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Report on the ESO Workshop

The Impact of Binaries on Stellar Evolution

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Henri M. J. Boffin[1]
Giacomo Beccari[1]
Monika G. Petr-Gotzens[1]

[1] ESO

The majority of stars have at least one companion and many will interact during their lifetimes, leading to significant changes in their structure, their further evolution and their chemical composition. One can therefore be sure that almost any kind of important or interesting class of objects has been influenced by binary evolution. This workshop aimed to address these important issues, and attracted 170 registered participants. The main conclusion of the workshop is that the textbooks need to be rewritten to account for the role of binarity in many areas of stellar evolution.

Figure 1. Group photo of the participants at the workshop.

Binarity and stellar evolution

The last few decades have seen a paradigm shift following the realisation that most stars are found in binary and multiple systems, with at least 50 % of all Sun-like 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 Sun-like stars (especially when the primary evolves onto the Asymptotic Giant Branch, AGB) and at least three quarters of all massive stars. Such interactions will often alter the structure and evolution of both components in the system. They will, in turn, lead to the production of exotic objects (for example, Algols, Blue Stragglers and other chemically peculiar stars) whose existence cannot be explained by the standard stellar evolution models. They may also lead to outcomes such as non-spherical planetary nebulae, or supernovae and gamma-ray bursts.

It should also be noted that one of the most luminous stars in our Galaxy, Eta Carinae, is a binary, and that the most massive stars may be the result of mergers. Moreover, the first ever gravitational wave detection, announced in 2016, arose from the merger of a binary black hole. As Ed van den Heuvel noted in the conference summary talk, three Nobel prizes have been awarded for work on binary stars (in 1993, 2002 and 2011), further illustrating the importance of binaries. Indeed, 2017 may bring another one for the detection of gravitational waves. In contrast, only two have been given for work on single stars, in 1967 and 1983.

The motivations for this meeting were therefore to examine in detail the impact of binaries on stellar evolution in both resolved and unresolved populations. In particular, Gaia will soon bring a wealth of new data in this area and the community needs to be ready to interpret them. This workshop on "The Impact of Binaries on Stellar Evolution" was therefore organised to discuss all of these issues in detail. The timeliness of the workshop was further highlighted by the attendance of 170 registered participants and many additional day visitors, filling up the ESO auditorium and taking in 23 invited talks and about 40 contributed talks. 98 posters were also discussed during two dedicated sessions, with poster viewings during the various breaks. It was a very busy week indeed!

Getting to know binaries

The workshop was introduced by Henri Boffin, who demonstrated the ubiquity of binary stars in the sky, from our closest neighbour Alpha Centauri to the brightest star in the sky Sirius, and including Alcor and Mizar in the Great Bear as well as the stars of the Trapezium in Orion. He also reviewed the various classes of binary stars and their importance in explaining many astrophysical phenomena.

Max Moe presented the latest analysis of the statistical properties of binary stars. He showed the latest number of companions as a function of primary mass; solar-like stars have on average 0.5 companions, while O stars have 2.1 companions. He also confirmed the most recent results showing that if only 15 % of Sun-like primaries will interact through Roche lobe overflow in the course of their lives, this fraction reaches an amazing 80–90 % for O-type primaries. He stressed the importance of the dependence of the mass ratio distribution on other parameters, particularly the mass of the primary star and the orbital period. The common use of a uniform mass ratio distribution in population synthesis models is thus a dangerous simplification that is no longer justified given the wealth of available data. An example of this was the survey presented by Jennifer Winters of 1125 M-type dwarfs closer than 25 pc; 26 % of the sample had companions. As the survey is limited to separations greater than 2 arcseconds, this is only a lower limit to the real binary fraction.

An important question is how binary stars form. Cathie Clarke showed that the formation of multiple stars is an integral part of star formation, with recent observations by the Atacama Large Millimeter/


NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

Figure 2. Planetary nebulae, some examples of which are shown here, are now in the majority thought to be the result of binary interactions.

Submillimeter Array (ALMA) and the Jansky Very Large Array (VLA) demonstrating that small clusters and non-hierarchical multiples are common in deeply embedded, very young protostars. Christine Ackerl illustrated this with a large survey of multiplicity among 3500 young stellar objects in Orion A using the VLT Infrared Survey Telescope for Astronomy (VISTA). Although such a survey is limited to the most distant (> 229 au) and luminous companions, they found a companion fraction of almost 8 % in the less dense parts of the star forming region. Pavel Kroupa stressed, however, that the binary fraction will decrease with time; interactions in the clusters where stars form will disrupt the widest systems as well as those with the most extreme mass ratios. While the initial binary fraction (i.e., for the youngest stars) is independent of primary mass, dynamical evolution removes binary companions from lower mass stars, leading to the observed difference in companion fractions between M, G and O stars.

Stars do not occur only in binary systems, but also in multiple systems. Triple systems, as Silvia Toonen explained, are not that rare; the fraction of low-mass stars in triple systems is 10–15 %, and this doubles for massive stars. The presence of the third component can have dramatic effects, leading to shrinkage of the inner binary or an increase in its eccentricity, thereby making mass transfer between the components easier.

Low-mass stars and mass transfer

Moving on to low- and intermediate-mass stars, Maurizio Salaris reminded the audience of the current challenges that face stellar evolution models, stressing the many parameters (sometimes with *ad hoc* values) that are in use. Here, as Paul Beck showed, the combination of astroseismology and binarity could come to the rescue, as illustrated by the example of an "Asterix & Obelix system": a binary system consisting of two red giants of almost the same mass (just a 1% difference) but quite different effective temperatures. Understanding how such small differences in mass lead to such a drastic effect should help to constrain stellar models.

Another key example of the effect of binary interaction in low- and intermediate-mass stars is represented by chemically polluted binaries, comprising such families as Barium, CH, S, or carbon-enhanced metal poor (CEMP-s) stars. Onno Pols gave an overview highlighting our lack of understanding of these stars. Each of these systems contains a white dwarf (WD) companion that produced the s-process elements which polluted the companion; they have orbital periods between 100 and 10 000 days, and are substantially eccentric, placing them in a region of the parameter space that should be empty according to the majority of theoretical models. More observational data, such as high-resolution spectroscopy combined with distances from Gaia, may help to solve this long-standing puzzle, as shown by Ana Escorza and Drisya Karinkuzhi.

There is no doubt that during their mass transfer, these stars also showed the characteristics of symbiotic stars, which are among the widest interacting binaries and contain a red giant and a hot companion, as reviewed by Jennifer Sokoloski. The cause of the enhanced mass loss from the giant in these systems is still unknown, as is the nature of the mass transfer itself. Understanding these objects — as well as their actual numbers — is important as they are sometimes considered to be a possible channel by which Type Ia supernovae are formed (see below). Similarly, cataclysmic variables are also important; they are the shorter-period analogues of symbiotic stars, in which a main sequence star is transferring mass to a WD. Anna Pala presented a 122-orbit HST programme to study such stars; the resulting findings also contradict theoretical expectations. Large surveys to better characterise such stars are clearly called for.

Moving further along the evolutionary sequence, Hans Van Winckel presented the latest results on post-asymptotic giant branch binaries (post-AGBs), which all have orbital periods between 100 and about 2000 days (another unexpected result!). Each pair appears to be surrounded by a circumbinary disc while the secondary also seems to possess a disc and most likely some kind of jet-like outflow, the origin of which is unknown.

The family of such puzzling stars was recently enlarged with the discovery of dusty post-red giant branch (post-RGB) stars, as Devika Kamath told us. These stars are not luminous enough to have an AGB progenitor and so must correspond to systems where the evolution of the primary was cut short on the RGB as a result of mass transfer. Several hundred such systems are now known in the Magellanic Clouds, so they cannot be easily dismissed.

Perhaps the most striking examples of binary interactions are planetary nebulae (PNe). These beautiful cosmic bubbles (Figure 2) are traditionally thought of as being the swansongs of low- and intermediate-mass stars before they end their lives as WDs. However, as David Jones explained, the fact that most PNe are now known to be axisymmetric with quite intricate shapes is most likely an indication of some type of binary processes. Of course, some of the central stars of PNe may not be a binary any more, as they could also be the result of the merger of the two stars from the original binary systems. In fact, some examples of mergers exist. Tomek Kaminski presented evidence of the badly named red novae, likely caused by merging stars.

Stellar clusters

In stellar evolution, the study of stars in clusters is advantageous as many parameters (for example, ages, distances and chemical compositions) can be considered fixed when comparing the stars. They are also a rich field in which to study binary stars. Robert Mathieu reviewed the many alternative pathways of stellar evolution that are present in open clusters. The colour-magnitude diagram clearly does not resemble a textbook example of a single population of stars, having as it does outliers such as photometric binaries, blue straggler stars, yellow stragglers, sub-subgiants and yellow giants, all of which are explained by binarity. He showed that at least a quarter of all stars in a cluster are not on single-star evolutionary paths. Francesco Ferraro reminded us in his review that blue straggler stars represented the first evidence of binaries in globular clusters and have since been used to probe the dynamical processes in such clusters. But Michela Mapelli explained that binaries themselves have a huge impact on the dynamics of clusters. Interactions inside a cluster could also explain the formation of binary black holes that would eventually merge.

Massive stars

Moving on to massive stars, Norbert Langer presented the many challenges to modelling massive stars, stating that "when mass increases, our ignorance also increases!" As most massive stars are members of binary pairs, many of them are interacting systems, one needs to address binarity to understand many processes. Note that if a star is not in a binary system now, it may have been in the past; either the companion having been ejected (explaining runaway stars) or the two stars merging (as could happen in the case of about a quarter of all massive stars!). Hugues Sana presented some of the most recent surveys of binarity in massive stars, showing that O stars in binaries have an apparently flat mass ratio distribution but a tendency to be in short-period systems, with little variation seen as a function of the environment or metallicity, thereby suggesting that these are relatively universal results arising from the physics of the formation process itself.

Nathan Smith explained that perhaps the most obvious result of binary interactions in massive stars are luminous blue variable stars (LBVs). Indeed, the single-star paradigm within which LBVs are a short transition phase between normal O stars and Wolf-Rayet stars is encountering numerous problems, including the fact that some supernova progenitors are now thought to have been LBVs — something that can't be reconciled with the standard paradigm. A binary model for LBVs would provide a much more natural explanation of all the observed characteristics. Observing such LBVs, and in particular the most dramatic example, Eta Carinae, requires the use of interferometric techniques and Joel Sanchez Bermudez showed how the Gravity instrument on the Very Large Telescope Interferometer is leading to a better understanding of this important object.

Exploding stars and black holes

A likely contender for this year's Nobel Prize in Physics is the detection of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO) instruments. Gravitational waves were shown to be the tell-tale signature of the merger of two massive black holes. Gijs Nelemans provided an overview of the challenges faced when doing such measurements and of the current theories that aim to explain how such binaries form. He also predicted a bright future for this new area of astronomy; from 2019 on, we shall be able to detect massive systems up to several Gpc away, and this limit will later be pushed to a redshift of 10, i.e., basically all of the visible Universe. Coen Neijssel also showed that we need a rather low metallicity to explain the observed events, as at solar metallicity the mass loss from massive stars would be too high to produce the kind of binary black holes that have been observed.

This was a natural point at which to discuss other explosive events in the Universe that are, unsurprisingly, also linked to binary stars. Nando Patat first reviewed our current knowledge of Type Ia supernovae. Showing some "back of the envelope" calculations — that were literally done on the back of an envelope (Figure 3) — he described how the double degenerate model (in which a supernova is the result of the merging of two WDs) went from being the underdog to being the most favoured theory, even though the problem is still far from being fully solved. Perhaps the most worrying aspect is that we are still unsure whether these supernovae are indeed the "standard candles" that astronomers think they are when measuring distances in the Universe.

That the double degenerate model is now in great favour was also illustrated in talks by Chris Pritchet and Na'ama Hallakoun. The latter presented an analysis of the SPY (ESO SN Ia Progenitor surveY) sample, which took about 2200 UVES spectra of about 800 WDs, measuring radial velocities with a precision of 1–2 km s^{-1}. Analysing a clean sample of 439 WDs for which they have multi-epoch spectra with high signal-to-noise ratio, they found that 10% consist of double degenerate systems with separations smaller than 4 au. The estimated merger rate is therefore more than enough to explain all observed Type Ia supernovae.

Moving further up in mass, Nial Tanvir discussed gamma-ray bursts (GRBs). It has long been known that the short GRBs originate from merging neutron stars, but evidence is now also mounting that even for long GRBs, binaries may be needed!

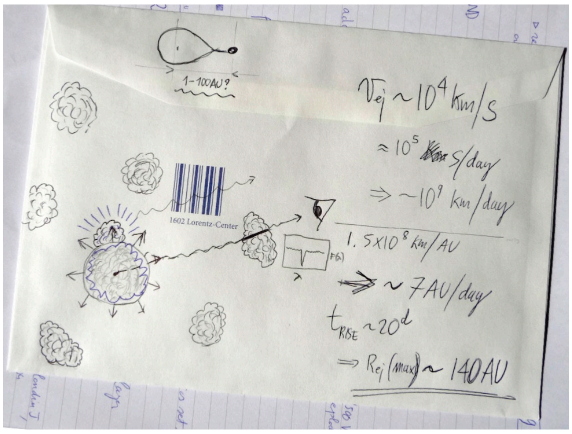

Figure 3. Nando Patat's "back of the envelope" calculation for the double degenerate model, showing how the merging of two WDs can lead to a Type Ia supernova.

A legacy

Else Starkenburg opened the last session of the conference, pointing to the fact that the lowest-metallicity stars that still exist today probably carry the imprint of very few supernovae in the early Universe. This turns out to be one of the key science goals of Pristine, a survey at the Canada-France-Hawaii telescope devoted to the search for the most metal-poor stars. Along the same lines, Sara Lucatello reviewed the present-day results on binary fractions at low metallicity. Evidence seems to suggest that CEMP stars likely originate from binaries. Moreover, preliminary data from the Lick Extremely Metal Poor (EMP) binary survey indicate a higher binary fraction at higher ([Fe/H] ≈ –2) metallicity. Putting it all together, Rob Izzard reviewed why we need to perform binary population synthesis, and how it is currently done. There are now more and more sophisticated codes that address many problems, although one needs to be sure that the correct physics is used. JJ Eldridge showed also how stellar models may be used in population and spectral analysis, while Laurent Eyer and Nami Mowlavi highlighted the observational side, stressing the fact that, with Gaia and the future Large Synoptic Survey Telescope (LSST), we are now entering a data-driven era and we need to prepare for it. Gaia will find and characterise tens of millions of binaries of various sorts, and is therefore bound to revolutionise the field – if we are ready to address the data flow.

We hope that this workshop will have a strong legacy and we have therefore assembled PDF files of most presentations via the programme webpage[1], as well as many of the posters[2]. We also prepared videos of the presentations that are also linked from this page. However, perhaps the most obvious outcome of the meeting is that textbooks need to be rewritten to take into account the importance of binarity in stellar evolution. We have therefore also embarked on producing a textbook that will comprise edited versions of most of the invited talks at the workshop. The book will be published by Cambridge University Press next year.

Acknowledgements

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Links

[1] Programme with links to presentations: http://www.eso.org/sci/meetings/2017/Imbase2017/program.html
[2] List of poster PDFs as well as poster abstract booklet: http://www.eso.org/sci/meetings/2017/Imbase2017/posters.html

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Forty Years at ESO — Bernard Delabre and Optical Designs

Tim de Zeeuw[1]
Samuel Lévêque[1]
Luca Pasquini[1]
Michèle Péron[1]
Jason Spyromilio[1]

[1] ESO

The optical designer Bernard Delabre has retired from ESO after 40 years at the forefront of telescope and instrument optics. A short overview of his achievements and his legacy of astronomical telescopes and instrumentation is presented. Bernard Delabre was