Icy Worlds of the Solar System

Earth is the only planet known to have liquid water, and water ice has been present over parts of the Earth for much of its history. Scientists have only recently come to understand how widespread the presence of ice is in our solar system. Deposits of water ice may exist in unexpected places, such as in the polar craters of Mercury, the closest planet to the Sun. Other ices, such as methane ice and nitrogen ice, abound in our solar system. These ices play an important role in the geological and atmospheric characteristics of the bodies in our solar system.

This book focuses on the occurrence and significance of water ice, and ices formed by other materials, in the solar system. The findings discussed are the result of three decades of spacecraft exploration of the planets, complemented by ground- and space-based observations. It considers the implications of the reservoirs of water ice for the presence of life elsewhere in our solar system, and for habitability by human explorers who may venture to these distant worlds in the future. Written at an accessible level, this book will be of interest to students and professionals in planetary science, geology, and related areas.

PAT DASCH is a consultant in the space industry specializing in policy and public outreach. She has published and broadcast on a wide variety of space-related topics for the past 20 years. Dasch has held a variety of positions, including Executive Director of the Washington DC-based National Space Society, and Editor in Chief of *Ad Astra*, the bi-monthly magazine of the National Space Society. She worked in solar system exploration at NASA Headquarters and has also acted as Director of the Dial-A-Shuttle broadcast program at the Johnson Space Center, and served as a research associate at the Lunar and Planetary Institute.

Icy Worlds of the Solar System

Edited by

Pat Dasch

CAMBRIDGE UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge, CB2 2RU, UK
40 West 20th Street, New York, NY 10011–4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 2004

Printed in the United Kingdom at the University Press, Cambridge

Typeface Swift Regular 9.75/14 pt. *System* LaTeX 2ε [TB]

A catalog record for this book is available from the British Library

Library of Congress Cataloging in Publication data
Icy worlds of the Solar System / edited by Pat Dasch
p. cm.
Includes bibliographical references and index.
ISBN 0 521 64048 2
1. Solar system. 2. Ice. I. Dasch, Pat.
QB505.I39 2004
523.2 – dc22 2003069573
ISBN 0 521 64048 2 hardback

Contents

List of contributors *page* viii
Preface xiii
Acknowledgements xiv

Introduction 1
JONATHAN I. LUNINE

1 The history and significance of ice on Earth 6
ROBERT BINDSCHADLER
The water planet 7
Early glaciations 8
Ice sheets, sea level, and climate 9
Ice sheet response 13
Snow and sea ice 15
Ice sheets and weather 17
Metamorphism of snow into ice 20
Climate tape recorder 21
Ice sheet facies 23
Ice sheet motion 24
Ice shelves 28
Ice landscaping 29
Meteorite catchers 30
Summary 32

2 Ice on Mercury and the Moon 33
BRYAN BUTLER
Mercury 33
The Moon 50
Future missions 58

3 How the Earth got its atmosphere 60
TOBIAS OWEN
How planets keep their atmospheres 60
Why small planets have different atmospheres 62

Frigid worlds, atmospheric evolution, and cosmic time travel 63
The sources of atmospheres: problems with meteorites 65
The sources of atmospheres: icy planetesimals? 67
Solar Composition Icy Planetesimals (SCIPs): a new type of icy planetesimal 69
The sources of atmospheres: a rocky component? 72
The importance of impact erosion 74
Tests of the model 75

4 The frozen landscape of Mars 79
MICHAEL T. MELLON
Mars: yesterday and today 79
Polar deposits 81
Seasons bring change 85
Shapes in the polar landscape 86
Deep in the ice cap 88
The sky above 89
The permafrost below 92
Buried ice from the past 94
Running water from frozen ground 95
Moving ice 98
At the limits of vision 99
Impact craters in the permafrost? 101
Climate change 103
An elusive resource 105
Hazards of living on ice 107
Life? 108
The future 109

5 The ice moons of Sol 110
PAUL M. SCHENK
Moon madness 112
Water! Water! 113
Organic stews? 114
Energy to spare 118
Ice worlds – Oceanus Amokium? 121

	Triton	132
	It's a not-so small world after all	134
6	Triton, Pluto, and beyond	139
	JOHN A. STANSBERRY	
	Pluto's story	141
	Triton and the Trans-Neptunian objects (TNOs)	144
	Triton and Pluto: twin siblings of a distant Sun	147
	Geology recorded in water ice "rock"	147
	Tidal evolution and giant impacts	150
	Kuiper Belt objects: cousins to Triton and Pluto	152
	Triton and Pluto today	152
	Nitrogen, methane, and atmospheres	152
	Ice transport and seasons	157
	The fate of Pluto's atmosphere	162
	Not yet explored	167
7	Comets: ices from the beginning of time	168
	DALE P. CRUIKSHANK	
	What are comets?	170
	The interstellar medium, and the death of stars	171
	Comets are formed	172
	The composition of comets	173
	Special properties of water ice	177
	What comets are made of	178
	Comet dust	179
	Where do comets come from?	182
	Space missions to comets	188
	Conclusion	189
	Index	190

Contributors

ROBERT BINDSCHADLER

Dr. Robert Bindschadler, a glaciologist at the NASA Goddard Space Flight Center, has been an active Antarctic field researcher for the past 20 years, has led 11 field expeditions to Antarctica, and has participated in many others to glaciers and ice caps around the world. He maintains an active interest in the dynamics of glaciers and ice sheets, primarily on Earth, investigating how remote sensing can be used to improve our understanding of the role of ice in the Earth's climate. He has advised the US Congress and the Vice President on the stability of ice sheets and ice shelves and served on many scientific commissions and study groups as an expert in glaciology and remote sensing of ice. Some of the more significant awards he has received are: Excellence in Federal Career (1989), the Antarctic Service Medal (1984), and the NASA Exceptional Scientific Achievement Medal (1994), and he was appointed a Goddard Senior Fellow (2000). He has published over 100 scientific papers including numerous review articles and has appeared on television and radio to comment on glaciological impacts of the climate on the world's ice sheets and glaciers. He currently is President of the International Glaciological Society, chairs the West Antarctic Ice Sheet Initiative, sits on the Editorial Board of the American Geophysical Union's Antarctic Research Series, and is an editor for the *Journal of Glaciology*.

BRYAN BUTLER

Bryan Butler was born and raised in northern Utah, where he attended undergraduate school at Utah State University. He graduated in 1988, earning BS degrees (Magna Cum Laude) in Electrical Engineering and Computer Science. From there, he went on to graduate work at Caltech, earning his MS in 1991 and his Ph.D. in 1994, both in Planetary Science. Since then he has been an employee of the National Radio Astronomy Observatory as a member of the scientific staff. His research focuses on the radio emission and radar scattering from solar system bodies,

including the planets, moons, asteroids, and comets, and the theory and implementation of radio interferometry.

DALE CRUIKSHANK

Dale Cruikshank is a Research Scientist in the Astrophysics Branch at NASA Ames Research Center. Prior to taking this position with NASA in 1988, he had been a tenured research faculty member at the University of Hawaii for nearly 18 years. Cruikshank's principal work is in the study of the surfaces and atmospheres of the planets and small bodies of the solar system, using the techniques of infrared spectroscopy, photometry, and radiometry, in which he has authored or coauthored about 250 research papers.

Cruikshank and his colleagues have discovered many of the ice species found on Pluto, Triton, and the satellites of Saturn and Uranus. Seeking to understand the dark red materials covering many satellites, comets, Kuiper Belt objects, Centaurs, and asteroids, Cruikshank has advanced the idea, with spectroscopic observational support, that complex organic material is an important constituent of the surface materials of these bodies. Cruikshank is a scientist on the Cassini mission to Saturn, the Space Infrared Telescope Facility (SIRTF), and the New Horizons mission to Pluto-Charon and the Kuiper Belt.

JONATHAN LUNINE

Jonathan I. Lunine is Professor of Planetary Sciences and of Physics, and chairs the Theoretical Astrophysics Program at the University of Arizona. His research interests center broadly on the formation and evolution of planets and planetary systems. He is an interdisciplinary scientist on the Cassini mission to Saturn, and on the James Webb Space Telescope. Dr. Lunine is the author of the book *Earth: Evolution of a Habitable World* (Cambridge University Press, 1999). He is a fellow of the American Association for the Advancement of Science and of the American Geophysical Union, which awarded him the James B. Macelwane medal, and winner of the Harold C. Urey Prize (American Astronomical Society) and Ya. Zeldovich Award of COSPAR's Commission B. Dr. Lunine earned a BS in Physics and Astronomy from the University of Rochester in 1980, followed by MS (1983) and Ph.D. (1985) degrees in Planetary Science from the California Institute of Technology.

MICHAEL MELLON

Michael T. Mellon is a planetary scientist at the Laboratory for Atmospheric and Space Physics at the University of Colorado at Boulder. His research has concentrated on the distribution and behavior of ice on Mars and he has made a detailed study of the similarities and differences between martian and terrestrial permafrost.

TOBY OWEN

Tobias Owen is a Professor of Astronomy at the Institute for Astronomy of the University of Hawaii. He is studying planets, satellites, and comets with the telescopes on Mauna Kea and by means of deep space exploration. Having participated in the Viking, Voyager, and Galileo missions, Owen is presently an Interdisciplinary Scientist and member of the Probe Mass Spectrometer, Aerosol Collection, and Pyrolysis and Consolidated Infrared Spectrometer Teams on the NASA–ESA Cassini Huygens mission to the Saturn system. He is also participating in the ESA Rosetta mission to Comet Churyumov-Gerasimenko.

PAUL SCHENK

Dr. Paul Schenk is a planetary geologist at the Lunar and Planetary Institute in Houston, Texas. He graduated from Washington University in Saint Louis and has been at the LPI since 1991, where he studies the geology and cratering history of the icy satellites of the outer solar system. Chief among his interests is mapping the topography of these bodies (and other planets) using stereo imaging and shape-from-shading techniques. He is currently completing topographic mapping of the large jovian satellites using available Voyager and Galileo imaging data, and preliminary topographic mapping of Saturn's satellites in preparation for Cassini's tour of the Saturn system beginning in late 2004.

JOHN STANSBERRY

John Stansberry is an assistant astronomer at Steward Observatory, the University of Arizona, in Tucson. He is a member of the Multiband Imaging Photometer for SIRTF (MIPS) instrument team. MIPS is the most sensitive camera ever built for use in the far-IR 20–200 micron range, and

was launched as a part of the Space Infrared Telescope Facility (SIRTF) on August 25, 2003. MIPS will be capable of accurately measuring the heat given off, not only by Pluto and Triton, but also by KBOs as small as 200 kilometers in diameter, and will also be useful for many astronomical observations.

Dr. Stansberry obtained his BA in Physics from Colorado College in 1985, and his Ph.D. in Planetary Science from the University of Arizona in 1995. His dissertation was on the interactions of the surfaces and atmospheres of Triton and Pluto. After his doctoral work, he has participated in an extensive program to observe Jupiter's moon, Io, in the infrared, mapping the locations, intensity, and variability of volcanic eruptions. He also was a member of the runner-up proposal to send a mission to Pluto and the Kuiper Belt, leading the development of a thermal imager that would have mapped surface temperatures on Pluto and Kuiper Belt objects.

PAT DASCH

Pat Dasch is a consultant to the space industry on space policy and public outreach issues and a writer who publishes on a wide variety of space-related topics. Recent projects include development of content for a PBS program on the future of human spaceflight, and development of strategic positions related to the future of internationally coordinated space missions for the Space Policy Summit held in Houston, TX, in October 2002.

She is editor in chief of the 4-volume reference work *Space Science for Students*, published in September 2002 by Macmillan Reference. Ms. Dasch has authored numerous articles on space exploration, and presented testimony to Congress. *Images of Earth*, co-authored with Peter Francis for George Philip (UK) and Prentice Hall in the US, in 1984, won the Geographical Society of Chicago prize for best remote sensing publication in 1985 and was carried by the Aviation Week Book Club. Ms. Dasch has also produced a number of educational slide sets, the most recent being "Life on Mars???" and "Asteroids."

Previously, Ms. Dasch was Executive Director of the National Space Society (1997–2001). From 1994–98 she was Editor in Chief of *Ad Astra* magazine, the magazine of the National Space Society, and from 1988–94 worked for SAIC as a planetary science analyst in the Solar

System Exploration Division at NASA Headquarters, Washington, DC. From 1983–87 she was director of the Dial-A-Shuttle program at the Johnson Space Center and a research associate at the Lunar and Planetary Institute in Houston working on shuttle Earth observations imagery.

Preface

In the last decade, information from the Galileo mission to the Jupiter system and advances in ground-based astronomy have greatly enhanced our reservoir of knowledge about ices in our solar system. An acceleration in the search for signs of life in the solar system (and the water that is necessary for the Earth-based life forms that we are familiar with) that followed the 1996 discovery of possible meteoritic evidence for the existence of ancient life on Mars, together with the technological revolution in both space- and Earth-based sensors, has resulted in significant new developments in understanding of the pervasive presence and geological significance of ices in our solar system.

In this book, recognized planetary experts interpret the role and impact of ice in our corner of the universe and debate the many outstanding questions that remain to be answered. Each chapter contains exciting, cutting-edge information revealing the complexity and wonder of the universe in which we live.

The findings from the Opportunity and Spirit rovers (Mars), the SMART-1 mission on route to the Moon and Cassini (saturnian system) will help to answer some of the outstanding questions about ice and will undoubtedly reveal new conundrums for our future contemplation.

Other missions planned for the future, such as the MESSENGER and BepiColombo missions to Mercury, and the New Horizons mission to Pluto and the Kuiper Belt, will continue this second wave of planetary exploration with rigorous surveys and collection of detailed scientific data.

Acknowledgements

First and foremost I want to thank the contributors to this book – Robert Bindschadler, Bryan Butler, Dale Cruikshank, Jonathan Lunine, Michael Mellon, Toby Owen, Paul Schenk, and John Stansberry – whose state-of-the-science knowledge, insights, and curiosity made this book possible.

My deepest gratitude to my husband, Julius, for his sustained support, encouragement, and interest throughout the evolution of this book, which appeared to be in constant revision right up to manuscript submission, as the scientific story continually rewrote itself with a steady stream of new and fascinating scientific developments.

My thanks to Simon Mitton, Jacqueline Garget, Carol Miller and Joseph Bottrill at Cambridge University Press for their perseverance and professional management of this project.