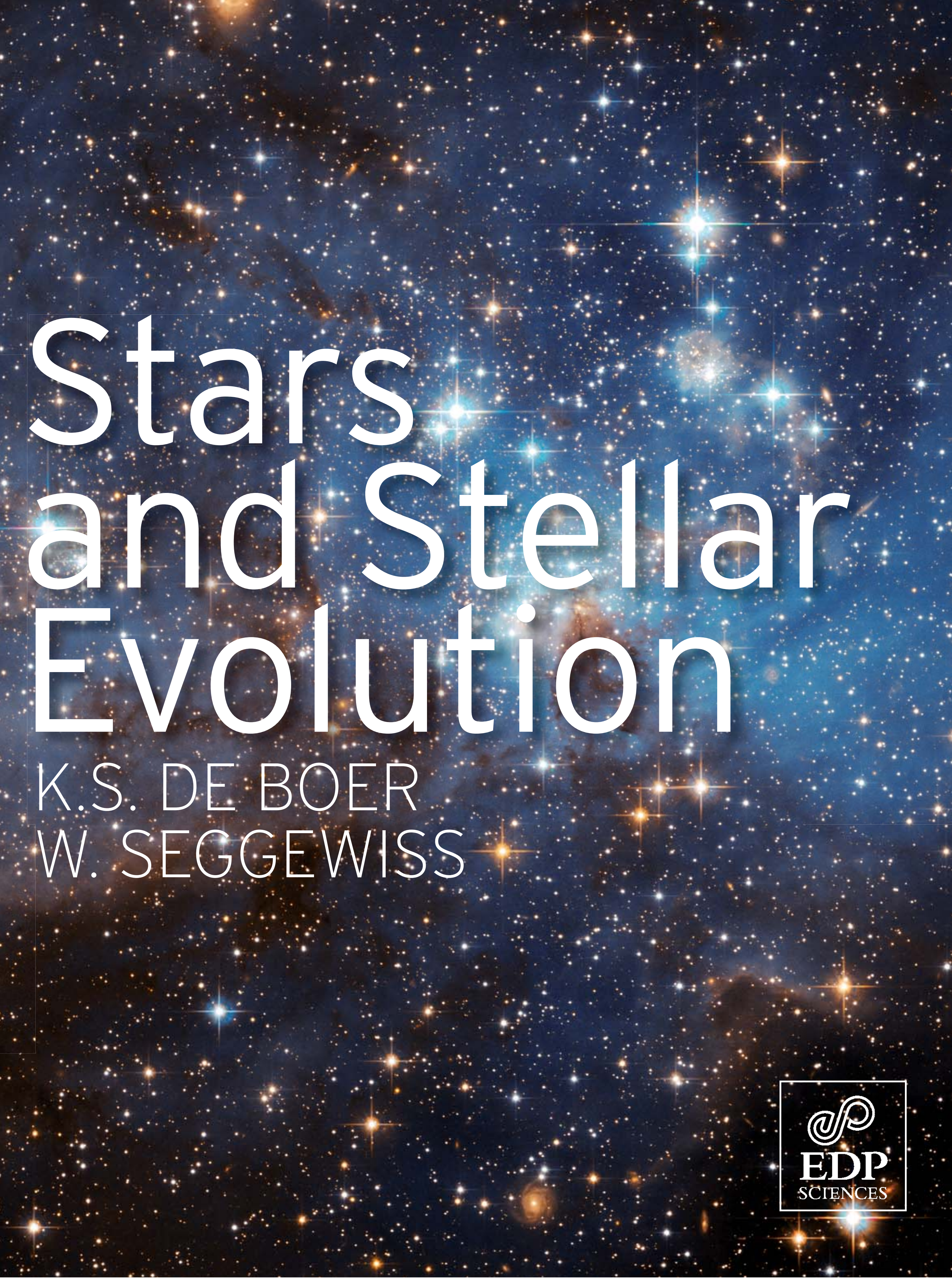

Stars and Stellar Evolution

K.S. DE BOER
W. SEGGEWISS

EDP SCIENCES

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K.S. de Boer and W. Seggewiss

EDP SCIENCES

17 avenue du Hoggar
Parc d' activités de Courtabeuf, B.P. 112
91944 Les Ulis Cedex A, France

Cover image: The stellar association LH 95 in the Large Magellanic Cloud showing star formation, young stars and old stars.
HST-ACS image, courtesy of D. Gouliermis and NASA/ESA

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Preface

Most of the baryonic mass in galaxies is stored in stars, and stars are the objects we can see easily. Stars come in a large variety of shapes and states, reflecting the different possibilities nature has, as well as the fact that stars evolve in the course of their lives.

The functioning and behaviour of stars is, of course, based on two levels of physics. One level is that of large scale structure. It is governed by gravity, macroscopic gas physics, and the way energy is transported through gas. The other level is that of microphysics. This includes the processes of nuclear fusion, the physical state of the gas (also under extreme conditions), and the effects chemical composition and ionization structure have on the energy transport by radiation and convection. The intimate interplay between the two levels, together with the fusion-driven changes taking place inside the star, make "stars and stellar evolution" a fascinating and very broad topic. Moreover, stars need not exist all by themselves (as the Sun does) but may exist in pairs, which can come to intensive interactions during their evolution.

The topic of the book touches on the questions "From where did the Sun come?" and "What will be its fate?". Yet, the Sun plays only a minor role in this text (except that its mass, size, and luminosity are the basis for the stellar units).

The emphasis is on all stars with all their evolutionary phases. The text does not aim to explain all the intricate physics for and in stars. Most of the standard physics is included, of course; for details of aspects not treated in depth, references to other texts are provided. But essential mechanisms are addressed. Nor does the text pretend to be a full review of the literature. But it gives the reference background as well as access to the specialized literature on the various topics. What has been attempted is to give a description for most (but not all) of the phases of evolution possible in their context, illustrated by numerous forms of the "Hertzsprung-Russell Diagram". The text thus rather aims at all those, the general astronomer and the observer alike, who need to understand where an encountered star can be placed in the vast parameterspace of stellar evolutionary states.

Two chapters deal with the nature of stellar ensembles, addressing interpretational problems encountered with their observations but also the possibilities to test theories about stars and their evolution. Here the application of all stellar evolutionary phases presented comes to bear on understanding large and distant stellar systems.

Numerous figures have been included from the literature. The aim was to include figures of didactical relevance while at the same time trying to have figures from original research works. Finding a balance there is not easy and, ultimately, the choice is always subjective. In several cases we had to adapt the figures to suit the readability or to better suit the didactical use, which in most cases meant enlarging the labelling, sometimes also adjusting the lay-out. We hope the original authors approve of those adaptions.

Various figures have been remade from original data. These are in particular Hertzsprung-Russell diagrams, in order to have them all in the same scale (i.e., the same axis ratios, 4 units in $\log L$ for 1 unit in $\log T_{\rm eff}$). All these can, after proper overall scaling, be overlain.

The text has its origins in our class on "Stars and Stellar Evolution", taught in german. The class has had its own evolution: the introduction of the "Bonn International Physics Programme" in 1998 provided the impetus to rework and translate the german write-up and to improve the description of many aspects of stars and their evolution. The text thus grew over the years.

The chapters of this book were composed by KSdB and WS with topical contributions from Tom Richtler (TR) and Tim Schrabback (TS) while several students allowed parts of text from their Theses to be included.

We thank Georges Meynet and Allen Sweigart for providing new data of model calculations which allowed us to (re-)make various figures. Georges generously supported our endeavour, gave extensive advice, prevented errors and proposed various improvements of the presentation. We thank Steve Shore for a critical reading of the manuscript and Michel Breger, Alvio Renzini, Detlev Schoenberner and Ed van den Heuvel for that of individual chapters; their suggestions helped to make the text in many places much clearer. Our colleagues Thibaut Decressin, Patrick Eggenberg, Michael Hilker, Norbert Langer, Maria Massi, Klaus Strassmeier, Allan Sweigart, Karel van der Hucht and Klaus Werner provided data and/or advice on various parts of the text. Over the years, numerous students made suggestions and we are grateful for their encouragement. We thank in particular Martin Altmann, Torsten Kaempf, Manuel Metz, Soroush Nasoudi, Jörg Sanner and Philip Willemsen for their contribution of diagrams and/or permission to include textparts of their respective theses.

We of course are indebted to many colleagues for their permission to include figures from their research papers in our text. Many colleagues gave additional advice related with these figures. As said, in many instances figures were adjusted in lay-out for the needs of this text.

Thanks go also to the respective publishers for their permission to reproduce figures from the original publications according to the respective copyright rules. These include: the European Southern Observatory for figures from Astronomy & Astrophysics and Astronomy & Astrophysics Supplement Series (through the Editor-in-Chief); the American Astronomical Society ("reproduced by permission of the AAS") for figures from the Astronomical Journal, the Astrophysical Journal, and the Astrophysical Journal Supplement; the Annual Review Corporation ("Reprinted, with permission, from the Annual Reviews of Astronomy and Astrophysics by Annual Reviews www.annualreviews.org"); the International Astronomical Union for figures from the proceedings of their Symposia and Colloquia; Springer and Kluwer for figures from the Astronomy & Astrophysics Review and some of their other publications ("With kind permission of Springer Science+Business Media"); Blackwell Publishers for figures from the Monthly Notices of the Royal astronomical Society; Wiley-VCH for figures from Reviews of Modern Astronomy; and the Publications of the astronomical Society of the Pacific (here the rights reside with its authors). Of course, with each figure the reference to the source is given.

A few figures have been obtained from sources, whose location has slipped from our memory. We request the authors of these figures to make this known to us so that proper credit can be given at a later stage.

Finally, we thank Marie-Louise Chaix, France Citrini, Jean Fontanieu and Jean-Marc Quilbé of EDPSciences for their essential and technical support.

We hope that all readers will benefit from this text. We will be grateful for all comments and suggestions for improvement.

September 2008

Klaus S. de Boer & Wilhelm Seggewiss
Sternwarte of the
Argelander Institut für Astronomie
Universität Bonn

Chapter 1

Introduction

1.1 Historical background

The brilliance of stars on a clear night at a place not yet affected by light pollution is amazing. The uneven distribution of stars over the sky, their range in brightness, and possibly the recognition that they have different shades of colour make stars fascinating objects.

1.1.1 History of the characterization of stars

With the realization in the 17th century that the Sun is a gigantic source of heat around which the planets revolve came the first thoughts about the nature of the nightly twinkling lights. If they were objects like the Sun, they really must be far away. Christian Huygens (1695; *Kosmotheoros*) tried to calculate the distance to the brightest star by comparing its brightness with the brightness of the Sun as seen through the same telescope[1]. He found from the so estimated intensity ratio that the distance to Sirius would be just a factor of four smaller than the real distance to that star (not knowing about and thus not considering the intrinsic differences between stars...).

Kepler and Galileo derived from planetary motions that the Earth revolves around the Sun. Galileo suggested that the distance of stars might be found using the **annual parallactic shift** of their positions, to implicitly prove that the Earth moves indeed. The first parallax was measured in 1838, independently by Bessel, by Henderson and by Struve. Once sufficient parallactic distances were known it became feasible to intercompare stars in a systematic manner. A **reference distance** was agreed upon: **10 pc** (parsec), the distance of a parallactic shift of 1/10 of an arcsecond. The brightness a star would have at this distance is since called **absolute magnitude**.

In particular Hertzsprung noted (based on parallaxes) at the beginning of the 20th century that red stars came in two kinds, the very luminous ones and the feeble ones. With knowledge of the Planck function (1900!) for radiating bodies, equal colour implied equal temperature and thus equal output of a unit surface area, so that the more luminous star had to have a large total surface, thus had to be big. This led to the type names **giant star** and **dwarf star**.

Spectroscopy was essential too. Using the knowledge of laboratory absorption and emission spectra of flames (late 19th century) as well as of atomic physics (early 20th century), explaining many a spectral line from atoms as well as from ions, one could start to investigate the chemical composition of stars. More importantly, understanding the spectral lines led to the derivation of the surface temperature of stars. Thus it became possible to sort the original spectral classifications (Secchi, Manny, Annie Cannon) into a **spectral sequence** *running parallel with temperature*. Russell combined the new spectral types with the absolute magnitudes of the stars.

[1] Huygens designed for that purpose a very small diaphragm to be mounted in front of the telescope which he then used to observe the Sun. In order to get, during day time, his eyes adapted to conditions of nightly observing, he sat a long time with a cloth wrapped around his head in the darkened living room with the telescope ready. Only then did he (with the help of an assistant) look through telescope and diaphragm to the Sun. It required many experiments to get everything (including diaphragm) right! (Story as retold by Andriesse 1994).