Astron. Astrophys. 334, 21–28 (1998)

ASTRONOMY
AND
ASTROPHYSICS

The rejuvenation of starburst regions due to massive close binary evolution

J. Van Bever and D. Vanbeveren

Astrophysical Institute, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium

Received 23 June 1997 / Accepted 11 December 1997

Abstract. We present the results of population number synthesis calculations on young starbursts in regions of solar metallicity (Z=0.02), using a Monte Carlo simulation of bursts containing 1000 stellar objects. They clearly show that one has to account for interacting binaries to get a correct image of these regions. Independently of all sorts of distributions such as initial mass function (IMF) or mass ratio distribution, interacting binary evolution makes starbursts look younger than they really are. What happens is that after some time, the area of the main sequence (MS) above the actual turnoff point of the Hertzsprung-Russell Diagram (HRD) gets crowded with accretion stars, which are part of the end product of mass transfer in close binaries. Shortly after their appearance, these accretion stars (blue Stragglers) begin to dominate the O star population in a starburst, proceeding to the moment where they are the only ones left (since at that particular stage, all the O type single stars and binary O type primaries have disappeared). As a consequence, if it is assumed that the entire population are single stars, or that the features of the starburst are solely due to single star evolution, the resulting age estimation of the starburst is wrong, i.e. the starburst may be considerably older than it appears.

Key words: binaries: close – blue stragglers – Hertzsprung–Russel (HR) diagram – galaxies: starbust – galaxies: stellar content

1. Introduction

The massive star content in young starburst regions has been the subject of numerous studies (see a.o. Leitherer 1996 for a review). Most studies only account for the effect of single star evolution. A first attempt to include interacting binaries was published by Vanbeveren et al. (1997a). It was concluded that binaries play an essential role. This has been criticized by Cerviño et al. (1996) and Shaerer & Vacca (1996). They concluded that interacting binary evolution cannot play a significant role, according to the following argument. In a burst, interaction between binary components occurs for the first time only after about 5 Myr since the start of star formation (in Sect. 2 we will critically examine the assumptions behind this proposition). Using results of evolutionary synthesis (Leitherer & Heckman 1995), they estimated the ages of a large number of starburst regions (e.g. Wolf-Rayet galaxies) and found that the majority of them are younger than 5 Myr, consequently eliminating interacting binaries as important contributors to the stellar population in these objects. The ages were determined using results which follow from models (e.g. Leitherer & Heckman 1995) that do NOT account for interacting binaries. This means that a conclusion concerning interacting binaries was drawn, using calculations where only single stars were considered. Therefore the question could, and as we will try to show, should be raised, as to how much binaries affect the age determination of young starbursts. The following simplified example illustrates what could happen. Assume that at a certain moment, 70 single stars with an average mass of 30 $M_\odot$ and 30 case B close binaries with average component masses of 30 $M_\odot$ + 20 $M_\odot$ are formed. In this way, we eliminate the influence of all kinds of distributions like IMF etc., but take a binary frequency corresponding to observations (Garmany et al. 1980). The first O star phase due to the unevolved single and binary stars lasts about 5 Myr. After 6 Myr roughly, the original 30 $M_\odot$ stars cross the Hertzsprung gap. At this stage the binaries interact, each producing a system very similar to V444 Cyg, which is classified as a WN5 + O6V system. The situation now is that the only O type stars we have are the 30 O6V stars, since the single stars have all evolved away from the main sequence. Since the expected O lifetime of a O6V star is about 2 to 3 Myr, an observer who only accounts for the effects of single stars will interpret the starburst as being younger than about 3 Myr, while in reality it is older than 6 Myr. Even though this is a very simple picture, the calculations including all the necessary details confirm that interacting binaries make starburst regions look younger than they really are (if of course, the binary frequency is not negligible). In Sect. 2 we briefly discuss the features of the massive binary evolution model that are relevant to this study. Sect. 3 deals with the various distributions and parameters that are involved in the problem, as well as with the used evolutionary tracks. Finally, our results are presented in Sect. 4.

2. The evolution model of massive binaries: a brief summary

The detailed description of the evolution of all sorts of massive binaries ($M_{prim} > 8$ $M_\odot$ - 10 $M_\odot$) can be found in Vanbeveren et al. (1997b). Here, we summarize briefly those aspects which are of importance to this study.

2.1. Luminous Blue Variables (LBV's)

Stars with mass larger than about 40 $M_\odot$ are thought to be subject to very large stellar wind (SW) mass losses at the end of core hydrogen burning or at the beginning of hydrogen shell burning. If the mass loss rate is large enough, it might keep the star from traveling to the red part of the HRD and, for not too small binary periods, prevent it from filling its Roche lobe in the process. In our code, we simply assumed that primaries (the most massive and fastest evolving component in a binary) with mass larger than 40 $M_\odot$ do not transfer mass to their companion for any binary period, but continue to evolve as a single star. This means that the first binaries that interact will be those with a primary of mass 40 $M_\odot$. Since for the most part, this happens after the hydrogen burning lifetime of the primary, the first signs of binary interaction in a starburst will occur only after about 5 Myr!

2.2. Case A and Br binaries with primary mass $\leq$ 40 $M_\odot$

Interacting binaries are divided into case A, Br, Bc and C systems, depending on the evolutionary state of the mass losing primary at the start of mass transfer. In case A and case Br systems (which are systems with periods typically lying in the range 1 to the order of 1000 days, depending on the primary mass), the mass transfer occurs during core hydrogen burning and early hydrogen shell burning respectively. The secondary may accrete some or all the matter that is lost by the primary. From this point on, the secondary is referred to as an accretion star. It looks younger, rejuvenated as it is due to the addition of new material and the subsequent growth of its convective core. At the end of mass transfer, it will have assumed a bluer and more luminous position in the HRD than at the start of mass transfer. It is precisely this feature that makes interacting binaries worth considering, and which leads to the crucial role that they may play in the age determination of starbursts. The value of the fraction β of the mass lost by the primary that is actually accreted by the secondary is still a matter of debate. The binaries with very low initial mass ratio (=q) (smaller than about 0.2, and also some of the systems with 0.2<q<0.4) are not expected to survive as binaries but will merge instead (see Sect. 2.5.). For the other case A and Br systems, mass transfer occurs on the thermal time scale of the mass losing component. If the thermal time scales of both components are significantly different from each other, as is the case for low q binaries, the secondary will expand rapidly and a contact phase begins. This may be accompanied by mass loss from the system. The limiting q between binaries that go into contact and those of which the secondary (probably) accretes everything (β=1: conservative RLOF) lies somewhere in the range 0.4 - 0.6 (Kippenhahn & Meyer-Hofmeister 1977) (see also Pols et al. 1991 for a more detailed justification). We used the value of 0.4 in our code, but the results are not affected by this choice. From comparisons between predicted distributions of the mass ratio of galactic WR+OB systems and the observed one (Vanbeveren et al. 1997b), it seems likely that mass transfer in the more massive close binaries (primary mass larger than about 20 $M_\odot$ and q $>$ 0.4) proceeds in a quasi-conservative way. We will present the results using the following formalism: β = 0 when q<0.2, $\beta = \beta_{max}(5q-1)$ when 0.2$\leq$q<0.4 and $\beta = \beta_{max}$ when q>0.4. In Sect. 4 we will show the influence of β_{max} by considering 2 values; 0.5 and 1.

2.3. Case Bc and C binaries

In case Bc and case C systems (periods roughly in the range 1000 to 2000 days) mass transfer begins during late hydrogen shell burning and helium shell burning respectively. The primary has developed a convective envelope before the moment mass transfer starts. The reaction of these stars to mass loss is to expand, which enhances the mass loss rate and makes it become a dynamical time scale process (Paczynski & Sienkiewicz 1972). The secondary finds it impossible to accrete all this transferred matter on such a short time and as a consequence a common envelope forms. In our code, we assumed that the secondary does not accrete any matter, but instead continues to evolve like a single star. Anticipating the results, we can say that these binaries will not make an important contribution to the population, since they are very rare (see Fig. 1 in Vanbeveren et al. 1997a).

2.4. Non-interacting binaries

For systems with periods larger than those associated with case C binaries (thus periods larger than about 2000 days), the components are simply too far away from each other for the primary to fill its Roche lobe at some stage during its evolution. It is obvious that we will treat the components of these systems as single stars as well.

2.5. Binaries with low initial mass ratio

There is a class of interacting binaries (with primary mass smaller than 40 $M_\odot$) that is an exception to the rules outlined above. These are systems with initial mass ratio less than about 0.2 (Sparks & Stecher 1974, Paczynski 1976). The classical Roche model does not apply anymore for these binaries. As the primary grows during its evolution, the secondary is dragged into its atmosphere. What the end product of this "merging" process may be is still uncertain. In our code, we just ignored the subsequent evolution of these systems, as it does not critically affect the main conclusion of the present paper.

2.6. Effect of primary supernova

A small asymmetry in the supernova explosion is sufficient to give the remaining neutron star a non-negligible push or kick, which is translated into a so called "kick velocity". Taking the pulsar velocity distribution obtained by Lyne & Lorimer (1994) as representative for the kick velocity distribution during a supernova event, we get an average kick velocity of about 450

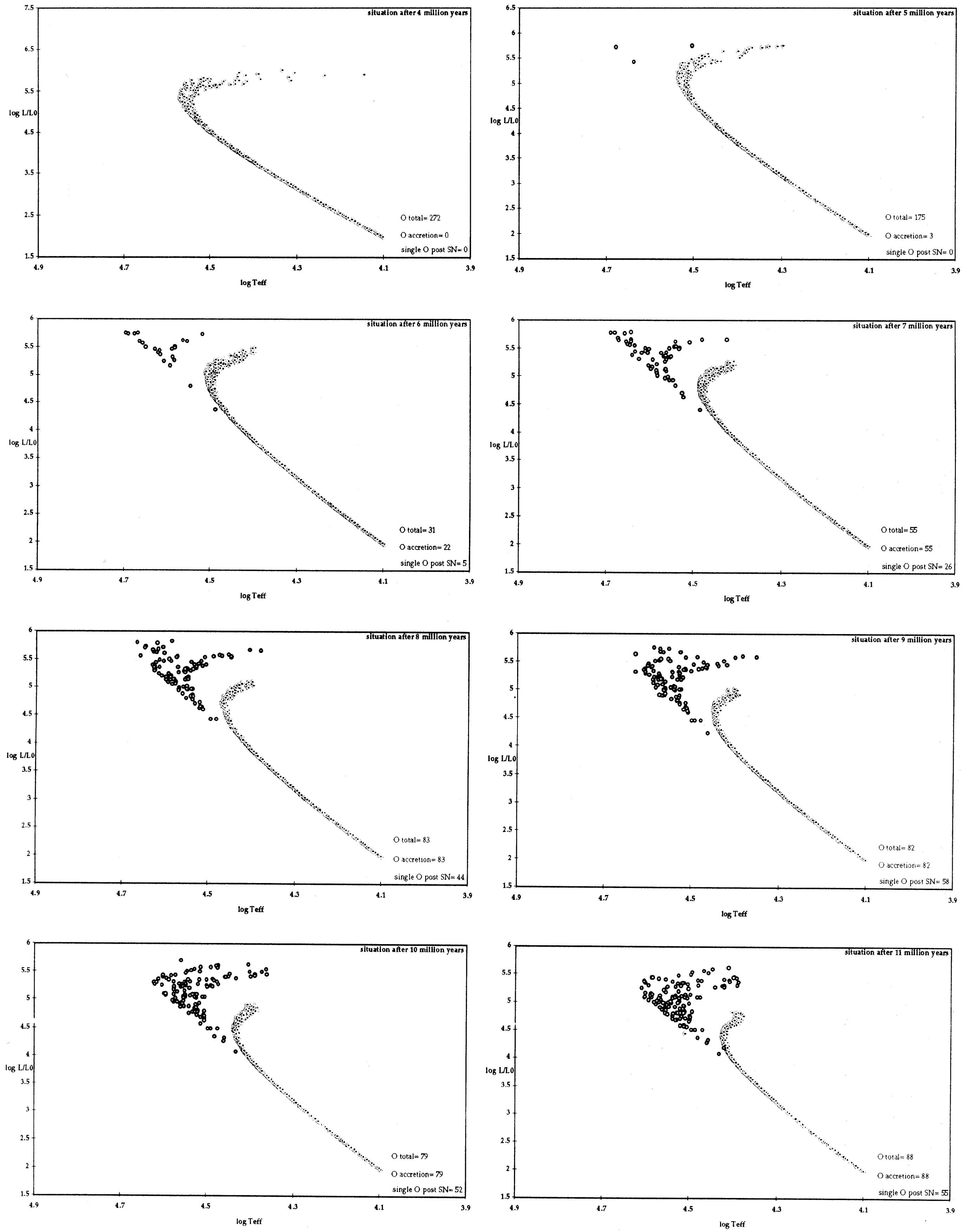

Fig. 1. The evolution between 4 and 11 Myr of a starburst which lasted 1 Myr, with an IMF $\propto M^{-2.7}$ and a flat Φ(q). the binary frequency was taken to be 80% and β_{max}=1.

km/s. There have been suggestions that this average could be substantially lower. However, our main statement that starbursts could be 'rejuvenated' by the presence of interacting binaries is not affected by this choice. Recently though, Lorimer et al. (1997) made a thorough study of the kinematic properties of pulsars, concluding that the average kick velocity should be approximately 500 km/s. This large value has the consequence that most systems will not survive the supernova as a binary (Vanbeveren et al. 1997 and De Donder et al. 1997), but instead, the newly acquired kinetic energy of the neutron star proves to be larger than its potential energy and the binary system is disrupted, leaving two isolated objects. This leads to stars which are single in appearance, but which have had a binary past, and possibly an interacting binary past. In other words, they could be accretion stars! An aspect that was not yet included in the calculations by Vanbeveren et al. (1997a) was the formation of black holes. The difference between a black hole and a neutron star in this context, is that we assume that no supernova (and thus no kick) is associated with the formation of the former object. This assumption follows from the trend that black hole binary candidates exhibit, to have lower spatial velocities than would be expected if they had received kick velocities at birth (Podsiadlowski et al. 1996). Theoretical considerations as well, seem to indicate that a large fraction - if not all - of the mass is swallowed by the newly formed black hole, instead of being ejected during a supernova explosion (Burrows 1987). As far as the limiting mass for black hole formation is concerned, we make use of the binary system consisting of the X-ray pulsar 4U 1223-62 and its optical companion Wray 977. Brown et al. (1996) traced back the evolution of this system and concluded that the progenitor of the pulsar must have had a mass of at least 36 $\mathrm{M}_{\odot}$ (see also Wijers 1996). Black holes must thus be formed from more massive binary components and we assume, in fair agreement with theory, a limiting mass of 40 $\mathrm{M}_{\odot}$ for black hole formation.

3. The evolutionary synthesis model

In order to perform evolutionary synthesis of a stellar aggregate, one needs:

- an evolution model for binaries
- an evolution model for single stars
- the lifetimes of single stars and binary components during their different evolutionary phases
- parameter distributions for objects at birth
- a binary frequency

For the accretion star tracks and associated lifetimes we used the evolutionary calculations made by the Brussels group (see the reviews of Vanbeveren 1991, 1994, 1996 and references therein). The single star data were taken from Schaller et al. (1992). Vanbeveren (1982) concluded that it is probable that the IMF of primaries is different from that of single stars. But since no estimates exist on how different they may be, we decided to adopt the same relation for both of them: IMF $\propto M^{-2.7}$ (Scalo 1986) (with a lower limit of 8 $\mathrm{M}_{\odot}$ and an upper limit of 100 $\mathrm{M}_{\odot}$). To investigate the influence of this distribution on the results, we made some calculations with other powers as well. The shape of the initial mass ratio distribution Φ(q) of massive close binaries is still a matter of debate. Hogeveen (1991) proposes a distribution which favors low q; Φ(q) $\propto q^{-2}$ when q>0.3 and flat elsewhere. Garmany (1980) however suggests Φ(q) $\propto q^{1/2}$. Even a flat distribution belongs to the possibilities. Accordingly, we accounted for every one of them in our study. The period distribution for massive binaries was taken to be the same as the one proposed by Popova et al. (1982) and Abt (1983) for other binaries: Π(P) $\propto$ 1/P (with a lower limit of 1 day and an upper limit of 10 years). The most crucial parameters in the problem are the binary frequency, and the interacting binary frequency. Garmany et al. (1980) stated that about 33% of all O type stars in the solar neighborhood are primaries of unevolved close binaries with q>0.2 and P<100 days. However, to avoid RLOF of the primary, massive binaries need to have much larger periods than that; roughly P $>$ 1000 to 2000 days! So we expect the interacting binary frequency among massive stars in the solar neighborhood to be higher than 0.33. In fact, if one tries to reproduce this observational percentage with our detailed binary evolution model described in Vanbeveren et al. (1997b), the interacting binary frequency of the initial population must be of the order of 0.5 to 0.6 (depending somewhat on the distributions used). In our calculations, given the IMF and Φ(q), we used the binary frequency which is necessary to reproduce the observational result of Garmany et al.. In doing so, we assume that the binary frequency in starburst regions with solar metallicity is the same as in the solar neighborhood.

4. Results: synthesized HRDs

We made Monte Carlo simulations of the evolution of starbursts of solar metallicity. We follow them by synthesizing HRDs for different epochs after the start of the starburst phase, and by keeping track of the number of the types of objects which are of relevance to our main statement. To count as a starburst, the star formation phase should be smaller than the lifetimes of the highest mass stars, here chosen to be stars of 100 $\mathrm{M}_{\odot}$. Typically, this gives star formation phases of the order of 10^6 yrs or less. We used the obvious value of 1 Myr throughout our calculations, as this does not turn out to be a crucial parameter in the problem. We will consider bursts of 1000 objects (single and binary). Note however, that for instance in so called Wolf-Rayet galaxies, the number of massive stars formed during such a starburst phase could be orders of magnitude larger than the one used here. But our value suffices to exhibit the effect of interacting binaries that we are trying to describe. Fig. 1 and 2 respectively show the evolution of a starburst with an IMF $\propto M^{-2.7}$, a flat Φ(q) and with β_{max}=1 and 0.5, between 4 Myr and 11 Myr after the start of the starburst phase. The early stages of the evolution of the starburst (0 Myr $\leq$ t $<$ 5 Myr) are completely dominated by single star evolution. At this point, the first - albeit timid - signs of the presence of interacting binaries become visible by the appearance of accretion stars (open dots). From now on, the influence of interacting binaries becomes stronger and stronger

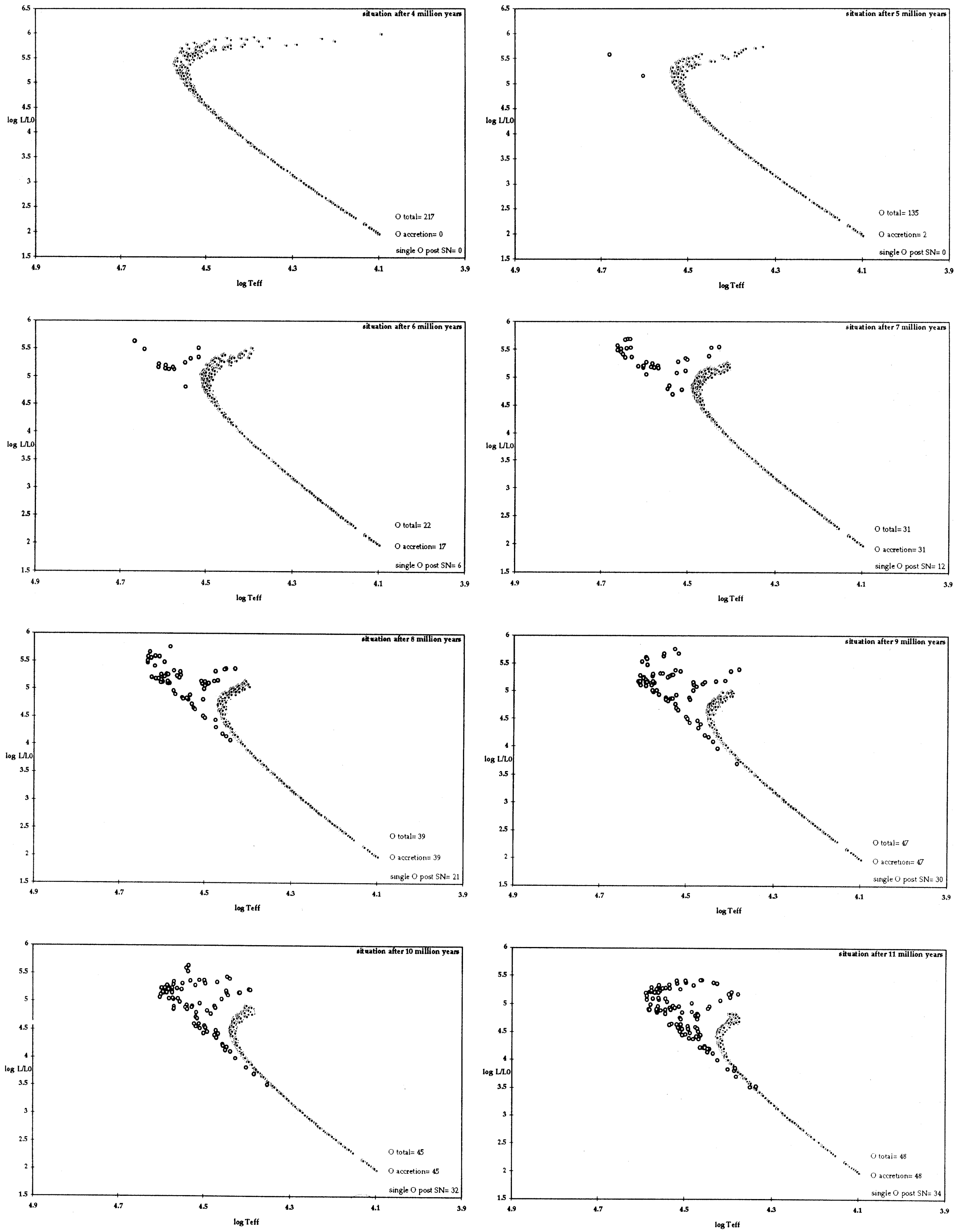

Fig. 2. Same as Fig. 1 but with β_{max}=0.5.

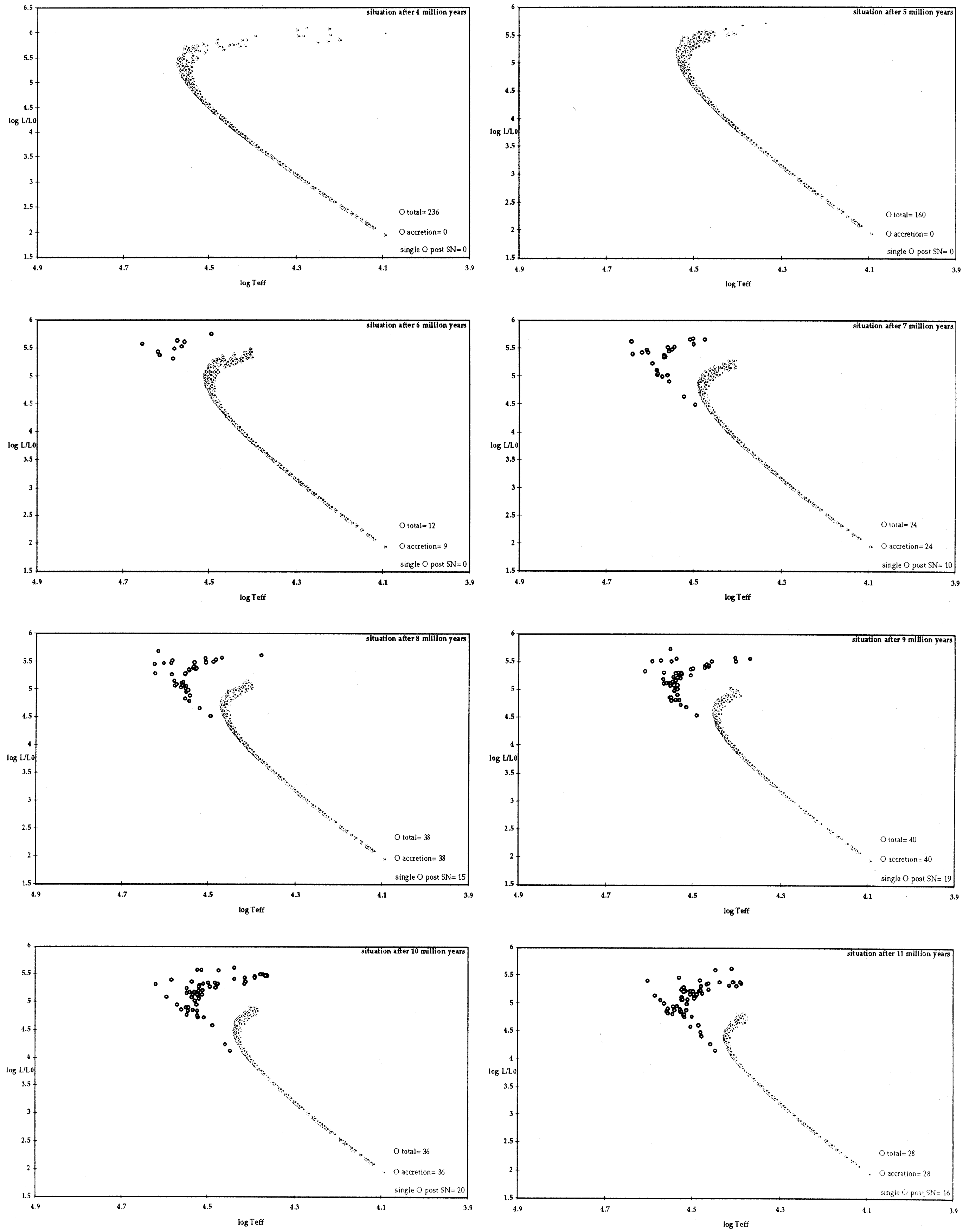

Fig. 3. Same as Fig. 1 but only taking 33% binaries. They all have q>0.2 and a period less than 100 days.

and they slowly overtake the single stars in contributing to the O star population. After some 7 Myr the upper part of the HRD is being completely controlled by accretion stars. This can also be seen from the number of O stars due to RLOF compared to the total number, as we compute these on every picture. To decide whether a star is an O star we used the calibration of Humphreys & Mc Elroy (1984). One notices that after about 7 Myr the entire O star population consists of accretion stars only! This is a fascinating situation, since, if a starburst is observed in such a phase, it exhibits O stars which, if believed to be single, will be given ages younger than about 5 Myr, while in reality the starburst is older than 7 Myr. Another interesting feature is the number of O stars that are former members of binaries but single at present, due to the supernova explosion of the original primary which disrupted the system. It appears that at the stage where the accretion stars dominate, they account - on average - for some 60% of the O star population, for β_{max}=1 as well as for β_{max}=0.5. So more than half of the accretion O stars are expected to be isolated stars, but remember that RLOF is responsible for their present evolutionary state. In Fig. 3 we present the same calculations, but this time we only took 33% binaries, which all had q $>$ 0.2 and P $<$ 100 days. In other words, we just accounted for those systems that are actually observed in reality. As one can see, the overall features are identical to the former results. Accretion stars still become the dominant and eventually only suppliers of O type stars in a starburst. Using all kinds of combinations of IMF and Φ(q) distributions does not change that fact either. The foregoing arguments seem to indicate strongly, that one needs to consider the influence of interacting binaries when studying a starburst region before making conclusions based on single star evolution only. However, the calculations we have made and the statements we have put forward so far are, strictly speaking, only applicable to environments whose metallicity is comparable to that of the solar neighborhood. When trying to reproduce the Wolf-Rayet star populations in the Magellanic Clouds (which both have a lower metallicity than the Galaxy) by taking account of single and binary stars, Vanbeveren (1995) concluded that it is probable that the binary frequency (and thus the interacting binary frequency as well) should be lower there compared to that of the Galaxy. As a matter of fact, there are signs that the binary frequency for massive stars is a increasing function of metallicity, reaching interacting binary frequencies as low as 8.5% for the SMC. If this is true, then it is quite clear that for very low metallicity environments the few accretion stars that are present will not be able to generate much confusion about the evolutionary state of the starburst, and that single star evolution will pretty much remain the dominant contributor to the O star population there.

5. Conclusions

In this paper we have made calculations on the evolution of the massive star population in starburst regions of solar metallicity taking account of single as well as binary stars. It is shown that single star evolution dominates the O star population in the early stages but that interacting binaries (by way of accretion stars) start taking over after about 5 to 6 million years, eventually becoming the only suppliers of O stars after about 7 million years. Attention is drawn to the fact that a non-negligible fraction of those accretion O stars ($\approx$60%) will be seen as isolated stars due to the supernova explosion of their former companions which disrupted the binary system. The consequence of all this is that the starburst will be given an age that is too young compared to its actual evolutionary state when only single star evolution is considered. A final important remark is that it may be possible for the binary frequency to be a increasing function of metallicity, leading to the suspicion that for very low metallicity environments the above-mentioned effect may be significantly reduced.

Acknowledgements. Part of this research was carried out in the framework of the project Service Centres and Research Network initiated and financed by the Belgian Federal Scientific Services (DWTC/SSTC)

References

Abt, H.A.: 1983, ARA&A 21, 343.
Brown, G.E., Weingartner, J.C., Wijers, R.A.M.J.: 1996, ApJ 463, 297.
Burrows, A.: 1987, in ‘SN 1987 A’, ESO Workshop 26, ed. I.J. Danziger, ESO Garching, p. 315.
Cerviño, M., Mas-Hesse, J.M., Kunth, D.: 1996, in ‘Wolf-Rayet Stars In The Framework Of Stellar Evolution’, 33rd Liège international Astrophysical Colloquium, p. 613.
De Donder, E.,Vanbeveren, D., Van Bever, J.: 1997, A&A 318, 812.
Garmany, C., Conti, P.S., Massey, P.: 1980, ApJ 242, 1063.
Hogeveen, S.J.: 1991, Ph. D. thesis, University of Amsterdam.
Humphreys, M.R., Mc Elroy, D.: 1984, ApJ 284, 565.
Kippenhahn, R., Meyer-Hofmeister, E.: 1977, A&A 54, 539.
Leitherer, C., Heckman, T.M.: 1995, ApJS 96, 9.
Leitherer, C.: 1996, in ‘Wolf-Rayet Stars In The Framework Of Stellar Evolution’, 33rd Liège international Astrophysical Colloquium, p. 591.
Lorimer, D.R., Bailes M., Harrison P.A.: 1997, MNRAS 289, 592
Lyne, A.G., Lorimer, D.R.:1994, Nature 369, 127.
Paczynski, B., Sienkiewicz, R.: 1972, Acta Astr. 22, 73.
Paczynski, B.: 1976, in ‘The Structure And Evolution Of Close Binary Systems’, eds. P. Eggleton, S. Mitton, J. Whelan (Dordrecht: Reidel), p. 75.
Podsiadlowski, P., Joss, P.C., Pols, O.R., Brandt, W.N.: 1996, in ‘Evolutionary Processes In Binary Stars’ NATO AS, eds; Wijers R.A.M.J., Davies M.B., Tout C.A., p. 181.
Pols, O.R., Coté, J., Waters, L.B.F.M.; Heise, J.: 1991, A&A 241, 419.
Popova, E.I., Tutukov, A.V., Yungelson, L.R.: 1982, ApJ&SS 88, 55.
Scalo, J.M.: 1986, Fundamentals of cosmic physics 11, 1.
Shaerer, D., Vacca, W.D.: 1996, in ‘Wolf-Rayet Stars In The Framework Of Stellar Evolution’, 33rd Liège international Astrophysical Colloquium, p. 641.
Shaller, G., Schaerer, D., Meynet, G., Maeder, A.: 1992, A&AS 96, 269.
Sparks, N.M., Stecher, T.P.: 1974, ApJ 188, 149.
Vanbeveren, D., Van Bever, J., De Donder, E.: 1997a, A&A 317, 487.
Vanbeveren, D., Van Rensbergen, W., De Loore, C.: 1997b, in ‘The Brightest Binaries’ Kluwer: Dordrecht.
Vanbeveren, D.: 1982, A&A, 115, 65.
Vanbeveren, D.: 1991, A&A 252, 159.

Vanbeveren, D.: 1994, in ‘Evolution Of Massive Stars: a Confrontation Between Theory And Observation’, eds. D. Vanbeveren, W. Van Rensbergen, C. De Loore (Kluwer: Dordrecht) p. 327.
Vanbeveren, D.: 1995, A&A 294, 107.
Vanbeveren, D.: 1996, in ‘Evolutionary Processes In Binary Stars’ NATO AS, eds; Wijers R.A.M.J., Davies M.B., Tout C.A., p. 155.
Wijers, R.A.M.J.: 1996, in ‘Evolutionary Processes In Binary Stars’ NATO AS, eds; Wijers R.A.M.J., Davies M.B., Tout C.A., p. 327.