1
Population and spectral synthesis: it doesn’t work without binaries

J.J. Eldridge and Elizabeth R. Stanway

Abstract

In this chapter we discuss the population and spectral synthesis of stellar populations. We describe the method required to achieve such synthesis and discuss examples where inclusion of interacting binaries are vital to reproducing the properties of observed stellar systems. These examples include the Hertzsprung-Russel diagram, massive star number counts, core-collapse supernovae and the ionising radiation from stellar populations that power both nearby HII regions and the epoch of reionization. We finally offer some speculations on the future paths of research in spectral synthesis.

1.1 What is population and spectral synthesis?

Population synthesis involves predicting the parameters of a population of stars through a combination of individual stellar models or empirical templates. Examples of stellar populations include those in individual star clusters, galaxies or those that give rise to a sample of transient events such as core-collapse supernovae or gravitational wave merger ‘chirps’. To make such predictions through population synthesis a number of stellar models, each predicting the properties and evolution of one star, are combined together with an initial parameter distribution to calculate a synthetic population that can be compared to observational constraints including stellar type ratios and transient event rates.

Spectral synthesis is the term for the combination of such a synthetic population with matched stellar atmosphere models that predict how each star of known surface temperature, gravity and composition would appear if observed across all wavelengths. The resulting composite spectral energy distribution can be convolved with the known parameters of individual detectors and telescopes. This step effectively observes the model population so it can be directly compared to the observational data. This technique is especially important when attempting to interpret unresolved stellar populations where individual stars cannot be studied and classified individually.

The first population synthesis models can be traced back to the first attempts to understand the stellar content of galaxies and star clusters [e.g. Tinsley, 1968, Tinsley and Gunn].

This material has been published in The Impact of Binaries on Stellar Evolution, Beccari G. & Boffin H.M.J. (Eds.). This version is free to view and download for personal use only. Not for re-distribution, re-sale or use in derivative works © 2018 Cambridge University Press.
There are now many codes that perform population and spectral synthesis. The evolutionary models most widely used to date carry the implicit assumption that most stars evolve as single stars, without any significant binary interaction, and thus relatively few evolutionary avenues are available [e.g. Leitherer et al., 1999, Bruzual and Charlot, 2003, Choi et al., 2016]. While these codes have allowed us to deepen our knowledge of stellar systems, they are limited by their single-star evolutionary paradigm. This is fundamentally an unphysical assumption. It is clear from other chapters in this book that the fraction of binary stars in stellar populations range from 20% for the lowest mass stars to 100% for more massive stars. As this volume also indicates, in many binaries at least one of the stars will have a substantially different evolutionary path to that of a single star. As a result, a failure to account for binary effects would be expected to compromise interpretation of stellar system parameters in any regime where these are significant for the dominant population.

Over the past few decades a number of groups have been attempting to account for interacting binaries in their population synthesis, and more rarely spectral synthesis. Groups computing population synthesis models include, for example, Tutukov and Yungelson (1996), Hurley et al. (2002), Willems and Kolb (2004), De Donder and Vanbeveren (2004), Zhang et al. (2005), Belczynski et al. (2007), Lipunov et al. (2009), Izzard et al. (2009), Toonen and Nelemans (2013), Eldridge et al. (2017). However from this list only De Donder and Vanbeveren (2004), Zhang et al. (2005) and Eldridge et al. (2017) also make spectral synthesis predictions. Inclusion of spectral synthesis within binary population synthesis models has confirmed that interacting binaries make a substantial change to the predictions of spectral synthesis and that the use of single star models can leads to errors in interpreting certain aspects of stellar populations.

In this chapter we first give a brief overview of how population and spectral synthesis is performed and highlight some of the key uncertainties. We then discuss selected example observations where interacting binaries make a substantial difference to how we understand the underlying stellar systems. These include the HR diagram of resolved stellar clusters, number counts of massive stars in galaxies, core-collapse supernovae, gravitational wave sources, the stellar populations of distant galaxies and the epoch of reionization.

### 1.2 How do you do it?

To perform a population synthesis one first has to gather or create a set of stellar evolution models from which to construct the synthetic population. It is possible either to use extant stellar models [e.g. Ekström et al., 2012] or to calculate your own [e.g. Choi et al., 2016, Eldridge et al., 2017]. It should be noted that these models themselves incorporate substantial uncertainties. There are many known problems in stellar evolution such as determination of mass-loss rates, rotation rates and how to implement convection that all impact on the certainty with which predictions of stellar properties at a given mass and age can be made. We can however test these models by comparing their properties to observed
individual stars such as the Sun or the physically well-constrained main-sequence stars in eclipsing binaries.

When computing models of interacting binary stars the situation is more complicated due to the extra physics that needs to be included in evolution codes. Prescriptions for Roche lobe overflow (RLOF) and common envelope evolution (CEE) must be included. An extensive body of literature exists exploring the uncertainties on each of these and the tunable parameters in any given prescription. Nonetheless, these are vital to account for the mass transfer from one star to the other in a binary, and to shrink the orbit to produce the tight post-mass transfer binaries we see in the Galaxy. The effects of any mass transfer on the subsequent evolution must then be considered.

There are two different approaches to modelling the evolution of binary stars. One of these is to use a detailed stellar evolution code [e.g. De Donder and Vanbeveren, 2004, Eldridge et al., 2017] however this has the drawback that each model can take several minutes to calculate. This means that to calculate a large grid of models in order to fully investigate the parameter space can take years on a single computer. With Universities investing in computational resources and large clusters it is beginning to become feasible to use detailed models to create the tens of thousands of models required for population synthesis.

Alternately approximate rapid codes, for example Hurley et al. [2002], approximate the evolution of binary stars by fitting functions to a smaller pre-calculated grid of detailed models and interpolating between them. While the evolution is only followed in an approximate manner, this method does allow multiple large grids to be rapidly calculated so that how uncertainties in the input physics effect the results of the population synthesis can be investigated, [e.g. de Mink et al., 2013]. Applications include exploring the effects of stellar rotation on evolutionary stages. Such a study would be challenging in a detailed code as the each model run would need to follow the transport of angular momentum through the star in detail, which makes the models difficult (and also time consuming) to calculate [e.g. Cantiello et al., 2007].

Once the individual stellar models are calculated they must be combined into a synthetic population. This is done by weighing each model by a factor that represents how likely it is to exist in a given scenario. For all populations we use an initial mass function that determines how likely it is that a star of a given stellar mass exists at a zero main-sequence age after the initial star formation episode. Examples include Kroupa et al. [1993] and Chabrier [2003]. These all are more modern versions of the model established by Salpeter [1955] where a power law representation was used to capture the observed fact that there are many more low mass than high mass stars.

In a binary population we must also describe the distribution of initial periods, eccentricities and secondary masses. Some of the most recent can be found in Moe and Di Stefano [2017]. The binary fraction is around 100% of stars being in binaries for stars ≥ 10 M⊙ with 70% of them close enough to have their evolution affected by binary interactions during their evolution [Sana et al., 2012]. For less massive stars, less massive than < 1 M⊙, the binary fraction drops to 20 to 40%.
The period distributions also vary with stellar mass. While Opik’s law is a good first estimate, studies tend to indicate that there may be more close binaries. Nonetheless a flat distribution in the mass ratio for the secondary seems a good approximation. More data is still required to gain a firm understanding, but the initial parameters of binaries are beginning to become well constrained.

To summarise we now know how to weight each of our binary models and have a model that follows the evolution of the stars, but there is one final complication: the first supernova. When a supernova occurs in a binary there are one of two possible outcomes, either the binary is unbound and the two stars go on to evolve as single stars or they remain bound and become a binary with a compact companion. These may evolve into a X-ray binary.

Determining whether the system is unbound or not depends on a few factors. First is the amount of ejecta in the supernova. It can be shown, assuming a circular pre-SN orbit, that if the ejecta mass is more than half the mass of the binary then the system is unbound. Therefore estimating how much mass goes into the remnant and how much is ejected is a key problem. Work such as Sukhbold et al. [2016] is showing that it may not be easy to determine this accurately. The final outcome of evolution appears to be chaotic over some mass ranges and depends on all the uncertainties put into the stellar model. However some simpler schemes exist to estimate the remnant mass and future work will allow us to understand this more.

The other factor is that in formation neutron stars and black holes appear to be given a momentum kick during core collapse which can range from a few 10s km/s up to 1000km/s! [e.g. Hobbs et al., 2005]. The source of the kick is currently being investigated by many groups [e.g. Bray and Eldridge, 2016, Janka, 2017]. It is important to consider this as kicks can change the orbital velocity of the compact remnant in the SN and this can lead to un-binding binaries that would have remained bound as well as keeping binaries bound that would otherwise have been unbound. Further complicating the issue is whether black hole have kicks or not; most prescriptions seem to indicate they must be weaker but there is limited observational evidence [e.g Mandel, 2016].

In our population synthesis the first supernova therefore creates multiple possible future evolutionary pathways for each binary. These have to be calculated and are usually accounted for by Monte Carlo methods, making models with a large number of different random kicks in direction and magnitude and weighting the results by a probability distribution. This is again where the rapid models have an advantage as many different models can be calculated quickly, while for detailed models some approximations must be made to calculate such stellar models in a reasonable timeframe.

Once a synthetic population is created it can be compared to observed stellar populations. For observations such as number counts, distributions of luminosities or orbital period distributions this can be fairly straightforward. The stumbling block is that typically the observations might only be in a few observed photometric filters, or comprise only the optical spectrum of a star. Most stellar models only give a bolometric luminosity and effective temperature for the stars, and so linking this to a spectrum or photometric V band magnitude requires an additional step.
It is possible to take the observations and process them, accounting for their selection functions, to get the required numbers to compare to the models. This is somewhat risky when we have an incomplete data set where there are large gaps in our knowledge. A more rigorous method is to take the stellar models and observe the models in a similar way. This can be done by attaching stellar atmosphere models to the stellar evolution models and creating a synthetic spectrum. Doing so requires bringing together a large number of different spectra from different sources as the physics of cool and hot stellar atmospheres can be very different and the best models for each regime may be produced by different teams and codes [e.g. Westera et al., 2002, Smith et al., 2002, Hamann et al., 2006, Gustafsson et al., 2008, Sander et al., 2012, Massey et al., 2013].

Matching the stellar model to the atmosphere model typically requires us to know the effective temperature, gravity and surface composition of our stellar model as these are the primary factors that determine the stellar spectra. Once this match is done it is possible to create either spectra for individual stars or for the entire population, allowing us to closely match the observations to the models and gain greater constraints even if the observational dataset is limited.

All these complications and uncertainties have in the past contributed to an air of distrust regarding binary population synthesis. However, today, the number of firm constraints on the uncertain parameters is increasing. Single model populations are being compared to a large number of varied observables, as performed by the BPASS team in Eldridge et al. [2017], giving additional confidence in their application. Other groups such as the Brussels group [e.g. Van Bever et al., 1999, Van Bever and Vanbeveren, 2000, Vanbeveren et al., 2007], binary community [e.g. Izzard et al., 2009, Claeys et al., 2014, Abate et al., 2015] and Yunnan groups [e.g. Zhang et al., 2005, Han et al., 2007, Han and Han, 2014, Zhang et al., 2015] are also doing very similar work.

The key result emerging from all these studies however is that we MUST include interacting binaries in our population and spectral synthesis. If we do not then we run the risk of drawing incorrect conclusions when studying systems using stellar population models as our tool.

### 1.3 Why are binaries important?

Binaries are important as they provide evolutionary pathways that are simply not accessible from single-star evolution. Single star models have for some time done a very good job of allowing us to understand stellar populations which, in the local Universe, are often old and metal rich and thus relatively unaffected by binary interactions. Recent observational evidence shows that stars are born with many of them in binaries, especially the most massive [e.g. Sana et al., 2012, Moe and Di Stefano, 2017] and so the effects on young stellar populations is likely to be more pronounced. As well as that, many stars stay in a binary system right to the last possible event in a binary’s life, when the two remnants of
the stars inspiral and merge due to the loss of orbital energy through gravitational radiation [e.g. Abbott et al., 2016, 2017]. This suggests we need to take a holistic view when attempting to model stellar populations. The effect of binaries will not always be obvious and may only become apparent in certain phases of evolution. For example, the main sequence evolution is not significantly affected by binary interactions (although mergers do occur and there are a few exceptional cases) when looking at a population. Most differences between predictions from single stars and binaries become apparent in post-main sequence phases of evolution and the eventual deaths-throes of massive stars in core-collapse supernovae.

Rather than concentrate on one detail of population and spectral synthesis predicts we will introduce a varied number of observations and show that in each case interacting binaries are required to explain the observed systems, using our own BPASS models [Eldridge et al. 2017] as a demonstration. We will first consider stellar populations, then consider spectral synthesis before finally speculating about the future directions of what population synthesis will be able to predict in future.

### 1.3.1 Blue stragglers on the HR diagram

For resolved stellar populations in clusters the effects of binary evolution are two-fold. There are two main binary interactions that affect the position of stars on a Hertzsprung-Russell diagram for example: mergers and mass transfer. These make more massive stars available at ages for a cluster well beyond their expected main-sequence turn off. They are well known in globular clusters for example as blue stragglers, for younger H II regions or open clusters identifying such stars is more difficult.

For clusters the age is frequently estimated by using single star isochrones, primarily from attempting to fit the main-sequence turn off. The existence of blue stragglers can directly affect the accuracy of this method. We show in Figure 1.1 an example fit to a single cluster, with single-star isochrones and a population including interacting binaries, which yield an isochronal contour plot. We see that for the well known cluster Cygnus OB, to fit the most luminous stars a maximum age of 3 Myrs is required from single stars, but with the binary population an older age of 5 Myrs is qualitatively a better match to the data. While this is an extreme example it shows that there is something that must be taken into consideration when attempting to evaluate the age of resolved clusters.

### 1.3.2 Number counts

Another basic observable of stellar populations are number counts. If stars can be typed then, say, the total number of O stars can be compared to the number of red supergiants (RSG) or Wolf-Rayet (WR) stars. This is a measurement of the number of main-sequence to post-main sequence stars: something that depends on the nuclear evolution of a stars core as well as the mass loss from the surface. For example in Figure 1.2 we show an
Population and spectral synthesis: it doesn’t work without binaries

Figure 1.1 The HR diagram of Cygnus OB2 [Kimbinki and Kobulnicky, 2012; Wright et al., 2015] compared to theoretical HR contours for single star (left panels) and binary star (right panels) populations. The models are for two different ages, 3 Myrs in the upper panels and 5 Myrs in the lower panels.

example comparing the observed number of red supergiants to Wolf-Rayet stars, post-main sequence stars that have retained or lost their hydrogen envelopes respectively. We can see here the dramatic change in the ratio of these two stellar types that arises due to the inclusion of binary interactions. The change is roughly around an order of magnitude due to the binary interactions providing an extra avenue for mass loss rather than stellar winds alone. The binary models appear to match the observations slightly better, although the lowest metallicity point in the SMC is closer to the single star evolution line. However the assumed scaling of mass-loss rates might be too strong or the assumption of constant star formation may also be wrong with the plot only based on ≈100 RSGs and 13 WRs.

1.3.3 SN progenitors

If the effect of interacting binaries is so dramatic that we can infer its presence from the number ratios of stars, we should also find this reflected in the number of stars that die
Figure 1.2 The ratio of the number of Wolf-Rayet stars to red supergiants as observed in galaxies at a single metallicity. Solid lines show BPASS binary models and dashed lines show single models. Points with error bars show observational constraints taken from the literature. All ratios include only stars with $\log(L/L_\odot) > 4.9$. The red lines show results for constant star formation from BPASS v1.0, while the black lines show similar results from BPASS v2.1 with IMF $M_{\text{max}} = 100M_\odot$, respectively. The WR/RSG observed ratios come from P. Massey (private communication).

with their hydrogen envelopes intact or removed. When core-collapse supernovae occur they have historically been classified by their observational characteristics, primarily their spectra and lightcurves. The broadest classification is made on whether they are hydrogen-rich, type II, or hydrogen-free, type Ib/c (note type Ia supernovae arise from thermonuclear detonations of carbon-oxygen white dwarfs and are identified by strong silicon lines).

As we show in Figure 1.3 the type II supernovae progenitors are known to be mostly red supergiants with some blue and yellow supergiants [see Smartt, 2015]. For type Ib/c supernovae the progenitors were long expected to be Wolf-Rayet stars but a problem with this was that if this was the case then they should have been directly detected in pre-explosion images of a sample of nearby explosions. This suggested that the progenitors were more likely to be lower-mass helium stars that were the result of binary interactions [Yoon et al., 2012, Eldridge et al., 2013]. Confirmation that this is likely to be the case came from observations of the progenitor of type Ib supernova, iPTF13bvn. Detailed modelling by many groups have shown that the most likely progenitor of this event is a binary system [Bersten et al., 2014, Eldridge and Maund, 2016, Yoon et al., 2017]. We can see this in Figure 1.3 as in single star predictions progenitors can only either be cool red supergiants or hot Wolf-Rayet stars. The binary predictions however fill a much greater space of
the HR diagram, especially filling the region where most progenitors have been observed to date.

However while progenitor detections provide direct evidence for the effects of binary evolution, the most compelling evidence comes from the relative rate of type Ib/c to type II progenitors. A consistent model should be able to predict both the WR/RSG ratio as well as the type Ib/c to II relative rate. The ratio is dependent on metallicity, with fewer type Ib/c supernovae at lower metallicities, but as shown by the recent study of Graur et al. [2017] the exact determination of the rate at a specific metallicity is difficult. If we restrict ourselves to nearby supernovae where host galaxies have metallicities in the range from Solar to maybe half Solar, we find a relative rate ratio of type Ib/c to type II supernovae or 0.29±0.17 [Eldridge et al. 2013, Xiao and Eldridge 2015], where again we are limited by large uncertainties. Despite these significant uncertainties in any comparison single star models predict ratio below this value while binary models predict a ratio close to or above this value. An exact match is difficult because star-formation history and metallicities distributions must be modelled of the stellar population. But a stellar population with a high binary fraction generally provides a better match to the observed ratio. This is consistent with multiple equivalent studies over a significant period of time [e.g. Podsiałowski et al. 1992, De Donder and Vanbeveren 1998]. Finally recent work by Zapartas et al. [2017] shows that progenitors dominated by a population of interacting binary stars also reproduced the observed core-collapse supernova delay time distribution better than a single star only population.

1.3.4 GW mergers

In a massive binary system, if it can survive two supernovae and remain bound then then two remnants, either neutron stars or black holes, will slowly inspiral due to emission of gravitational radiation [e.g. Abbott et al. 2016, 2017]. Since the detection of the first merging black hole binary, GW150917, there have been to date 5 pairs of merging black holes and one double neutron star merger detected. To round off our holistic study of population synthesis of massive stars, the same model that explains the observed post-main sequence star ratios and supernova relative rates of different types also needs to predict the mass range and rate of these binaries. This is still work in progress and there are many binary evolution codes now attempting to predict the rate of these mergers as well as the masses of the observed merging objects. While this is important, the same codes also need to make sure they correctly predict the other, more visible aspects of stellar evolution that lead up to formation of the remnants, rather than just the final ripples in space-time from the merger of those remnants.
Figure 1.3 HR diagrams showing the predicted location of SN progenitors from BPASS v2.1 models compared to the position of observed SN progenitors. The upper panel is for single star populations and the lower panel is for binary star populations. The black contours are for progenitors expected to form black holes, the light grey contours are for type II progenitors and the dark grey contours are for type Ib/c progenitors. The points are observations taken from Smartt [2015], the plus’ are observed type IIP progenitors, the diamonds are type IIP progenitors with upper limits on the luminosity, the asterisks are type IIb progenitors, the crosses are the progenitors of 1987A and 1993J, the triangle is for the type Ib progenitor of iPTF13bvn and the square is for the candidate black-hole forming event from Adams et al. [2017].
1.4 Galaxies near and far

The populations and distribution of stars within the Milky Way and other galaxies in the local Universe reflects thirteen billion years of evolution and complexity. While some of the stars, particularly the massive stars, observed nearby formed in the locations where they observed, others may have formed elsewhere within a gravitationally bound system, or even in satellite stellar populations or progenitor galaxies which merged over time into the current host. Most, if not all, incorporate metals and other material which have been processed by one or more earlier stellar populations and their resultant supernovae.

A full understanding of the stellar populations nearby thus requires an overview of processes which extend to cosmological scales in both time and distance, including (but not limited to) the thermal history of the Universe and variations in its chemical enrichment over cosmic time.

Our primary information on these processes is derived from starlight, sometimes reprocessed through dust or gas along the line of sight. However for all but the most nearby galaxies, direct imaging and resolution of individual stars is technically impossible [although note the existence of a claimed single-star, caustic-crossing lensing event in a distant $z=1.5$ galaxy, Kelly et al., 2016]. The angular scales and sensitivity required exceed the limits of even an ELT-class telescope. In a best case scenario, it may be possible to measure the integrated light from a single star forming region (down to $\sim 30$ pc in resolution) making use of the spatial magnification associated with gravitational lensing [e.g. Johnson et al., 2017]. However in a more normal case, resolving scales below 1 kpc in galaxies is difficult from space, and requires adaptive optics and/or exceptional conditions from the ground. As a result, the emission detected represents the integrated light of one or more stellar populations. In many cases, ultraviolet and optical light will be dominated by some combination of the youngest and most massive stars, simply because these outshine their more numerous but much fainter fellows. These can be fit with a simple stellar population, or with a straight-forward model such as one continuously forming stars at a constant rate. At long wavelengths, moving towards the infrared, or for galaxies dominated by a massive underlying old stellar population, the contributions of different elements of the stellar population, or from different stages of the star formation history, can be more equal [e.g. Kauffmann et al., 2003]. In these cases, knowledge of both the stellar mass function and the star formation history is required, or needs to be derived from the available data. In such instances, the outputs of a stellar population and spectral synthesis code are an essential tool for interpreting galaxy photometry and spectroscopy.

This has been recognised for many years, and a number of spectral synthesis models have been developed with the specific aim of modelling the complex stellar populations seen in galaxies. These include the very successful GALAXEV model set [Bruzual and Charlot, 2003 and later references] which combines theoretical stellar evolution tracks with simple star formation histories and applies empirical models for nebula emission at young stellar ages, and the MAGPHYS models [da Cunha et al., 2008] which aim primarily to explore the non-stellar components of galaxies, extending into the infrared and submillime-
tre, coupling these to the parent stellar population through an energy balance between dust absorption and re-emission. These and similar models have been used with great success to explore the properties of galaxies in the nearby Universe, where empirical calibration and multiple analysis methods can be used to check their application and precision [e.g. Tremonti et al., 2004, Brinchmann et al., 2004, Taylor et al., 2011]. However, as observational samples of galaxies push to earlier times, when the Universe was less metal rich, star formation occurred with a higher specific rate density, and the stellar populations are significantly younger [see e.g. Madau and Dickinson, 2014, for a recent review], we are moving into new regimes, where the efficacy of such models has not been tested. What is more, the identification of extreme classes of local galaxies which share similar physical conditions, and are thus classed as analogues to galaxies in the distant Universe [e.g. Heckman et al., 2005, Cardamone et al., 2009, Amorín et al., 2014, Stanway and Davies, 2014], has demonstrated that even nearby galaxy-scale stellar systems can lie well outside the normal range of properties predicted by the older generation of population synthesis models.

At the same time, the same distant or extreme galaxy spectra present an interesting opportunity to test and constrain stellar modelling. The conditions which prevail in different regions of the Universe, and at different epochs of cosmic history, are often rare in the local Universe. In particular the distant Universe (where the galaxies we observe emitted their light within a few billion years after the Big Bang) has attracted interest in this respect. As mentioned above, the stellar populations at those early times are typically young (<1 Gyr in age), and form from gas clouds with both a lower overall metal enrichment (well below half-Solar), and potentially very different abundance ratios to those common in the local Universe (due to different enrichment processes). While old stellar populations such as Globular Clusters nearby tend to be enhanced in alpha-process elements, as the result of a higher ratio of core-collapse supernovae to other nucleosynthesis channels, at high redshifts we see the same alpha-enhancement in much younger stellar populations, dominated by more massive stars. At the same time observations of galaxies in the distant Universe are weighted towards the rest-frame ultraviolet spectral region, redshifted longwards of the atmospheric cut-off and into the observed frame optical or near-infrared.

Each of these conditions suggest that aspects of massive star evolution, including their spectral evolution, lifetimes and metal yields, are likely to be far more clearly manifest in distant galaxies (and their local analogues) than in typical galaxies in the local Universe. In this regime, binary interactions are expected to be important. Thus while binary stellar population models are required to interpret the light of these integrated stellar populations, the same observations place a constraint on the models: any that fail to reproduce the observed properties of star-forming galaxies given plausible assumptions must be considered as suspect.
1.5 Ionizing radiation fields and H II regions

Early indications of the unusual stellar populations dominant in the distant Universe came in the detection of nebular line emission, particularly from lines requiring a hard ionising radiation spectrum such as the rest-frame ultraviolet He II 1640 Angstrom emission line from galaxies at $z > 2$. These appeared to include both broad [e.g. Shapley et al., 2003] and narrow [e.g. Erb et al., 2010] components, suggestive of strong stellar winds and intensely ionised nebular regions respectively, while exhibiting no evidence for an AGN-powered emission component. Studies of the He II feature have recently been complemented by observations of sources with C III] and C IV in emission again, with strong constraints indicating a likely stellar source for their photoionization [e.g. Stark et al., 2015a,b, Maseda et al., 2017]. At the same time, galaxies at still earlier times ($z > 5$) were exhibiting very blue ultraviolet colours [e.g. Stanway et al., 2005, Bouwens et al., 2010]. While there is certainly evolution in the dust extinction in the galaxy population, the slopes observed were suggestive of a much hotter stellar spectrum than typical at lower redshifts, and a resultant excess of hard ionising photons.

Early theoretical work suggesting that Population III (i.e. essentially metal-free, primordial stars) were required to explain these observations [e.g. Schaerer, 2003, Jimenez and Haiman, 2006] overlooked alternative sources of hard ionising photons, in particular the strongly metal-dependant contribution of binary evolution pathways, and the hot stars they produce. Initial work on the spectral synthesis application of the BPASS binary stellar evolution models was inspired, at least in part, by the desire to confront these observations [see Eldridge and Stanway, 2009, 2012]. It demonstrated that inclusion of binary evolution pathways was capable of generating stronger ionising photon radiation fields, and provided a good fit to a range of observations in both extreme local sources and to galaxies in the distant Universe.

More recently, both the weight of evidence for physical conditions in these systems and the models required to interpret them have developed significantly. The advent of multi-object near-infrared spectrographs on large telescopes (notably MOSFIRE on Keck), have rendered the rest-frame optical accessible at $z > 2$, and allowed for direct comparison between the strong recombination line spectral diagnostics seen in large local surveys such as the SDSS and those observed in distant galaxies. One of the most striking results has been the discovery of an offset in the Baldwin, Phillips and Terlevich (BPT, 1981) photoionization-sensitive diagnostic diagrams, cementing the requirement for a hard ionizing radiation spectrum [e.g. Masters et al., 2014, Holden et al., 2016]. The same offset is seen in selected local analogue galaxies, which have similarly high star formation densities [Stanway et al., 2014].

Crucially, a number of these galaxies, while clearly consistent with a star forming galaxy locus, lie above the ‘Maximal starburst line defined by Kewley et al. [2001]. This requires that their stellar radiation field is harder than that derived from a combination of single star spectral synthesis and nebular emission models. As a number of studies have now shown [e.g. Stanway et al., 2014, 2016, Steidel et al., 2014, 2016, Strom et al., 2017]
Götberg et al. [2017], Xiao et al. [2018] have now shown, binary spectral synthesis has two important effects which tend to produce harder galaxy spectral models. Firstly, binary interactions lead to the inclusion in synthetic populations of stripped helium stars, and also stars which undergo significant rotational mixing. The resultant higher surface temperatures result in atmosphere models which emit a significant fraction of their light shortwards of the Lyman limit, creating large and hot photoionization regions. Secondly, the range of timescales for evolution of such stars extends the ionizing lifetime of a stellar population beyond the few Myr required for the most massive stars to live and die in a single star model. This extended lifetime increases the fraction of galaxies and range of conditions in which large photoionised regions are expected, and also boosts the contribution of these to galaxies with continuous or ongoing starbursts.

Given the important role of metal opacities in driving stellar winds, and the effect these have on stellar evolution, such binary effects are strongly metallicity dependent. Consequently, the effects of binary evolution are relatively slight in the bulk of highly metal-enriched, slowly star-forming local galaxies, explaining the success of single star models in fitting these. Nonetheless, an analysis of star forming regions in local dwarf and spiral galaxies suggests that BPASS binary models perform at least as well as single star models in fitting their recombination line ratios, while yielding slightly higher typical ages [Xiao et al., 2018, submitted].

The increasingly clear importance of binary population synthesis in interpreting distant galaxies can largely be attributed to the effects of cosmic metallicity evolution, together with a shift towards younger stellar populations.

1.6 Photon production, photon escape and reionization

The hardness of the stellar radiation field is a key ingredient in understanding the role of galaxies in a key phase change in the thermal history of the Universe: the epoch of reionization. During this period, the first luminous sources - most likely star-forming galaxies gradually ionised their immediate surroundings for the first time since hydrogen atoms formed at $z \sim 1100$. Individual galaxy-scale H II regions expanded and overlapped over an extended period, until the Universe was highly ionised. The topography of ionised gas in this epoch should thus reflect both the distribution of star forming galaxies, and the ionizing photon output of their stellar populations. The Square Kilometer Array (SKA) will explore the power spectrum of the epoch of reionization. Detailed mapping of the ionisation balance intergalactic medium at this time is still well beyond our capacity, and will likely remain so until the next generation of HI mapping telescopes is designed and constructed.

Nonetheless, strong observational constraints on the reionization transition do already exist. Signals imprinted on the cosmic microwave background suggest that the Universe was 50% ionised somewhere around $z \sim 9$. Evolution in the characteristics of Lyman-alpha line emission, and the detection of ionised troughs in the absorption spectra of distant sources (sometimes known as cosmic lighthouses), suggest that the ionised fraction
was rapidly rising between $z \sim 6$ and $z \sim 10$ [see Planck Collaboration et al., 2016, and references therein], although line of sight variations make a definitive timeline challenging to establish.

However reconciling this thermal history, observed in neutral hydrogen, with the star formation history, observed in rest-frame ultraviolet stellar emission, has proved challenging. Considerable flexibility exists in estimates of parameters such as clumpiness (and hence self-shielding) in the intergalactic medium, its density and precise temperature. Nonetheless most estimates have suggested that the observed galaxy population may struggle to produce sufficient photons to reionize the Universe [see e.g. Robertson et al., 2015].

A key theoretical input into such estimates is the ionizing photon production efficiency, $\xi_{\text{ion}}$. This gives the rate of ionizing photons (emitted shortwards of the Lyman limit) that will arise from a population with a given rest-1500 Angstrom continuum luminosity density. Since the former cannot be directly observed even in the local Universe, the latter is used as an observable proxy for ionisation, and $\xi_{\text{ion}}$ is determined from theoretical arguments, indirect measurements or appropriate population synthesis models (or, more usually, a combination of all three). As figure 1.4 demonstrates, the value of this parameter is sensitive to both the stellar metallicity and age of an ongoing continuous starburst. It is also sensitive to more complex star formation history, and, needless to say, to the stellar population synthesis model being used. In particular, the presence of binary stars in a modelled population has a strong metallicity-dependent effect, suppressing $\xi_{\text{ion}}$ at metallicities close to Solar and strongly boosting it at low metallicities.

Both the requirements of reconciling reionization timescales with galaxy observations [e.g. Wilkins et al., 2016, Ma et al., 2016, Stanway et al., 2016], and the indirect measurements that can be obtained by considering the reprocessed nebular emission spectrum in individual galaxies [e.g. Stark et al., 2015b, Shivaei et al., 2017], push the required values of $\xi_{\text{ion}}$ well above those suggested by spectral synthesis models that neglect binary evolution effects, while favouring the BPASS models, with their harder ionizing spectrum, and resultant higher ionizing photon production efficiency.

### 1.7 Looking forward

While significant progress has been made on studying the effects of interacting binaries on the population and spectral synthesis there is still much to do. Much of this resolves around extending the spectral synthesis to the supernovae created by a binary population.

As discussed above the relative rate of different SN types can only be reproduced by a stellar population including binaries, which increases the number of stars that lose their hydrogen envelope. However an important question is, what will those supernova actually look like? Do they match the observed lightcurves and spectra of the SNe? To date SN lightcurve models consider a few different models and only recently have large numbers of models been computed.

What is required is a supernova population and spectral synthesis, analogous to the stel-
Figure 1.4 The metallicity and stellar population age dependence of the ionizing photon production efficiency, $\xi_{\text{ion}}$. This model-dependent parameter is crucial for placing observational constraints on the ionizing photon production during the reionization epoch. We show value for binary populations (solid, coloured lines) and single star populations (broken lines), at four different times after the onset of a constant, ongoing starburst event. Here we use the BPASS v2.1 models of Eldridge et al. [2017].

lar population and spectral synthesis. Groups are now taking this models and using various open source supernova simulation codes to predict the observed lightcurves of SNe. The general result is that single stars the light curves differ only slightly due to the different internal structure of the stellar models, as they are broadly the same. However due to the variety of progenitor structures that arise from binary interactions a much greater range of possible lightcurves are possible.

Future work and synthesis like this are key, especially studies and models that explore the full possible variety of binary evolution pathways. For the first time we will have a prediction as to what the full variety of possible stellar explosions may be, not only so we can match models to observed explosions but also begin to understand what types of stellar deaths we may be missing due to their faintness of rapid evolution.

Further work is also required to improve the connection between modelling of simple stellar populations and that of entire galaxies. In the latter, the effects of dust, diffuse interstellar emission and complex star formation histories are often important and difficult to disentangle or quantify. These can manifest in varied ways, affecting not only galaxy photometry and line emission but also less obvious properties, such as the chemical composition and abundance patterns resulting from previous generations of supernovae (commonly believed to lead to $\alpha$-element enhancement in old stellar populations locally). Nonetheless, distant galaxies provide laboratories probing conditions atypical of the local Universe.
There is increasing evidence from observations of such sources for specific photoionization phenomena that need to be explained. These appear common in the unusual, metal poor and star-formation dense, environments probed by young, distant galaxies, while remaining rare in the resolved stellar populations studied locally.

Recent observations of distant galaxies suggest that the photospheric iron abundance is significantly lower, relative to nebular oxygen abundance, than assumed in common binary (and most other) models [Steidel et al., 2016]. With the imminent launch of the James Webb Space Telescope, observations of photospheric line blanketing in (rest-frame) far-ultraviolet spectra of distant galaxies will become more straightforward and may be complemented by improved measurements of both stellar and nebular abundance in the rest-frame optical. Improved modelling, with a better understanding of the abundance patterns and their effects on stellar evolution, will be required to fully interpret such data.

Another example of an ongoing challenge is the strength of the He II emission line observed in strongly star-forming galaxies. Observations suggest that this is underestimated in models, which implies that these underestimate the far-UV hard ionizing radiation field. Either a change in the stellar population, for example a steeper IMF, or an improved treatment of components such as accreting compact binaries may be required to resolve this challenge, and must be accompanied by an understanding of why such changes are required in the conditions specific to the sources under observation.

1.8 Summary

In this chapter we have discussed some of the current findings in population and spectral synthesis that show why including interacting binaries is important. Also we have shown, by discussing a broad range of observables, how by using a holistic view and considering varied and different observations it is becoming possible to firmly constrain the uncertainties of binary population synthesis and increase the predictive power and usefulness of the many binary pop synth codes.

References

C. Abate, O. R. Pols, R. J. Stancliffe, R. G. Izzard, A. I. Karakas, T. C. Beers, and Y. S. Lee. Modelling the observed properties of carbon-enhanced metal-poor stars using binary population synthesis. A&A, 581:A62, September 2015. doi: 10.1051/0004-6361/201526200.

B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, and et al. Properties of the Binary Black Hole Merger GW150914. Physical Review Letters, 116(24):241102, June 2016. doi: 10.1103/PhysRevLett.116.241102.

B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, and et al. Multi-messenger Observations of a
Population and spectral synthesis: it doesn't work without binaries

and Stellar Tracks (MIST). I. Solar-scaled Models. ApJ, 823:102, June 2016. doi: 10.3847/0004-637X/823/2/102.

J. S. W. Claeys, O. R. Pols, R. G. Izzard, J. Vink, and F. W. M. Verbunt. Theoretical uncertainties of the Type Ia supernova rate. A&A, 563:A83, March 2014. doi: 10.1051/0004-6361/201322714.

E. da Cunha, S. Charlot, and D. Elbaz. A simple model to interpret the ultraviolet, optical and infrared emission from galaxies. MNRAS, 388:1595–1617, August 2008. doi: 10.1111/j.1365-2966.2008.13535.x.

E. De Donder and D. Vanbeveren. The relative frequency of type II and L(b,c) supernovae and the birth rate of double compact star binaries. A&A, 333:557–564, May 1998.

E. De Donder and D. Vanbeveren. The influence of binaries on galactic chemical evolution. New Ast. Rev., 48:861–975, September 2004. doi: 10.1016/j.newar.2004.07.001.

S. E. de Mink, N. Langer, R. G. Izzard, H. Sana, and A. de Koter. The Rotation Rates of Massive Stars: The Role of Binary Interaction through Tides, Mass Transfer, and Mergers. ApJ, 764:166, February 2013. doi: 10.1088/0004-637X/764/2/166.

S. Ekström, C. Georgy, P. Eggenberger, G. Meynet, N. Mowlavi, A. Wytenbach, A. Granada, T. Decressin, R. Hirschi, U. Frischknecht, C. Charbonnel, and A. Maeder. Grids of stellar models with rotation. I. Models from 0.8 to 120 M⊙ at solar metallicity (Z = 0.014). A&A, 537:A146, January 2012. doi: 10.1051/0004-6361/201117751.

J. J. Eldridge and J. R. Maund. The disappearance of the helium-giant progenitor of the Type Ib supernova iPTF13bvn and constraints on its companion. MNRAS, 461:L117–L121, September 2016. doi: 10.1093/mnrasl/slw099.

J. J. Eldridge and E. R. Stanway. Spectral population synthesis including massive binaries. MNRAS, 400:1019–1028, December 2009. doi: 10.1111/j.1365-2966.2009.15514.x.

J. J. Eldridge and E. R. Stanway. The effect of stellar evolution uncertainties on the rest-frame ultraviolet stellar lines of C IV and He II in high-redshift Lyman-break galaxies. MNRAS, 419:479–489, January 2012. doi: 10.1111/j.1365-2966.2011.19713.x.

J. J. Eldridge, M. Fraser, S. J. Smartt, J. R. Maund, and R. M. Crockett. The death of massive stars - II. Observational constraints on the progenitors of Type Ibc supernovae. MNRAS, 436:774–795, November 2013. doi: 10.1093/mnras/stt1612.

J. J. Eldridge, E. R. Stanway, L. Xiao, L. A. S. McClelland, G. Taylor, M. Ng, S. M. L. Greis, and J. C. Bray. Binary Population and Spectral Synthesis Version 2.1: Construction, Observational Verification, and New Results. PASA, 34:e058, November 2017. doi: 10.1017/pasa.2017.51.

D. K. Erb, M. Pettini, A. E. Shapley, C. C. Steidel, D. R. Law, and N. A. Reddy. Physical Conditions in a Young, Unreddened, Low-metallicity Galaxy at High Redshift. ApJ, 719:1168–1190, August 2010. doi: 10.1088/0004-637X/719/2/1168.

Y. Götberg, S. E. de Mink, and J. H. Groh. Ionizing spectra of stars that lose their envelope through interaction with a binary companion: role of metallicity. A&A, 608:A11, November 2017. doi: 10.1051/0004-6361/201730472.

O. Graur, F. B. Bianco, S. Huang, M. Modjaz, I. Shivvers, A. V. Filippenko, W. Li, and J. J. Eldridge. LOSS Revisited. I. Unraveling Correlations Between Supernova Rates and Galaxy Properties, as Measured in a Reanalysis of the Lick Observatory Supernova Search. ApJ, 837:120, March 2017. doi: 10.3847/1538-4357/aa5eb8.

B. Gustafsson, B. Edvardsson, K. Eriksson, E. Jorgensen, A. Nordlund and B. Plez. A grid of MARCS model atmospheres for late-type stars. I. Methods and general properties. A&A, 486:951–970, August 2008. doi: 10.1051/0004-6361:200809724.

W.-R. Hamann, G. Gräfener, and A. Liebmann. The Galactic WN stars. Spectral analyses with line-blanketed model atmospheres versus stellar evolution models with and
Event in the MACS1149 Galaxy Cluster Field. *The Astronomer’s Telegram*, 9097, May 2016.

L. J. Kewley, M. A. Dopita, R. S. Sutherland, C. A. Heisler, and J. Trevena. Theoretical Modeling of Starburst Galaxies. *ApJ*, 556:121–140, July 2001. doi: 10.1086/321545.

D. C. Kiminki and H. A. Kobulnicky. An Updated Look at Binary Characteristics of Massive Stars in the Cygnus OB2 Association. *ApJ*, 751:4, May 2012. doi: 10.1088/ 0004-637X/751/1/4.

P. Kroupa, C. A. Tout, and G. Gilmore. The distribution of low-mass stars in the Galactic disc. *MNRAS*, 262:545–587, June 1993. doi: 10.1093/mnras/262.3.545.

C. Leitherer, D. Schaerer, J. D. Goldader, R. M. G. Delgado, C. Robert, D. F. Kune, D. F. de Mello, D. Devost, and T. M. Heckman. Starbursts99: Synthesis Models for Galaxies with Active Star Formation. *ApJS*, 123:3–40, July 1999. doi: 10.1086/313233.

V. M. Lipunov, K. A. Postnov, M. E. Prokhorov, and A. I. Bogomazov. Description of the “Scenario Machine”. *Astronomy Reports*, 53:915–940, October 2009. doi: 10.1134/S1063772909100047.

X. Ma, P. F. Hopkins, D. Kasen, E. Quataert, C.-A. Faucher-Giguère, D. Kereš, N. Murray, and A. Strom. Binary stars can provide the ‘missing photons’ needed for reionization. *MNRAS*, 459:3614–3619, July 2016. doi: 10.1093/mnras/stw941.

P. Madau and M. Dickinson. Cosmic Star-Formation History. *ARA&A*, 52:415–486, August 2014. doi: 10.1146/annurev-astro-081811-125615.

I. Mandel. Estimates of black hole natal kick velocities from observations of low-mass X-ray binaries. *MNRAS*, 456:578–581, February 2016. doi: 10.1093/mnras/stw2733.

M. V. Maseda, J. Brinchmann, M. Franx, R. Bacon, R. J. Bouwens, K. B. Schmidt, L. A. Boogaard, T. Contini, A. Feltre, H. Inami, W. Kollatschny, R. A. Marino, J. Richard, A. Verhamme, and L. Wisotzki. The MUSE Hubble Ultra Deep Field Survey. IV. Global properties of C III] emitters. *A&A*, 608:A4, November 2017. doi: 10.1051/ 0004-6361/201730985.

P. Massey, K. F. Neugent, D. J. Hillier, and J. Puls. A Bake-off between CMFGEN and FASTWIND: Modeling the Physical Properties of SMC and LMC O-type Stars. *ApJ*, 768:6, May 2013. doi: 10.1088/0004-637X/768/1/6.

D. Masters, P. McCarthy, B. Siana, M. Malkan, B. Mobasher, H. Atek, A. Henry, C. L. Martin, M. Rafelski, N. P. Hathi, C. Scarlata, N. R. Ross, A. J. Bunker, G. Blanc, A. G. Bedregal, A. Dominguez, J. Colbert, H. Teplitz, and A. Dressler. Physical Properties of Emission-line Galaxies at z ~ 2 from Near-infrared Spectroscopy with Magellan FIRE. *ApJ*, 785:153, April 2014. doi: 10.1088/0004-637X/785/2/153.

M. Moe and R. Di Stefano. Mind Your Ps and Qs: The Interrelation between Period (P) and Mass-ratio (Q) Distributions of Binary Stars. *ApJS*, 230:15, June 2017. doi: 10.3847/1538-4365/aa6fb6.

Planck Collaboration, P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, and et al. Planck 2015 results. XIII. Cosmological parameters. *A&A*, 594:A13, September 2016. doi: 10.1051/0004-6361/201525830.

P. Podsialowski, P. C. Joss, and J. J. L. Hsu. Presupernova evolution in massive interacting binaries. *ApJ*, 391:246–264, May 1992. doi: 10.1086/171341.

B. E. Robertson, R. S. Ellis, S. R. Furlanetto, and J. S. Dunlop. Cosmic Reionization and Early Star-forming Galaxies: A Joint Analysis of New Constraints from Planck and the Hubble Space Telescope. *ApJL*, 802:L19, April 2015. doi: 10.1088/2041-8205/ 802/2/L19.
H. Sana, S. E. de Mink, A. de Koter, N. Langer, C. J. Evans, M. Gieles, E. Gosset, R. G. Izzard, J.-B. Le Bouquin, and F. R. N. Schneider. Binary Interaction Dominates the Evolution of Massive Stars. *Science*, 337:444, July 2012. doi: 10.1126/science.1223344.

A. Sander, W.-R. Hamann, and H. Todt. The Galactic WC stars. Stellar parameters from spectral analyses indicate a new evolutionary sequence. *A&A*, 540:A144, April 2012. doi: 10.1051/0004-6361/201117830.

D. Schaerer. The transition from Population III to normal galaxies: Lyalpha and He II emission and the ionising properties of high redshift starburst galaxies. *A&A*, 397:527–538, January 2003. doi: 10.1051/0004-6361:20021525.

A. E. Shapley, C. C. Steidel, M. Pettini, and K. L. Adelberger. Rest-Frame Ultraviolet Spectra of z ≃ 3 Lyman Break Galaxies. *ApJ*, 588:65–89, May 2003. doi: 10.1086/373922.

I. Shivaei, N. A. Reddy, B. Siana, A. E. Shapley, M. Kriek, B. Mobasher, W. R. Freeman, R. L. Sanders, A. L. Coil, S. H. Price, T. Fetherolf, M. Azadi, G. Leung, and T. Zick. The MOSDEF Survey: Direct Observational Constraints on the Ionizing Photon Production Efficiency, $\xi_{ion}$, at $z' > 2$. *ArXiv e-prints*, October 2017.

S. J. Smartt. Observational Constraints on the Progenitors of Core-Collapse Supernovae: The Case for Missing High-Mass Stars. *PASA*, 32:e016, April 2015. doi: 10.1017/pasa.2015.17.

L. J. Smith, R. P. F. Norris, and P. A. Crowther. Realistic ionizing fluxes for young stellar populations from 0.05 to 2 $Z_{\odot}$. *MNRAS*, 337:1309–1328, December 2002. doi: 10.1046/j.1365-8711.2002.06042.x.

E. R. Stanway and L. J. M. Davies. Establishing an analogue population for the most distant galaxies. *MNRAS*, 439:2474–2484, April 2014. doi: 10.1093/mnras/stu104.

E. R. Stanway, R. G. McMahon, and A. J. Bunker. Near-infrared properties of i-drop galaxies in the Hubble Ultra Deep Field. *MNRAS*, 359:1184–1192, May 2005. doi: 10.1111/j.1365-2966.2005.08977.x.

E. R. Stanway, J. J. Eldridge, S. M. L. Greis, L. J. M. Davies, S. M. Wilkins, and M. N. Bremer. Interpreting high [O III]/H$\beta$ ratios with maturing starbursts. *MNRAS*, 444:3466–3472, November 2014. doi: 10.1093/mnras/stu1682.

E. R. Stanway, J. J. Eldridge, and G. D. Becker. Stellar population effects on the inferred photon density at reionization. *MNRAS*, 456:485–499, February 2016. doi: 10.1093/mnras/stv2661.

D. P. Stark, J. Richard, S. Charlot, B. Clément, R. Ellis, B. Siana, B. Robertson, M. Schenker, J. Gutkin, and A. Wofford. Spectroscopic detections of C III $\lambda$1909 Å at $z \sim 6$–7: a new probe of early star-forming galaxies and cosmic reionization. *MNRAS*, 450:1846–1855, June 2015a. doi: 10.1093/mnras/stv688.

D. P. Stark, G. Walth, S. Charlot, B. Clément, A. Feltre, J. Gutkin, J. Richard, R. Mainali, B. Robertson, B. Siana, M. Tang, and M. Schenker. Spectroscopic detection of C IV $\lambda$1548 in a galaxy at $z = 7.045$: implications for the ionizing spectra of reionization-era galaxies. *MNRAS*, 454:1393–1403, December 2015b. doi: 10.1093/mnras/stv1907.

C. C. Steidel, G. C. Rudie, A. L. Strom, M. Pettini, N. A. Reddy, A. E. Shapley, R. F. Trainor, D. K. Erb, M. L. Turner, N. P. Konidaris, K. R. Kulas, G. Mace, K. Matthews, and I. S. McLean. Strong Nebular Line Ratios in the Spectra of z > 2-3 Star Forming Galaxies: First Results from KBSS-MOSFIRE. *ApJ*, 795:165, November 2014. doi: 10.1088/0004-637X/795/2/165.
Population and spectral synthesis: it doesn't work without binaries

C. C. Steidel, A. L. Strom, M. Pettini, G. C. Rudie, N. A. Reddy, and R. F. Trainor. Reconciling the Stellar and Nebular Spectra of High-redshift Galaxies. *ApJ*, 826:159, August 2016. doi: 10.3847/0004-637X/826/2/159.

A. L. Strom, C. C. Steidel, G. C. Rudie, R. F. Trainor, M. Pettini, and N. A. Reddy. Nebular Emission Line Ratios in z ∼ 2-3 Star-forming Galaxies with KBSS-MOSFIRE: Exploring the Impact of Ionization, Excitation, and Nitrogen-to-Oxygen Ratio. *ApJ*, 836:164, February 2017. doi: 10.3847/1538-4357/836/2/164.

T. Sukhbold, T. Ertl, S. E. Woosley, J. M. Brown, and H.-T. Janka. Core-collapse Supernovae from 9 to 120 Solar Masses Based on Neutrino-powered Explosions. *ApJ*, 821:38, April 2016. doi: 10.3847/0004-637X/821/1/38.

E. N. Taylor, A. M. Hopkins, I. K. Baldry, M. J. I. Brown, S. P. Driver, L. S. Kelvin, D. T. Hill, A. S. G. Robotham, J. Bland-Hawthorn, D. H. Jones, R. G. Sharp, D. Thomas, J. Liske, J. Loveday, P. Norberg, J. A. Peacock, S. P. Bamford, S. Brough, M. Cawthron, E. Cameron, C. J. Conselice, S. M. Croom, C. S. Frenk, M. Gunawardhana, K. Kuijken, R. C. Nichol, H. R. Parkinson, S. Phillipps, K. A. Pimbblet, C. C. Popescu, M. Prescott, W. J. Sutherland, R. J. Tuffs, E. van Kampen, and D. Wijesinghe. Galaxy And Mass Assembly (GAMA): stellar mass estimates. *MNRAS*, 418:1587–1620, December 2011. doi: 10.1111/j.1365-2966.2011.19536.x.

B. M. Tinsley. Evolution of the Stars and Gas in Galaxies. *ApJ*, 151:547, February 1968. doi: 10.1086/149455.

B. M. Tinsley and J. E. Gunn. Evolutionary synthesis of the stellar population in elliptical galaxies. I - Ingredients, broad-band colors, and infrared features. *ApJ*, 203:52–62, January 1976. doi: 10.1086/154046.

S. Toonen and G. Nelemans. The effect of common-envelope evolution on the visible population of post-common-envelope binaries. *A&A*, 557:A87, September 2013. doi: 10.1051/0004-6361/201321753.

C. A. Tremonti, T. M. Heckman, G. Kauffmann, J. Brinchmann, S. Charlot, S. D. M. White, M. Seibert, E. W. Peng, D. J. Schlegel, A. Uomoto, M. Fukugita, and J. Brinkmann. The Origin of the Mass-Metallicity Relation: Insights from 53,000 Star-forming Galaxies in the Sloan Digital Sky Survey. *ApJ*, 613:898–913, October 2004. doi: 10.1086/423264.

A. Tutukov and L. Yungelson. Double-degenerate semidetached binaries with helium secondaries: cataclysmic variables, supersoft X-ray sources, supernovae and accretion-induced collapses. *MNRAS*, 280:1035–1045, June 1996. doi: 10.1093/mnras/280.4.1035.

J. Van Bever and D. Van Beveren. Hard X-rays emitted by starbursts as predicted by population synthesis models including a realistic fraction of interacting binaries. *A&A*, 358:462–470, June 2000.

J. Van Bever, H. Belkus, D. Van Beveren, and W. Van Rensbergen. The effect of close binary evolution on photoionization models for evolving starbursts. *NewA*, 4:173–190, June 1999. doi: 10.1016/S1384-1076(99)00011-1.

D. Van Beveren, J. Van Bever, and H. Belkus. The Wolf-Rayet Population Predicted by Massive Single Star and Massive Binary Evolution. *ApJL*, 662:L107–L110, June 2007. doi: 10.1086/519454.

P. Westera, T. Lejeune, R. Buser, F. Cuisinier, and G. Bruzual. A standard stellar library for evolutionary synthesis. III. Metallicity calibration. *A&A*, 381:524–538, January 2002. doi: 10.1051/0004-6361:20011493.

S. M. Wilkins, Y. Feng, T. Di-Matteo, R. Croft, E. R. Stanway, R. J. Bouwens, and
P. Thomas. The Lyman-continuum photon production efficiency in the high-redshift Universe. *MNRAS*, 458:L6–L9, May 2016. doi: 10.1093/mnrasl/slw007.

B. Willems and U. Kolb. Detached white dwarf main-sequence star binaries. *A&A*, 419:1057–1076, June 2004. doi: 10.1051/0004-6361:20040085.

N. J. Wright, J. E. Drew, and M. Mohr-Smith. The massive star population of Cygnus OB2. *MNRAS*, 449:741–760, May 2015. doi: 10.1093/mnras/stv323.

L. Xiao and J. J. Eldridge. Core-collapse supernovae rate synthesis within 11 Mpc. *MNRAS*, 452:2597–2605, September 2015. doi: 10.1093/mnras/stv1425.

L. Xiao, J. J. Eldridge, and E. R. Stanway. Emission Line Diagnostics of HII regions. *MNRAS submitted*, 999:99999, 2018.

S.-C. Yoon, G. Gräfener, J. S. Vink, A. Kozyreva, and R. G. Izzard. On the nature and detectability of Type Ib/c supernova progenitors. *A&A*, 544:L11, August 2012. doi: 10.1051/0004-6361/201219790.

S.-C. Yoon, L. Dessart, and A. Clocchiatti. Type Ib and IIb Supernova Progenitors in Interacting Binary Systems. *ApJ*, 840:10, May 2017. doi: 10.3847/1538-4357/aa6afe.

E. Zapartas, S. E. de Mink, R. G. Izzard, S.-C. Yoon, C. Badenes, Y. Götberg, A. de Koter, C. J. Neijssel, M. Renzo, A. Schootemeijer, and T. S. Shrotriya. Delay-time distribution of core-collapse supernovae with late events resulting from binary interaction. *A&A*, 601:A29, May 2017. doi: 10.1051/0004-6361/201629685.

F. Zhang, L. Li, and Z. Han. Evolutionary population synthesis for binary stellar population at high spectral resolution: integrated spectral energy distributions and absorption-feature indices. *MNRAS*, 364:503–514, December 2005. doi: 10.1111/j.1365-2966.2005.09563.x.

F. Zhang, L. Li, L. Cheng, L. Wang, X. Kang, Y. Zhuang, and Z. Han. Radiation fields of intermediate-age stellar populations with binaries as ionizing sources of H II regions. *MNRAS*, 447:L21–L25, February 2015. doi: 10.1093/mnrasl/slu170.