particle impact experiment	136
4.10	Energy analyzer as a high-flux dust mass spectrometer	142
4.11	References	148
Chapter 5: Hypervelocity Impacts of Macroscopic Bodies		
5.1	Asteroid impacts on the Earth	154
5.2	Description of mass spectrometer to study shock-induced vaporization and ionization of minerals	156
5.3	References	163
Appendix A: Isotopes of Selected Elements		166
Appendix B: Ion Definitions Used in Simulations		169

List of Figures

Chapter 1

Figure 1.1. Impact ionization scenario	5
Figure 1.2. Design of PIA and PUMA dust mass spectrometers	7
Figure 1.3. Reflectron design	8
Figure 1.4. Design of the Cassini Cosmic Dust Analyzer	10

Chapter 2

Figure 2.1. Original Dustbuster design	18
Figure 2.2. Early Dustbuster designs	19
Figure 2.3. Design of the working version of the Dustbuster	22
Figure 2.4. Simulation of ion trajectories in Dustbuster	26
Figure 2.5. Trajectories of ions originating near center of target plate	30
Figure 2.6. Trajectories of ions originating at intermediate distance	31
Figure 2.7. Trajectories of ions originating near outside of target plate	32
Figure 2.8. Effect of the curvature of the front grid on mass resolution	33
Figure 2.9. Charge-sensitive wires and photodiodes for particle measurement	39
Figure 2.10. Simulated signals on charge-sensitive wires and photodiodes	40

Chapter 3

Figure 3.1. Photograph of Dustbuster prototype	46
Figure 3.2. Diagram of target plate section used in experiments	47

Figure 3.3. Experimental setup for laser ionization experiments	49
Figure 3.4. Typical laser ionization mass spectra from stainless steel	52
Figure 3.5. Average of 12 laser ionization mass spectra from copper	55
Figure 3.6. Typical laser ionization mass spectra from copper	56
Figure 3.7. Average of 9 laser ionization mass spectra from chalcopyrite	58
Figure 3.8. Typical laser ionization mass spectra from chalcopyrite	59
Figure 3.9. Typical laser ionization mass spectra from dolomite	62
Figure 3.10. Typical laser ionization mass spectra from chlorite	64
Figure 3.11. Typical laser ionization mass spectra from olivine	66
 Chapter 4	
Figure 4.1. Design of van de Graaff dust accelerator at Concordia College	82
Figure 4.2. Details of dust reservoir of van de Graaff dust accelerator	83
Figure 4.3. Diagram of pulsed ion energy analyzer	87
Figure 4.4. Simulated ion trajectories in pulsed ion energy analyzer	89
Figure 4.5. Experimental setup for microparticle impacts on energy analyzer	90
Figure 4.6. Typical mass spectra from impacts on energy analyzer	93
Figure 4.7. Experimental setup for microparticle impacts on Dustbuster	102
Figure 4.8. Velocity and mass of microparticles studied	105
Figure 4.9. Mass and charge of accelerated microparticles	106
Figure 4.10. Typical Dustbuster spectra from particles with known velocity	108
Figure 4.11. Typical Dustbuster spectra from particles with unknown velocity	114
Figure 4.12. Dissimilar spectra from similar impacting particles	124

Figure 4.13. Electric field as function of distance between particle and plate	127
Figure 4.14. Energy dissipated by electron impact and kinetic energy	130
Figure 4.15. Electrostatic potentials of charged particles near impact plate	133
Figure 4.16. Vibrating orifice aerosol generator (VOAG)	139
Figure 4.17. Droplets produced using VOAG	140
Figure 4.18. High-flux cosmic dust mass spectrometer	143
Figure 4.19. Simulated ion trajectories on high-flux dust analyzer	146
Figure 4.20. Simulated mass resolution on high-flux dust analyzer	147

Chapter 5

Figure 5.1. Setup for shock-induced mineral vaporization mass spectrometry	158
Figure 5.2. Details of mineral vaporization mass spectrometer	159
Figure 5.3. Electrodes for pulsed orthogonal ion extraction	160

Appendix B

Figure B.1. Coordinate system for defining ions in SIMION	170
Figure B.2. Isotropic ion distribution as function of angle from normal	176
Figure B.3. Cosine ion distribution as function of angle from normal	177
Figure B.4. Cosine-squared ion distribution as function of angle from normal	178

List of Tables

Chapter 4

Table 4.1. Description of mass spectra peaks	121
--	-----

Appendix A

Table A.1. Abundances and masses of stable isotopes of selected elements	167
--	-----

Abbreviations and Acronyms

AU	Astronomical unit
CDA	Cosmic Dust Analyzer
CIDA	Cometary and Interstellar Dust Analyzer
GORID	Geostationary ORbit Impact Detector
IR	infrared
MCP	microchannel plate ion detector
m/z	mass to charge ratio
PIA	Particulate Impact Analyzer
PUMA	Russian acronym for 'dust impact mass analyzer'
SIMS	secondary ion mass spectrometry
UV	ultraviolet
VOAG	vibrating orifice aerosol generator