
Fundamental Astronomy

Hannu Karttunen · Pekka Kröger ·
Heikki Oja · Markku Poutanen ·
Karl Johan Donner
Editors

Fundamental Astronomy

Sixth Edition
With 419 Illustrations
Including 34 Colour Plates
and 83 Exercises with Solutions

 Springer

Editors

Hannu Karttunen
Tuorla Observatory
University of Turku
Piikkiö, Finland

Markku Poutanen
Dept. Geodesy & Geodynamics
Finnish Geodetic Institute
Masala, Finland

Pekka Kröger
Helsinki, Finland

Karl Johan Donner
Finnish Geodetic Institute
Helsinki, Finland

Heikki Oja
Observatory and Astrophysics
Laboratory
University of Helsinki
Helsinki, Finland

ISBN 978-3-662-53044-3

ISBN 978-3-662-53045-0 (eBook)

DOI 10.1007/978-3-662-53045-0

Library of Congress Control Number: 2016957787

Springer Heidelberg New York Dordrecht London

© Springer-Verlag Berlin Heidelberg 1987, 1994, 1996, 2003, 2007, 2017

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Cover illustration: Atacama Large Millimeter/submillimeter Array (ALMA) is an interferometer telescope composed of 66 antennas. ALMA observes molecular gas and dust of the cool Universe—building blocks of stars, planetary systems, galaxies and life itself. Credit: ESO/ Y. Beletsky

Printed on acid-free paper

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

Preface to the Sixth Edition

As the title suggests, this book is about fundamental things that one might expect to remain fairly the same. Yet astronomy has evolved enormously over the last few years, and only a few chapters of this book have been left unmodified.

Since the book is used also by many amateurs, the introductory chapter has been extended to give a brief summary of different celestial objects to “soften” the jump to rather technical topics.

The chapter on the solar system was very long. It has now been split into two separate chapters. Chapter 7 deals with general properties of the solar system. Individual objects are discussed in Chap. 8, which is more prone to change when new data will accumulate. Also, new data on exoplanets is obtained at an increasing rate. Therefore exoplanets are given a chapter of their own; it is at the end of the book, since it is closely related to astrobiology, already included in the previous edition. These last chapters may change more than the rest of the book in the future.

These changes mean that the numbering of formulas and figures has changed quite extensively after the previous version of the book.

Cosmology and galactic astronomy have still been evolving rapidly. Therefore there are many revisions to the chapters on the Milky Way, galaxies, and cosmology.

In addition, several other chapters contain smaller revisions and many of the previous images have been replaced with newer ones.

Helsinki, Finland
April 2016

Hannu Karttunen
Pekka Kröger
Heikki Oja
Markku Poutanen
Karl Johan Donner

Preface to the First Edition

The main purpose of this book is to serve as a university textbook for a first course in astronomy. However, we believe that the audience will also include many serious amateurs, who often find the popular texts too trivial. The lack of a good handbook for amateurs has become a problem lately, as more and more people are buying personal computers and need exact, but comprehensible, mathematical formalism for their programs. The reader of this book is assumed to have only a standard high-school knowledge of mathematics and physics (as they are taught in Finland); everything more advanced is usually derived step by step from simple basic principles. The mathematical background needed includes plane trigonometry, basic differential and integral calculus, and (only in the chapter dealing with celestial mechanics) some vector calculus. Some mathematical concepts the reader may not be familiar with are briefly explained in the appendices or can be understood by studying the numerous exercises and examples. However, most of the book can be read with very little knowledge of mathematics, and even if the reader skips the mathematically more involved sections, (s)he should get a good overview of the field of astronomy.

This book has evolved in the course of many years and through the work of several authors and editors. The first version consisted of lecture notes by one of the editors (Oja). These were later modified and augmented by the other editors and authors. Hannu Karttunen wrote the chapters on spherical astronomy and celestial mechanics; Vilppu Piirola added parts to the chapter on observational instruments, and Göran Sandell wrote the part about radio astronomy; chapters on magnitudes, radiation mechanisms and temperature were rewritten by the editors; Markku Poutanen wrote the chapter on the solar system; Juhani Kyröläinen expanded the chapter on stellar spectra; Timo Rahunen rewrote most of the chapters on stellar structure and evolution; Ilkka Tuominen revised the chapter on the Sun; Kalevi Mattila wrote the chapter on interstellar matter; Tapio Markkanen wrote the chapters on star clusters and the Milky Way; Karl Johan Donner wrote the major part of the chapter on galaxies; Mauri Valtonen wrote parts of the galaxy chapter, and, in collaboration with Pekka Teerikorpi, the chapter on cosmology. Finally, the resulting, somewhat inhomogeneous, material was made consistent by the editors.

The English text was written by the editors, who translated parts of the original Finnish text, and rewrote other parts, updating the text and correcting

errors found in the original edition. The parts of text set in smaller print are less important material that may still be of interest to the reader.

For the illustrations, we received help from Veikko Sinkkonen, Mirva Vuori and several observatories and individuals mentioned in the figure captions. In the practical work, we were assisted by Arja Kyröläinen and Merja Karsma. A part of the translation was read and corrected by Brian Skiff. We want to express our warmest thanks to all of them.

Financial support was given by the Finnish Ministry of Education and Suomalaisen kirjallisuuden edistämisyhteisön valtuuskunta (a foundation promoting Finnish literature), to whom we express our gratitude.

Helsinki, Finland
June 1987

Hannu Karttunen
Pekka Kröger
Heikki Oja
Markku Poutanen
Karl Johan Donner

Contents

1	Introduction	1
1.1	Celestial Objects	1
1.2	The Role of Astronomy	3
1.3	Astronomical Objects of Research	4
1.4	The Scale of the Universe	10
2	Spherical Astronomy	11
2.1	Spherical Trigonometry	11
2.2	The Earth	14
2.3	The Celestial Sphere	16
2.4	The Horizontal System	16
2.5	The Equatorial System	17
2.6	Rising and Setting Times	20
2.7	The Ecliptic System	21
2.8	The Galactic Coordinates	22
2.9	Perturbations of Coordinates	22
2.10	Positional Astronomy	27
2.11	Constellations	31
2.12	Star Catalogues and Maps	31
2.13	Sidereal and Solar Time	34
2.14	Astronomical Time Systems	38
2.15	Calendars	40
2.16	Examples	45
2.17	Exercises	49
3	Observations and Instruments	51
3.1	Observing Through the Atmosphere	51
3.2	Optical Telescopes	54
3.3	Detectors and Instruments	64
3.4	Radio Telescopes	74
3.5	Other Wavelength Regions	80
3.6	Other Forms of Energy	85
3.7	Examples	89
3.8	Exercises	90
4	Photometric Concepts and Magnitudes	91
4.1	Intensity, Flux Density and Luminosity	91

4.2	Apparent Magnitudes	93
4.3	Magnitude Systems	94
4.4	Absolute Magnitudes	96
4.5	Extinction and Optical Thickness	97
4.6	Examples	99
4.7	Exercises	101
5	Radiation Mechanisms	103
5.1	Radiation of Atoms and Molecules	103
5.2	The Hydrogen Atom	105
5.3	Line Profiles	107
5.4	Quantum Numbers, Selection Rules, Population Numbers	108
5.5	Molecular Spectra	111
5.6	Continuous Spectra	111
5.7	Blackbody Radiation	111
5.8	Temperatures	114
5.9	Other Radiation Mechanisms	116
5.10	Radiative Transfer	117
5.11	Examples	118
5.12	Exercises	120
6	Celestial Mechanics	123
6.1	Equations of Motion	123
6.2	Solution of the Equation of Motion	124
6.3	Equation of the Orbit and Kepler's First Law	126
6.4	Orbital Elements	127
6.5	Kepler's Second and Third Law	128
6.6	Systems of Several Bodies	130
6.7	Orbit Determination	131
6.8	Position in the Orbit	132
6.9	Escape Velocity	133
6.10	Virial Theorem	134
6.11	The Jeans Limit	135
6.12	Examples	136
6.13	Exercises	140
7	The Solar System	141
7.1	Classification of Objects	141
7.2	Planetary Configurations	143
7.3	Orbit of the Earth and Visibility of the Sun	145
7.4	The Orbit of the Moon	147
7.5	Eclipses and Occultations	149
7.6	The Structure and Surfaces of Planets	151
7.7	Atmospheres and Magnetospheres	154
7.8	Albedos	160
7.9	Photometry, Polarimetry and Spectroscopy	162
7.10	Thermal Radiation of the Planets	166
7.11	Origin of the Solar System	167
7.12	Nice Models	174

7.13	Examples	175
7.14	Exercises	178
8	Objects of the Solar System	181
8.1	Mercury	181
8.2	Venus	185
8.3	The Earth and the Moon	188
8.4	Mars	196
8.5	Jupiter	199
8.6	Saturn	205
8.7	Uranus	208
8.8	Neptune	211
8.9	Dwarf Planets	212
8.10	Minor Bodies	214
8.11	Asteroids	214
8.12	Comets	219
8.13	Meteoroids	222
8.14	Interplanetary Dust and Other Particles	224
8.15	Examples	224
8.16	Exercises	225
9	Stellar Spectra	227
9.1	Measuring Spectra	227
9.2	The Harvard Spectral Classification	229
9.3	The Yerkes Spectral Classification	232
9.4	Peculiar Spectra	234
9.5	The Hertzsprung–Russell Diagram	235
9.6	Model Atmospheres	236
9.7	What Do the Observations Tell Us?	237
9.8	Exercise	239
10	Binary Stars and Stellar Masses	241
10.1	Visual Binaries	241
10.2	Astrometric Binary Stars	242
10.3	Spectroscopic Binaries	243
10.4	Photometric Binary Stars	244
10.5	Examples	246
10.6	Exercises	247
11	Stellar Structure	249
11.1	Internal Equilibrium Conditions	249
11.2	Physical State of the Gas	252
11.3	Stellar Energy Sources	254
11.4	Stellar Models	257
11.5	Examples	260
11.6	Exercises	262
12	Stellar Evolution	263
12.1	Evolutionary Time Scales	263
12.2	The Contraction of Stars Towards the Main Sequence	264

12.3	The Main Sequence Phase	267
12.4	The Giant Phase	269
12.5	The Final Stages of Evolution	271
12.6	The Evolution of Close Binary Stars	272
12.7	Comparison with Observations	275
12.8	The Origin of the Elements	277
12.9	Example	280
12.10	Exercises	281
13	The Sun	283
13.1	Internal Structure	283
13.2	The Atmosphere	286
13.3	Solar Activity	290
13.4	Solar Wind and Space Weather	296
13.5	Example	297
13.6	Exercises	297
14	Variable Stars	299
14.1	Classification	299
14.2	Pulsating Variables	301
14.3	Eruptive Variables	303
14.4	Supernovae	308
14.5	Examples	312
14.6	Exercises	312
15	Compact Stars	313
15.1	White Dwarfs	313
15.2	Neutron Stars	315
15.3	Black Holes	320
15.4	X-ray Binaries	322
15.5	Examples	325
15.6	Exercises	326
16	The Interstellar Medium	327
16.1	Interstellar Dust	327
16.2	Interstellar Gas	337
16.3	Interstellar Molecules	345
16.4	The Formation of Protostars	348
16.5	Planetary Nebulae	349
16.6	Supernova Remnants	350
16.7	The Hot Corona of the Milky Way	353
16.8	Cosmic Rays and the Interstellar Magnetic Field	354
16.9	Examples	356
16.10	Exercises	357
17	Star Clusters and Associations	359
17.1	Associations	359
17.2	Open Star Clusters	361
17.3	Globular Star Clusters	363
17.4	Example	364

17.5	Exercises	365
18	The Milky Way	367
18.1	Methods of Distance Measurement	367
18.2	Stellar Statistics	371
18.3	The Rotation of the Milky Way	375
18.4	Structural Components of the Milky Way	380
18.5	The Formation and Evolution of the Milky Way	383
18.6	Examples	385
18.7	Exercises	386
19	Galaxies	387
19.1	The Classification of Galaxies	387
19.2	Luminosities and Masses	392
19.3	Galactic Structures	397
19.4	Dynamics of Galaxies	401
19.5	Stellar Ages and Element Abundances in Galaxies	404
19.6	Systems of Galaxies	405
19.7	Active Galaxies and Quasars	409
19.8	The Origin and Evolution of Galaxies	416
19.9	Exercises	420
20	Cosmology	421
20.1	Cosmological Observations	421
20.2	The Cosmological Principle	426
20.3	Homogeneous and Isotropic Universes	427
20.4	The Friedmann Models	429
20.5	Cosmological Tests	431
20.6	History of the Universe	433
20.7	The Formation of Structure	435
20.8	The Future of the Universe	439
20.9	Examples	442
20.10	Exercises	443
21	Astrobiology	445
21.1	What Is Life?	445
21.2	Chemistry of Life	446
21.3	Prerequisites of Life	448
21.4	Hazards	448
21.5	Origin of Life	450
21.6	Are We Martians?	452
21.7	Life in the Solar System	454
21.8	Detecting Life	454
21.9	SETI—Detecting Intelligent Life	455
21.10	Number of Civilisations	456
21.11	Exercises	457
22	Exoplanets	459
22.1	Other Planetary Systems	459
22.2	Observational Methods	459

22.3	Properties of Exoplanets	461
22.4	Exercises	462
Appendix A	Mathematics	463
A.1	Geometry	463
A.2	Conic Sections	464
A.3	Taylor Series	465
A.4	Vector Calculus	465
A.5	Matrices	467
A.6	Multiple Integrals	469
A.7	Numerical Solution of an Equation	470
Appendix B	Theory of Relativity	473
B.1	Basic Concepts	473
B.2	Lorentz Transformation. Minkowski Space	474
B.3	General Relativity	475
B.4	Tests of General Relativity	476
Appendix C	Tables	477
	Answers to Exercises	501
	Further Reading	507
	Photograph Credits	511
	Colour Supplement	513
	Index	533