SOLAR SYSTEM ICES

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Europa, smallest of Jupiter's four Galilean satellites (diameter: 3138 km), is covered with an ice shell 10 to 150 km thick. The ice-rich surface, shown here in a Galileo view, is remarkably free of impact craters and is crossed by innumerable narrow ridges, dark bands, dark spots and fragmented crustal blocks. These features are stark evidence that Europa's ice crust is undergoing disruption and deformation. At upper right are a series of wedge-shaped bands first observed by Voyager in 1979. These bands form by fracturing and spreading of the ice crust, which allows new crustal material to intrude from below. The big questions raised by these and new Galileo observations concern the nature of the material below the ice crust. Is it warm soft mantle ice or is it liquid water, forming a global sub-crustal ocean? If liquid, it is conceivable that pre-life chemistry may have developed in this cold deep ocean. A Europa Orbiter sometime in the 21st century may be required to answer these questions. This image was obtained in February 1997 from a distance of 82,000 km and covers an area roughly 675 km across. (Courtesy from the Imaging Science Team of the NASA/JPL Galileo spacecraft).

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PREFACE

Moderately-to-highly volatile molecules are usually called "ices" by astrophysicists when they are in the solid state either as pure solids, solid mixtures, hydrates or clathrate hydrates. Molecules such as H_2O, NH_3, SO_2, CO_2, CH_4, CO, and N_2 are present as ices in the solar system and represent a large fraction of the mass of the outer solar system. To understand the evolution of the solar system, from its initial state as a nebula to its current stage as planets, icy satellites and comets, an excellent knowledge of the composition and properties of ices formed from the above-mentioned molecules is thus of utmost importance.

The Voyager 1 and 2, the Vega and Giotto spacecraft, and numerous recent ground-based investigations have provided a wealth of new and high quality information on the composition, surface morphology and physical properties of solar system planetary surfaces. This area of research expands continuously, as space missions currently in operation (Galileo, ISO, Mars missions), planned programs (Cassini-Huygens, Rosetta, Fast Pluto Flyby, ...) as well as new ground-based instrumentation contribute to our knowledge of the structure, composition and evolution of icy solar system bodies by providing us with data of higher signal to noise ratio, better spectral and spatial resolutions. Supporting laboratory measurements of the physico-chemical and electromagnetic properties of ices and theoretical and numerical models provide the basis and framework for interpretations of these new observations.

More than ten years ago (January 1984), the NATO International Workshop "Ices in the Solar System" was organized in Nice (France) on this topics. With about 80 participants and 60 talks, this workshop was very successful and stimulating. Many of the observing techniques required for an adequate study of the characteristics of ices, e.g. infrared spectroscopy, were not very powerful then. The impressive improvement of these techniques in the intervening years and a wealth of new observational discoveries have greatly stimulated and fueled the growth of the community interested by icy bodies.

From many discussions with colleagues, we realized that it was timely to review once more the state of our knowledge about solar system ices and this idea developed into the "Solar System Ices" symposium held in March 1995 at Toulouse. The Conference was attended by 145 scientists from 16 different countries.

The Symposium's first objective was to provide an overview of the existing observations of the icy planetary bodies (Mars, some satellites of Jupiter, Saturn and Uranus, Triton, Pluto and Charon, the outer planets' rings, and comets) as well as reviewing similar data about the Earth from the perspective as one of the nine planets of the solar system. The latest theoretical and numerical models used to analyze these observational facts had to be reviewed and discussed, as well as the status of

our knowledge of the physical and chemical properties of planetary ices deduced from laboratory measurements and simulations.

A second objective of the Symposium was to identify what were the main unresolved problems concerning solar system icy bodies, to anticipate new research areas in response to observational returns expected from future space missions and ground-based observing facilities currently in development, and to determine what would be soon needed in laboratory simulations and modelling efforts.

The Symposium was organized around 37 invited papers and with 11 oral contributions chosen for their complementarity with the invited talks. Also, 76 posters were presented by the participants. The invited papers were solicited to provide a complete coverage of the fields defined above. The 32 chapters of this book represent essentially the symposium content and structure. Seventeen contributed papers were published as regular papers in a special issue of *Planetary and Space Science* (Vol. 44, n° 9, September 1996).

The first, and most extensive, part of the book is devoted to the "Physics and Chemistry of Ices" (13 chapters) and focuses on our knowledge of the thermodynamical, mechanical and electromagnetic properties of ices and the chemistry of ices. This material is largely based on laboratory experiments applied to planetary science-related questions. Most of the chapters discuss how to utilize the available data, what limitations are associated to their use in numerical models and what this implies for several important questions in planetary science that involve ices.

The second part of the book deals with the "Ices in the Primitive Solar Nebula and in Comets" (4 chapters). The first three chapters discuss the origin of icy solar system objects, what links these objects to the interstellar medium and to the primitive solar nebula, and what is the role played by ices with regard to their evolution towards their current physical state and their chemical composition. A chapter reviewing the composition and physical properties of comets completes this part.

The third part covers the topics "Ices in the terrestrial planets" (3 chapters) and discusses some of the surface and atmospheric properties of Earth and Mars ices. The Earth is viewed as an object on which unique studies can be carried out and that, of course, can not be performed anywhere else in the solar system. In particular, the direct comparison of remote sensing observations with ground truth is possible. Observations of the Earth also provide a close view of the complexity of the physical and chemical processes taking place within the limited number of ices to which we have access on it (*e.g.* H_2O and a few hydrates). The various aspects related to the presence of water ice on Mars are not treated because these are already extensively covered in the University of Arizona Press series' book "Mars" (mainly in chapters 16, 23, and 28). Some implications of specific physico-chemical properties of the ices on both planets are also discussed in several chapters of Part I.

The final part of the book is about "Ices in the Outer Planets and Satellites" (12 chapters) and it starts with a critical overview of the geology and geodynamics of the icy satellites as revealed by the Voyager instruments. The surface composition and properties of the icy satellites, the rings, the Pluto-Charon system and the Kuiper belt objects, as largely deduced from UV-to-IR spectroscopy and photometry, are then reviewed in five chapters. An extensive review about the occurrence of ice particles in the planetary atmospheres (including that of the terrestrial planets) and about the surface / atmosphere interactions will be found here that complements the two papers in Part II where Earth and Mars cloud properties are discussed. For the sake of completeness, the last paper reviews the evidence for the presence of ices in the interior of the giant planets.

Although progress in some of these areas of scientific research is quite rapid, we hope that this book will provide, for many years, to students and scientists a unique and detailed overview of the various aspects related to the presence of ices in the solar system, and will stimulate new vocations and open new directions for research.

B. Schmitt
C. de Bergh
M. Festou

September 1997

IN MEMORIAM

Jan Rosenqvist, Astronomer at the Observatoire de Paris, and one of the session Chairs at the meeting, passed away shortly after the conference. Jan was a caring friend and an unanimously esteemed colleague. He left us much too soon. Jan will remain forever in the memories of all those who had the chance to closely interact with him.

Jürgen H. Rahe, Science Program Director for Exploration of the Solar System at NASA Headquarters, in Washington, enthusiastically encouraged us to organize this event. His moral support and the financial assistance he provided from NASA were essential to the success of the meeting. Jürgen died in a tragic accident caused by a severe storm in June 1997. He was a warm, wonderful person, always looking for ways to help. An accomplished scientist and stimulating colleague, he became an excellent manager at NASA, and was strongly committed to international collaboration. He will be deeply missed by the entire community.

We dedicate this book to their memory.

The Editors

ACKNOWLEDGMENTS

Many people have contributed to the success of the "Solar System Ices" Conference and helped us to produce this book.

The scientific program was tailored with the invaluable assistance of the Members of the conference Scientific Organizing Committee, Akiva Bar-Nun, Jean-Pierre Bibring, Roger Clark, Angioletta Coradini, Marcello Coradini, Dale Cruikshank, Eberhardt Grün, Bruce Hapke, Bob Johnson, Torrence Johnson, Jürgen Klinger, Jonathan Lunine, William McKinnon, Dirk Möhlmann, Doug Nash, Tobias Owen, John Pearl, Jürgen Rahe, Francis Rocard, Farid Salama, Christophe Sotin, Gerhard Schwehm, Giovanni Strazzulla, and Pierre Thomas. The invited speakers and other chapter authors deserve our special thanks for providing the larger community with a written record of the conference content and a current overview of the role that ices play in formation and evolution of the solar system. The authors and speakers kindly agreed to organize their talks and chapter contents prior to the Conference to achieve harmony, yet present complementary points of view. Hopefully, the reader will find their efforts commendable.

This conference, held in March 1995 in Toulouse, proceeded smoothly due largely to the effectiveness of the Local Organizing Committee, especially Régine Bernhard and Chantal Taillades, and the session Chairs.

Numerous agencies and institutions supported this conference: The European Space Agency, through the very early support of M. Coradini, Secretary of its Solar System Working Group, the National Aeronautics and Space Administration and Jürgen Rahe, Science Program Director for Exploration of the Solar System, who provided grants to a number of U.S. participants, the Centre National d'Etudes Spatiales and F. Rocard, the Scientific Program Division Secretary, the International Science Foundation of Washington, who allocated grants to several eastern Europe participants, the Institut National des Sciences de l'Univers from the Centre National de la Recherche Scientifique of France, the "Région Midi-Pyrénées", the city of Toulouse which hosted a kind reception in the honor of the conference participants in the unique City Hall's "salle des Illustres", the University Paul Sabatier of Toulouse, the Observatoire Midi-Pyrénées, the Laboratoire d'Astrophysique de Toulouse, the Observatoire de Paris and its Département de Recherche Spatiale, and the Laboratoire de Glaciologie et Géophysique de l'Environnement of Grenoble. We also appreciated the moral support of COSPAR.

The edition and the production of this book was made possible thanks to exceptional financial support from the Laboratoire de Glaciologie et Géophysique de l'Environnement of Grenoble (LGGE) and from the Dépar-

tement de Recherche Spatiale (DESPA) of the Observatoire de Paris. We wish to thank many individuals from LGGE, and especially Catherine Ritz, for their moral support and their assistance in many of the numerous tasks associated with the chapter review process and the production of the book. We would like to express our special thanks to Dominique Lopes, from the Département d'Astrophysique Relativiste et de Cosmologie of the Observatoire de Paris, who assisted the Authors in assembling their texts in Kluwer's LaTeX format after having tirelessly checked and edited them, and also for having produced the many additional pages required to render the manuscript ready for the camera.

Again, we express our deepest thanks to the fifty-nine collaborating authors, the real architects of this book. Finally, let us say that we particularly appreciated the time and effort spent by the Reviewers whose names are listed below. Their careful reading of the manuscripts, their thougthful and constructive comments, greatly strengthened the quality of this book and widened its scope.

B. Schmitt
C. de Bergh
M. Festou
September 1997

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