FUNDAMENTAL ASTRONOMY

Second Enlarged Edition

H. Karttunen
P. Kröger
H. Oja
M. Poutanen
K. J. Donner
Editors

Springer
Verlag

H. Karttunen P. Kröger H. Oja
M. Poutanen K. J. Donner (Eds.)

Fundamental Astronomy

Second Enlarged Edition
With 399 Illustrations Including 36 Colour Plates

Springer-Verlag
Berlin Heidelberg New York
London Paris Tokyo
Hong Kong Barcelona
Budapest

Dr. *Hannu Karttunen*
Center for Scientific Computing Ltd., P.O. Box 405,
FIN-02101 Espoo, Finland

Dr. *Pekka Kröger*
Isonniitynkatu 9 C 9,
FIN-00520 Helsinki, Finland

Dr. *Heikki Oja*
Observatory, P.O. Box 14,
FIN-00014 University of Helsinki, Finland

Dr. *Markku Poutanen*
Finnish Geodetic Institute, Ilmalankatu 1A,
FIN-00240 Helsinki, Finland

Dr. *Karl Johan Donner*
Observatory, P.O. Box 14,
FIN-00014 University of Helsinki, Finland

Cover photograph: The 15-m SEST (Swedish-ESO Submillimetre Telescope) at La Silla, Chile. (Photograph European Southern Observatory)

Frontispiece: The η Carinae nebula, NGC3372, is a giant HII region in the Carina spiral arm of our galaxy at a distance of 8000 light-years. (Photograph European Southern Observatory)

Title of the original Finnish edition: *Tähtitieteen perusteet* (Ursan julkaisuja 21)

Sources for the illustrations are given in the captions and more fully at the end of the book. Most of the uncredited illustrations are

ISBN 3-540-57203-1 2. Auflage Springer-Verlag Berlin Heidelberg New York
ISBN 0-387-57203-1 2nd edition Springer-Verlag New York Berlin Heidelberg

ISBN 3-540-17264-5 1. Auflage Springer-Verlag Berlin Heidelberg New York
ISBN 0-387-17264-5 1st edition Springer-Verlag New York Berlin Heidelberg

Library of Congress Cataloging-in-Publication Data. Tähtitieteen perusteet. English. Fundamental astronomy / editors, H. Karttunen ... [et. al.]. – 2nd enl. ed. p. cm. Includes bibliographical references and index. ISBN 3-540-57203-1. – ISBN 0-387-57203-1 1. Astronomy. I. Karttunen, Hannu. II. Title. QB43.2.T2613 1993 520–dc20 93-31098

Printed in Germany

Production editor: A. Kübler, Springer-Verlag Heidelberg
Typesetting: K + V Fotosatz GmbH, D-64743 Beerfelden
Printing: Druckhaus Beltz, D-69502 Hemsbach
Binding: J. Schäffer GmbH & Co. KG, D-67269 Grünstadt
SPIN: 10126078 55/3140 – 5 4 3 2 1 0 – Printed on acid-free paper

H. Karttunen P. Kröger H. Oja
M. Poutanen K.J. Donner (Eds.)

Fundamental Astronomy

Preface to the Second Edition

For this second English edition, the text was brought up to date to correspond to the situation as of April 1993. Small revisions were made throughout the book, and some sections in Chapters 3 (Observations and Instruments), 8 (The Solar System), 13 (The Sun), and 18 (The Milky Way) were rewritten. Many new photographs were added, some of them as replacements for older ones.

In many reviews of this book's English as well as German first editions, more exercises were expected at the ends of the chapters. We have added worked-out examples to nearly all chapters that didn't have them before, and we added some homework problems to the chapters too. The answers to these problems are to be found at the end of the Appendices. We hope the new examples and problems facilitate the work of the instructor who may choose to use this book.

We want to thank Dr. Christian Naundorf of Bonn, Drs. Erik Heyn Olsen and J.O. Petersen of Copenhagen, Dr. Björn Sundelius of Göteborg, and an anonymous German book buyer, who pointed out many typographical errors and inaccuracies in our book. For financial support in modifying the second English edition, we thank Suomalaisen kirjallisuuden edistämisvarojen valtuuskunta.

Helsinki, October 1993 *The Editors*

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 edistämisvarojen valtuuskunta (a foundation promoting Finnish literature), to whom we express our gratitude.

Helsinki, June 1987 *The Editors*

Contents

Chapter 1 Introduction

1.1 The Role of Astronomy

On a dark, cloudless night, at a distant location far away from the city lights, the starry sky can be seen in all its splendour (Fig. 1.1). It is easy to understand how these thousands of lights in the sky have affected people throughout the ages. After the Sun, necessary to all life, the Moon, governing the night sky and continuously changing its phases, is the most conspicuous object in the sky. The stars seem to stay fixed. Only some relatively bright objects, the planets, move with respect to the stars.

The phenomena of the sky aroused people's interest a long time ago. The Cro Magnon people made bone engravings 30,000 years ago, which may depict the phases of the Moon. These calendars are the oldest astronomical documents, 25,000 years older than writing.

Agriculture required a good knowledge of the seasons. Religious rituals and prognostication were based on the locations of the celestial bodies. Thus time reckoning be-

Fig. 1.1. The North America nebula in the constellation of Cygnus. The brightest star on the right is α Cygni or Deneb. (Photo M. Poutanen and H. Virtanen)

came more and more accurate, and people learned to calculate the movements of celestial bodies in advance.

During the rapid development of seafaring, when voyages extended farther and farther from home ports, position determination presented a problem for which astronomy offered a practical solution. Solving these problems of navigation were the most important tasks of astronomy in the 17th and 18th centuries, when the first precise tables on the movements of the planets and on other celestial phenomena were published. The basis for these developments was the discovery of the laws governing the motions of the planets by Copernicus, Tycho Brahe, Kepler, Galilei and Newton.

Astronomical research has changed man's view of the world from geocentric, anthropocentric conceptions to the modern view of a vast universe where man and the Earth play an insignificant role. Astronomy has taught us the real scale of the nature surrounding us.

Modern astronomy is fundamental science, motivated mainly by man's curiosity, his wish to know more about Nature and the Universe. Astronomy has a central role in forming a scientific view of the world. "A scientific view of the world" means a model of the universe based on observations, thoroughly tested theories and logical reasoning. Observations are always the ultimate test of a model: if the model does not fit the observations, it has to be changed, and this process must not be limited by any philosophical, political or religious conceptions or beliefs.

1.2 Astronomical Objects of Research

Modern astronomy explores the whole Universe and its different forms of matter and energy. Astronomers study the contents of the Universe from the level of elementary particles and molecules (with masses of 10^{-30} kg) to the largest superclusters of galaxies (with masses of 10^{50} kg).

Astronomy can be divided into different branches in several ways. The division can be made according to either *the methods* or *the objects of research*.

The Earth (Fig. 1.2) is of interest to astronomy for many reasons. Nearly all observations must be made through *the atmosphere*, and the phenomena of the upper atmosphere and magnetosphere reflect the state of interplanetary space. The Earth is also the most important object of comparison for planetologists.

The Moon is still studied by astronomical methods, although spacecraft and astronauts have visited its surface and brought samples back to the Earth. To amateur astronomers, the Moon is an interesting and easy object for observations.

In the study of *the planets* of the solar system, the situation in the 1980's was the same as in lunar exploration 20 years earlier: the surfaces of the planets and their moons have been mapped by fly-bys of spacecraft or by orbiters, and spacecraft have softlanded on Mars and Venus. This kind of exploration has tremendously added to our knowledge of the conditions on the planets. Continuous monitoring of the planets, however, can still only be made from the Earth, and many bodies in the solar system still await their spacecraft.

The Solar System is governed by *the Sun*, which produces energy in its centre by nuclear fusion. The Sun is our nearest *star*, and its study lends insight into conditions on other stars.

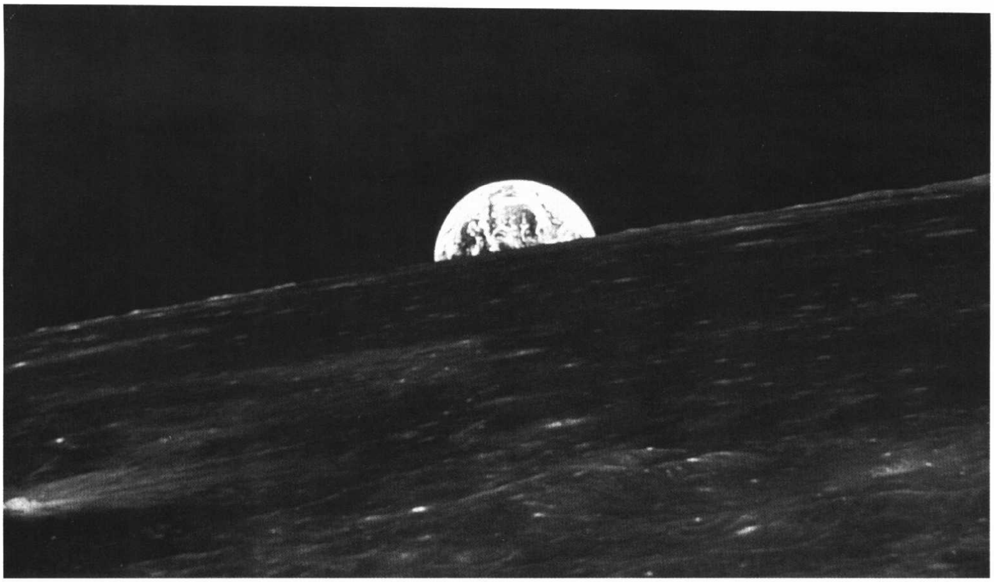

Fig. 1.2. The Earth as seen from the Moon. The picture was taken on the last Apollo flight in December, 1972. (Photo NASA)

Some thousands of stars can be seen with the naked eye, but even a small telescope reveals millions of them. Stars can be classified according to their observed characteristics. A majority are like the Sun; we call them *main sequence stars*. However, some stars are much larger, *giants* or *supergiants*, and some are much smaller, *white dwarfs*. Different types of stars represent different stages of stellar evolution. Most stars are components of *binary* or *multiple systems*; many are *variable*: their brightness is not constant.

Among the newest objects studied by astronomers are the *compact stars: neutron stars* and *black holes*. In them, matter has been so greatly compressed and the gravitational field is so strong that Einstein's general theory of relativity must be used to describe matter and space.

Stars are points of light in an otherwise seemingly empty space. Yet *interstellar space* is not empty, but contains large clouds of *atoms, molecules, elementary particles* and *dust*. New matter is injected into interstellar space by erupting and exploding stars; at other places, new stars are formed from contracting interstellar clouds.

Stars are not evenly distributed in space, but form concentrations, *clusters of stars*. These consist of stars born near each other, and in some cases, remaining together for billions of years.

The largest concentration of stars in the sky is *the Milky Way*. It is a massive stellar system, a *galaxy*, consisting of over 200 billion stars. All the stars visible to the naked eye belong to the Milky Way. Light travels across our galaxy in 100,000 years.

The Milky Way is not the only galaxy, but one of almost innumerable others. Galaxies often form *clusters of galaxies*, and these clusters can be clumped together into *superclusters*. Galaxies are seen at all distances as far away as our observations reach. Still further out we see *quasars* – the light of the most distant quasars we see now was emitted when the Universe was one-tenth of its present age.

The largest object studied by astronomers is the whole *Universe*. *Cosmology*, once the domain of theologicians and philosophers, has become the subject of physical theories and concrete astronomical observations.

Table 1.1. The share of different branches of astronomy in *Astronomy and Astrophysics Abstracts* for the second half of 1991. This index service contains short abstracts of all astronomical articles published during the half year covered by the book

Branch	Pages	Percent
Astronomical instruments and techniques	95	8
Positional astronomy, celestial mechanics	27	2
Space research	14	1
Theoretical astrophysics	177	15
Sun	112	10
Earth	35	3
Planetary system	120	10
Stars	201	17
Interstellar matter, nebulae	72	6
Radio sources, x-ray sources, cosmic rays	39	3
Stellar system, galaxy, extragalactic objects, cosmology	284	24

Among the different branches of research, *spherical,* or *positional, astronomy* studies the coordinate systems on the celestial sphere, their changes and the apparent places of celestial bodies in the sky. *Celestial mechanics* studies the movements of bodies in the solar system, in stellar systems and among the galaxies and clusters of galaxies. *Astrophysics* studies celestial objects, using methods of modern physics. It thus has a central position in almost all branches of astronomy (Table 1.1).

Astronomy can be divided into different areas according to *the wavelength* used in observations. We can speak of *radio, infrared, optical, ultraviolet, x-ray* or *gamma astronomy,* depending on which wavelengths of the electromagnetic spectrum are used. In the future, *neutrinos* and *gravitational waves* may also be observed.

1.3 The Scale of the Universe

The masses and sizes of astronomical objects are usually enormously large. But to understand their properties, the smallest parts of matter, molecules, atoms and elementary particles, must be studied. The densities, temperatures and magnetic fields in the Universe vary within much larger limits than can be reached in laboratories on the Earth.

The greatest natural density met on the Earth is 22,500 kg/m^3 (osmium), while in neutron stars, densities of the order of 10^{18} kg/m^3 are possible. The density in the best vacuum achieved on the Earth is only 10^{-9} kg/m^3, but in interstellar space, the density of the gas may be 10^{-21} kg/m^3 or still less. Modern accelerators can give particles energies of the order of 10^{11} electron volts (eV). Cosmic rays coming from the sky may have energies of over 10^{20} eV.

It has taken man a long time to grasp the vast dimensions of space. The scale of the solar system was known relatively well already in the 17th century, the first measurements of stellar distances were made in the 1830's, and the distances to the galaxies were established only in the 1920's.

We can get some kind of picture of the distances involved (Fig. 1.3) by considering the time required for light to travel from a source to the retina of the human eye. It takes 8 minutes for light to travel from the Sun, 5 1/2 hours from Pluto and 4 years

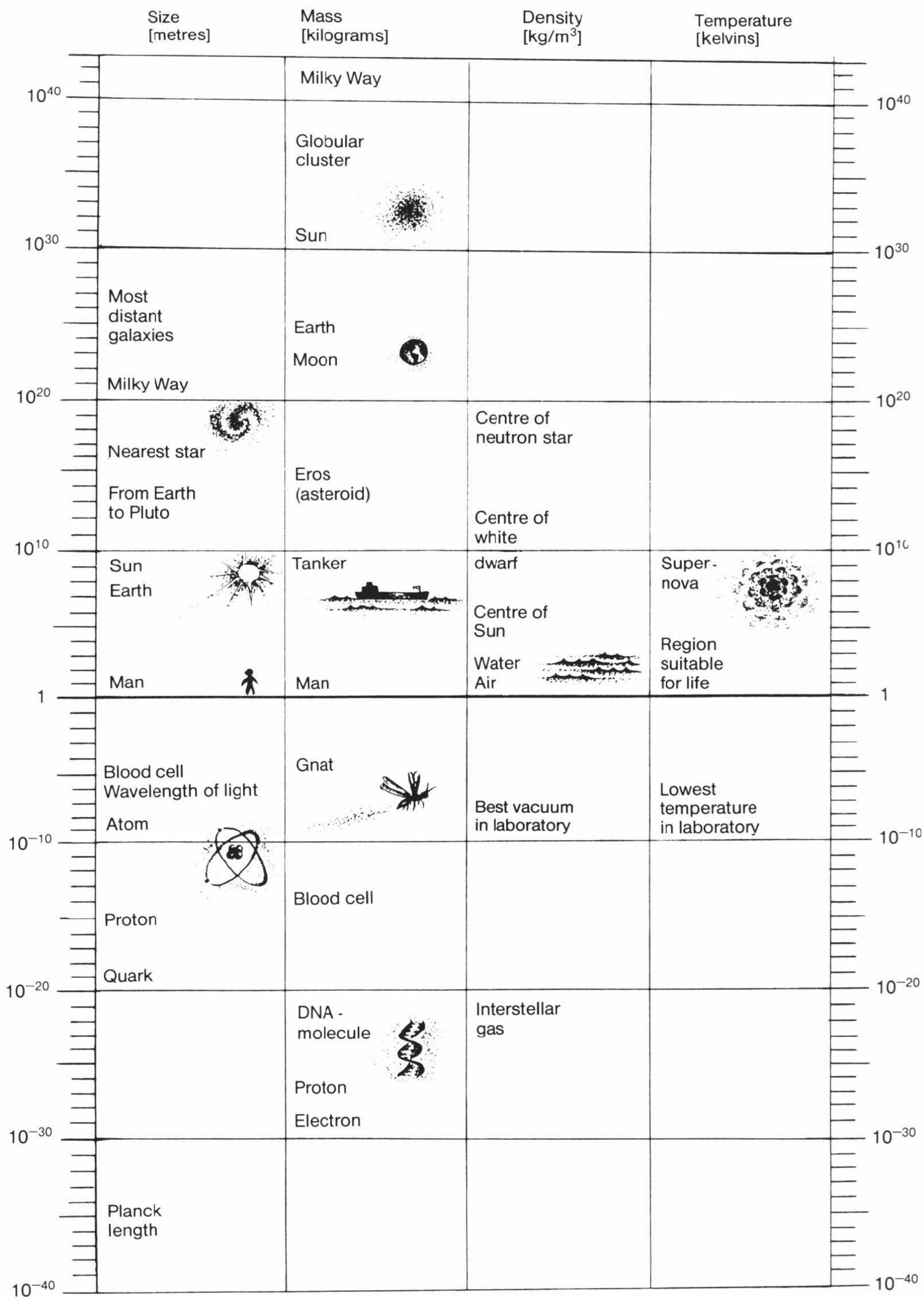

Fig. 1.3. The dimensions of the Universe