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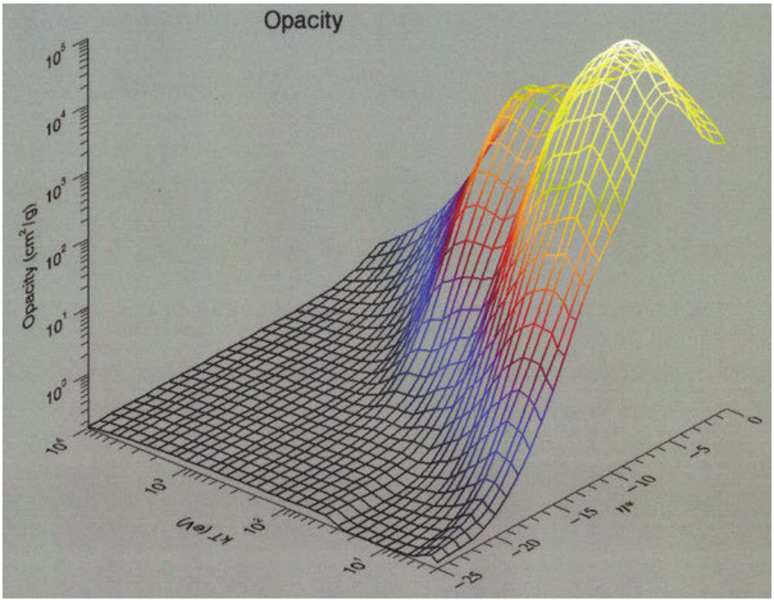
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10^4
10^3
10^2
10^1
10^0
kT (eV)
η
0
-5
-10
-15
-20
-25

Walter F. Huebner • W. David Barfield

Opacity

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The frontispiece illustration shows a 3-D surface plot of the total Rosseland mean opacity of oxygen as a function of the degeneracy parameter and temperature. The sample data were extracted from the opacity code ATOMIC and visualized using the opacity visualization tool OVID (Courtesy Leslie Welser-Sherrill, Los Alamos National Laboratory)

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Preface

"The essential principle of the fallen world appears to be discreteness or opacity." This quote is from an essay by Northrope Frye on "[Wm.] Blake's Treatment of the Archetype." The essay appeared in *English Institute Essays*, ed. A. S. Downer, Columbia U. Press (1951). However, *this* book on opacity is a scientific treatise of a property of matter that describes its resistance (attenuation, i.e., absorption and scattering also known as extinction) to transmission of electromagnetic radiation (or, more explicitly, resistance to energy transport by photons). It is written with a positive disposition and is of a quantitative nature. We stress modern methods as well as historical development for calculating and measuring opacities.

The book was developed over many years. We follow the advances of opacity calculations and measurements over more than half a century. Many new techniques, particularly in the area of non-local thermodynamic equilibrium (non-LTE) opacity, are being developed that will revolutionize radiative transfer in the foreseeable future. We only briefly introduce this rapidly expanding field. Another area of relevant research not covered in this book is based on quantum molecular dynamics (QMD) for dense plasmas. QMD automatically includes electron degeneracy and collective effects.

In some applications, opacities are used for mixtures involving chemical compounds undergoing phase changes as the temperature and density or pressure change with time. For example, opacities have been used inconsistently from various different sources for changing density – temperature regions, ignoring that they represent different elemental compositions, i.e., heterogeneous chemical equilibrium between gas and condensed phases has been ignored. As a typical example, the opacity of a dust-containing interstellar molecular cloud may be used in modeling early stages of star formation while the opacity used for the evolution of that star at a later stage comes from a different source or model and has a different elemental (chemical) composition. In other applications, phase changes may involve formation (or destruction) of liquid droplets or dust particles containing layered materials with different heats of melting, vaporization, or sublimation. To circumvent such problems, we discuss minimization of the Gibbs free energy as a tool for applying the applicable phase transformations from solid to liquid to gas to plasma (or the reverse sequence) in calculating the equation of state and the associated opacity, thus preserving the basic elemental (chemical) composition during phase changes.

The nature of opacities requires us to apply many different disciplines in which the same well-established symbol is used to refer to very different quantities, even though symbols to represent many commonly used quantities have been recommended by several international organizations. Unfortunately, the alphabet does not provide the large number of options to uniquely define by a single letter all quantities we encounter in a multidisciplinary treatise. We tried to be creative and modified symbols with subscripts, superscripts, and various accent designations to make our symbols distinct but similar to established usage. There is room for further improvement in this area. For example, we use α for the chemical potential, α_o for the fine structure constant, α_p for the polarizability, α_e for the molecular vibration-rotation coupling constant, etc. When we use α for other purposes locally, its meaning is defined at that time. When we use it as a dummy variable, its use will be apparent. A list of symbols is provided in Appendix A.

The meanings of most commonly encountered basic quantities in radiation processes have also been standardized by international agreements, e.g., the International Union of Pure and Applied Physics, the International Union of Pure and Applied Chemistry, the International Commission on Radiation Units and Measurements, the International Standards Organization, the American Illuminating Engineering Society, and the Royal Society of London. However, several basic and internationally defined quantities have conflicting names in astronomy. Examples include radiance, irradiance, exitance, flux, and intensity. Making matters worse, many books use different definitions for various physical and chemical quantities. Even though many books use the MKS system of units and SI units are based on the MKS system, the definition of physical quantities are not always consistent. Since this book deals with subjects of interest to plasma physics and astronomy, and astronomers and astrophysicists regrettably do not always abide by these conventions, we will use the terminology and definitions endorsed by many international bodies, but occasionally point out astronomical usage. We will quote units associated with these quantities to dispel any confusion. Appendix B, which contains also a glossary of terms and a list of commonly used abbreviations, should be consulted in case of any remaining confusion. Appendix C provides some mathematical functions useful for opacity calculations.

Another area of confusion widely encountered in the literature is the terminology for some definitions such as line strength. The definition for line strength is exactly the same for atoms and molecules. However, for molecules (see, e.g., the section on the just-overlapping lines model), the line strength is often defined by the frequency (or wavenumber) integrated absorption cross section of a line. This is incorrect. We have tried to avoid confusions of this type, but again, there is room for further improvements.

We also try to use SI units consistently throughout the book. However, atomic units are widely used in calculating atomic and molecular structure and closely related quantities such as cross sections, electrical and thermal conductivities, etc.

Thus, in some cases we also provide equations using atomic units. Since many different disciplines are involved in opacity and equation of state calculations, we provide Appendix D: Units, Conversion Factors, and Fundamental Physical Constants to ease the burden for readers from different fields. Finally, Appendix E provides some relevant websites.

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Acknowledgments

This book started as a review paper of opacity calculations, but soon expanded beyond acceptable limits for publication in a professional journal. The ideas in the book were developed in close collaboration with our colleague and friend A. L. Merts, whose contributions we acknowledge posthumously. He worked diligently on sections of quantum mechanics including autoionization, quantum defect methods applied to oscillator strengths, and molecular absorption.

In the description of quantum mechanical methods (Chaps. 3 and 5) we have shamelessly paraphrased cited sources. We wish to thank the many authors and journals who have granted us permission to do so. In particular, we want to thank David P. Kilcrease who suggested helpful explanations, read the entire manuscript, and recommended its declassification based on his expertise in opacities. Among those of our friends and colleagues who have read various sections of the manuscript and contributed significantly are: James Colgan, who provided valuable input on non-LTE opacity calculations; Robert D. Cowan, whose atomic physics code was used extensively; Christopher M. Sharp, who made valuable comments about molecular opacities and the effects of phase transitions on equations of state (EOS); and Jeremy B. Tatum, who clarified questions about polarizabilities. We benefited from many discussions with J. Abdallah, Jr., A. N. Cox, C. Iglesias, J. J. Keady, N. H. Magee, Jr., F. Rogers, M. Sherrill, and R. Whittaker, who provided insights to various sections of the manuscript.

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