THE IMPACT OF BINARY STARS ON STELLAR EVOLUTION

Stars are mostly found in binary and multiple systems, with at least 50% of all solarlike stars having companions; this fraction approaches 100% for the most massive stars. A large proportion of the stars in these systems interact and alter the structure and evolution of their components, leading to exotic objects such as Algol variables, blue stragglers and other chemically peculiar stars, but also to phenomena such as nonspherical planetary nebulae, supernovae and gamma-ray bursts. While it is understood that binaries play a critical role in the initial mass function, the interactions among binary systems also significantly affect the dynamical evolution of stellar clusters and galaxies. This interdisciplinary volume presents results from state-of-the-art models and observations aimed at studying the impact of binaries on stellar evolution in resolved and unresolved populations. Serving as a bridge between observational and theoretical astronomy, it is a comprehensive review for researchers and advanced students of astrophysics.

GIACOMO BECCARI is a staff astronomer at the European Southern Observatory. His work is focused on the study of Blue Straggler stars in Globular Clusters. He is a former winner of the Levi-Montalcini Prize and coauthor of *The Ecology of Blue Straggler Stars* (2014).

HENRI M. J. BOFFIN is a staff astronomer at the European Southern Observatory. Recently he has shown the importance of binary stars in explaining planetary nebulae, including discovering the binary star of Fleming 1. He pioneered the use of optical interferometry to study mass transfer in symbiotic stars.

CAMBRIDGE ASTROPHYSICS SERIES

Series editors:

Titles available in the series

27. *RR Lyrae Stars*
    by Horace A. Smith
28. *Cataclysmic Variable Stars*
    by Brian Warner
29. *The Magellanic Clouds*
    by Bengt E.Westerlund
30. *Globular Cluster Systems*
    by Keith M. Ashman and Stephen E. Zepf
33. *The Origin and Evolution of Planetary Nebulae*
    by Sun Kwok
34. *Solar and Stellar Magnetic Activity*
    by Carolus J. Schrijver and Cornelis Zwaan
35. *The Galaxies of the Local Group*
    by Sidney van den Bergh
36. *Stellar Rotation*
    by Jean-Louis Tassoul
37. *Extreme Ultraviolet Astronomy*
    by Martin A. Barstow and Jay B. Holberg
39. *Compact Stellar X-ray Sources*
    edited by Walter H. G. Lewin and Michiel van der Klis
40. *Evolutionary Processes in Binary and Multiple Stars*
    by Peter Eggleton
41. *The Physics of the Cosmic Microwave Background*
    by Pavel D. Naselsky, Dmitry I. Novikov and Igor D. Novikov
42. *Molecular Collisions in the Interstellar Medium, 2nd Edition*
    by David Flower
43. *Classical Novae, 2nd Edition*
    edited by M. F. Bode and A. Evans
44. *Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere*
    by Kenneth J. H. Phillips, Uri Feldman and Enrico Landi
45. *From Luminous Hot Stars to Starburst Galaxies*
    by Peter S. Conti, Paul A. Crowther and Claus Leitherer
46. *Sunspots and Starspots*
    by John H. Thomas and Nigel O. Weiss
47. *Accretion Processes in Star Formation, 2nd Edition*
    by Lee Hartmann

Cambridge University Press
978-1-108-42858-3 — The Impact of Binary Stars on Stellar Evolution
Edited by Giacomo Beccari , Henri M. J. Boffin
Frontmatter
More Information

48. *Pulsar Astronomy, 4th Edition*
    by Andrew Lyne and Francis Graham-Smith
49. *Astrophysical Jets and Beams*
    by Michael D. Smith
50. *Maser Sources in Astrophysics*
    by Malcolm Gray
51. *Gamma-ray Bursts*
    edited by Chryssa Kouveliotou, Ralph A. M. J. Wijers and Stan Woosley
52. *Physics and Chemistry of Circumstellar Dust Shells*
    by Hans-Peter Gail and Erwin Sedlmayr
53. *Cosmic Magnetic Fields*
    by Philipp P. Kronberg
54. *The Impact of Binary Stars on Stellar Evolution*
    by Giacomo Beccari and Henri M. J. Boffin

THE IMPACT OF BINARY STARS ON STELLAR EVOLUTION

Edited by

GIACOMO BECCARI
European Southern Observatory

HENRI M. J. BOFFIN
European Southern Observatory

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108428583
DOI: 10.1017/9781108553070

First published 2019

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalogue record for this publication is available from the British Library.

Library of Congress Cataloging-in-Publication Data
Names: Beccari, Giacomo, editor. | Boffin, H. (Henri), 1965– editor.
Title: The impact of binary stars on stellar evolution / edited by Giacomo Beccari (European Southern Observatory, Garching), Henri M. J. Boffin (European Southern Observatory, Garching).
Description: Cambridge, United Kingdom ; New York, NY : Cambridge University Press, 2019. | Series: Cambridge astrophysics series ; 54
Identifiers: LCCN 2018042461 | ISBN 9781108428583 (hardback)
Subjects: LCSH: Stars–Evolution. | Double stars.
Classification: LCC QB806 .I567 2019 | DDC 523.8–dc23
LC record available at https://lccn.loc.gov/2018042461

ISBN 978-1-108-42858-3 Hardback

Contents

Cambridge University Press
978-1-108-42858-3 — The Impact of Binary Stars on Stellar Evolution
Edited by Giacomo Beccari , Henri M. J. Boffin
Frontmatter
More Information

Contributors

Marc Audard
Department of Astronomy, University of Geneva, Chemin d'Ecogia, 1290 Versoix, Switzerland

Henri M. J. Boffin
European Southern Observatory, Karl-Schwarzschild-str. 2, 85748 Garching, Germany

Cathie J. Clarke
Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, United Kingdom

Sylvia Ekström
Department of Astronomy, University of Geneva, Maillettes 51 – Sauverny, 1290 Versoix, Switzerland

J. J. Eldridge
Department of Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand

Dafydd W. Evans
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, United Kingdom

Laurent Eyer
Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland

Francesco R. Ferraro
Department of Physics and Astronomy, Bologna University, Gobetti 93/2, I–40129 Bologna, Italy

CAMBRIDGE
Cambridge University Press
978-1-108-42858-3 — The Impact of Binary Stars on Stellar Evolution
Edited by Giacomo Beccari , Henri M. J. Boffin
Frontmatter
More Information

Cyril Georgy
Department of Astronomy, University of Geneva, Maillettes 51 – Sauverny, 1290 Versoix, Switzerland

Ghina M. Halabi
Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, United Kingdom

Na'ama Hallakoun
School of Physics and Astronomy, Tel Aviv University, 6997801 Tel Aviv, Israel

Edward P. J. van den Heuvel
Anton Pannekoek Institute of Astronomy, University of Amsterdam, Science Park 904, 1098XH Amsterdam, The Netherlands

Simon Hodgkin
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, United Kingdom

Berry Holl
Department of Astronomy, University of Geneva, Chemin d'Ecogia, 1290 Versoix, Switzerland

Robert G. Izzard
Astrophysics Research Group, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, GU2 7XH, United Kingdom
Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, United Kingdom

Tereza Jerabkova
European Southern Observatory, Karl-Schwarzschild-str. 2, 85748 Garching, Germany

David Jones
Institute for Astrophysics in Canarias, E-38205 La Laguna, Tenerife, Spain

Pavel Kroupa
Helmholtz-Institut für Strahlen und Kernphysik, Universität Bonn
Astronomical Institute, Charles University in Prague, Czech Republic

Barbara Lanzoni
Department of Physics and Astronomy, Bologna University, Gobetti 93/2, I–40129 Bologna, Italy

Isabelle Lecoeur-Taibi
Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland

Emily M. Leiner
University of Wisconsin–Madison, 475 N. Charter St., Madison, WI 53706, USA

Sara Lucatello
National Institute of Astrophysics (INAF) – Astronomical Observatory in Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy

Michela Mapelli
Institute for Astrophysics and Particle Physics, University of Innsbruck, Technikerstrasse 25/8, A–6020, Innsbruck, Austria
National Institute of Astrophysics (INAF) – Astronomical Observatory in Padova, Vicolo dell'Osservatorio 5, I–35122, Padova, Italy

Robert D. Mathieu
University of Wisconsin–Madison, 475 N. Charter St., Madison, WI 53706, USA

Andrea Mehner
European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago de Chile, Chile

Maxwell Moe
Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA

Nami Mowlavi
Department of Astronomy, University of Geneva, Chemin d'Ecogia, 1290 Versoix, Switzerland

Ulisse Munari
National Institute of Astrophysics (INAF), Astronomical Observatory of Padova, 36012 Asiago (VI), Italy

Gijs Nelemans
Department of Astrophysics/Institute for Mathematics, Astrophysics and Particle Physics (IMAPP), Radboud University, Nijmegen, The Netherlands
Institute of Astronomy, Catholic University (KU) Leuven, Leuven, Belgium

Ferdinando Patat
European Southern Observatory, Karl-Schwarzschild-str. 2, 85748 Garching, Germany

Dimitri Pourbaix
Institute of Astronomy and Astrophysics, Free University of Brussels (ULB), 1050, Brussels, Belgium

Andrej Prša
Villanova University, Department of Astrophysics and Planetary Sciences, 800 E Lancaster Avenue, Villanova, PA 19085, USA

Lorenzo Rimoldini
Department of Astronomy, University of Geneva, Chemin d'Ecogia, 1290 Versoix, Switzerland

Maurizio Salaris
Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool, L3 5RF, United Kingdom

Hugues Sana
Institute of Astrophysics, Catholic University Leuven, Celestijnlaan 200D, 3001 Leuven, Belgium

George Seabroke
Mullard Space Science Laboratory, University College London, Dorking, Surrey, United Kingdom

Elizabeth R. Stanway
Department of Physics, University of Warwick, Gibbet Hill Road, Coventry, CV4 7AL, United Kingdom

Nial R. Tanvir
Department of Physics and Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, United Kingdom

Hans van Winckel
Institute for Astronomy, Catholic University, Leuven, Celestijnlaan 200D, 3001 Leuven, Belgium

Lukasz Wyrzykowsi
Warsaw University Astronomical Observatory, Al. Ujazdowskie 4, PL-00-478 Warsaw, Poland

Foreword

Some 40 years ago Abt and Lewis (1976) discovered that more than half of all solarlike stars are members of binary systems. Inspection of their period distribution shows that many of them have orbital dimensions such that at some point in time they will interact with one another. A few years later the same was found to hold for the B2-B5 main-sequence stars (Abt and Lewis, 1978; Abt, 1979, 1983), and more recently Abt et al. (1990) found that on average one B2-B5 main-sequence star has 0.8 companions more massive than two solar masses, and 1.9 companions more massive than the Sun. Other studies have shown that these high percentages of potentially interacting binaries are found all along the main sequence. In recent years, Sana et al. (2012) discovered that binary evolution even completely dominates the evolution of the massive OB-type stars. It thus appears that a large fraction of all stars will during their lives interact with a companion star. It is for this reason, as Henri Boffin expresses in his introduction chapter (see Chapter 1), that the textbooks on stellar evolution will have to be rewritten, since so far, these concentrated mostly on the evolution of single stars. In view of the high incidence of binary interactions among all kinds of stars, it is not surprising that almost any kind of important or interesting class of stellar object in the sky has been found to be related to binary evolution, as is demonstrated by the following nonexhaustive list of examples, which also figure prominently in this book.

Novae are stars that suddenly appear in the sky and rise to a luminosity of between 10^4 and 10^6 times the luminosity of the Sun, and then fade away over several weeks to months. They are close binaries consisting of a white dwarf and a normal solarlike star. The white dwarf is the seat of the explosive behaviour. Also, dwarf novae, which flare up to much lower luminosities than novae, are binary systems of the same type.

The brightest X-ray sources in the sky are the X-ray binaries, which consist of a normal star and a neutron star or a black hole. The same is true for the microquasars, of which SS 433 and Cygnus X-3 are key examples. They show relativistic jet outflows, closely resembling those of the supermassive black holes in quasars and Active Galaxy Nuclei.

All three classes of Type I supernovae, which together form about half of all supernovae, are products of binary evolution. Their defining characteristic is the lack of hydrogen in their spectra. The Type Ia supernovae are thermonuclear explosions of carbon-oxygen white dwarfs, triggered by mass transfer from a companion star. Type Ib and Ic supernovae are core-collapse supernovae in which, before the explosion, the cores have been stripped of their hydrogen-rich envelopes by binary interaction.

Binary radio pulsars are products of evolution of binaries in which both stars have reached their final state; in most cases the companion of the pulsar is a neutron star or a white dwarf, and in a few cases a brown dwarf. Particularly the double neutron stars, of which we now know 20 cases in our Galaxy, are objects of outstanding (astro-)physical importance. Thanks to the fact that radio pulsars are extremely accurate clocks, close double neutron stars allow one to measure at least four General and Special Relativistic effects with extremely high precision, yielding highly precise mass measurements of neutron stars, with uncertainties below a fraction of a promille. This was first demonstrated for the Hulse–Taylor binary pulsar PSR B1913+16, discovered in 1974. It has a 7h45m orbital period and an orbital eccentricity of 0.617, induced by the second supernova explosion in the system. The highly accurate measurement of the rate of orbital decay of this system is, as Taylor and Weisberg (1989) showed, in exact agreement with the predictions of Einstein's General Theory of Relativity for orbital decay due to the emission of gravitational waves. This earned Joseph Taylor and Russell Hulse the 1993 Physics Nobel Prize. Of the presently known 20 double neutron stars, about half have orbital periods sufficiently short to show the same relativistic effects as the Hulse–Taylor system, and in some systems, these can be measured with even higher precision than in that system (Kramer and Stairs, 2008).

Another binary-related Physics Nobel Prize was the one of 2002 for Riccardo Giacconi, for discovering the first celestial X-ray sources, which are the *X-ray binaries*.

And a third binary-related Physics Nobel Prize was that of 2011, awarded to Saul Perlmutter, Brian Schmidt and Adam Riess for the discovery of Dark Energy, by using the 'standard-candle' properties of the *Type Ia supernovae*: exploding white dwarfs in binary systems.

The fourth binary-related Physics Nobel Prize is the one of 2017, awarded to the Laser Interferometer Gravitational-Wave Observatory (LIGO) pioneers for the detection of gravitational waves from merging *double black holes*. Apart from showing for the first time that double black-hole binaries exist in nature, the LIGO–Virgo detections of gravitational waves show, as had been predicted based on binary-star evolution, that the strongest gravitational wave sources in the Universe are the merger events of close double black holes and close double neutron stars.

Most of the 20 double neutron stars known in our Galaxy are in the galactic disk, and are clear products of binary evolution; two of them are found in globular clusters and are expected to have formed by gravitational capture processes in the dense cores of these clusters. The same is expected to be true for double black holes: the majority are expected to have formed by binary evolution, and a fraction may also have formed by gravitational capture processes in dense star clusters.

The first LIGO-observed merger event of a double neutron star GW170817 was accompanied by a *short Gamma-Ray Burst*. We therefore now know for sure that also these Gamma-Ray Bursts, which are among the most energetic explosions in the Universe, are due to a binary interaction, in this case of two neutron stars, as had been predicted by Eichler et al. (1989).

Apart from the aforementioned quite spectacular binary stellar phenomena, many other important and intriguing stellar phenomena appear to be due to binary interactions: *runaway OB stars, barium stars (giants as well as dwarfs), millisecond radio pulsars, Carbon Enhanced Metal Poor (CEMP) stars, blue stragglers in open as well as globular clusters, nuclei of planetary nebulae, symbiotic stars and supersoft X-ray sources*. All these objects are extensively discussed in this volume.

Even the *Luminous Blue Variables* (LBVs), whose properties, so far, had always been thought to be due to instabilities in the most massive single stars, appear now to be products of binary-star evolution (Smith and Tombleson, 2015). As pointed out in Chapter 11 in this volume, the LBVs can therefore no longer be considered as progenitors for the formation of Wolf–Rayet stars through single-star evolution. This implies that the only remaining channel to form *Wolf–Rayet stars* is through binary-star evolution.

It is amazing to see that now more Physics Nobel prizes have been awarded for binary-related physics than to single-star physics (the latter were the prize of 1974 for the discovery of radio pulsars; the prize of 1983 for the Chandrasekhar limit and for stellar nucleosynthesis; and the prize of 2002, which partially was for the detection of the neutrinos of Supernova 1987A).

In the July 2017 European Southern Observatory (ESO) workshop on 'The Impact of Binaries on Stellar Evolution', the world's leading experts in binary-star evolution and binary-related objects and phenomena were the invited speakers. They reviewed the present state of the art in their respective fields, and the many still unsolved problems. Most of these reviews are now collected in this book, which gives an excellent and most fascinating overview of all what we presently know about the role of binaries in stellar evolution.

It is clear from this book that we are still at the beginning of understanding how wide-ranging the effects of binary evolution are among the stars. Apart from being an excellent and up-to-date overview of the subject, this book therefore also is an inspiring starting point for future research.

Edward P. J. van den Heuvel

References

Abt, H. A., and Levy, S. G. 1976. Multiplicity among Solar-Type Stars. *ApJS*, **30**, 273–306.

Abt, H. A., and Levy, S. G. 1978. Binaries among B2-B5 IV, V Absorption and Emission stars. *ApJS*, **36**, 241–250.

Abt, H. A. 1979. The Frequencies of Binaries on the Main Sequence. *AJ*, **84**, 1591–1598.

Abt, H. A. 1983. Normal and Abnormal Binary Frequencies. *ARA&A*, **21**, 343–372.

Abt, H. A., Gomez, A. E., and Levy, S. G. 1990. The Frequency and Formation Mechanism of B2-B5 Main-Sequence Binaries. *ApJS*, **74**, 551–573.

Eichler, D., Livio, M., Piran, T., and Schramm, D. N. 1989. Nucleosynthesis, Neutrino Bursts and Gamma-Rays from Coalescing Neutron Stars. *Nature*, **340**, 126–128.

Kramer, M., and Stairs, I. H. 2008. The Double Pulsar. *ARA&A*, **46**, 541.

Sana, H., de Mink, S. E., de Koter, A., et al., 2012. Binary Interaction Dominates the Evolution of Massive Stars. *Science*, **337**, 444–446.

Smith, N., and Tombleson, R. 2015. Luminous Blue Variables Are Antisocial: Their Isolation Implies That They Are Kicked Mass Gainers in Binary Evolution. *MNRAS*, **447**, 598–617.

Taylor, J. H., and Weisberg, J. M. 1989. Further Experimental Tests of Relativistic Gravity Using the Binary Pulsar PSR 1913 + 16. *AJ*, **345**, 434–450.

Introduction

The last decades have seen a paradigm shift with the realisation that stars are mostly found in binary and multiple systems, with at least 50% of all solarlike stars having companions – a fraction that most likely goes up to 100% for the most massive stars. Moreover, a large fraction of them will interact in some way or another: at least half of the binary systems containing solarlike stars, in particular when the primary will evolve on the Asymptotic Giant Branch, and at least three quarters of all massive stars. Such interactions often will alter the structure and evolution of both components in the system. This will, in turn, lead to the production of exotic objects whose existence cannot be explained by the standard stellar evolution models. One should also not forget that one of the most luminous stars in our Galaxy, η Carinae, is a binary, while the most massive stars may be the results of mergers. Moreover, in 2016, we saw the first ever announcement of gravitational wave detection, coming from the merging of a binary black hole.

A workshop on 'The Impact of Binaries on Stellar Evolution' was therefore organised at the Garching Headquarters of the European Southern Observatory (ESO) to discuss in detail all these issues. The relevance and timeliness of the workshop was obvious, given the 170 registered participants who filled the ESO auditorium, together with many day-visitors, to listen during one week to 23 invited talks, close to 40 contributed talks and discuss in two dedicated sessions and during the various breaks the 98 posters presented.

The success was such that it was felt that the workshop should have some legacy, and we therefore decided to make a book based on the invited talks at the ESO workshop. These are by no means proceedings, but instead carefully selected invited reviews by world experts that present the current state in their field.

All in all, there are 21 chapters to read in a book that we hope will cater to a very wide audience and get finally binaries the attention they deserve. We also hope that this book is the first in a series of new textbooks to be written!