On Rejuvenation in Massive Binary Systems

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ABSTRACT

We introduce a set of stellar models for massive stars whose evolution has been affected by mass transfer in a binary system, at a range of metallicities. As noted by other authors, the effect of such mass transfer is frequently more than just rejuvenation. We find that, whilst stars with convective cores which have accreted only H-rich matter rejuvenate as expected, those stars which have accreted He-rich matter (for example at the end stages of conservative mass transfer) evolve in a way that is qualitatively similar to rejuvenated stars of much higher metallicity. Thus the effects of non-conservative evolution depend strongly on whether He-rich matter is amongst the portion accreted or ejected. This may lead to a significant divergence in binary evolution paths with only a small difference in initial assumptions. We compare our models to observed systems and find approximate formulae for the effect of mass accretion on the effective age and metallicity of the resulting star.

Key words: stars: Early-type – stars: abundances

1 INTRODUCTION

The effects of binary evolution on massive stars are many and complex. In the simplest case, the two stars do not interact at all; wide systems which evolve essentially as two single stars make up about half of all binaries. In closer systems, the stars affect each other via the interaction of their winds, via tidal interaction and, most importantly for their later evolution, via Roche lobe overflow (RLOF). Whilst there are many massive binaries which can be surmised to have gone through this phase (e.g. Podsiadlowski, Joss & Hsu 1992; Wellstein & Langer 1999), the amounts of mass and angular momentum transfer are frequently rather poorly-constrained and appear to vary between systems (Langer et al. 2003; Petrovic, Langer & van der Hucht 2005). In turn, the amount of mass and angular momentum transfer determines whether the stars enter a common envelope phase (Webbink 1984; Beer et al. 2006), and this has a strong effect on the resulting masses and period of the system at the end of interaction, if the two stars do not merge. The current parameters of observable massive binaries are vital in pinning down the many uncertainties about the mass transfer process. Models for massive binary evolution over wide ranges of parameter space and physical complexity have been computed by several groups (e.g. Nelson & Eggleton 2001; Petrovic et al. 2005; Podsiadlowski et al. 1992; de Donder & Vanbeveren 2004) although most concentrate only on solar metallicity (for an exception see de Loore & Vanbeveren 1994). The general consensus seems to be that several different mass transfer mechanisms must be responsible; for example, some systems require strongly non-conservative mass transfer (Clark et al. 2002), whereas some require at least quasi-conservative mass transfer to reach their current parameters from a plausible starting point (Wellstein & Langer 1999; van Rensbergen, de Loore & Vanbeveren 2005).

The outcomes of binary evolution are also important to models of massive star populations. Observations suggest that the cluster O-star binary fraction is high, perhaps greater than 75 per cent and maybe approaching 100 per cent when hard-to-observe areas of the parameter space are considered (Mason et al. 1998). B star binary fractions are also large (Raboud 1996). Given that it is much easier to unbind a binary than to create one from two initially single stars, this suggests that nearly all massive stars have at least one companion at formation. A high initial binary fraction is also suggested by the some models of star formation (e.g. Delgado-Donate et al. 2004) and may be required to reproduce the observed number of stars with runaway velocities (de Donder, Vanbeveren & van Bever 1997, Dray et al. 2005). If this is the case, then many single massive stars in late stages of evolution may have had a binary past (Vanbeveren et al. 1998). The output of massive binary simulations is therefore also of much use as an input to population synthesis models (e.g. Hurley, Tout & Pols 2002; O’Shaughnessy, Kalogera & Belczynski 2006; Podsiadlowski et al. 2004). Here, one must make a decision as to which approximations to use in describing the evolution of binaries, because to use full evolutionary tracks can take prohibitively long.

For both investigation of individual massive stars and whole-population properties, then, the behaviour of the secondary of a binary system after it has accreted mass is at least of interest and may be of vital importance. Previous investigations of this behaviour (Braun & Langer 1995; Vanbeveren & de Loore 1994) have sug-
suggested that the usual assumption about the evolution of such stars, that they are rejuvenated by some amount (Hellings 1983) and thereafter evolve similarly to a younger star of their new mass, is true in some cases but not all the time. In particular, mass accretion on to a massive main-sequence star, even if it is of the same composition as the surface of the star, causes the convective core to expand, leading to a molecular weight discontinuity at the core boundary. Braun & Langer (1995) did not consider the accretion of He-enhanced matter but it is likely that this too may have a strong effect. Such enriched matter is likely to be transferred in the last stages of conservative mass transfer, or in later mass-transfer stages after an initial one (e.g. case AB mass transfer), when the core of the donor star has been nearly exposed. When matter of a higher molecular weight is accreted on top of matter of a lower molecular weight, the thermohaline instability occurs (Kippenhahn, Rüschaffe & Thomas 1980). Analogously to the more commonly-known thermohaline mixing process in oceanography, this instability allows mixing downwards of the accreted matter to occur locally even if overall the criteria for convective stability are met. This effect has also been investigated for lower-mass stars by Chen & Han (2004) in the context of blue straggler populations.

In particular, previous investigations (Dray & Tout 2006) have suggested to us that the threshold mass above which a star goes through a Wolf-Rayet (WR) phase at the end of its lifetime is substantially reduced for stars which have accreted He-rich matter. Wolf-Rayet stars are the H- and He-depleted cores of the initially most massive stars, stripped of their envelopes by high levels of mass loss, and as such are the likely progenitors of long gamma-ray bursts (GRBs). Originally (Paczyński 1973) it was thought that this mass loss was a result of Roche lobe overflow in a binary system but more recent models have suggested that the vast majority of WR stars can arise without any form of interaction with other stars, via rotationally-enhanced wind mass loss only (Maeder & Meynet 2000). However, the large binary fraction amongst O stars, which (at least in the single star scenario) are the sole progenitors of WR stars suggests that duplicity is important. If the threshold mass for WR formation is substantially lowered amongst secondaries it could have effects on both the CNO enrichment from the system and the ratio of type-II to type-Ibc supernovae. This may be particularly important at low metallicity where it is hard to form a WR-type star via stellar winds only. In this paper we investigate this behaviour in further detail, with a particular emphasis on finding approximations to the behaviour of these rejuvenated stars which can be used in population synthesis models.

2 MODELS

Modelling massive binary stars is a pursuit hampered by the massive parameter space involved. This parameter space is at least three-dimensional, since one must consider the initial primary mass, the mass ratio and the initial period to get reasonable coverage of a population. Added to these is the uncertainty inherent in the modelling of single massive stars – in particular, the mass-loss rates and any coverage of rotation. We are interested in the effects of metallicity and the amount of mass transferred, a further two variables. In previous work (e.g. Dray & Tout 2005) we have dealt with this complexity by running large grids of models using the STARS code (Eggleton 1971; Pols et al. 1995, 1998 and references therein) in a quasi-simultaneous mode (see e.g. Pols 1994), and then checking the accuracy of edge cases against full models using the more recent fully simultaneous version of the code, TWIN (Nelson & Eggleton 2001; Eggleton & Kiseleva-Eggleton 2001). However, in this paper we are more interested in the detailed behaviour of accreting stars rather than the specific fate of binaries containing them (e.g. the period evolution) or integrated whole-population properties. We therefore run smaller grids of models using only the TWIN code, allowing for a reasonable range of metallicities and initial masses but not covering the entire range of different combinations. As is apparent below, the evolution of the accreting stars that we simulate appears to be quite straightforwardly generalisable to accreting stars in general. In particular we focus our attention on two series of models, 18 x 9 grids of mass ratio and period for an initial primary mass of 16.6M⊙ over a range of metallicities from 0.03 to 0.0001 and 14 x 9 grids of mass ratio and period for solar metallicity and initial primary mass between 10 and 20M⊙. This covers in detail the mass range over which it is possible that conservatively-accreting secondaries reach the threshold mass for WR evolution, where we have previously found interesting behaviour with less-detailed models. Over the mass range around the WR threshold the systems which avoid common envelope evolution are in the case A (mass transfer begins whilst the donor is undergoing core hydro-
The composition difference is infinitesimal. In cases where the core is convective and accretion leads to a significant amount of helium-enriched matter being deposited on the surface of the star, this can essentially lead to mixing of the entire star, with the central hydrogen abundance increased and a consequent lengthening (rejuvenation) of the main-sequence lifetime in comparison to what is expected for a star of the new mass (Braun & Langer 1995). As in Chen & Han (2004), we also assume that the accretion stream impacts the surface of the accretor with zero falling velocity and, as necessitated by the use of a one-dimensional code, is deposited in a homogeneous layer over the surface of the star.

We do not consider the effects of rotation or magnetic fields in our models. Both of these may have a strong effect on the evolution (Petrovic et al. 2005; Heger, Woosley & Spruit 2005), particularly in tandem with binary interaction via the accretion of angular momentum; however, there are still significant uncertainties, particularly in regard to the effect of magnetic fields, and some models of magnetised, rotating stars evolve more similarly to non-magnetised, non-rotating stars than to stars with rotation alone (Maeder & Meynet 2004). Rotation may also limit the amount of matter which can be accreted (Packet 1981; see also section 3).

Angular momentum loss via winds is treated as in Hurley et al. (2000), as is the potential accretion of wind matter from one star by the other via the Bondi-Hoyle process. Wind accretion is not applied if both winds are strong, as expressed in terms of wind momentum (Walder & Folini 2000); here we would expect a colliding wind system instead. Whilst we consider a form of non-conservative accretion in the following section, we do so in order to look at the behaviour of the accreting star if there is no further interaction in the system. For those purposes we treat it as a single star and there is no need to specify a mode of angular momentum loss during Roche Lobe overflow. If the two stars evolve into contact we halt the evolution of the system and do not follow it any further. In many schemes for contact and common-envelope evolution these secondary accretes no further matter after the onset of this phase (e.g. Webbink 1984) and in that case its evolution should be similar to that of a star which has accreted only a portion of the available matter, as with rapidly-rotating stars. However, once again, significant uncertainties are involved in the common-envelope phase which make it difficult to follow.

3 EVOLUTION WITH AMOUNT TRANSFERRED

Before looking at full conservative mass transfer sequences, it is interesting to follow how the amount of accretion affects the subsequent evolution. It is likely that most accretion events are non-conservative, not least because of the effects of accreting angular momentum (e.g Packet 1981). Therefore if there is a significant difference in the subsequent behaviour of accreting stars with the amount of matter they are able to accrete, this may lead to systems following quite different evolutionary paths depending on their accretion history.

Another consideration for stars which accrete only a portion of the transferred matter is which portion they accrete. At least in the case of the initial occurrence of RLOF in the binary, the material which is first transferred will be at the same composition as the accreting star. Thermohaline mixing is therefore a relatively minor consideration. However, later on in the same accretion episode the donor may have been stripped down to the helium-enhanced regions near its core, leaving the transferred matter significantly helium-enriched (Fig. 1). If this matter is accreted, deep mixing...
the internal chemical structures differ.

As noted by Braun & Langer (1995), it is often not possible to fully match the evolution of an accretion star to a single star model because we find that accretion stars are overluminous in comparison with models. Note that fitting is not carried out against the star's luminosity; in general the ZAMS by some amount of time which is governed by (an approximation to) the core hydrogen abundance increase (hence the time of RLOF — in particular, for case A systems, we can find a later time of maximum mass with shorter period, whereas RLOF always starts earlier with a shorter period. However, the bulk of the helium accretion is likely to continue throughout the star's lifetime and persists even though the star remains overluminous for its type, which should also affect the effective metallicity of the new star has not increased. In some respects this behaviour is not particularly surprising, as it is expected both from theory and observation that stars which have accreted a lot of helium will have raised surface helium abundances (Blaauw 1993, Vanbeveren & de Loore 1994) and the surface abundances have an effect on the assumed mass-loss rates and hence the evolution. However, this similarity to higher-metallicity evolution continues throughout the star’s lifetime and persists even though the star remains overluminous for its type, which should also affect the mass-loss rates. In panel 3 of Fig. 2, for example, the accretor undergoes a WR phase at the end of its lifetime. Although this phase is short, it is important both in terms of the potential chemical enrichment from the star (as there are high mass-loss rates combined with unusual surface abundances) and the type of final explosion one would expect to see (this model produces a type Ib supernova, whereas the closest same-metallicity match, shown in grey, would produce a type II supernova). Whilst the effective metallicity of this star remains the same, if one defines a 'helium metallicity' — that is, increase in core H-burning lifetime). We use the simple formula from Tout et al. (1997),

\[ t' = \frac{M}{M' \tau_{MS}} t, \]

where \( t \) is the age of the secondary at the time of maximum mass, \( t' \) is the effective age after rejuvenation, \( M \) and \( M' \) are the initial and post-RLOF masses of the secondary (assumed for these stars to be proportional to the remaining fraction of unburnt hydrogen in the convective core, see Tout et al. 1997 for details) and \( \tau_{MS} \) and \( \tau'_{MS} \) are the main-sequence lifetimes of single stars at the old and new masses of the secondary. For the main-sequence lifetimes we also use their fitting formulae, which depend only on mass. This gives us an effective time offset, which can compared with the best-fit model and depends only on the initial mass, age and amount accreted by the secondary. As is indicated in Fig. 2, this approximate formula produces good results here, provided that the accreted matter is similar in composition to the surface of the accreting star. However, for nearly or wholly conservative mass transfer we find a better fit to tracks for stars close to the new rejuvenated mass, but of a higher metallicity. This holds true even though the effective metallicity of the new star has not increased. In some respects this behaviour is not particularly surprising, as it is expected both from theory and observation that stars which have accreted a lot of helium will have raised surface helium abundances (Blaauw 1993, Vanbeveren & de Loore 1994) and the surface abundances have an effect on the assumed mass-loss rates and hence the evolution. However, this similarity to higher-metallicity evolution continues throughout the star’s lifetime and persists even though the star remains overluminous for its type, which should also affect the mass-loss rates. In panel 3 of Fig. 2, for example, the accretor undergoes a WR phase at the end of its lifetime. Although this phase is short, it is important both in terms of the potential chemical enrichment from the star (as there are high mass-loss rates combined with unusual surface abundances) and the type of final explosion one would expect to see (this model produces a type Ib supernova, whereas the closest same-metallicity match, shown in grey, would produce a type II supernova). Whilst the effective metallicity of this star remains the same, if one defines a 'helium metallicity' — that is,

### Table 1

| Amount of matter accepted | Secondary mass at end of transfer | Matching single star model | Matching single star time offset/years | Matching single star metallicity |
|---------------------------|----------------------------------|---------------------------|--------------------------------------|---------------------------------|
| 10 %                      | 16.9M⊙                          | 16.5M⊙                   | 8.4 \times 10^6                     | 0.02                            |
| 20 %                      | 17.2M⊙                          | 17.5M⊙                   | 7.3 \times 10^6                     | 0.02                            |
| 30 %                      | 18.5M⊙                          | 18.6M⊙                   | 5.4 \times 10^6                     | 0.02                            |
| 40 %                      | 19.8M⊙                          | 19.9M⊙                   | 5.3 \times 10^6                     | 0.02                            |
| 50 %                      | 21.1M⊙                          | 21.5M⊙                   | 4.5 \times 10^6                     | 0.02                            |
| 60 %                      | 22.4M⊙                          | 22.9M⊙                   | 4.7 \times 10^6                     | 0.02                            |
| 70 %                      | 23.7M⊙                          | 24.6M⊙                   | 4.8 \times 10^6                     | 0.03                            |
| 80 %                      | 24.9M⊙                          | 26.1M⊙                   | 4.2 \times 10^6                     | 0.03                            |
| 90 %                      | 26.2M⊙                          | 27.2M⊙                   | 2.9 \times 10^6                     | 0.05                            |
| 100 %                     | 27.5M⊙                          | 28.3M⊙                   | 2.6 \times 10^6                     | 0.05                            |

1 Note that fitting is not carried out against the star’s luminosity; in general we find that accretion stars are overluminous in comparison with models which otherwise fit the mass, type and effective temperature evolution with time well. As noted by Braun & Langer (1995), it is often not possible to fully match the evolution of an accretion star to a single star model because the internal chemical structures differ.

2 This time may be substantially different from the time of the initial onset of RLOF — in particular, for case A systems, we can find a later time of maximum mass with shorter period, whereas RLOF always starts earlier with a shorter period. However, the bulk of the helium accretion is likely to occur towards the end of the accretion period.
be a reasonable predictor of the behaviour of an accretion star. It should also be noted that the above formula is of course specific to the initial element mix used in the input models to the STARS code and therefore the precise calibration to the results of other codes may vary.

### 4 BEHAVIOUR WITH MASSES AND METALLICITY

The behaviour of accretion stars in conservative mass transfer binaries is, unsurprisingly, similar to the 90% and 100% mass transfer cases discussed above. As an extremely rough guide, the subsequent evolution of a star which has accreted all the matter supplied to it (in a system which avoids common envelope, at least) is similar to that of a single star, initially a few tenths of a solar mass above the maximum mass the accretion star reaches and a factor of a few greater in metallicity. For example, many secondaries from binaries at a metallicity of 0.004 behave similarly to stars at solar metallicity in their later evolution. However the comparison is not completely exact; the new star remains overluminous throughout its lifetime (for example Fig. 3) and hence the single star which is a best fit to the HR diagram position of a secondary is not generally the same single star which is a best fit to the mass evolution. Since the HR diagram position is not particularly meaningful for WR models which are not coupled with detailed atmospheric models, because their vigorous mass loss results in ill-defined outer radii, we concentrate on models which are a good fit to the evolutionary type and mass distribution. As in the example above, this behaviour leads to many more secondaries ending their lives in a WR phase than otherwise expected.

#### 4.1 Mass

The effect of initial masses on the outcome of binary evolution, and in particular the range of masses which avoid contact at solar metallicity, has already been studied by e.g. Pols (1994) and Wellstein, Langer & Braun (2001) and we refer the interested reader to those papers for more detailed discussion. We find good agreement with their findings, in particular with regard to the parameter space of contact avoidance (e.g. Fig. 5 in Pols (1994) and Fig. 13 in Wellstein et al. (2001) vs. the second panel of Fig. 4 and the sixth panel of Fig. 5 in this paper). As found by those authors, the parameter space in which there is stable case-B mass transfer vanishes as initial primary mass increases, leaving only case-A systems able to avoid contact above some initial primary mass (in our case around 15M\(_\odot\)). This puts relatively stringent constraints on the initial parameters of systems which appear to have evolved conservatively.

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3 Of course, if mass transfer is not conservative then the area of contact avoidance increases significantly (Dray & Tout 2005).
Figure 4. Initial period – initial mass ratio diagrams showing the fate of systems with initially 16.6 $M_\odot$ primaries at varying metallicity. The numbers shown at each point are the maximum masses attained by the secondary. Systems shown in grey go through a contact or common envelope phase. Those in black avoid contact and the secondary evolves through to the end of its life without going through a Wolf-Rayet phase; systems shown in red, blue and green end their lives in WNL, WNE and WC phases respectively. The effect of decreasing stellar radii with decreasing metallicity means that the behaviour of low-metallicity systems is similar to those at higher metallicity but lower mass, but with a lower-period boundary between case-A and case-B mass transfer systems. Grey boxes indicate systems which would undergo RLOF at or soon after formation.

(e.g. Wellstein & Langer 1999). The area of contact-free evolution, in general, is bounded on the upper edge of case B by systems in which the secondary expands rapidly enough during accretion to come into contact and on the lower edge of case A by systems which survive an initial phase of stable mass transfer but in which the evolution of the secondary overtakes that of the primary and leads to unstable reverse mass transfer. As we adopt a grid to cover the parameter space rather than a distribution of initial parameters designed to explore the edge cases, we also find a small area in period just above the case A/case B boundary in which only a small range of mass ratios are contact-free (e.g. $P_i = 5$ days in the third panel of Fig. 5) and some $q = 0.95$ systems evolve into contact. For these systems, the secondary’s evolutionary stage is close enough to that of the primary that it is already nearly filling its Roche Lobe when mass transfer is initiated, i.e. even relatively moderate mass transfer produces a contact situation.

4.2 Metallicity and enhanced-metallicity rejuvenation
Metallicity affects the evolution of a binary in several ways. First, the radius of a lower-metallicity star is generally smaller at the equivalent evolutionary stage – so a lower-metallicity binary avoids RLOF for longer. This means that, for example, the initial period boundary between case-A and case-B mass transfer is lower at lower metallicity. For the metallicity range ($Z = 0.03 - 0.0001$) shown in Fig. 4, this boundary decreases from over 5 days to around 2 days – a significant drop, because at least at the higher metallicities over this mass range it is only case-A systems which avoid common envelope evolution. However, a second effect of the radius decrease at low metallicity is that the secondary star also has a smaller radius, thus rendering some case-B systems stable against contact which at higher metallicities would not have been. In fact, the behaviour in terms of contact/non-contact systems (see Pols 1994; Wellstein et al. 2001; Dray & Tout 2005) with decreasing metallicity is similar to that with decreasing mass (Fig. 5) after the differences in the case-A/case-B boundary are accounted for. The smaller radius of the secondary also affects short-period case-A systems. As described in Wellstein et al. (2001), there is a class of systems with short initial periods which evolve in a contact-free manner through an initial case-A mass-transfer phase but, because this happens very early on in the lifetime of the binary, the secondary’s evolution then overtakes that of the primary and it attempts a later phase of reverse case-B mass transfer whilst the primary is still in its core hydrogen burning phase and this leads to contact. These systems lie under the main area of contact-free evolution in Figs. 4 and 5 and can be identified by their high secondary masses at the time of contact. Because the smaller radii at lower metallicities delay the onset of mass transfer, more systems at low
Figure 5. As Fig. 4 but for varying initial mass at solar metallicity. Although the number of stable case-B mass transfer systems decreases with increasing mass, until by 15$M_{\odot}$ none remain, the number of stable case-A systems increases.

metallicity avoid this fate and hence the area of contact-free evolution extends downward in period significantly. The combination of these effects leads to there being virtually no overlap at all between the parameter space of contact-free case-A systems at metallicity 0.03 and metallicity 0.0001. A further effect, mainly important for the higher-mass end of the parameter space we look at here, is that line-driven wind mass-loss rates are lower at lower metallicity. As less mass is lost in the wind of the primary, more mass is potentially available for transfer to the secondary, and the angular momentum lost this way also affects the period evolution.

The effects of enhanced-metallicity rejuvenation are apparent in Figs. 4 and 5 from the final subtype distribution of the contact-free secondaries (indicated by colour$^4$). At solar metallicity, single star models with the same physical ingredients as the binary models used here do not go through a WR phase unless they are initially over around 28$M_{\odot}$. However, an initially 14$^{+1.2}_{-0.5}M_{\odot} P = 3$ days binary – that is, one with a combined mass which is lower than the single star WR-forming limit – produces a secondary which goes through a WN phase. Given that the primary, after its envelope is stripped by RLOF, can also appear as a WN or WN-like star (although this phase is unlikely to be concurrent with the WR phase of the secondary), this is very much a two for the price of none channel for WR production! However, the stripped primary is usually undermassive for a WR star and may be underluminous, so it is uncertain whether it would be observable as one. In contrast, accreting secondaries are overluminous and can go through both WN and WC phases. As is shown in Fig. 6, the effect of enhanced-metallicity rejuvenation is similar, although not identical, to a straightforward upwards shift in metallicity over the range for which we have detailed coverage of the transition region. In fact Fig. 6 is not quite comparing like with like. We are showing the initial masses for WR formation for single stars against the maximum masses of secondaries which become WR stars. At the point of maximum mass, the secondaries are not ZAMS stars; the closest single star equivalent is one which is partway through the main sequence and has already (especially if it is of high metallicity) lost some mass. For example, the closest match to the evolution of the solar-metallicity secondary which forms the lower accretion star WN mass limit shown in Fig. 6 is a single star with initial mass closer to 23$M_{\odot}$, offsetting the limit upwards by just over half a solar mass. In fact, there is not one single maximum-mass limit for a secondary to undergo WR evolution at a particular metallicity – whether it does or not depends on the amount of helium accreted, the amount of helium synthesised in the secondary’s core before the onset of mass transfer and the time of mass transfer (e.g. Braun & Langer 1995) both of which are determined by the initial binary parameters. Thus there is some variation in the threshold mass –

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$^4$ It should be noted that the criteria used to classify a star as WR or not include that its effective temperature obey $\log_{10}(T_{\text{eff}}/K) > 4.0$. This, combined with the sometimes rather sensitive response of evolutionary tracks to small increases in mass loss, is what leads to the occasionally ragged boundary between the parameter space of WR subtypes.
5 DISCUSSION

The effects of conservative accretion which we have looked at in this paper can manifest observationally in a number of ways. For instance, if at least some mass transfer is helium-enriched, we would expect a corresponding increase in the type Ib/c/type II supernova rate ratio, the (runaway) WR star population and the CNO production from massive stars. What is not clear is whether such effects can be distinguishable against the uncertainties arising from the question of how much matter can be accreted in any given binary.

If one assumes that primaries of binaries have a Salpeter IMF, mass transfer is conservative, the initial mass ratio distribution of binary systems is flat and the initial period distribution is flat in log(P), the inclusion of enhanced-metallicity rejuvenation in initially solar-metallicity accretion stars increases the population of secondaries which go through a WR phase by about 30% (excluding those systems which survive common-envelope evolution). At the metallicity of the Small Magellanic Cloud the population is nearly doubled. This suggests that this is potentially an observable effect, if it can be distinguished from the other uncertainties which beset binary evolution. Since WR stars produce much larger amounts of carbon and other elements in their winds than stars which do not go through a WR phase, this population increase may have implications for the enrichment from WR stars (e.g. Dray & Tout 2003), even though stars in binaries which avoid a contact phase and go on to become WR-like are a relatively small part of the total population. It is also worth considering what happens to binaries which interact and do not manage to avoid contact. If the outcome is a period of common-envelope evolution during which the secondary accretes no further matter, followed by further evolution as a detached but close binary, then we would expect the evolution of the secondary to continue as discussed in section 3 and enhanced-metallicity evolution would have a negligible effect in most cases. If instead the components of the binary merge as a consequence of this process – a fate which may happen to a majority of interacting binaries – then it is likely that the structure of the resulting star will have been quite thoroughly mixed and it would behave similarly to the conservatively-accreting secondaries previously discussed. If this happens, the population of binary-formed WR stars may be much larger than estimated above. It is also interesting to note that a large proportion of these binary-formed WR stars would be single during their WR phase.

However, whether or not it can fit the whole-population properties, a successful model of massive-binary evolution must also be able to explain individual systems. In particular, the properties of individual systems may be used to constrain the model set used because, with the large number of free or poorly-constrained parameters available to vary in population synthesis, it is not hard to make most of the possible populations fit in some way or other. The rejuvenation effects discussed in this paper only come into effect if there is either conservative of nearly-conservative mass transfer or if there is a late mass transfer event (not necessarily wholly conservative) in which matter from a star with an already strongly helium-enriched surface composition is transferred across. As discussed above, if only the first ten percent or so of matter in a mass transfer event can be accreted (e.g. Packet 1981; Dewi 2006; but see also Petrovic et al. 2005, in which mass transfer is linked to rotation in such a way that an initial mass transfer event can be non-conservative but a later event more nearly conservative) then the potential metallicity gain-like effects of accretion would be basically negligible. However, if some proportion of systems do accrete a large amount of helium-enriched matter, then this could produce

\[ \text{Figure 6. Mass limits for stars to end their lives in WN and WC sub-phases for single star models with the same physical ingredients as the binary models. Note that the criterion for WR evolution used here (surface hydrogen abundance below 0.4 by mass and log(T_e/K) > 4) is less meaningful at the highest metallicity shown here, because the low initial hydrogen abundance makes the production of stars that fulfil it rather easy. Also shown are the lowest maximum-mass limits for stars to end their lives in the WC and WN phases (upper and lower thick black lines) for those metallicities at which we have performed a complete parameter study of the region in which the transition occurs.} \]
potentially observable effects, at least in individual systems. Thus observation of these effects could potentially be used to provide some constraint on the amount of matter accreted in a binary. However, as noted previously, it is probable that the amount of matter which can be accreted is variable and affected by a wide range of other parameters, not least rotation (Langer et al. 2003). In our previous work modelling binary populations (with slightly less detailed models; see e.g. Dray & Tout 2006), based on the 20 known WR binaries with measured masses in the catalogue of van der Hucht (2001) we found that no particular accretion scenario is favoured for all stars – most systems which are easy to fit if we assume conservative evolution are also easy to fit using non-conservative evolution but different starting parameters. Some systems require nearly-conservative evolution (e.g. Dray 2006) and some require non-conservative evolution. There is a further group of binaries whose period is too small to fit well (and which are therefore presumably post-common envelope systems, whose evolution we have not followed in detail due to the large uncertainty surrounding common envelope evolution) and a couple of unusual systems whose origin may be dynamical. Some dynamically-formed systems are likely because some stars have exchanged companions in dense environments in the past (Vanbeveren 2005). This may also be the case in those systems which contain two very massive stars, such as WR20a and WR47, although these are expected if the initial binary distribution is skewed towards twin systems in which both stars start with similar masses (Pinsoneault & Stanek 2006), perhaps as a natural result of the mode of massive star formation (Bonnell & Bate 2006). Investigations of whole-population properties with these models (Dray et al. 2005; Dray 2006) again suggested a picture in which some mass transfer is conservative and some not. In this rather complex scenario, the uncertainty associated with mass transfer is so much greater than that associated with the precise effects of rejuvenation that not only is it difficult to say anything concrete about the latter from comparison of whole-population properties with models, but constraints on the mass accreted in an individual binary, if not coupled to a detailed understanding of that binary’s previous evolution, may say little about the mass transfer situation in general other that providing a rather weak limit.

It may still be possible to observe the effects of enhanced-metallicity rejuvenation in individual stars and groups of stars. In particular, we expect from our models that these effects would be most visible in the time period after the SN explosion of the primary in a system which has been undergoing mass transfer (if the SN order is not reversed – see e.g. Pols 1994). If the SN does not unbind the system, then the result would be a massive star – compact object binary. Cyg X–3 is an example of such a system in which there is a WR star; however, it is very unusual (Lommen et al. 2005). The most common fate, as discussed in Dray et al. (2005) is that the system is split by the SN kick, and the potentially-rejuvenated component becomes a high-velocity runaway star. Many runaway O stars have been observed to have enhanced surface helium abundances (Blauw 1993), as found in our models. A notable subgroup of the WR population is the WNS stars, which differ significantly from normal WR stars (Marchenko et al. 1998). Many of these stars are measurable runaways or appear to have moved a significant distance from their place of birth and very few are in binaries. Whilst it has been suggested that they could be the result of massive star–compact object mergers (i.e. a type of Thorne–Żytkow object, Vanbeveren et al. 1998; Cherepashchuk & Moffat 1994), it is quite possible that they are just the unusual WR stars which result from secondary evolution in an accreting binary. Tracking of these stars and of runaway O stars back to their places of origin and a comparison of the metallicity of that area with their apparent metallicity from massive star evolutionary tracks and surface compositions could potentially give a limit on how important enhanced-metallicity rejuvenation is, and whether it is an effect that needs to be included in population synthesis models or not.

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