



ASTRONOMY AND ASTROPHYSICS LIBRARY

Series Editors:

G. Börner, Garching, Germany
A. Burkert, München, Germany
W. B. Burton, Charlottesville, VA, USA and
Leiden, The Netherlands
M. A. Dopita, Canberra, Australia
A. Eckart, Köln, Germany
E. K. Grebel, Heidelberg, Germany
B. Leibundgut, Garching, Germany
A. Maeder, Saunerny, Switzerland
V. Trimble, College Park, MD, and Irvine, CA, USA

Josef Kallrath · Eugene F. Milone

Eclipsing Binary Stars: Modeling and Analysis

Second Edition

 Springer

Josef Kallrath
Department of Astronomy
University of Florida
Gainesville, FL 32611-2055
USA
josef.kallrath@web.de

Eugene F. Milone
Department of Physics & Astronomy
University of Calgary
2500 University Drive NW
Calgary, AB T2N 1N4
Canada
milone@ucalgary.ca

ISSN 0941-7834

ISBN 978-1-4419-0698-4

e-ISBN 978-1-4419-0699-1

DOI 10.1007/978-1-4419-0699-1

Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2009928498

© Springer Science+Business Media, LLC 1999, 2009

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Professori Dr. Hans Schmidt,

magisto doctissimo ac clarissimo, patri et amico
hoc opus votis optimis D.D.D.¹

To Harlan Smith and Adriaan Wesselink,

teachers extraordinaire, and, to my great fortune,
my graduate advisors.²

¹ Josef Kallrath.

² Eugene F. Milone.

Foreword

Have you ever stopped at a construction project on the way to your office and the day's astrophysics? Remember the other onlookers – folks just enjoying the spectacle, as we all do in following developments away from our areas of active work? We are excited and thrilled when the Hubble Space Telescope discovers an Einstein Cross, when the marvelous pulsars enter our lives, and when computer scientists put a little box on our desk that outperforms yesterday's giant machines. We are free to make use of such achievements and we respect the imagination and discipline needed to bring them about, just as onlookers respect the abilities and planning needed to create a building they may later use. After all, each of us contributes in our own areas as best as we can.

In addition to the serious onlookers there will be passersby who take only a casual look at the site. They may use the building later, but have little or no interest in its construction and give no thought to the resources needed to bring it to completion. Upon arriving at work, those persons write astronomy and astrophysics books at various levels, in which they must say something about close binary stars. Usually a page or two will do, and the emphasis is on the MLR (mass, luminosity, radius) data obtained only from binaries. The role of binaries in stellar evolution also may be awarded a page or so, perhaps meshed with binaries being homes of black holes and neutron stars. We live in an era of ever more applied research, with national priorities set by the interests and judgments of select committees. Consequently, most authors tell us the answer to one central question: What have binaries done for us lately? Well, of course, binaries are alive and well as sources of fundamental information on many fronts. But what of the fun, intrigue, and beauty of close binaries?

However, I do not want to be hard on the generic text authors because I remember my initial reaction to binaries. A fellow graduate student (later a very accomplished researcher) was doing a binary star project and I could not imagine why he was so interested. He tried to explain it all, but it just was not working: subject = non-exciting. However, I soon was into binaries anyway, just due to being surrounded by binary star work (yes, with appalling conformity). Time went by and then something happened to turn the view around – it was Su Shu Huang's work on ϵ Aurigae and also on β Lyrae. Here was pure distilled cleverness and insight. Huang looked at problems that had been examined exhaustively by several of the most celebrated astrophysicists and saw things that had eluded everyone. Suddenly binaries were

locales where mystery could transform into understanding if one looked in the right way. But where does one learn to do this sort of thing, in a course? Not at most schools. Can one learn from a book? Well, there are books on binary stars, but they mainly serve as repositories of formulas, derivations, and diagrams, and some follow the ideas of only one person or “school.” A few books give recipes for procedures developed by their authors, usually without providing insight. There has long been a need for a book that takes a wide view of binary star models and their interface with observations, and that is the goal set by Josef Kallrath and Eugene F. Milone, who together have broad experience in binary star models and observations. Their creation has conscientious coverage throughout most of the “models versus observations” field. It can guide interested persons into the overall field and be a helpful companion as they explore new examples, such as in the *initial approach* (what is going on?), a *settling-in stage* (is it a standard situation or are there complications?), *getting up to speed* (developing intuition and extracting maximum information), and finally *evaluation of results*.

Examine the Contents to see a variety of topics not found in the few preceding books in this general area. Here we find extensive treatment of history, terminology, observational methods, accuracy, binary models *from the ground up*, system morphology, a sense of where things are going, perspectives for long-range development, guides to exploration of the literature, and even philosophy. Although not all important categories of binaries are covered, nor are all individual binaries of special interest, the coverage in this first edition is remarkable. Protest marches for inclusion of symbiotics, ultra-compact X-ray binaries, etc., in future editions may well be successful. For now the emphasis is on more general considerations. We see a balance between *hands-on* and *automated* analysis. Extreme *hands-on* advocates typically get things roughly right and can recognize novel features but fail to extract all available information. Extreme advocates of the *automated* school can reach optimal solutions for standard cases but miss anything new (there is more to astrophysics than parameter adjustment). We need to navigate between these extremes.

The names of some luminaries of the binary star field may seem to be under-represented, for example, those in structure and evolution. Should we not be reading more about Eggleton, Kippenhahn, Lucy, Ostriker, Paczynski, Plavec, Taam, van den Heuvel, Webbink, etc.? But remember that it is a book about direct representation of observations through models and must be kept to a reasonable size, and there are excellent books on structure and evolution.

Although the scope is limited to models, observations, and related mathematics, there is something here for everyone. Thus we learn that the Kolmogorov–Smirnov test is not, after all, a way to distinguish vodkas. And there are binaries for everyone. Game players will like the one that stays in eclipse 90% of the time and comes out for only 10% (*PK Boo*). Gadget aficionados prefer the remote paging device, *b Per*. We have a thing to play in *TV Cet* and a place to stay in *HO Tel*. And then there is the only star with a question mark in its name (*Y Sex?*). So peruse the book, learn from it, and enjoy close binaries. If you happen to find some MLR data along the way, so much the better.

R. E. Wilson

Preface to the Second Edition

Di, coeptis . . . *adspirare meis* (Gods, aid my undertaking)
Ovid (43 B.C.–A.D. 17), *Metamorphoses* 1,2-4

The second edition arose from the authors' and the publisher's observations that 10 years after the first edition a new edition is needed to cover the impressively long list of new physical features and analyzing methods in eclipsing binary (*EB*) star analysis. Direct distance estimation through *EB* analysis is one of the highlights. Complete derivation of the ephemerides and third-body orbital parameters from light and radial velocity curves is another. Incorporation of interpolation-based approximations to stellar atmospheres has become common practice. Limb-darkening coefficients do not need to be entered explicitly but are locally computed as function of temperature, gravity, wavelength, and chemical composition.

EB research has made great contributions to stellar astrophysics for over a century, e.g., resolution of the Algol paradox, insights into the physics of cataclysmic variables, and improved understanding of W UMa stars. Bright *EB*s can be observed and analyzed for orbital and physical properties to high accuracy with even modest equipment. The advent of larger telescopes and powerful instrumentation also allows analysis and distance estimations of *EB*s in Local Group galaxies even as far as M31 and M33. Large telescopes also allows the observation and study of eclipsing very-low-mass stars, brown dwarfs and planets, and even planets in *EB*s. The detection of extra-solar planets by transit methods is a field not entirely outside the *EB* research where *EB* techniques have been used successfully.

The Kepler mission¹ (cf. Koch et al. (2006)) launched on March 6th, 2009, the GAIA mission to be launched in 2012 or the *Large Synoptic Survey Telescope* (LSST; <http://www.lsst.org/>), in discussion for after 2015, will add a new challenge to the field: The analysis of large numbers of *EB* light curves from surveys. Finally, enhanced or completely new software is available for *EB* research. PHOEBE (Sect. 8.2) is an example of a platform-independent *EB* software with an attractive graphical user interface.

¹ Updated details are at <http://www.kepler.arc.nasa.gov>.

The proceedings of IAU Symposium No. 240 (2006) [entitled *Binary Stars as Critical Tools & Tests in Contemporary Astrophysics*, edited by Hartkopf et al. (2007)] provide an excellent overview on state-of-the-art and ongoing activities in close binary research. They briefly review major advances in instrumentation and techniques, new observing and reduction methods, and discuss binary stars as critical tools and tests for studying a wide variety of astrophysical problems. *Tools of the Trade and the Products they Produce: Modeling of Eclipsing Binary Observables* edited by Milone et al. (2008) is another source highlighting recent advances. We see strong enhancements both in physics and in *EB* software:

- additional physical features
 1. an alternative method to derive a binary's ephemeris;
 2. effects of third bodies on light curves and radial velocity curves;
 3. *EBs* with intrinsically variable components;
 4. stellar atmosphere approximation functions;
 5. direct distance estimation;
 6. color indices as indicators of individual temperatures;
 7. spectral energy distribution as independent data source; and
 8. main sequence constraints;
- enhanced programs and new software;
- techniques for analyzing large numbers of light curves, and;
- *EBs* in extra-solar planet research.

We largely retain the structure of the first edition. Some sections have been added to the existing chapters, especially the *Eclipsing Binary Guide for Researchers in Other Fields* in Chap. 1. What is now called Chap. 5 hosts most of the new material. Chapters 5, 6, and 7 of the first edition are now Chaps. 6, 7, and 8 of this second edition.

Last but not least: The book is now part of Springer's *Astronomy and Astrophysics Library Series* which both indicates and acknowledges its wider relevance for astronomy and astrophysics.

Gainesville, FL, US
Calgary, AB, Canada

Josef Kallrath
Eugene F. Milone

Preface to the First Edition

Di, coeptis . . . *adspirare meis*

(*Gods, aid my undertaking*)

Ovid (43 B.C.–A.D. 17), *Metamorphoses* 1,2-4

This book arose from the realization that light curve modeling has not had a full expository treatment in 40 years. The last major exposition was that of Russell & Merrill (1952), and that treatment dealt exclusively with the Russell–Merrill spherical star model and with the process of light curve rectification. The present work may be the first comprehensive exposition of the merits of the major modern light curve analysis methods, notwithstanding the pioneer efforts of many investigators beginning with Kopal (1950), who again described mainly his own efforts. The need for a sourcebook and didactic presentation on the subject was recognized in the course of planning a conference on light curve modeling which was held in Buenos Aires and Cordoba in July–August, 1991. The proceedings of the Argentina meetings (Milone 1993) review the current state of light curve modeling methods and focus on special topics but do not give a general review. The only previous meeting devoted exclusively to the topic of comparative light curve modeling methods was IAU Colloquium No. 16 in Philadelphia in September 1971.

Although there is an extensive literature on eclipsing binary research, the paucity of instructional materials in the area of light curve analysis is striking. The graduate student, the researcher, or the advanced amateur astronomer must struggle through journal articles or conference proceedings and must read between the lines to glean the details of the modeling process. Most of the didactic books on light curve modeling date to the presynthetic light curve era. The monograph by Russell & Merrill (1952) is one major example and that by Kopal (1959) is another. Yet the need is acute: As with many other areas of science, the computer revolution has given many astronomers, amateur as well as professional, the tools to attempt light curve solutions. In this work, we provide a suitable background for the new modeler, a useful source book for the experienced modeler, and a springboard for the development of new modeling ideas. For the Wilson–Devinney approach in particular, we elaborate on some of the subtle details that determine the success or failure of light curve computation.

Methods of analyzing eclipsing binary data involve

1. the specification of an astrophysical model;
2. the selection of an algorithm to determine the parameters; and
3. the estimation of the errors of the parameters.

The focus of the book is primarily on models and algorithms rather than on model applications and individual binaries. Nevertheless, models and algorithms are illustrated through investigations of individual stars. The review by Wilson (1994) deals with the intuitive connection between binary star models and light curves and the historical development of the field. Here we concentrate on the mathematical formulation of models and the mathematical background of the algorithms. We present a self-contained, elementary treatment of the subject wherever possible. The book is written for the reader who is familiar with the basic concepts and techniques of calculus and linear algebra. As an aid to the exploration of higher-level material, a brief introduction into the theory of optimization and least squares methods is provided in Appendix IV. Besides presenting the physical and mathematical framework, we have tried to present the material so that it is not far from actual implementation.

The book consists of four major parts: Introductory material (Chaps. 1 and 2); the physical and mathematical core (Chaps. 3 and 4); practical approaches (Chaps. 5 and 6); and the authors' views on the structure of future light curve programs (Chap. 7). The appendices provide further mathematical details on specific topics and applications and point to other sources. The structure of the book should assist readers who are taking their first steps into the field to get a sound overview and also experienced researchers who are seeking a source book of formulas and references.

Chapter 1 gives a nonmathematical overview of the field. In particular, the issues of what can be derived from eclipsing binary stars and why these data are relevant to astrophysics in general are considered. Here we introduce the general concept of equipotential surfaces. Because an eclipsing binary analyst needs understanding of observational data, some background on the database and methods of data acquisition is necessary. Therefore, in Chap. 2 we review observational methods relevant to data analysis. Chapter 3 contains a general approach to light curve modeling. The chief concern is the solution of the direct problem: computing light curves, radial velocity curves, and other observables for a given set of parameters. To this end, a mathematical framework is presented for the relevant astrophysics. The inverse problem of the determination of eclipsing binary parameters is discussed in Chap. 4. As in Chap. 3, we present a formal approach that may serve as a platform for further developments in data analysis. Besides attending to critical issues in light curve analysis, the formulation allows various methods to be related and discussed from a common point of view. Chapter 5 gives characteristics of existing light curve programs and coding details for some of them. Here, the purpose is to provide the new light curve analyst with an overview to explore concepts relevant to the field, including the astrophysics of particular programs and how they work. Because the Wilson–Devinney program is the most frequently used light curve analysis tool, Chap. 6 discusses special eclipsing binary cases analyzed with the Wilson–Devinney program and related programs. In order not to overburden Chaps. 5 and 6, most of

the practical details of the Wilson–Devinney program are collected in Appendix D.1. Chapter 7 summarizes ideas and strategies for building light curve programs and previews the coming decade. It is intended as a stimulant to further eclipsing binary research and light curve program development.

Some topics that are covered only briefly will have more extensive treatment in some later edition. A first group covers further model extensions requiring time rather than phase as input quantity, e.g., variable periods, apsidal motion, eclipsing binaries with intrinsically variable components, spot migration, circumstellar flows. Other extensions will focus on particular types of binaries: cataclysmic variables, symbiotic stars and other red-giant binaries, W Serpentis stars, high, low, and ultralow mass X-ray binaries, binaries with atmospheric eclipses, and individual strange objects such as ϵ Aurigae, β Lyrae, and Cygnus X-1.

Gainesville, FL, US
Calgary, AB, Canada

Josef Kallrath
Eugene F. Milone

References

- Hartkopf, W. I., Guinan, E. F., & Harmanec, P. (eds.): 2007, *Binary Stars as Critical Tools and Tests in Contemporary Astrophysics*, No. 240 in Proceedings IAU Symposium, Dordrecht, Holland, Kluwer Academic Publishers
- Koch, D., Borucki, W., Basri, G., Brown, T., Caldwell, D., Christensen-Dalsgaard, J., Cochran, W., Dunham, E., Gautier, T. N., Geary, J., Gilliland, R., Jenkins, J., Kondo, Y., Latham, D., Lissauer, J., & Monet, D.: 2006, The Kepler Mission: Astrophysics and Eclipsing Binaries, *Ap. Sp. Sci.* **304**, 391–395
- Kopal, Z.: 1950, The Computation of Elements of Eclipsing Binary Stars, *Harvard Observatory Monograph* **8**, 1–181
- Kopal, Z.: 1959, *Close Binary Systems*, Chapman & Hall, London
- Milone, E. F. (ed.): 1993, *Light Curve Modeling of Eclipsing Binary Stars*, Springer, New York
- Milone, E. F., Leahy, D. A., & Hobill, D. W.: 2008, *Short-Period Binary Stars: Observations, Analyses, and Results*, Vol. 352 of *Astrophysics and Space Science Library*, Springer, Dordrecht, The Netherlands
- Russell, H. N. & Merrill, J. E.: 1952, The Determination of the Elements of Eclipsing Binary Stars, *Princeton. Obs. Contr.* **26**, 1–96
- Wilson, R. E.: 1994, Binary-Star Light-Curve Models, *PASP* **106**, 921–941

Acknowledgments

Robert E. Wilson¹ provided unstinting help in the clarification and exposition of his model and program and in carefully reviewing drafts of the present volume. Dirk Terrell¹ provided a great deal of help in explicating and coding details of the light curve modeling improvements. Andrew T. Young² provided valuable discussions concerning photometry. It is a pleasure to thank A. M. Cherepashchuk³ for translating an important segment of his work into English for inclusion in the chapter on what we call “The Russian School” of light curve modeling.

Albert P. Linnell,⁴ Stephen Mochnacki,⁵ and Petr Hadrava⁶ provided detailed material on their light curve programs. Dirk Terrell provided a description of his Windows PC interface to the Wilson–Devinney program. David H. Bradstreet⁷ made Binary Maker 2.0 and 3.0 available to us; his program helped us to produce many of the pictures in this book.

We are grateful to a number of colleagues who read the manuscript critically and made many valuable suggestions, especially Horst Drechsel,⁸ Paul Etzel,⁹ Hilmar Duerbeck,¹⁰ Horst Fichtner,¹¹ Jason McVean,¹² Petr Hadrava, Edward Olson,¹³

¹ Department of Astronomy, University of Florida, Gainesville, Florida, USA.

² Astronomy Department, San Diego State University, San Diego, California, USA.

³ Sternberg Astronomical Institute, Moscow, Russia.

⁴ Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.

⁵ Department of Astronomy, University of Toronto, Toronto, Ontario, Canada.

⁶ Astronomical Institute, Academy of Sciences of the Czech Republic, Ondřejov, Czech Republic.

⁷ Department of Physical Sciences, Eastern College, St. Davids, Pennsylvania, USA.

⁸ Universitätssternwarte Bamberg, Bamberg, Germany.

⁹ Astronomy Department, San Diego State University, San Diego, California, USA.

¹⁰ WE/OBSS, Brussels Free University (VUB), Brussels, Belgium.

¹¹ Fakultät für Physik und Astronomie, Ruhr-Universität Bochum, Bochum, Germany.

¹² Department of Physics and Astronomy, University of Calgary, Calgary, AB.

¹³ Department of Astronomy, University of Illinois, Urbana, USA.

Johannes P. Schlöder,¹⁴ Klaus Strassmeier,¹⁵ Richard Walker,¹⁶ and Robert E. Wilson. Parts of the manuscript were also read by Bernd-Christoph Kämper¹⁷, Hilde Domgörgen,¹⁸ and Olaf Evers.²⁴ Bernd-Christoph Kämper, Horst Fichtner, and Eric Leblanc,¹⁹ have been very helpful in checking out references.

We are grateful also to a number of colleagues who provided illustrations: Fred Babott,²⁰ Horst Drechsel, Hilmar W. Duerbeck, Jason MvVean, Jaydeep Mukherjee,²¹ Colin D. Scarfe,²² Dirk Terrell, and Robert E. Wilson. Finally, we thank Michael Alperowitz²³ and Robert C. Schmiel²⁴ for careful checking of the ancient Greek and Latin proverbs and historical quotations and to Christine Bohlender¹⁸ and Norbert Vormbrock¹⁸ who helped in the production of postscript graphics.

The second edition benefited again strongly from Robert E. Wilson's encouraging support, extensive discussions, and personal notes on his light curve program. The time spent with Bob and the hospitality in his house was also a personal enjoyment. Walter Van Hamme²⁵ helped to clarify various points on the stellar atmosphere option added to the Wilson–Devinney program. Andrej Prša²⁶ provided additional explanations on his software package PHOEBE and created Fig. 8.4 for this book. Hilmar Duerbeck,²⁷ Roland Idaczyk²⁸, and Steffen Rebennack²⁹ read the manuscript carefully, identified subtle problems, and made valuable suggestions. Steve Howell³⁰ reviewed the photometric material in Chaps. 1 and 2 and made numerous helpful suggestions. Petr Hadrava read parts of the manuscript and corrected minor problems. Steffen Rebennack supported the LaTeX-embedded production of the figures. Springer's editing team was very constructive and our main editor, Harry Blom, patiently allowed this book to become mature and reach its current state. Finally, Alex Jack helped with proofreading.

¹⁴ Interdisziplinäres Zentrum für wissenschaftliches Rechnen (IWR) der Universität Heidelberg, Heidelberg, Germany.

¹⁵ Universitätssternwarte Wien, Vienna, Austria.

¹⁶ US Naval Observatory, Flagstaff Station, Flagstaff, Arizona, USA.

¹⁷ Universitätsbibliothek Stuttgart, Stuttgart, Germany.

¹⁸ BASF SE, Ludwigshafen, Germany.

¹⁹ DAO, Herzberg Institute of Astrophysics, Victoria, BC

²⁰ Rothney Astronomical Observatory, University of Calgary, Calgary, AB.

²¹ Department of Astronomy, University of Florida, Gainesville, Florida, USA.

²² Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada.

²³ Seminar für klassische Philologie der Universität Heidelberg, Germany.

²⁴ Department of Greek and Latin, University of Calgary, Calgary, AB.

²⁵ Department of Physics, Florida International University, Miami, FL 33199, USA.

²⁶ Villanova University, Dept. Astron. Astrophys., 800 E Lancaster Ave, Villanova, PA 19085, USA.

²⁷ WE/OBSS, Brussels Free University (VUB), Brussels, Belgium.

²⁸ Ngaio, Wellington 6035, New Zealand.

²⁹ Center for Applied Optimization, University of Florida, Gainesville, FL.

³⁰ WIYN, NOAO, Tucson, AZ.

Contents

Foreword	vii
Preface to the Second Edition	ix
Preface to the First Edition	xi
References	xiii
Acknowledgments	xv
List of Figures	xxvii
Journal Abbreviations	xxxi
Acronyms and Abbreviations	xxxiii
Mathematical Nomenclature and Symbols, Physical Units	xxxv

Part I Introduction

1 Introduction	3
1.1 Eclipsing Binaries and Other Variable Stars	3
1.1.1 Eclipsing Variables	5
1.1.1.1 Algols	5
1.1.1.2 β Lyrae	6
1.1.1.3 W Ursae Majoris or W UMa	6
1.1.2 Pulsating Variables	7
1.1.3 Eruptive Variables	8
1.2 Overview of the Problem	10
1.2.1 Why Binary Stars Are Important	10
1.2.1.1 Visual Double Stars	11
1.2.1.2 Spectroscopic Binaries	13
1.2.1.3 Eclipsing Binaries	14

- 1.2.2 Phenomenological Classification of Eclipsing Binary Light Curves 15
- 1.2.3 Morphological Classification of Eclipsing Binaries 18
- 1.2.4 What Can Be Derived from Eclipsing Binaries 22
- 1.2.5 Why Data Derived from Eclipsing Binaries Are Important 22
- 1.3 The History of Light Curve Modeling 23
 - 1.3.1 The Pioneers – The Age of Geometry 23
 - 1.3.2 The Age of Computational Astrophysics 24
 - 1.3.3 Determining Astrophysical Parameters 25
 - 1.3.4 Later Generations of Light Curve Models 25
 - 1.3.5 Astrophysical Problems Solved by Light Curve Methods 26
- 1.4 EB Guide for Researchers in Other Fields 27
 - 1.4.1 Eclipsing Binaries and Standard Candles 27
 - 1.4.2 Eclipsing Binaries in ExtraSolar Planet Research 28
 - 1.4.3 Nomenclature: Primary and Secondary Component 29
 - 1.4.4 Where Are the Radii? 29
 - 1.4.5 Precession and Apsidal Motion 29
 - 1.4.6 Looking for Eclipsing Binary Standard Software 30
 - 1.4.7 Analytic Techniques and Numerical Analysis 30
- 1.5 Selected Bibliography 30
- References 31

- 2 The Database and Methods of Data Acquisition 37**
 - 2.1 Photometry 37
 - 2.1.1 Photoelectric Photometry 37
 - 2.1.2 Two-Star Photometers 39
 - 2.1.3 Photoelectric Observations 41
 - 2.1.4 Imaging Data 43
 - 2.1.5 Photometric Data Reduction 44
 - 2.1.6 Significance of Cluster Photometry 47
 - 2.2 Spectroscopy 48
 - 2.2.1 Radial Velocities 51
 - 2.2.2 Spectrophotometry 53
 - 2.2.3 Line-Profile Analysis 55
 - 2.3 Polarimetry 57
 - 2.4 Magnetometry 59
 - 2.5 Doppler Profile Mapping 60
 - 2.6 Advice to Observers 60
 - 2.7 Eclipsing Binary Data from Surveys 62
 - 2.8 Terminology: “Primary Minimum” and “Primary Star” 65
 - 2.9 Selected Bibliography 66
 - References 67

Part II Modeling and Analysis

3 A General Approach to Modeling Eclipsing Binaries	75
3.1 System Geometry and Dynamics	77
3.1.1 Coordinates and Basic Geometrical Quantities	77
3.1.2 Dynamics and Orbits	82
3.1.2.1 Circular Orbits	85
3.1.2.2 Eccentric Orbits	85
3.1.3 Spherical Models	89
3.1.4 Ellipsoidal Models	92
3.1.5 Roche Geometry and Equipotential Surfaces	95
3.1.5.1 Circular Orbits and Synchronous Rotation	96
3.1.5.2 Circular Orbits and Asynchronous Rotation	98
3.1.5.3 Eccentric Orbits and Asynchronous Rotation	101
3.1.5.4 Approaches Including Radiation Pressure	103
3.1.6 Binary Star Morphology	109
3.2 Modeling Stellar Radiative Properties	114
3.2.1 Gravity Brightening	115
3.2.2 Stellar Atmosphere Models	119
3.2.3 Analytic Approximations for Computing Intensities	119
3.2.4 Center-to-Limb Variation	120
3.2.5 Reflection Effect	123
3.2.6 Integrated Monochromatic Flux	128
3.3 Modeling Aspect and Eclipses	128
3.4 Sources and Treatment of Perturbations	131
3.4.1 Third Light	131
3.4.2 Star Spots and Other Phenomena of Active Regions	132
3.4.3 Atmospheric Eclipses	136
3.4.4 Circumstellar Matter in Binaries	137
3.4.4.1 Gas Streams	139
3.4.4.2 Gas Stream in the <i>VV Orionis System</i>	140
3.4.4.3 Disks and Rings	142
3.4.4.4 Stellar Winds	144
3.4.4.5 Attenuating Clouds	144
3.5 Modeling Radial Velocity Curves	145
3.6 Modeling Line Profiles	150
3.7 Modeling Polarization Curves	152
3.8 Modeling Pulse Arrival Times	155
3.9 Self-Consistent Treatment of Parallaxes	156
3.10 Chromospheric and Coronal Modeling	157
3.11 Spectral Energy Distribution	158
3.12 Interstellar Extinction	159
3.13 Selected Bibliography	160
References	161

- 4 Determination of Eclipsing Binary Parameters** 169
 - 4.1 Mathematical Formulation of the Inverse Problem 169
 - 4.1.1 The Inverse Problem from the Astronomer’s Perspective 173
 - 4.1.1.1 The Input Database 173
 - 4.1.1.2 General Problems of Nonlinear Parameter Fitting .. 174
 - 4.1.1.3 Special Problems of Nonlinear Parameter Fitting
in Light Curve Analysis..... 175
 - 4.1.1.4 On the Use of Constraints 178
 - 4.1.1.5 Assignment of Weights 179
 - 4.1.1.6 Simultaneous Fitting 182
 - 4.2 A Brief Review of Nonlinear Least-Squares Problems 183
 - 4.2.1 Nonlinear Unconstrained Least-Squares Methods 184
 - 4.2.2 Nonlinear Constrained Least-Squares Methods 185
 - 4.3 Least-Squares Techniques Used in Eclipsing Binary Data Analysis .. 186
 - 4.3.1 A Classical Approach: Differential Corrections 187
 - 4.3.2 Multiple Subset Method and Interactive Branching 190
 - 4.3.3 Damped Differential Corrections and Levenberg–Marquard
Algorithm 190
 - 4.3.4 Derivative-Free Methods 191
 - 4.3.4.1 The Simplex Algorithm 192
 - 4.3.4.2 Powell’s Direction Method 196
 - 4.3.4.3 Simulated Annealing 197
 - 4.3.5 Other Approaches 198
 - 4.4 A Priori and A Posteriori Steps in Light Curve Analysis 198
 - 4.4.1 Estimating Initial Parameters 198
 - 4.4.2 Criteria for Terminating Iterations 202
 - 4.4.3 The Interpretation of Errors Derived from Fitting 204
 - 4.4.4 Calculating Absolute Stellar Parameters from a Light
Curve Solution 205
 - 4.4.4.1 The Complete Data Case 206
 - 4.4.4.2 The Incomplete Data Case 209
 - 4.5 Suggestions for Improving Performance 210
 - 4.5.1 Utilizing Symmetry Properties 211
 - 4.5.2 Interpolation Techniques 211
 - 4.5.3 Surface Grid Design 213
 - 4.5.4 Analytic Partial Derivatives 214
 - 4.5.5 Accurate Finite Difference Approximation 216
 - 4.6 Selected Bibliography 216
 - References 217

- 5 Advanced Topics and Techniques** 221
 - 5.1 Extended Sets of Observables and Parameters 221
 - 5.1.1 Inclusion of Absolute Parameters in Light Curve Analysis ... 222
 - 5.1.2 Determining Individual Temperatures 224

- 5.1.2.1 Temperature Estimations 224
- 5.1.2.2 Color Indices as Individual Temperature Indicators . . . 226
- 5.1.2.3 Both Temperatures from Absolute Light Curves . . . 228
- 5.1.3 Traditional Distance Estimation 230
- 5.1.4 Direct Distance Estimation 231
- 5.1.5 Main-Sequence Constraints 233
- 5.1.6 Intrinsic Variability of Eclipsing Binaries’ Components 234
- 5.2 Multiple Star Systems and their Dynamics 235
 - 5.2.1 Third-Body Effects on Light and Radial Velocity Curves 235
 - 5.2.2 Ephemerides Derived from Whole Light Curves and Radial Velocity Curves 238
- 5.3 Analyzing Large Numbers of Light Curves 241
 - 5.3.1 Techniques for Analyzing Large Numbers of Light Curves . . 241
 - 5.3.2 The Matching Approach 242
 - 5.3.2.1 Solving Linear Regression Problems 243
 - 5.3.2.2 Generation and Storage of the Archive Curves 243
 - 5.3.3 The Expert Rule Approach 244
 - 5.3.4 Simplified Physical Models 244
 - 5.3.5 Artificial Neural Networks 245
- 5.4 Extrasolar Planets 245
 - 5.4.1 General Comments About Substellar Objects 247
 - 5.4.2 Methods to Find “Small”-Mass Companions 247
 - 5.4.2.1 Astrometry Variations 248
 - 5.4.2.2 Direct Imaging and Spectroscopy 248
 - 5.4.2.3 Radial Velocity Variations of the Visible Component 249
 - 5.4.2.4 Gravitational Lensing 249
 - 5.4.2.5 Transit Eclipses 250
 - 5.4.2.6 Indirect Effects: O–C Variation 251
 - 5.4.2.7 Effects on Disks 251
 - 5.4.3 Star–Planet Systems and Eclipsing Binary Models 251
 - 5.4.3.1 Comparing Stars, Brown Dwarfs, and Planets 251
 - 5.4.3.2 Transit Geometry and Modeling Approaches 252
 - 5.4.3.3 Representing Planets in the WD Model 254
 - 5.4.3.4 HD 209458b: Transit Analysis of an ExtraSolar Planet 255
 - 5.4.3.5 The OGLE-TR-56 Star Planet System 257
- 5.5 Selected Bibliography 258
- References 258

Part III Light Curve Programs and Software Packages

- 6 Light Curve Models and Software 265**
 - 6.1 Distinction Between Models and Programs 265
 - 6.2 Synthetic Light Curve Models 266

6.2.1	The Russell–Merrill Model and Technique	266
6.2.2	The “Eclipsing Binary Orbit Program” EBOP	273
6.2.3	The Wood Model and the WINK program	277
6.3	Physical Models: Roche Geometry Based Programs	277
6.3.1	Binnendijk’s Model	278
6.3.2	Hadrava’s Program FOTEL	278
6.3.3	Hill’s Model	279
6.3.4	Linnell’s Model	279
6.3.5	Rucinski’s Model	282
6.3.6	Wilson–Devinney Models	282
6.3.6.1	The 1998 Wilson–Devinney Model	282
6.3.6.2	New Features in the 1999–2007 Models	287
6.4	Chereshchuk’s Model	289
6.5	Other Approaches	295
6.5.1	Budding’s Eclipsing Binary Model	295
6.5.2	Kopal’s Frequency Domain Method	295
6.5.3	Mochnacki’s General Synthesis Code, GENSYN	297
6.5.4	Collier–Mochnacki–Hendry GDDSYN Spotted General Synthesis Code	297
6.5.5	Other Spot Analysis Methods	298
6.6	Selected Bibliography	298
	References	299
7	The Wilson–Devinney Program: Extensions and Applications	305
7.1	Current Capabilities of WDx2007	306
7.2	Atmospheric Options	307
7.2.1	Kurucz Atmospheres in WDx2007	307
7.2.2	Kurucz Atmospheres in WD	309
7.3	Applications and Extensions	310
7.3.1	The Eclipsing X-Ray Binary <i>HD 77581/Vela X-1</i>	311
7.3.2	The Eclipsing Binaries in <i>NGC 5466</i>	312
7.3.3	The Binary <i>H235</i> in the Open Cluster <i>NGC 752</i>	315
7.3.4	The Field Binary <i>V728 Hercules</i>	317
7.3.5	The Eclipsing Binaries in <i>M71</i>	317
7.3.6	The Eclipsing Binaries in 47 Tuc	319
7.3.7	The Well-Studied System <i>AI Phoenicis</i>	320
7.3.8	HP Draconis	321
7.3.9	Fitting of Line Profiles	324
7.4	The Future	324
7.4.1	“The Future” as Envisioned in 1999	324
7.4.2	The Future (as Seen in 2009)	326
	References	327

8 Light Curve Software with Graphical User Interface and Visualization 331

8.1 Binary Maker 331

8.2 PHOEBE 335

8.3 NIGHTFALL 337

8.4 Graphics Packages 337

References 339

9 The Structure of Light Curve Programs and the Outlook for the Future 341

9.1 Structure of a General Light Curve Analysis Program 341

9.1.1 Framework of the Light Curve Models 342

9.1.2 Framework to Embed Least-Squares Solvers 343

9.2 Procedural Philosophies 344

9.3 Code Maintenance and Modification 345

9.4 Prospects and Expectations 346

References 348

Part IV Appendix

A Brief Review of Mathematical Optimization 351

A.1 Unconstrained Optimization 351

A.2 Constrained Optimization 356

A.2.1 Foundations and Some Theorems 356

A.2.2 Sequential Quadratic Algorithms 359

A.3 Unconstrained Least-Squares Procedures 360

A.3.1 Linear Case: Normal Equations 361

A.3.2 The Linear Case: An Orthogonalization Method 362

A.3.3 Nonlinear Case: A Gauß–Newton Method 364

A.4 Constrained Least-Squares Procedures 367

A.5 Selected Bibliography 368

B Estimation of Fitted Parameter Errors: The Details 369

B.1 The Kolmogorov–Smirnov Test 369

B.2 Sensitivity Analysis and the Use of Simulated Light Curves 370

B.3 Deriving Bounds for Parameters: The Grid Approach 371

C Geometry and Coordinate Systems 373

C.1 Rotation of Coordinate Systems 373

C.2 Volume and Surface Elements in Spherical Coordinates 374

C.3 Roche Coordinates 378

C.4 Solving Kepler’s Equation 379

D	The Russell–Merrill Model	381
D.1	Ellipticity Correction in the Russell–Merrill Model	381
E	Subroutines of the Wilson–Devinney Program	385
E.1	ATM – Interfacing Stellar Model ATMospheres	386
E.2	ATMx – Interfacing Stellar Model ATMospheres	386
E.3	BBL – Basic BLock	386
E.4	BinNum – A Search and Binning Utility	387
E.5	BOLO – Bolometric Corrections	387
E.6	CofPrep – Limb-Darkening Coefficient Preparation	387
E.7	CLOUD – Atmospheric Eclipse Parameters	387
E.8	CONJPH – Conjunction Phases	388
E.9	DGMPRD – Matrix–Vector Multiplication	388
E.10	DMINV – Matrix Inversion	388
E.11	DURA – Constraint on X-Ray Eclipse Duration	388
E.12	ELLONE – Lagrangian Points and Critical Potentials	388
E.13	FOUR – Representing Eclipse Horizon	390
E.14	FOURLS – Representing Eclipse Horizon	390
E.15	GABS – Polar Gravity Acceleration	391
E.16	JDPH – Conversion of Julian Day Number and Phase	391
E.17	KEPLER – Solving the Kepler Equation	391
E.18	LC and DC – The Main Programs	391
E.19	LCR – Aspect Independent Surface Computations	392
E.20	LEGENDRE – Legendre Polynomials	392
E.21	LIGHT – Projections, Horizon, and Eclipse Effects	393
E.22	LimbDark – Limb Darkening	394
E.23	LinPro – Line Profiles	394
E.24	LUM – Scaling of Polar Normal Intensity	394
E.25	LUMP – Modeling Multiple Reflection	394
E.26	MLRG – Computing Absolute Dimensions	396
E.27	MODLOG – Handling Constraints Efficiently	396
E.28	NEKMIN – Connecting Surface of Over-Contact Binaries	396
E.29	OLUMP – Modeling the Reflection Effect	396
E.30	OMEGA* – Computing $\Omega(r)$	404
E.31	PLANCKINT – Planck Intensity	405
E.32	READLC* – Reading Program Control Parameters	405
E.33	RING – The Interface Ring of an Over-Contact Binary	405
E.34	RanGau – Generation of Gaussian Random Numbers	405
E.35	RanUni – Generation of Uniform Random Numbers	405
E.36	ROMQ – Distance Computation of Surface Points	405
E.37	ROMQSP – Distance Computation of Surface Points	406
E.38	SIMPLEX* – Simplex Algorithm	406
E.39	SinCos – Surface Grid Sine and Cosines	406
E.40	SQUARE – Building and Solving the Normal Equations	406

E.41 SPOT – Modeling Spots 406

E.42 SSR* – Computation of Curves and Residuals 407

E.43 SURFAS – Generating the Surfaces of the Components 407

E.44 VOLUME – Keeping Stellar Volume Constant 407

References 407

F Glossary of Symbols 411

Index 417

List of Figures

1.1	Classes of light curves	16
1.2	U, V, and infrared light curves of <i>Algol</i>	18
1.3	Projections of equipotential Roche surfaces	19
1.4	Roche potential and shape of a detached binary system	20
1.5	Roche potential and shape of a semi-detached binary	21
1.6	Roche potential and shape of an over-contact binary	21
2.1	RADS instrument on the RAD's 41-cm telescope	40
2.2	RADS differential photometry	40
2.3	CCD image frame of the globular cluster <i>NGC 5466</i>	48
2.4	Spectra of early spectral-type eclipsing binaries	49
2.5	Radial velocity curve of <i>AI Phoenixis</i>	51
2.6	Cross-correlation functions for <i>RW Comae Berenices</i>	52
2.7	An R_J light curve taken by the Baker–Nunn patrol camera	63
3.1	Definition of a right-handed Cartesian coordinate system	78
3.2	Definition of spherical polar coordinates	78
3.3	Surface normal and line-of-sight	79
3.4	Plane-of-sky coordinates I	80
3.5	Plane-of-sky coordinates II	81
3.6	Orbital elements of a binary system	83
3.7	Relationships between phase and orbital quantities	84
3.8	The orbit of <i>HR 6469</i> with $e = 0.672$	86
3.9	True anomaly and eccentric anomaly	87
3.10	Schematic light curve in the spherical model	90
3.11	Angular momentum vectors of orbital and stellar rotation	99
3.12	Nonsynchronous rotation	100
3.13	<i>Inner</i> radiation pressure effects	105
3.14	Effects of full radiation pressure	108
3.15	Lagrangian points L_1^p and L_2^p in the <i>BF Aurigae</i> system	109
3.16	The double-contact binary <i>RZ Scuti</i>	113
3.17	Center-to-limb variation	121
3.18	Light variation caused purely by the reflection effect	124
3.19	Light curves with albedo varying from 0 to 1	127
3.20	Geometrical condition for visible points	129

3.21	Projected plane-of-sky distance	130
3.22	Sun spots	133
3.23	Trajectories in a binary system	141
3.24	Gas streams in <i>VV Orionis</i>	142
3.25	Disk formation in <i>SX Cassiopeiae</i>	143
3.26	Modeling of the Rossiter effect in <i>AB Andromedae</i>	147
3.27	Radial velocity curves for point masses	148
3.28	Variation in the intrinsic line profile	151
3.29	Line profiles and Rossiter effect	151
3.30	Polarization curves of <i>SX Cassiopeiae</i>	154
3.31	He II spectroheliogram image of the Sun	158
4.1	Sum of the squared residuals versus parameters	175
4.2	Sum of the squared residuals versus parameters	176
4.3	Contour plot of $\sum wr^2$ versus T and i	177
4.4	Contour plot of $\sum wr^2$ versus q and Ω	178
4.5	Noise contributions in various regimes of star brightness	180
4.6	The geometry of the Simplex algorithm	193
4.7	Flow chart of the Simplex algorithm	195
4.8	Geometry of contact times	200
5.1	Planet transiting in front of a star	253
5.2	The star has radius R	253
5.3	The HST transit light curve and best-fit model	255
5.4	The radial velocity curve and best fit model	256
6.1	The relation among δ/r_g , $k = r_s/r_g$, and α	268
6.2	Geometry of the secondary eclipse of <i>RT Lacertae</i>	272
6.3	The infrared light and color curves of <i>RT Lacertae</i>	273
6.4	Basic eclipse geometry	290
6.5	More complex models: The X-Ray system <i>SS433</i>	294
7.1	<i>HD 77581</i> light curve and radial velocities, Vela X-1 pulse delays	312
7.2	Light curves of <i>NH31</i> in the globular cluster <i>NGC 5466</i>	313
7.3	Light curve of the over-contact system <i>H235</i>	316
7.4	Radial velocities of the over-contact system <i>H235</i>	316
7.5	Cluster magnitude diagram of <i>M71</i> with isochrones	318
7.6	B primary minimum of the <i>HP Draconis</i> light curve	322
7.7	B secondary minimum of the <i>HP Draconis</i> light curve	323
7.8	Fitting line profiles	323
8.1	The limit of an eclipse of an over-contact system. Created with the help of BM2 (Bradstreet 1993)	332
8.2	Shallow eclipses. Created with the help of BM2 (Bradstreet 1993)	333
8.3	Deep eclipses. Created with the help of BM2 (Bradstreet 1993)	334
8.4	A screen-shot of the PHOEBE graphical user interface	336
8.5	High-angle, three-dimensional analysis of the residuals	338
8.6	Low-angle, three-dimensional analysis of the residuals	338
B.1	Standard deviation of the fit versus mass ratio	371
C.1	Rotation of Cartesian coordinate systems	374

C.2	Derivation of the surface element	378
E.1	Structure of subroutine BBL	387
E.2	The WD main program: LC	391
E.3	The WD main program: DC	392
E.4	Subroutine LCR	393
E.5	Geometry of the reflection effect 1	397
E.6	Geometry of the reflection effect 2	398
E.7	Geometry of the reflection effect 3	399
E.8	Geometry of the reflection effect 4	400
E.9	Geometry of the reflection effect 5	402
E.10	Geometry of the reflection effect 6	403

Journal Abbreviations

<i>ACM Trans. Math. Software</i>	<i>ACM Transactions on Mathematical Software</i>
<i>Acta Astron.</i>	<i>Acta Astronomica</i>
<i>AJ</i>	<i>The Astronomical Journal</i>
<i>Ann. Rev. Astron. Astrophys.</i>	<i>Annual Review of Astronomy and Astrophysics</i>
<i>ApJ</i>	<i>The Astrophysical Journal</i>
<i>ApJ Suppl</i>	<i>The Astrophysical Journal Supplement Series</i>
<i>Ap. Sp. Sci.</i>	<i>Astrophysics and Space Science</i>
<i>A&A</i>	<i>Astronomy and Astrophysics</i>
<i>A&A Suppl.</i>	<i>Astronomy and Astrophysics Supplement Series</i>
<i>Astron. Nachr.</i>	<i>Astronomische Nachrichten</i>
<i>Astron. Rep.</i>	<i>Astronomical Report</i>
<i>BAAS</i>	<i>Bulletin of the American Astronomical Society</i>
<i>Bull. Math. Biol.</i>	<i>Bulletin of Mathematical Biology</i>
<i>CMDA</i>	<i>Celestial Mechanics and Dynamical Astronomy</i>
<i>Comp. J.</i>	<i>The Computer Journal</i>
<i>J. Comp. Phys.</i>	<i>Journal of Computational Physics</i>
<i>Mem. R. Astron. Soc.</i>	<i>Memoirs of the Royal Astronomical Society</i>
<i>MNASSA</i>	<i>Monthly Notices of the Royal Astronomical Society of Southern Africa</i>
<i>MNRAS</i>	<i>Monthly Notices of the Royal Astronomical Society</i>
<i>Quart. Appl. Math.</i>	<i>Quarterly of Applied Mathematics</i>
<i>Observatory</i>	<i>The Observatory</i>
<i>PASP</i>	<i>Publications of the Astronomical Society of the Pacific</i>

Sov. Astron.

Space Sci. Rev.

Vistas

Zeitschr. f. Astrophys.

Soviet Astronomy

Space Science Reviews

Vistas in Astronomy

Zeitschrift für Astrophysik

Acronyms and Abbreviations

ως συνελῶς εἰπεῖν

(to say it short)

APT	automatic photometric telescope
CCD	charge coupled device
CCF	cross-correlation function
CDM	conjugate direction method
CLV	center-to-limb variation
CMD	color-magnitude diagram
DLS	damped least squares
EB	eclipsing binary
HST	Hubble Space Telescope
IAU	International Astronomical Union
IPMs	interior point methods
JDN	Julian Day Number
MACHO	massive compact halo object
MSC	main sequence constraint
NDE	Nelson–Davis–Etzel; usually used to refer to the NDE model
NLP	nonlinear programming
OGLE	optical gravitational lensing experiment
PMT	photomultiplier tube
RADS	Rapid Alternate Detection System
RV	radial velocity
SB1	single-lined spectroscopic binary
SB2	double-lined spectroscopic binary
SED	spectral energy distribution
SI	physical units according to the <i>Système International</i>
SQP	sequential quadratic programming
WD	Wilson–Devinney; used to refer to the Wilson–Devinney model or program
w.r.t.	with respect to
ZAMS	zero-age Main Sequence

Mathematical Nomenclature and Symbols, Physical Units

“What’s in a name?”

Shakespeare: *Romeo and Juliet*, ii, 2

A few general rules are observed: vectors are marked as bold characters, *e.g.*, \mathbf{x} , \mathbf{n} , or \mathbf{r} . The product $\mathbf{a} \cdot \mathbf{b}$ of two vectors $\mathbf{a}, \mathbf{b} \in \mathbb{R}^n$ is always understood as the scalar product $\mathbf{a}^T \mathbf{b} = \sum_{i=1}^n a_i b_i$. Matrices are indicated with sans serif font, *e.g.*, \mathbf{A} . The list below gives our mathematical symbols and operators.

\mathbb{R}^n	the n -dimensional vector space of real (column) vectors with n components
∇	gradient operator $\nabla := \nabla_x = \frac{\partial}{\partial \mathbf{x}} = \left(\frac{\partial}{\partial x_1}, \dots, \frac{\partial}{\partial x_n} \right)^T$ applied to a scalar-valued function f
$:=$	defines the quantity on the left side of an equation by the term on the right side of the equation
\equiv	quantity on the left side of the equation is set identically to the term on the right side of the equation
\doteq	indicates approximation, as in a first-order Taylor series expansion
\mathbf{x}^T	the transposed vector, $\mathbf{x}^T := (x_1, \dots, x_n)$ is a row vector
\mathbf{e}_i	unit vector associated with the i th coordinate axis
\mathbb{I}	identity matrix of appropriate dimension
$\mathcal{M}(m, n)$	set of matrices with m rows and n columns
\forall	it represents “for all”

Superscripts indicate attributes of a quantity, *e.g.*, L^{bol} , a bolometric luminosity. Subscripts are used for indexing and counting. The subscript j is always used to refer to one of the binary components. To avoid confusion with the symbols R and L , the radii and luminosities of the binary components are written in calligraphic style \mathcal{R} and \mathcal{L} if they are in absolute (or solar) units. Symbols used in this book are listed in Appendix F.

Throughout this book we mostly use SI units. However, when referring to original papers or figures, CGS or even special units such as \AA cannot be avoided. Where possible we give only generic physical dimensions of quantities, such as mass, length, time, energy.

Part I
Introduction