PETRENKO, VICTOR F. and ROBERT W. WHITWORTH, 1999. *The physics of ice.* Oxford, etc., Oxford University Press, 384 pp. ISBN 0-19851-895-1, Hardback. £70.

At last there is a book of sufficient detail and scope, yet manageable size, that can be used as a text for graduate courses in ice physics. And students will want to keep it as a reference for their careers in the broad field of glaciology. This book is the first comprehensive treatment of the physics of ice to be written in the last 25 years. It provides an up-to-date discussion of the properties of ice and an interpretation of these properties in terms of the structure of the water molecule and ice crystals. The authors state that they have three aims in writing *The physics of ice*: it is intended to serve as a reference work on the physics of this unique and important material, as a critical review of the current knowledge and understanding of the different properties of ice, and as a text for graduate students. They succeed in each of these aims. The book is well written and, for the most part, contains just the right amount of detail. It will be useful to both graduate students and active researchers in the field. The bibliography is quite substantial, containing many references from the last 10 years as well as many classic papers.

Two previous books on ice are Hobbs' (1974) *Ice physics* and Fletcher's (1970) *The chemical physics of ice.* The former is a comprehensive reference tome, with extensive coverage of basic physical properties, nucleation, growth and ice in the atmosphere, while the latter is an excellent account of a few selected topics. Both are out of print, and there has been much experimental and theoretical research since these works were published. This new book provides a much-needed account of advances in ice physics since these earlier books were written.

Here I present an outline of the book, with some mention of what I feel are the strong points and those areas that are omitted or discussed too briefly. These comments are based on what I cover in an ice physics course and what I feel are important topics for a practicing glaciologist.

Petrenko and Whitworth's book is divided into 13 chapters, each directed to the discussion of one property or a related group of properties. Some of the chapters are relatively brief; others are quite detailed, reflecting the expertise of the authors. When used as a text for a course in ice physics, the less detailed chapters will require substantial introduction and additional discussion of the relevant theoretical concepts. One would also need to include some discussion on nucleation and growth of ice crystals, as this is missing from the book.

The Introduction gives a brief discussion of the water molecule and hydrogen bonding. It is unfortunate that there is not a more in-depth discussion of the shape of the molecule and its tetrahedral coordination, as this is key to the structure of all of the other phases of ice as well. Such a discussion could include a more detailed explanation of wave-function models leading to the non-colinear shape of the molecule, and more than a brief mention of the older yet still useful concept of lone pair orbitals as a model for the four-fold coordination.

The second chapter gives a complete discussion of the structure of ice Ih. It begins with the formation of ice from the liquid, although no mention is made at this point of the Clausius–Clapeyron equation in relation to the change in density and the phase diagram. The crystal structure of this ice is then discussed, followed by a clear discussion of proton disorder and zero point entropy. The phase diagram of water and the "perfect" crystal structures of the other phases of ice are relegated to a chapter near the end of the book.

Chapter 3 looks at properties of ice that are related to this perfect crystal structure, such as elasticity, thermal properties and vibrational spectroscopy. Single-crystal elastic constants are tabulated and discussed in terms of bonds in the crystal. There is no mention of seismic wave speeds and their temperature dependence for polycrystalline ice, but these are perhaps too far into the applied realm. The section on thermal properties is unnecessarily brief, especially considering the wealth of classical theories for these properties. Thermal expansion and conductivity are discussed, although there is no mention of the anisotropy of thermal conductivity, which is important in models of crystal growth. The discussion of heat capacity is quite terse, and its relation to an integral over vibrational modes, of which Debye and Einstein theories are approximations, is not given explicitly. This would be a welcome addition, as it would help strengthen the link between thermal properties and vibrational spectroscopy. There is also no discussion or tabulation of the thermal diffusivity and its temperature dependence, even though this is a useful (but derived) parameter. The final sections on lattice vibrations and on the modeling of these perfect crystal properties are clear and up to date. Because of the brevity of this chapter, some review of phonons, heat capacity and Debye theory would be required when used as graduate text.

Following these perfect crystal properties, the authors do not proceed with an introduction to the general concept of point defects in a crystal. Instead, they move into a discussion of electrical properties, and chapters 4 and 5 are in-depth discussions of the theoretical and observational aspects, respectively, of these electrical properties. The level of detail represents the expertise of the first author. Protonic defects are introduced only as needed for Jaccard's theory of conductivity and dielectric relaxation in ice. There are summaries of the theory and of the appropriate time constants; these are helpful when reading the chapter on experimental observations. This latter chapter includes excellent discussions of the experimental problems encountered with electrodes on ice samples, measured electrical properties and the effects of doping on these properties.

Chapter 6 then discusses point defects in general, including protonic (ionic and Bjerrum) and molecular defects (vacancies and interstitials), and impurities. Equilibrium concentrations and migration of such defects are explained in the context of ice structure. The chapter concludes with a useful summary of the types of defects and their role in electrical properties. There is also a summary table of parameters such as activation energies, effective charge, concentration and mobility of the protonic defects.

Chapter 7 presents a clear and thorough discussion of dislocations, including an introduction to dislocation mechanics. There are also sections on planar defects and grain boundaries. This chapter reflects the expertise of the second author, and is well illustrated with drawings and photographs. Dislocation velocities are related to stress, proton disorder and dielectric relaxation, following the ideas of Glen and Whitworth. This, plus the discussion of grain boundaries, then leads into chapter 8 on creep and brittle failure of ice. Orowan's equation relating strain rate to dislocation density and velocity is presented, leading to the basic power-law rheology for single crystals. Both basal and non-basal glide are summarized. These ideas, and grain-boundary sliding, then provide the motivation for the following section on the creep of polycrystalline ice. The introduction to this section is quite informative, as it presents the possible mechanisms of polycrystalline creep and a discussion of the different parts of a creep curve (primary, secondary and tertiary creep). The authors correctly point out that tertiary creep is of most significance to glaciology, although the flow law is often defined using measurements of secondary creep. They also note that hydrostatic pressure may cause an increase in deformation rate because of increasing proximity to the melting point, but they do not introduce the concepts of homologous temperature or activation volume. The actual discussion of the specific form of the flow law for polycrystalline ice is somewhat limited. There is little discussion of the tensorial nature of the flow law, and its dependence on the second invariant of the deviatoric stress. The possibility of, and experimental tests for, a more complex flow law, which could involve the third invariant, are not mentioned. Obvious omissions are a summary of experimentally derived creep parameters for polycrystalline ice and a discussion of diffusional (Nabarro–Herring or Coble) creep, which is thought to occur at low stress levels. A discussion of deformation maps, which show regions of different creep mechanisms in temperature-stress (or strain-rate) space, is likewise missing.

Chapter 9 is a short but thorough summary of the optical properties of ice. It begins with a chart of the electromagnetic spectrum and a helpful presentation of the often confusing units used in the different fields of spectroscopy, followed by a summary of electromagnetic wave propagation in solids. Real and imaginary parts of the refractive index over a broad range of frequencies are presented, although the Kramer–Kronig relations used to derive these indicies are not described. There are brief but useful sections on the details of the infrared, visible and UV spectrum.

Chapter 10 is an up-to-date account of the surface of ice, with a detailed discussion of the properties and thickness of the "liquid-like" layer found on the free surface and at the interface between ice and other solids. The electrical properties of this layer are also discussed, but there is no mention of the (possibly) viscous properties of this layer, which might be important in the creep of debris-rich ice or sliding at temperatures below the melting point.

Chapter 11 begins with an overview of the phase diagram of water and the introduction of the Clausius–Clapeyron equation. This is followed by a discussion of the different phases, including the more recently discovered phases like ordered ice Ih and ionic ice, which was first predicted theoretically. The structures of the different phases are presented, as well as some of their properties. There are also short sections on the existing knowledge of the vibrational spectra of these other phases and on clathrate hydrates. Had this chapter come earlier, the authors could perhaps have related some of the basic properties (e.g. vibrational, electrical and mechanical) of these phases to those of ice Ih in the appropriate chapters.

A brief summary of ice in Nature is given in chapter 12. This will be especially useful when the book is used as a graduate text, as it relates many of the physical properties discussed throughout the book to ice in the real world. The book concludes with a chapter on the adhesion and friction of ice, a topic that might more appropriately follow the chapter on surface properties.

In addition to the remarks already made, there are a few other apparent omissions in the book. These include: no discussion of the structure of the liquid phase and how it relates to that of the water molecule and of ice; no discussion of the physics of regelation, which is a property unique to ice; only one sentence and no photograph devoted to the beautiful internal melt ("Tyndall") figures, which may occur because of anisotropic thermal properties and can lead to negative internal pressures; only a brief discussion of the albedo of ice and snow; and no discussion of the material properties of the other phases of ice, which are important given the recent interest in these ices within the moons of Jupiter and Saturn, as well as because of the possible links between proton disorder, dislocation motion and dielectric relaxation.

However, these are only minor omissions given the scope and detail of the book, and the authors do an admirable job of attaining the three goals they put forth in the preface. I have benefited from its summary of our current understanding of the properties of ice, and it will serve well as the text for my semester-long course in ice physics.

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