

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).

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Edited by Giacomo Beccari , Henri M. J. Boffin

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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: *run-away 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

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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!

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Frontmatter

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