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The number of B-type binary mass gainers in general, binary Be stars in particular, predicted by close binary evolution

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Abstract. Compared to earlier studies on the subject, we use results of intermediate mass case B close binary evolution computed with updated data, to predict the population of B-type accretion stars for different regions of star formation, in the Galaxy and in the Magellanic Clouds. We will make a distinction between accretion stars with a (helium burning) subdwarf, respectively white dwarf and neutron star companion. Our population model incorporates recent ideas on asymmetric supernova explosions. Establishing a link between the formation of B-type accretion stars (mass gainers) and the formation of Be stars enables us to get an idea about the importance of close binary evolution on the Be star phenomenon. A comparison between the obtained results and the observations, related to regions of continuous star formation and starburst regions, reveals that only a minority of the Be stars (less than 20% and possibly as low as 5%) is due to close binary evolution.

Key words: binaries: close – stars: evolution – Galaxy: stellar content – galaxies: stellar content – Magellanic Clouds

1. Introduction

Be stars form a subset of the B-type dwarfs and giants showing Hα emission features which are typical for the presence of a circumstellar disk. They are known to be rapid rotators. However, not all rapid rotators show a Be-type spectrum. Furthermore, the emission line character of a Be star can disappear temporarily and reappear again at a later moment, although the rotational velocity of the star does not change. It is therefore generally accepted that rapid rotation is a necessary ingredient for the Be phenomenon, but not a sufficient one. The evolutionary state of Be stars is still a matter of debate, especially the importance of binaries and their evolutionary processes. Transfer of matter lost by a primary (mass loser) during its Roche lobe overflow (RLOF) may spin up the secondary (mass gainer) or at least its outer layers (Packet, 1981). This spun up mass gainer may then turn into a Be star because of the Be mechanism. Most of the B-type mass gainers formed this way should have a subdwarf (sdOB), white dwarf (WD) or a neutron star (NS) companion. It can readily be checked that such low mass binary components are hard to detect from radial velocity shift measurements. The importance of the binary channel for Be star formation can be estimated by comparing star numbers predicted by close binary (CB) evolution with observations. A first attempt appeared in Pols et al. (1991), for Be stars in stellar environments where star formation is continuous. They concluded that no more than 60% of the population of known Be stars should be formed by close binary interaction. Due to the lack of detailed computations on close binary evolution, they restricted their study to the Galaxy. For the remaining lifetime of the mass gainer after the mass transfer (= the lifetime of the possible Be star), they had to adopt a qualitative relation suggested by van den Heuvel (1969). Furthermore, it was assumed that the supernova (SN) explosion of a massive primary is spherically symmetric, which implies that in most cases the binary is not disrupted (Blaauw, 1961). Instead, a Be+neutron star system (Be+NS) forms.

An extended set of evolutionary computations has been performed by de Loore and Vanbeveren (1994, 1995) and Vanbeveren, van Rensbergen and de Loore (1996), for case B CBs with intermediate mass and massive primaries, for the Galaxy, the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC), using OPAL opacities. The evolution of the gainer is continued after RLOF until the end of its own core hydrogen burning (CHB) phase. Instead of the qualitative relation mentioned above, we thus have explicitly computed remaining lifetimes of the mass gainer.

Using recent measurements of pulsar proper motions (Harrison et al., 1993) and a new pulsar distance scale (Taylor and Cordes, 1993), Lyne and Lorimer (1994) obtained a pulsar velocity distribution f(v_p) that is described very well by the following relation:

$$f(v_p) = 1.96\cdot10^{-6} {v_p}^{3/2} e^{-3v_p/514}\,, \quad (1)$$

v_p in km/s, (see also Vanbeveren et al., 1996).

These velocities reflect the kick velocity a compact star may get because of an asymmetric SN explosion. Notice that this distribution implies an average kick velocity of 450 km/s which is substantially larger than any previous estimate. We therefore expect that a large number of binaries are disrupted during the SN explosion. The effect of an asymmetric SN explosion on the fraction of Be stars with a neutron star companion has been studied by Portegies Zwart (1995). However, he used a constant value for the kick velocity (instead of a kick velocity distribution) which obviously simplifies the computations. Furthermore, similarly as in the paper of Pols et al. (1991), he adopted the same qualitative relation for the remaining lifetime of a mass gainer after mass transfer.

In the present paper we will consider the following questions:

• Using new results on close binary evolution, how much does our population number synthesis differ from earlier studies for galactic regions of continuous star formation?

• How different is the B-type mass gainer population in the Magellanic Clouds when compared to the Galaxy?

• What is the effect of an asymmetric SN explosion on the predicted number of B-type mass gainers with a NS companion?

• How does the B-type mass gainer population in starburst regions vary with time, and how does this compare to observations?

The binary population model of the present paper and its relation to Be stars are summarized in Sect. 2. Sect. 3 deals with the results. In Sect. 4 the results are critically discussed and a comparison with observations and earlier computations is made.

2. The binary number population model

A binary number population model obviously needs:

- a model for close binary evolution
- the timescales of the different evolutionary phases
- the mass, mass ratio and period distribution of binaries
- the close binary frequency

2.1. A possible Be phase during close binary evolution

Within our present day knowledge about stellar evolution, we are unable to define unambiguously a Be phase for a B-type star. A different approach is necessary to estimate the importance of close binary evolution on the Be star formation. Most of the Be stars are rapid rotators. In Sect. 4 we will study the meaning of this statement. In a close binary, angular momentum transfer always accompanies mass transfer, i.e., mass transfer will at least spin-up the outer layers of the mass gainer. Whether the whole star will be spun-up is a matter of debate. This spin-up process is clearly visible in Algol binaries where mass transfer is still going on. In a number of them the B-type companion is indeed a Be star. It is therefore tempting to identify the post-mass transfer phase of the mass gainer in a close binary as a phase where the star shows the effects of fast rotation, and where it may thus show Be-type features. In the present paper we will determine the number of B-type mass gainers formed through close binary evolution. We prefer to use the latter term and then to discuss separately the link between the number of B-type mass gainers and Be stars.

2.2. The close binary evolution model

In this paper we will use the classical definitions of case A, case Br, case Bc and case C binaries. The detailed close binary evolution model used in the present paper has been discussed at length by Vanbeveren et al. (1996). We account for:

a. Common envelope evolution of binaries with a mass ratio q $<$ 0.2, a process generally referred to as 'spiral-in' (Livio and Soker, 1988; Taam and Bodenheimer, 1989, 1991). We use the prescription discussed by Webbink (1984). Most of these binaries merge into one star. What happens then is unknown. A possible scenario would be that the primary acts as if he accretes the mass of the low mass component. Since in most of the binaries mass transfer starts when the primary has completed its core hydrogen burning, it can readily be understood that accretion of matter does not rejuvenate the primary, as would happen when a core hydrogen burning star accretes matter (e.g., Podsiadlowski et al., 1992; de Loore and Vanbeveren, 1992). This means that the remaining hydrogen burning lifetime of the merging product should be very small if this scenario applies. In the present paper we decided to omit the binaries who merge, since we think that their contribution to the B-type mass gainer fraction is negligible (and thus, the same is true for the Be binary fraction).

b. Quasi-conservative evolution of case Br systems following the formalism of Vanbeveren et al. (1979). Two parameters characterize this type of evolution: β = the fraction of mass lost by the primary due to RLOF, accreted by the secondary.

α = a parameter describing the specific angular momentum taken away by matter leaving the system.

If during the RLOF phase of a case Br close binary, significant mass loss from the system occurs on the Kelvin-Helmholtz timescale (= the RLOF timescale), this can to our knowledge only happen through the following two processes:

- Material leaves the binary through the second Lagrangian point L_2, forming a ring around the binary.
- Material lost by the primary gains sufficient energy from the orbit by dynamical friction to be pushed out of the binary.

The first process corresponds to $\alpha \geq 6$, according to the particle trajectory calculations of Flannery and Ulrich (1977). When we consider the second possibility, we can try to estimate α by using a similar description as the spiral-in process of Webbink (1984). If $\Delta M = M_{10} - M_1$ denotes the mass lost by the primary due to RLOF, then the evolution of the orbital parameters can be computed by assuming that the orbital energy is converted with some efficiency α_{CE} into potential energy of that part of the envelope of the primary that has to be dispersed to infinity,

Table 1a. The remaining hydrogen burning lifetime of a galactic mass gainer after Roche lobe overflow for β = 0.5. M_1 = original mass of the primary in solar units and M_2 = original mass of the secondary in solar units. The lifetimes are expressed in units of 10^6 yr.

		M_2										
		1	**2**	**3**	**4**	**5**	**8**	**10**	**12**	**15**	**20**	**25**
	3	1106	310.7									
	4	750.7	262.5	108.6								
	5	421.8	193.5	99.37	22.54							
	6	341.0	165.4	92.06	45.08	23.66						
	7	262.3	136.5	81.10	41.38	32.04						
	8	195.7	111.3	71.23	37.69	32.49						
	9	167.2	98.45	66.44	37.39	32.95	5.594					
	10	139.4	85.83	61.46	37.08	30.38	11.19					
	11	113.7	74.21	56.51	36.78	29.36	12.31	5.295				
	12	101.6	69.12	51.63	36.48	28.33	13.43	6.981				
	13	89.74	64.11	46.74	34.77	27.48	13.80	8.275	2.514			
	14	78.16	59.23	41.94	33.07	26.62	14.16	9.188	5.028			
	15	71.53	54.44	39.05	31.42	24.75	13.74	9.896	5.652			
M_1	**16**	66.83	49.76	36.89	30.34	22.87	13.32	9.568	6.277	2.762		
	17	62.24	45.19	34.77	29.27	22.98	13.67	9.640	6.674	3.488		
	18	57.75	40.84	32.75	28.21	23.58	14.02	9.962	7.071	3.794		
	19	53.36	38.78	31.67	27.18	22.60	13.50	9.786	7.357	4.268		
	20	49.07	36.76	30.62	26.16	21.63	12.98	9.808	7.643	4.644		
	21	44.87	34.79	29.58	25.14	20.64	13.09	10.04	7.789	4.864	1.725	
	22	40.89	32.91	28.56	24.14	19.71	13.21	10.21	7.935	5.084	2.060	
	23	38.99	31.91	27.57	23.16	19.32	12.85	10.13	7.878	5.303	2.394	
	24	37.14	30.92	26.59	22.20	18.94	12.49	10.04	7.820	5.523	2.599	
	25	35.33	29.96	25.63	21.26	18.57	12.52	9.952	7.870	5.743	2.803	
	26	33.56	29.02	24.69	20.33	18.20	12.54	9.870	7.921	5.793	3.000	1.445
	27	32.37	28.09	23.78	19.78	17.83	12.32	9.787	8.011	5.844	3.195	1.538
	28	31.47	27.19	22.88	19.41	17.48	12.70	9.705	8.102	5.894	3.309	1.716
	29	30.58	26.30	22.00	19.05	17.12	12.57	9.622	8.016	5.944	3.424	1.793
	30	29.72	25.44	21.13	18.69	16.78	12.44	9.540	7.930	5.995	3.498	1.909

i.e.,

$$\frac{GM_{10}\,(1-\beta)\,\Delta M}{\lambda R_0} = \alpha_{CE}\left(\frac{GM_1M_2}{2a} - \frac{GM_{10}M_{20}}{2a_0}\right), \quad (2)$$

M_2 = M_{20} + $\beta\Delta$M.

The parameter λ describes the relative binding energy of the mass (1-β)ΔM to the primary. R_0 is the Roche radius of the primary at the onset of the RLOF. When β = 0.5, the foregoing prescription corresponds to large values of α in formula 3 as well (i.e., $\alpha > 6$ when q = 0.9 and $\alpha > 3$ when q = 0.3). Similarly as was done by Pols et al. (1991) and by Portegies Zwart (1995), we define a minimum value for q (q_{min}) above which β is assumed to be constant (and equal to β_{max}) for case Br binaries. We will study the effect of β and α on our results assuming β_{max} = 0.5 and 1 (conservative RLOF) and α = 3 and 6. In between 0.2 and q_{min} (for q $\leq$ 0.2 the spiral-in process is at work and thus β = 0), we assume that β varies linearly with q. To explore the effect of q_{min} on our results, we have chosen two values: q_{min} = 0.4 and 0.6.

c. Case Bc and case C systems evolve through a common envelope phase, i.e., no mass transfer. The contribution to the Be binary population should therefore be negligible.

d. At the end of its life, the primary of a massive close binary (primary mass larger than 8-10 $M_\odot$) experiences a SN explosion, the final remnant being a compact star, i.e., a neutron star or a black hole. A small asymmetry of the SN ejecta is sufficient to give the compact star a substantial kick velocity v_{kick}. The effect of an asymmetric SN explosion on the system parameters has been studied by Sutantyo (1978) (see also Verbunt et al., 1990, and Wijers et al., 1992). We used his formalism. The distribution of kick velocities is given by Eq. 1.

2.3. The timescales of the different evolutionary phases

The three timescales that are necessary here are the core hydrogen burning lifetime, the helium burning lifetime of the remnant of Roche lobe overflow and the remaining lifetime of the mass gainer after the mass transfer phase. All lifetimes were taken from the detailed and updated libraries of binary evolution computations of de Loore and Vanbeveren (1994, 1995)

Table 1b. Same as Table 1a. but for β = 1.

		M_2										
		1	**2**	**3**	**4**	**5**	**8**	**10**	**12**	**15**	**20**	**25**
	3	303.0	139.6									
	4	174.2	98.71	58.41								
	5	112.7	72.80	52.59	14.54							
	6	84.06	61.29	42.88	29.08	10.41						
	7	67.03	49.74	36.13	27.81	20.82						
	8	55.57	39.70	31.77	26.53	20.59						
	9	44.41	34.51	29.18	23.97	18.71	4.830					
	10	37.49	31.06	26.56	21.42	17.74	9.660					
	11	32.73	28.42	23.99	19.58	17.18	9.829	3.434				
	12	30.14	25.84	21.47	17.74	16.50	9.997	6.867				
	13	27.61	23.32	19.62	16.93	15.06	9.921	7.348	2.616			
	14	25.14	20.86	18.60	16.12	14.48	9.844	7.433	5.232			
	15	22.73	19.45	17.60	15.68	14.65	9.752	7.770	5.515			
M_1	**16**	20.37	18.46	16.61	14.72	12.69	9.660	7.842	5.798	1.884		
	17	19.30	17.49	15.65	14.22	12.71	9.577	7.444	5.885	3.769		
	18	18.35	16.54	14.73	13.76	12.74	9.494	7.693	5.973	4.183		
	19	17.42	15.61	14.27	13.31	12.31	9.249	7.349	6.080	4.235		
	20	16.51	14.75	13.83	12.87	11.88	9.005	7.523	6.187	4.287		
	21	15.62	14.30	13.38	12.44	11.46	8.841	7.349	6.262	4.500	1.149	
	22	14.77	13.87	12.95	12.01	11.04	8.676	7.390	6.336	4.712	2.298	
	23	14.35	13.44	12.53	11.59	10.63	8.539	7.240	6.173	4.786	2.646	
	24	13.93	13.03	12.11	11.18	10.23	8.401	7.195	6.010	4.859	2.993	
	25	13.52	12.62	11.71	10.78	10.03	8.217	6.963	5.943	4.868	3.074	
	26	13.13	12.22	11.31	10.39	9.851	8.033	7.074	5.876	4.876	3.042	0.929
	27	12.74	11.83	10.92	10.14	9.676	7.888	6.976	5.916	4.859	3.197	1.858
	28	12.35	11.45	10.54	9.964	9.504	7.742	6.768	5.956	4.842	3.184	1.919
	29	11.98	11.08	10.23	9.792	9.335	7.891	6.700	5.876	4.853	3.340	2.009
	30	11.61	10.71	10.06	9.624	9.170	7.805	6.548	5.797	4.865	3.322	2.127

and Vanbeveren, van Rensbergen and de Loore (1996). The assumptions behind these computations are:

1. Accretion is treated using the model proposed by Neo et al. (1975).

2. Rapid mass accretion implies an increase of the convective core and the formation of important semi-convective zones. The boundary of the convective core is always determined by the Schwarzschild criterion whereas semi-convection is treated with the method outlined by Schwarzschild and Harm (1958).

In Table 1 we summarize these data. We only list the values holding for the Galaxy. The values holding for the SMC are about 10% larger. Notice that also the whole core hydrogen burning lifetime is about 10% larger in the SMC when compared to the Galaxy. This means that we do not expect large differences between the Galaxy and the Magellanic Clouds as far as relative numbers (B-type mass gainer/all B-type stars) are concerned.

2.4. The mass, mass ratio and period distribution of binaries

Although the IMF of single stars could be different from the IMF of primaries of CBs (Vanbeveren, 1982), we will use the same power law for both, i.e., IMF $\propto M^{-2.7}$ (Scalo, 1986). We assume that the IMF is constant in time in regions of continuous star formation (at least within the lifetime of the lightest star in our sample: 3 $M_\odot$).
Although selection effects can not be excluded, the orbital period distribution of B-type close binaries satisfies $\Pi(P) \propto 1/P$ (Popova et al., 1982; Abt, 1983).
The mass ratio distribution of B-type CBs decreases towards q = 1 (Trimble, 1990; Tout, 1991; Hogeveen, 1991). The B-type binary data of Wolff and of Abt and Levy suggest a mass ratio distribution $\Phi(q) \propto (1 + q)^{-3}$ if q $\geq$ 0.25. However, due to small number statistics and selection effects, a steeper distribution and even a flat distribution can not be excluded. Similarly as was done by Pols et al. (1991), we computed the population numbers using the mass distribution of Hogeveen (1991) and a flat distribution.

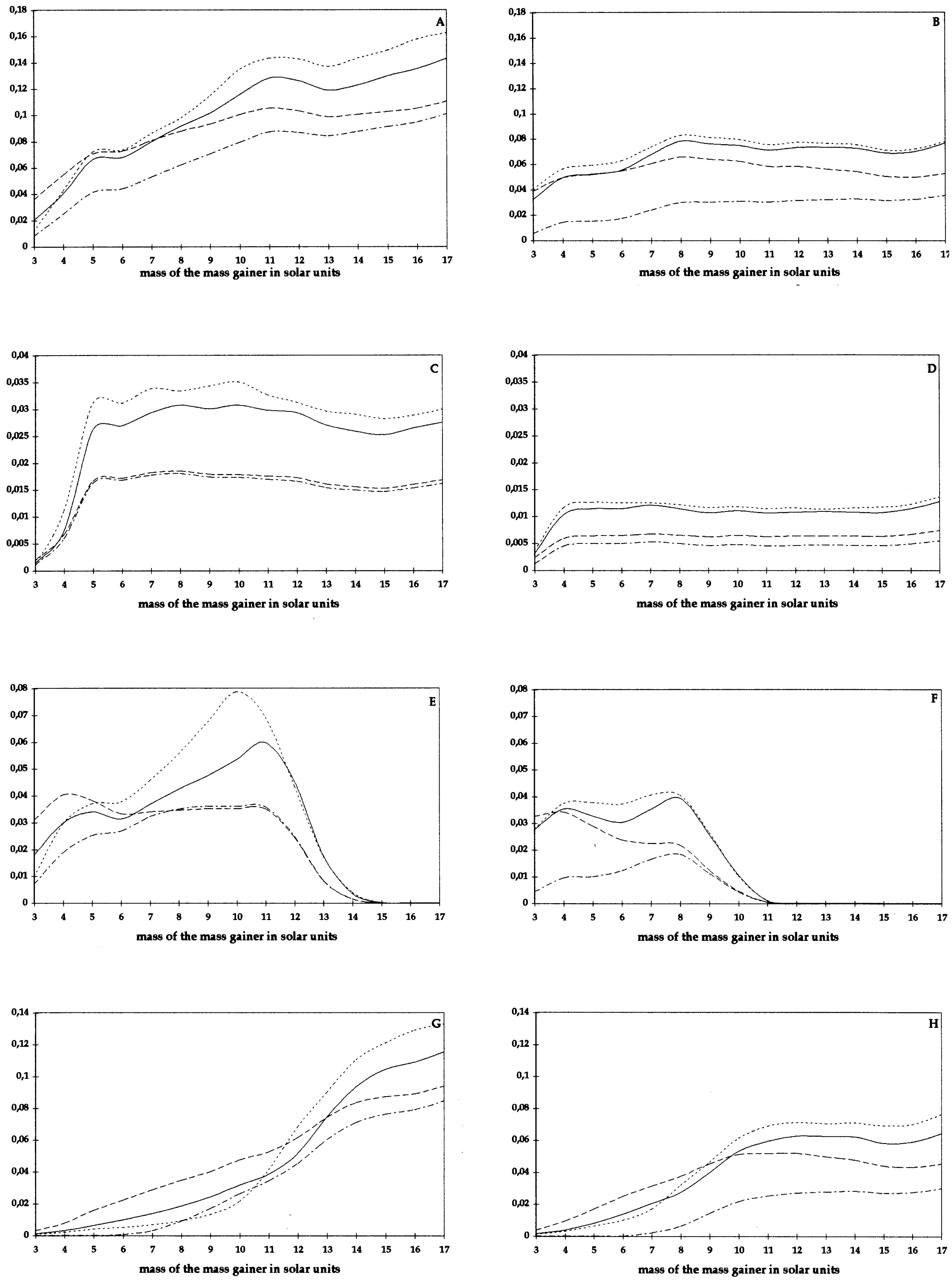


Fig. 1. a, b The fraction of B-type mass gainers relative to the total number of B-type stars of the same mass. The four lines correspond to model 1 (full line), model 4 (dashed line), model 5 (dash-dotted line) and model 6 (dotted line). The models were chosen in order for any other model to lie between the top and bottom line in the figure. For the values of the parameters used in the different models, see Table 2. Left figures show the situation for β_{max} = 1 in systems with q>q_{min} and right figures the situation for β_{max} = 0.5. **c, d** Same as 1a, b but for mass gainers with a subdwarf helium burning companion. **e, f** Same as 1a, b but for mass gainers with a white dwarf companion. **g, h** Same as 1a, b but for mass gainers that have a neutron star companion.

Table 2. The fraction of mass gainers relative to all stars in the same range of spectral type.

environment	β_{max}	model	q_{min}	$\Phi(q)$	IMF power	α	allB-types	B0-B5	B0-B3
Galaxy	1	1	0.6	flat	-2.7	3	0.031	0.055	0.084
		2	0.6	flat	-2	3	0.039	0.059	0.081
		3	0.6	flat	-2.7	6	0.017	0.041	0.072
		4	0.6	Hogeveen	-2.7	3	0.044	0.064	0.082
		5	0.6	Hogeveen	-2.7	6	0.016	0.035	0.056
		6	0.4	flat	-2.7	3	0.026	0.060	0.093
		7	0.4	flat	-2.7	6	0.020	0.053	0.088
	0.5	1	0.6	flat	-2.7	3	0.039	0.053	0.065
		2	0.6	flat	-2	3	0.048	0.061	0.072
		3	0.6	flat	-2.7	6	0.014	0.027	0.038
		4	0.6	Hogeveen	-2.7	3	0.043	0.052	0.059
		5	0.6	Hogeveen	-2.7	6	0.009	0.017	0.023
		6	0.4	flat	-2.7	3	0.040	0.057	0.070
		7	0.4	flat	-2.7	6	0.018	0.033	0.045
SMC	1	1	0.6	flat	-2.7	3	0.034	0.057	0.081

2.5. The binary frequency

Wolff (1978) searched for duplicity in 73 B7-B9 stars and found 12 binaries with a mass ratio q $>$ 0.25 and a period P $\leq$ 100 days. From a study of 39 B2-B5 stars, Abt and Levy (1978) concluded that 25-30% of those are binaries with q $>$ 0.25 and P $\leq$ 10 years. Applying the period distribution discussed above to Wolff's data, it follows that in the B7-B9 spectral range the CB frequency ($\leq$ 10 years, q $\geq$ 0.25) is around 30% as well. We will always assume that 30% of the B-type stars are primaries of close binaries with q $\geq$ 0.25 and P $\leq$ 10 years. It can readily be checked that all our results scale linearly with this percentage.

Our number frequencies are computed as functions of mass. Observations are always given as functions of spectral type. Comparison between theory and observations is performed using the mass-spectral type relation of Harmanec (1988).

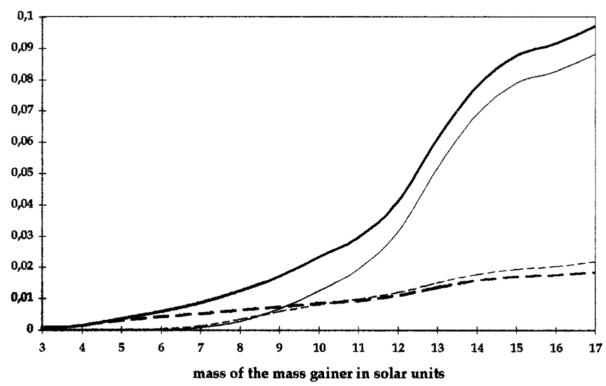


Fig. 2. The fraction, relative to all B-type stars, of the mass gainers with a neutron star companion compared to the fraction of single mass gainers. Results are shown for model 1 and model 3 (which differ only in the amount of specific angular momentum lost during non-conservative RLOF, i.e., α = 3 for model 1 and α = 6 for model 3), in the case of β_{max} = 1. Thick lines are used for model 1 and thin lines for model 3. Full lines denote single mass gainers and dashed lines denote mass gainers that have a neutron star companion.

3. Computations

3.1. The total number of B-type mass gainers in regions of continuous star formation

Figs. 1 illustrate the fraction of B-type mass gainers to all B-type stars (mass gainers included) of the same mass predicted by CB evolution. Results are shown for the Galaxy, for different values of the parameters in our model. We separately consider B-type mass gainers with a helium burning subdwarf companion, a WD companion and the B-type mass gainers of binaries where the primary underwent a SN explosion (we call them Be_{sn}). The latter class will be discussed in more detail in the next subsection. In Table 2 we give the overall fraction of B-type mass gainers. We consider three cases: all B-types, B-types equal to B5 and earlier, and B-types equal to B3 and earlier. We conclude:

• With the q-distribution of Hogeveen, respectively with a flat one, CB evolution where case Br binaries with q $> q_{min}$ evolve in a conservative way (β_{max} = 1), predicts that at most 5% (resp. 4%) of all B-type stars are post-RLOF mass gainers resulting from case Br binaries. On average 20% of this class should have a subdwarf companion, 70% a WD companion and 10% are post-SN B-type mass gainers.

• As far as all the B-type stars are concerned, the fractions are only slightly dependent on the adopted β_{max}. However, looking only at the spectral types B3 and earlier, one sees that the

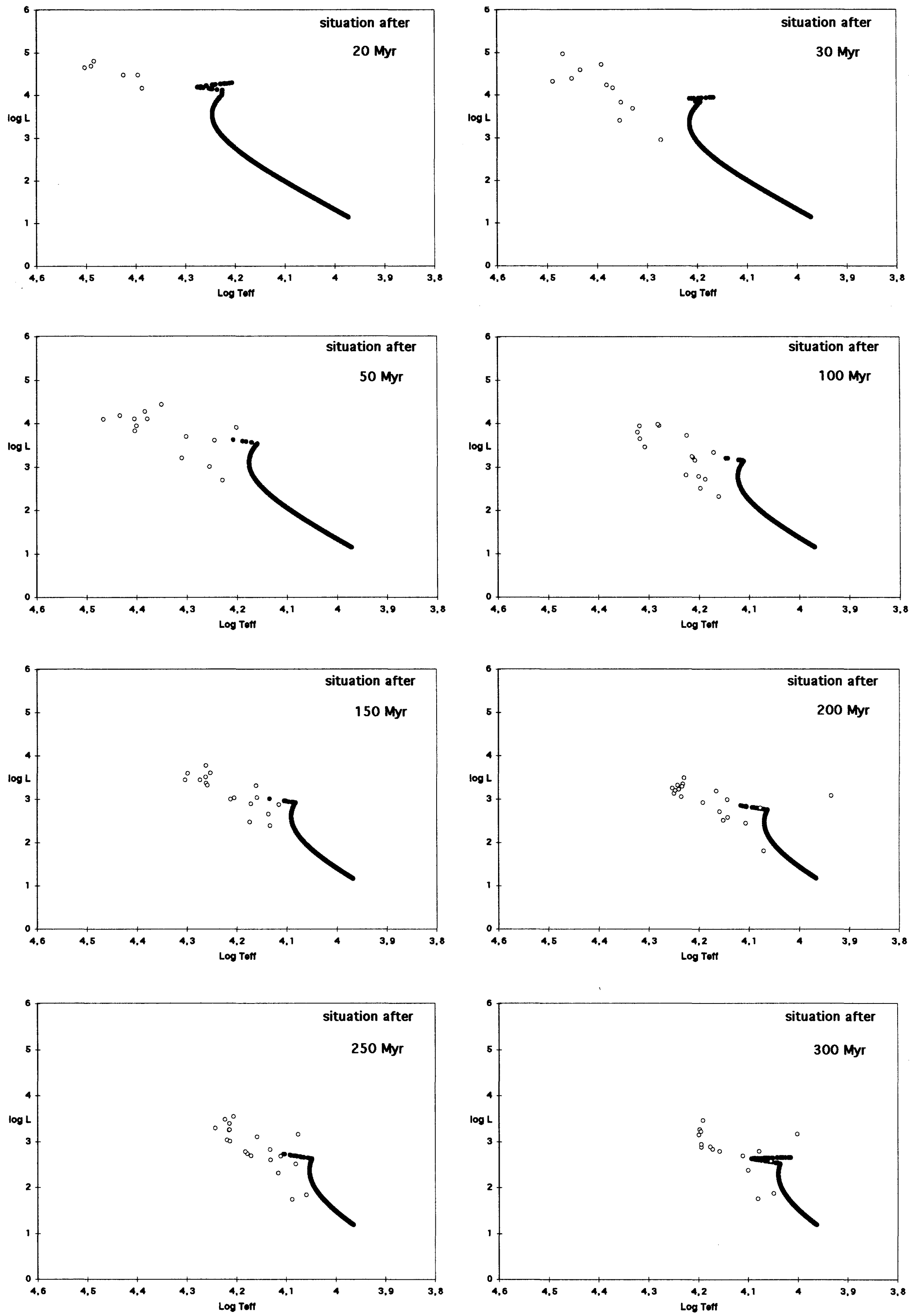


Fig. 3. The evolution in time of the HR diagram of an instantaneous starburst consisting of 4000 stars, in the Galaxy. The parameter values used are those of model 1.

Table 3. The age, the observed and the predicted fraction of Be stars relative to the number of B0-B5 stars, for clusters in the Galaxy and in the Magellanic Clouds. The references 1 = Mermilliod (1981, 1982), 2 = Slettebak (1985), 3 = Waelkens et al. (1990), 4 = Sanduleak (1990), 5 = Grebel (1995).

environment	cluster	age (Myr)	observed Be fraction	predicted Be-type mass gainer fraction		references
				β=1	β=0.5	
Galaxy	h & χ Per	<20	0.25-0.5	0.014	0.016	1,2,3
	NGC 663	22	0.4	0.015	0.017	1,4
	NGC 3760	22	0.33	0.015	0.017	1,2
	α Per	50	0.2	0.032	0.031	1,2
	Pleiades	80	0.24	0.043	0.042	1,2
Magellanic Clouds	NGC 330	19	0.27	0.004	0.007	5
	NGC 2004	20	0.11	0.005	0.007	5
	NGC 1818	25	0.2	0.007	0.009	5

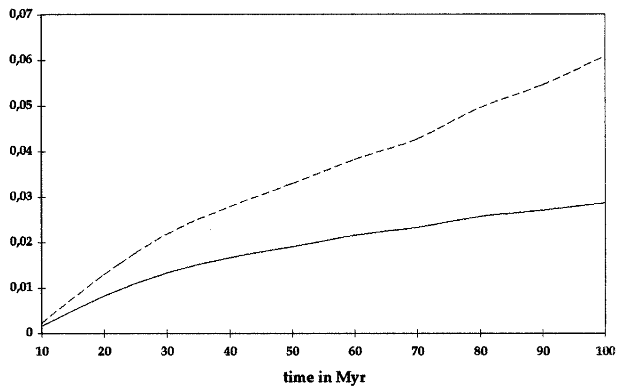


Fig. 4. The evolution in time of the theoretically predicted fraction of all B-type mass gainers relative to all B-type stars (in the limit of an infinite number of stars), for the same starburst as in Fig. 3 (full line). The same fraction but restricted to spectral types earlier than or equal to B5 is shown as well (dashed line).

fractions for β_{max} = 0.5 are (on average) a factor 1.6 lower than those for β_{max} = 1.

• The results for the SMC are very similar to the Galactic ones. Since the LMC has a metallicity between that of the SMC and that of the Galaxy, the similarity is a fortiori true for the LMC. This means that the population of mass gainers formed through CBs should be very similar in the Galaxy and in the MCs, if the binary fraction and the period and mass ratio distributions are independent from metallicity.

• The most important difference between our results and those of earlier studies on galactic regions of continuous star formation (e.g., Pols et al., 1991) (besides the formation of a substantial number of single mass gainers, Sect. 3.2), is that our number of mass gainers with an sdOB companion is about a factor 2 smaller. This is due to the different timescales used in the 2 studies. For masses lower than about 5 $M_\odot$, our helium burning lifetimes are much smaller than the ones used by Pols et al. (which are those of Paczynski (1971) and Habets (1986) from back in the seventies and eighties). On top of that, for most systems our explicitly calculated remaining hydrogen burning lifetimes are longer than those predicted by the formula of van den Heuvel. The combination of these 2 factors explains the observed difference.

3.2. The number of B-type stars with a neutron star companion

Fig. 2 shows the fraction of B-type mass gainers in binaries where the original primary already experienced a supernova explosion, assuming the v_{kick} distribution given by Eq. 1. A flat mass ratio distribution is used (the mass ratio distribution of Hogeveen leads to similar conclusions). We distinguish single B-type mass gainers (descendants of disrupted binaries) from B-type mass gainers with a neutron star companion. A very interesting feature arises when one compares models that only differ in the amount of specific angular momentum that is lost during non-conservative RLOF, i.e., α = 3 versus α = 6. Observations reveal that we don't know of any system consisting of a Be star and a neutron star, in which the Be star has a mass lower than about 7 to 8 $M_\odot$. As can be seen in Fig. 2, models with α = 6 reproduce this property quite nicely. Notice that a similar conclusion was made by Portegies Zwart (1995). Other important conclusions:

a. In most cases, more than half of the massive binaries formed with a B-type primary (B-type massive binaries) are disrupted during the first supernova explosion. Of course, in the case where we take α = 6, more angular momentum is lost during non-conservative RLOF and consequently more systems will merge before the SN of the primary can take place. In this context, it can be understood that in the particular model where β_{max} = 0.5 and α = 6, we find that only 1 out of 3 B-type massive binaries formed, will be a system that did not merge due to

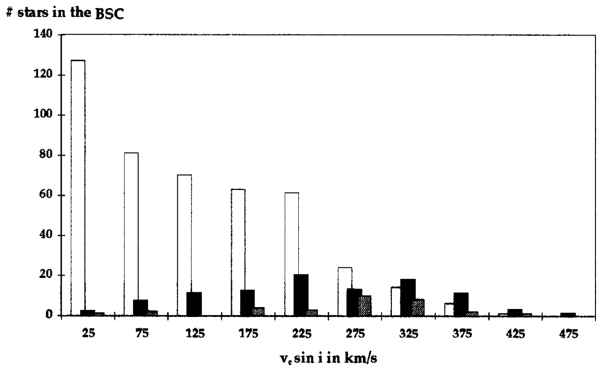


Fig. 5. Histogram of the v sini values of the B-type stars listed in the SIMBAD Bright Star Catalogue. We make a distinction between Be stars (black bars), Bn and Bnn stars (gray bars) and 'normal' main sequence B-type stars (white bars).

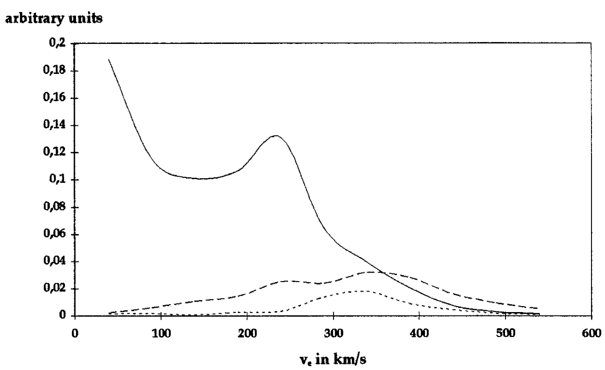


Fig. 6. The theoretically predicted equatorial velocity distributions (method of Lucy, 1974) corresponding to the histogram in Fig. 5. The full line represents the 'normal' B-type stars, the dashed line the Be stars and the dotted line the Bn and Bnn stars.

RLOF and which remained bound after the SN of the primary.

b. At most 1%-2% of all B-type stars with spectral type earlier than B3 have a neutron star companion.

c. About 3%-4% of all B-type stars with spectral type earlier than B3 may be single binary mass gainers.

3.3. The starburst model

To study the number of mass gainers predicted by CB evolution in starburst regions (rich clusters, associations), we generated an instantaneous starburst population by means of a Monte Carlo method, accounting for the IMF, binary frequency, binary period and mass ratio distribution discussed in Sect. 2. To assure enough stars in all bins of interest, we used 4000 stars with mass larger than 1.5 $M_\odot$. For binaries the Brussels tracks were taken, for single stars we used the primary evolution according to the Brussels tracks as well. As was the case for regions of continuous star formation, we used the CB evolution model discussed in Sect. 2. Fig. 3 illustrates the evolution in time of the HR diagram of the starburst. We emphasize the occurrence of CB post-RLOF secondaries. Fig. 4 gives the evolution of the fraction of mass gainers relative to all B-type stars. Observational fractions for young clusters are usually given relative to all B-type stars with spectral type between B0 and B5. In Fig. 4 we show the corresponding predicted fraction as well. The figure gives the situation corresponding to an infinite number of stars in the starburst, to make sure that the results are free of statistical fluctuation caused by small number statistics (in other words, all finite sums in our formalism become integrals). We conclude:

• Mass gainers are predominantly the bluest stars of the whole starburst (Blue Stragglers) and are situated in an HRD region where normal B-type stars have disappeared.

• The overall evolution of a starburst and of the number ratios of interest are very similar in the Galaxy and in the SMC, thus also in the LMC.

• The fraction of mass gainers in starbursts predicted by CB evolution is always very small. Clusters that are younger than 50 million years have a B-type mass gainer to all B0-B5 type star ratio $\sim$ 1-4%.

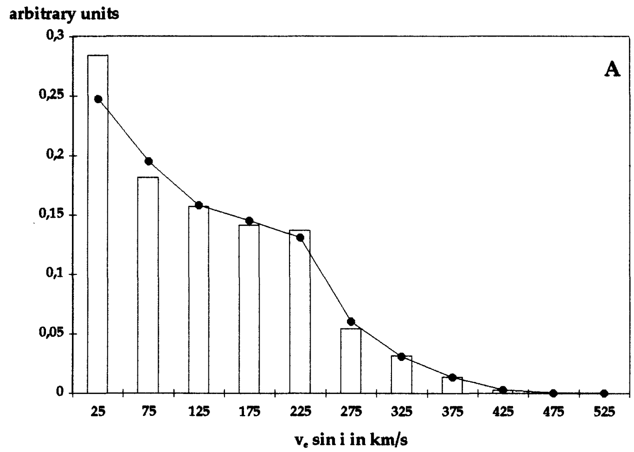
• We also made some test calculations with a starburst that lasts between 1 and 10 million years. The overall conclusions above are not critically affected.

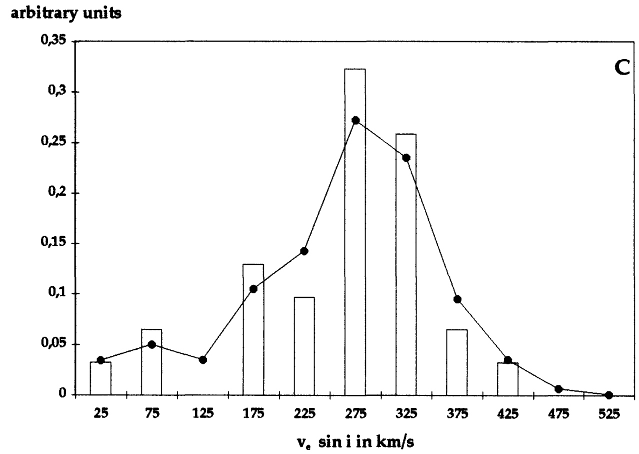
• The conclusions given above are largely independent from the adopted q-distribution and even from the exact shape of the IMF, provided that not too extreme values for the exponent are assumed.

4. Comparison to observations

4.1. Continuous star forming regions

In Sect. 2.1 we linked the Be phase to a phase where a star can be a rapid rotator. However, the Be stars are not the only class of fast rotators; Bn and Bnn stars are very fast rotators as well whereas there is a significant number of 'normal' B-type stars (i.e., not yet classified as Be, Bn or Bnn) rotating as fast as Be stars. Using the actual SIMBAD Bright Star Catalogue (BSC), Fig. 5 gives the distribution of known $v_e sini$ values of the Be stars (98 stars), the Bn and Bnn stars (31 stars) and the 'normal' B-type stars (447 stars) (we have chosen a bin width of 50 km/s). We assume that these distributions are representative of the whole population in the BSC, i.e., 166 Be stars, 104 Bn and Bnn stars and 1275 'normal' B-type stars. We then applied the statistical method described by Lucy (1974) to transform the three $v_e sini$ distributions into v_e distributions using a standard error of half the chosen bin width, i.e. 25 km/s. Notice that compared to other methods (e.g., Balona, 1975), the v_e distribution does not need to be pre-specified (by this we mean in the form of polynomials, exponentials, etc.). Instead, it tries to find





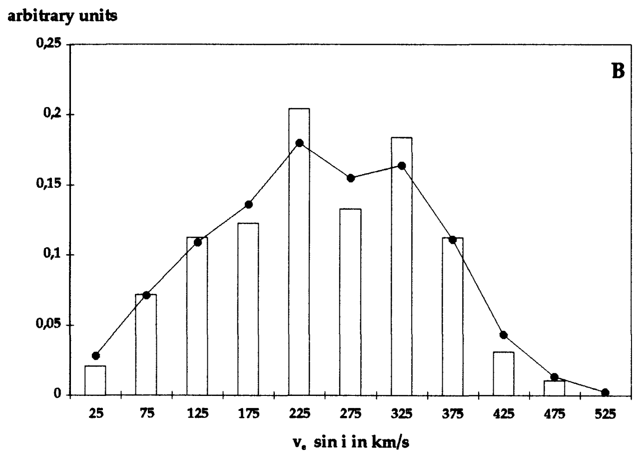


Fig. 7a–c. To get an idea about the accuracy of our predictions on a particular distribution, we show the histogram of the observations (bars) together with the expected v sini distribution, starting from the equatorial velocity distribution of Fig. 6 (line). Fig. 7a does this for the normal B-type stars, Fig. 7b for the Be stars and Fig. 7c for the Bn and Bnn stars.

the v_e distribution that reproduces the observed $v_e sini$ with a significance-level $> 95\%$. They are shown in Fig. 6. In Fig. 7 we compare the observed $v_e sini$ distribution with the theoretical one corresponding with the distributions of Fig. 6. As can be noticed, the overall correspondence is very good. A number of interesting features do result:

• The average equatorial velocity of the Be, Bn and Bnn sample is about the same, i.e., $\langle v_e \rangle$ = 350 km/s, which is around 0.75-0.85 times the critical break-up velocity. Notice that this value is significantly larger than predicted by a.o. Balona (1975). The average equatorial velocity of the 'normal' B-type stars is about 180 km/s. That is, on average, Be, Bn and Bnn stars rotate approximately twice as fast as 'normal' B-type stars.

• However, comparing the v_e distribution of 'normal' B-type stars with the one of Be (and Bn and Bnn) stars, we have to conclude that a significant number of 'normal' B-type stars have equatorial velocities as high as those of the Be stars. Most of the Be+Bn+Bnn stars have $v_e > 200$ km/s, but the number of 'normal' B-type stars with $v_e > 200$ km/s is twice as large. Using 300 km/s as a limit, we still have to conclude that there are at least as many 'normal' B-type stars as there are Be+Bn+Bnn-type stars.

• The overall fraction of Be+Bn+Bnn stars to all B-type stars is about 18%. If we consider the Be, Bn and Bnn stars as fast rotators, we at least have to double this percentage to have a realistic number of all rapid rotators in the sample that can be compared to the predicted numbers in Sect. 3.

• The foregoing conclusions apply to all B-type stars. However, very similar values and conclusions are reached when we only take B-type stars with spectral type between B0 and B5.

• When we compare the estimated fraction of rapid rotators resulting from CB evolution (the number of mass gainers) and the observed fraction ($\sim 36\%$), we conclude that less than 20% of all rapid rotators, thus also less than 20% of all Be stars, are formed through close binary evolution.

4.2. Starburst regions

By far the most convincing argument for the statement that only a small fraction of Be stars is formed through close binary evolution, comes from the results for starbursts. In Table 3 we summarize data for 7 rich clusters in the Galaxy and in the MCs. The Be fraction is always relative to the number of B0-B5 stars.

We also give the theoretically expected fraction of mass gainers predicted by CB evolution. We conclude:

• The percentage of mass gainers formed through CB evolution in starburst regions is very small. Linking the mass gainers to Be stars formed through close binary evolution, the results for NGC 663 and NGC 3760 suggest a binary Be star percentage $< 10\%$. When we also account for the fact that there may be roughly as many 'normal' B-type rapid rotators as Be (+Bn+Bnn) stars, we are forced to conclude that the upper limit of Be stars formed through binary evolution mentioned above may be as low as 5%.

5. Final remarks

Since by definition Be stars contain disks and are rotating rapidly, it was tempting in the early study of Be stars to link them to close binaries where mass transfer was going on, or where mass transfer did spin-up the mass gainer who then became a Be star. About 18% of all B-type stars are either Be, Bn or Bnn. Their average equatorial velocity equals 350 km/sec, which is about 75% of the critical break-up velocity. The present study reveals that at least as many 'normal' B-type stars have rotational velocities similar to those of the Be, Bn and Bnn stars. Comparison of the number of B-type mass gainers predicted by theory with observations (for starbursts as well as for regions of continuous star formation), forces us to conclude that only a small fraction of the Be star population ($< 20\%$ and possibly as low as 5%) are close binary products. The others must originate differently.

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