Part3: Star Formation Processes and Chemical Evolution

Invited Reviews

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Massive Star Formation and Evolution in Local Group Galaxies: Successes and Difficulties.

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Abstract. Local Group galaxies allow us to test some properties of massive star evolution which are inaccessible in our Galaxy, in particular the effects of different metallicities. Thus, after showing that we still do not know the exact process by which massive stars are formed, we examine the differences in the distributions of O-stars, blue and red supergiants and WR stars in the Local Group. The number ratios WR/O and WN/WC are well accounted for by stellar models in which the mass-loss rates depend on the metallicity, Z, as predicted by stellar wind theories. The number ratio of red supergiants to WR stars is growing for decreasing Z. Although this behaviour is qualitatively well explained, the models need some extra mixing to fit the observational data. The same is true for the explanation of the He- and N-excesses in O, B and A supergiants. Rotation and related mixing processes certainly play a major role in massive star evolution. The relative number of Be-stars is higher at lower Z, which suggests that rotation is faster, also with more mixing, in small, irregular low-metallicity galaxies.

1. Introduction

The Local Group of galaxies offers us a template for the study of galaxies in the deep universe. This statement, often mentioned at this meeting, is especially true for massive stars in the Milky Way. The closest massive stars of low Z lie in the dwarf and irregular galaxies of the Local Group.

The knowledge of the properties of massive stars at low Z are essential in two respects: a) in order to provide tests of the theory of massive star evolution and of nucleosynthesis at all metallicities Z; b) in order to correctly interpret the integrated spectra of highly redshifted galaxies as well as their nucleosynthesis, and those of QSOs. Most interestingly, it has been shown (cf. Maeder & Conti 1994) that the careful study of the integrated spectrum of a starburst may provide information on the total mass of the starburst, on its age, on the intensity of the burst, its duration and maybe its IMF.

2. Pre-main Sequence Evolution of Massive Stars

This is one of the fields of stellar evolution where we know the least, in the Galaxy and *a fortiori* in the Local Group. On the whole, we can distinguish three evolutionary scenarios:

- Classical scenario (constant mass contraction)
- Accretion, followed by coalescence
- Accretion with growing accretion rates

- Classical scenario

  Pre-MS models evolve at constant mass with tracks in the HR diagram, which are nearly horizontal from red to blue and are characterized by the Kelvin-Helmholtz timescale (cf. Iben 1965; see also Appendix in Bernasconi & Maeder 1996). The Kelvin-Helmholtz timescale is typically 1% of the MS lifetime.

- Accretion and coalescence scenario

  Originally the accretion scenario has been applied to low- and intermediate-mass stars (cf. Palla & Stahler 1993). For massive stars it is usually assumed (cf. Bonnell et al. 1998; Stahler 1998) that the accretion onto massive stars should be inhibited by their high luminosity: the high radiation pressure is pushing the dust outwards, momentum is transferred to the gas and the infall should be reversed. The problem was studied with a model of spherical accretion by Wolfire & Cassinelli (1987). They showed that if accretion rates are too high, i.e. of about 10^{-2} yr^{-1} or more, the luminosity of the shock itself would be high enough to reverse the accretion. On the contrary, if accretion rates are too low (i.e. smaller than 10^{-4} $M_\odot$ yr^{-1} at 30 $M_\odot$) the momentum of the accreting matter will be lower than the momentum of the stellar radiation. Nevertheless, we note that a domain in between is permitted.

  Bonnell et al. (1998) and Stahler (1998), assuming the impossibility of forming massive stars by accretion only, proposed that massive stars with $M > 10$ $M_\odot$ form through collision and coalescence of intermediate mass stars already advanced in the process of mass accretion. Predictions for these models are apparently quite favourable, in particular since massive stars should lie at the cluster center and therefore should look younger. However, one constraint rather difficult to match (in my opinion) is the fact that the whole process might not be fast enough, i.e. shorter than 10^6 yr. For that a very high stellar density of about 10^4 stars pc^{-3} would be necessary, which is possible in some but not in all cases. Moreover, the formation of a 60 $M_\odot$ star or more would require more collisions and probably more time.

- Accretion with growing rates

  The starting point of this model (cf. Norberg et al. 1999) is that until we know the accretion rates for stars of various masses we cannot say whether they are in the "permitted" or "forbidden" domains, even more so as accretion disks are likely to be optically thick and will protect themselves from radiation. Indeed, the locations of the birthlines in the HR diagram are very sensitive to the accretion rates. Thus we may use this property to get an estimate of the accretion rates. All data on T-Tauri, Ae- and B-Herbig stars have been collected by Norberg et al. (1999) who searched for the best adjustment of a birthline as shown in Fig. 1

  Adjustments of the form:

$$\dot{\rm M}_{\rm accr} = \dot{\rm M}(0.7\ {\rm M}_\odot) \cdot \left(\frac{M}{{\rm M}_\odot}\right)^\alpha \tag{1}$$

have been tested and the results of Fig. 1 support a slope of $\alpha = 1.5$, which shows that the accretion rates are growing quickly with increasing stellar mass. Quite interestingly, Churchwell (1998) has shown that the mass outflows are growing with the considered mass with a power of about 1 and that the ratio of the accreted mass with respect to the infalling matter is of the order of 1/5 (the difference is attributed to the outflows). It is particularly noticeable that the accretion rates given by expression (1) lie in the "permitted" domain (cf. Wolfire & Cassinelli 1987). Thus we think that the objections against the formation of massive stars by accretion are not valid, since the accretion rates are likely to be large enough for massive stars and to correspond to the permitted domain. Recent observations of a very luminous ultra-compact region by Watson et al. (1997) support a red location of the upper part of the birthline (cf. Bernasconi & Maeder 1996).

On the whole, it is essential to better know the process by which massive stars form, since their role in spectral and chemical evolution is so important.

3. O-stars, Blue and Red Supergiants, WR Stars in the Local Group

3.1. The cases of O and WR stars in the Local Group and in starbursts

To analyse the number ratios of massive stars in galaxies we must clearly distinguish between a) the case of constant star formation rate (SFR) over the last few 10^7 yr and b) the case of recent starbursts. Case a) applies to sufficiently large enough regions of nearby galaxies. Since up to now there is no evidence for differences of the initial mass function (IMF) in these galaxies, the observed differences in the number ratios are only the result of differences in stellar evolution. As shown by Table 1 (cf. Maeder & Conti 1994) the number ratios WR/O and WC/WN are decreasing with decreasing metallicity Z.

Table 1. Number ratios of O-type and WR stars in nearby galaxies.

Galaxy	Z	WR/O	WC/WR	WC/WN
M31	0.035	0.24	0.44	0.79
Milky Way				
ring 6–7.5 kpc	0.029	0.205	0.55	1.22
ring 7.5–9 kpc	0.020	0.104	0.48	0.92
ring 9.5–11 kpc	0.013	0.033	0.33	0.49
M33	0.013	0.06	0.52	1.08
LMC	0.006	0.04	0.20	0.26
NGC 6822	0.005	0.02	–	–
SMC	0.002	0.017	0.11	0.13
IC 1613	0.002	0.02	–	–

Metallicity has little effect on the inner structure of massive stars, since the opacity is mainly due to electron scattering. However, in atmospheres at

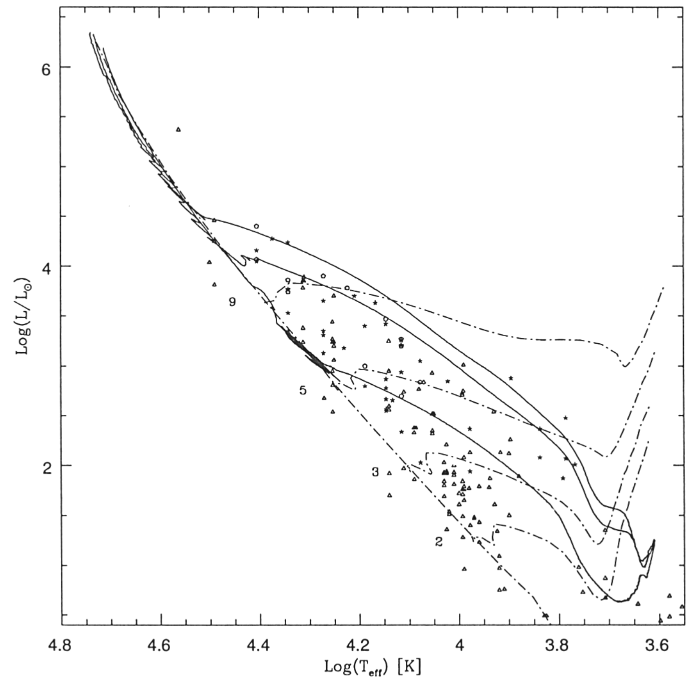

Figure 1. Observations of pre-MS stars collected by Norberg et al. (1999) with the best fit of birthlines (continuous line) calculated with accretion rates following expression (1), with a slope of $\alpha = 1.5$. The top line corresponds to $\dot{M}(0.7\,M_\odot) = 10^{-5}\,M_\odot yr^{-1}$, the second line to $5 \cdot 10^{-6}\,M_\odot yr^{-1}$ and the third to $1 \cdot 10^{-6}\,M_\odot yr^{-1}$. The dash-dotted lines show some tracks with constant mass.

larger Z, photoionisation and line opacities are larger, which leads to stronger mass-loss rates by stellar winds. The formation of WR stars, which are bare cores, is thus favoured, which produces an increase of the WR/O ratios as well as of the WC/WN ratio, since WC stars (with products of partial He-burning) represent a more advanced degree of peeling-off than WN stars (with products of CNO-burning). The agreement between the results of Table 1 and the Geneva models is very satisfactory (cf. Maeder & Meynet 1994). The star numbers as well as the main chemical abundance ratios of WN and WC stars are correctly reproduced (although the comparisons show a better agreement for enhanced $\dot{M}$-rates; this effect may be related to the indication for mixing discussed in Sections 3 and 4 below).

Case b) of O and WR stars in starbursts has gained an increased importance over recent years. Even if the O- and WR stars cannot be resolved individually in distant galaxies, their numbers may be inferred from the integrated spectrum of the galaxies. For example, the nebular Hβ line is sensitive to the number of ionizing O-stars and the emission line HeII 4686 is an indicator for the number of WN stars. In this way, Vacca & Conti (1992) were able to estimate the number ratios of WN to O-type stars in many galaxies with recent starbursts (cf. also Schaerer 1996). We notice that the observed WN/O ratios are much larger than in LG galaxies, typically by a factor of 3 to 5, as shown in Table 1. The current interpretation supported by numerical models of starbursts (cf. Arnault et al. 1989; Meynet 1995) is that these objects are just picked up a few million years after a strong peak of star formation. These peaks, which occur in very localised regions, often observed as blue knots in distant galaxies, seem to have a short duration. It is interesting that from the various number ratios of massive stars we may get some information on the mass of the starburst, on its duration, its age and maybe on its IMF as well.

3.2. Blue and red supergiants: differences in LG galaxies

We have known for a long time that there is a gradient of the number ratio RSG/BSG for red-to-blue supergiants in the Galaxy and that this gradient is not the same in the LMC and SMC (cf. Meylan & Maeder 1982; Humphreys 1983): the ratio RSG/BSG is much larger at lower metallicities. The galactic gradient of BSG in the Milky Way is about the same as that of O-stars, i.e. a surface density of O-stars (projected onto the galactic plane) which increases by about a factor of 2 over a distance of 5 kpc centered on the Sun. The gradient of WR stars has the same sign as that of O-stars but is much steeper, as shown in Table 1, while the galactic gradient of RSG is, on the contrary, growing with galactocentric distance. The number ratio of RSG/WR grows steeply with decreasing metallicity, as originally found by Maeder et al. 1980 (for more recent figures, see van der Hucht et al. 1988). At the same time the above authors noticed that the number ratio (WR + RSG)/O-stars is about constant in the various galaxies. Updated statistics of the number ratios RSG/WR in the Local Group are shown in Fig. 2 below (from Massey & Johnson 1998).

There is another interesting (and related) property of RSG, namely their upper luminosity limit which is higher at lower metallicity (cf. Massey & Johnson 1998). For example, for NGC 6822, stars up to 25–30 $M_{\odot}$ are able to form RSG, while in M33 this limit is about 18 $M_{\odot}$ and in M31 approximately 13–15 $M_{\odot}$.

The most simple interpretation of both the above behaviour of the mass limit as well as the observed properties of the RSG/WR and (RSG+WR)/O ratios is the following one (cf. Maeder et al. 1980): the lifetime t_{He} of the helium burning phase is shared mainly between the red supergiants and the WR stars, i.e.

$$t_{\mathrm{He}} \simeq t_{\mathrm{RSG}} + t_{\mathrm{WR}}$$

We ignore here the blue supergiants, which may often be in an extended MS phase. For high Z, mass loss is important, bare cores are formed rapidly and thus most of the He-burning phase is spent as a WR star. For low Z, the massive stars spend most of their He-burning lifetime in the RSG stage (at least up to about 30 $M_{\odot}$). This explains why the ratio RSG/WR is increasing for decreasing metallicity and also why the observed upper mass limit of RSG is at the same time larger. The approximate constancy of (RSG+WR)/O stars just results from the fact that the lifetimes of the He-burning phase and of the

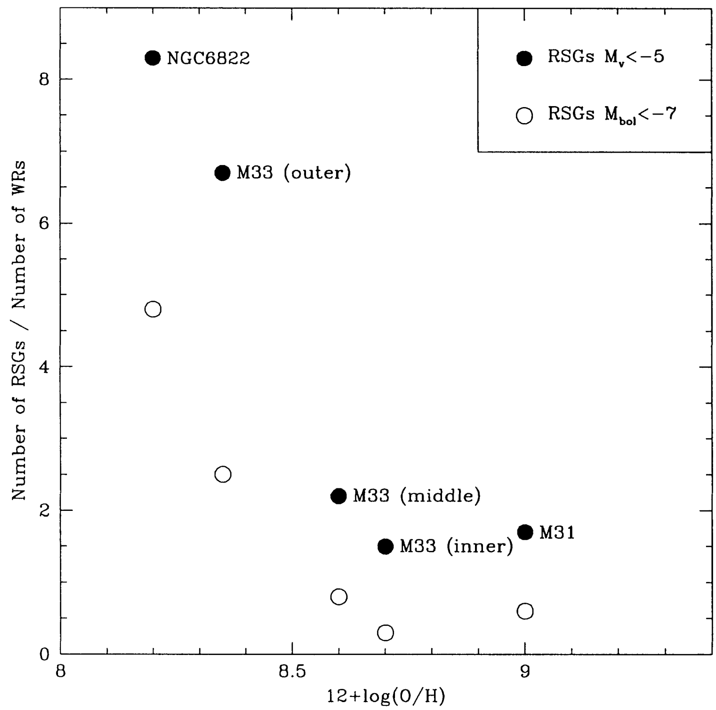

Figure 2. The variation of the number ratio RSG/WR with metallicities for some galaxies in the Local Group (cf. Massey & Johnson 1998).

H-burning phase are almost unchanged by mass loss (cf. Chiosi & Maeder 1986; this is true at least as long as the size of the He-core is not significantly reduced by mass loss, a requirement which is equivalent to saying that there is not a long WC phase).

3.3. The present situation of the stellar models and the need for more mixing

The first point to be noted is that at solar metallicity the current Geneva models (cf. Schaller et al. 1992) well reproduce the observed numbers of red giants and red supergiants with respect to the number of MS stars over the whole range of stellar luminosities (cf. Meynet 1992). However, as discussed by Langer & Maeder (1995) most of the available sets of models with low Z fail to predict enough RSGs (some sets succeed at low Z, but then their results do not fit at solar Z!). In general, the evolutionary tracks reach the RSG stage at low Z only after the end of the He-burning phase and the evolution is then too short to explain the observed number of RSGs. What is the remedy? More mass loss would be a solution, which we cannot entirely discard as long as we do not have

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accurate determinations of the $\dot{M}$-rates over the whole HR diagram at low Z. However, it seems very unlikely that the $\dot{M}$-rates are higher at low Z, and in view of the results below on chemical abundances it appears more likely that massive stars at low Z have more additional mixing effects, thus producing a larger core (and milder internal chemical gradients) which would then favour the formation of red supergiants.

There are several other interesting indications in favour of more mixing than usually predicted in massive stars. One is the fact that the main sequence of clusters (in the Galaxy, LMC and SMC) seems to extend far out to the red with respect to the predicted location (cf. Meylan & Maeder 1983; Meynet et al. 1993). A related fact is that there is no observed gap at the end of the main sequence for clusters either in the Galaxy, the LMC or SMC (Fitzpatrick & Garmany 1990). In this context it is likely that part, if not most, of the blue supergiants are not on blue loops, but rather near the end of the main sequence phase, which is somehow extended by mixing. If the mixing is due to rotation, as suggested below, it may be variable from star to star, and the same is true for the main sequence extension, a fact which will produce the absence of a visible gap at the end of the main sequence.

3.4. Chemical abundances in supergiants

Globally, the observed chemical abundances of He and N well support the above view that there is more mixing than currently predicted in massive star models. For O-stars it appears that there are no rapidly rotating O-stars which do not show an excess of Helium (cf. Herrero et al. 1998). Also, many B-stars show N-excesses, and Boron depletions were found to go along with the N-excesses (cf. Venn et al. 1996; Fliegner et al. 1996). This shows that the mixing processes occur simultaneously in both the deep interior and at the stellar surface, which supports the view that there is global mixing.

The majority of OBA supergiants exhibit He- and N-excesses with respect to the local abundances in the considered galaxy (Galaxy, LMC and SMC) according to many spectroscopic studies (e.g. Gies & Lambert 1992; Fitzpatrick & Bohannan 1993; Smith & Howarth 1994; Barbuy et al. 1996; Venn 1995; Venn et al. 1998). These recent studies well support Walborn's conjecture (1998) that the general rule in OBA supergiants is an He- and N-enrichment and that only the small peculiar subgroup of the so-called OBC stars shows the usual local chemical abundances. Venn has shown that the observed enrichments in some galactic A-supergiants (at the level of about 15 $M_\odot$) are lower than they would be if the stars had experienced convective dredge-up like the red supergiants. This means that these A-supergiants are probably not on blue loops, but may come directly from the main sequence where they went through an additional mixing process.

The most striking point on chemical abundances in supergiants comes now: while galactic A-supergiants have N/H excesses up to about a factor 2 to 3, A-supergiants in the SMC show N/H excesses up to factors 10 to 20 (cf. Venn et al. 1998). What is the reason for these very high excesses? The most logical conclusion seems that there is more mixing in SMC supergiants and maybe larger rotational velocities. Further results shown in Section 4 below support this view.

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We may also note that if the N/H excesses in the SMC A-supergiants are as large as shown by Venn, it is almost impossible that all of the observed N-excess is of secondary origin. In view of current C/N ratios, which are of the order of about 4 typically, we notice that even if all the C would have been processed to N by the CN cycle (which is far from being the case in A-supergiants at 15 $M_\odot$!) the expected N/H excess would reach at most a factor of about 4 instead of 10 or 20 as observed. Thus I would suggest that N-excesses as large as those observed in SMC A-supergiants are the signature of a production of primary nitrogen in massive stars at low metallicity. Interestingly, there is also evidence for primary nitrogen at low Z in dwarf galaxies, moreover large N/C ratios are observed in UV absorption systems in front of QSOs, and there are large NV/CIV ratios in QSOs (Hamann & Ferland 1993). These results lead to the conjecture that rotational mixing may lead massive stars, in the supergiant and maybe in some WR stages, to be the injectors of primary Nitrogen in the early phases of the chemical evolution of galaxies.

4. Stellar Rotation and its Possible Relevance to Star Populations in Galaxies

4.1. Observed fraction of Be-stars in the LG galaxies

Several authors have noticed, over the last decade, the large fraction of Be-stars in some young clusters of the SMC (cf. Grebel et al. 1994, 1996; Grebel 1997). In the spectral range of O9 to B3 stars the fraction $\frac{\mathrm{Be}}{\mathrm{B+Be}}$ of Be-stars with respect to normal B- and Be-stars is as high as 50% or more in the SMC while it is typically in the range of 10 to 20% for clusters in the Galaxy. A more systematic study of the fraction of Be-stars is now in progress by Maeder et al. (1999). As the fraction of Be-stars likely depends on both age and metallicity, we select, in order to test the influence of metallicity, only clusters with ages in the range of 10^7 yr to $2 \cdot 10^7$ yr for which reliable spectroscopic determinations of the frequency of Be-stars have been made. This selection leads to

3 clusters in the inner regions of the Galaxy	129 stars
8 clusters in the outer regions of the Galaxy	188 stars
4 clusters in the LMC	184 stars
1 cluster in the SMC (NGC 330)	126 stars

Figure 3 shows the fraction of Be-stars as a function of the average local metallicity for the four groups of clusters mentioned above. In this figure we clearly notice the growth of the fraction Be/(B+Be) for decreasing metallicity in the age range considered. Various luminosity intervals are considered in Fig. 3. The interval of $M_\mathrm{V} = -5$ to $M_\mathrm{V} = -1.4$ includes the spectral types B0 to B3. Changes of the luminosity limit as shown in Fig. 3 do not affect the observed trend. It is known that the Be-phenomenon is intermittent over timescales of the order of years or decades. This means that the trend shown in Fig. 3 is probably even steeper in reality, since the surveys of Be-stars are more complete and cover a longer time interval for clusters in the Galaxy than in the LMC and SMC.

A possible interpretation of Fig. 3 could be that the distributions of the axial rotation velocities in the three galaxies are the same, but that the Be-

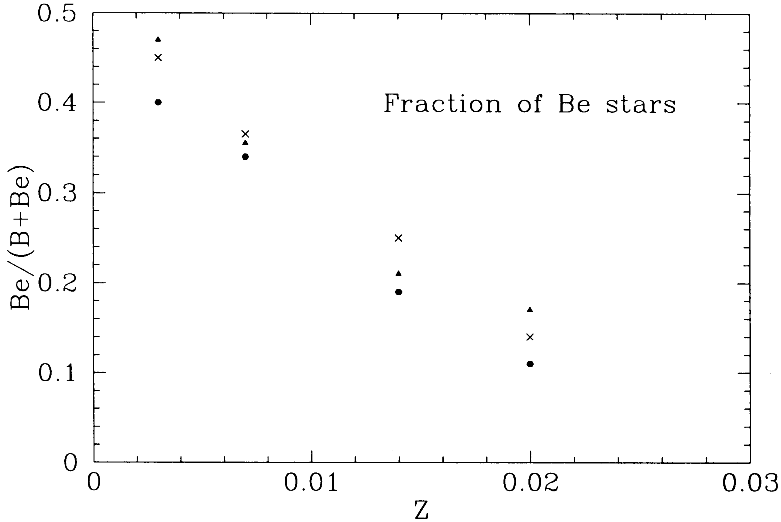

Figure 3. Number ratios Be/(B+Be) stars as a function of the average metallicity for groups of clusters in the Galaxy, the LMC and SMC. Only clusters in the range of ages between $1 \cdot 10^7$ and $2 \cdot 10^7$ yr are considered. The results of various luminosity intervals are shown as well. Triangles: M_V between –4 and –2. Crosses: –5, –2; Dots: –5, –1.4 (B0 to B3 stars).

phenomenon is more visible at lower Z. This is very unlikely, since in general the mass-loss rates at lower Z are smaller. The expressions for the anisotropic winds in rotating stars have recently been derived (cf. Maeder 1999, paper IV) and they show that more mass is injected per unit of time in the equatorial ring when the opacity is larger and when it grows rapidly with decreasing T. Thus, massive stars at low Z are not a better case for ring visibility.

The trend of Fig. 3 may reflect real differences in the distributions of rotational velocities in the Galaxy, the LMC and SMC, in the sense that there may be an increasing fraction of fast rotators when we go from the Milky Way to the SMC. The above result by Venn et al. (1998) showing much higher N/H ratios in A-supergiants of the SMC than in the Galaxy supports this view. However, the main question is: what is the basic physical reason for the trend shown in Fig. 3? Possibly, the observed relation is related to the process of star formation, which occurs with some differences in the three galaxies. In star formation the main challenge for a contracting star is to remove angular momentum, therefore we interpret the trend of Fig. 3 as meaning that more angular momentum is removed for star formation in the Galaxy than in the SMC. How is this possible? This may not be related to the metallicity directly, but rather to differences in the average magnetic fields in these galaxies. Indeed, it is likely that the field is weaker in small irregular galaxies than in large spirals since the galactic dynamos are building the magnetic field. If the field is weaker in the SMC, the magnetic coupling between a contracting star and its surroundings is weaker and the star is less slowed down by the coupling. Thus, the relation of Fig. 3 should rather be attributed to the magnetic field than to metallicity, but since the metallicity is also lower in small irregular galaxies this may lead to the relation shown in Fig. 3. Of course, we could also examine other physical processes for the relation of Fig. 3. One possibility could be that at higher Z the collapse occurs faster, since more energy can be dissipated by dust grains. The faster collapse could generate more turbulence and more dissipation of the angular momentum.

Anyhow, the important conclusion from Fig. 3 is that massive star formation appears to lead to faster axial rotation in the LMC and SMC, which might be a general property of small irregular galaxies with lower Z. If so, this means that the evolution of massive stars is drastically influenced by rotational mixing, with large consequences for the number ratios of the stellar populations of massive stars and for the nucleosynthesis. The evidence of N-excesses in A-supergiants, of primary N in dwarf galaxies and of large excesses of N/C in some QSOs, may be related effects.

4.2. Models of rotating stars

Models of rotating stars are in progress at Geneva Observatory, they account for a number of physical effects which have been re-discussed recently:

- The role of the horizontal geostrophic turbulence which maintains a so-called "shellular" rotation (cf. Zahn 1992).
- The hydrostatic effects of rotational distortion (cf. Meynet & Maeder 1997).
- Shear mixing (Maeder 1997).
- A new study of meridional circulation, taking account of the μ-gradients (cf. Maeder & Zahn 1998).
- The anisotropic stellar winds in rotating stars and their role for the loss of angular momentum (cf. Maeder 1999).

The first results of the new models confirm in particular a variable extension of the main sequence with rotation, as well as a general enrichment in Helium and Nitrogen for rotating massive stars at the end of the Main Sequence (cf. also Meynet 1998). We are at the beginning of an intense phase of exploration of the effects of rotation in massive stars, which may lead to significant revisions of the model results for massive star populations and nucleosynthesis. In this context massive stars in the Local Group galaxies are a key test before the application of the models to the more distant universe.

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Discussion

Schulte-Ladbeck: André, as you form a massive star, you have to accrete an enormous amount of mass to get a high-mass star (as you showed). Now, due to conservation of angular momentum, you would expect to spin-up the core, possibly very rapidly, to break up. Could you discuss any ideas that you might have to avoid such a "spin-up crisis"?

Maeder: Firstly, I must clearly state that there are no pre-main sequence models including consistently the effects of rotation. Dissipation of the angular momentum is likely to occur in the accretion disk by turbulence and radiation. In addition magnetic coupling between the star, the disk and the surrounding cloud seems to be essential.

Gurzadyan: Which is the basic character of accretion in the considered models - disk or spherical? Obviously, the regime is crucial for the outcome.

Maeder: In the first models of pre-main sequence evolution with accretion some authors took constant accretion rates. The models by Bernasconi & Maeder (1996) used spherical accretion from a molecular cloud. Clearly complete models should include infall from a molecular cloud onto the accretion disk, treat the physics of the disk and obtain the accretion rate on the central star, the evolution of which is then followed. Such calculations are in progress by R Behrend in Geneva.

Käufl: Stecklum and Käufl have found an accretion disk around one galactic UC HII region. It shows up at about 10μm as a dust disk (cf. ESO Press Release 08/98 (24 June 1998)).

Maeder: Thank you, this is precisely the kind of result which may allow us to know which of the two theories for massive star formation is the right one. Concerning the result you are mentioning, it seems that the presence of a dust disk around a luminous UC HII region is in support of the accretion scenario and does not imply collision-induced massive star formation.

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Hutchings: Are there statistics on global variations of binary fraction which correlate with rotation and Be star fraction statistics, and also with Z?

Maeder: It would be beautiful, for star formation theories and also for star evolution, to know whether the fraction of binaries is changing with metallicity, but I think we do not have enough information yet.

Laney: The usual metal deficiencies cited for the LMC from HII regions are about 1.4-2 (LMC) and 4-5 (SMC). You cited z=0.006 (LMC) and 0.002 (SMC)! Why are these values so much lower than usual?

Maeder: The exact values of the metallicities of the LMC and SMC depend on whether you consider [Fe/H] or [O/H]. I think we use the [Fe/H] current values, which may explain the relatively low values quoted in the table of WR/O number ratios vs. metallicity.

Schmutz: You mentioned that there might be primary Nitrogen showing up on the surface of stars. How is this possible?

Maeder: In order to produce primary Nitrogen, it is necessary to have mixing of the H- and He-burning zones. In this way, new ^{12}C from the 3α reaction may be transported into regions where the CNO cycle is active, thus the ^{12}C will be turned to ^{14}N. The question is whether physical processes of rotational mixing are able to effectively produce the necessary mixing.

Feast: When the high frequency of Be stars in NGC 330 (SMC) was first noticed (MNRAS 159, 113, 1972), this suggested that there must be rather few slow rotators amongst the massive stars in this cluster. This in turn suggests that angular momentum has gone into stellar rotation rather than orbital motion in binaries and suggests a low frequency of binaries in the cluster. Two possible eclipsing binaries have been found in the cluster (Balona MNRAS 256, 425, 1992) but more work is required. Perhaps the effects you describe (due to high rotation) are linked to the lack of binaries in the population rather than directly to the metallicity.

Maeder: It is quite possible, as you are suggesting, that the high fraction of Be stars in NGC 330 is accompanied by a low frequency of binaries, although the observations are still insufficient to confirm this interesting suggestion. However, I think that the deep reason for the high Be frequency (and maybe low binary frequency) is related to the physics of star formation, which proceeds differently in the SMC and in the Galaxy, as a result of differences in basic parameters, such as metallicity, or maybe magnetic field which would change the rate of ambipolar diffusion and of angular momentum removal.